

Article

# Coastal Wind in East Iceland Using Sentinel-1 and Model Data Reanalysis

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## Abstract

This study evaluates three wind data sources in East Iceland's coastal environment: the high-resolution Synthetic Aperture Radar (SAR)-based Sentinel-1, the regional reanalysis Copernicus Arctic Regional Reanalysis (CARRA), and the global reanalysis ECMWF Reanalysis v5 (ERA5). We focus on assessing the advantages and limitations of each dataset, especially considering their differences in spatial and temporal resolutions. While ERA5 aligns well with CARRA and Sentinel-1 offshore, it tends to underestimate wind speeds and misrepresent wind directions near complex coastlines and fjords, with Root Mean Squared Difference (RMSD) values reaching up to 3.98 m/s in these areas. CARRA's higher resolution allows it to better capture coastal wind dynamics and shows strong agreement with Sentinel-1. Sentinel-1 excels in revealing detailed local wind features, such as katabatic winds in fjords, highlighting the value of satellite observations in complex terrain. By combining these complementary datasets, this study enhances understanding of coastal wind variability and supports improved hazard assessment in Iceland's challenging coastal environments.

**Keywords:** synthetic aperture radar; reanalysis data; Sentinel-1; wind assessment



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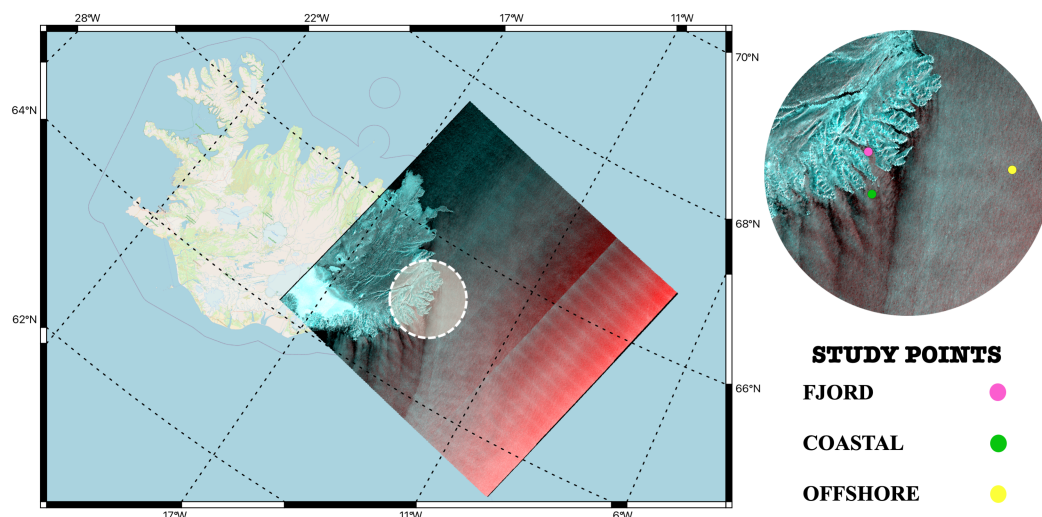
## 1. Introduction

Wind speed is a crucial determinant in various domains like wind energy generation, coastal protection, fisheries, and navigation [1]. Understanding wind patterns helps prevent coastal erosion and landslides, which are caused by wind-driven processes that destabilize soil and rock formations, exacerbating slope instability and leading to rock avalanches, especially along coastal cliffs and steep slopes [1–3]. Wind also affects ocean currents and nutrient distribution, influencing fish habitats and migration routes [4]. Accurate wind forecasts ensure safe navigation and guide vessel routes to avoid hazards. Additionally, coastal and near-offshore wind resources are key for renewable energy, helping countries reduce fossil fuel dependence [5]. Effective wind monitoring and predictive models are vital for protecting coastal communities and infrastructure, ensuring the safety and sustainability of human activities and natural processes.

There are various ways to measure wind speed, each with its advantages and limitations [6]. Traditional in-situ measurements provide high accuracy but are significantly limited in spatial coverage and can be logistically challenging, especially in offshore areas [7]. Currently, the most commonly used wind information sources are numerical weather models that provide comprehensive, gridded datasets of atmospheric conditions [8]. However, even though numerical weather models offer broader coverage,

they are still limited in terms of spatial resolution, parameterization of physical phenomena in the atmosphere, and the measurement data used in initialization and assimilation in the model [9]. Moreover, models provide lower performance accuracy when approaching more complex terrains e.g., coastal areas [10,11]. Satellite-based remote sensing using Synthetic Aperture Radar (SAR) offers unprecedented opportunities when it comes to high spatial resolution [12]. Despite its low temporal resolution, the ability to obtain detailed wind patterns even in fjords makes it a powerful tool for monitoring and analyzing wind-related coastal processes. Accordingly, each source has unique strengths and limitations, making them complementary in providing an extensive understanding of near-surface wind. These issues are particularly exacerbated when considering the different conditions affecting wind measurement in coastal and offshore scenarios. Specifically, the heat fluxes and the turbulence affect differently the near-surface wind at diverse heights, making its robust computation cumbersome. This needs to be addressed, as it potentially leads to limitations in the investigation of multiple aspects of ocean wind relevant to sustainability and climate change adaptation, such as power generation and air-sea fluxes [13,14].

Iceland's coast exemplifies the challenges of coastal wind assessment, as conditions vary noticeably due to the interplay of local current circulation and long-range climatic influences such as sea surface temperature oscillations and heat exchange across atmospheric and oceanic systems [15]. These environmental complexities have direct implications for safety and infrastructure, as coastal landslides and rock avalanches pose substantial risks to Icelandic communities. Such events are frequently triggered or intensified by strong winds interacting with the region's unstable geological features [16]. Therefore, accurate and timely wind speed and direction information are essential for hazard assessment and mitigation. The dynamic coastal environment of Iceland, characterized by steep cliffs and unstable slopes, requires precise wind monitoring to predict and manage these natural hazards effectively. In this study, we evaluate the relevance and accuracy of several wind products, focusing on a high-risk test case area in East Iceland, illustrated in Figure 1.



**Figure 1.** Geographical area investigated in this study. False-color composite representation (HH and HV polarization as Red and Green/Blue) of Sentinel-1 SAR images for 1 February 2018. Fjord point (pink dot), located in the Reyðarfjörður; Coastal point (green dot) 5 km south-east of Stöðvarfjörður; Offshore point (yellow dot) 50 km from the East Iceland coast. The false-color composite Sentinel-1 scene illustrates the intensity of the backscatter in dB, where higher values, i.e., bright areas, correspond to the rougher surface and therefore higher wind speed, and darker areas correspond to a smoother ocean surface and thus, lower wind speed.

Offshore and coastal wind assessment using both SAR-based products and reanalyses has advanced substantially in recent years, offering valuable insights into wind dynamics over marine environments. SAR-based wind measurements leverage the radar's ability to detect ocean surface roughness, which correlates with wind speed and direction [8]. Reanalysis datasets, such as ERA5, assimilate a wide range of observational data to provide comprehensive spatiotemporal coverage of wind fields, offering a coherent representation of historical weather conditions and supporting long-term analyses of offshore and coastal wind patterns for climate research and renewable energy assessments [9].

Recent studies, such as [17], have demonstrated the value of high-resolution calibrated and validated SAR ocean surface wind data for coastal and offshore wind mapping, particularly around the Australian coast. Their work highlights the potential of SAR products for operational and climatological applications in coastal regions, reinforcing the importance of detailed validation and calibration methods. Similarly, ref. [18] provides an in-depth comparison between the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis winds and Advanced Scatterometer (ASCAT) data in the Mediterranean Basin, emphasizing the challenges of model performance in coastal areas and the critical role of high-resolution observational datasets in identifying systematic discrepancies.

Integrating SAR with reanalyses improves the accuracy of wind assessments, enhancing our understanding of wind variability, extremes, and trends in marine environments [19,20]. These integrated approaches are pivotal for studying offshore wind resources, coastal wind patterns, and their environmental impacts. In this context, our study builds upon this body of work by contributing a focused comparison across varied coastal environments, fjord, coastal, and offshore, using Sentinel-1 SAR, ERA5, and CARRA wind fields to better understand wind dynamics in the complex terrain surrounding Iceland.

In this research, we conduct a comprehensive analysis of three wind data sources: the high-resolution SAR-based Sentinel-1 wind product, the global reanalysis ERA5, and the regional reanalysis CARRA. Our primary focus is to validate the Sentinel-1 wind product due to its high spatial resolution and its capability to provide valuable complementary information in coastal areas, where traditional reanalyses like ERA5 and CARRA often struggle to capture localized wind dynamics. By comparing the differences and similarities between these data sources through experiments involving multiple study points that vary in their distances from the coastline and wind conditions, we aim to assess the relevance of Sentinel-1 as an additional wind data source.

We would like to highlight that the core objective of our work is not to equate ERA5, CARRA, and Sentinel-1 Ocean (OCN) in terms of resolution, model configuration, or statistical independence. Instead, our intention is to evaluate the performance and limitations of these widely used operational wind products as they are typically used by end users, that is, in their standard, uncorrected form. All datasets were analyzed without filtering, masking, or applying stability adjustments, in order to preserve their original characteristics and to reflect practical usage scenarios. The ultimate goal of this study is to enhance the understanding and application of remote sensing technologies in coastal hazard assessment, ultimately contributing to the development of more effective mitigation strategies for Iceland's vulnerable coastal regions.

The wind datasets and analysis methodology are described in Section 2. Experimental results are presented in Section 3, followed by discussion and conclusions in Section 4.

## 2. Data and Methods

### 2.1. Datasets

#### 2.1.1. Remote Sensing

During the last few decades, SAR has become one of the key sensors that monitor the Earth's surface and significantly improved various applications. Nowadays, there are a few SAR systems that are orbiting the Earth, providing complementary observations with different characteristics. In this study, we are particularly focused on the Sentinel-1 SAR mission operated by the European Space Agency (ESA) as part of the Copernicus Programme. Sentinel-1 data are publicly available for non-commercial use and can be accessed through the Copernicus portal [21]. Sentinel-1 operates in the C-band frequency range, which offers a good balance between resolution and penetration capabilities through various weather conditions and vegetation. It includes two polar-orbit Sentinel-1A and Sentinel-1B missions that provide multiple sensing modes in single and dual polarization at 40 m spatial resolution.

The Sentinel-1 Level-2 OCN Ocean Wind Field (OWI) product is a fully calibrated and operational dataset derived from Sentinel-1 Level-1 SAR imagery. It provides wind speed and direction at 10 m above the ocean surface, retrieved via inversion of the Normalized Radar Cross Section (NRCS) using Geophysical Model Functions (GMFs). By default, the GMF applied in this product is C-band Model (CMOD)-IFR2, part of the CMOD family of models designed to convert NRCS values into wind estimates [22]. Wind speed is directly retrieved from the SAR backscatter, while wind direction is generally extracted from co-located auxiliary numerical weather prediction (NWP) data, interpolated in space and time to the SAR acquisition. The resulting wind vector fields are provided in ground-range geometry with a spatial resolution of 1 km. For this study, we extracted available Sentinel-1 Level-2 OCN scenes for the East Iceland coast for 4 years from 1 January 2018 to 31 December 2021. Sentinel-1 revisits the region of interest once in a few days, passing either at around 7:00 UTC or 18:00 UTC.

#### 2.1.2. Reanalyses

*Global reanalysis:* ERA5 is the fifth-generation global reanalysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) [9,23]. It is based on a 4D-Var data assimilation scheme within the Integrated Forecasting System (IFS), which combines a global atmospheric model with a variety of observations, including remote sensing and surface measurements. With a horizontal resolution of approximately 31 km and 137 vertical levels, ERA5 provides a consistent, hourly estimate of atmospheric parameters since 1950. Despite its coarse resolution and its connection to CARRA, ERA5 remains a critical part of our study. Its global coverage, hourly resolution, and long-term consistency make it a widely accepted benchmark, especially in data-sparse regions like Iceland. While ERA5 cannot capture fine-scale wind variability in fjords, it provides a robust synoptic-scale reference. Its inclusion allows for a meaningful assessment of the added value offered by higher-resolution products like CARRA and Sentinel-1 SAR, aligning with our goal of evaluating operational wind products as they are typically used in practice.

*Regional reanalysis:* The CARRA is a high-resolution regional reanalysis tailored for the Arctic region, providing 3-hourly analyses and hourly short-range forecasts at 2.5 km spatial resolution. It is built using the HARMONIE-AROME NWP model (cycle 40h1.1), a convection-permitting non-hydrostatic model designed for short-range weather prediction in high-latitude regions [24]. CARRA assimilates additional local observations and benefits from refined representations of regional physiography, orography, and sea ice, which significantly enhance its ability to resolve fine-scale atmospheric features compared to global models. While it uses ERA5 as its lateral boundary condition, CARRA offers

improved accuracy in reproducing wind dynamics in coastal and topographically complex areas [25]. In this study, we use the CARRA-West domain, covering Svalbard, Iceland, Greenland, and the Canadian Archipelago [26]. Both ERA5 and CARRA datasets were obtained from the Copernicus Climate Data Store.

## 2.2. Methodology

### Preprocessing

In total, we collected 718 Sentinel-1 Level-2 OCN scenes near East Iceland starting from 1 January 2018 to 31 December 2021. This 4-year period was chosen based on a higher occurrence of available scenes in the Sentinel-1 data covering the area, in contrast to the years before and after. We have selected three study points that represent different wind conditions from the coastline point of view: (a) *Fjord point* (65.024° N, −13.927° E) is located in Reyðarfjörður, East Iceland's longest fjord, stretching about 30 km inland and reaching up to 6–7 km in width; (b) *Coastal point* (64.844° N, −13.625° E) is located approximately 5 km from the coast of Stöðvarfjörður and expected to have some influence from the coastline; (c) *Offshore point* (65.326° N, −12.303° E) is located 50 km from the East Iceland coast in the open ocean. The main reasons for choosing this specific region of interest: (a) we wanted to use one of the study points located in a long and wide Iceland fjord (see the pink dot on Figure 1 circular map), therefore, we chose East Iceland which has a significant diversity of fjords of varying widths and lengths; (b) based on several studies [27,28], the continental area near the Fjord and Coastal study points is one of the highest landslide and rock avalanche risk locations in Iceland making the obtaining of accurate wind information in this area even more valuable.

For reanalyses, we employed the 10 m *u*- and *v*-components of wind, calculating the wind speed via  $\sqrt{u^2 + v^2}$ . Accordingly, wind speed and direction at 10 m above the ocean surface were acquired from both ERA5 and CARRA for three representative locations, fjord, coastal, and offshore, and co-located with Sentinel-1 data both spatially and temporally.

The Sentinel-1 Level-2 OCN product was extracted for the East Iceland coast over a four-year period from 1 January 2018 to 31 December 2021. Given Sentinel-1's revisit frequency of several days, with overpasses typically occurring around 07:00 UTC or 18:00 UTC, we ensured temporal alignment by selecting the nearest available time steps from the reanalyses. For ERA5, which provides hourly data, we extracted the model outputs that matched the Sentinel-1 overpass times (07:00 or 18:00 UTC). For CARRA, which offers 3-hourly data, we used the time step closest to the Sentinel-1 acquisition, 06:00 or 18:00 UTC, respectively, to minimize the temporal mismatch. While interpolation between time steps could improve temporal consistency [29], we deliberately used the nearest available value to maintain consistency with the core objective of this study, evaluating the standard, operational forms of each product as they are typically delivered and used.

ERA5 data were extracted as single grid points closest to the respective study sites due to its relatively coarse resolution of 31 km. In the case of the Fjord location, the nearest ERA5 grid point falls approximately 1 km inland, which may lead to slightly lower wind speed values due to land influence. However, given the available options, as well as considering the grid structure and the need for a consistent dataset comparison, this remains the most suitable representation for ERA5 in that location.

For CARRA and Sentinel-1, which offer higher spatial resolutions, we computed the mean of the four nearest grid points to reduce sampling variability and ensure a more representative and statistically robust comparison. The closer spatial alignment between CARRA and Sentinel-1 allows for a more detailed and consistent assessment of wind behavior in complex coastal settings. This approach helps to ensure that our

comparisons used data sources that were as closely matched as possible in both space and time, improving the reliability and consistency of the inter-product evaluation.

It is important to note that no post-processing corrections, filtering, or masking were applied to the Sentinel-1 Level-2 OCN OWI wind speed data. It is known that potential artifacts caused by high backscatter from targets such as ships or offshore platforms may give artificially high wind speeds in some SAR wind results, particularly in coastal areas or near maritime traffic. Similarly, low wind speed retrievals from SAR can be less reliable due to inherent sensitivity limitations. The Sentinel-1 OCN product inherently assumes neutral atmospheric stability, which is standard practice due to the lack of concurrent stratification data.

Since all wind data in our study are provided at the same 10 m reference height, without any modification or post-processing, our approach preserves both the capabilities and limitations of the datasets as they would appear to the typical end-users and thus allows for a consistent basis for comparison.

To evaluate the wind speed from multiple data sources, several statistical metrics are employed to assess their performance and mutual consistency. In this study, we apply Root Mean Square Difference (RMSD), Standard Deviation (STD), and Pearson Correlation Coefficient (R), based on a dataset comprising 718 Sentinel-1 wind speed observations matched with corresponding values from reanalysis products. RMSD quantifies the average magnitude of differences between paired wind speed values from each dataset, reflecting the discrepancies across Sentinel-1, ERA5, and CARRA without assuming any single dataset as the absolute reference. Although RMSD is computed using the same formula as RMSE, it specifically emphasizes that these values represent differences between datasets rather than errors relative to true observations. The RMSD between two datasets is computed as follows:

$$\text{RMSD} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2} \quad (1)$$

where  $x_i$  and  $y_i$  represent paired wind speed values from two different datasets, and  $N$  is the total number of paired observations [30].

STD provides a measure of spread or variability within each dataset, while R reflects the strength and direction of the linear relationship. These metrics, when considered together, offer a comprehensive picture of data quality by capturing accuracy (RMSD), variability (STD), and structural similarity (R) [31].

Wind direction was assessed using wind rose plots for visual comparison only. The main focus is on wind speed, which is independently derived in each product. In Sentinel-1 OWI, wind direction is assigned from the background wind field provided by numerical weather prediction models, so it is not independently retrieved from SAR data.

Although in-situ measurements are typically prioritized for model validation due to their direct observational nature, such data are unfortunately publicly unavailable for the East Iceland region covered in this study. Consequently, we adopt Sentinel-1 as our reference product, as it provides the most spatially resolved and observation-based information available for our area of interest. This decision is supported by previous studies that have validated SAR wind retrievals against in-situ observations in both offshore and coastal zones, confirming their reliability and accuracy [29,32,33]. Moreover, in our previous work, Sentinel-1 was explicitly compared with in-situ data and reanalyses in the Northern Norway region, reinforcing its suitability as a reference dataset [34].

### 3. Experimental Results

#### 3.1. Wind Speed Evaluation

##### 3.1.1. Statistical Metrics

##### Single-Source Metrics

Table 1 displays essential parameters related to wind speed from individual data sources, including minimum, mean, maximum values, and standard deviations. These metrics provided insights into the characteristics of each data source independently. The highest variation between the metrics can be seen for Fjord point with the standard deviation twice smaller for ERA5 than CARRA and Sentinel-1 sources. That specifically indicates the larger amount of wind speed variability, especially for the CARRA which has the highest standard deviation value of 3.84. For the Coastal point, the pattern remains the same with the lowest standard deviation for the ERA5 and a higher value for CARRA. Offshore point provides very similar values for each data source without any significant differences in the standard deviation meaning that the variability between the wind speed values was comparable between the wind products used in this study.

**Table 1.** Statistical parameters related to wind speed from individual data sources, including the standard deviation ( $\sigma$ ), minimum, mean, and maximum wind speed values in m/s for three distinct study points: Fjord, Coastal, and Offshore. S-1 refers to the Sentinel-1 OWI product.

Metrics [m/s]	Fjord			Coastal			Offshore		
	S-1	ERA5	CARRA	S-1	ERA5	CARRA	S-1	ERA5	CARRA
$\sigma$	3.59	1.68	3.84	4.37	3.33	4.50	4.65	4.22	4.41
min	0.0	0.1	0.3	0.0	0.1	0.3	0.0	0.6	0.5
mean	5.1	3.1	6.0	7.1	6.2	8.1	8.5	8.8	8.8
max	21.1	10.4	22.0	21.9	20.0	26.0	26.1	22.5	25.4

Regarding wind speed values, the minimum values appear similar across all sources and study points, indicating a consistent baseline. However, it is important to note that Sentinel-1 SAR winds consistently report exact zero as the minimum due to retrieval limitations under low wind conditions, whereas both ERA5 and CARRA provide non-zero minimum values, reflecting their ability to resolve low winds more reliably. Nevertheless, the mean values highlight notable differences: ERA5 has lower wind speeds than CARRA and Sentinel-1 in the Fjord, likely due to the coarse spatial resolution. In contrast, for the Coastal and Offshore points, the mean values from ERA5 are more aligned with those from CARRA and Sentinel-1, suggesting that the impact of complex landscapes decreases as the distance from the coast increases. The maximum values further illustrate these discrepancies. ERA5 clearly shows lower wind speeds at the Fjord point, but the differences are less pronounced at the Coastal and Offshore points. This underestimation by ERA5 at the Fjord point highlights its difficulty in accurately capturing extreme wind events in complex terrains. In contrast, CARRA and Sentinel-1 display very similar values for minimum, mean, and maximum wind speeds across all study points, underscoring higher accuracy and better spatial resolution of Sentinel-1 and CARRA compared to ERA5.

Overall, these observations support the conclusion that while ERA5 struggles with accuracy in complex coastal terrains, both reanalysis sources, ERA5 and CARRA, show improved agreement with Sentinel-1 data as the distance from the coastline increases. Moreover, the consistency and similarity in CARRA and Sentinel-1 performance across all metrics demonstrates its reliability and suitability for applications requiring precise wind speed measurements.

### Comparative Metrics Between Data Sources

Table 2 focuses on comparative metrics, illustrating differences between the sources. Here we apply RMSD and Pearson correlation coefficient to identify the differences and similarities between Sentinel-1, ERA5, and CARRA. While our study includes a cross-source comparison, our primary focus is on Sentinel-1, selected as our reference data since it is the closest source we have to actual measurement methods and serves as the benchmark against the reanalysis models. For the Fjord point, we observe the largest difference in RMSD values between ERA5 and CARRA with the highest RMSD of 3.98. In relation to the reference source, the ERA5 results in a higher RMSD than CARRA, indicating greater divergence from Sentinel-1 values. This disparity is most likely connected to ERA5 coarse resolution that makes it difficult to model complex coastal terrain accurately, and data assimilation challenges. As we move further from the fjord, these challenges partially disappear, which is especially evident in similar RMSD values for ERA5 and CARRA compared to Sentinel-1 for both Coastal and Offshore points, reinforcing the assumptions mentioned above. In contrast, with a spatial resolution similar to Sentinel-1, CARRA exhibits lower RMSD values signifying closer agreement with Sentinel-1. Although for offshore and coastal points the RMSD values are not that high and are very similar for both ERA5 and CARRA, the high RMSD values obtained for the Fjord point can result in notable overestimation or underestimation in assessing wind conditions. These findings underscore the impact of spatial resolution on wind speed assessment accuracy and highlight that increasing distance from the coastline correlates with better agreement between the Sentinel-1 data and the reanalysis data.

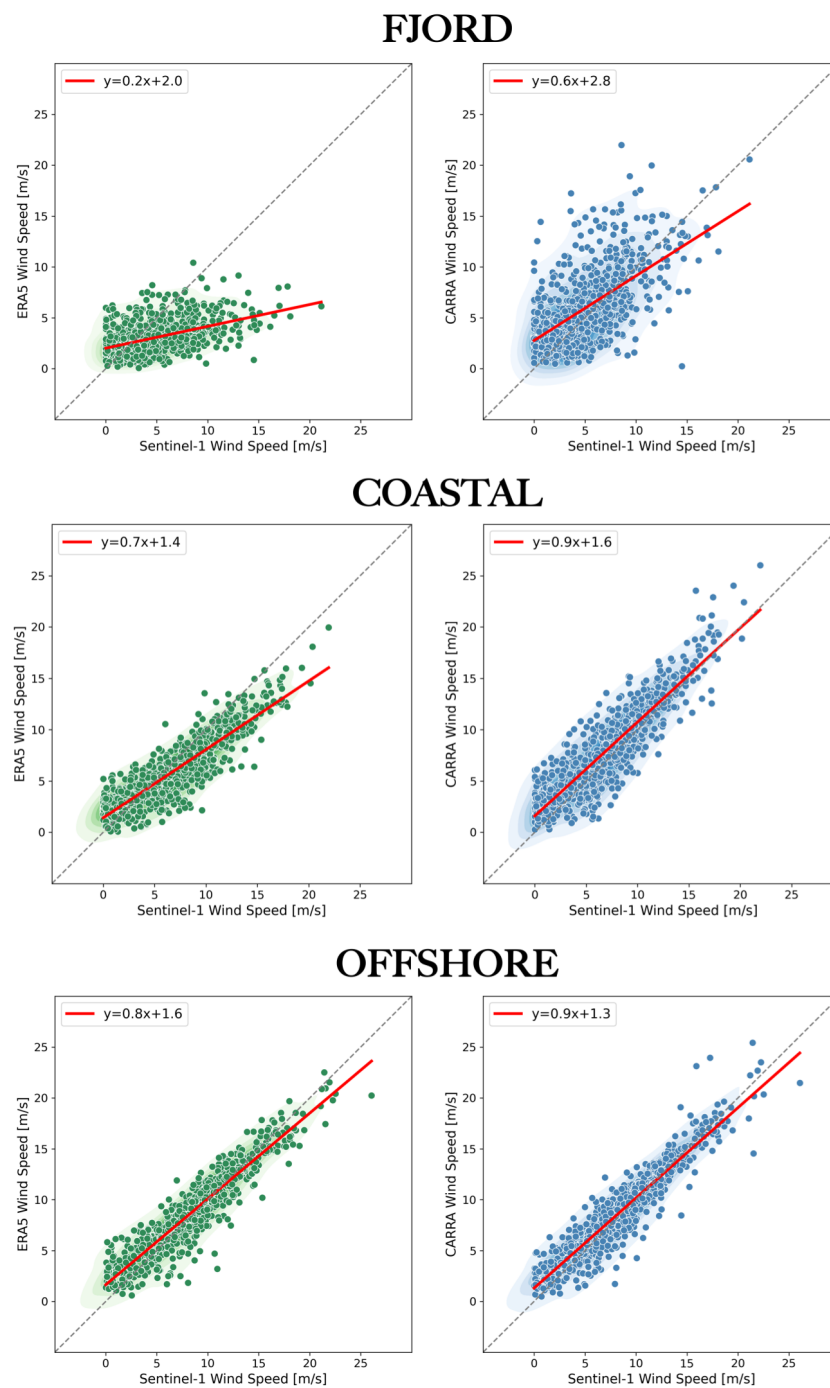
We can draw similar conclusions from the Pearson correlation coefficient values obtained with reanalysis products with respect to Sentinel-1. For the Fjord point, the correlation coefficients reveal varying degrees of linear relationships between Sentinel-1 and the reanalysis products. Correlations of 0.49 and 0.59 correspond to the moderate relationship between the data sources, suggesting a noticeable but not strong association with the Sentinel-1 data. However, CARRA exhibits a robust correlation with ERA5 equal to 0.79. Nevertheless, in connection to the reference source, these results suggest that CARRA provides a more accurate representation of wind speeds observed by Sentinel-1, likely due to its higher spatial resolution. In contrast, the Coastal and Offshore points, exhibit a strong and relatively similar linear relationship between the data sources. It is also worth mentioning that the Offshore point still provides the highest correlation values between Sentinel-1 and both reanalysis products. Overall, these findings underscore strong agreement and relationship between ERA5 and CARRA, at the same time the reliability of each data source in capturing wind speed variability across diverse marine environments, with CARRA generally exhibiting slightly higher correlations compared to ERA5 in closer alignment with Sentinel-1 observations.

**Table 2.** Cross-correlation and -RMSD matrix between the different wind speed data sources for several study points, i.e., Fjord, Coastal, Offshore. The values below the diagonal (light pink) show RMSD values, while the upper values (light blue) display Pearson correlation coefficients. S-1 corresponds to the Sentinel-1 OWI product.

Data Source	Fjord			Coastal			Offshore		
	S-1	ERA5	CARRA	S-1	ERA5	CARRA	S-1	ERA5	CARRA
S-1		0.46	0.59		0.88	0.89		0.93	0.93
ERA5	3.77		0.79	2.37		0.90	1.70		0.95
CARRA	3.47	3.98		2.31	2.88		1.74	1.32	

### 3.1.2. Scatterplots

Figure 2 illustrates the scatterplots obtained from comparing the wind speed from the Sentinel-1 with global ERA5 and regional CARRA reanalysis. The Sentinel-1 values are plotted on the horizontal axis, while other sources are plotted along the respective vertical axes. The heatmaps plotted in the background provide additional insights into the wind speed distribution across the scatterplots, e.g., darker regions in the heatmap correspond to a higher density of data points. Additionally, linear regressions were fitted to each scatterplot.

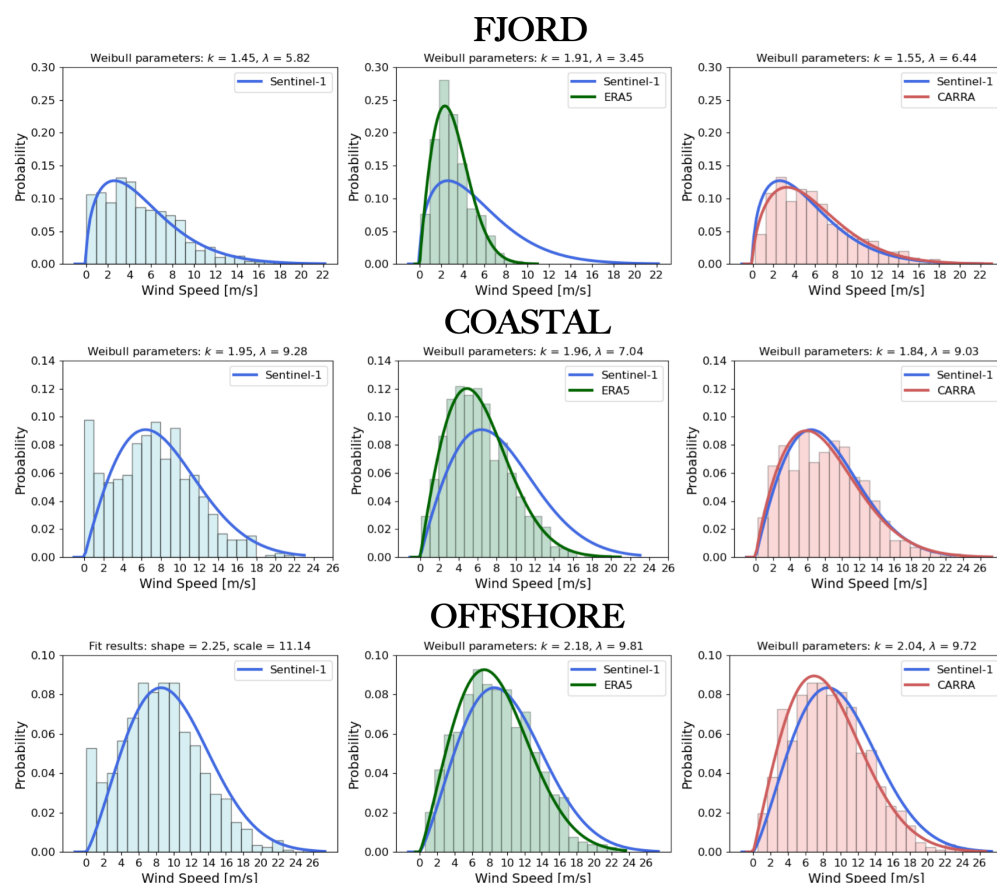


**Figure 2.** Scatterplots of wind speed data from Sentinel-1 plotted on the horizontal axes versus global reanalysis ERA5 and regional reanalysis CARRA plotted on the vertical axes, respectively. The scatterplots demonstrate the wind speed for several study points: Fjord, Coastal, and Offshore.

The scatterplots demonstrate a very strong positive linear relationship between Sentinel-1 and both reanalyses for Coastal and Offshore points. Moreover, the slope and intercept parameters only have small changes for these two points, and the Sentinel-1/CARRA are closest to the unity slope. Furthermore, the close clustering of data points additionally illustrates the clear similarity between Sentinel-1 and ERA5/CARRA. The situation is slightly different for the Fjord point. In contrast to the Coastal and Offshore points, the scatterplots for the Fjord point show a sparser distribution of points with a wider dispersion of points across the plot, meaning that there is a lower similarity between the Sentinel-1 and both reanalysis data points.

### 3.1.3. Wind Speed Distribution

To properly assess offshore wind resources in a given region, an accurate representation of the wind speed distribution is crucial. The Weibull distribution is commonly used for this purpose since it provides a good fit for offshore wind speed data [35]. It has two crucial parameters: (a) the scale parameter  $\lambda$  specifies the ratio of horizontal to vertical extent of the distribution; (b) the shape parameter  $k$  indicates the skewness of the distribution. Figure 3 shows the wind speed histogram for the three study points and the different data sources, as well as the corresponding estimated Weibull probability distribution. Moreover, it illustrates the corresponding Weibull parameters, namely  $k$  and  $\lambda$ .



**Figure 3.** Weibull probability density function and observed wind speed histograms of Sentinel-1, ERA5, and CARRA for several test points: Fjord, Coastal, and Offshore. Additionally, the figure displays the Weibull shape ( $k$ ) and scale ( $\lambda$ ) parameters obtained for each source.

At the Fjord point, notable distinctions among the data sources become evident. The histograms depicting the frequency of actual wind speed values illustrate varying characteristics. Sentinel-1 exhibits a broader distribution with a lower peak, suggesting a

wider range of wind speeds centered around a moderate average speed. On the contrary, ERA5 shows a more peaked histogram, indicating that wind speeds tend to cluster consistently around a lower average speed. CARRA distribution lies between these two extremes, narrower than Sentinel-1 but with a higher average wind speed than ERA5. Consequently, ERA5 shows greater consistency but lower wind speeds, whereas Sentinel-1 and CARRA display higher average wind speeds with more variability, notably with CARRA having the highest average wind speed among the sources. Considering the significant spatial resolution differences between ERA5 and the other sources, alongside the proximity of this point to the coast, ERA5 appears to underestimate wind speeds compared to higher-resolution products like Sentinel-1 and CARRA. The Weibull distribution, derived from estimated parameters based on wind speed data, provides a probabilistic model that describes the overall wind speed variability for each data source. It allows us to characterize the typical wind conditions beyond individual measurements, highlighting differences in wind behavior captured by each dataset. In our previous research, we demonstrated that even sparse temporal data can effectively represent denser datasets over time [34]. Thus, the Weibull distribution offers an insightful estimate of the overall wind conditions at the site, covering broader aspects beyond specific observations. The Weibull parameters further highlight the differing characteristics and reliability of each data source in capturing the wind speed distribution at this location.

For the Coastal point, both Sentinel-1 and CARRA histograms suggest relatively broad distributions with higher average wind speeds, indicating significant variability around a high mean wind speed. In contrast, ERA5, similar to observations at the Fjord point, exhibits a more peaked histogram, indicating wind speeds are consistently grouped around a lower average speed compared to the other two sources. Despite these differences, the variability between the three sources appears slightly reduced in this coastal context. It is worth mentioning that the Weibull probability density functions for Sentinel-1 and CARRA are quite similar for each study point. However, for Coastal point the curves are remarkably identical, almost perfectly matching, indicating an even stronger similarity between these two sources.

The Offshore point, situated as the most distant location in our study, exhibits closely aligned values with minimal discrepancies across all three wind speed data sources. Sentinel-1 indicates a relatively narrow distribution with a higher average wind speed, suggesting less variability and consistently higher wind speeds. Similarly, ERA5 also shows a narrow distribution, albeit with a slightly lower average wind speed compared to Sentinel-1. CARRA displays a similar pattern to ERA5 but with a slightly broader distribution. At this location, both the histograms and Weibull probability density functions illustrate notable similarities across the data sources, highlighting a more uniform representation compared to points closer to the coast. The Weibull parameters further reinforce this observation, showing less divergence among Sentinel-1, ERA5, and CARRA. Overall, Sentinel-1 consistently reflects the highest and most consistent wind speeds among the sources, while both reanalysis datasets indicate slightly lower average wind speeds with comparable consistency at the Offshore point. Moreover, Sentinel-1 data shows a pronounced tendency toward higher frequencies of wind speed values close to zero. This pattern could be connected to various factors: physical properties such as the water surface remaining smooth at very low wind speeds or the presence of algae and oil slicks, issues related to algorithm calibration, or instances of no wind in the region.

From the abovementioned results, we can conclude that, despite the low temporal resolution, the Sentinel-1 wind speed product demonstrates its importance and relevance for the coastal areas as it offers high-resolution and real-time observations that enhance the accuracy and reliability of wind speed data compared to commonly used models. Moreover,

Sentinel-1 provides very similar wind information to CARRA, both showing a robust performance in the coastal areas. In contrast, the ERA5 seems to underestimate the wind speed, which is especially evident for the Fjord and Coastal points. It can be the consequence of various equally significant reasons. The coarser spatial resolution of ERA5 smooths out fine-scale wind features that can be captured by higher-resolution Sentinel-1. Coastal areas have complex topography and land-sea interactions that the standard wind models often fail to accurately represent, due to their simplified parameterizations and broader averaging. The limitations in data assimilation, as well as the challenges in accurately representing sea state, surface roughness, and coastal meteorological phenomena, further contribute to the ERA5 underestimation of wind speeds in the coastal regions. Nevertheless, it is crucial since this underestimation can result in overlooking the erosive power of wind on coastal cliffs, leading to unexpected landslides and rock avalanches, inaccurate energy production forecasts, and imprecise predictions of sea conditions. Additionally, it is important to highlight once more a known limitation of the SAR wind product, across all study points, Sentinel-1 consistently reports a high frequency of zero wind speed values. This artifact, clearly visible in the distributions, reflects the limited sensitivity of SAR to very low wind conditions and may impact the overall interpretation.

### 3.2. Wind Direction

Although our study primarily focused on wind speed, wind direction is also a crucial parameter that can have a significant impact on both environmental and human activities. Accurate assessment of wind direction helps in predicting weather patterns, ensuring the safety of maritime activities, and optimizing the performance of wind turbines for renewable energy generation [36]. Moreover, wind direction plays a key role in seawater mixing, affecting local ecosystems and biological productivity [37,38]. Furthermore, a better understanding of wind direction patterns can help predict potential landslide zones, implement early warning systems, and design mitigation strategies to protect local communities and infrastructure [39].

Figure 4 demonstrates the wind roses of all data sources for three study sites, displaying the occurrences of wind directions and a rough representation of the wind speed distribution for each wind direction sector, allowing for a visual comparison.

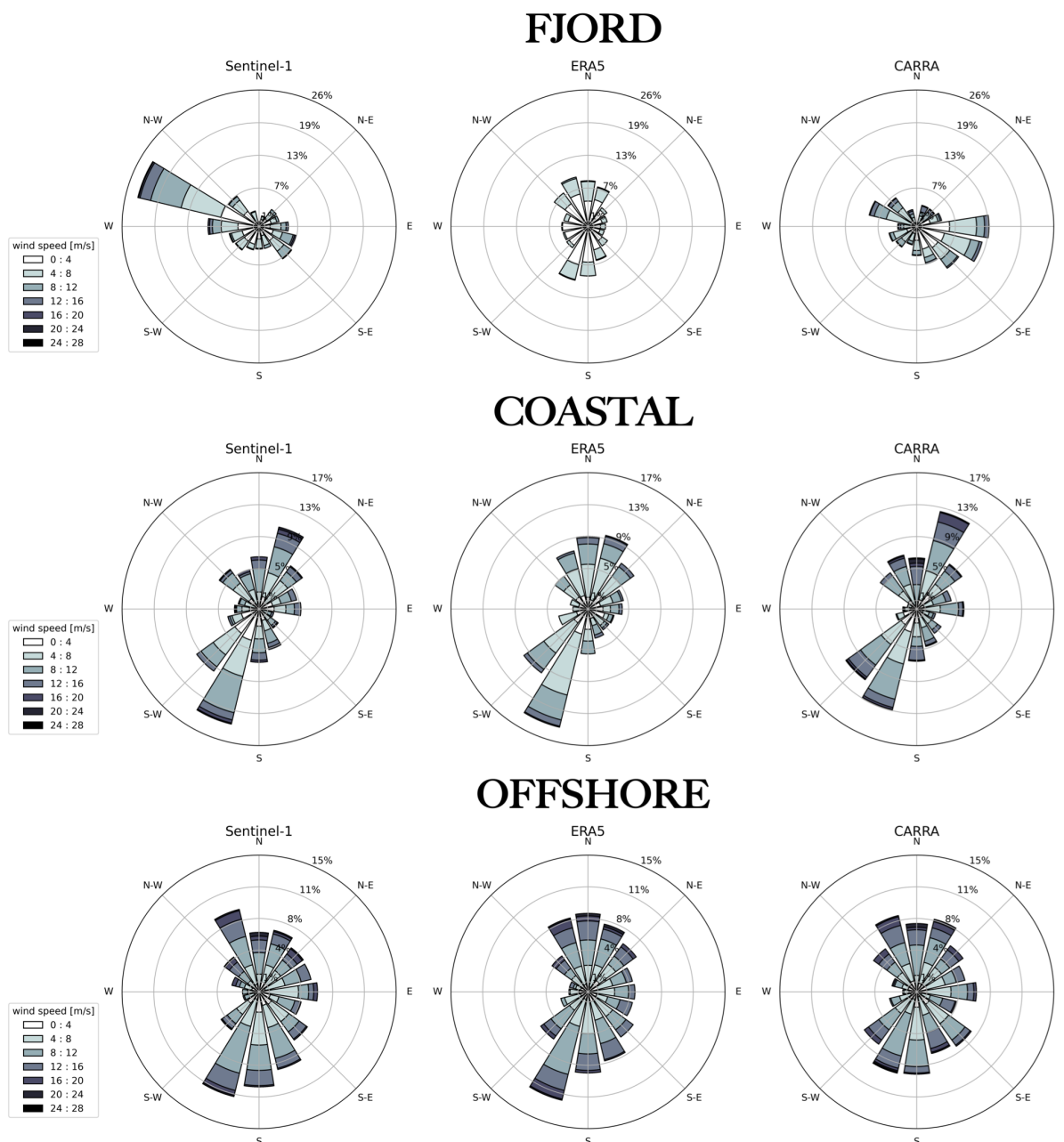
The wind rose for the Fjord site reveals distinct patterns among the data sources. Sentinel-1 predominantly shows winds coming from the west-northwest following the fjord direction. This might be a result of katabatic winds, in which cold and dense air flows from the inland of Iceland down to the warmer sea level, a phenomenon previously observed in Northern Norway and Svalbard [40]. ERA5 indicates lower wind speeds with winds coming primarily from the north or south. In contrast, CARRA displays wind patterns aligned with the fjord's direction, as expected due to its higher spatial resolution, however, it also shows a higher frequency of winds coming from the sea than from the inland. Although Sentinel-1 wind direction is assigned from a numerical weather prediction model and is not fully independent, the differences between ERA5 and Sentinel-1 likely arise because ERA5 represents more inland conditions while Sentinel-1 wind directions are spatially interpolated over the fjord's water surface.

At the Coastal site, Sentinel-1 and CARRA exhibit strong similarities, showing a slightly narrower sector of winds coming from the north-northeast compared to ERA5. The wind direction appears influenced by the land-sea boundary, with a limited frequency of winds from the west and east.

The Offshore site shows minor differences among the wind roses. CARRA has more sectors with wind frequencies of around 8%, while Sentinel-1 and ERA5 indicate an 11% frequency for winds from the south-southwest sector. This discrepancy might be due to

slight deviations in wind direction, as the southwest sector shows lower frequencies in Sentinel-1 and ERA5 compared to CARRA.

These observations emphasize the importance of assessing wind direction in coastal areas, where complex fjord topography and mountains significantly influence the wind field over the ocean. While it is challenging to accurately compare wind directions at the Fjord point due to the variance between data sources, the Coastal and Offshore points show similar performance across the sources. This highlights the relevance of Sentinel-1 high-resolution data, which can capture small-scale wind patterns and formations that might be overlooked by regional reanalyses and are likely missed by global reanalyses.



**Figure 4.** Wind roses displaying the wind direction distributions from the Sentinel-1, ERA5, and CARRA data sources for Fjord, Coastal, and Offshore points.

#### 4. Conclusions and Discussion

In this study, the analysis reveals important insights into the performance of different wind data sources for three locations that vary considerably in wind conditions and distance

to the continent. ERA5 data, being generally consistent with CARRA and Sentinel-1 data for offshore locations, demonstrates significant limitations when approaching the coastline, particularly in fjords. Specifically, ERA5 tends to underestimate wind speeds and provides unreasonable wind direction data in these areas. This discrepancy underscores the challenges of modeling wind behavior in complex terrains using lower-resolution data.

The regional CARRA model, with its higher spatial resolution, shows a marked improvement in capturing wind speed and direction along the coast of Iceland, compared to global ERA5. Its results are very similar to those obtained from Sentinel-1, indicating that CARRA is well-suited for coastal wind analysis. This alignment suggests that CARRA can effectively complement Sentinel-1 data, providing a robust framework for understanding wind patterns in coastal regions.

An intriguing finding from our study is Sentinel-1 potential to capture unique wind patterns within fjords, such as katabatic winds, which illustrates its role as a prominent and relevant source for assessing wind conditions in these areas. This capability highlights Sentinel-1 advantage over other data sources, particularly due to its high resolution and ability to reveal detailed wind dynamics in complex environments.

It is worth mentioning that we do not aim to generalize the wind dynamics of Reyðarfjörður to other locations. Rather, it serves as a focused test case to assess product performance in complex terrain. The findings are specific to this region and illustrate broader challenges in modeling coastal wind fields with coarse-resolution data.

Despite promising results, this study presents several opportunities for refinement and further investigation. First, the indication of localized wind phenomena such as katabatic flows in fjords highlights the need for targeted validation using ground-based instrumentation or airborne campaigns. These efforts could not only confirm the presence and structure of katabatic winds but also enable detailed analysis of short-term wind events such as storms or polar lows, which were beyond the scope of this study but are of high relevance for hazard monitoring and forecasting.

An important limitation of the methods in this study is that it is geographically limited to a single fjord in Iceland. To assess the broader applicability of our findings, similar inter-comparisons should be conducted in other coastal environments with diverse climatic and topographic conditions. Another limitation relates to the temporal collocation of datasets. While we carefully selected the nearest available time steps to match Sentinel-1 overpasses, minimizing the mismatch to a maximum of one hour, CARRA's 3-hourly resolution can still introduce some temporal uncertainty. Although wind conditions in our study areas were generally stable enough that this likely did not cause major discrepancies, future work could benefit from temporal interpolation to improve precision in more dynamic wind regimes.

Future work could also consider the application of atmospheric stability corrections to SAR wind retrievals, particularly in stratified conditions commonly found in coastal zones. While the current study relied on standard, uncorrected wind products to preserve end-user relevance, applying corrections using flux algorithms when appropriate atmospheric data is available could help quantify the benefits and limitations of stability adjustments.

Furthermore, additional filtering techniques to identify and mitigate anomalous SAR pixels, such as those influenced by ships, platforms, or extremely low wind conditions, could further improve the robustness of SAR-based wind analysis. Exploring these enhancements in conjunction with reanalysis data would support more accurate wind field characterization for both operational and research applications in coastal hazard monitoring, renewable energy planning, and atmospheric modeling.

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## Abbreviations

The following abbreviations are used in this manuscript:

SAR	Synthetic Aperture Radar
OWI	Ocean Wind Field
NWP	Numerical Weather Prediction
ECMWF	European Centre for Medium-Range Weather Forecasts
NRCS	Normalised Radar Cross Section
GMF	Geophysical Model Function
RMSD	Root Mean Squared Difference
STD	Standard Deviation

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