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

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Lia Rapella^{1,2,*}, Davide Faranda^{1,3,5}, Marco Gaetani⁶, Philippe Drobinski⁴ and Mireia 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 LMD-IPSL, École Polytechnique, Institut Polytechnique de Paris, CNRS, Palaiseau, France

³ London Mathematical Laboratory, 8 Margravine Gardens, London W6 8RH, British Islands

⁴ LMD-IPSL, École Polytechnique, Institut Polytechnique de Paris, ENS, PSL Research University, Sorbonne Université, CNRS, Palaiseau, France

⁵ Laboratoire de Météorologie Dynamique, École Normale Supérieure, PSL research University & IPSL, 75005 Paris, France

⁶ Scuola Universitaria Superiore IUSS, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italia

* Author to whom any correspondence should be addressed.

E-mail: lia.rapella@lmd.ipsl.fr

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Supplementary material for this article is available [online](#)

Abstract

Off-shore wind energy in Europe 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 internal climate variability have 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.

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 [34], 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 [34]. 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 [18], in the world. In this context, renewable

energy (RE) plays 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 [10, 35, 39, 40], and their demand [36].

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 [46]. 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 [17]. 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 production⁷ (W_{pot}), according to the working regimes of a wind turbine [30], depends on the wind speed V by the following relation:

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

where V_R is the rated speed (13 m s^{-1}), V_i (3.5 m s^{-1}) and V_o (25 m s^{-1}) are the cut-in and cut-off speed respectively⁸ [29].

When the cut-off threshold is overcome, the turbines are stopped 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 1 h [11]. 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* [23], especially in autumn and winter (supplementary, *Extra-tropical cyclones*).

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 possible 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 generate them (supplementary, *Weather regimes*). While Grams et al [26] have already analyzed 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 [4] and Corti et al [8] 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 winds⁹ 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 a large area, 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 [25, 32].

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 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 datasets are publicly available at the Copernicus Climate Data Centre [7] on regular latitude-longitude grid, at $0.25^\circ \times 0.25^\circ$ resolution¹⁰.

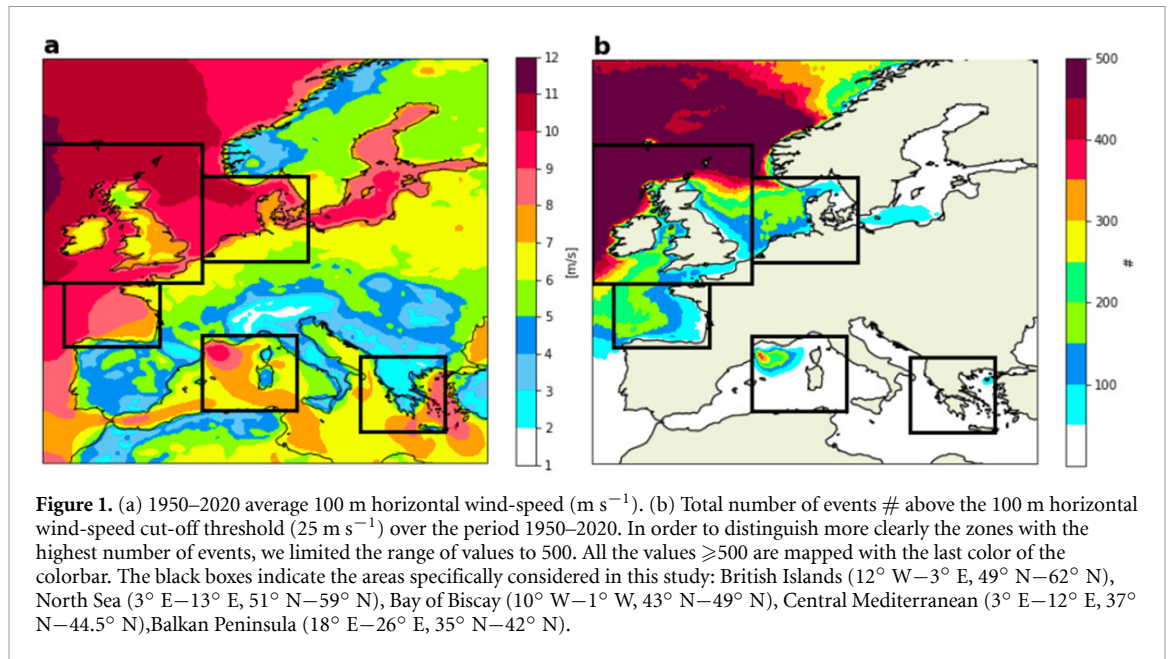
For our analysis we used two subsets of ERA5 [27], *ERA5 hourly data on single levels from 1950 to 1978* [15] and *ERA5 hourly data on single levels from 1979 to present* [16], covering a period from 1950 to 2020 and selecting 6-hourly values, at 00:00, 06:00, 12:00 and 18:00. In particular, we selected three variables:

⁷ Dimensionless indicator of the potential power production at each location and time.

⁸ 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.

⁹ See section 2 for the definition of ‘extreme winds’.

¹⁰ This resolution corresponds approximately to 27.75 km^2 .



- 100 m u -component of wind, u ($[\text{m s}^{-1}]$): eastward horizontal component of wind speed, measured at 100 m above the Earth surface;
- 100 m v -component of wind, v ($[\text{m s}^{-1}]$): northward horizontal component of wind speed, measured at 100 m above the Earth surface;
- geopotential, z ($[\text{m}^2 \text{ s}^{-2}]$), 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: $-12^\circ \text{ W} - 30^\circ \text{ E}$, $32^\circ \text{ N} - 70^\circ \text{ N}$.

To obtain the horizontal wind speed at 100 m¹¹, 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 m s^{-2}).

In figure 1, panel (a), it is represented the mean 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 m s^{-1} 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'

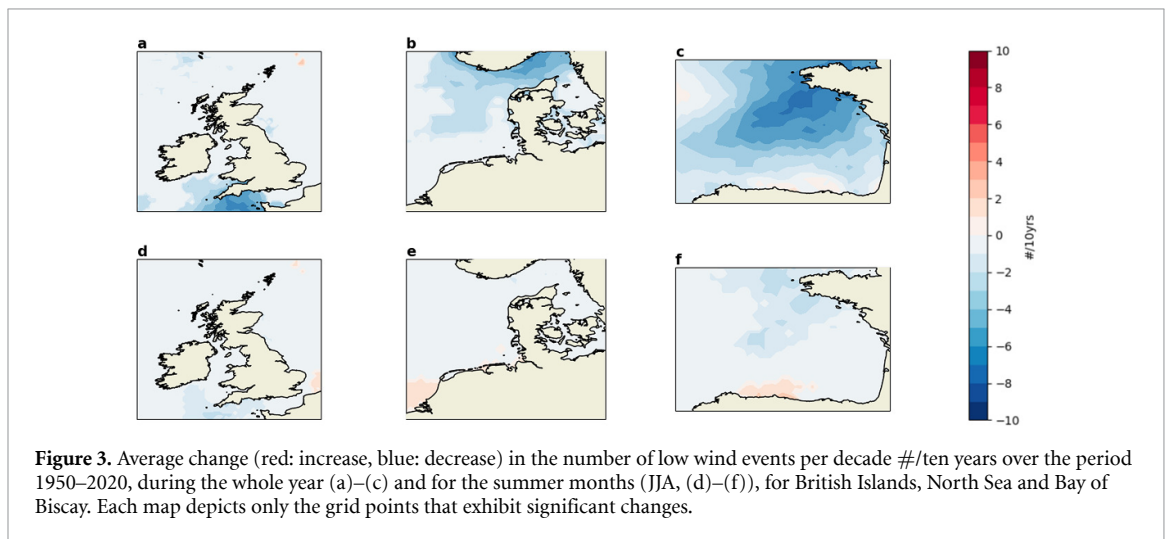
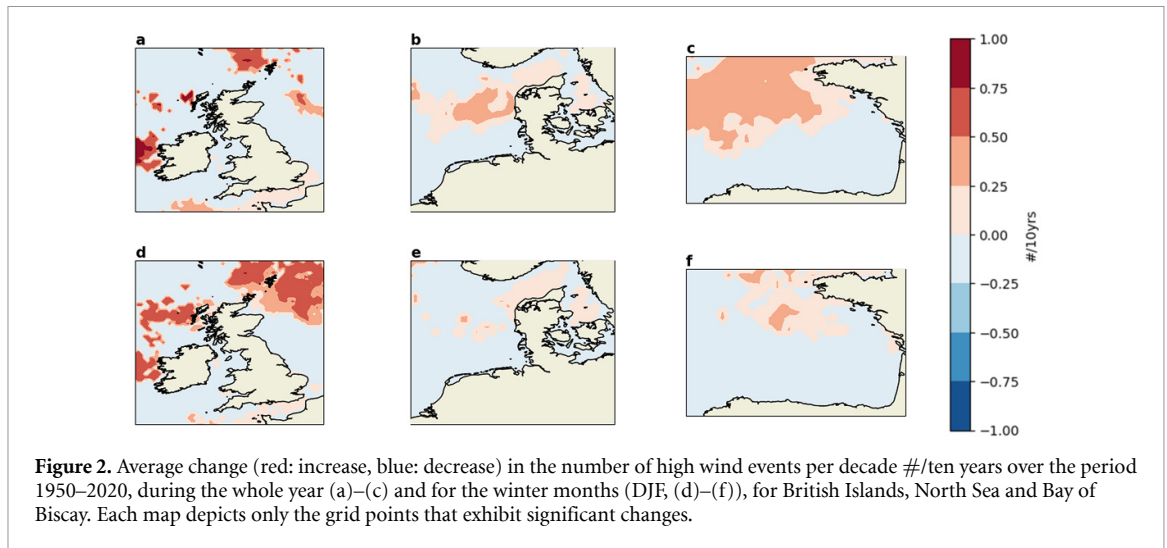
those with the wind speed under the cut-in threshold. Moreover, we will consider as event every time-step with the wind speed that satisfies one of these two latter constraints.

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 favorable to the installation of offshore wind farms because they experience quasi-constant wind patterns. Specifically, the Bay of Biscay, the British Islands and the North Sea lie on the Atlantic storm track [13]; Central Mediterranean and the Balkan Peninsula are affected by the Mistral and Etesian wind patterns, respectively [43]. During the summer months (June–July–August) 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, we investigated the existence of significant long-term changes in the occurrence of extreme events during the period 1950–2020. With this aim, we analyzed their trends, separately region by region, by means of the Mann–Kendall test at 95% level of confidence [37]. We computed the test not only considering the

¹¹ 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.



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 and for the winter months, for British Islands, North Sea, Bay of Biscay. 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 the Balkan Peninsula (not shown), 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 and for the summer months, for British Islands, North Sea, Bay of Biscay. 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.

We want to stress that reanalysis is not always the best tool for evaluating wind speed long-term variability, since there are still issues about its ability to reproduce wind-speed trends [19, 42] and different reanalysis can even disagree with each other [2, 47]. In fact, the reanalysis products could be affected by errors in the observations and in the assimilation procedure. Therefore, to have more robust results, it would be recommended to use a multi-reanalysis approach. Nevertheless, Faranda *et al* [21] studied trends in atmospheric circulation using different reanalysis (ERA5, NCEP) and gridded interpolated data (EOBS) finding that the qualitative results of large-scale circulation trends analysis remain largely unaffected. Moreover, three recent works have recently appeared pointing to the possibility of attributing different events to climate change on the basis of reanalysis only: Faranda *et al* [20], Cadiou *et al* [5], Ginesta *et al* [24].

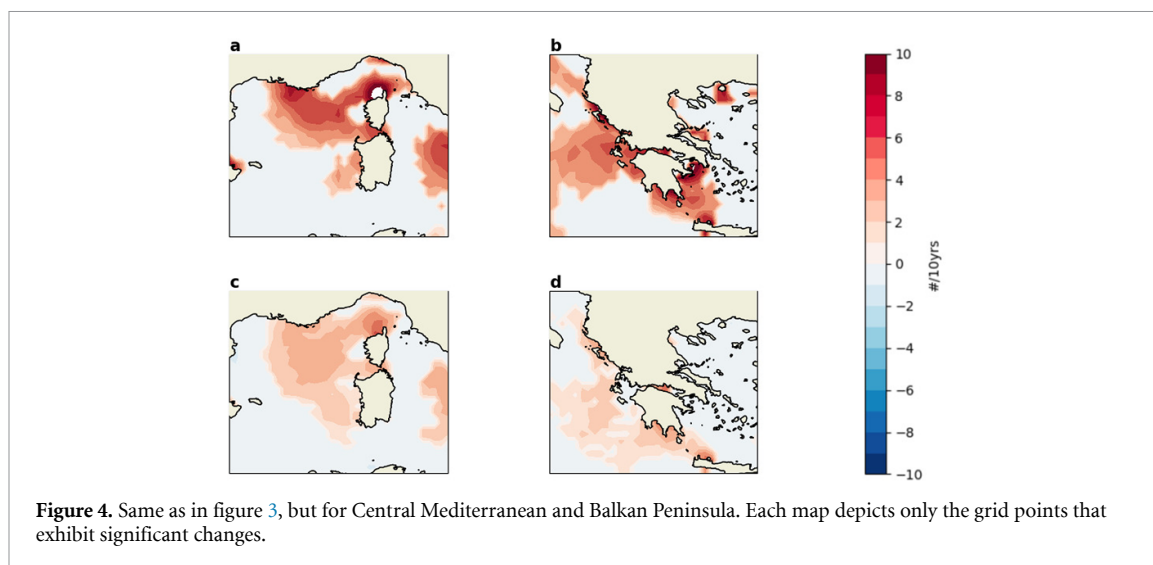


Table 1. Number of affected grid points with the corresponding spatial area (km²) above the 95th percentile (high winds) and above the 99th percentile (low winds) for all the areas considered in this study.

Region	High winds		Low winds	
British Islands	419	11627	1104	30636
North Sea	207	5744	668	18537
Bay of Biscay	244	6771	505	14014
Central Mediterranean	85	2359	778	21590
Balkan Peninsula	47	1304	671	18620

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 datasets 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 (table 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 (85).

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 height¹², 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 ϕ the value of ϕ at the same instant averaged over the month for all the

period 1950–2020. For example, to the value of the geopotential height on the 01 February 1953 at 06:00 we subtracted the mean of the geopotential height values on every day of February at 6 a.m. from 1950 to 2020. Then, we grouped the selected time-steps in two sub-periods, past period (1 January 1950–30 June 1985) and present period (1 July 1985–31 December 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. Moreover, to better understand the nature of these differences, we analyzed the North Atlantic Oscillation (NAO) index distributions for both periods, by means of a two-sided Cramér–von Mises test at the 95% level of confidence [9] (supplementary, *Weather regimes*).

As shown in figure 5, high winds in British Islands, North Sea and Bay of Biscay occur during the NAO+ phases. In the second period, the positive ϕ 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 (supplementary, figure 1). For these two regions, a significant change in the NAO distribution between present and past period has been found, with a weak shift

¹² Going forward, the geopotential height will be referred to as ϕ .

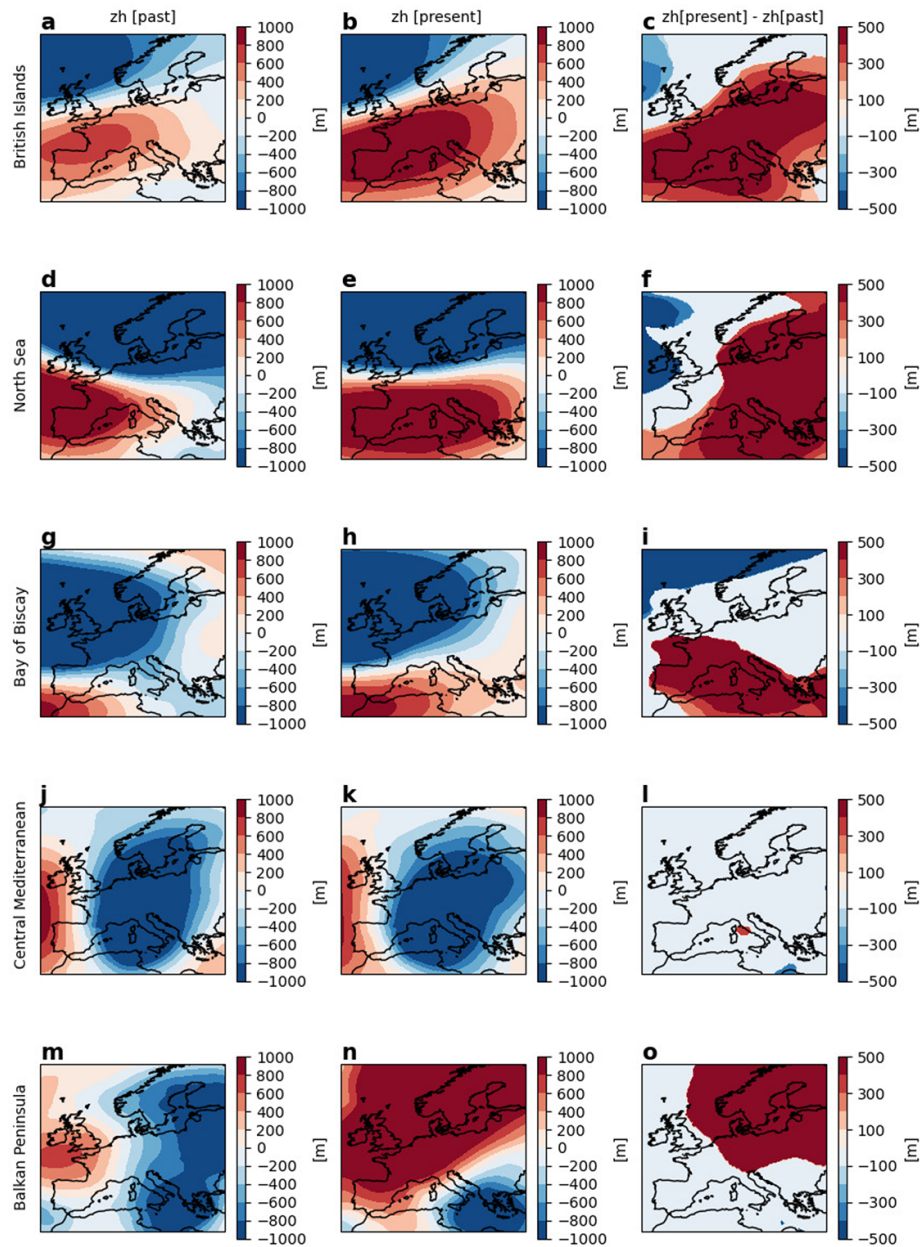


Figure 5. High winds. Composites of the geopotential height anomalies over the time-steps with the number of affected grid points above the 95th percentile for the period 1 January 1950–30 June 1985 (a), (d), (g), (j), (m) and for the period 1 July 1985–31 December 2020 (b), (e), (h), (k), (n); difference between the climatology of present and past anomalies (c), (f), (i), (l), (o). British Islands (a)–(c), North Sea (d)–(f), Bay of Biscay (g)–(i), Central Mediterranean (j)–(l), Balkan Peninsula (m)–(o). In the third column, shadings indicate significant changes.

Table 2. Number of events with the number of affected grid points above the 95th percentile (high winds, left column of each side) and above the 99th percentile (low winds, right column of each side) for the past period (1 January 1950–30 June 1985) and for the present (1 July 1985–31 December 2020) for all the areas considered in this study.

Region	Past period		Present period	
British Islands	176	552	281	382
North Sea	38	493	59	369
Bay of Biscay	29	585	56	389
Central Mediterranean	32	531	31	513
Balkan Peninsula	9	477	10	561

towards more positive (neutral) NAO phases in the present period for the British Islands (North Sea) (supplementary, figures 3 and 4). Instead, an Atlantic

ridge pattern is found for the Central Mediterranean (figure 5) and, in the first period, for Balkan Peninsula (figure 5), for which then it shifts to a Scandinavian

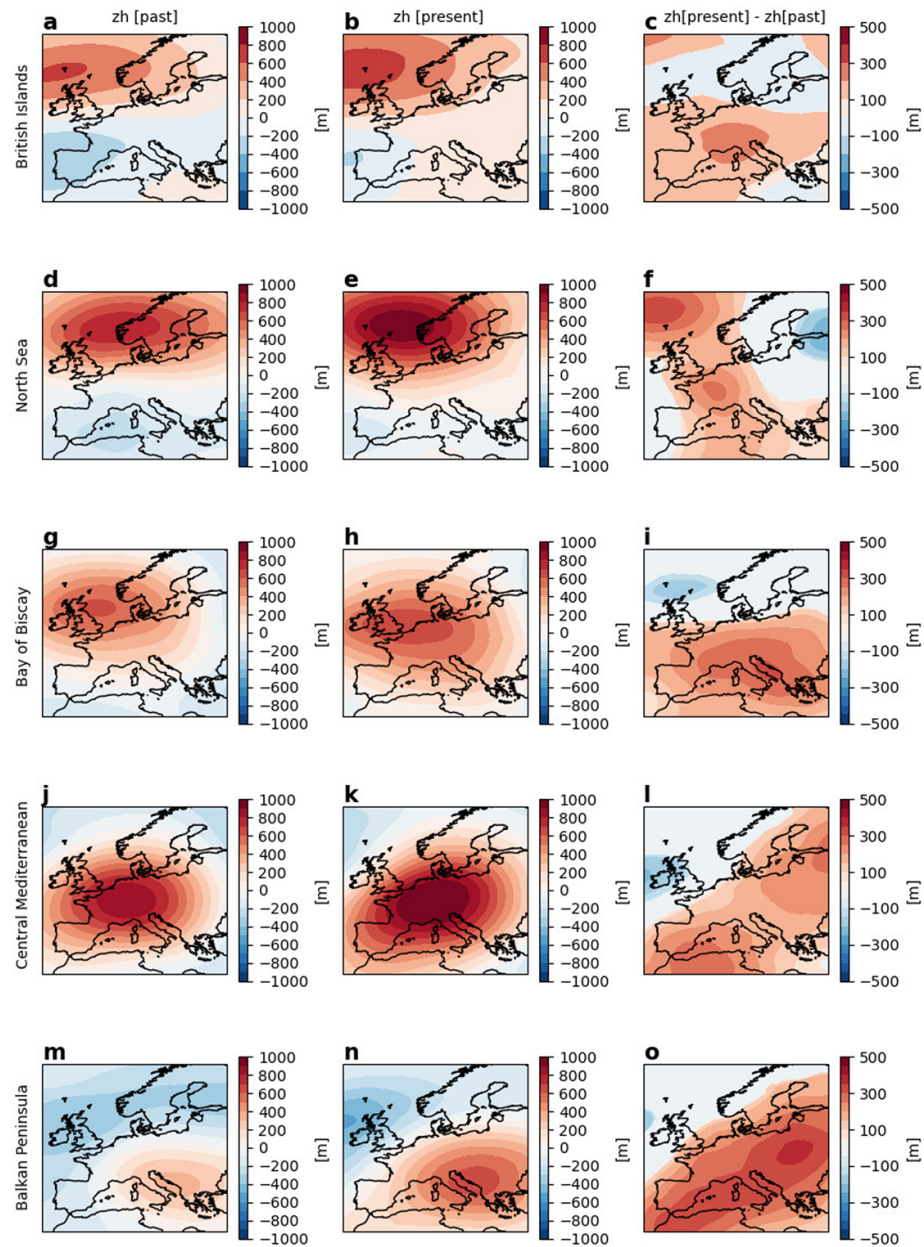


Figure 6. Low winds. Composites of the geopotential height anomalies over the time-steps with the number of affected grid points above the 99th percentile for the period 1 January 1950–30 June 1985 (a), (d), (g), (j), (m) and for the period 1 July 1985–31 December 2020 (b), (e), (h), (k), (n); difference between the climatology of present and past anomalies (c), (f), (i), (l), (o). British Islands (a)–(c), North Sea (d)–(f), Bay of Biscay (g)–(i), Central Mediterranean (j)–(l), Balkan Peninsula (m)–(o). In the third column, shadings indicate significant changes.

blocking, with the center of the low pressure system remaining located over the Balkan Peninsula. According to this behavior, figure 7 (supplementary) displays a significant shift from positive to neutral NAO values in the present period. 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 (supplementary, figure 1) and changes, both positive and negative, in Balkan Peninsula (supplementary, figure 1).

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 6), and no significant changes in the NAO distribution between present and past period have been found (figures 8–12, supplementary). 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 ϕ patterns (figure 6), 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 [22], where a strengthening in the anti-cyclones intensity is found over this region.

To account the possible influence of the low-frequency natural variability, the El Niño-Southern Oscillation (ENSO) and the Atlantic Multi-decadal Oscillation (AMO) (supplementary, *ENSO and AMO*) distributions have been studied [20], as done for the NAO index. Regarding the high winds, we detected significant changes between past and present period in the ENSO distribution for British Islands (shift to neutral values), Bay of Biscay and Central Mediterranean (negative shift), and in the AMO distribution for Bay of Biscay, Central Mediterranean (shift to lower values) and Balkan Peninsula (higher values). Therefore, for these mentioned regions, we cannot reject the hypothesis that ENSO and AMO variability have influenced the behavior of the high winds.

For the low winds, we found significant changes in the ENSO and AMO distribution for all the regions, with weak positive shift in the mean values in the present period and/or marked changes in the shape of the distributions between the two periods. This implies that changes in the low wind speed behavior can not be linked only to climate change but they are also related to the internal climate variability, which plays a relevant role.

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, analyzing the changes in the average geopotential height anomalies and in the average 100 m horizontal wind speed between the past period (1 January 1950–30 June 1985) and the present period (1 July 1985–31 December 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 other locations. 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 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.

In determining the behavior of low-winds events, only ENSO and AMO played a significant role, while for high winds in British Islands, North Sea and Balkan Peninsula we found a significant link also to NAO phases.

Our analyses, focused on historical climate data for the period 1950–2020, have shown that climate change and internal climate variability intervene together in affecting wind power availability over Europe during extreme weather events. To perform the analyses, as underlined at the end of section 3, we chose to only use ERA5 reanalysis data-sets, and not a multi-reanalysis approach. Furthermore, we did not make use of models due to their limitations in providing a coherent picture of low-frequency modes of variability and their interactions [6], as well as inconsistencies between numerical models and reanalysis when it comes to temporal variations in the atmospheric states—which is at the basis of our analysis [38].

In addition, we point out that in this study we have considered every grid point as a potential location for the installation of wind turbines. However, this is only possible in areas where the sea depth is less than 1 km. Therefore, to increase the relevance of our results, it would be beneficial to only consider the grid points with an average sea depth of less than 1000 m.

A natural continuation of this study will be to look at future climate scenarios. Various studies suggest that climate change will not considerably affect the average near-surface wind speed [28, 41] and therefore the average energy production. However, our analysis could motivate further research by specifically looking at extreme low/high winds that could not necessarily follow the behavior of average wind speed. In this context, it will be appropriate to use the new convection permitting simulations available at high resolutions [1]. A natural strategy to ensure robustness of the results would be the use of *ensembles* climate simulations corresponding to different shared socio-economic pathways.

The results of our work are consistent with the previous literature that analyzed the influence of the

weather patterns, and consequently of the wind conditions, on the wind power generation [3, 14, 45, 48]. In particular, our paper has taken a clue from the work of Grams *et al* [26]. 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 considerations with the results of our study, we can state that the planning of new wind farms should take into account also the behavior of the extreme wind events, which can represent a threat to an efficient operation of the installations. We finally remind that, to ensure that meaningful results are obtained, it is fundamental the use of suitable data-sets and an adequate time period to capture detectable trends.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://cds.climate.copernicus.eu#!/home>.

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Author contributions

L R performed the analyses. L R and D F 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.

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