Response to RC1

Thank you for your comments.

The scientific value of this paper lies in the fact that it provides validation of the Sentinel-1 wind speed data against in-situ measurements. We have also contacted Ifremer and CLS and they have confirmed that they have validated Sentinel-1 data only against numerical models and so no "private" validation against in-situ data exists.

We feel that validation against in-situ measurements is an important step towards the increased use of Sentinel-1 data for wind resource assessment purposes and that such validation results and details of the methodologies used should be in the public domain.

It is encouraging to see that Reviewer 2 agrees with this view.

Response to RC2

Thank you for your detailed comments. These have now been incorporated into the document with changes highlighted below. For ease of review, responses to each comment have also been provided in a marked-up version of your original supplemental document which has also been uploaded.

Validation of Sentinel-1 offshore winds and average wind power estimation around Ireland

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Abstract. In this paper, surface wind speed and average wind power derived from Sentinel-1 Synthetic Aperture Radar Level 2 OCN product were validated against four weather buoys and three coastal weather stations around Ireland. A total of 1,544 match-up points was obtained over a two-year period running from May 2017 to May 2019. The match-up comparison showed that the satellite underestimated the wind speed compared to in situ devices, with an average bias of 0.4 m/s, which decreased linearly as a function of wind speed. Long-term statistics using all the available data, while assuming a Weibull law for the wind speed, were also produced and resulted in a significant reduction of the bias. Additionally, the average wind power was found to be consistent with in situ data, resulting in an error of 10% and 5% for weather buoys and coastal stations, respectively. These results showed that the Sentinel-1 Level 2 OCN product can be used to estimate the wind speed distribution, even in

coastal areas. Maps of the average and seasonal wind speed and wind power illustrated that the error was spatially dependent, which should be taken into considerations when working with Sentinel-1 SAR data.

1 Introduction

With the ever-increasing interest in offshore wind energy and the rise of floating turbines, the estimation of the available wind energy over large offshore areas has become necessary. According to the Global Wind Energy Council (Global wind statistics 2014), offshore wind power costs are expected to reduce by about 45% by 2050. One factor that can be associated with cost reduction is the increasing availability of accurate remote sensing data over large areas with a high resolution which can significantly reduce project risk at site finding stage. Moreover, the measurement of offshore wind speed contributes to the understanding of marine phenomena and boundary layer processes. Low altitude meteorological parameters, such as wind, are therefore key parameters in the modelling of the Earth system.

Several studies have already attempted to assess the offshore wind energy potential using spaceborne scatterometers, such as ERS-1, ERS-2, NSCAT, QuickSCAT and ASCAT (Sánchez et al., 2007; Pimenta et al., 2008; Karagali et al., 2014; Bentamy and Croize-Fillon, 2014; Remmers et al., 2019). However, the spatial resolution of these instruments is at best 12.5 km^2, which prevents the assessment in coastal areas (0-20 km from the shore) and the study of fine sub-mesoscale processes that can affect turbine yields and climate processes. In this framework, spaceborne Synthetic Aperture Radar (SAR) sensors offer a much higher spatial resolution, allowing for wind speed retrieval with a level of detail not discernible from scatterometer data.

In this study, the Sentinel-1 A and B Level 2 OCN product produced by the European Space Agency (ESA) was validated. This product, derived from SAR observations, provides measurement of neutral surface wind speed and direction at 10 m above sea level (a.s.l.) with a spatial resolution of 1 km^2. Even though this type of analysis was previously performed in other parts of Europe (Hasager et al., 2015), it has never been conducted using both marine and coastal in situ measurements at a national scale in Ireland, which has a significant offshore wind resource (Remmers et al., 2019). Moreover, to the authors' knowledge, the Sentinel-1 level 2 OCN product has not yet been validated against in situ measurements, with the exceptions of one match-up comparison in the waters adjacent to the Korean peninsula (Jang et al., 2019). Similarly, long term statistics retrieved using this product, such as the average wind power, which is the most relevant for the wind energy industry, have never been analysed before.

The aim of this study was to validate and the Sentinel-1 A and B Level 2 OCN product against in situ measurements in Ireland and asses this data ability to describe the wind resources. First the satellite product and the study area are introduced, next the methodology is provided and finally, the results are presented and discussed.

2 Data and Methodology

2.1 Sentinel-1 SAR Level 2 OCN

Sentinel-1 A and B are two polar-orbiting satellites equipped with C-band SAR. This sensor which records surface roughness, has the advantage of operating at wavelengths not impeded by cloud cover or a lack of illumination and can acquire data over a site during day or night in all weather conditions. The Sentinel-1 Level 2 OCN product includes a component called Ocean Wind Fields (OWI) which is a ground range gridded estimate of the surface wind speed and direction at 10 m a.s.l, assuming a neutral atmospheric stratification, with a spatial resolution of 1 km2. The two satellites are located on the same orbit 180° apart and at an altitude close to 700 km. In Irish coastal waters, the acquisition mode is Interferometric Wide (IW) swath using the TOPSAR technique which provide a better quality product by enhance the image homogeneity (ESA, 2019). All Sentinel-1A and B SAR images in IW acquisition mode from May 1, 2017 to May 1, 2019, in the area located around Ireland between 51°N and 56°N in latitude and 5°W and 16°W in longitude, were collected (n=5,509). The quality flag for these data ranges from 0 to 3 (0 being the best and 3 the worst) and, following visual inspection, only data with a quality flag ≤ 2 were used for the validation. The Level 2 product tiles were combined into a gridded map for the area of interest, in order to form a data cube where each pixel had a corresponding time series of measurements. The revisit rate ranges from 10 to 20 passes per month for most areas in Irish waters, which occur in the morning around 6.30 am or in the evening around 6 pm, Greenwich Mean Time (GMT) in the winter and Irish Standard Time (IST) in the summer. Figure 1 shows the number of samples for each pixel and Figure 2 shows the average daily passing time of the satellites. The impact on quality flag from landmass contamination was visible with the reduced sample size in coastal area.

2.2 In situ instruments

2.2.1 Weather Buoys

Ireland's Marine Institute operates five offshore weather buoys named M2, M3, M4, M5 and M6. Their location is shown on Figure 3. The data from these were downloaded from the Marine Institute website with a two-year time series ranging from May 1st 2017 to May 1st 2019. The hourly product corresponds to the wind speed averaged over a period of 10 minutes every hour at 3 m a.s.l.. As a result of extensive maintenance periods, the buoys are not always functioning leading to a lack of measurements in the dataset, up to several months, for some locations. Due to this phenomenon, and to a poor offshore coverage frequency from Sentinel-1 satellites, the M6 buoy was excluded in the validation analysis.

In order to compare Sentinel-1 SAR Level 2 OCN product with this network of instruments, the in situ buoy measurements were extrapolated from 3 m to 10 m a.s.l.. The following log law was used, assuming a neutral atmospheric stratification (Carvalho et al., 2017):

$$U_{10} = \frac{\ln\left(\frac{Z_{sat}}{Z_0}\right)}{\ln\left(\frac{Z_{buoy}}{Z_0}\right)} . U_{buoy} \quad \text{Eq. (1)}$$

where U_{10} is the wind speed at 10 m in m.s^{-1}, U_{buoy}, the wind speed measured by the buoys in m.s^{-1}, Z_{sat} the altitude of the satellite measurements in m, Z_{buoy} the altitude of the buoy measurements in m, and Z_0 the roughness length of the sea surface taken as 0.0002 m *(Charnock, 1955)*. Table 1 gives the exact locations of these buoys and their percentage of availability.

2.2.2 Coastal weather stations

Three weather stations operated and maintained by Met Éireann, the Irish weather forecasting service, were used to validate the Sentinel-1 SAR Level 2 OCN wind speeds in coastal areas. These three stations were considered for the validation analysis because they are located close to the shore (less than 200 m, see Figure 3), at a low altitude (approx. 20 m), and far from any hills or relief. The stations are situated on the west coast of Ireland at Sherkin Island, Mace Head, and Malin Head, and have continuous wind speed records during the two-year period of study (Table 2). The predominant wind direction on the Irish west coast is eastward, flowing from the sea to toward the land. Simulations of these type of flows have shown that for a moderate coastal slope, onshore wind speeds recorded at proximity to the shore can equate the wind speeds at sea just before reaching the coast (Bassi Marinho Pires et al., 2015). Following this principle, the wind speed derived from satellite measurement were not scaled to the weather station terrain elevation, but instead were considered as being in the same streamline and kept at the OCN product elevation of 10 m a.s.l.. The weather station data were compared with Sentinel-1 SAR Level 2 OCN wind speeds measured with the closest pixel without quality flag. Due to the complex Irish coast line and to avoid land contaminate, the OCN measurement were one or two pixels away from the shore (i.e. 1 or 2 km).

2.3 Assessment criteria

The error e_i between Sentinel-1 Level 2 OCN wind speed, denoted U_i, and the in situ measurement, denoted u_i, is defined as follows:

$$e_i = U_i - u_i \quad \text{Eq. (2).}$$

The criteria used in the comparison were the mean error (or bias), the standard deviation (σ), the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE) and the linear correlation coefficient (R), respectively defined by:

$$Bias = \frac{1}{N}\sum_{i=1}^{N} e_i \quad \text{Eq. (3)}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(e_i - Bias)^2} \quad \text{Eq. (4)}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {e_i}^2} \quad \text{Eq. (5)}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|e_i| \quad \text{Eq. (6)}$$

$$R = \frac{1}{\sigma_U \sigma_u (N-1)}\sum_{i=1}^{N}(U_i - U)(u_i - u) \quad \text{Eq. (7)}$$

where U and u denote the mean of satellite and in situ wind speeds respectively, σ_U and σ_u their standard deviation, and N the number of match up samples.

2.4 Wind distribution estimation

The average wind power density P in W.m^{-2}, simply called wind power in the following, is the average kinetic energy passing through a unit of surface per unit of time. It can be estimated directly from the wind speed time series using the following formula:

$$P = 0.5\rho(1/N)\sum_{i=1}^{N} {U_i}^3 \quad \text{Eq. (8)}$$

where ρ is the air density (1.245 g.m^{-3} at 10°C) and U_i the wind speed. However, in order to compensate for the low number of samples provided by the satellites, some prior knowledge on the surface wind speed distribution can be used. It is assumed here that it follows a classical Weibull law which is fitted to the empirical histogram. The Weibull law probability density function is given by:

$$pdf(U) = \frac{k}{\lambda}\left(\frac{U}{\lambda}\right)^{k-1} e^{-(U/\lambda)^k} \quad \text{Eq. (9)}$$

where λ is a scaling parameter in m.s^{-1} and k a dimensionless shape parameter. The parameters of the best Weibull law corresponding to the dataset are obtained by the method of the moments (Pavia and O'Brien, 1986):

$$k = (\sigma/\mu)^{-1.086} \quad \text{Eq. (10)}$$

$$\lambda = \frac{\mu}{\Gamma\left(\frac{1}{k}+1\right)} \quad \text{Eq. (11)}$$

where μ is the mean wind speed and σ its standard deviation. This method allows for prediction of the correct wind speed distribution without having the full information about it, thus enhancing the amount of information that can be obtained from the satellite data. In order to verify the accuracy of the method and of the satellite measurements, the parameters obtained with this method were compared with the parameters obtained with the in situ data in the same way. The wind power as a function of these parameters is given by the following formula (Justus et al., 1976):

$$P = 0.5\ \rho\lambda^3\Gamma(1 + 3/k) \quad \text{Eq. (12)}$$

where Γ is the Gamma function.

3. Discussion

3.1 Match-up comparison

The main objective of the Sentinel-1 SAR surface wind comparison with in situ data was to highlight the agreement and dissonance between the two. Sentinel-1 SAR Level 2 OCN surface wind data and in situ wind data were collocated in space and time. Since the spatial resolution of this product is very high (1 km^2) and offshore winds have a low spatial heterogeneity caused by sea surface homogeneity, the spatial resolution was slightly degraded in order to increase the number of samples. The best remotely sensed value, both in term of quality and distance, from the pixel directly adjacent to the in situ measurement (i.e. 3 km^2) was chosen for the match-up comparison.

In the time domain, each in situ measurement with the corresponding satellite measurement performed in a 30 mn time interval before or after were selected for the analysis. For all buoys, the wind speed correlation with the remotely sensed data at a one-hour time interval was around 0.99, which showed that the time difference between the satellite and in situ data does not

introduce a significant source of error. Another factor in this respect is that Sentinel-1 SAR Level 2 OCN spatial averaging at the resolution of 1 km^2 may somewhat compensate for the lack of time averaging. However, the bias due to these differences in the measurement technique, in space and time, is difficult to predict theoretically. Therefore, the bias can be caused not only by the SAR sensor intrinsic error, but also by the different scales of measurement. Another source of potential error derived from the assumption of neutral atmospheric stability when scaling the buoy data from 3 m to 10 m a.s.l using Equation (1). Hence, the overall bias needed to be evaluated empirically through a match-up comparison.

The bias for all available data was found to be -0.42 $m.s^{-1}$ and -0.39 $m.s^{-1}$ and the RMSE 1.41 $m.s^{-1}$ and 1.51 $m.s^{-1}$ for the buoys and weather stations, respectively (Table 3 & 4). These results showed that Sentinel-1 SAR Level 2 OCN is underestimating the in situ wind speed. A very high linear correlation coefficient of 0.93 for the buoys and 0.92 for the weather stations demonstrated that Sentinel-1 SAR data are suitable for estimating the local wind speed. For all locations, the number of match-up samples over the two-year period of study was above 150, which is known to be the minimum number of samples needed to obtain correct wind speed statistics (Bentami and Croize-Fillon, 2014). The results also showed that the errors calculated with offshore buoys or coastal stations are very consistent. Therefore, it can be concluded that, taking the bias into account, Sentinel-1 SAR can be used to estimate the wind speed up to 1 km from the shore, which is the resolution of the instrument and the required distance to avoid land contamination.

The bias was found to be wind speed dependent. Figure 4 (left) shows that the bias was stronger at small wind speed values and reduced as the wind speed increased. This is consistent with the fact that Sentinel-1 SAR uses the sea state in order to estimate surface winds. Indeed, low wind speeds do not necessarily cause a significant effect on the sea state and, consequently, the instrument does not always accurately estimate the surface winds. This problem is already well known and often leads to an unrealistically high number of very low wind speed values. This can be seen on the scatter plot in Figure 4 (right), which also confirmed the results related to the bias.

As expected, the satellites also underestimated the wind power. The average error in the wind power was 6% for the weather buoys and 13% for the coastal weather stations, respectively (Figures 5 & 6). Since the wind power is proportional to the cube of the wind speed, a higher error (approx. 20%) would be expected. However, since the underestimation is mainly affecting low wind speed values and not so much strong values, the resulting error on the wind power was reduced. The higher bias for two of the coastal weather stations, namely, Mace Head and Malin head, may be caused by generally lower wind speeds near the coast and, therefore, the effect of the bias was amplified at those locations.

3.2 Impact of intra-diurnal variability

The main limitation of satellite remote sensing to accurately assess the offshore wind resource derives from their reduced temporal coverage and revisit time at a given location. Since wind speeds can have strong daily variations, the impact due to the lack of intra-diurnal measurements needs to be investigated. To do so, for each match-up between the satellites and the in situ instruments, all the in situ measurements from that 24-hour period were added to the in situ data before computing the statistics (Figure 7). The bias and the error on the wind power assessment were increased on average by 9.14% across the 7

sites as shown in Table 7. It can be concluded that the lack of intra-diurnal satellite data has a relatively small impact on the results. Since the satellites pass different locations at different times of day, some in situ locations were more affected than others. However, the increase of error on the wind power due to intra-diurnal variability was always below 7% of the total wind power.

3.3 Impact of the scarce temporal coverage

In this section all the available in situ data over the two-year period of study were taken into account, including days for which there was no satellite pass. In order to compare statistics derived from the same time periods, the histograms of in situ data were computed using all of the available periods and the histogram of satellite data with satellite measurements available during these periods (Figures 5 & 6). These figures showed that, although the histograms produced from the satellite data exhibited important discrepancies compared to the one produced from the in situ data, the SAR measurements were nonetheless sufficient to correctly estimate the Weibull laws describing wind speed statistics (in red for Sentinel-1 Level 2 OCN and in green for in situ devices in the figures). The analysis revealed a strong overall agreement between the in situ and SAR wind speed distributions, as can be seen in Tables 8 & 9. The Weibull parameters and the corresponding wind powers had very similar results, with wind power errors below approx. 10% and approx. 5% for the weather buoys and the coastal weather stations, respectively. These results were quite remarkable given the fact that the wind power is proportional to the cube of the wind speed, meaning that its calculation has a strong magnifying effect on the error. This also means that Sentinel-1 SAR is able to retrieve the average wind power over large areas with a high spatial resolution and a reasonable error.

The results show that the percentage error on the average wind power was lowest for the coastal weather stations. This may indicate that they could be more reliable than weather buoys, perhaps due to the presence of waves and the relatively low altitude of the buoys. In that case, the error in offshore locations could be overestimated due to inaccuracies with the weather buoy data, although there is no possibility of proving this with certitude. The validation of the Level 2 OCN product should be further investigated in coastal area since land contamination and coastal topography can introduce bias. Another interesting feature is that the bias observed in the match-up comparison seemed to disappear in this climatological analysis. The main difference between the match-up comparison and the analysis performed here arises from including in situ data even when satellite data were not available. In this study, satellite data can be unavailable for two reasons: no data were recorded as a consequence of the relatively low revisit time of the satellite, or the data recorded were discarded if it was flagged as 'bad quality'. The former should not have any effect on the long-term statistics since an increase in sample size will result in a better Weibull distribution. However, the latter might actually introduce an artificial bias in the match-up comparison by limiting it to a specific type of situation in which satellite measurements are easier to perform. For example, if good quality flags are more likely to correspond to turbulent situations, then the different scales at which the measurements are performed (10 minutes for in situ devices and 1 km^2 for the satellite) can introduce a discrepancy. In that case, measurements in space will be less affected by the turbulence and closer to the average long-term distribution due to Kolmogorov's laws (Kolmogorov, 1941) stipulating that the variability linked to turbulence scales as function of $\Delta t^{1/2}$ in time and only as a function of $\Delta x^{1/3}$ in space. Finally, when the in situ database includes all types of situations, the in situ distributions converge towards the one obtained with the satellite data.

3.4 Wind resource assessment in Irish coastal waters

In this section, the use of the Sentinel-1 Level 2 OCN product to assess wind resources around Ireland at 10 m a.s.l. with a 1 km^2 spatial resolution is presented. A clear separation of the mean wind speed into two different areas was clearly visible (Figure 7). The northwest area, starting above 53 °N and going until the beginning of the North Channel between Ireland and Scotland, was characterised by a climate of strong winds (above 9 $m.s^{-1}$), while the rest of the map had a more moderate wind climate, with a mean generally around 8 $m.s^{-1}$. This was consistent with the observations obtained from spaceborne scatterometers (Remmers et al., 2019).

In terms of wind power, the results logically revealed a similar pattern with an increased heterogeneity, due to the fact that the wind power is connected to the cube of the wind speed (Figure 8). The northwest area had an average wind power of 700 W m-2 in comparison with 500 W m-2 for the rest of the map, resulting in an overall difference of 20% between the two areas. It is interesting to note that the central area of the Irish sea also has a significant potential in terms of wind power, although lower than that of the northwest area. Regarding coastal areas, a steep horizontal gradient was observed from the shore up to 15-20 km offshore, with the exception of the remote peninsulas on the west coast where the gradient was much shorter or non-existent. In both analyses, the apparent swats can be attributed to the low sample size of satellite data which correlates with Figure 1. The better spatial resolution of SAR data inevitably reduces the revisiting time and therefore the sample size. With time, these artefacts will diminish as the satellite will acquires additional data.

The seasonal averages of wind speed and wind power showed expected trends of low and strong winds typical of the summer and winter seasons, respectively (Figures 9 & 10). Autumn was also associated with strong winds, which corolated to the cyclonic activity in the North Atlantic Ocean ending their trajectory in this area of Western Europe. The wind climate during spring was much more moderate than that of autumn.

As shown in Figures 7 to 10, the tracks of the satellites were still visible. This discrepancy can be related to several factors such as instrument bias associated with the incidence angle, difference in the number of samples (Figure 1) affecting the quality of the Weibull fits, or simply a difference in the average time of the day at which the satellites pass (Figure 2) resulting to a different impact of the intra-diurnal variability. Unfortunately, no clear correlation was found between these factors and the anomalies on the maps. It was only found that the edges of the swaths have more unrealistic values, which could be due to the incidence angle or the instrument thermal noise. As a consequence, a margin of 5 pixels (roughly equivalent to 5 km) was removed from the swaths before creating the maps. The areas with less observations also had a less reliable assessment of the mean wind speed and power, however, this limitation should disappear in the future as more samples will become available. It can be concluded that the accuracy was dependent upon location, which is a factor that should be considered when using Santinel-1 SAR data. The results also highlighted the necessity for additional in situ validation points for satellite products and showed that there is a need to improve the Sentinel-1 level 2 OCN product algorithm at the edges of the swaths, perhaps through the application of machine learning techniques.

4. Conclusion

Measurements from the Sentinel-1 Level 2 OCN product were compared with measurements from four weather buoys and three coastal weather stations located around Ireland. The match-up comparison indicated that the satellites underestimated the in situ data by 0.4 $m.s^{-1}$ on average, with an RMSE of 1.45 $m.s^{-1}$. These results were consistent between the weather buoys and the coastal weather station data. The bias was found to be stronger for low wind speeds, and to linearly decrease with an increase of wind speed strength. However, this discrepancy disappeared when the long-term statistics were computed including all available in situ data. This could be associated with the in situ measurements performed at a very different spatial scale to that of the satellite measurements (a few cm^2 versus 1 km^2). In any case, it was concluded that the Sentinel-1 Level 2 OCN product can be used to estimate the long-term wind speed distribution and the average wind power. This result could be obtained by using the method of the moments and assuming a Weibull law in order to compensate for the low temporal coverage of the satellites. Even though more investigation is needed to assess the OCN product in coastal area, this study showed that this remotely sensed data can be used to assess the wind resources in coastal areas as close as 1 km to the shore.

The fact that the satellites always pass at the same hour of the day, limiting their ability to record the intra-diurnal variability, was investigated and its effects on the long-term statistics was found to be minor. Finally, the error on the average wind power was found to be on the order of 10% and 5% for weather buoys and coastal weather stations, respectively. This result was quite remarkable given the fact that the wind power is proportional to the cube of the wind speed, which strongly enhances the original error from the wind speed. Maps of the average wind speed and wind power around Ireland were presented with a resolution of 1 km2. These maps indicated that the algorithm used to develop the Sentinel-1 Level 2 OCN product needs to be improved since the satellite swaths were still visible. Users should exercise caution when working with Sentinel-1 SAR data since a location-dependent error was found at the swath edges. The cause of this discrepancy could not be identified, but perhaps a machine learning technique based on a learning dataset of in situ data could be used to mitigate this effect.

Future studies could focus on the combined use of SAR and scatterometer measured wind speed in order to create climatologies constructed using a longer period than the two-year period of this study. This could be particularly interesting to more accurately estimate the offshore wind energy resource. Another important application in the future would be to modify the acquisition mode in coastal areas for the satellites carrying SAR, in order to obtain the required information to estimate the wave heights. This information, only available in open seas with Sentinel-1, would be useful to correlate the wind and wave energy and thus provide a more detailed description of the marine environment for optimising offshore wind farm siting.

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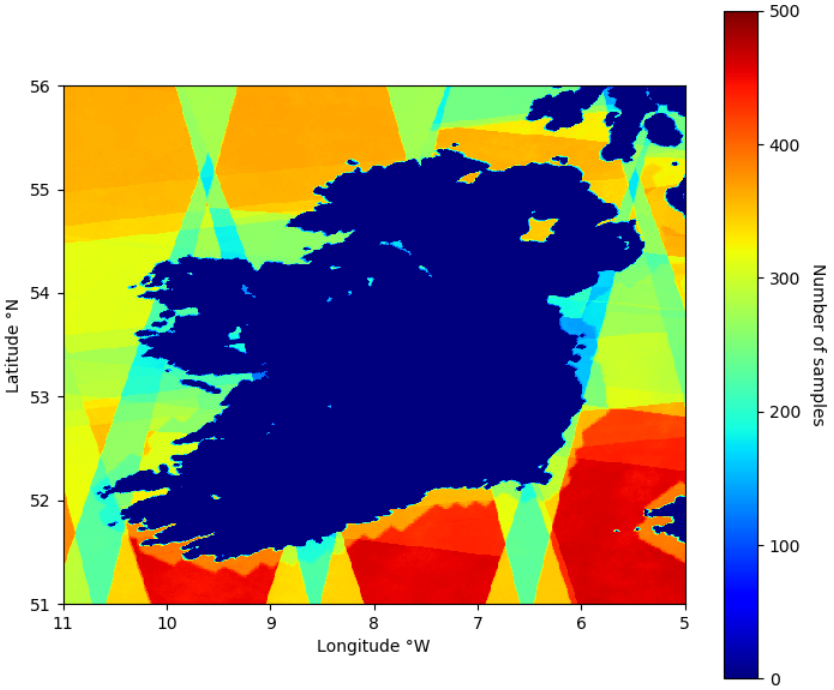

Figure 1: Number of Sentinel-1 A and B passes across Ireland over a two-year period running from May 2017 to May 2019 with an acceptable quality flag (≤ 2).

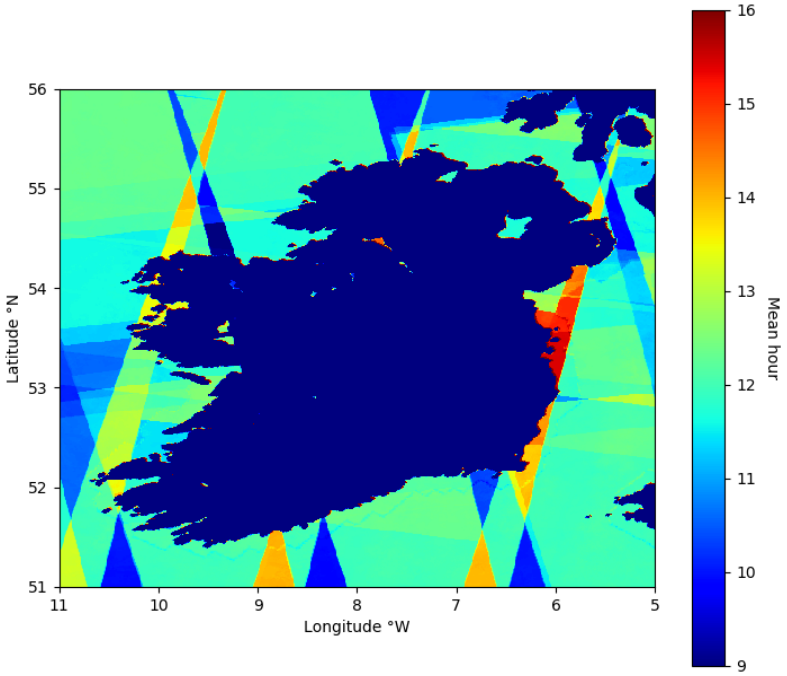

Figure 2: Average daily hour of Sentinel-1 A and B passes across Ireland over a two-year period running from May 2017 to May 2019 with an acceptable quality flag (≤ 2).

380

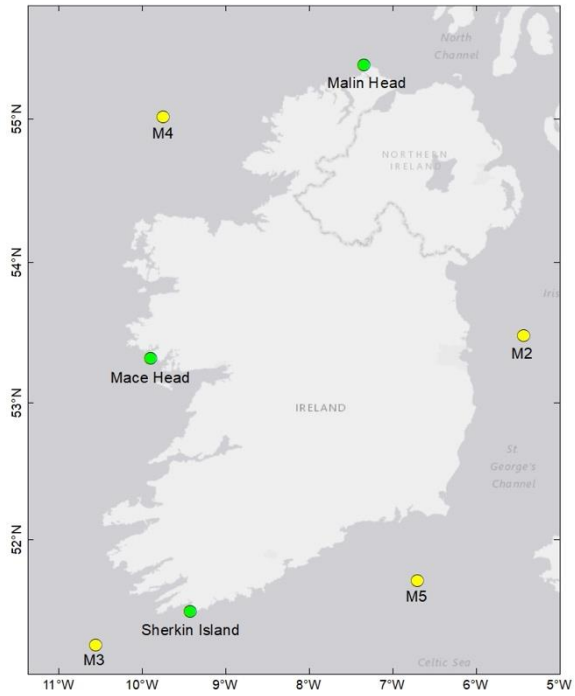

Figure 3: Location of metocean buoys (yellow) and coastal weather stations (green) used in the validation of Sentinel-1 SAR surface winds.

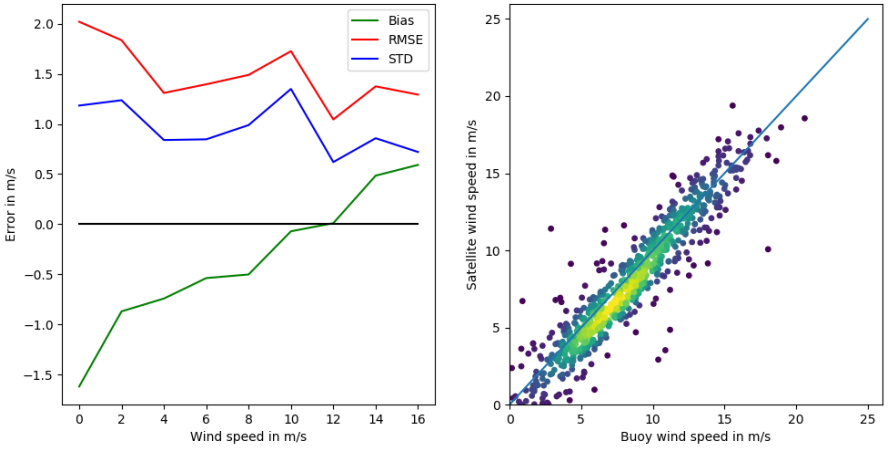

Figure 4: Statistical representation of the Sentinel-1 Level 2 OCN error against weather buoy data as a function of SAR wind speeds (left), and scatter plot versus weather buoy data (right).

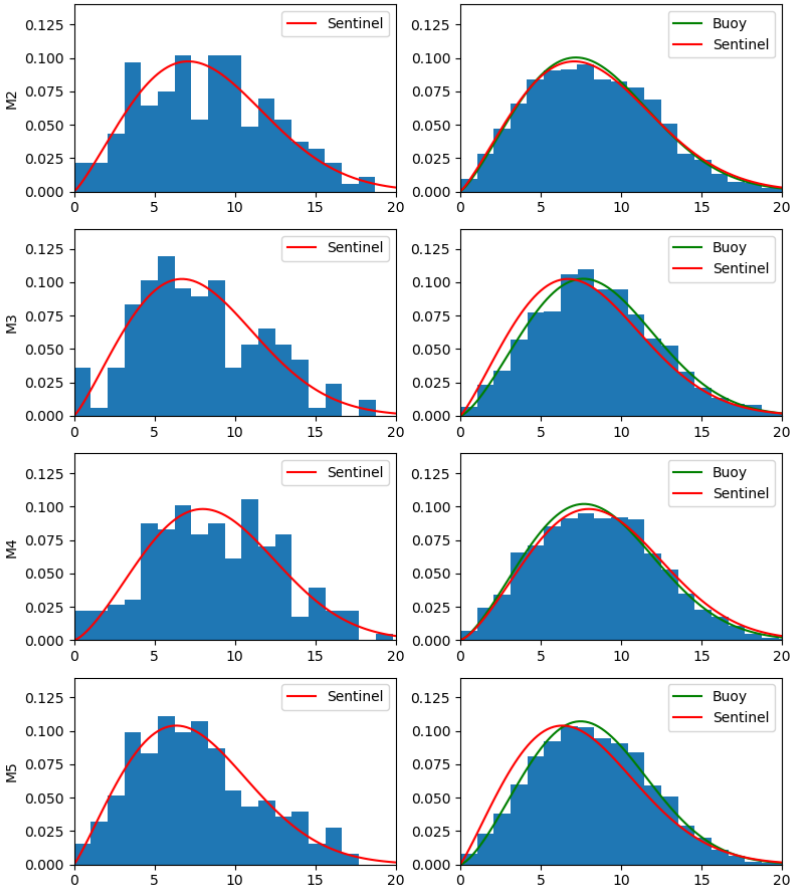

Figure 5: Wind speed histograms of Sentinel-1 SAR Level 2 OCN (right) and in situ (left) data in m s-1 with corresponding Weibull fits for the weather buoy data compared with those produced from the SAR data at the same locations

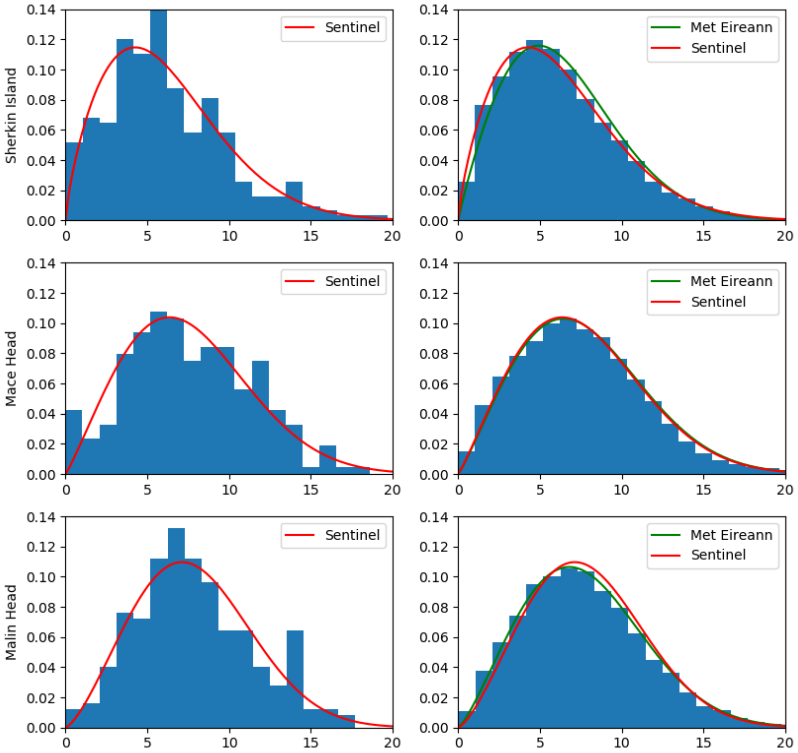

Figure 6. Wind speed histograms of Sentinel-1 SAR Level 2 OCN (right) and in situ (left) data in m s-1 with corresponding Weibull fits for the coastal weather station data compared with those produced from the SAR data at the same locations.

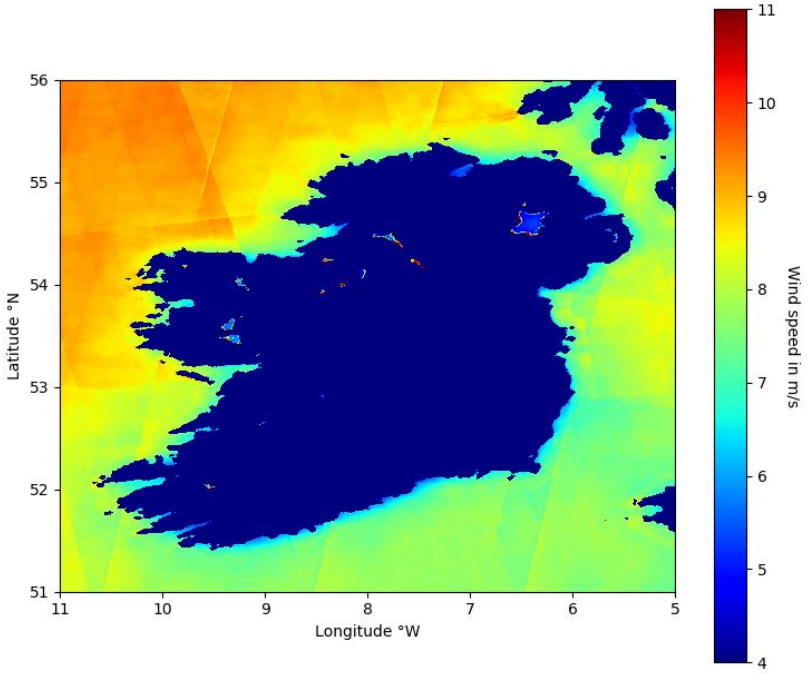

Figure 7: Average wind speed off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product. Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

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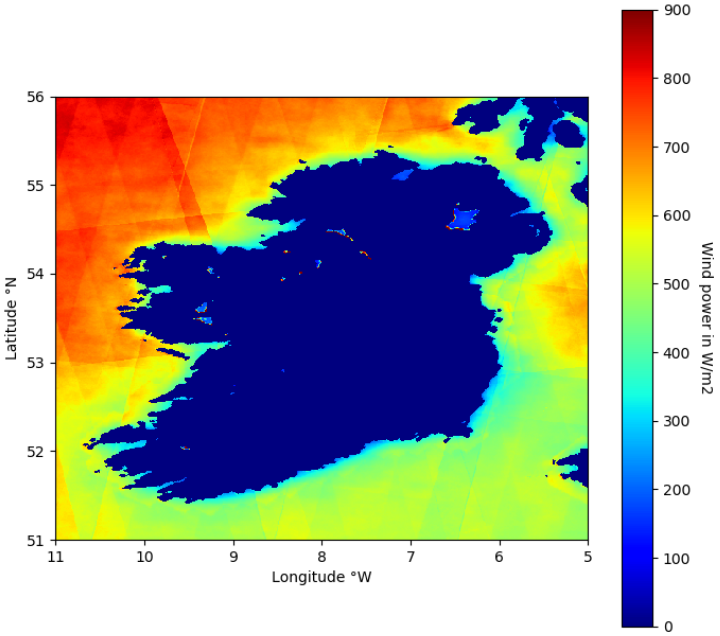

Figure 8: Wind power off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product. Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

410

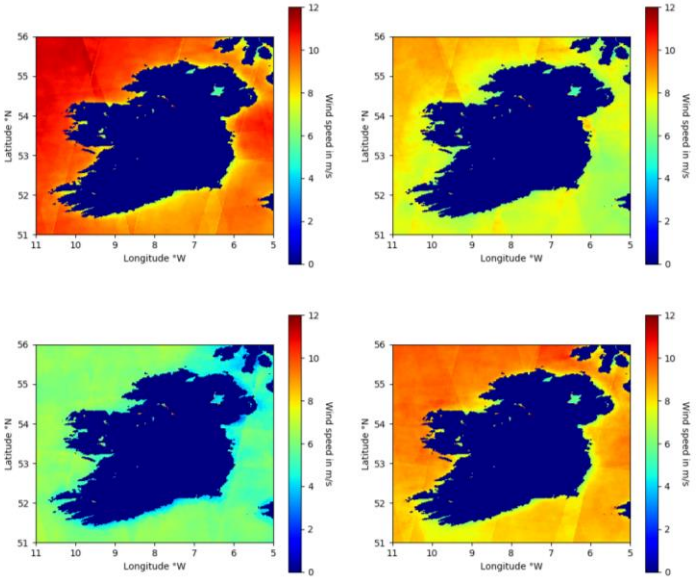

Figure 9: Seasonal average wind speed off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product (top left: winter, top right: spring, lower left: summer, lower right: autumn). Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

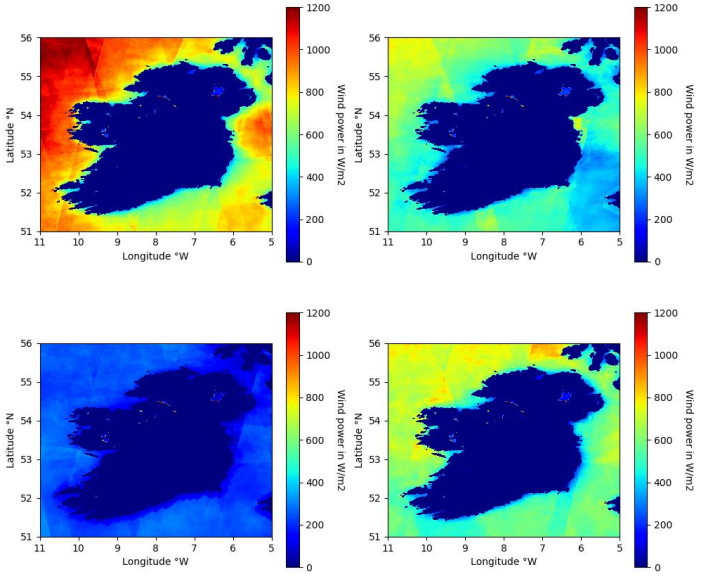

Figure 10: Seasonal wind power off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product (top left: winter, top right: spring, lower left: summer, lower right: autumn). Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

Name	Type	Latitude	longitude	Altitude in m	% of availability
M2	Metocean buoy	53.48°N	05.42°W	3	63
M3	Metocean buoy	51.21°N	10.55°W	3	59
M4	Metocean buoy	55.00°N	09.99°W	3	72
M5	Metocean buoy	51.69°N	06.70°W	3	85

Table 1: Location and characteristics of the weather buoys used in the comparison with Sentinel-1 SAR Level 2 OCN product.

Name	Type	Latitude	Longitude	Altitude in m	% of availability
Sherkin Island	Weather station	51.47°N	9.42°W	21	100
Mace Head	Weather station	53.32°N	9.90°W	21	100
Malin Head	Weather station	55.37°N	7.34°W	20	100

435 **Table 2: Location and characteristics of the coastal weather stations used in the comparison with Sentinel-1 SAR Level 2 OCN product.**

Buoy	N samples (SAR)	Mean (SAR)	Mean (in situ)	Bias (m/s)	Percentile 90% (SAR)	Percentile 90% (in situ)	RMSE	MAE	R
M2	179	8.29	8.58	-0.29	13.73	13.64	1.41	1.12	0.94
M3	161	7.86	8.31	-0.45	13.31	13.10	1.74	1.12	0.89
M4	219	8.86	9.00	-0.14	13.98	14.25	1.35	1.01	0.94
M5	242	7.6	8.34	-0.74	13.08	13.39	1.14	0.81	0.95
Total	801	8.15	8.57	-0.42	13.52	13.59	1.41	1.02	0.93

Table 3: Results of the match-up comparison of satellite measured wind speeds with in situ measured wind speeds from weather buoys.

Mast	N samples (SAR)	Mean (SAR)	Mean (in situ)	Bias (m/s)	Percentile 90% (SAR)	Percentile 90% (in situ)	RMSE	MAE	R
Sherkin Island	297	6.15	6.17	-0.12	10.86	10.80	1.47	1.15	0.92
Mace Head	206	7.61	8.36	-0.75	12.66	13.63	1.42	1.11	0.94
Malin Head	240	7.91	8.34	-0.43	13.37	13.89	1.55	1.23	0.92
Total	743	7.12	7.52	-0.39	12.30	12.77	1.51	1.18	0.93

Table 4: Results of the match-up comparison of satellite measured wind speeds with in situ measured wind speeds from coastal weather stations.

Buoy	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	Wind power in W/m² (SAR)	Wind power in W/m² (in situ)	% of error on wind power
M2	2.19	2.34	9.37	9.68	613	641	-4.28
M3	2.18	2.44	8.87	9.37	524	564	-7.04
M4	2.41	2.56	9.99	10.14	689	693	-0.47
M5	2.12	2.51	8.58	9.40	485	559	-13.19
Total	2.22	2.46	9.20	9.65	578	614	-6.24

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Table 5: Comparison of wind speed long-term statistics obtained from the four weather buoys with the ones obtained from the SAR data.

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Mast	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	Wind power in W/m² (SAR)	Wind power in W/m² (in situ)	% of error on wind power
Sherkin Island	1.75	1.86	6.91	7.06	315	311	1.48
Mace Head	2.12	2.19	8.59	9.44	487	627	-22.41
Malin Head	2.40	2.28	8.92	9.41	492	601	-18.07
Total	2.09	2.11	8.14	8.64	431	513	-13.00

Table 6: Comparison of wind speed long-term statistics obtained from the three coastal weather stations with the ones obtained from the SAR data.

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Buoy	Bias in m/s	Bias in m/s (including in situ intra-day data)	% of error on wind power	% of error on wind power (including in situ intra-day data)
M2	-0.29	-0.48	-4.28	-11.10
M3	-0.45	-0.68	-7.04	-14.36
M4	-0.14	-0.2	-0.47	-2.50
M5	-0.74	-0.84	-13.19	-15.32
Sherkin Island	-0.12	-0.32	1.48	-6.04
Mace Head	-0.75	-0.78	-22.41	-25.28
Malin Head	-0.43	-0.21	-18.07	-13.11
Total	-0.42	-0.50	-9.14	-10.82

Table 7: Increase in the bias and the error on the wind power when intra-diurnal data of in situ measurements are taken into account, compared with the same results obtained for the match-up comparison.

Buoy	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	Wind power in W/m2 (SAR)	Wind power in W/m2 (in situ)	% of error on wind power
M2	2.19	2.26	9.37	9.31	613	586	4.69
M3	2.18	2.41	8.87	9.56	524	604	-13.22
M4	2.41	2.41	9.99	9.62	689	615	11.99
M5	2.12	2.45	8.58	9.27	485	544	-10.93

Table 8: Comparison of the long-term wind speed statistics produced from the weather buoy data with those produced from the SAR data at the same locations.

Buoy	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	SAR Wind power (W/m^2)	In situ Wind power (W/m^2)	% of error on wind power
Sherkin Island	1.75	1.92	6.91	7.21	315	319	-1.08
Mace Head	2.12	2.13	8.59	8.69	487	502	-2.99
Malin Head	2.40	2.26	8.92	8.78	492	492	0.15

Table 9: Comparison of the long-term wind speed statistics produced from the coastal weather station data with those produced from the SAR data.

Validation of Sentinel-1 offshore winds and average wind power estimation around Ireland

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Abstract. In this paper, surface wind speed and average wind power derived from Sentinel-1 Synthetic Aperture Radar Level 2 OCN product were validated against four weather buoys and three coastal weather stations around Ireland. A total of 1,544 match-up points was obtained over a two-year period running from May 2017 to May 2019. The match-up comparison showed that the satellite underestimated the wind speed compared to in situ devices, with an average bias of 0.4 m/s, which decreased linearly as a function of wind speed. Long-term statistics using all the available data, while assuming a Weibull law for the wind speed, were also produced and resulted in a significant reduction of the bias. Additionally, the average wind power was found to be consistent with in situ data, resulting in an error of 10% and 5% for weather buoys and coastal stations, respectively. These results showed that the Sentinel-1 Level 2 OCN product can be used to estimate the wind speed distribution, even in coastal areas. Maps of the average and seasonal wind speed and wind power illustrated that the error was spatially dependent, which should be taken into considerations when working with Sentinel-1 SAR data.

1 Introduction

With the ever-increasing interest in offshore wind energy and the rise of floating turbines, the estimation of the available wind energy over large offshore areas has become necessary. According to the Global Wind Energy Council (Global wind statistics 2014), offshore wind power costs are expected to reduce by about 45% by 2050. One factor that can be associated with cost reduction is the increasing availability of accurate remote sensing data over large areas with a high resolution which can significantly reduce project risk at site finding stage. Moreover, the measurement of offshore wind speed contributes to the understanding of marine phenomena and boundary layer processes. Low altitude meteorological parameters, such as wind, are therefore key parameters in the modelling of the Earth system.

Several studies have already attempted to assess the offshore wind energy potential using spaceborne scatterometers, such as ERS-1, ERS-2, NSCAT, QuickSCAT and ASCAT (Sánchez et al., 2007; Pimenta et al., 2008; Karagali et al., 2014; Bentamy and Croize-Fillon, 2014; Remmers et al., 2019). However, the spatial resolution of these instruments is at best 12.5 km^2, which prevents the assessment in coastal areas (0-20 km from the shore) and the study of fine sub-mesoscale processes that can affect

turbine yields and climate processes. In this framework, spaceborne Synthetic Aperture Radar (SAR) sensors offer a much higher spatial resolution, allowing for wind speed retrieval with a level of detail not discernible from scatterometer data.

In this study, the Sentinel-1 A and B Level 2 OCN product produced by the European Space Agency (ESA) was validated. This product, derived from SAR observations, provides measurement of neutral surface wind speed and direction at 10 m above sea level (a.s.l.) with a spatial resolution of 1 km^2. Even though this type of analysis was previously performed in other parts of Europe (Hasager et al., 2015), it has never been conducted using both marine and coastal in situ measurements at a national scale in Ireland, which has a significant offshore wind resource (Remmers et al., 2019). Moreover, to the authors' knowledge, the Sentinel-1 level 2 OCN product has not yet been validated against in situ measurements, with the exceptions of one match-up comparison in the waters adjacent to the Korean peninsula (Jang et al., 2019). Similarly, long term statistics retrieved using this product, such as the average wind power, which is the most relevant for the wind energy industry, have never been analysed before.

The aim of this study was to validate and the Sentinel-1 A and B Level 2 OCN product against in situ measurements in Ireland and asses this data ability to describe the wind resources. First the satellite product and the study area are introduced, next the methodology is provided and finally, the results are presented and discussed.

2 Data and Methodology

2.1 Sentinel-1 SAR Level 2 OCN

Sentinel-1 A and B are two polar-orbiting satellites equipped with C-band SAR. This sensor which records surface roughness, has the advantage of operating at wavelengths not impeded by cloud cover or a lack of illumination and can acquire data over a site during day or night in all weather conditions. The Sentinel-1 Level 2 OCN product includes a component called Ocean Wind Fields (OWI) which is a ground range gridded estimate of the surface wind speed and direction at 10 m a.s.l, assuming a neutral atmospheric stratification, with a spatial resolution of 1 km2. The two satellites are located on the same orbit 180° apart and at an altitude close to 700 km. In Irish coastal waters, the acquisition mode is Interferometric Wide (IW) swath using the TOPSAR technique which provide a better quality product by enhance the image homogeneity (ESA, 2019). All Sentinel-1A and B SAR images in IW acquisition mode from May 1, 2017 to May 1, 2019, in the area located around Ireland between 51°N and 56°N in latitude and 5°W and 16°W in longitude, were collected (n=5,509). The quality flag for these data ranges from 0 to 3 (0 being the best and 3 the worst) and, following visual inspection, only data with a quality flag ≤ 2 were used for the validation. The Level 2 product tiles were combined into a gridded map for the area of interest, in order to form a data cube where each pixel had a corresponding time series of measurements. The revisit rate ranges from 10 to 20 passes per month for most areas in Irish waters, which occur in the morning around 6.30 am or in the evening around 6 pm, Greenwich Mean Time (GMT) in the winter and Irish Standard Time (IST) in the summer. Figure 1 shows the number of samples for each pixel and

Figure 2 shows the average daily passing time of the satellites. The impact on quality flag from landmass contamination was visible with the reduced sample size in coastal area.

2.2 In situ instruments

2.2.1 Weather Buoys

Ireland's Marine Institute operates five offshore weather buoys named M2, M3, M4, M5 and M6. Their location is shown on Figure 3. The data from these were downloaded from the Marine Institute website with a two-year time series ranging from May 1st 2017 to May 1st 2019. The hourly product corresponds to the wind speed averaged over a period of 10 minutes every hour at 3 m a.s.l.. As a result of extensive maintenance periods, the buoys are not always functioning leading to a lack of measurements in the dataset, up to several months, for some locations. Due to this phenomenon, and to a poor offshore coverage frequency from Sentinel-1 satellites, the M6 buoy was excluded in the validation analysis.

In order to compare Sentinel-1 SAR Level 2 OCN product with this network of instruments, the in situ buoy measurements were extrapolated from 3 m to 10 m a.s.l.. The following log law was used, assuming a neutral atmospheric stratification (Carvalho et al., 2017):

$$U_{10} = \frac{\ln\left(\frac{Z_{sat}}{Z_0}\right)}{\ln\left(\frac{Z_{buoy}}{Z_0}\right)} . U_{buoy} \qquad \text{Eq. (1)}$$

where U_{10} is the wind speed at 10 m in m.s^{-1}, U_{buoy}, the wind speed measured by the buoys in m.s^{-1}, Z_{sat} the altitude of the satellite measurements in m, Z_{buoy} the altitude of the buoy measurements in m, and Z_0 the roughness length of the sea surface taken as 0.0002 m *(Charnock, 1955)*. Table 1 gives the exact locations of these buoys and their percentage of availability.

2.2.2 Coastal weather stations

Three weather stations operated and maintained by Met Éireann, the Irish weather forecasting service, were used to validate the Sentinel-1 SAR Level 2 OCN wind speeds in coastal areas. These three stations were considered for the validation analysis because they are located close to the shore (less than 200 m, see Figure 3), at a low altitude (approx. 20 m), and far from any hills or relief. The stations are situated on the west coast of Ireland at Sherkin Island, Mace Head, and Malin Head, and have continuous wind speed records during the two-year period of study (Table 2). The predominant wind direction on the Irish west coast is eastward, flowing from the sea to toward the land. Simulations of these type of flows have shown that for a moderate coastal slope, onshore wind speeds recorded at proximity to the shore can equate the wind speeds at sea just before reaching the coast (Bassi Marinho Pires et al., 2015). Following this principle, the wind speed derived from satellite measurement were not scaled to the weather station terrain elevation, but instead were considered as being in the same streamline and kept at the OCN product elevation of 10 m a.s.l.. The weather station data were compared with Sentinel-1 SAR

Level 2 OCN wind speeds measured with the closest pixel without quality flag. Due to the complex Irish coast line and to avoid land contaminate, the OCN measurement were one or two pixels away from the shore (i.e. 1 or 2 km).

2.3 Assessment criteria

The error e_i between Sentinel-1 Level 2 OCN wind speed, denoted U_i, and the in situ measurement, denoted u_i, is defined as follows:

$$e_i = U_i - u_i \quad \text{Eq. (2).}$$

The criteria used in the comparison were the mean error (or bias), the standard deviation (σ), the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE) and the linear correlation coefficient (R), respectively defined by:

$$Bias = \frac{1}{N}\sum_{i=1}^{N} e_i \quad \text{Eq. (3)}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(e_i - Bias)^2} \quad \text{Eq. (4)}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {e_i}^2} \quad \text{Eq. (5)}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|e_i| \quad \text{Eq. (6)}$$

$$R = \frac{1}{\sigma_U \sigma_u (N-1)}\sum_{i=1}^{N}(U_i - U)(u_i - u) \quad \text{Eq. (7)}$$

where U and u denote the mean of satellite and in situ wind speeds respectively, σ_U and σ_u their standard deviation, and N the number of match up samples.

2.4 Wind distribution estimation

The average wind power density P in W.m^{-2}, simply called wind power in the following, is the average kinetic energy passing through a unit of surface per unit of time. It can be estimated directly from the wind speed time series using the following formula:

$$P = 0.5\rho(1/N)\sum_{i=1}^{N} {U_i}^3 \quad \text{Eq. (8)}$$

where ρ is the air density (1.245 g.m^{-3} at 10°C) and U_i the wind speed. However, in order to compensate for the low number of samples provided by the satellites, some prior knowledge on the surface wind speed distribution can be used. It is assumed here that it follows a classical Weibull law which is fitted to the empirical histogram. The Weibull law probability density function is given by:

$$pdf(U) = \frac{k}{\lambda}\left(\frac{U}{\lambda}\right)^{k-1} e^{-(U/\lambda)^k} \quad \text{Eq. (9)}$$

where λ is a scaling parameter in m.s^{-1} and k a dimensionless shape parameter. The parameters of the best Weibull law corresponding to the dataset are obtained by the method of the moments (Pavia and O'Brien, 1986):

$$k = (\sigma/\mu)^{-1.086} \quad \text{Eq. (10)}$$

$$\lambda = \frac{\mu}{\Gamma\left(\frac{1}{k}+1\right)} \quad \text{Eq. (11)}$$

where μ is the mean wind speed and σ its standard deviation. This method allows for prediction of the correct wind speed distribution without having the full information about it, thus enhancing the amount of information that can be obtained from the satellite data. In order to verify the accuracy of the method and of the satellite measurements, the parameters obtained with this method were compared with the parameters obtained with the in situ data in the same way. The wind power as a function of these parameters is given by the following formula (Justus et al., 1976):

$$P = 0.5\,\rho\lambda^3\Gamma(1+3/k) \quad \text{Eq. (12)}$$

where Γ is the Gamma function.

3. Discussion

3.1 Match-up comparison

The main objective of the Sentinel-1 SAR surface wind comparison with in situ data was to highlight the agreement and dissonance between the two. Sentinel-1 SAR Level 2 OCN surface wind data and in situ wind data were collocated in space and time. Since the spatial resolution of this product is very high (1 km^2) and offshore winds have a low spatial heterogeneity caused by sea surface homogeneity, the spatial resolution was slightly degraded in order to increase the number of samples. The best remotely sensed value, both in term of quality and distance, from the pixel directly adjacent to the in situ measurement (i.e. 3 km^2) was chosen for the match-up comparison.

In the time domain, each in situ measurement with the corresponding satellite measurement performed in a 30 mn time interval before or after were selected for the analysis. For all buoys, the wind speed correlation with the remotely sensed data at a one-hour time interval was around 0.99, which showed that the time difference between the satellite and in situ data does not introduce a significant source of error. Another factor in this respect is that Sentinel-1 SAR Level 2 OCN spatial averaging at the resolution of 1 km^2 may somewhat compensate for the lack of time averaging. However, the bias due to these differences in the measurement technique, in space and time, is difficult to predict theoretically. Therefore, the bias can be caused not only by the SAR sensor intrinsic error, but also by the different scales of measurement. Another source of potential error derived from the assumption of neutral atmospheric stability when scaling the buoy data from 3 m to 10 m a.s.l using Equation (1). Hence, the overall bias needed to be evaluated empirically through a match-up comparison.

The bias for all available data was found to be -0.42 $m.s^{-1}$ and -0.39 $m.s^{-1}$ and the RMSE 1.41 $m.s^{-1}$ and 1.51 $m.s^{-1}$ for the buoys and weather stations, respectively (Table 3 & 4). These results showed that Sentinel-1 SAR Level 2 OCN is underestimating the in situ wind speed. A very high linear correlation coefficient of 0.93 for the buoys and 0.92 for the weather stations demonstrated that Sentinel-1 SAR data are suitable for estimating the local wind speed. For all locations, the number of match-up samples over the two-year period of study was above 150, which is known to be the minimum number of samples needed to obtain correct wind speed statistics (Bentami and Croize-Fillon, 2014). The results also showed that the errors calculated with offshore buoys or coastal stations are very consistent. Therefore, it can be concluded that, taking the bias into account, Sentinel-1 SAR can be used to estimate the wind speed up to 1 km from the shore, which is the resolution of the instrument and the required distance to avoid land contamination.

The bias was found to be wind speed dependent. Figure 4 (left) shows that the bias was stronger at small wind speed values and reduced as the wind speed increased. This is consistent with the fact that Sentinel-1 SAR uses the sea state in order to estimate surface winds. Indeed, low wind speeds do not necessarily cause a significant effect on the sea state and, consequently, the instrument does not always accurately estimate the surface winds. This problem is already well known and often leads to an unrealistically high number of very low wind speed values. This can be seen on the scatter plot in Figure 4 (right), which also confirmed the results related to the bias.

As expected, the satellites also underestimated the wind power. The average error in the wind power was 6% for the weather buoys and 13% for the coastal weather stations, respectively (Figures 5 & 6). Since the wind power is proportional to the cube of the wind speed, a higher error (approx. 20%) would be expected. However, since the underestimation is mainly affecting low wind speed values and not so much strong values, the resulting error on the wind power was reduced. The higher bias for two of the coastal weather stations, namely, Mace Head and Malin head, may be caused by generally lower wind speeds near the coast and, therefore, the effect of the bias was amplified at those locations.

3.2 Impact of intra-diurnal variability

The main limitation of satellite remote sensing to accurately assess the offshore wind resource derives from their reduced temporal coverage and revisit time at a given location. Since wind speeds can have strong daily variations, the impact due to the lack of intra-diurnal measurements needs to be investigated. To do so, for each match-up between the satellites and the in situ instruments, all the in situ measurements from that 24-hour period were added to the in situ data before computing the statistics (Figure 7). The bias and the error on the wind power assessment were increased on average by 9.14% across the 7 sites as shown in Table 7. It can be concluded that the lack of intra-diurnal satellite data has a relatively small impact on the results. Since the satellites pass different locations at different times of day, some in situ locations were more affected than others. However, the increase of error on the wind power due to intra-diurnal variability was always below 7% of the total wind power.

3.3 Impact of the scarce temporal coverage

In this section all the available in situ data over the two-year period of study were taken into account, including days for which there was no satellite pass. In order to compare statistics derived from the same time periods, the histograms of in situ data were computed using all of the available periods and the histogram of satellite data with satellite measurements available during these periods (Figures 5 & 6). These figures showed that, although the histograms produced from the satellite data exhibited important discrepancies compared to the one produced from the in situ data, the SAR measurements were nonetheless sufficient to correctly estimate the Weibull laws describing wind speed statistics (in red for Sentinel-1 Level 2 OCN and in green for in situ devices in the figures). The analysis revealed a strong overall agreement between the in situ and SAR wind speed distributions, as can be seen in Tables 8 & 9. The Weibull parameters and the corresponding wind powers had very similar results, with wind power errors below approx. 10% and approx. 5% for the weather buoys and the coastal weather stations, respectively. These results were quite remarkable given the fact that the wind power is proportional to the cube of the wind speed, meaning that its calculation has a strong magnifying effect on the error. ~~This also means that Sentinel-1 SAR is able to retrieve the average wind power over large areas with a high spatial resolution and a reasonable error.~~

The results show that the percentage error on the average wind power was lowest for the coastal weather stations. This may indicate that they could be more reliable than weather buoys, perhaps due to the presence of waves and the relatively low altitude of the buoys. In that case, the error in offshore locations could be overestimated due to inaccuracies with the weather buoy data, although there is no possibility

of proving this with certitude. The validation of the Level 2 OCN product should be further investigated in coastal area since land contamination and coastal topography can introduce bias. Another interesting feature is that the bias observed in the match-up comparison seemed to disappear in this climatological analysis. The main difference between the match-up comparison and the analysis performed here arises from including in situ data even when satellite data were not available. In this study, satellite data can be unavailable for two reasons: no data were recorded as a consequence of the relatively low revisit time of the satellite, or the data recorded were discarded if it was flagged as 'bad quality'. The former should not have any effect on the long-term statistics since an increase in sample size will result in a better Weibull distribution. However, the latter might actually introduce an artificial bias in the match-up comparison by limiting it to a specific type of situation in which satellite measurements are easier to perform. For example, if good quality flags are more likely to correspond to turbulent situations, then the different scales at which the measurements are performed (10 minutes for in situ devices and 1 km^2 for the satellite) can introduce a discrepancy. In that case, measurements in space will be less affected by the turbulence and closer to the average long-term distribution due to Kolmogorov's laws (Kolmogorov, 1941) stipulating that the variability linked to turbulence scales as function of $\Delta t^{1/2}$ in time and only as a function of $\Delta x^{1/3}$ in space. Finally, when the in situ database includes all types of situations, the in situ distributions converge towards the one obtained with the satellite data.

3.4 Wind resource assessment in Irish coastal waters

In this section, the use of the Sentinel-1 Level 2 OCN product to assess wind resources around Ireland at 10 m a.s.l. with a 1 km^2 spatial resolution is discussed. A clear separation of the mean wind speed into two different areas was clearly visible (Figure 7). The northwest area, starting above 53 °N and going until the beginning of the North Channel between Ireland and Scotland, was characterised by a climate of strong winds (above 9 $m.s^{-1}$), while the rest of the map had a more moderate wind climate, with a mean generally around 8 $m.s^{-1}$. This was consistent with the observations obtained from spaceborne scatterometers (Remmers et al., 2019).

In terms of wind power, the results logically revealed a similar pattern with an increased heterogeneity, due to the fact that the wind power is connected to the cube of the wind speed (Figure 8). The northwest area had an average wind power of 700 W m-2 in comparison with 500 W m-2 for the rest of the map, resulting in an overall difference of 20% between the two areas. It is interesting to note that the central area of the Irish sea also has a significant potential in terms of wind power, although lower than that of the northwest area. Regarding coastal areas, a steep horizontal gradient was observed from the shore up to 15-20 km offshore, with the exception of the remote peninsulas on the west coast where the gradient was much shorter or non-existent. In both analyses, the apparent swats can be attributed to the low sample size of satellite data which correlates with Figure 1. The better spatial resolution of SAR data inevitably reduces the revisiting time and therefore the sample size. With time, these artefacts will diminish as the satellite will acquires additional data.

The seasonal averages of wind speed and wind power showed expected trends of low and strong winds typical of the summer and winter seasons, respectively (Figures 9 & 10). Autumn was also associated with strong winds, which corolated to the cyclonic activity in the North Atlantic Ocean ending their trajectory in this area of Western Europe. The wind climate during spring was much more moderate than that of autumn.

As shown in Figures 7 to 10, the tracks of the satellites were still visible. This discrepancy can be related to several factors such as instrument bias associated with the incidence angle, difference in the number of samples (Figure 1) affecting the quality of the Weibull fits, or simply a difference in the average time of the day at which the satellites pass (Figure 2) resulting to a different impact of the intra-diurnal variability. Unfortunately, no clear correlation was found between these factors and the anomalies on the maps. It was only found that the edges of the swaths have more unrealistic values, which could be due to the incidence angle or the instrument thermal noise. As a consequence, a margin of 5 pixels (roughly equivalent to 5 km) was removed from the swaths before creating the maps. The areas with less observations also had a less reliable assessment of the mean wind speed and power, however, this limitation should disappear in the future as more samples will become available. It can be concluded that the accuracy was dependent upon location, which is a factor that should be considered when using Santinel-1 SAR data. The results also highlighted the necessity for additional in situ validation points for satellite products and showed that there is a need to improve the Sentinel-1 level 2 OCN product algorithm at the edges of the swaths, perhaps through the application of machine learning techniques.

4. Conclusion

Measurements from the Sentinel-1 Level 2 OCN product were compared with measurements from four weather buoys and three coastal weather stations located around Ireland. The match-up comparison indicated that the satellites underestimated the in situ data by 0.4 $m.s^{-1}$ on average, with an RMSE of 1.45 $m.s^{-1}$. These results were consistent between the weather buoys and the coastal weather station data. The bias was found to be stronger for low wind speeds, and to linearly decrease with an increase of wind speed strength. However, this discrepancy disappeared when the long-term statistics were computed including all available in situ data. This could be associated with the in situ measurements performed at a very different spatial scale to that of the satellite measurements (a few cm^2 versus 1 km^2). In any case, it was concluded that the Sentinel-1 Level 2 OCN product can be used to estimate the long-term wind speed distribution and the average wind power. This result could be obtained by using the method of the moments and assuming a Weibull law in order to compensate for the low temporal coverage of the satellites. Even though more investigation is needed to assess the OCN product in coastal area, this study showed that this remotely sensed data can be used to assess the wind resources in coastal areas as close as 1 km to the shore.

The fact that the satellites always pass at the same hour of the day, limiting their ability to record the intra-diurnal variability, was investigated and its effects on the long-term statistics was found to be minor. Finally, the error on the average wind power was found to be on the order of 10% and 5% for weather buoys and coastal weather stations, respectively. This result was quite remarkable given the fact that the wind power is proportional to the cube of the wind speed, which strongly enhances the original error from the wind speed. Maps of the average wind speed and wind power around Ireland were presented with a resolution of 1 km2. These maps indicated that the algorithm used to develop the Sentinel-1 Level 2 OCN product needs to be improved since the satellite swaths were still visible. Users should exercise caution when working with Sentinel-1 SAR data since a location-dependent error was found at the swath edges. The cause of this discrepancy could not be identified, but perhaps a machine learning technique based on a learning dataset of in situ data could be used to mitigate this effect.

Future studies could focus on the combined use of SAR and scatterometer measured wind speed in order to create climatologies constructed using a longer period than the two-year period of this study. This could be particularly interesting to more accurately estimate the offshore wind energy resource. Another important application in the future would be to modify the

acquisition mode in coastal areas for the satellites carrying SAR, in order to obtain the required information to estimate the wave heights. This information, only available in open seas with Sentinel-1, would be useful to correlate the wind and wave energy and thus provide a more detailed description of the marine environment for optimising offshore wind farm siting.

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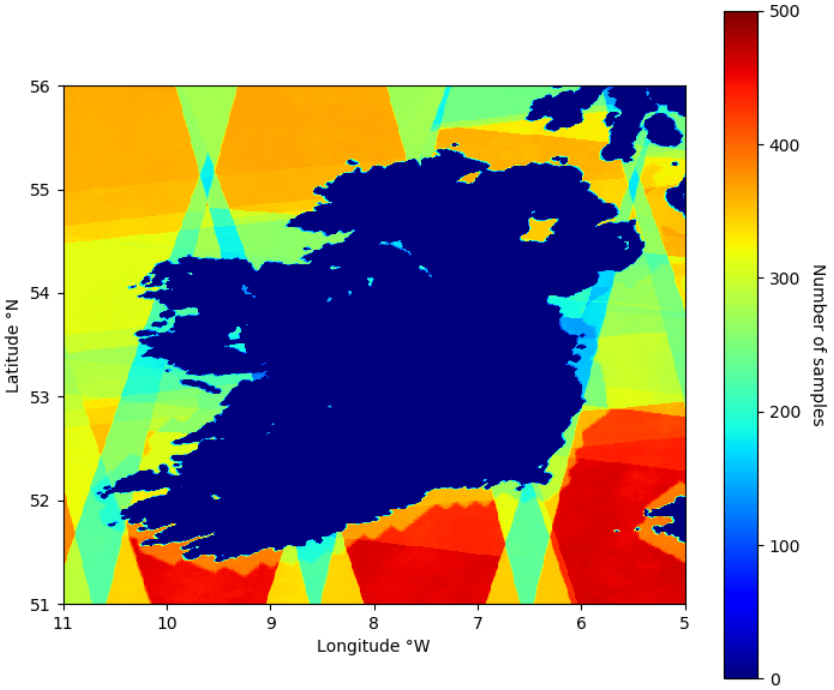

Figure 1: Number of Sentinel-1 A and B passes across Ireland over a two-year period running from May 2017 to May 2019 with an acceptable quality flag (≤ 2).

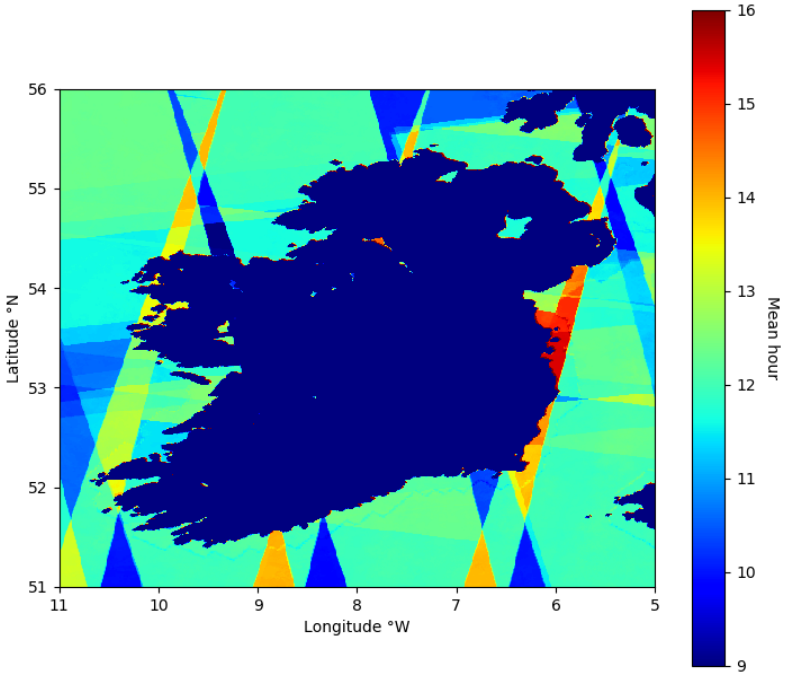

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Figure 2: Average daily hour of Sentinel-1 A and B passes across Ireland over a two-year period running from May 2017 to May 2019 with an acceptable quality flag (≤ 2).

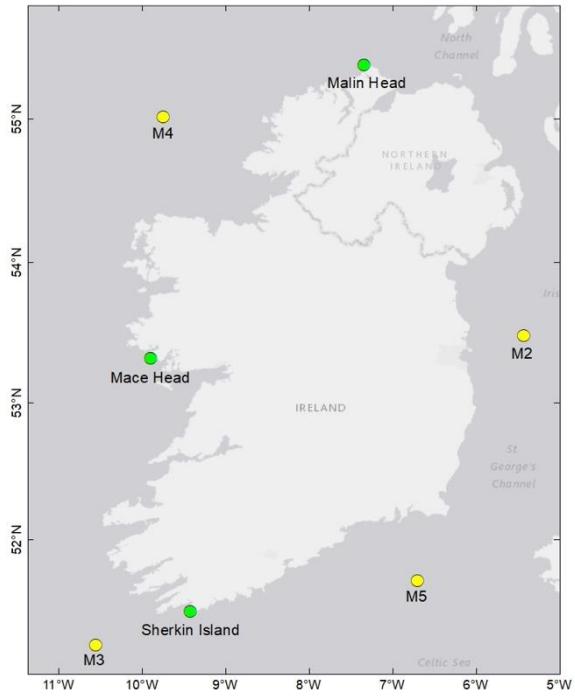

Figure 3: Location of metocean buoys (yellow) and coastal weather stations (green) used in the validation of Sentinel-1 SAR surface winds.

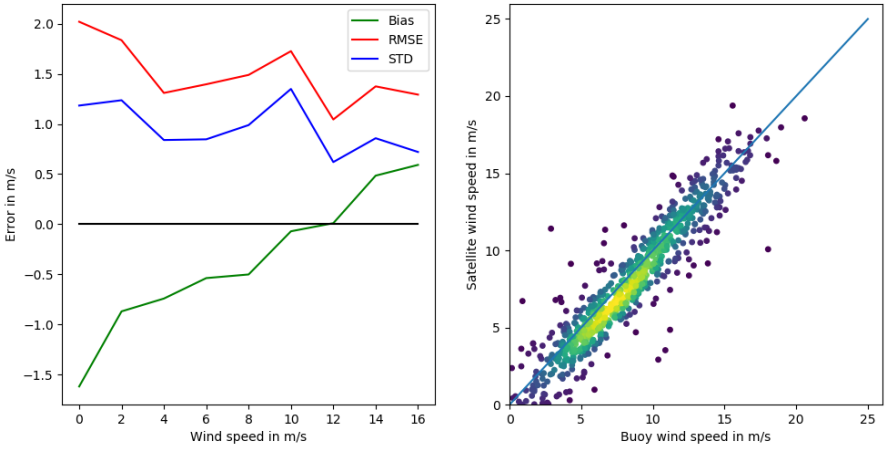

Figure 4: Statistical representation of the Sentinel-1 Level 2 OCN error against weather buoy data as a function of SAR wind speeds (left), and scatter plot versus weather buoy data (right).

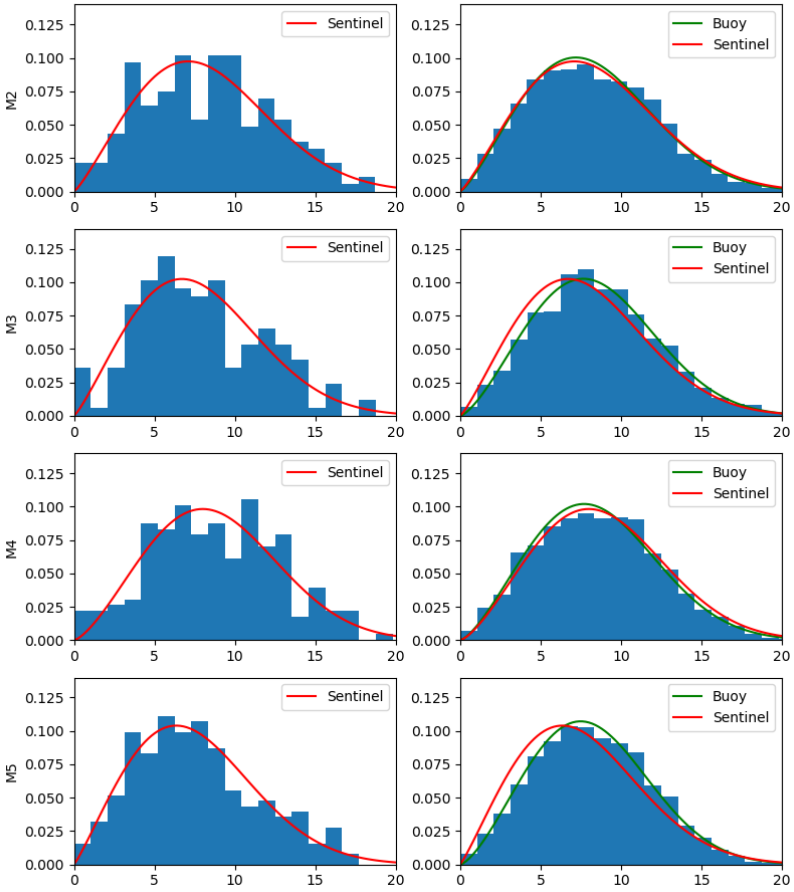

Figure 5: Wind speed histograms of Sentinel-1 SAR Level 2 OCN (right) and in situ (left) data in m s-1 with corresponding Weibull fits for the weather buoy data compared with those produced from the SAR data at the same locations

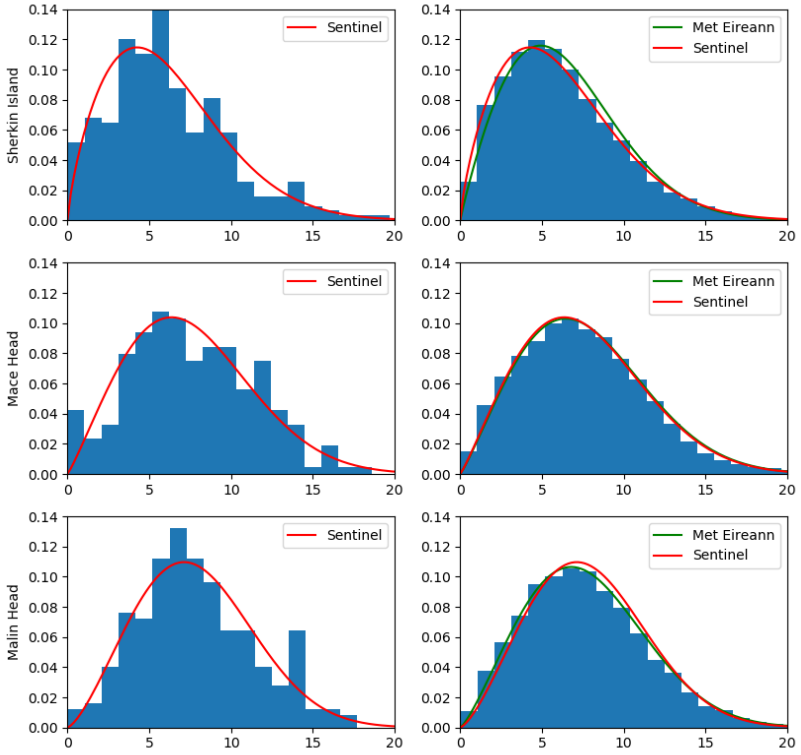

Figure 6. Wind speed histograms of Sentinel-1 SAR Level 2 OCN (right) and in situ (left) data in m s-1 with corresponding Weibull fits for the coastal weather station data compared with those produced from the SAR data at the same locations.

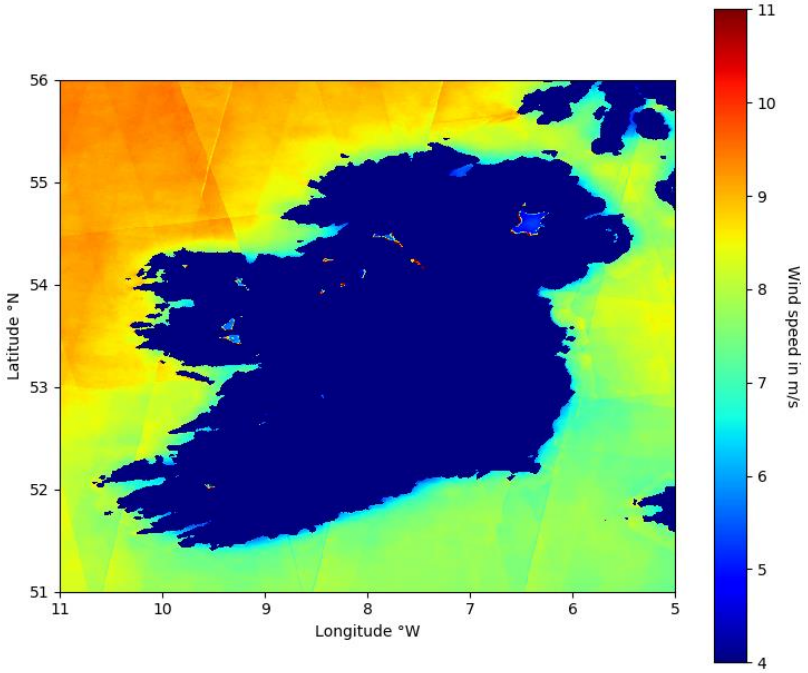

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Figure 7: Average wind speed off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product. Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

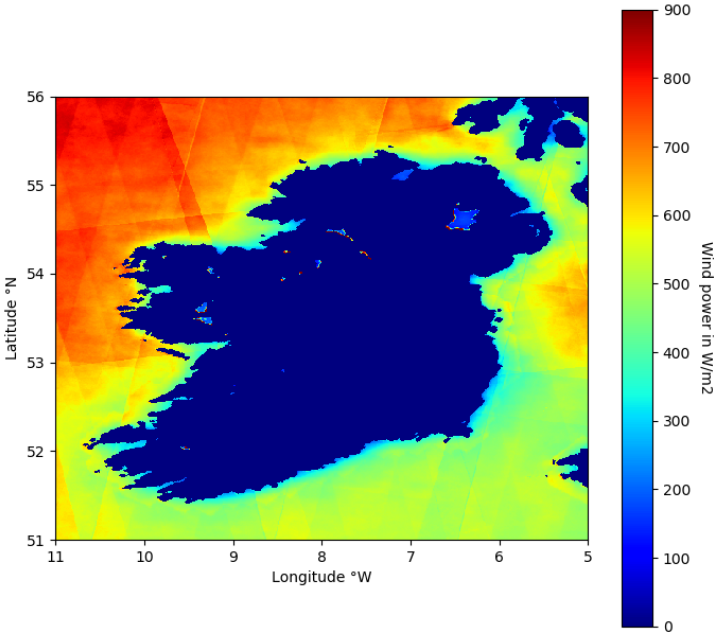

Figure 8: Wind power off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product. Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

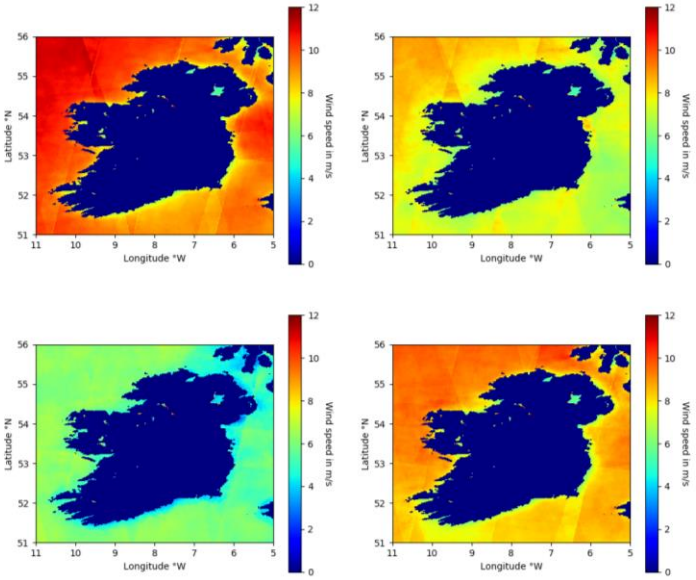

Figure 9: Seasonal average wind speed off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product (top left: winter, top right: spring, lower left: summer, lower right: autumn). Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

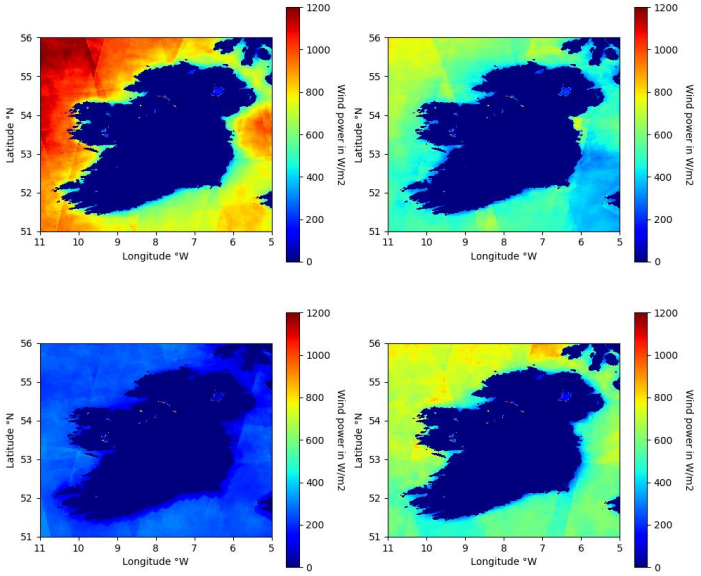

Figure 10: Seasonal wind power off Ireland over a two-year period running from May 2017 to May 2019 retrieved using the Sentinel-1 SAR Level 2 OCN product (top left: winter, top right: spring, lower left: summer, lower right: autumn). Satellite tracks are visible, particularly in the, northeast. These are an artefact of the analysis.

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Name	Type	Latitude	longitude	Altitude in m	% of availability
M2	Metocean buoy	53.48°N	05.42°W	3	63
M3	Metocean buoy	51.21°N	10.55°W	3	59
M4	Metocean buoy	55.00°N	09.99°W	3	72
M5	Metocean buoy	51.69°N	06.70°W	3	85

410 **Table 1: Location and characteristics of the weather buoys used in the comparison with Sentinel-1 SAR Level 2 OCN product.**

Name	Type	Latitude	Longitude	Altitude in m	% of availability
Sherkin Island	Weather station	51.47°N	9.42°W	21	100
Mace Head	Weather station	53.32°N	9.90°W	21	100
Malin Head	Weather station	55.37°N	7.34°W	20	100

Table 2: Location and characteristics of the coastal weather stations used in the comparison with Sentinel-1 SAR Level 2 OCN product.

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Buoy	N samples (SAR)	Mean (SAR)	Mean (in situ)	Bias (m/s)	Percentile 90% (SAR)	Percentile 90% (in situ)	RMSE	MAE	R
M2	179	8.29	8.58	-0.29	13.73	13.64	1.41	1.12	0.94
M3	161	7.86	8.31	-0.45	13.31	13.10	1.74	1.12	0.89
M4	219	8.86	9.00	-0.14	13.98	14.25	1.35	1.01	0.94
M5	242	7.6	8.34	-0.74	13.08	13.39	1.14	0.81	0.95
Total	801	8.15	8.57	-0.42	13.52	13.59	1.41	1.02	0.93

Table 3: Results of the match-up comparison of satellite measured wind speeds with in situ measured wind speeds from weather buoys.

Mast	N samples (SAR)	Mean (SAR)	Mean (in situ)	Bias (m/s)	Percentile 90% (SAR)	Percentile 90% (in situ)	RMSE	MAE	R
Sherkin Island	297	6.15	6.17	-0.12	10.86	10.80	1.47	1.15	0.92
Mace Head	206	7.61	8.36	-0.75	12.66	13.63	1.42	1.11	0.94
Malin Head	240	7.91	8.34	-0.43	13.37	13.89	1.55	1.23	0.92
Total	743	7.12	7.52	-0.39	12.30	12.77	1.51	1.18	0.93

Table 4: Results of the match-up comparison of satellite measured wind speeds with in situ measured wind speeds from coastal weather stations.

Buoy	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	Wind power in W/m² (SAR)	Wind power in W/m² (in situ)	% of error on wind power
M2	2.19	2.34	9.37	9.68	613	641	-4.28
M3	2.18	2.44	8.87	9.37	524	564	-7.04
M4	2.41	2.56	9.99	10.14	689	693	-0.47
M5	2.12	2.51	8.58	9.40	485	559	-13.19
Total	2.22	2.46	9.20	9.65	578	614	-6.24

Table 5: Comparison of wind speed long-term statistics obtained from the four weather buoys with the ones obtained from the SAR data.

Mast	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	Wind power in W/m² (SAR)	Wind power in W/m² (in situ)	% of error on wind power
Sherkin Island	1.75	1.86	6.91	7.06	315	311	1.48
Mace Head	2.12	2.19	8.59	9.44	487	627	-22.41
Malin Head	2.40	2.28	8.92	9.41	492	601	-18.07
Total	2.09	2.11	8.14	8.64	431	513	-13.00

Table 6: Comparison of wind speed long-term statistics obtained from the three coastal weather stations with the ones obtained from the SAR data.

Buoy	Bias in m/s	Bias in m/s (including in situ intra-day data)	% of error on wind power	% of error on wind power (including in situ intra-day data)
M2	-0.29	-0.48	-4.28	-11.10
M3	-0.45	-0.68	-7.04	-14.36
M4	-0.14	-0.2	-0.47	-2.50
M5	-0.74	-0.84	-13.19	-15.32
Sherkin Island	-0.12	-0.32	1.48	-6.04
Mace Head	-0.75	-0.78	-22.41	-25.28
Malin Head	-0.43	-0.21	-18.07	-13.11
Total	-0.42	-0.50	-9.14	-10.82

Table 7: Increase in the bias and the error on the wind power when intra-diurnal data of in situ measurements are taken into account, compared with the same results obtained for the match-up comparison.

Buoy	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	Wind power in W/m2 (SAR)	Wind power in W/m2 (in situ)	% of error on wind power
M2	2.19	2.26	9.37	9.31	613	586	4.69
M3	2.18	2.41	8.87	9.56	524	604	-13.22
M4	2.41	2.41	9.99	9.62	689	615	11.99
M5	2.12	2.45	8.58	9.27	485	544	-10.93

Table 8: Comparison of the long-term wind speed statistics produced from the weather buoy data with those produced from the SAR data at the same locations.

Buoy	K (SAR)	K (in situ)	λ (SAR)	λ (in situ)	SAR Wind power (W/m²)	In situ Wind power (W/m²)	% of error on wind power
Sherkin Island	1.75	1.92	6.91	7.21	315	319	-1.08
Mace Head	2.12	2.13	8.59	8.69	487	502	-2.99
Malin Head	2.40	2.26	8.92	8.78	492	492	0.15

Table 9: Comparison of the long-term wind speed statistics produced from the coastal weather station data with those produced from the SAR data.