



Climate change on extreme winds already affects off-shore wind power availability in Europe

Lia Rapella, Davide Faranda, Marco Gaetani, Philippe Drobinski, Mireia
Ginesta

► To cite this version:

Lia Rapella, Davide Faranda, Marco Gaetani, Philippe Drobinski, Mireia Ginesta. Climate change on extreme winds already affects off-shore wind power availability in Europe. *Environmental Research Letters*, 2023, 18 (3), pp.034040. 10.1088/1748-9326/acbdb2 . hal-03840084v1

HAL Id: hal-03840084

<https://hal.science/hal-03840084v1>

Submitted on 4 Nov 2022 (v1), last revised 25 Jul 2023 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Climate change on extreme winds already affects off-shore wind power availability in Europe

Lia Rapella¹, Davide Faranda^{1,2,3}, Marco Gaetani⁴,
Philippe Drobinski³ and Mireia F. Ginesta¹

¹ Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212
CEA-CNRS-UVSQ, Université Paris-Saclay & IPSL, CE Saclay l'Orme des
Merisiers, 91191, Gif-sur-Yvette, France

² London Mathematical Laboratory, 8 Margravine Gardens, London, W6 8RH,
British Islands

³ LMD-IPSL, Ecole Polytechnique, Institut Polytechnique de Paris, ENS, PSL
Research University, Sorbonne Université, CNRS, Palaiseau, France

⁴ Scuola Universitaria Superiore IUSS, Palazzo del Broletto, Piazza della
Vittoria 15, 27100 Pavia, Italia

E-mail: lia.rapella01@universitadipavia.it

4 November 2022

Abstract. In Europe, off-shore wind energy plays a key role in the transition to renewable energy, and its usage is expected to increase in the next few decades. According to the working regimes of a wind turbine, wind energy production can be disrupted by extreme atmospheric events related to low wind speed below the cut-in wind speed and high wind speed above the cut-out wind speed. The purpose of this work is to estimate the behavior of extreme winds on the European panorama, over the period 1950-2020, in order to investigate the large-scale weather regimes related to them and their impact on off-shore wind energy availability. We detected significant changes in the frequency of high and low extreme wind events, proving that climate change or long-term climate variability has already affected the off-shore wind power output. Moreover, the analysis of weather regimes showed that high and low extreme wind events can occur simultaneously over Europe. Our results suggest the necessity to implement efficient European energy management policies, to minimize the deficit in wind power supply.

Keywords: Extreme winds - Climate change - Off-shore wind power availability

1. Introduction

Climate change is one of the most urgent challenges that humankind confront nowadays. As reported by the Intergovernmental Panel of Climate Change Synthesis Report, adaptation and mitigation are the main guidelines to follow in order to reduce and manage the impacts of climate change. Substantial cuts in greenhouse gas emissions are necessary to reduce climate risks in the future (XXI century and beyond) as they can contribute to climate-resilient pathways for sustainable development [1]. To this purpose, the European Union (EU) has planned ambitious strategies: to cut emissions by at least 55% with respect to the values in 1990 by 2030 (and 80% by 2050) and to become, by 2050, the first “net-zero” carbon continent, *i.e.* able to compensate all emissions of CO₂ [2], in the world. In this context, renewable energy (RE) play a key role: on one hand their development and extensive usage can slow down climate change effects and help to obtain the “net-zero” carbon goal, on the other hand substantial local changes in atmospheric conditions could modify, for better or worse, their efficiency [3] [4] [5] [6], and their demand [7].

Due to its increasing price competitiveness and the development of high-efficiency technologies, wind energy is playing, and it will play more and more in the future, a significant role in the transition to a RE system [8]. To gain the climate targets, the EU is planning to scale up the off-shore wind industry from the 12 GW capacity currently installed to 60 GW by 2030, and to 300 GW by 2050 [9]. Nevertheless, wind energy is one of the most variable and weather-dependent RE, because of its natural dependence on the wind speed, which can vary at different time scales, ranging from small-scale turbulence to seasonal oscillations and up to long-term climate variability. Moreover, wind energy can be heavily affected by extreme events, since under these conditions winds can easily reach such speeds to force the turbines to be parked or idled, or, conversely, not be strong enough to move them, thus interrupting the energy production.

Indeed, the potential wind power production[‡] (W_{pot}), according to the working regimes of a wind turbine [10], depends on the wind speed V by the following relation:

$$W_{pot} = \begin{cases} 0 & \text{if } V < V_i \\ \frac{V^3 - V_i^3}{V_R^3 - V_i^3} & \text{if } V_i \leq V < V_R \\ 1 & \text{if } V_R \leq V < V_o \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where V_R is the rated speed ($13 \frac{m}{s}$), V_i ($3.5 \frac{m}{s}$) and V_o ($25 \frac{m}{s}$) are the cut-in and cut-off speed respectively[§] [11].

When the cut-off threshold is overcome, the turbines stop working for security reasons (*storm control*), and the loss in the wind power production can be high, ranging from the 50% of the installed capacity in half an hour to 70% in one hour [12]. Similarly, the turbines do not work when the wind speed is lower than the cut-in threshold, with consequent losses in the W_{pot} .

In Europe, high-speed winds are mainly associated with the passage of the so called *extra-tropical* or *mid-latitude cyclones* [13], especially in autumn and winter. This type

[‡] Dimensionless indicator of the potential power production at each location and time.

[§] We chose these values because they are the most common, but we specify that they are not universal and they correspond to a specific wind turbine technology.

of cyclone is defined as a synoptic scale low pressure system that occurs in the middle latitudes, *i.e.* between 30° and 60° latitude from the equator [14]. They are formed in regions of strong baroclinicity, which are the regions associated with a strong meridional temperature gradient. In the Northern hemisphere, winds flow counterclockwise around the cyclone, and they can reach high speeds. *Vice versa*, areas of high pressure are called *anticyclones*: winds flow around their center clockwise^{||} and they are usually characterized by a mild intensity.

Extra-tropical cyclones (anticyclones) are identified with local minima[¶] (maxima) in the geopotential height at a certain pressure level [15], which represents the height of a pressure surface in the atmosphere above the sea level. The separation of the isohypses, *i.e.* lines of equal geopotential height, also gives a measure of the wind speed: the smaller the separation, the higher the wind speed (and *vice versa*).

Changes in the intensity or frequency of the cyclones (anticyclones) can cause changes in the occurrence of intense storms or low-speed winds events, with serious impacts on the electric power generation. Therefore, it is of strong interest having information about their features and tracks, as well as knowing which weather regimes are related to them, where by weather regime we mean a quasi-stationary and recurring large-scale spatial circulation pattern, typically defined in terms of atmospheric variables (*e.g.* geopotential height, pressure, *etc.*), which persists for an extended period (usually from 10 days to a month). While Grams *et al.* [16] have already analysed the importance of weather regimes in the average wind energy production by assuming stationarity in weather regimes over the historical period (1979-2015), here we extend this viewpoint by specifically looking at the relationship between extreme high/low-speed wind conditions and weather regimes and by releasing the assumption of weather regime stationary. Indeed, Brönniman *et al.* [17] and Corti *et al.* [18] evidenced that significant trends in extreme winds frequency in the historical period exist, as well as that natural atmospheric circulation regimes have already changed due to anthropogenic forcing. This motivates the present study.

Identifying which weather regimes are associated with extreme winds⁺ is of prominent importance in order to have a complete view of the distribution of the European wind energy resources. In fact, if the same weather regime affects different zones, we could have simultaneous multiple outages in the turbines operation with consequent shortages in the wind energy supply. In a future scenario with only RE, this might even lead to partial or total blackouts, with heavy impacts especially on cities and urban areas. Contrariwise, if the weather regimes that cause extreme wind events differ from area to area, with the perspective of European energy management policies, which provide investments for the construction of infrastructures aimed to distribution, storage and energy transmission, it would be possible to redirect the energy to the affected zones and thus avoid temporary blackouts [19] [20].

In light of these considerations, the general purpose of this work is to estimate the behavior of extreme winds on the European panorama, over the period 1950-2020, in order to investigate the large-scale weather regimes related to them and their impact

^{||} In the Northern hemisphere.

[¶] In order to filter the cyclones from other low-pressure systems, there are usually introduced also empirical *minimum* thresholds, *e.g.* in the duration or in the intensity [21].

⁺ See Section 2 for the definition of “extreme winds”.

on off-shore wind energy availability.

The paper is organized as follows. In section 2, we present the data which we will use in our forthcoming analysis. In section 3, we investigate the presence of significant trends in the occurrence of high/low-speed wind events, over selected periods and regions, by means of a non-parametric trend test. Finally, in section 4, we investigate the weather regimes at which the high/low-speed wind events occur, in order to detect changes in their pattern, before drawing our conclusions in section 5.

2. Data and methods

The more recent climate reanalysis released by the European Centre for Medium-Range Weather Forecasts is ERA5, which provides data, from 1950 to present, over different timescales, describing many atmospheric, land-surface and oceans parameters together with estimates of uncertainty. These data-sets are publicly available at the Copernicus Climate Data Centre [22] on regular latitude-longitude grid, at $0.25^\circ \times 0.25^\circ$ resolution.

For our analysis we used two subsets of ERA5 [23], *ERA5 hourly data on single levels from 1950 to 1978* [24] and *ERA5 hourly data on single levels from 1979 to present* [25], covering a period from 1950 to 2020 and selecting 6-hourly values, at 00:00, 06:00, 12:00 and 18:00. In particular, we selected three variables:

- 100 m u-component of wind, u ($[\frac{m}{s}]$): eastward horizontal component of wind speed, measured at 100 m above the Earth surface;
- 100 m v-component of wind, v ($[\frac{m}{s}]$): northward horizontal component of wind speed, measured at 100 m above the Earth surface;
- geopotential, z ($[\frac{m^2}{s^2}]$), at 500 hPa: the gravitational potential energy of a unit mass, at a particular location at the surface of the Earth, relative to mean sea level;

and we extracted a sub-region corresponding to the European area: $-12^\circ W$ - $30^\circ E$, $32^\circ N$ - $70^\circ N$.

To obtain the horizontal wind speed at 100 m^{*}, V , we combined the u-component of wind with the v-component:

$$V = \sqrt{u^2 + v^2} \quad (2)$$

To calculate the geopotential height, zh , instead, we simply divided z by the Earth's gravitational acceleration ($9.80665 \frac{m}{s^2}$).

In figure 1, panel **a**, it is represented the climatology[‡] of the horizontal wind speed at 100 m over the period 1950-2020. As shown by the map, the strongest winds blow off-shore, with a peak of $11.12 \frac{m}{s}$ off the British Islands.

In this paper, we will refer to “extreme (wind) events” as the wind events with the wind speed in the non-operating regime, according to (1). We will call “high wind events” the wind events with the wind speed over the cut-off threshold and “low wind events” those with the wind speed under the cut-in threshold. Moreover, we will consider as event every time-step with the wind speed that satisfies one of these two latter

^{*} We use the wind speed at 100 m as reference wind speed for the off-shore turbines, which have a typical hub height ranging from 80 m to 120 m.

[‡] The climatology of a variable is the variable's mean value over a certain period of time.

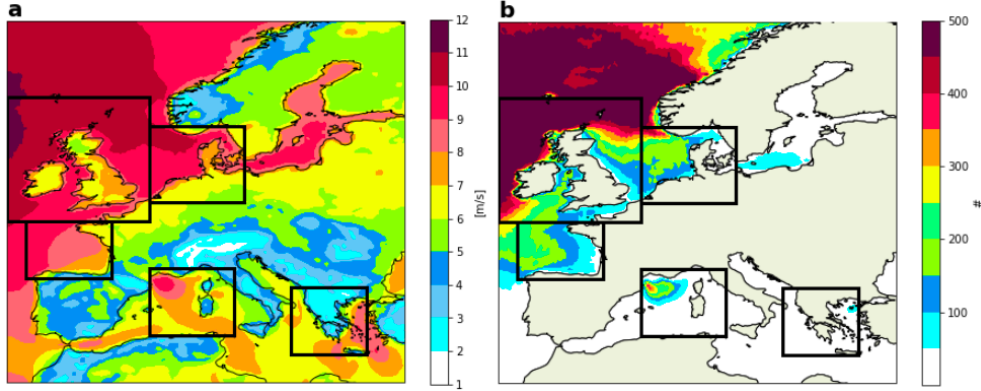


Figure 1. (a) 1950-2020 average 100 m horizontal wind-speed [$\frac{m}{s}$]. (b) Total number of events # above the 100 m horizontal wind-speed cut-off threshold ($25 \frac{m}{s}$) over the period 1950-2020. In order to distinguish more clearly the zones with the highest number of events, we limited the range of values to 500. All the values ≥ 500 are mapped with the last color of the colorbar. The black boxes indicate the areas specifically considered in this study: British Islands ($12^{\circ}W$ - $3^{\circ}E$, $49^{\circ}N$ - $62^{\circ}N$), North Sea ($3^{\circ}E$ - $13^{\circ}E$, $51^{\circ}N$ - $59^{\circ}N$), Bay of Biscay ($10^{\circ}W$ - $1^{\circ}W$, $43^{\circ}N$ - $49^{\circ}N$), Central Mediterranean ($3^{\circ}E$ - $12^{\circ}E$, $37^{\circ}N$ - $44.5^{\circ}N$), Balkan Peninsula ($18^{\circ}E$ - $26^{\circ}E$, $35^{\circ}N$ - $42^{\circ}N$)

constraints.

To have a clearer view of which zones are affected by high wind events, we first masked the 100 m horizontal wind speed, keeping only the values higher than the cut-off speed. We then counted, grid point by grid point, the number of events during the period 1950-2020 that satisfy this latter constraint (figure 1, panel b). As expected, we found that this condition occurs mainly off-shore, and we focused especially on five regions, where high winds are observed more frequently and where most of the farms are installed: British Islands, North Sea, Balkan Peninsula, and the areas off the south of France and north of Spain. These regions are particularly favourable to the installation of offshore wind farms because they are affected by quasi-constant wind patterns. Specifically, the Bay of Biscay, the British Islands and the North Sea lie on the Atlantic storm track [26]; Central Mediterranean and the Balkan Peninsula are affected by the Mistral and Etesian wind patterns, respectively [27]. During the summer months (June-July-August, JJA) no high wind events are detected, while the peak occurs in winter (December-January-February, DJF).

3. Trends in wind events

Focusing on the regions indicated in Figure 1, to investigate if there exist significant long-term changes in the occurrence of extreme events during the period 1950-2020 and to quantify them, we analysed the trends, separately region by region, by means of the Mann Kendall test at 95% level of confidence [28]. We computed the test not only considering the number of events during the whole year, but also apiece for summer and winter, during which most of the events occur respectively for the low and the high wind events.

Figure 2 shows the average change, per decade, in the number of high wind events, over the period 1950-2020, during the whole year (a, b, c) and for the winter months (d, e, f), for British Islands (a, b), North Sea (c, d), Bay of Biscay (e, f). In large part of these regions a significant increasing trend is detected throughout the years and for the DJF period (figure 2), as well as in very small areas of Central Mediterranean. In Balkan Peninsula, instead, in both cases, where detected, the trends are significantly decreasing.

Figure 3 shows the average change, per decade, in the number of low wind events, over the period 1950-2020, during the whole year (a, b, c) and for the summer months (d, e, f), for British Islands (a, b), North Sea (c, d), Bay of Biscay (e, f). For these latter regions it is observed a general average decrease in the number of these events, with a significant negative trend particularly strong in the number of events during the whole year. Contrariwise, in Central Mediterranean and Balkan Peninsula, the number of low wind events has markedly increased, especially considering its trend during the whole year, as shown in figure 4.

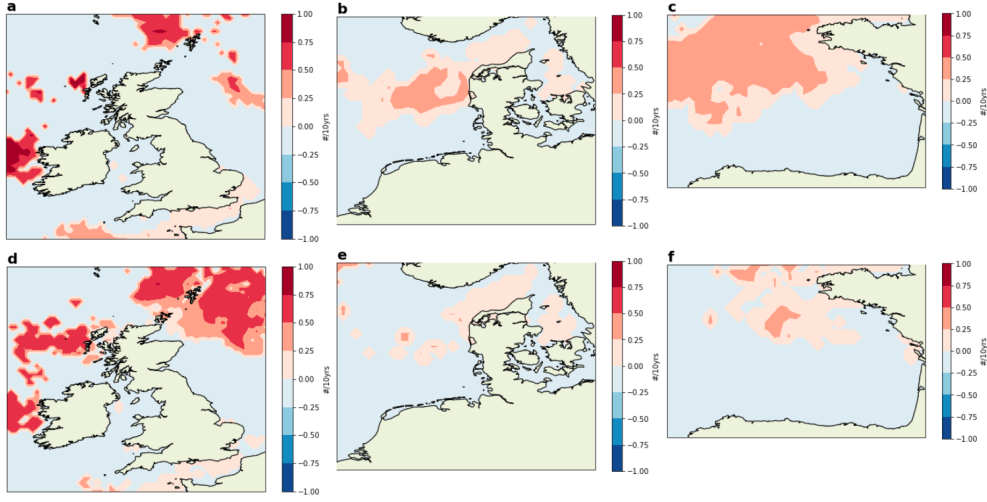


Figure 2. Average change (red: increase, blue: decrease) in the number of high wind events per decade $\#/10\text{yrs}$ over the period 1950-2020, during the whole year (a, b, c) and for the winter months (DJF, d, e, f), for British Islands, North Sea and Bay of Biscay. Shadings indicate significant changes.

4. Weather regimes analysis for high/low wind events

Since we want to investigate the extreme events that may have, in each region, the most widespread impact on the off-shore wind energy production, we restricted the analysis to the events that involve a high number of grid points. To do so, starting from the data-sets with only the 6-hourly wind speed values over the cut-off threshold and under the cut-in threshold, we selected, separately for each zone, the time-steps with the number of affected grid points respectively above the 95th percentile and the 99th percentile [1].

As expected, the British Islands is the region with the most widespread high winds (457 time-steps identified), followed at a distance by North Sea (97) and Bay of Biscay

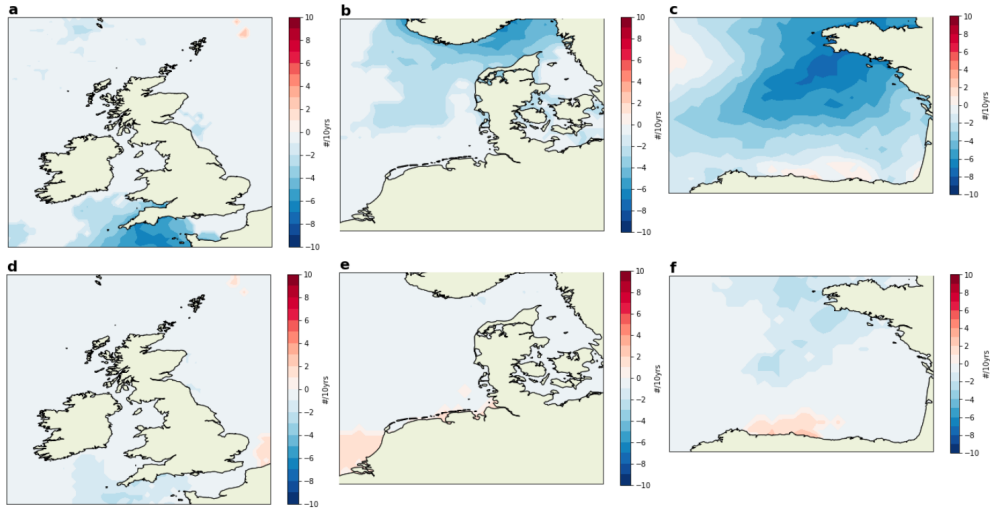


Figure 3. Average change (red: increase, blue: decrease) in the number of low wind events per decade $\# / 10 \text{ yrs}$ over the period 1950-2020, during the whole year (a, b, c) and for the summer months (JJA, d, e, f), for British Islands, North Sea and Bay of Biscay. Shadings indicate significant changes.

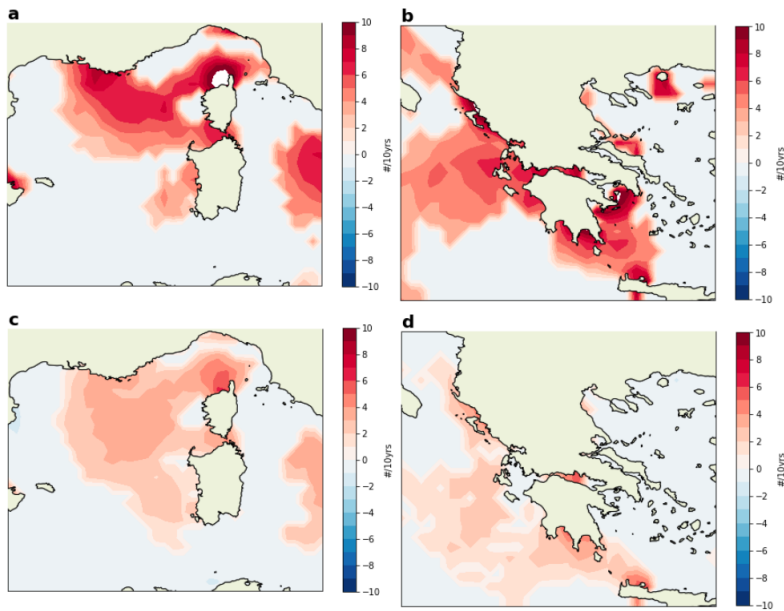


Figure 4. Same as in figure 3, but for Central Mediterranean and Balkan Peninsula. Shadings indicate significant changes.

(85).

By a cross-check with a European storm database [29], which covers the period 1948-2020, we found for these three areas coincidences between high winds and intense storms, particularly during the winter months: 23 concurrences for the British Islands, 27 for North Sea and 18 for the Bay of Biscay, as reported in tables A1, A2, A3 (5).

Region	High winds	Low winds
British Islands	419	1104
North Sea	207	668
Bay of Biscay	244	505
Central Mediterranean	85	778
Balkan Peninsula	47	671

Table 1. Number of affected grid points above the 95th percentile (**high winds**) and above the 99th percentile (**low winds**) for all the areas considered in this study.

Considering the European synoptic atmospheric circulation, four weather regimes have been traditionally identified to classify the weather over the continent [30] [31] [32]. Weather regimes are typical maps where high/low pressure systems are arranged in different patterns, corresponding to different positions of the mid-latitude jet stream:

- (i) North Atlantic Oscillation (NAO) positive (+): low pressure anomalies over Iceland and higher than normal pressure in Central and Southern Europe. The NAO+ is generally associated with wet/windy weather over Northern Europe and dry/warm weather in Southern Europe.
- (ii) NAO negative (-): an anomalous high pressure system covers the area over Greenland and Iceland, while negative anomalies concern the south, with opposite meteorological features than the NAO+.
- (iii) Scandinavian Blocking: higher than normal pressure over the Scandinavian Peninsula and low pressure anomalies in South-Western Europe; this pattern is often associated with cold spells in winter and heatwaves in summer, mostly over Central and Northern Europe.
- (iv) Atlantic Ridge: positive pressure anomalies in the mid-eastern Atlantic and negative anomalies over Europe. This regime leads to warm spells over the Iberian Peninsula and South of France, cold conditions over Eastern Europe and intense precipitations in correspondence to the maximum pressure gradients.

In order to identify the different weather regimes associated with the occurrence of extreme wind events and to detect changes in their pattern, we took some preliminary steps.

Firstly, for each region, we computed the anomalies in the geopotential height, for the high and low wind events, over the time-steps selected following the procedure mentioned above. To do this, for each time-step we subtracted to zh the value of zh at the same instant averaged over the period 1950-2020. For example, to the value of the geopotential height on the 01/02/1953 at 06:00 we subtracted the mean of the geopotential height values on the first of February at 6 a.m. from 1950 to 2020. Then, we grouped the selected time-steps in two sub-periods, past

period (01/01/1950-30/06/1985) and present period (01/07/1985-31/12/2020), and we computed the anomalies in the geopotential height averaged over these two time-windows, together with the difference between present and past average anomalies. To test the significance of the differences we applied the bootstrap method, at the 95th level of confidence.

As shown in figure 5, high winds in British Islands (**a, b, c**), North Sea (**d, e, f**) and Bay of Biscay (**g, h, i**) occur during the NAO+ phases. In the second period, the positive zh anomalies become more intense and widespread over Central-Southern Europe, and the gradient between positive and negative anomalies is accentuated, leading to a higher frequency of these extreme events (table 2) over the zones considered and to stronger winds over the British Islands and North Sea (figure 6, **a-f**). Instead, an Atlantic ridge pattern is found for the Central Mediterranean (figure 5, **j, k, l**) and, in the first period, for Balkan Peninsula (figure 5, **m, n, o**), for which then it shifts to a Scandinavian blocking, with the center of the low pressure system remaining located over the Balkan Peninsula. In both cases, contrary to what happened for the areas in North Europe (British Islands, North Sea and Bay of Biscay), there are substantially no changes in the occurrence of high winds. However, there is a slight decrease in their intensity in Central Mediterranean (figure 6, **j-l**) and changes, both positive and negative, in Balkan Peninsula (figure 6, **m-o**).

Regarding the low winds, in each period and for each region, their occurrence is related to a blocking pattern with the high pressure zone over the affected area (figure 7). In all cases, in the second period the intensity of the positive anomalies increases, leading to stronger pressure gradients and to higher anticyclonic (clockwise) winds, causing a significant reduction in the number of low wind events (table 2). In Balkan Peninsula, on the contrary, we detected a slight increase in the average number of days with low winds: indeed, by looking at the associated zh patterns (figure 7, **m-o**), rather than changes in the pressure gradients we observe an extension of the high pressure area over the Mediterranean. This is consistent with the results presented in [33], where a strengthening in the anticyclones intensity is found over this region.

To measure the presence of clusters in the events occurring over the selected time-steps and to detect changes in their behaviour, we computed the persistence[34] and the number of clusters, separately for each region and for both sub-periods (tables 3, 4). Nevertheless, even if there are slight changes in the persistence values, none of them is statistically significant (bootstrap method at the 95th level of confidence).

Region	01/01/1950-30/06/1985		01/07/1985-31/12/2020	
British Islands	176	552	281	382
North Sea	38	493	59	369
Bay of Biscay	29	585	56	372
Central Mediterranean	32	531	31	513
Balkan Peninsula	9	477	10	561

Table 2. Number of events with the number of affected grid points above the 95th percentile (**high winds**) and above the 99th percentile (**low winds**) for the past period (01/01/1950 – 30/06/1985) and for the present (01/07/1985 – 31/12/2020) for all the areas considered in this study.

Region	01/01/1950-30/06/1985		01/07/1985-31/12/2020	
British Islands	10.53	118	11.11	131
North Sea	9.38	27	8.33	37
Bay of Biscay	9.38	21	7.89	37
Central Mediterranean	10.17	16	8.7	20
Balkan Peninsula	6	5	11.32	5

Table 3. Persistence ($[h]$) and number of clusters for high winds, for the past (01/01/1950 – 30/06/1985) and for the present (01/07/1985 – 31/12/2020) period for all the areas considered in this study.

Region	01/01/1950-30/06/1985		01/07/1985-31/12/2020	
British Islands	11.32	244	11.11	246
North Sea	8.57	304	8.33	301
Bay of Biscay	8.7	329	9.09	319
Central Mediterranean	9.38	324	9.84	315
Balkan Peninsula	9.68	315	10.34	303

Table 4. Persistence ($[h]$) and number of clusters for low winds, for the past (01/01/1950 – 30/06/1985) and for the present (01/07/1985 – 31/12/2020) period for all the areas considered in this study.

5. Concluding remarks

In this work, we have estimated the behavior of extreme winds on the European panorama, over the period 1950-2020, and related them to the large-scale weather regimes, drawing conclusions on their potential impacts on off-shore wind energy availability. In particular, we focused on five regions: British Islands, North Sea, Bay of Biscay, Central Mediterranean and Balkan Peninsula. By means of the Mann Kendall test, we have detected the presence of significant trends in the occurrence of wind events with the wind speed above the cut-out threshold and below the cut-in threshold, during the period 1950-2020. In British Islands, North Sea and Bay of Biscay a significant increasing trend has been observed for high winds, and a decreasing trend for low winds. Contrariwise, in Central Mediterranean and Balkan Peninsula, the number of low wind events has increased. Finally, we have identified the weather regimes at which the extreme wind events occur, analysing the changes in the average geopotential height anomalies and in the average 100 m horizontal wind speed between the past period (01/01/1950-30/06/1985) and the present period (01/07/1985-31/12/2020). The low winds events are related to blocking patterns with the high pressure zone centered over the affected area. This implies that extreme events with the wind speed under the cut-in threshold can not occur, on average, at the same time at different locations. Whether this condition will persist also in future climates, simultaneous multiple outages can be avoided, *e.g.* by transferring energy from an area with higher availability to those affected by low winds conditions. Conversely, we have found that high winds for British Islands, North Sea and Bay of Biscay were related to the same weather regime, namely the NAO+ phase. This fact could lead, in the future, to widespread shortages in the wind energy supply, possibly leading to partial or total blackouts, with heavy impacts especially on cities and urban areas, in a scenario where energy is produced mostly by renewable sources. We remark that, although the frequency of extreme events related to high winds is relatively modest compared to the low wind ones, they could lead to heavier impacts. In fact, high

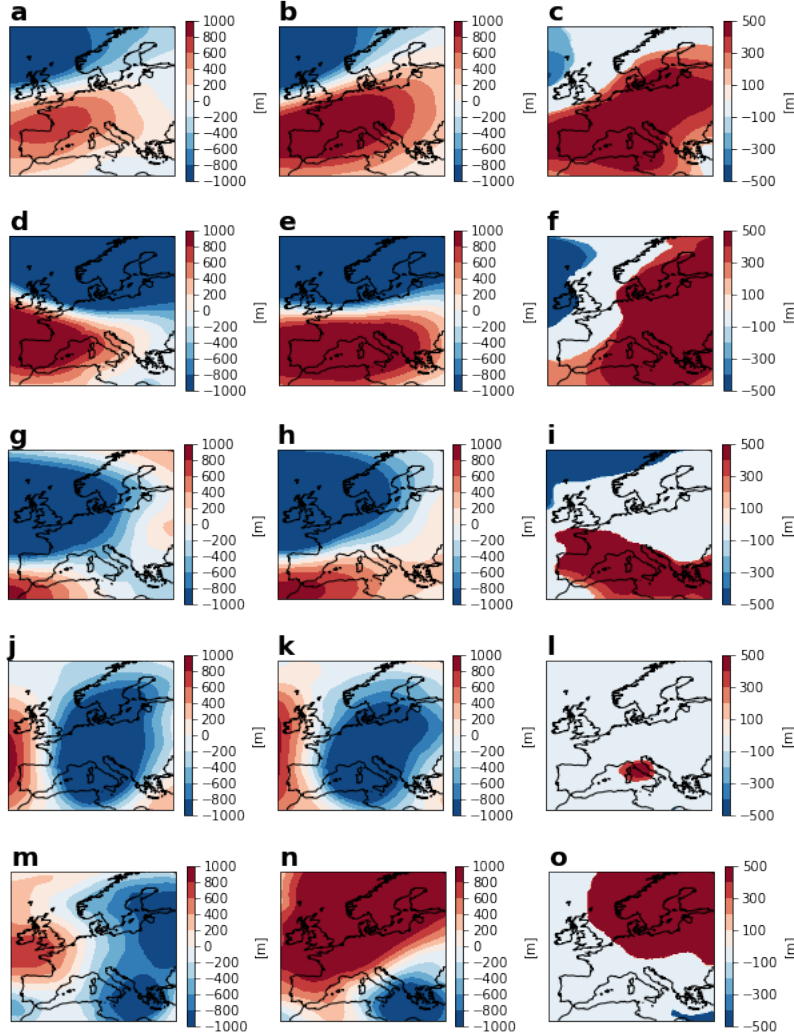


Figure 5. High winds. Geopotential height anomalies averaged over the time-steps selected for the period 01/01/1950-30/06/1985 (a, d, g, j, m) and for the period 01/07/1985-31/12/2020 (b, e, h, k, n); difference between the climatology of present and past anomalies (c, f, i, l, o). British Islands (a, b, c), North Sea (d, e, f), Bay of Biscay (g, h, i), Central Mediterranean (j, k, l), Balkan Peninsula (m, n, o). In the third column, shadings indicate significant changes.

winds not only prevent the RE infrastructures from operating, because of the storm control, but they may damage and sometimes even destroy the wind turbines, making maintenance interventions necessary and so extending the downtime.

Since our analyses, focused on historical climate data for the period 1950-2020, have shown that climate change already affects wind power availability over Europe during extreme weather events, the natural continuation of this study will be to look at future climate scenarios. Various studies suggest that climate change will not consid-

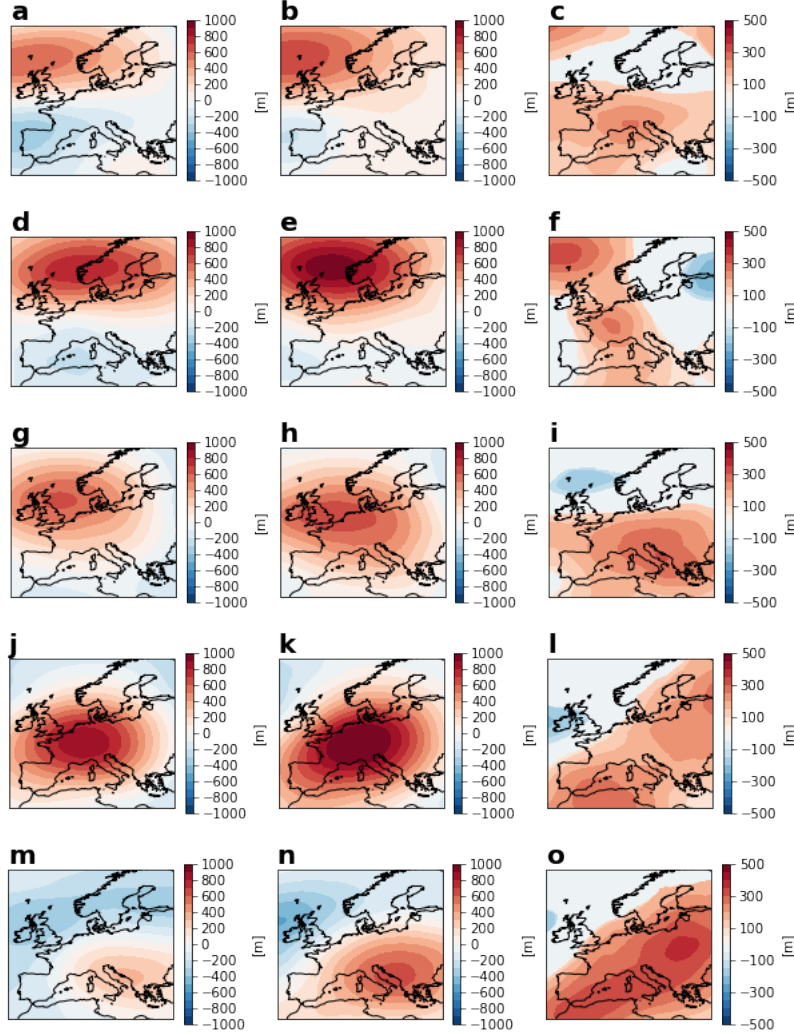


Figure 7. Same as in figure 5, but for **low winds**. In the third column, shadings indicate significant changes.

influence of the weather patterns, and consequently of the wind conditions, on the
 wind power generation [38] [39] [40] [41]. In particular, our paper has taken a clue
 from the work of Grams *et al.* [16]. In their paper, Grams *et al.* underline the lack of
 well-deployed installations and of an efficient electric European net that could handle
 electricity deficit periods. In addition, they stress the necessity to plan the installation
 of new capacity basing on the meteorological understanding. Combining these con-
 siderations with the results of our study, we can state that the planning of new wind
 farms should take into account also the behaviour of the extreme wind events, which
 can represent a threat to an efficient operation of the installations. Furthermore, to
 deal with this problem, it would be necessary to implement European policies for the
 energy management that provide the construction of infrastructures aimed to distri-

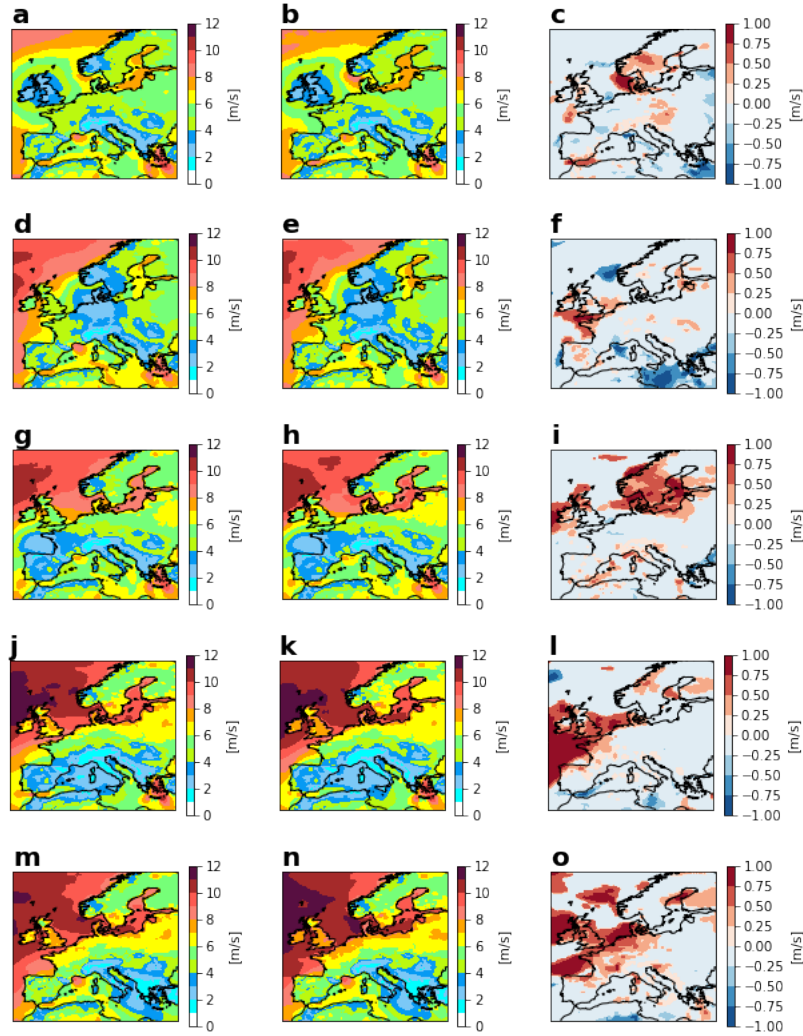


Figure 8. Same as in figure 6, but for **low winds**. In the third column, shadings indicate significant changes.

269 bution, storage and energy transmission, which could be used during the extreme wind
 270 events to avoid temporary blackouts. Nevertheless, the expected improvement in the
 271 wind power generation technology [42] [43] could make possible the construction of
 272 wind turbines able to produce energy at lower/higher wind speeds than the actual
 273 cut-in and cut-out wind speeds. This fact would lead to changes in the wind resources
 274 distribution, due to the possibility of constructing wind turbines in areas currently
 275 unsuitable, and, for the existing infrastructures, it would lead to a significant increase
 276 in their wind energy production.

Acknowledgments

This work has received support from the European Union’s Horizon 2020 research and innovation programme (Grant agreement No. 101003469, XAIDA) and funding by the Erasmus+ Programme in collaboration with the University of Pavia and by the Commissariat à l’Energie Atomique et aux Energies Alternatives (CEA).

Author contributions

LR performed the analyses. LR and DF conceived the study and wrote the paper. The authors declare that they have NO affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

Data availability statement

ERA5 is the latest climate reanalysis being produced by ECMWF as part of implementing the EU- funded Copernicus Climate Change Service (C3S), providing hourly data on atmospheric, land-surface and sea-state parameters together with estimates of uncertainty from 1979 to present day. ERA5 data are available on the C3S Climate Data Store on regular latitude-longitude grids at $0.25^\circ \times 0.25^\circ$ resolution at <https://cds.climate.copernicus.eu/#!/home>.

Appendix

Day(s) of high winds	Name(s) of the storm	Region affected
31/01/1953	North Sea Flood	British Islands
16/02/1962	The Sheffiled Gale	British Islands
11/01/1974	Irish Windstorm	British Islands
24/11/1981	1981 November Storm	British Islands
14/02/1989	Scottish Windstorm	British Islands
26-27/02/1990	Vivian	British Islands
08/01/1993	Braer Storm	British Islands
10-12/01/1993	Braer Storm	British Islands
15/01/1993	Braer Storm	British Islands
17/01/1993	Braer Storm	British Islands
12/01/2005	Erwin (Gudrun)	British Islands
11/01/2007	Franz	British Islands
25/01/2008	Paula	British Islands
08/12/2011	Friedhelm (Bawbag)	British Islands
25/12/2011	Patrick	British Islands
19/12/2013	Bernd (Emily)	British Islands
24/12/2013	Dirk	British Islands
10/12/2014	Alexandra	British Islands
10/01/2015	Elon, Felix, Hermann	British Islands
12/01/2015	Elon, Felix, Hermann	British Islands

Table A1. Day(s) of high winds and name(s) of the storm for the British Islands.

Day(s) of high winds	Name(s) of the storm	Region affected
01/02/1953	North Sea Flood	North Sea
16/02/1962	The Sheffield Gale	North Sea
23/02/1967	"Adolph Bermpohl" storm	North Sea
15/01/1968	The Glasgow Hurricane	North Sea
03/01/1976	Capella Storm	North Sea
24/11/1981	1981 November Storm	North Sea
18/01/1983	Christiansborg Storm	North Sea
16/10/1987	Great Storm of 1987	North Sea
14/02/1989	Scottish Windstorm	North Sea
25/01/1990	Burns' Day Storm (Daria)	North Sea
08/02/1990	Judith	North Sea
26/02/1990	Vivian	North Sea
28/01/1994	Lore	North Sea
27/12/1998	Boxing Day Storm (Stephen)	North Sea
03/12/1999	Anatol	North Sea
08/01/2005	Erwin (Gudrun)	North Sea
14/01/2007	Franz	North Sea
09/11/2007	Tilo (Andrea)	North Sea
27/11/2011	Berit (Xaver)	North Sea
09/12/2011	Friedhelm (Bawbag)	North Sea
03/01/2012	Ulli (Emil)	North Sea
24/12/2013	Dirk	North Sea
09-10/01/2015	Elon, Felix, Hermann	North Sea
29/10/2017	Storm Herwart	North Sea
09/02/2020	Storm Ciara	North Sea
16/02/2020	Storm Ciara, Storm Dennis	North Sea

Table A2. Day(s) of high winds and name(s) of the storm for North Sea.

Day(s) of high winds	Name(s) of the storm	Region affected
11/02/1974	Norway Windostorm	Bay of Biscay
15/10/1987	Great Storm of 1987	Bay of Biscay
25/01/1990	Burns' Day Storm (Daria)	Bay of Biscay
07/02/1990	Judith	Bay of Biscay
10/01/1993	Braer Storm	Bay of Biscay
26-27/12/1999	Lothar, Martin	Bay of Biscay
30/10/2000	Oratia	Bay of Biscay
24/01/2009	Klaus	Bay of Biscay
09/02/2009	Quinten	Bay of Biscay
13/12/2013	Ivar	Bay of Biscay
15-16/12/2013	Ivar	Bay of Biscay
23-24/12/2013	Ivar	Bay of Biscay
05/02/2014	Nadia (Brigid)	Bay of Biscay
14/02/2014	Stephanie	Bay of Biscay
27/12/2020	Storm Bella	Bay of Biscay

Table A3. Day(s) of high winds and name(s) of the storm for Bay of Biscay.

References

- [1] IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp., 2014
- [2] European Commission 2022 <https://climate.ec.europa.eu/eu-action/>

- 301 european-green-deal/delivering-european-green-deal_en
- 302 [3] Crook J A, Jones L A, Forster P M and Crook R 2011 Climate change impacts on future
- 303 photovoltaic and concentrated solar power energy output *Energy Environ. Sci.* 4 3101
- 304 [4] Patt A, Pfenninger S and Lilliestam J 2013 Vulnerability of solar energy infrastructure and
- 305 output to climate change *Climatic Change* 121 93-102
- 306 [5] Rose S, Jaramillo P, Small M J, Grossmann I and Apt J 2012 Quantifying the hurricane risk to
- 307 offshore wind turbines *Proceedings of the National Academy of Sciences of the United States*
- 308 *of America* 109(9) 3247–3252
- 309 [6] Steiner A, Kohler C, Metzinger I, Braun A, Zirkelbach M, Ernst D, Tran P and Ritter B 2017
- 310 Critical weather situations for renewable energies - Part A: Cyclone detection for wind power
- 311 *Renewable Energy* 101 41-50
- 312 [7] Perera A T D, Nik V M, Chen D, Scartezzini J-L and Hong T 2020 Quantifying the impacts of
- 313 climate change and extreme climate events on energy systems *Nat Energy* 5 150–159
- 314 [8] Velenturf APM, Emery AR, Hodgson DM, Barlow NLM, Mohtaj Khorasani AM, Van Alstine
- 315 J, Peterson EL, Piazzolo S and Thorp M 2021 Geoscience Solutions for Sustainable Offshore
- 316 Wind Development. *Earth Sci. Syst. Soc.* 1:10042. doi: 10.3389/esss.2021.10042
- 317 [9] An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future
- 318 European Commission 2022 [https://energy.ec.europa.eu/topics/renewable-energy/](https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en)
- 319 [offshore-renewable-energy_en](https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en)
- 320 [10] Mathew S 2006 *Wind energy: fundamentals, resource analysis and economics* (Berlin,
- 321 Heidelberg: Springer)
- 322 [11] Jerez S, Thais F, Tobin I, Wild M, Colette A, Yiou P and Vautard R 2015 The CLIMIX model:
- 323 A tool to create and evaluate spatially-resolved scenarios of photovoltaic and wind power
- 324 development *Ren. and Sust. En. Rev.* 42 1-15 ISSN 1364-0321
- 325 [12] Cutululis N A, Litong-Palima M and Sørensen P E 2012 Offshore Wind Power Production in
- 326 Critical Weather Conditions *Proceedings of EWEA 2012 - European Wind Energy Conference*
- 327 *& Exhibition European Wind Energy Association (EWEA)*
- 328 [13] Froude L S R, Bengtsson L and Hodges K I 2007 The prediction of extratropical storm tracks
- 329 by the ECMWF and NCEP ensemble prediction systems *Monthly Weather Review* 135(7)
- 330 2545-2567
- 331 [14] Wallace J M and Hobbs P V 2006 *Atmospheric Science, An Introductory Survey* (Atmospheric
- 332 Pr)
- 333 [15] Neu U, Akperov M G, Bellenbaum N, Benestad R, Blender R, Caballero R, Cocozza
- 334 A, Dacre H F, Feng Y, Fraedrich K *et al.* 2013 IMILAST: A Community Effort to
- 335 Intercompare Extratropical Cyclone Detection and Tracking Algorithms *Bulletin of the*
- 336 *American Meteorological Society* 94(4) 529-547.
- 337 [16] Grams C M, Beerli R, Pfenninger S, Staffell I and Wernli H 2017 Balancing Europe's wind
- 338 power output through spatial deployment informed by weather regimes *Nature Clim Change*
- 339 7 557-562
- 340 [17] Brönnimann S, Martius O, Von Waldow H, Welker C, Luterbacher J, Compo G P, Sardeshmukh
- 341 P D and Usbeck T 2012 Extreme winds at northern mid-latitudes since 1871 *Meteorologische*
- 342 *Zeitschrift* 21 1 013-027
- 343 [18] Corti S., Molteni F and Palmer T 1999 Signature of recent climate change in frequencies of
- 344 natural atmospheric circulation regimes *Nature* 398, 799–802
- 345 [19] Monforti F, Gaetani M, and Vignati E 2016 How synchronous is wind energy production
- 346 among European countries? *Renewable and Sustainable Energy Reviews*, 59, 1622–1638.
- 347 <https://doi.org/10.1016/j.rser.2015.12.318>
- 348 [20] Gonçalves A, Liberato M L R and Nieto R 2021 Wind Energy Assessment during High-Impact
- 349 Winter Storms in Southwestern Europe *Atmosphere* 12(4) 509
- 350 [21] Ulbrich U, Leckebusch G C and Pinto J 2009 Extra-tropical cyclones in the present and future
- 351 climate: a review *Theor Appl Climatol* 96 117-131
- 352 [22] Copernicus 2022 <https://www.copernicus.eu/en>
- 353 [23] Gualtieri G 2021 Reliability of ERA5 Reanalysis Data for Wind Resource Assessment: A
- 354 Comparison against Tall Towers *Energies* 14(14) 4169
- 355 [24] ERA5 hourly data on single levels from 1950 to 1978 *Coper-*
- 356 *nicus* 2021 [https://cds.climate.copernicus.eu/cdsapp#!/dataset/](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-preliminary-back-extension?tab=overview)
- 357 [reanalysis-era5-single-levels-preliminary-back-extension?tab=overview](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-preliminary-back-extension?tab=overview)
- 358 [25] ERA5 hourly data on single levels from 1979 to present *Copernicus* 2021 [https://cds.climate.](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview)
- 359 [copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview)
- 360 [26] Dong B, Sutton R T, Woollings T and Hodges K 2013 Variability of the North Atlantic summer
- 361 storm track: mechanisms and impacts on European climate *Environ Res Lett* 8

- [27] Ulbrich U Lionello P Belušić D Jacobeit J Knippertz P Kuglitsch F G Leckebusch G C Luterbacher J Maugeri M Maheras P Nissen K M Pavan V Pinto J G Saaroni H Seubert S Toreti A Xoplaki E and Ziv B 2012 5 - Climate of the Mediterranean: Synoptic Patterns, Temperature, Precipitation, Winds, and Their Extremes *Elsevier* 301-346
- [28] Pymannkendall 1.4.2 <https://pypi.org/project/pymannkendall/>
- [29] Faranda D 2021 European Storm Database – 1948-2020
- [30] Vautard R 1990 Multiple Weather Regimes over the North Atlantic: Analysis of Precursors and Successors *Monthly Weather Review* 118(10) 2056-2081
- [31] Hurrell J W, Kushnir Y and Ottersen G 2011 An overview of the North Atlantic oscillation The North Atlantic Oscillation: Climatic Significance and Environmental Impact (American Geophysical Union) Geophysical Monograph Series 134
- [32] Cassou C 2008 Intraseasonal interaction between the Madden–Julian oscillation and the North Atlantic Oscillation *Nature* 455 523-527
- [33] Fery L, Dubrulle B, Podvin B, Pons F, and Faranda D, Learning a weather dictionary of atmospheric patterns using Latent Dirichlet Allocation (preprint version) *Geophysical Research Letters, American Geophysical Union*, In press, 10.21203/rs.3.rs-608588/v1. hal-03258523
- [34] Moloney N, Faranda D and Sato Y 2019 An overview of the extremal index. *Chaos: An Interdisciplinary Journal of Nonlinear Science, American Institute of Physics* 29 (2), pp.022101. (10.1063/1.5079656)
- [35] Tobin I, Vautard R, Balog I, Bréon F-M, Jerez S, Ruti P M, Thais F, Vrac M and Yiou P 2015 Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections *Climatic Change* 128 99–112.
- [36] Hdidouan D and Staffell I 2017 The impact of climate change on the levelised cost of wind energy *Renew Energy* 101 575–592
- [37] Ban N, Caillaud C, Coppola E, Pichelli E, Sobolowski S, Adinolfi M, Ahrens B, Alias A, Anders I, Bastin S *et al.* 2021 The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation *Climate Dynamics*
- [38] Brayshaw D J, Troccoli A, Fordham R and Methven J 2011 The impact of large scale atmospheric circulation patterns on wind power generation and its potential predictability: a case study over the British Islands *Renew. Energy* 36 2087–96
- [39] Caroline R E, Brayshaw D J, Methven J, Cox J and Pearce O 2013 Implications of the North Atlantic Oscillation for a British Islands–Norway Renewable power system *Energy Policy* 62 1420-1427
- [40] Zubiate L, McDermott F, Sweeney C and O'Malley M. 2017 Spatial variability in winter NAO–wind speed relationships in western Europe linked to concomitant states of the East Atlantic and Scandinavian patterns *Q J R Meteorol Soc.* 143 552–562
- [41] Van der Wiel K, Bloomfield H C, Lee R W, Stoop L P, Blackport R, Screen J A and Selten F M 2019 The influence of weather regimes on European renewable energy production and demand *Environ. Res. Lett.* 14 094010
- [42] Bošnjaković M, Katinić M, Santa R and Marić D 2022 Wind Turbine Technology Trends *Appl. Sci.* 12 8653
- [43] Díaz H and Guedes Soares C 2020 Review of the current status, technology and future trends of offshore wind farms *Ocean Engineering*