

Satellite-based offshore wind data close to the coast: comparison with onshore meteorological mast records and microscale CFD simulations

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Abstract. Satellite observation of environmental phenomena is becoming increasingly accurate, complementing pre-existing measurement techniques. In this work, the offshore wind field recorded by Sentinel-1 on February 6th, 2021, close to the Southwestern Iceland coast is compared with the anemometric measurements provided by a relatively dense network of weather stations in the Reykjanes peninsula and microscale CFD simulations that use the Hvassahraun weather station data to approximate wind velocity and direction in offshore locations. The three methodologies show a good agreement in the 10-minute velocity magnitudes for the set of considered offshore locations, while the 10-minute mean wind direction shows certain scattering, although with a consistent prevalence of Eastern wind directions, in agreement with the anemometric data. The results show obvious complementarities among the three approaches, suggesting further studies to improve accuracy, especially for capturing local effects impacting wind magnitude and directionality.

1. Introduction

The offshore deployment of renewable wind energy systems requires reliable tools for wind resource assessment in remote locations, for which in situ measurements are rarely available. This is of utmost importance for identifying wind-rich ocean areas, but also for assessing wind-induced actions in the infrastructures associated with energy islands, whose concept has been developed in the frame of the MODENERLANDS Cost Action [1].

The use of satellite imagery for assessing offshore wind resources has been previously proposed [2], however there are still uncertainties associated to its level of accuracy as in contrast with traditional anemometric measurements, these are extended instantaneous wind fields obtained for a limited number of events separated among them, hence associated to very different mesoscale events. This work aims to contribute to a better understanding of the potential of satellite imagery for accurate wind assessment in offshore applications by leveraging an extended



network of conventional weather stations in Southwestern Iceland, microscale computational fluid dynamics (CFD) modelling and wind data available in the Copernicus database [3].

This collaborative research is part of the networking activities fostered by the MODERNERLANDS Cost Action. In March 2024, Antonio J. Álvarez completed a Short-Term Scientific Mission (STSM) at the Laboratório Nacional de Energia e Geologia (LNEG) in Portugal, funded by the MODENERLANDS COST Action. For the trainee, the main objective of the STSM was to get acquainted with satellite-based technology to obtain wind velocity data in offshore locations. In collaboration with researchers of the LNEG and Reykjavik University, the results of a first application case in the Southwestern coast of Iceland were presented at the MODENERLANDS Strategic Workshop that took place in Bochum (Germany) in September 2024 [4]. In this work, we are presenting the results of additional studies in the same area, expanding the in-situ measurements and incorporating a microscale CFD model for a more accurate extrapolation of onshore wind data to offshore locations. In section 3, the results obtained for an event in February 2021 are reported.

2. Data and Methodology

2.1 Weather data from traditional weather stations on land

Traditional weather stations in onshore locations represent the standard approach in the assessment of wind magnitude and direction in the atmospheric boundary layer. It is a methodology that is currently fully developed and therefore offers a trusted source of information.

There are several automated weather stations in operation on the Reykjanes peninsula (Southwestern Iceland) that gather information on the instantaneous weather conditions. An overview of the ones referred to in this study is given in Table 1, while their location along the coast is depicted in Fig. 1. The weather information in terms of mean and peak values is traditionally recorded every 10 minutes [5].

Table 1. Weather stations on the Reykjanes Peninsula used in this study, their names, numbers, locations and height above mean sea level [6].

Station name	Station no.	Alias (Fig. 1)	Location WGS 84		Height above m.s.l. (m)
			LAT (°)	LONG (°)	
Reykjavik airport (RFLUG)	1477	S1	64.12845	-21.9407	12
Reykjavik (REITR)	1475	S2	64.12755	-21.9020	52
Straumsvik (STRAU)	1473	S3	64.04380	-22.0404	7
Hvassahraun (HVASR)	7370	S4	64.01970	-22.0919	41
Hvassahraun (HVASS)	1370	S5	64.00930	-22.1404	34
Reykjanesbraut (RBRAU)	31363	S6	64.00267	-22.2296	25
Keflavik airport (KEFLA)	1350	S7	63.98290	-22.6005	51
Gardskagaviti (GARDUR)	1453	S8	64.08172	-22.6893	4
Grindavik (GRVIK)	1361	S9	63.84378	-22.4170	9
Selvogur (SELVG)	31380	S10	63.84560	-21.6959	20
Eyrbakki (EYRAR)	1395	S11	63.86920	-21.1602	3

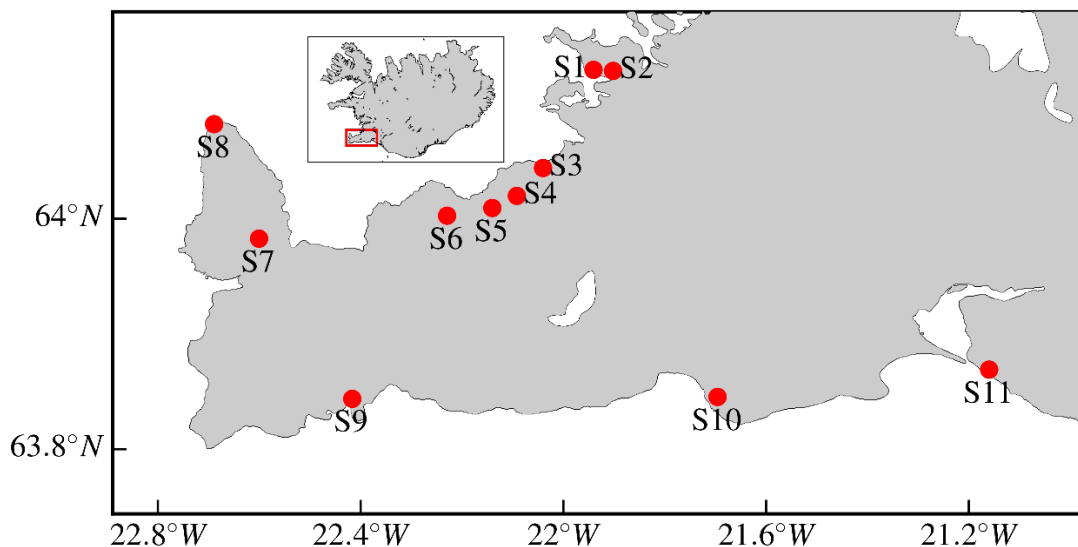


Figure 1. Location of weather stations along the coast of the Reykjanes peninsula in Southwestern Iceland.

Hvassahraun weather station (HVASS; no. 1370; S5), is shown in Fig. 2 as an example of a typical met station. It is located at an altitude of 41 meters above sea level on a lava plain where there is minimal wind disturbance due to the landscape. To the west and northeast, the sea is 2.5–4 km away, and the Reykjanes Mountain range rises to 300–500 meters in elevation about 10 km to the south. The weather station carries out traditional automatic weather measurements of temperature, humidity, barometric pressure, precipitation, wind direction and wind speed.



Figure 2. A typical automated meteorological station in Hvassahraun (HVASS, no. 1370), view towards the North (photo Á. Th. Gunnlaugsson) [6].

2.2 Offshore wind assessment based on satellite imagery

Earth observation satellites such as Sentinel-1 have on board Synthetic Aperture Radar (SAR) instruments that enable the observation of the Earth's surface through clouds. Instantaneous wind speed can be obtained from a SAR satellite imagery after applying some corrections such as removing border and thermal noise, removing land and sea objects, speckle filtering... and so on. Afterwards, the instantaneous velocity magnitude and direction at 10m above the sea level are calculated by applying the CMOD5 algorithm [7]. This method uses the backscattered parameter value associated with each pixel of the image, and gathered in 2x2 km² tiles, obtaining for each one the instantaneous value of the velocity magnitude and direction. This process is integrated into the Sentinel Application Platform (SNAP).

With the results from the CMOD5 model is possible to infer the wind magnitude at offshore locations for each pixel of the image. In this manner, the obtained velocities are instantaneous, however, in most cases, the available data from meteorological stations is time-averaged, usually as 10-minute average values. In order to calculate the equivalent 10-minute average velocity from the satellite image, we are modifying the method proposed by [8] as follows. In our application, we start by getting the instantaneous velocity magnitude of the specific point in the SAR image for which we want to calculate the 10-minute average velocity. Using this velocity, the distance covered by a particle in half the time of the time-averaging interval is obtained. This distance is the radius of a circumference with a centre at the targeted location where the time-averaged velocity is being computed. Then, we calculate the mean wind velocity using the data of all the pixels located inside the circumference. Once the time averaged velocity magnitude is calculated, this is considered as the reference velocity for calculating a new radius and the process is repeated iteratively until a stable convergence criterion is met. After convergence is reached, we calculate the time-averaged wind magnitude and direction considering the points located inside the circle used for calculating the time-averaged velocity for which CMOD5-based wind velocities are available.

2.3 Microscale CFD simulations

A reliable wind resource assessment in a given region is crucial for the effective development of wind energy projects. Traditionally, such assessments often rely on limited anemometric data combined with geostatistical methods, often resulting in low accuracy. To increase the precision, both linear and non-linear wind flow models are developed, using input data from meteorological stations or numerical weather prediction models. Linear models are generally suitable for flat terrain but perform poorly in complex topographies. With advances in computational power, non-linear models, particularly computational fluid dynamics (CFD), have become more widely used, offering significantly improved accuracy for complex terrain. Moreover, CFD models allow for the inclusion of thermal stratification effects, further enhancing the precision of wind resource assessment. In this context, WindSim is used to estimate wind speeds at specific offshore locations, using data (wind speed and direction) from a single onshore meteorological station. These estimates are then compared with the satellite-derived wind data.

WindSim solves the Reynolds-averaged Navier–Stokes (RANS) equations, which are derived from the original Navier–Stokes equations through a time-averaging process [9], [10]. The core principles and capabilities of WindSim are thoroughly documented in the literature [11], [12], [13]. The software is organised into six modular components, with the “Terrain” and “Wind Field” modules being the most relevant to this work. The Terrain module defines the 3D simulation domain using elevation data (sourced from [14]) and surface roughness information derived from CORINE Land Cover 2018 data and satellite imagery. It also allows users to set the spatial

resolution of the computational mesh. The Wind Field module establishes the initial and boundary conditions for the simulation. These conditions can be defined analytically (e.g., assuming a constant flow) or through nesting, enabling the incorporation of data from a previous coarser spatial resolution simulation in WindSim or a mesoscale model. In this study, 12 wind direction sectors, each spanning 30°, were considered to capture the directional variability of wind flow across the domain.

A limitation of the WindSim version used in this study is the maximum number of cells allowed for domain discretisation, specifically, no more than 1,000 points per grid horizontal direction. To comply with this constraint, the entire study area was initially simulated using a coarser resolution of 300 meters. Then, the region was divided into multiple nesting domains, allowing high-resolution simulations (50 meters) to be obtained while remaining within the limits of the software. This approach is particularly important in coastal interface zones, where complex terrain and abrupt changes in orography and roughness characteristics significantly influence wind flow patterns. The simulations were carried out under the assumption of neutral atmospheric stability conditions. All data were extracted to a height of 10m above the ground/sea level.

3. Application case

The methodologies described in the previous section have been applied to an event on the 6th of February 2021 at 19:06:39 hours UTC, which is the instant at which the SAR image adopted as an application case was taken (Fig. 3). The location of the onshore weather stations and the offshore points considered for obtaining the 10-minute mean wind speeds are reported in Fig. 4. Aiming at assessing the accuracy of the proposed approach 10-minute mean wind velocities at 19:00 hours have been gathered from the available weather stations in the Reykjanes peninsula, reporting the values in Table 2. Following the procedure outlined in section 2.2, the 10-minute average wind magnitude and direction have been obtained, and the values are reported in Table 3 and Fig. 5a and 5b. Similarly, CFD-based mean wind speed values based on the application of a micro-scale CFD model for extrapolating the wind data at the Hvasshraun (HVASS - S5) weather station are reported in Table 4 and Fig. 5a and 5b. All the refer to an height of 10m above the mean sea level.

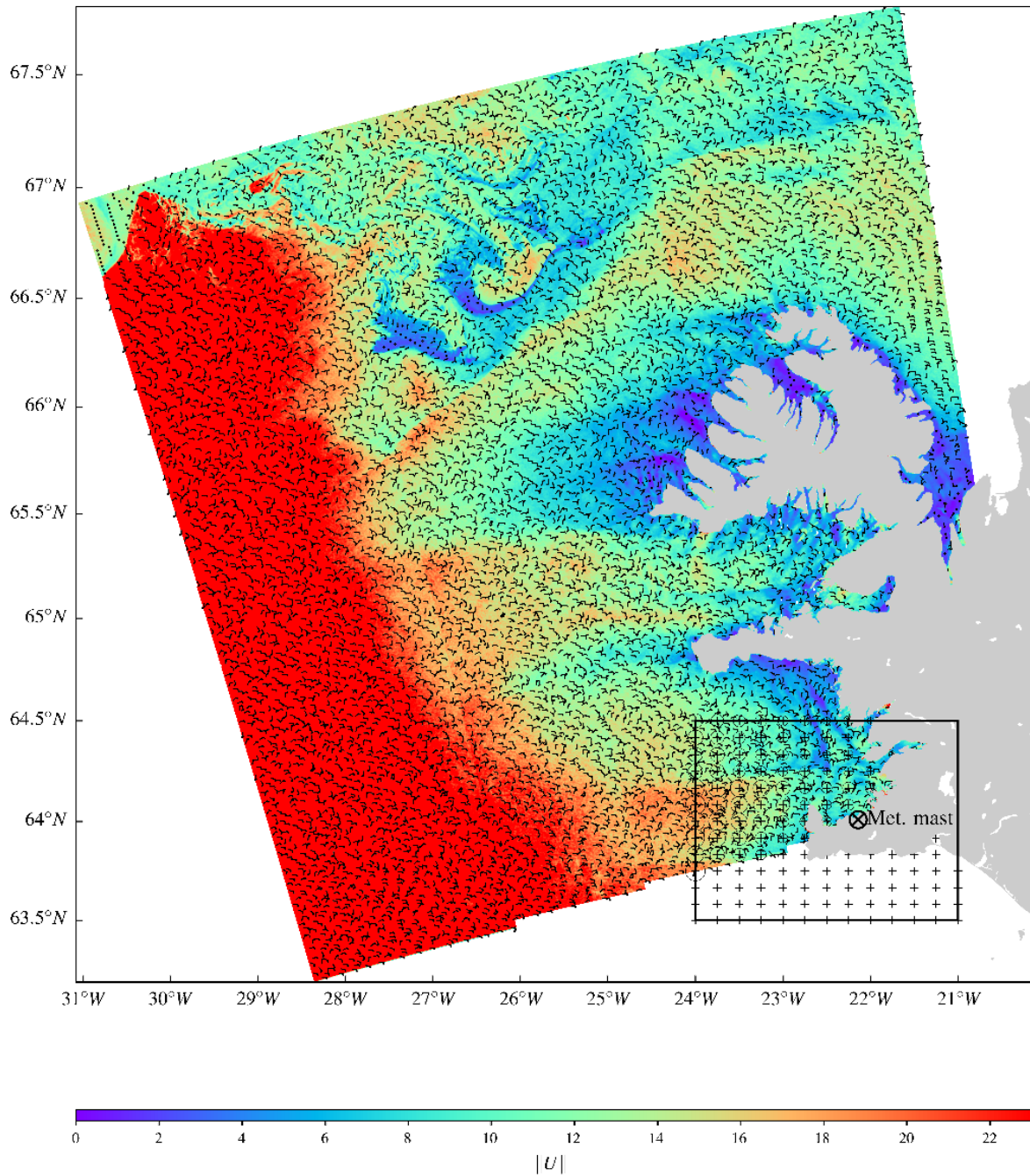


Figure 3. Instantaneous wind speed (U) on the sea in Southwester Iceland, 2021-02-06 19:06:39 UTC evaluated from SAR satellite imagery taken from the Copernicus database [3].

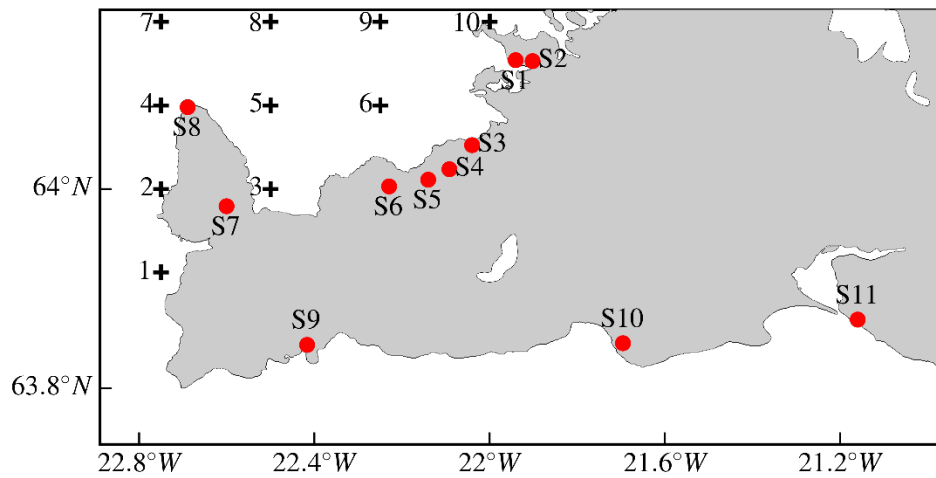


Figure 4. Location of offshore wind assessment grid and conventional weather stations on the Reykjanes Peninsula.

Table 2. 10-minute wind speeds at weather stations on the Reykjanes Peninsula on the 6th of February 2021, at 19:00:00 and 19:10:00 UTC time.

Name	Alias	Day	Time	Mean Wind Direction [°]	Mean Wind Speed [m/s]
Reykjavik airport (RFLUG)	S1	2021-02-06	19:00:00	90	7.5
Reykjavik (REITR)	S2	2021-02-06	19:00:00	93	5.9
Straumsvik	S3	2021-02-06	19:00:00	84	6.7
Hvassahraun (HVASR)	S4	2021-02-06	19:00:00	92.8	7.4
Hvassahraun (HVASS)	S5	2021-02-06	19:10:00	97	9.28
			19:00:00	88.2	8.1
Reykjanesbraut	S6	2021-02-06	19:00:00	88.4	9.46
			19:10:00	82	6.9
Keflavik airport (KEFLA)	S7	2021-02-06	19:00:00		
Gardskagaviti (Gardur)	S8	2021-02-06	19:00:00	87	11.1
Grindavik	S9	2021-02-06	19:00:00	78	10.6
Selvogur	S10	2021-02-06	19:00:00	57	8.9
Eyrbakki	S11	2021-02-06	19:00:00	42	6.2

Table 3. 10-minute wind speeds at offshore locations in Fig. 4 evaluated from the 6th of February 2021, at 19:06:39 UTC time SAR satellite image.

Offshore point	Longitude [°]	Latitude [°]	SAR Mean Wind Speed [m/s]	CMOD5 Mean Wind Speed [m/s]	CMOD5 Mean Wind Dir. [°]
1	-22.7500	63.9167	6.5	6.3	52.5
2	-22.7500	64.0000	9.3	8.4	154.0
3	-22.5000	64.0000	9.1	7.1	71.7
4	-22.7500	64.0833	8.8	7.8	76.2
5	-22.5000	64.0833	8.7	7.8	75.2
6	-22.2500	64.0833	10.2	7.9	76.0
7	-22.7500	64.1667	10.0	8.1	113.4
8	-22.5000	64.1667	9.5	8.5	63.1
9	-22.2500	64.1667	11.2	10.7	57.3
10	-22.0000	64.1667	9.4	9.2	85.7

Table 4. 10-minute wind speeds at CFD model using data from the weather station Hvasshraun (HVASS/S5) on the Reykjanes Peninsula on the 6th of February 2021, at 19:00:00 and 19:10:00 UTC time.

Offshore point	CFD Mean Wind Speed [m/s]		CFD Mean Wind Dir. [°]	
	19:00:00 UTC	19:10:00 UTC	19:00:00 UTC	19:10:00 UTC
1	7.7	9.0	89.2	89.4
2	8.6	10.0	89.3	89.5
3	9.5	11.1	89.4	89.6
4	9.3	10.9	89.4	89.6
5	9.6	11.3	89.5	89.7
6	9.7	11.4	89.4	89.6
7	10.5	12.2	89.5	89.7
8	10.4	12.2	89.5	89.7
9	10.3	12.1	89.5	89.7
10	8.7	10.1	89.3	87.5

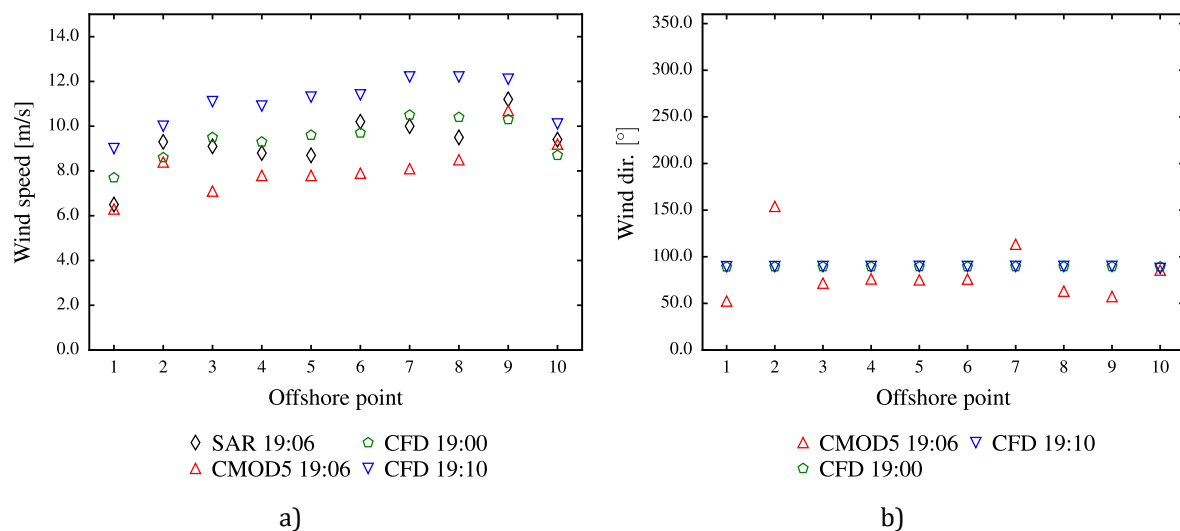


Figure 5. Mean wind speed and direction for February 6, 2021, at 19:00 and 19:10: a) Mean wind speed and b) Mean wind direction.

The inspection of the results of the mean velocity magnitude obtained from the SAR image (Table 3), applying two different methods: *i*) averaging of instantaneous wind magnitude for each pixel and *ii*) CMOD5-based values, shows differences of about 10-20%, a consequence of the different approaches adopted. The qualitative comparison of the mean wind speeds with the weather station data in Table 3 is good, identifying a slightly better general agreement between weather station data and CMOD5 results. Furthermore, 10-minute mean wind directions for the Easterly wind consistently reported by the onshore weather stations in the area agree with the general trend in the offshore points, although there is an obvious scattering and a certain shift towards the North in the satellite-based data. It should be noted that this Eastern wind is coming from land, therefore posing an additional challenge for satellite-based wind assessment [2].

The results from the CFD application (Table 4) also show good agreement with the offshore data, despite some biases. Overall, the largest errors occur at offshore points close to the coast, i.e. offshore point #1 and #2 exhibiting the greatest deviation. These discrepancies can be partially attributed to *i*) the spatial resolution of the model and *ii*) the assumption of neutral atmospheric stability, which simplifies the representation of the atmospheric stratification and its effects on wind flow. The discrepancies are also highest for the 19:10:00 time step.

Nevertheless, the CFD model appears capable of capturing the spatial distribution patterns of offshore wind speed when compared with the satellite data. Regarding the wind direction, the model showed greater difficulty in accurately reproducing the spatial distribution, especially for longer distances from the reference met station (S5). This limitation may be associated with the reduced ability of the CFD model to simulate complex meteorological phenomena that develop within the simulation domain, since the model relies on steady-state boundary conditions to generate wind fields for each wind direction sector simulated. Therefore, rapid or dynamic changes in wind direction caused by local effects such as coastal breezes, topographic interactions, and atmospheric instability can be difficult to simulate.

4. Conclusions and future work

For the 6th of February 2021 event reported herein, along with additional events in the same area that have been studied previously, it is observed that 10-minute mean wind magnitudes in offshore locations close to the Reykjanes Peninsula (Southwestern Iceland) obtained from SAR satellite images show qualitatively a good agreement with the values recorded over an extended network of standard on-land weather stations in the area. For the 10-minute mean wind direction, some scattering in the satellite-based data is observed, with a certain departure from the onshore in-situ values. Although some biases were observed, particularly near coastal points such as the offshore point #1, the CFD model demonstrated overall good agreement with the satellite based offshore wind data, especially for the 19:10:00 time step. The model is thus able to capture the spatial wind speed distribution patterns seen in the satellite observations.

Further studies are required for a quantitative assessment of the accuracy levels offered by satellite-based data, along with the potential dependency of the accuracy on the particular offshore location being considered or seasonal atmospheric characteristics. Future work will also focus on enhancing the spatial resolution of the CFD model, incorporating additional onshore meteorological stations, and accounting for the effects of atmospheric instability, which can significantly influence wind speed profiles and model accuracy. These improvements will be essential for strengthening the assessment of offshore wind energy potential based on data from onshore meteorological masts.

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