

Article

Assessment of Coastal Winds in Iceland Using Sentinel-1, Reanalysis, and MET Observations

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Abstract

This research evaluates three wind data sources, the Sentinel-1 wind product, the global reanalysis ERA5, and the regional reanalysis CARRA, across Iceland's North, South, West, and East coastal regions. The analysis mainly focuses on validating Sentinel-1 high-resolution capabilities for capturing fine-scale wind patterns in coastal zones, where traditional reanalyses may have tangible limitations. Performance is evaluated through intercomparison of datasets and analysis of regional wind speed variability, with in situ coastal meteorological observations providing ground-truth validation. The results highlight the relative strengths and limitations of each source, offering guidance for improving wind-driven and wind-dependent applications in Iceland's coastal regions, such as hazard assessment, marine operations, and renewable energy planning.

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



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1. Introduction

Wind speed plays a vital role across diverse sectors, including renewable energy production, coastal management, fisheries, and maritime navigation [1,2]. By analyzing wind patterns, we can mitigate risks of coastal erosion and landslide phenomena often driven by wind-induced destabilization of soil and rock. This destabilization can amplify slope instability, leading to rockfalls and avalanches, particularly along cliffs and steep coastal terrains [3,4]. Moreover, wind influences ocean dynamics by shaping currents and dispersing nutrients, which are essential for fish habitats and migratory patterns [5]. Accurate wind forecasting is crucial for safe and efficient navigation, enabling vessels to avoid hazardous routes. Comprehensive wind monitoring and predictive modeling are indispensable tools for safeguarding coastal communities, supporting infrastructure resilience, and promoting balance between human activities and natural ecosystems.

Wind speed can be measured using various methods, each with distinct strengths and limitations. Traditional in situ measurements are considered highly accurate but offer limited spatial coverage and are logistically challenging, especially for offshore scenarios [6,7]. Numerical weather models, widely used to receive wind data, provide comprehensive coverage but are often constrained by spatial resolution and difficulties in modeling complex terrains like coastal areas [8–11]. Satellite-based Synthetic Aperture Radar (SAR) addresses some of these gaps, offering high spatial resolution valid for detailed wind pattern analysis, even in complex regions like fjords, though its temporal resolution remains low [12]. Coastal and offshore measurements face additional challenges from varying heat fluxes

and turbulence, complicating wind computation and impacting applications like renewable energy and air–sea flux studies [13,14]. Iceland’s coast exemplifies these complexities, with local and large-scale climatic interactions influencing wind dynamics [15]. Together, these methods complement one another, advancing the understanding of near-surface winds critical for sustainability and climate adaptation.

Iceland’s coastal regions are exposed to persistent and often strong winds due to frequent cyclonic activity over the North Atlantic and the influence of prevailing westerly winds. Wind patterns are influenced by local topography, with fjords and valleys channeling flows and glaciers. Local effects, including katabatic flows from glaciers and coastal channeling, further modulate wind speed and direction. These factors combine to create complex spatial patterns of wind speed and direction across the island [16,17].

Climate change is amplifying the risk of coastal landslides and rock avalanches in Iceland, posing significant threats to both infrastructure and communities. These events are increasingly influenced by changing wind patterns and unstable geological conditions, driven by sea-level rise, climate variability, and intensified storm activity [18]. Accurate and timely wind data are essential not only for assessing and mitigating these natural hazards but also for supporting renewable energy strategies, as wind resources play a key role in Iceland’s transition to sustainable energy. This study specifically evaluates the performance of various wind data sources, focusing on different areas alongside the Icelandic coast.

SAR-based wind measurements and reanalysis datasets have become essential tools for offshore and coastal wind assessments. SAR provides detailed information on ocean surface roughness, from which wind speed and direction can be retrieved [8]. Global reanalyses such as ERA5 integrate diverse observational data into comprehensive spatiotemporal fields, enabling long-term analyses of wind variability, climate change, and renewable energy potential [9]. The complementary use of SAR and reanalysis data has proven effective in improving wind characterization by combining high spatial detail with long-term temporal coverage.

In recent years, significant progress has been made in applying SAR and both global and regional reanalyses to wind field assessment in high-latitude and Icelandic coastal environments. SAR has been widely employed to map offshore wind climates around Iceland, providing detailed insights into wind variability and mesoscale circulation patterns, which compare well with results from numerical weather prediction models (e.g., HARMONIE, NORA10) [19]. Meanwhile, reanalyses such as ERA5 have been evaluated for their fidelity in subpolar regions, including the Iceland–Greenland seas, demonstrating strong performance in capturing surface-layer meteorology and spatial variability, though with reduced accuracy near complex coastal zones and marginal ice areas [17]. The more recent regional reanalysis CARRA offers higher spatial resolution and improved representation of Arctic and North Atlantic conditions, further complementing global reanalysis products. Building on this foundation, our study advances the integrated assessment of coastal and offshore wind patterns around Iceland by leveraging the complementary strengths of Sentinel-1 SAR, ERA5, and CARRA data sources.

This study provides a comprehensive analysis of three wind data sources: Sentinel-1’s high-resolution SAR-based wind product, the global reanalysis ERA5, and the regional reanalysis CARRA, across various coastal regions in Iceland (North, South, West, and East). To ensure representativeness, validation sites were selected along Iceland’s coasts, encompassing a variety of wind exposure conditions, including open coastal stretches, fjords, and topographically sheltered locations. The primary focus is on validating the Sentinel-1 wind product, given its high spatial resolution and ability to capture detailed wind patterns in coastal areas where traditional reanalyses like ERA5 and CARRA may be limited. Although the general limitations of ERA5 and CARRA are well known, it remains important

to assess the differences, complementary advantages, and potential limitations of these datasets, particularly given their substantial differences in spatial and temporal resolutions, which can make each data source particularly suited to different applications. In this respect, the study evaluates the performance of these datasets across Iceland's coastal regions, analyzes spatial variations in wind speed, and compares results with climatological in situ measurements from coastal meteorological stations. Although in situ data are located near the coast, these sites effectively capture the main patterns of regional wind variability. Ultimately, this research seeks to advance the application of remote sensing technologies for coastal hazard assessment and support the development of effective mitigation strategies for Iceland's vulnerable coastal zones.

The following section begins with a detailed description of the methods, including a description of the data sources utilized and the analysis approach applied. This is followed by the results and a discussion of the findings. The final section provides a concise conclusion, summarizing the key insights from the study.

2. Methods

2.1. Datasets

2.1.1. Remote Sensing

Over recent decades, SAR sensors have become a vital tool for monitoring the Earth's surface, enabling advancements across various applications. Among the active SAR missions, the European Space Agency's (ESA) Sentinel-1, part of the Copernicus Programme, is particularly noteworthy due to its publicly accessible data, available via the Copernicus portal [20]. It operates in the C-band frequency range, offering high spatial resolution and robust performance under various weather conditions. The mission initially included two satellites, Sentinel-1A and Sentinel-1B, which provide single and dual polarization modes at the highest spatial resolution of 20 m. Recently, Sentinel-1C was launched, further enhancing the mission's observational capacity and ensuring the continuity of data.

For the analysis, we used the Sentinel-1 Level-2 OCN OWI product, acquired between 1 January 2016, and 31 December 2023, covering a continuous eight-year study period. This product provides calibrated ocean surface wind information, including speed and direction, derived from Normalized Radar Cross Section (NRCS) inversion of Level-1 SAR images. The wind vectors are gridded at 1 km resolution and represent conditions 10 m above the ocean surface. The analysis was conducted at locations approximately 10 km off the coasts of North, South, East, and West Iceland.

2.1.2. Reanalyses

Global reanalysis: ERA5, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), is a fifth-generation global reanalysis with a spatial resolution of approximately 31 km [9], while its coarse resolution limits its ability to capture submesoscale and even some mesoscale features and complex coastal topography, ERA5 provides high temporal resolution with hourly wind data and is publicly available via the Copernicus Climate Change Service [21].

Regional reanalysis: The Copernicus Arctic Regional Reanalysis (CARRA) offers higher-resolution data with 3-hourly analyses and hourly forecasts at 2.5 km resolution. It is divided into two domains, CARRA-East and CARRA-West, with this study focusing on the Western domain covering regions like Iceland, Greenland, and Svalbard [22]. CARRA leverages the HARMONIE-AROME model with ERA5 as boundary conditions, incorporating enhanced data assimilation and refined regional orography [23].

2.1.3. In Situ

The monthly average climatological wind speed data from coastal stations, obtained from the Icelandic Meteorological Office (MET), offer a valuable perspective on long-term wind behavior near the coastline [24]. These averages are derived from sustained observations over extended periods, providing a robust representation of local wind conditions. Due to the coastline, wind speeds at these stations might be reduced compared to those measured 10 km offshore. The extent of this reduction varies depending on local topography, as terrain can create sheltering effects that dampen wind intensity. However, because these are monthly climatological averages, the impact of short-term fluctuations and localized wind anomalies is largely smoothed out. This makes the data a reliable source for studying general wind patterns and trends, even if the absolute values differ slightly from offshore conditions.

2.2. Methodology

2.2.1. Preprocessing

Over the study period, Sentinel-1 scenes were collected from locations approximately 10 km offshore across Iceland's four coastal regions: North, South, East, and West, as illustrated in Figure 1. Figure 1 illustrates Iceland's terrain and bathymetry, along with meteorological stations marked by colored circles and offshore study locations indicated by hexagons. These points were selected to capture diverse wind conditions influenced by regional geographic and climatic variability. Additionally, the chosen locations align with meteorological stations that provide monthly average wind data for the years used in the study. Table 1 summarizes the most essential characteristic differences in the datasets used in this study.

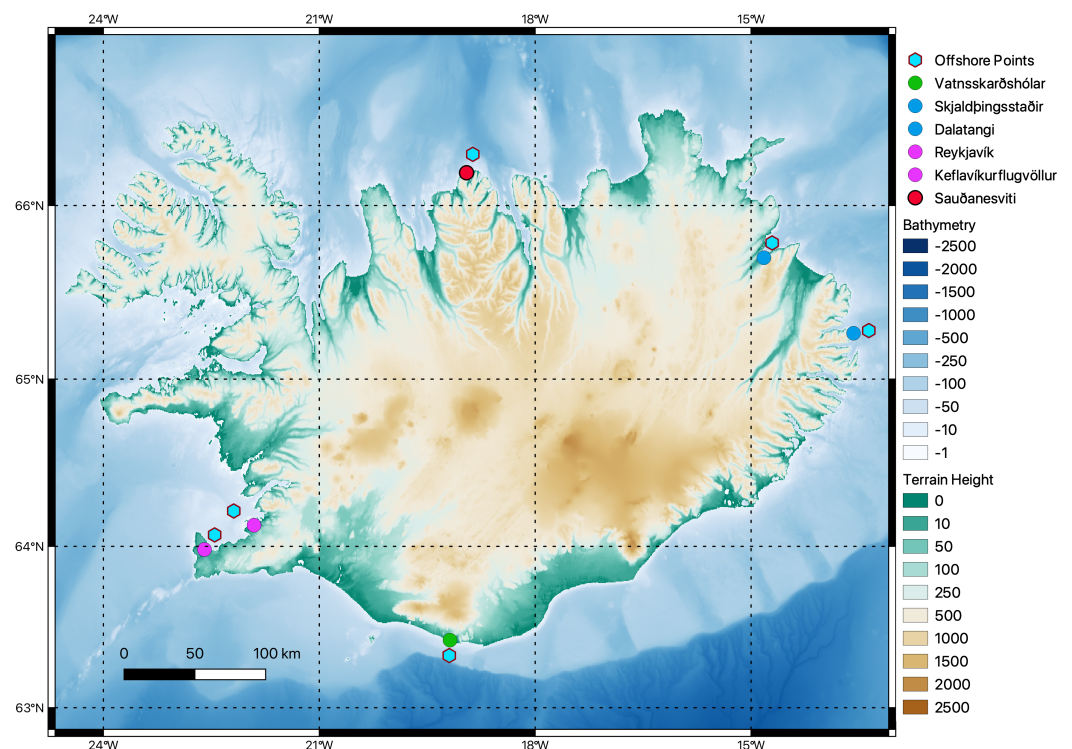


Figure 1. Geographical area investigated in this study. The map shows Iceland with terrain height and bathymetry information from GEBCO. Coastal meteorological stations are indicated by colored circle points (green—South, red—North, blue—East, purple—West), and study locations, approximately 10 km from the coast, are marked with hexagonal points. A legend is included to distinguish regions and features.

Table 1. Overview of dataset characteristics.

	MET	S1 OWI	ERA5	CARRA
Temporal resolution (ΔT)	monthly average	1–3 days	1 h	3 h
Spatial resolution	single point	1 km	31 km	2.5 km

For the South, data were obtained near Vatnsskarðshólar (-19.193° E, 63.325° N), with 2086 scenes used. For the North, observations came from a point near Sauðanesviti (-18.867° E, 66.289° N), with a total of 2351 scenes analyzed. In the West, data were gathered from two points near Keflavíkurflugvöllur (-22.455° E, 64.071° N) and Reykjavík (-22.189° E, 64.214° N), yielding 1963 scenes in total. The East included two study points near Dalatangi (-13.3615° E, 65.2837° N) and Skjaldþingsstaðir (-14.707° E, 65.787° N), contributing 2352 scenes to the dataset.

These locations were chosen to ensure coverage of Iceland’s diverse coastal environments and to provide a comprehensive understanding of wind patterns across the country. Each region’s unique topography, such as fjords in the East or the open ocean exposure in the South, makes accurate wind data vital for local climate studies and risk assessments.

For the reanalysis data, we used the 10 m u- and v-components of wind to calculate wind speed via $\sqrt{u^2 + v^2}$. Wind speed and direction at 10 m above the ocean surface were extracted from both ERA5 and CARRA for all study points and matched with Sentinel-1 data spatially and temporally. For the lower-resolution ERA5, the grid point closest to the study location was selected. For the higher-resolution CARRA and Sentinel-1 data sources, the representative value at each site was derived as the average of the four nearest grid points, providing a balanced depiction of local wind conditions, minimizing small-scale sampling effects, and ensuring more statistically robust results. Temporally, we selected the nearest available data to the Sentinel-1 acquisition times without performing interpolation or other time-matching methods; while interpolation between time steps could improve temporal consistency, we deliberately used the nearest available value to maintain consistency with the core objective of this study, namely, evaluating each data source in its standard, operational form as it is typically delivered to end users.

Figure 2 provides a zoomed-in view of the Skjaldþingsstaðir meteorological station and the corresponding offshore point, illustrating the grids and spatial resolutions of the different datasets (ERA5, CARRA, and Sentinel-1) used in this study, as well as the distance from the nearest available data point to the selected offshore locations. The ERA5 point is approximately 4 km from the offshore location, the four nearest CARRA points are roughly 1.5 km away, and Sentinel-1’s four closest observations are located less than 1 km from the offshore point. This visualization highlights how the spatial resolution and proximity of each dataset to the reference offshore location can influence comparisons and analyses.

It is important to note that artifacts, such as high backscatter from ships or offshore platforms, can in some cases lead to artificially high wind speeds in Sentinel-1 SAR measurements, particularly near coasts or in regions with heavy maritime traffic. Likewise, retrievals under very low wind conditions may be less reliable due to the reduced sensitivity of SAR in such scenarios. Nevertheless, we recognize and acknowledge these issues as potential limitations of the SAR-based data products. Despite these known issues, no post-processing, corrections, filtering, or masking were applied to the Sentinel-1 Level-2 OCN OWI wind speed data. All wind data are provided at a 10 m reference height and were used in their original form, as delivered to end-users. This choice allows us to evaluate the products in their standard, unfiltered state, thereby preserving both strengths and limitations and providing a realistic basis for comparison across different regions and conditions.

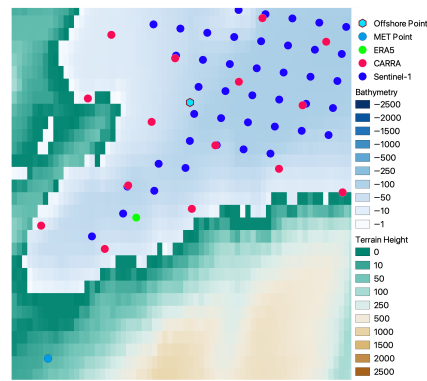


Figure 2. Zoomed-in view of the Skjaldbingsstaðir meteorological point and the corresponding offshore point. The figure also displays the ERA5, CARRA, and Sentinel-1 points restricted to water areas, illustrating the distances from the offshore point to the nearest grid points in each dataset.

2.2.2. Evaluation Metrics

To evaluate the accuracy and reliability of multiple data sources, we use three metrics: Root Mean Square Error (RMSE), standard deviation, and Pearson correlation coefficient. RMSE measures the average difference between observed and predicted values. Standard deviation indicates data variability, while the Pearson correlation coefficient evaluates the linear relationship between variables [25]. Together, these metrics assess accuracy, consistency, and correlation strength, providing a comprehensive evaluation of data quality and relevance.

3. Results and Discussion

3.1. Intercomparison of Wind Speed Products

3.1.1. Scatterplots Comparison

Figure 3 demonstrates the scatterplots comparing wind speed data across Sentinel-1, ERA5, and CARRA for various geographic locations across the Icelandic coastline, covering the North, South, East, and West. These comparisons highlight the relationships between the data sources, including their agreement and divergence, as quantified by scatter density, linear regression parameters (slope and intercept), and evaluation metrics such as RMSE (reported in m/s) and Pearson correlation coefficients.

Sentinel-1 vs. ERA5: Among the three data source pairs, Sentinel-1 and ERA5 exhibit the strongest agreement, as evidenced by dense scatterplots near the diagonal line. The relationship between these datasets is consistent across all regions, with regression parameters indicating a relatively high correlation. This is further supported by the relatively low RMSE and high Pearson correlation coefficients observed across regions, especially for the Northern ($RMSE: 1.99$, $r: 0.89$) and Southern points ($RMSE: 2.23$, $r: 0.88$). Even in regions where scatter density may slightly decrease, such as the Eastern and Western points, the agreement remains robust. The dense clustering, combined with regression slopes close to 1, suggests that Sentinel-1 and ERA5 provide comparable wind speed estimates, despite their significant differences in spatial resolution. This strong agreement may stem from the broader-scale atmospheric dynamics captured well by the global ERA5 reanalysis, aligning with the features detected by Sentinel-1.

Sentinel-1 vs. CARRA: The Sentinel-1 and CARRA pair closely follow the diagonal line, although the scatter density is slightly lower than that observed for Sentinel-1 and ERA5. This is reflected in the regional RMSE and Pearson correlation values, which are generally higher and lower, respectively, than those for Sentinel-1 and ERA5. For example, in the North, the RMSE of 3.40 and Pearson correlation of 0.72 indicate a slightly weaker alignment, with similar patterns emerging in the South. For the Eastern points,

the RMSE increases to 3.84 and 3.70, with correlations dropping to 0.61 and 0.56. Similarly, the Western points show reduced scatter density compared to Sentinel-1 and ERA5. In general, the regression analysis suggests a somewhat consistent but less closely related connection. The reduced scatter density may reflect differences in how CARRA represents mesoscale atmospheric phenomena compared to the finer-resolution Sentinel-1 data. Interestingly, despite the spatial resolution similarity between Sentinel-1 and CARRA, it does not translate into a denser scatter, suggesting that factors beyond resolution, such as retrieval methodologies or data assimilation techniques, may strongly influence their agreement.

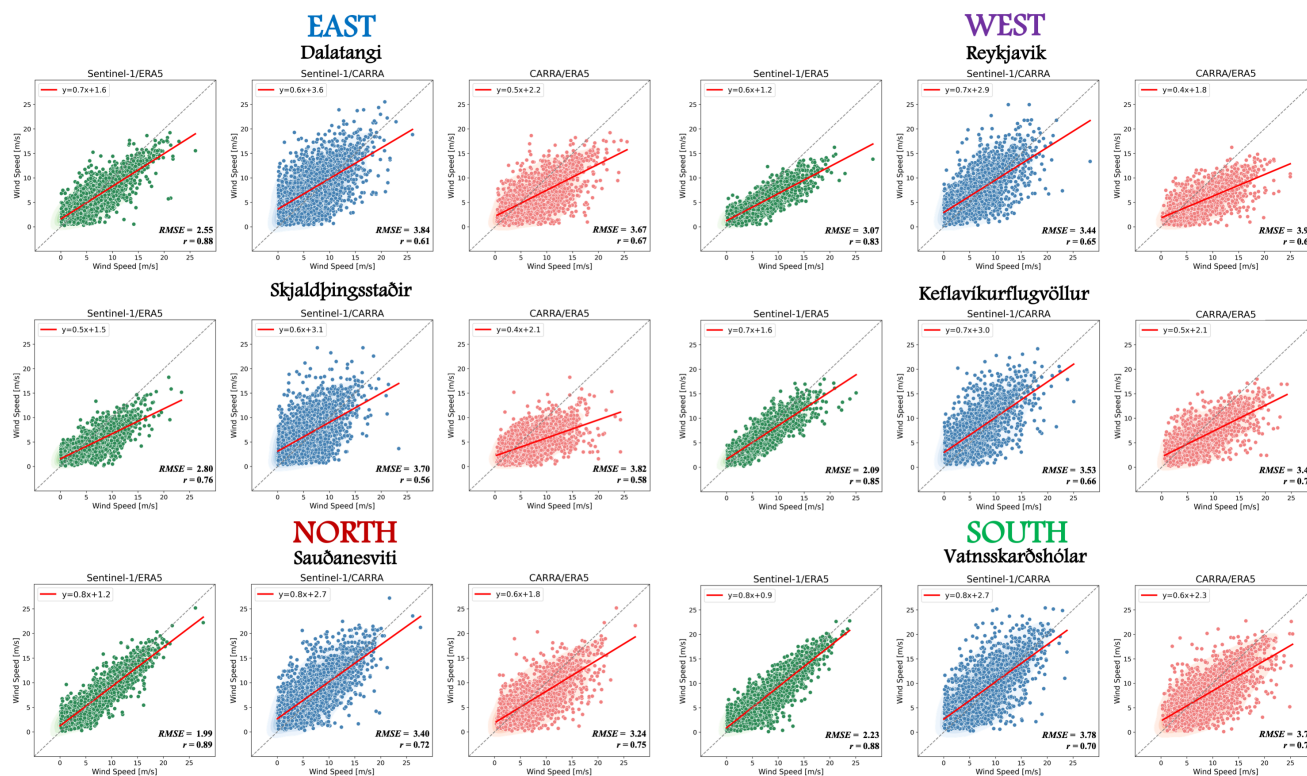


Figure 3. Scatterplots comparing wind speed data among Sentinel-1, ERA5, and CARRA for various study points across the North, South, East, and West of Iceland. The comparisons include Sentinel-1 versus ERA5, Sentinel-1 versus CARRA, and ERA5 versus CARRA. The plots also display the linear regression parameters (slope and intercept), as well as evaluation metrics such as RMSE (expressed in m/s) and Pearson correlation coefficient, to assess the agreement and divergence between the datasets.

CARRA vs. ERA5: The CARRA vs. ERA5 comparison reveals a comparable correlation to the Sentinel-1/ERA5 and Sentinel-1/CARRA pair but with notable differences in scatter distribution and alignment with the diagonal line; while the scatter density is similar, the points exhibit a more pronounced skew toward higher values, as reflected in the regression equations. This indicates that CARRA and ERA5 often diverge in their wind speed estimates, particularly at higher wind speeds. The weaker connection between CARRA and ERA5 is particularly surprising given their intrinsic connection: CARRA is a high-resolution regional refinement of ERA5, designed to provide enhanced insights for the Nordic and Arctic regions. Thus, it would be expected for these two reanalysis products to exhibit a stronger relationship, especially compared to Sentinel-1 and ERA5, which differ even more in spatial resolution and data generation methodologies. However, even though this finding may seem counterintuitive—since we would rather assume a higher correlation either between two connected reanalyses or two high-resolution products—Sentinel-1 and ERA5, despite their significant differences, exhibit a closer relationship. The observed

weaker correlation between CARRA and ERA5 suggests that the refinement process in CARRA focused more on capturing mesoscale features and local topographical influences, which may introduce deviations from the broader-scale patterns represented in ERA5.

Geographical patterns suggest that the agreement among datasets varies regionally, influenced by local topography and atmospheric dynamics. Sentinel-1 and ERA5 consistently show the strongest correlation across all regions, while the pairs involving CARRA generally exhibit weaker agreement, particularly in areas with complex terrain, such as the East and West. Scatterplots and associated metrics, including higher RMSE and lower correlation values, indicate that comparisons involving CARRA tend to have reduced precision and accuracy in wind speed estimates near the Icelandic coast. This suggests that while CARRA's fine-scale resolution captures localized phenomena, it may introduce greater deviations when compared to Sentinel-1 and ERA5.

The regional grouping into North, South, East, and West further highlights how topographic complexity and exposure to different large-scale atmospheric systems affect dataset performance. The relatively high agreement in the North and South likely reflects more open coastal exposure and fewer small-scale topographic barriers, which allow both Sentinel-1 and ERA5 to capture large-scale wind dynamics consistently. In contrast, the East and West are characterized by more rugged coastlines and stronger interactions between synoptic winds and local orographic effects, which appear to amplify the discrepancies, particularly in CARRA.

The weaker agreement involving CARRA is especially noteworthy given that it is a regional downscaling of ERA5; while the added resolution enables CARRA to better resolve mesoscale processes and topography-induced variability, it may also amplify localized deviations that are not consistently reflected in Sentinel-1 or ERA5. This points to an important trade-off between spatial resolution and consistency across datasets: higher resolution does not necessarily equate to better agreement, especially in regions where local atmospheric dynamics are highly complex.

From an application perspective, these results suggest that ERA5 may be a more reliable complement to Sentinel-1 for broad-scale wind speed characterization along Iceland's coast, while CARRA should be used with caution in areas of complex topography. At the same time, the observed regional discrepancies emphasize the need for careful site-specific validation when employing reanalysis products for wind energy assessment, climate studies, or operational forecasting.

3.1.2. Wind Speed Distribution

Figure 4 compares the Weibull probability density function (PDF) with observed wind speed histograms from three different data sources: Sentinel-1, ERA5, and CARRA, across multiple study points located along the coast of Iceland. These study points are organized into four regions: North, South, Eastern, and Western. The purpose of the graph is to visually assess the differences and similarities between the wind speed distributions obtained from the three wind speed sources and to display the corresponding shape and scale parameters of the Weibull distribution for each dataset and study point.

In the North region, the shape and scale parameters of the Weibull distributions derived from the three data sources demonstrate a general similarity. Specifically, the PDFs for Sentinel-1 and CARRA are nearly identical, with both distributions overlapping almost perfectly. This suggests that the wind speed data from these two sources exhibit very similar statistical characteristics. On the other hand, the ERA5 distribution is slightly different from both Sentinel-1 and CARRA, with subtle differences in the shape and scale of the wind speed distribution. Nevertheless, the overall trend of the ERA5 PDF still aligns with the general wind speed characteristics observed in the North region.

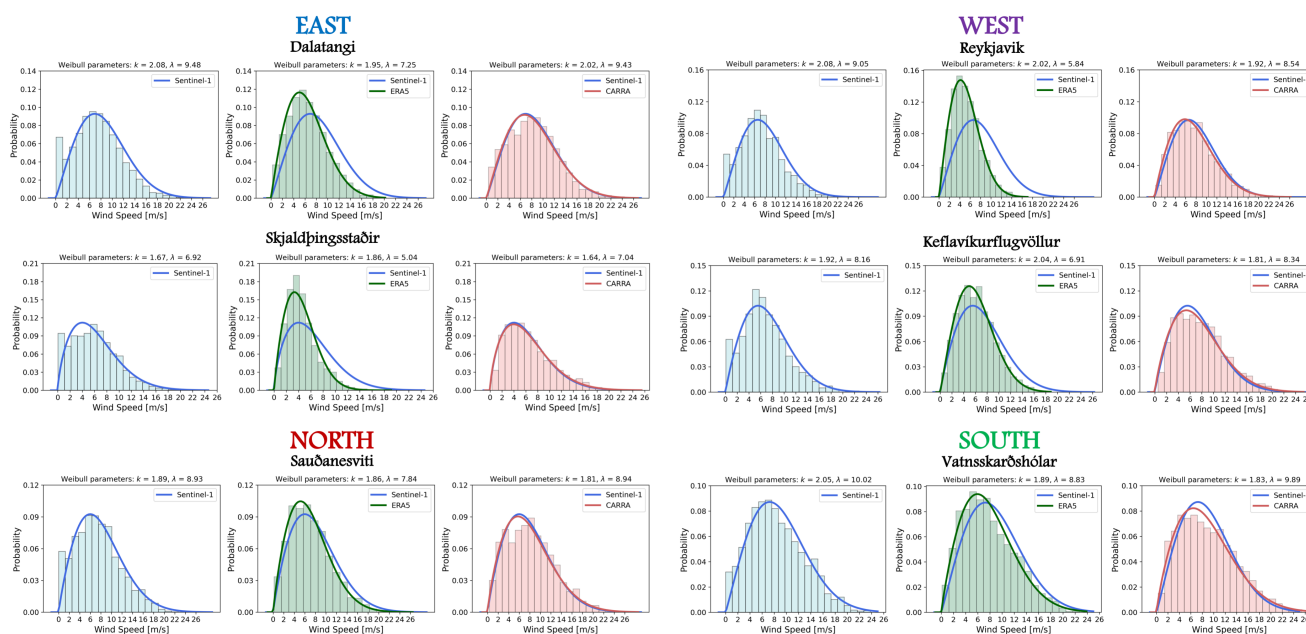


Figure 4. Weibull probability density function alongside observed wind speed histograms of Sentinel-1, ERA5, and CARRA for multiple study points located along the coast of Iceland. Additionally, the Weibull shape (k) and scale (λ) parameters obtained for each data source and study point are displayed.

The differences between the sources in the South region are more pronounced. The wind speed distribution for Sentinel-1 reveals slight deviations from both ERA5 and CARRA. The distribution from ERA5 shows a minor shift in both the shape and scale of the wind speed data, making it less aligned with the Sentinel-1 distribution. Similarly, the CARRA distribution differs from Sentinel-1, although the deviation is not as significant as that of ERA5. This suggests that the wind speed patterns in the South region are more complex, and the datasets may capture different atmospheric conditions.

For the Eastern region, two study points are considered. For the Dalatangi point, the PDFs from Sentinel-1 and CARRA again show a high degree of similarity, closely overlapping. This indicates that these two datasets produce almost identical representations of the wind speed distribution in this area. However, the ERA5 distribution differs more noticeably, particularly in terms of both shape and scale, suggesting that ERA5 captures a different pattern of wind conditions for this region. For the Skjaldfingsstaðir point in the Eastern region, although the wind speed distributions from Sentinel-1 and CARRA still show strong overlap, ERA5 deviates more significantly from these two datasets. ERA5's PDF exhibits noticeable differences in both scale and shape, suggesting that it might be capturing a distinct atmospheric scenario or exhibiting a modeling artifact that is not reflected in the other datasets. Additionally, in both Eastern points, ERA5 appears to be slightly underestimating the wind speed compared to the other sources.

In the Western region, the wind speed distributions show varying degrees of overlap and divergence across the two study points. In the Reykjavik point, the PDFs for Sentinel-1 and CARRA again show a similar trend, though they do not perfectly overlap. The ERA5 distribution reveals more noticeable differences, particularly in scale, suggesting that ERA5 captures a different wind speed pattern compared to Sentinel-1 and CARRA. In the Keflavíkurflugvöllur point of the Western region, while there is still some overlap between the PDFs of Sentinel-1 and CARRA, it is not as perfect as in other regions. ERA5 shows a distribution that deviates in both shape and scale from the other two datasets, further emphasizing the differences in how each dataset models the wind speed distribution in this part of Iceland. Similarly to the Eastern region, ERA5 in the Western region appears to

be slightly underestimating wind speed when compared to Sentinel-1 and CARRA, with its PDF showing lower wind speeds, especially in terms of the scale parameter.

The previous section showed that ERA5 was more closely correlated with Sentinel-1, indicating that ERA5 captures broad regional wind speed trends similar to Sentinel-1. However, in the analysis of Weibull PDFs, Sentinel-1 aligns more closely with CARRA, particularly in terms of the detailed shape and scale of wind speed distributions. This suggests that while ERA5 performs well at capturing overall patterns, it may smooth out finer details, leading to an underestimation of wind speeds in certain regions, especially the Eastern and Western points. In contrast, CARRA appears to better reflect localized wind speed characteristics, aligning more precisely with Sentinel-1 in this aspect, which might be due to the more similar spatial resolutions of both sources. One notable feature, evident at every study point and across all regions, is the systematically higher frequency of near-zero wind speed values in the Sentinel-1 OWI product relative to both reanalysis data sources. This tendency, visible in both the scatterplots and the wind speed histograms, reflects a known characteristic of SAR's reduced sensitivity in weak wind regimes and suggests that the lowest wind speed estimates from Sentinel-1 should be interpreted with some caution.

3.2. Comparison with MET

The comparison with MET data constitutes the most important part of this study, as it highlights the novel contributions of our work. Our approach builds on previous studies, including [26], where Sentinel-1 OWI was compared with high-temporal-resolution in situ observations offshore at Goliat to assess its reliability, and [27], where differences between the same datasets were evaluated under a range of Icelandic conditions, including fjord, coastal, and offshore sites. In the current study, we incorporate the only available MET source for Iceland, which is located along the coast. Although the MET stations are coastal, they provide a valuable reference for validation. We expect that the offshore locations selected for Sentinel-1, ERA5, and CARRA will generally show slightly higher wind speeds compared to the coastal MET stations, reflecting the influence of exposure to open ocean conditions.

3.2.1. Boxplot Analysis

Figure 5 illustrates the boxplots of monthly average wind speed distributions from Sentinel-1, ERA5, CARRA, and Iceland Met Office datasets for multiple study points located along the coast of Iceland. Boxplots provide a graphical summary of data distributions. In particular, the box represents the interquartile range, where 50% of the data points lie, with the horizontal line inside the box indicating the median. The whiskers, i.e., lines extending from the box, represent data within 1.5 times the interquartile range from the lower and upper quartiles. Rhombus above and below the whiskers indicate outliers, representing extreme values.

The Icelandic Meteorological Office provides monthly average wind speeds from stations located on the coast, while the points for the other data sources, namely ERA5, CARRA, and Sentinel-1, were extracted approximately 10 km from the coast. Consequently, we expect variability between the MET observations and the other sources, driven mainly by complex terrain and coastal effects. Moreover, previous studies suggest that ERA5 tends to underestimate wind speeds, so we assume it should align more closely with MET values [26,28].

The wind speed patterns for Eastern points, i.e., Dalatangi and Skjaldþingsstaðir indicate ERA5 is the closest source to the MET data. For Dalatangi, ERA5 shows a median of around 6.5 m/s, while for Skjaldþingsstaðir, the median is approximately 4.5 m/s. Notably, the MET data for Skjaldþingsstaðir includes an outlier above the graph. Sentinel-1

encompasses the full range of MET’s variability, including high-wind values, but tends to overestimate these extremes. CARRA seems to be the least accurate source, with an outlier above the whisker for Dalatangi.

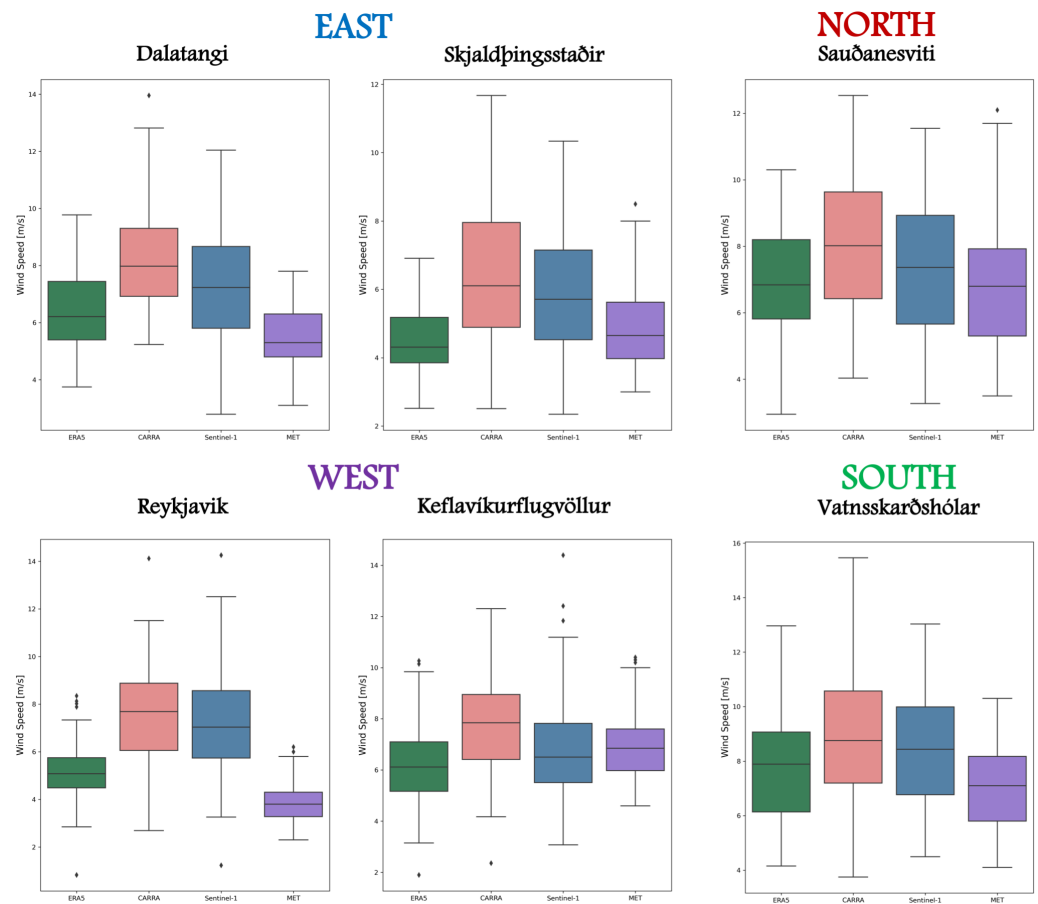


Figure 5. Box plots showing monthly average wind speed distributions from Sentinel-1, ERA5, CARRA, and Iceland Met Office datasets for multiple study points located along the coast of Iceland.

For the North and South points, ERA5 and Sentinel-1 perform similarly and show closer alignment with MET values than CARRA. ERA5 demonstrates consistent reliability, reflecting coastal wind patterns while maintaining accuracy relative to MET observations. Sentinel-1 captures variability but occasionally exaggerates high-wind values. CARRA exhibits less precision, particularly in these locations.

At the Western points, all datasets show more outliers above and below the boxplot whiskers, indicating greater variability. However, for Keflavíkurlugvöllur point each source remains a close approximation to MET values. At Reykjavík, ERA5 offers the most accurate representation of wind conditions compared to MET. This aligns with the expectation that for our case ERA5’s underestimation tendencies will be mitigated in comparison to the station on the coast, where wind speeds decrease due to terrain complexity.

3.2.2. Taylor Diagram Assessment

Figure 6 displays Taylor diagrams for wind speed data from Sentinel-1, ERA5, CARRA, and Iceland Met Office datasets for multiple study points located along the coast of Iceland. Taylor diagrams offer a visual comparison of model performance against a reference source, i.e., MET, summarizing the correlation coefficient, standard deviation, and root-mean-square error. These metrics together indicate how closely the datasets align with the MET observations.

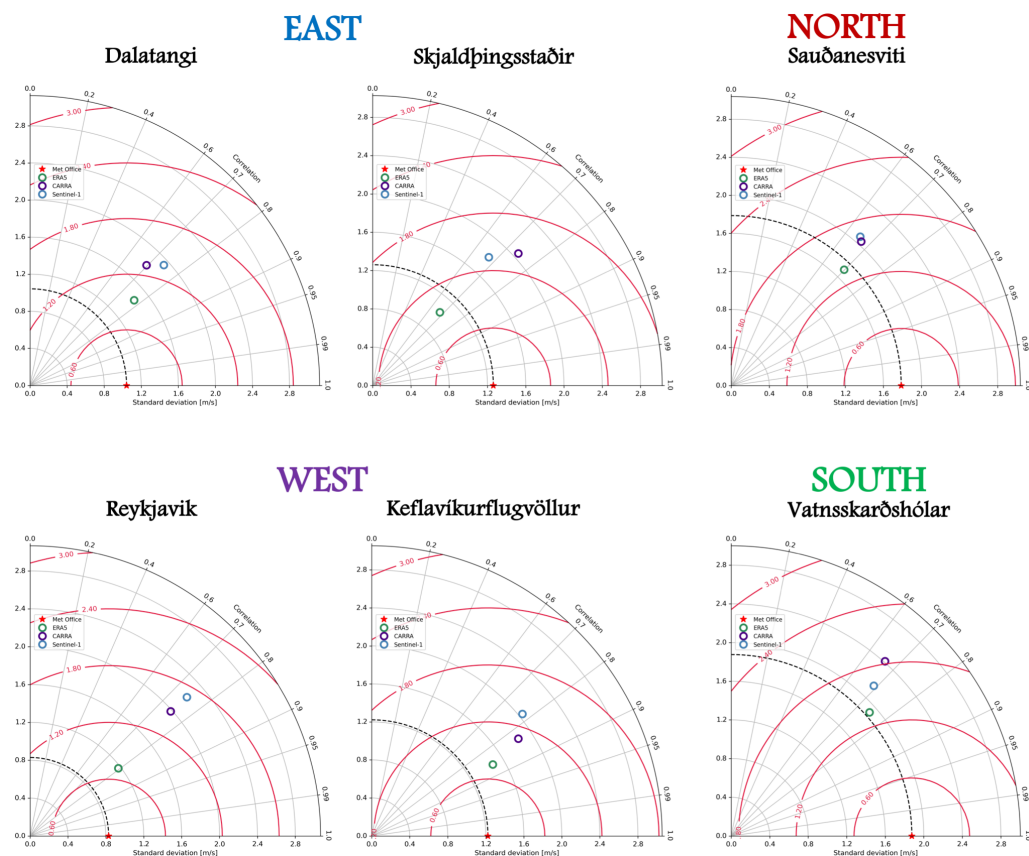


Figure 6. Taylor diagrams for wind speed data from Sentinel-1, ERA5, CARRA, and Iceland Met Office datasets for multiple study points located along the coast of Iceland. The red contours display the RMSE value of the data sources compared to the reference source (MET observations).

At the Eastern and Western points, ERA5 consistently exhibits better alignment with MET values. The proximity of the MET station to the coast likely moderates discrepancies, and ERA5's underestimation of wind speeds may result in a smoother convergence with MET observations. Conversely, Sentinel-1 and CARRA show larger deviations, often overlapping in performance but failing to match ERA5's consistency.

The North point is particularly noteworthy, as all sources demonstrate relatively similar performance, clustering closer to the reference source on the Taylor diagram. This suggests that in this region, differences between the datasets are less pronounced, possibly due to more uniform terrain or wind conditions.

At South point, ERA5 demonstrates an exceptional performance, nearly overlapping the MET reference source, highlighting its ability to capture wind speed characteristics accurately. Sentinel-1 is also close to the MET reference, similar to the Northern point, likely due to the region's relatively straightforward terrain. This alignment reinforces the assumption that less complex terrain aids in achieving higher accuracy among all sources.

These results once again strengthen the hypothesis that ERA5 aligns most closely with MET values, as shown by the box-plot and Taylor plot comparisons. This closer match is largely attributable to ERA5's coarser spatial resolution, which tends to underestimate wind speeds and smooth out local coastal effects, thereby reproducing the reduced values observed at the MET stations. In contrast, both Sentinel-1 and CARRA generally produce higher wind speeds, reflecting the offshore exposure of their sampling locations as well as their finer spatial resolution, which resolves stronger winds over open water. The differences between offshore datasets and sheltered coastal stations are particularly pronounced in North and South Iceland and at one East location, where open-ocean exposure spans nearly 180 degrees, while other sites are more fjord-influenced. This underscores the im-

portance of considering site representativeness and local topography when comparing offshore and in situ measurements. Differences in terrain, coastline orientation, and exposure mean that in situ stations, though mostly located near the coast, effectively sample only a subset of the regional wind variability, while high-resolution datasets capture broader spatial gradients.

At the same time, distinguishing between Sentinel-1 and CARRA remains particularly challenging, as performance metrics are often similar across locations. However, at sites with more straightforward terrains, such as points in North and South Iceland, the impact of spatial resolution and dataset characteristics becomes more evident, with higher-resolution datasets better reproducing local variations in wind speed and direction. This emphasizes that both analysis resolution and site representativeness are key factors when interpreting differences between satellite and reanalysis products in coastal environments.

3.2.3. Anomalies Quantification

Figure 7 demonstrates the seasonal average histograms of the wind speed differences between Sentinel-1, ERA5, and CARRA relative to the Icelandic Meteorological Office at various points along Iceland’s coastline. These histograms illustrate the distribution and magnitude of discrepancies for each dataset compared to the reference.

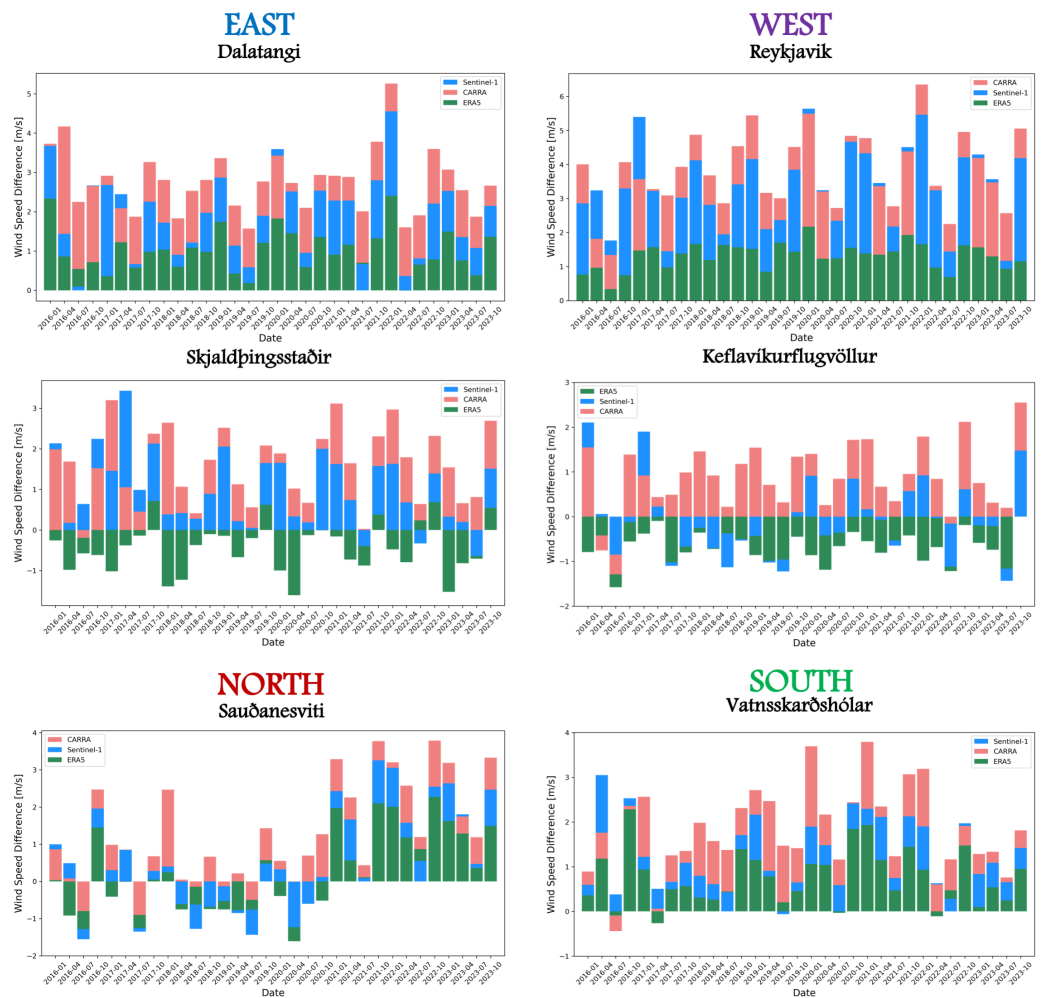


Figure 7. Seasonal average histograms of the wind speed difference between Sentinel-1, ERA5, and CARRA versus Icelandic Met Office across various points along the Icelandic coastline.

CARRA consistently demonstrates the largest differences across all locations, with particularly noticeable positive anomalies. This pattern suggests a tendency to overestimate

wind speeds relative to the reference source, making it the least accurate. Sentinel-1 exhibits moderate differences, generally falling between ERA5 and CARRA; while it also overestimates wind speeds, its deviations are less pronounced than those of CARRA, showing a more balanced performance. ERA5 stands out as the closest to the MET reference, with the smallest differences across most points. Its slight underestimation of wind speeds results in discrepancies that align more closely with MET values.

An interesting observation is that the largest anomalies for all sources and points occur predominantly in autumn and winter. These seasons, characterized by higher wind speeds in the Northern Hemisphere, accentuate discrepancies between datasets and the reference. The amplified wind activity during these months highlights the challenges for models and satellite-derived datasets in capturing extreme conditions accurately, particularly in regions with complex coastal terrain.

These results emphasize that ERA5 provides the closest match to MET observations, further reinforcing the findings from the Taylor diagrams and boxplots, which established ERA5 as the closest dataset relative to the reference source. Sentinel-1 offers a reasonable alternative, with slightly larger differences than ERA5. However, given its higher spatial resolution and the challenging comparison scenario, where the reference stations are located on land, Sentinel-1 proves to be a valuable complementary data source, particularly for applications that require capturing smaller-scale wind phenomena and detailed spatial variability. Conversely, CARRA tends to significantly overestimate wind speeds, especially during high-wind seasons, making it the least accurate dataset for capturing seasonal wind speed variability along Iceland's coastline. Overall, the choice between ERA5 and Sentinel-1 should be guided by the specific usage scenario, as each data source has strengths that make it more appropriate for particular purposes.

4. Conclusions

This study assessed the performance of Sentinel-1 SAR wind products, ERA5 global reanalysis, and CARRA regional reanalysis across four coastal regions of Iceland, using intercomparisons and validation against in situ observations from the Icelandic Meteorological Office.

Across Iceland's coastal regions, the three wind datasets displayed distinct and consistent performance patterns. Sentinel-1 and ERA5 showed the highest overall agreement, despite large differences in spatial resolution and retrieval methodology, an outcome that was somewhat unexpected given ERA5's coarser resolution. CARRA, although designed as a high-resolution regional refinement of ERA5, often diverged more from ERA5 than Sentinel-1 did, especially in regions with complex terrain. This suggests that localized mesoscale representation in CARRA can amplify differences from broader-scale patterns.

ERA5 tended to slightly underestimate wind speeds along the Icelandic coast, which, counterintuitively, often improved its agreement with coastal in situ observations. This is likely because ERA5, as a coarser-resolution global reanalysis, smooths over small-scale terrain-induced accelerations and decelerations, capturing broad atmospheric patterns rather than fine-scale local effects. Sentinel-1, in contrast, with its high spatial resolution, was able to capture fine-scale variability, including localized high-wind events, but this also led to occasional overestimations compared to the in situ reference. CARRA, designed as a high-resolution regional reanalysis, generally overestimated wind speeds, particularly in regions with complex terrain and during autumn and winter when extreme winds are more frequent. This behavior suggests that while CARRA better resolves mesoscale processes and orographic influences, these features can amplify differences from both coarser reanalyses and point-based observations.

Seasonal and regional discrepancies, summarized quantitatively in Figure 7, highlight how dataset performance is strongly influenced by both temporal and spatial factors. Winter months, characterized by more intense and frequent high-wind events, tend to magnify divergences, emphasizing the challenge of accurately representing extreme conditions. Overall, no single dataset is universally optimal, and the choice of wind product should depend on both spatial scale and the specific research or operational objectives.

Future work will explore the fusion of Sentinel-1 and reanalysis products to leverage the high spatial resolution of SAR with the temporal consistency of ERA5 and CARRA, improving coastal and offshore wind characterization. Additionally, applying atmospheric stability corrections to SAR wind retrievals, especially under stratified coastal conditions, could refine wind estimates, with flux-based algorithms used where appropriate data are available. Enhanced filtering techniques to identify and mitigate anomalous SAR pixels, such as those affected by ships, platforms, or very low wind speeds, would further improve data robustness. Combining these improvements with reanalysis products would support more accurate wind field representation, benefiting applications in coastal hazard monitoring, renewable energy planning, and atmospheric modeling.

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Abbreviations

The following abbreviations are used in this manuscript:

ESA	European Space Agency
SAR	Synthetic Aperture Radar
CARRA	Copernicus Arctic Regional Reanalysis
MET	Icelandic Meteorological Office
OWI	Ocean Wind Field
ECMWF	European Centre for Medium-Range Weather Forecasts
NRCS	Normalised Radar Cross Section
GMF	Geophysical Model Function
RMSE	Root Mean Squared Error
PDF	Probability Density Function

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