RESEARCH ARTICLE

Observed onshore precipitation changes after the installation of offshore wind farms

Nicolas Al Fahel[1] · Cristina L. Archer[1]

Abstract

The goal of this study is to assess the extent to which offshore wind farms can inadvertently affect precipitation at nearby onshore locations. As the winds slow down over an offshore wind farm due to the extraction of kinetic energy from the air flow by the turbines, a pattern of convergence upstream and divergence downstream of the farm is formed, which respectively may enhance precipitation offshore and reduce precipitation near the shore. To verify this hypothesis, we used observed precipitation data collected near two offshore wind farms in the western UK: Walney and Burbo Bank, built in 2011–2014 and 2005–2007, respectively. For each farm, we identified a "treatment" site, a meteorological station likely to be affected by the wake of the wind farm for a certain wind direction range, and a "control" site, unaffected by the farm for the same wind direction range. We used a difference-in-differences (DiD) approach between the precipitation data at the treatment and control sites before and after the construction of the wind farms to determine the net impact of the offshore farms on precipitation patterns at the shore. We found the following statistically significant signals at Walney after the construction of the wind farms: decreased wind speed (-1.1 knots on average), reduced precipitation rate (-0.003 mm/h), and reduced positive precipitation rate (i.e., only including hours with non-zero precipitation, -0.080 mm/h). At Burbo Bank, wind speed and positive precipitation were reduced after the farm was built (-1.45 knots and -0.080 mm/h, respectively) with statistical significance, but no statistically significant drop in the hourly precipitation rate was found. All observed statistically significant changes were small in magnitude (order of 11% of the average or less). We speculate that, since Burbo Bank is very close to the shore (distance < 8 km), the divergence pattern cannot always form with sufficient strength to cause a precipitation suppression at the shore, which may explain the a less clear signal at that site. By contrast, the Walney farm is located ~ 15 km away from the shore, which, we believe, is sufficient for the divergence zone to reach the shore.

Keywords Offshore wind farms · Precipitation · Divergence · Convergence · Difference-in-differences

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1 Introduction

As wind farms are being built onshore and offshore to provide clean and renewable energy, evidence of small, unintentional effects on local weather is being found. A literature review of such evidence with respect to near-surface temperature can be found in Archer et al. (2019) for onshore wind farms and in Siedersleben et al. (2018) for offshore wind farms. However, literature on the impact of wind farms, onshore or offshore, on precipitation patterns is rare. The only paper that thoroughly explores such impact is a modeling study by Pan et al. (2018) on precipitation during hurricane Harvey. They found precipitation to be enhanced upstream and reduced downstream of a large hypothetical wind farm array in the Gulf of Mexico based on simulations.

The mechanism proposed for the precipitation change is illustrated in Fig. 1b. Upstream of the wind farm, the undisturbed wind speed is U_0. At the wind farm, the extraction of kinetic energy from the air flow by the wind turbines causes a strong reduction of the wind ($U_1 << U_0$), which induces the formation of a convergence zone ahead of the offshore farm. Convergence zones are associated with upward motions, which enhances precipitation. Downwind of the farm, a turbulent wake forms in which wind speed starts to recover ($U_2 > U_1$). A divergence zone forms past the offshore wind farm, close to the shore, associated with downward motion, which reduces precipitation.

The enhancement of precipitation in areas of horizontal wind convergence—and vice versa, the suppression of precipitation where horizontal winds diverge—is a well-known phenomenon in meteorology that has been observed at many scales. At the global scale, the inter-tropical convergence zone (ITCZ) is the band around the equator where the trade winds from both hemispheres converge and cause enhanced convection and precipitation (Waliser and Jiang 2015); in the Hadley cells, the descending branches around $\pm$ 30° of latitude are associated with high surface pressure, horizontal wind divergence, and lack of precipitation, thus corresponding to the location of most arid deserts on Earth (Lu and Vecchi 2015). At the regional scale, the convergence of the two sea breezes in Florida, one from the Atlantic and the other from the Gulf of Mexico, is responsible for enhanced convection and thunderstorms (Shepherd et al. 2001). Lastly, thunderstorm activity is found to be enhanced ahead of and over urban centers due to the larger surface roughness, lower wind speed, wind convergence, and higher temperature over cities (Haberlie et al. 2015).

The physical explanation for the enhancement of precipitation due to convergence—and suppression due to wind divergence—lies in the continuity equation, which represents the conservation of mass in the atmospheric system (Holton 1992). Since air is incompressible, the only possible physical response to horizontal wind convergence is upward motion, which causes upward displacement of moisture and eventually condensation and precipitation. Vice versa, in the presence of diverging horizontal winds, descending air from aloft is the only mechanism to replace the diverging air near the surface. Thus, downward motion and compressional warming effectively reduce precipitation.

Despite the sound physical explanation and the modeling evidence provided by Pan et al. (2018) for the case of idealized offshore wind farms, there is no observational study of the effect of real offshore wind farms on precipitation. This is the research gap that the present paper will try to fill.

a) Control: Land effect only
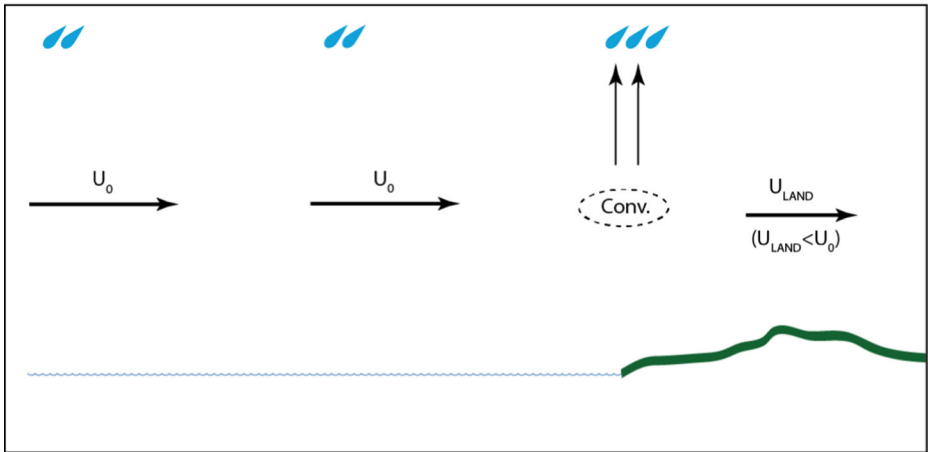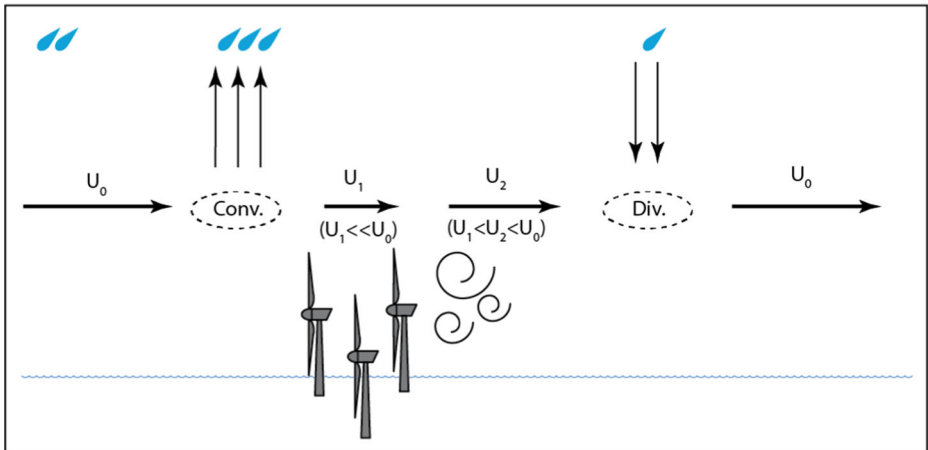

b) Offshore wind farm effect

Fig. 1 Sketch of the effects of divergence and convergence on precipitation for **a** the land effect only (control case), by which the sea–land transition causes convergence and enhanced precipitation at the shore due to changes in surface roughness, and **b** the offshore wind farm effect, by which the wake recovery causes divergence and reduced precipitation past the farm, near the shore. In reality, both effects **a** and **b** overlap and the net effect at the shore is, likely, lower precipitation than in **a**. The droplets represent precipitation intensity, while the spirals represent wake turbulence

2 Methodology

In this paper, we seek observational evidence of an effect of offshore wind farms on precipitation patterns near the coast (i.e., onshore). Based on time series of meteorological data (wind and precipitation), we aim to identify statistical differences in precipitation amounts in the vicinity of offshore farms before and after their construction ("Time periods"). Because of its empirical nature, our study relies on data availability and quality, resulting from thorough site selection and data cleaning processes (Section 2.2), as well as

on the definition of relevant metrics (Section 2.4). The statistical distribution of such metrics and the result of our analysis are provided in Section 2.5.

2.1 Time periods

The period of study is determined by available records at the weather stations and thus varies from one site to another. The two sites that were selected for this study are described in Section 2.2. For one of them, the time series ranges from January 1, 1995, to December 31, 2018; for the second site, the time series starts on January 1, 1997, and extends to December 31, 2018. Such time series are divided into three distinct periods:

1. The pre-farm period, which starts on January 1 (00:00) of the first year included in the time series (either 1995 or 1997) and ends on December 31 (23:00) of the year preceding the year during which the construction of the wind farms at each site began.
2. The construction period, which starts on January 1 (00:00) of the year during which the construction of the oldest farm (at each site) began and ends on December 31 (23:00) of the commissioning year of the latest farm at each site.
3. The post-farm period, which starts on January 1 (00:00) of the year following the commissioning year of the latest farm at each site and ends on December 31 (23:00), 2018.

To identify an effect of offshore wind farms on precipitation patterns, we compared pre-farm time series of precipitation data (see Section 2.2) with post-farm data and tested for statistically significant differences. The construction years were removed from the dataset to avoid noise and bias due to the progressive construction and commissioning of the turbines.

It is worthwhile to notice that both post- and pre-farm periods vary, by definition, from one site to the next and are likely to be of unequal length. Consequently, a one-to-one comparison of precipitation amounts or frequency distribution from these two periods would be inappropriate. Furthermore, there is evidence that rainfall patterns in the UK are affected by climatic oscillations in general, such as the North Atlantic Oscillation (NAO) (Fowler and Kilsby 2002) or El Niño (Pinault 2018), which operate on 5–10-year and 1.5–7-year cycles, respectively.

To address both the uneven lengths of the time series and the effect of oscillations, which translate into cycles and lagged responses in the data, we identified all permutations of four consecutive years at each site (referred to as "sub-periods" in this paper), in both pre- and post-farm periods and proceeded to compare all possible pairs at each site. Such comparisons were reproduced for each of the variables defined in Section 2.4.

2.2 Site selection

We used a difference-in-differences (DiD) approach involving both a "treatment" station (i.e., a meteorological site near an offshore wind farm) and a "control" station (i.e., a meteorological site near the treatment site but not affected by the wake of the wind farm).

Site selection resulted from a three-step process. First, we selected the offshore wind farms based on the following: those with 50 turbines or fewer must lie within 10 km from the shore, while larger farms (50–100 turbines) must lie within 20 km, to ensure that the wake-induced divergence zone (which is affected by the number of turbines) can reach the shore under, at least, some weather conditions. In addition, the wind farm must have been in operation for at least 4 years by the end of 2018 (i.e., since 2014 or before), as shorter periods may be affected by short-term climate oscillations.

Next, we selected the treatment sites based on the following criteria:

1. The meteorological station must be located at or near the shore in the proximity of an offshore wind farm;
2. The meteorological station must record precipitation, wind speed, and wind direction on an hourly basis, so that it is possible to isolate only those records with wind direction from the offshore wind farm toward the land (i.e., onshore wind). A meteorological station that only collects, for example, 12-h precipitation totals would not be adequate because the wind direction may shift during a 12-h period;
3. The meteorological data must be publicly available at no cost.

Lastly, a control site lying within 100 km from the treatment site and in the same climate district as the latter must be identified, to ensure that weather variables follow similar patterns at both locations. To be selected, the weather station at the control site must also record precipitation and wind data on an hourly basis and over the same time period as the treatment.

In 2018, only five countries in Europe had operational wind farms within 20 km from their shores (Denmark, UK, the Netherlands, Germany, and Sweden), but the UK was the only country to meet all criteria of the treatment/control site selection process. Out of the four potential treatment sites that were identified, only two could be coupled with an adequate control site, and thus were retained for this study. These two sites are located on the Western coast (Irish Sea) of Great Britain. These sites are referred to as Walney (Fig. 2a) and Crosby (Fig. 2b) and are named after the location of their weather stations (Met Office ID 1078 and 17309, respectively). Their geographical coordinates are (54.1247 N, 3.25657 W) and (53.497 N, 3.0563 W), respectively. Both sites share a common control site, Saint Bees, named after the location of its weather station (Met Office Id 1055). The geographical coordinates of this control site are (54.5177 N, 3.61345 W).

The Walney site actually encompasses four wind farms, all built between 2010 and 2014, and an additional wind farm, Walney Extension, which was commissioned in September 2018. In total, the Walney farm complex is composed of 327 wind turbines of various manufacturers and characteristics (Table 1). The post-farm years for Walney are 2015–2018. Note that Walney Extension was added during this post-farm period. This is acceptable as the Extension is located upstream from Walney 1 and 2, away from the shore; thus its effect, if any, would enhance the impact of Walney 1 and 2 on onshore precipitation, and not dilute it.

The Crosby site is mainly composed of the Burbo Bank wind farm, which was built between 2005 and 2007, and is located in the Liverpool Bay within 10 km from the treatment weather station (Crosby, ID 17309). Based on these construction dates, the post-farm years for this site are 2008–2018. Similar to Walney, the Burbo Bank farm underwent an extension (Burbo Bank Extension), whose construction started in 2014, for a full commissioning in April 2017. The effect of this extension, also located upstream from the original farm, if any, would enhance the precipitation drop during post-construction years. It is worthwhile noting that other wind farms are located west of Burbo Bank farm and are within the angle of influence of the latter on Crosby station (as shown in Fig. 2). However, these farms are located beyond the 20-km threshold identified as a requirement for site selection.

2.3 Data

The meteorological observations used in this study were downloaded free of charge from the UK Meteorological Office (Met Office hereafter). The Met Office Integrated Data Archive System (MIDAS) dataset was used for this study. It incorporates data from a network of
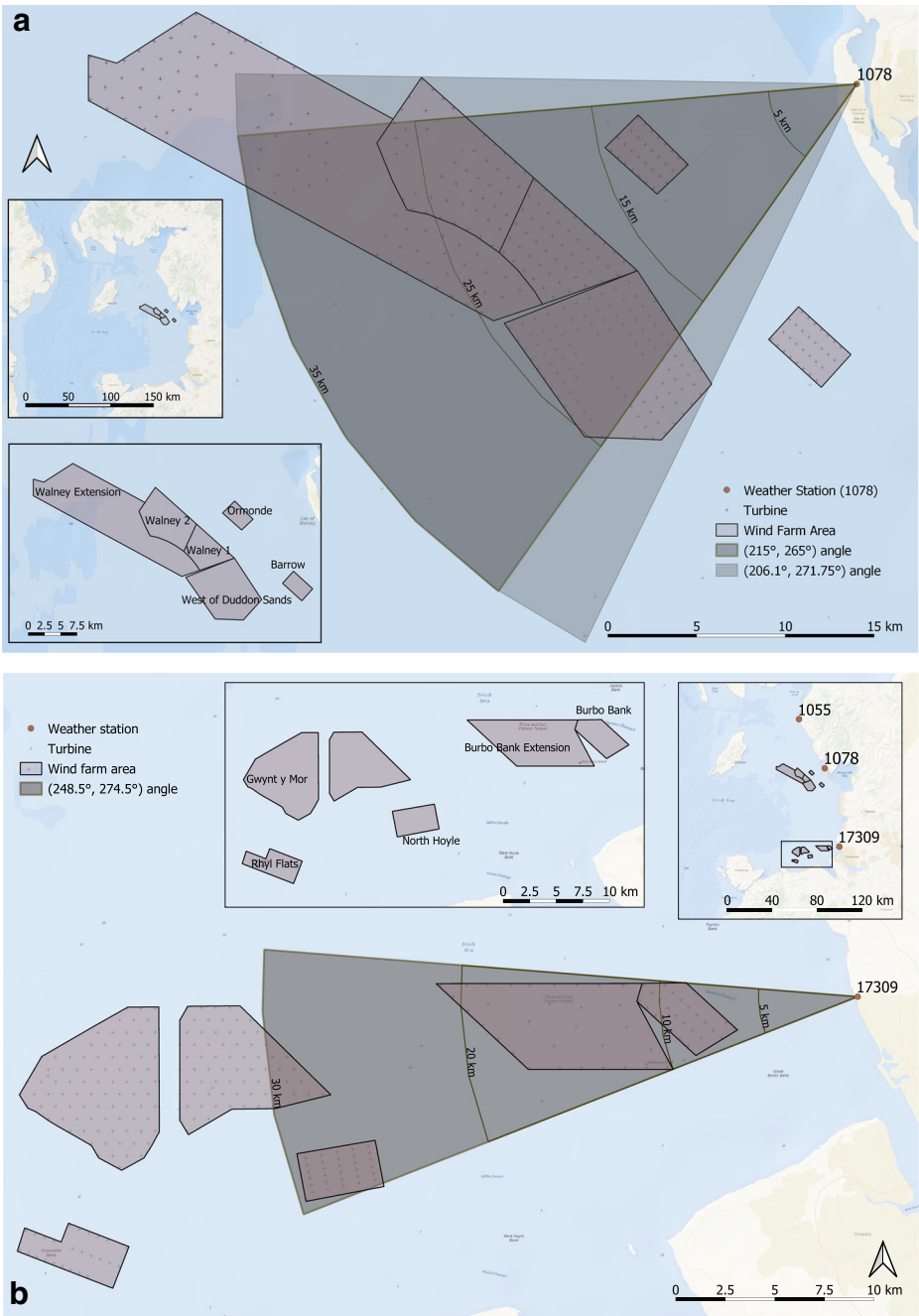
Fig. 2 Maps of the Walney (**a**) and Crosby (**b**) sites, showing the angles of influence of the wind farms

land and marine surface stations. A direct implication of the need for hourly records over long time periods (over 20 years for both sites) is that relatively few weather stations within

Table 1 Details of the two wind farm sites analyzed in this study, Walney and Crosby, from https://www.4coffshore.com/offshorewind/

Farm	Turbine type	Hub height (m)	Number of turbines	Rated speed (m/s)	Cut-in speed (m/s)	Cut-out speed (m/s)	Construction years
Walney (Site 1)							
Ordmonde	REpower 5 MW	90	30	13.0	3.5	30.0	2010–2012
Walney 1	SWT 3.6–107	83.5	51	16.5	3.5	25.0	2010–2011
Walney 2	SWT 3.6–108	90.15	51	12.0	3.0	25.0	2011–2012
West of Duddon Sands	SWT 3.6–120	90	108	12.0	3.5	25.0	2012–2014
Walney Extension	SWT 7.0–154	105	47	13.0	3.0	25.0	2017–2018
	V164 8.25 MW	105	40	13.0	4.0	25.0	
Crosby (Site 2)							
Burbo Bank	SWT 3.6–107	83.5	25	16.5	3.5	25.0	2005–2007
Burbo Bank Extension	V164 8.0 MW	105	32	13.0	4.0	25.0	2014–2017

the MIDAS network have been measuring precipitation at such high resolution and for such an extended period of time, which de facto limited the number of treatment and control sites which could be included in this study. The MIDAS database encompasses 17 different datasets, two of which were used here. Hourly wind direction and wind speed records were downloaded from the UK Mean Wind Dataset, which reports hourly 10-min averages of (1) wind speed (in knots) with an accuracy requirement of 1 knot or 10%, and (2) wind direction (in degrees, using the meteorological convention) with a 5° accuracy. Precipitation data were taken from the MIDAS Hourly Rainfall Data, in which the reported accumulation of rainfall is the amount of liquid precipitation plus the liquid equivalent of any solid precipitation. Such number is reported in millimeters per hour with an accuracy of 0.2 mm (or finer). All observations reported in the MIDAS database are subject to quality control by the Met Office. It was critical that stations located at selected sites be included in both datasets. The merging of the two datasets by station ID and by date resulted in some data point being dropped and in the final sample sizes reported in Table 2. Given that a calendar year contains 8760 hours, over the pre-farm period for Walney (15 years), the yearly average number of missing records is 300 (or 3%). Records with both wind speed and wind direction equal to 0 were interpreted as absence of wind for those particular hours and were dropped from the final samples.

Due to changing measurement technologies, the data in some cases were collected by means of different instruments present at the two sites, such that two or more observations could be reported for some of the hourly records. For the sake of consistency in comparing treatment–control pairs, only data with a message type of SREW (Synoptic Rainfall Europe West) were retained, as it was common to all stations considered in this study. This was done regardless of the magnitude of the values reported by SREW relative to other message types.

In this paper, the effect of offshore wind farms on onshore precipitation is studied by defining an angle of influence of the farms on the treatment sites. Such angle is used in the analysis to isolate hourly precipitation and wind speed records for which the wind blows from the farms. These angles (Fig. 2) are obtained by connecting each edge of the relevant offshore farms to the weather stations. The angles of influence for Walney and Crosby are

southwesterly (206.10°–271.75°) and westerly (248.50°–274.50°) respectively. However, at Walney, this angle had to be narrowed to (215.00°–265.00°) due to (1) the low resolution of the wind direction observations (5°), (2) the great distance from shore to the turbines located on the outskirts of the farm, (3) the low density of turbines at the edges of the farms, and (4) a suspected wind acceleration on the outskirts of the farm. Such modification of the angle of influence did not prove relevant at Crosby as it did not significantly affect the results of the comparison of pre- and post-farm precipitation data.

Looking at the percentage of hourly records with wind direction within the angle of influence of the farms (Table 2), it is worthwhile noting that, for each site, such percentages are stable across periods (variation is contained within 1%), although the periods are of different lengths. The treatment stations record more observations with wind direction contained in the range of influence of the farm than their respective control (+5% at Walney and +3% at Crosby).

The angle of influence is also reported on the wind roses and precipitation roses (Figs. 3, 4, 5, and 6), representing the joint frequency distribution of wind speed/direction and precipitation/direction, respectively, for both sites, as well as for the (common) control site. Such roses are useful to (1) characterize the weather patterns at a given site, (2) compare weather patterns during pre- and post-farm years at the treatment site, and (3) compare any noticeable pre-/post-farm difference at the treatment site with the same difference at the control site.

At Crosby (Fig. 4), wind with direction in the 248.50°– 274.50° range occurs about 13–14% of the time and is characterized by a relatively high frequency of very high speed winds (> 25 knots). During the pre-farm years, the frequency of the winds in the range of influence of the wind farm is slightly lower than in the post-farm years (although no obvious change in the wind speed is apparent). This could potentially be problematic in the context of a DiD analysis as the wind rose at the control station (Fig. 4b, d) undergoes no noticeable variation between pre- and post-farm years. At Walney (Fig. 3), however, the wind roses of both the treatment and the control stations appear relatively stable over time in the angle of interest with a satisfying alignment of such angle with one of the two dominant wind directions at the treatment, southwesterly (the other one being northwesterly). Wind with direction in the 206.10°–271.75° angle occurs about 22% of the time and is characterized by a relatively high frequency of medium to high speed winds (15–25 knots).

Likewise, the visual inspection of the precipitation roses (Figs. 5 for Walney and 6 for Crosby) only reveals minor changes in precipitation patterns over time and does not clearly

Table 2 Sample size (for pre- vs. post-farm years) at both sites and their control, for both unrestricted samples (total number of records for desired years) and restricted to data with wind direction within the angle of influence specific to each site

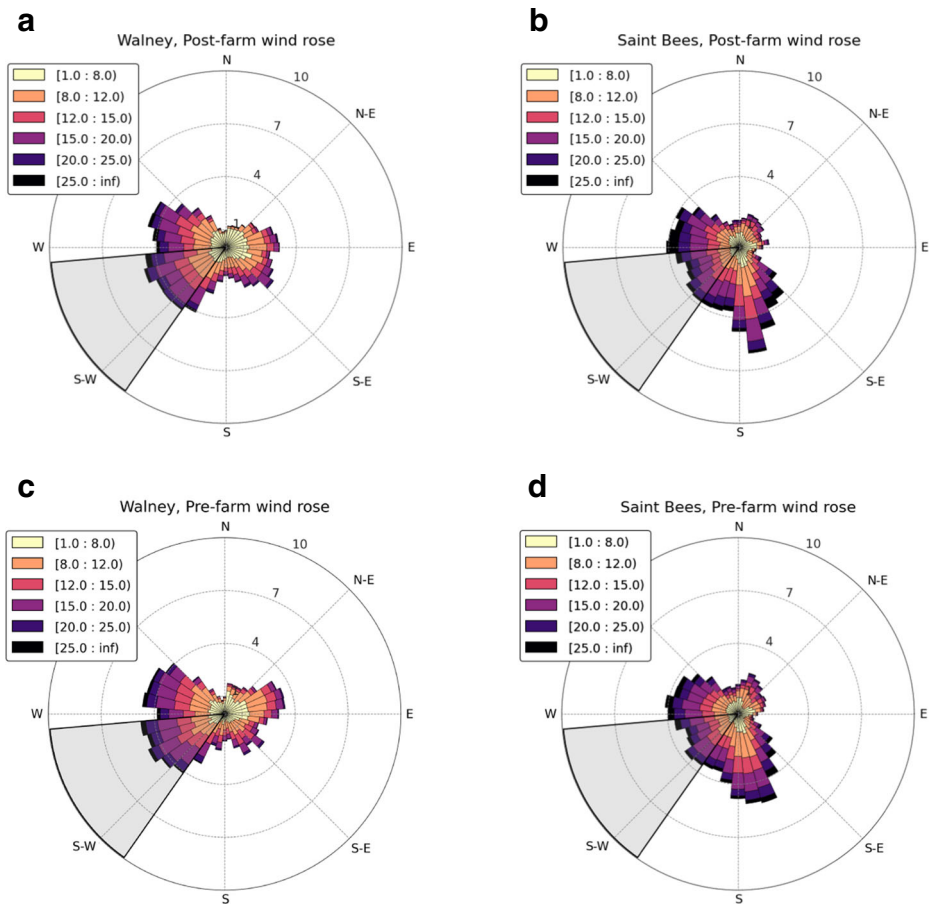|	Pre-farm		Post-farm	
	Total	Restricted	Total	Restricted
Walney				
Treatment	126,892	28,686 (22.61%)	34,839	7810 (22.42%)
Control	127,513	21,923 (17.19%)	34,780	6093 (17.52%)
Crosby				
Treatment	67,624	9047 (13.38%)	95,503	13,370 (14.00%)
Control	67,400	7008 (10.40%)	94,576	10,683 (11.30%)

Fig. 3 Post- (top) and pre-farm (bottom) wind roses at Walney (left), and at its control (right)

suggest any influence of the farm in the post-farm years. Some minor changes can be seen for easterly and southeasterly directions at both sites, not associated with the wind farm.

In brief, the visual inspection of the wind and precipitation roses, albeit revealing some variations over time, does not suggest any clear association between these changes and the construction of the wind farms. This is supported by the calculation of correlation coefficients between precipitation intensity (expressed in mm/h) and wind direction for pre- and post-farm years that were found to be of the order of 0.01. This indicates that a such relationship is not straightforward, which motivates the use of a DiD approach.

2.4 Variable definitions

As detailed in the Section 1, any potential impact of offshore wind farms on onshore precipitation patterns must arise from the wind farm wake, i.e., a region of reduced wind speed when compared with the surrounding areas. Therefore, we first seek evidence of a statistically significant difference in wind speed pre- and post-farm, more specifically, a
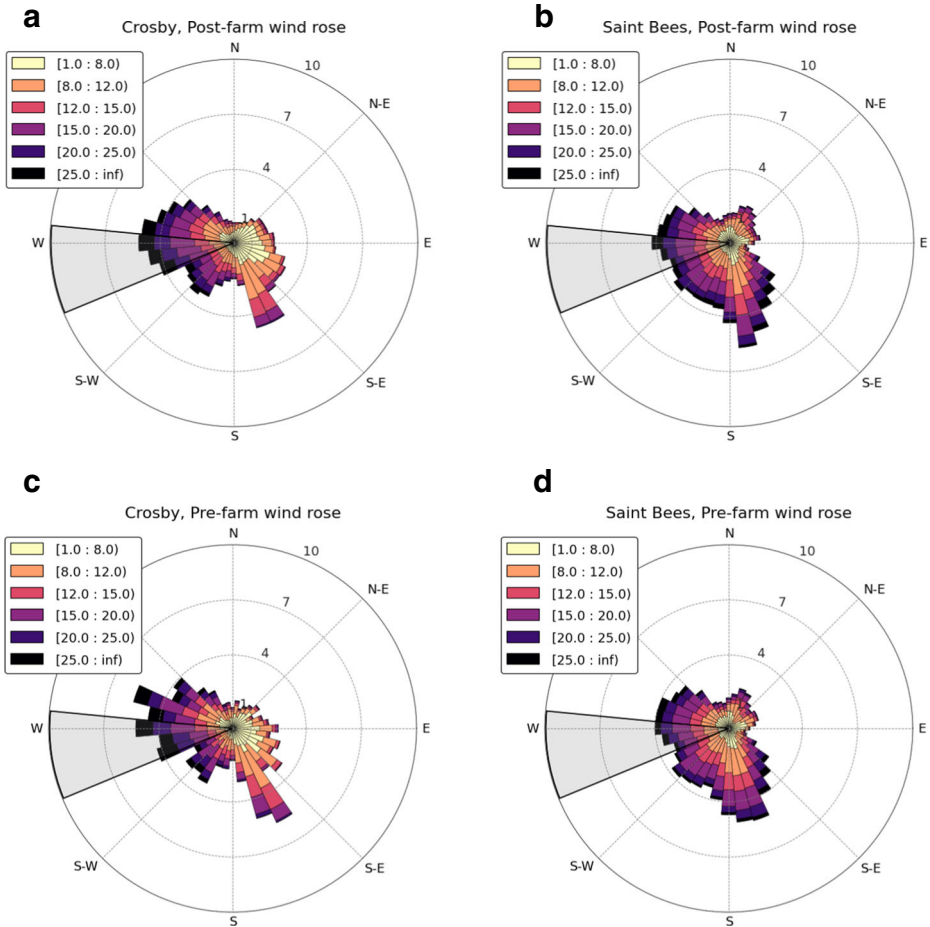
Fig. 4 Post- (top) and pre-farm (bottom) wind roses at Crosby (left), and at its control (right)

decrease in wind speed at the onshore location after the farm. To that end, we define for each subperiod (i.e., for each pre- and post-farm permutation), the average wind speed as:

$$\overline{U} = \frac{\sum_{h=1}^{N} U_h}{N},$$ (1)

where N is the number of valid hourly wind speed and precipitation records (for wind directions within the range of influence of the wind farm) over either the pre- or post-farm period of interest, and U_h is the wind speed recorded during hour h (in knots).

Next, in order to assess whether the expected precipitation reduction occurs with statistical significance, we define for each subperiod the average hourly precipitation rate (i.e., precipitation intensity) as:

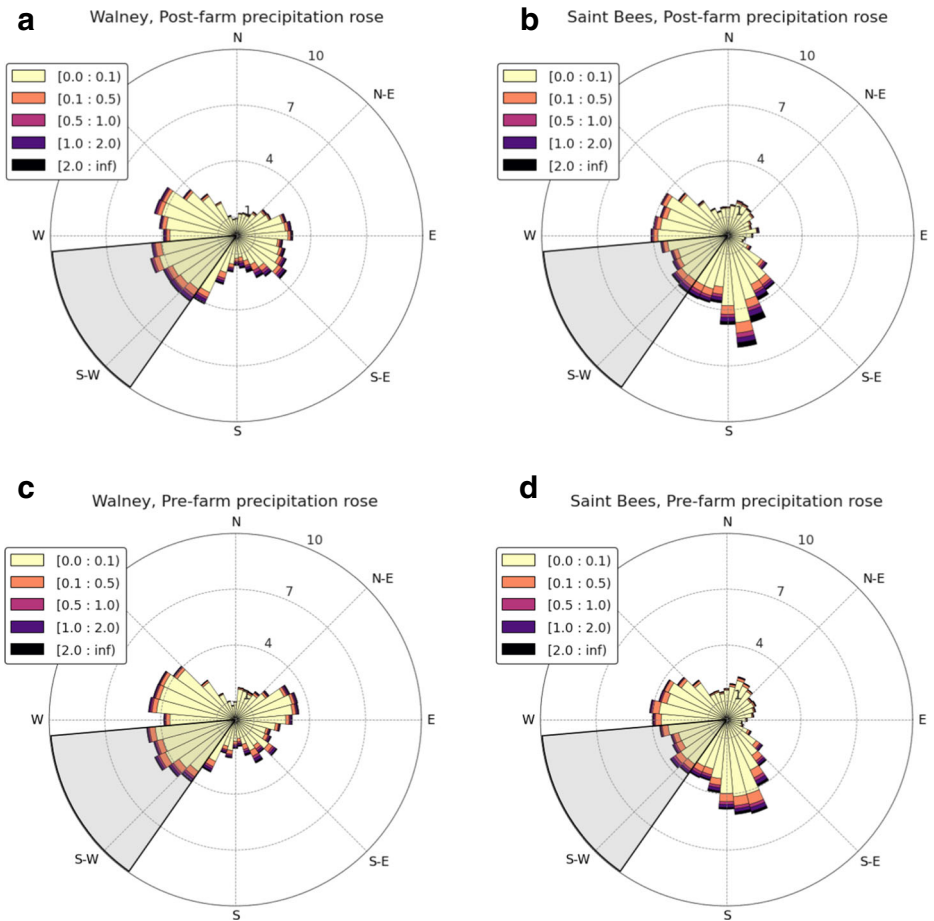$$\overline{P} = \frac{\sum_{h=1}^{N} P_h}{N},$$ (2)

Fig. 5 Post- (top) and pre-farm (bottom) precipitation roses at Walney (left), and at its control Saint Bees (right)

where P_h is the amount of precipitation recorded during hour h (mm/hr). Note that P_h was often 0, as no precipitation occurred frequently. Consequently, the values of $\overline{P}$ were rather small, which could potentially make the signal-to-noise ratio too small.

As such, we introduced a new positive-defined variable, called positive precipitation PP_h, the average of which is:

$$\overline{PP} = \frac{\sum_{h=1}^{N_p} P_h}{N_p}, \tag{3}$$

where N_p is the number of records with non-zero precipitation (i.e., $P_h > 0$) in the pre- or post-farm period of interest for wind directions within the range of influence of the wind farm. Since $PP_h = P_h$ when $P_h > 0$, thus N_p is always lower than N.
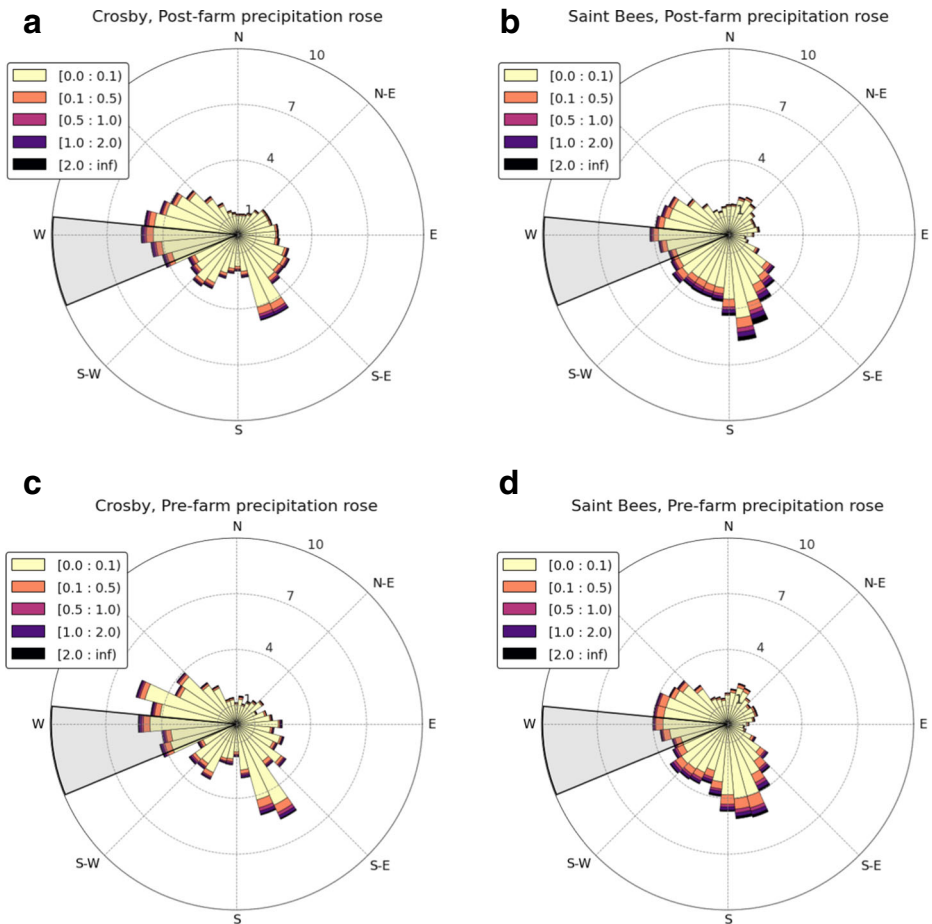
Fig. 6 Post- (top) and pre-farm (bottom) precipitation roses at Crosby (left), and at its control Saint Bees (right)

2.5 Statistical tools

Due to both uneven time periods pre- and post-farm and evidence of a cyclical effect in meteorological data, we identify permutations of four consecutive years pre- and post-farm, use them to generate subsamples of the data, and compare the distribution of the variables for every possible permutation pair at each site:

- At Walney, only one 4-year permutation was available post-farm (2015–2018) and 12 in the pre-farm period 1995–2009.
- At Crosby, eight 4-year permutations were identified post-farm (2008–2018) and five in the pre-farm period (1997–2004).

Initial methodological considerations involved calculating the mean (of each variable) over each pre- and post-farm subperiod and testing for statistical difference using (1-sample) non-parametric t tests and (2-sample) K–S tests. The results of such analysis, not

shown here, were counterintuitive as they revealed simultaneously a statistically significant decrease in wind speed and a statistically significant increase in post-farm precipitation. After further analysis, these results were actually found to be evidence of the existence of an underlying phenomenon, possibly related to climate variability, leading to enhanced precipitation in the more recent years. Such a phenomenon would thus undermine our results.

In order to account for such a phenomenon, we developed a DiD methodology in which the construction of an offshore wind farm is assimilated to a treatment, the net effect of which is assumed to be a decrease in both wind speed and precipitation. Such an analysis requires an adequate control station (i.e., a station located in the vicinity of the treatment site that is not affected by the presence of a farm). Should a phenomenon of enhanced precipitation over time exist, it would equally influence precipitation distributions at both the treatment and the control sites. With a DiD analysis, such an effect can be subtracted out (Table 3). For each pair of pre- and post-farm subperiods, the net effect of the farm is calculated by subtracting the difference in pre- and post-farm means of variable X at the control station from the difference in those means at the treatment station (either Walney or Crosby).

3 Results

3.1 Wind speed frequency distribution changes

As a preliminary analysis, we compared the wind speed and precipitation distributions pre- and post-farm at both sites. At Walney (Fig. 7), the average wind speed (restricted sample) drops from 13.43 knots pre-farm to 12.70 knots post-farm, while at the control the mean speed increases from 13.97 to 14.25 knots during the post-farm years. At Walney, the Weibull fits on the control and treatment observed wind speeds are very similar in the pre-farm period. However, in the post-farm period, the Weibull fit of the treatment data clearly peaks at a lower speed than in the control, while the control curve is slightly shifted to the right. The larger difference between the means and the peaks in the two curves post-farm than pre-farm suggests a wind speed reduction at Walney after the wind farm.

Likewise, at Crosby (Fig. 8), the mean speed drops from 17.86 to 16.99 knots post-farm while its control experiences an increase in that mean from 14.47 to 15.16 knots over the same period. Wind speed is on average higher at the treatment station than at the control (17.86 knots vs. 14.47 knots pre-farm, a difference of 3.4 knots out of 14.47 knots, or 23%). The difference is reduced in the post-farm years compared with the pre-farm context (a difference of 1.8 knots out of 15.15 knots, or 12%), which again supports the hypothesis that wind speed is even lower at Crosby than at the control site post wind farm.

Table 3 Schematic matrix of a DiD computation

	Pre-farm	Post-farm
Treatment	$\overline{X}_{t,pre}$	$\overline{X}_{t,post}$
Control	$\overline{X}_{c,pre}$	$\overline{X}_{c,post}$
	Net effect of the treatment	
	$(\overline{X}_{t,post} - \overline{X}_{t,pre}) - (\overline{X}_{c,post} - \overline{X}_{c,pre})$	

Fig. 7 Pre-farm (bottom) and post-farm (top) frequency distributions of hourly wind speed at Walney and at its control site (Saint Bees)

3.2 Precipitation frequency distribution changes

The frequency distributions of hourly precipitation at the two treatment sites (Walney and Crosby) vs. their control (Saint Bees) show that all three sites, regardless of the angle of influence, experience enhanced precipitation over time (not shown). This could be empirical evidence of weather oscillations like the NAO. Indeed, a review of the observed
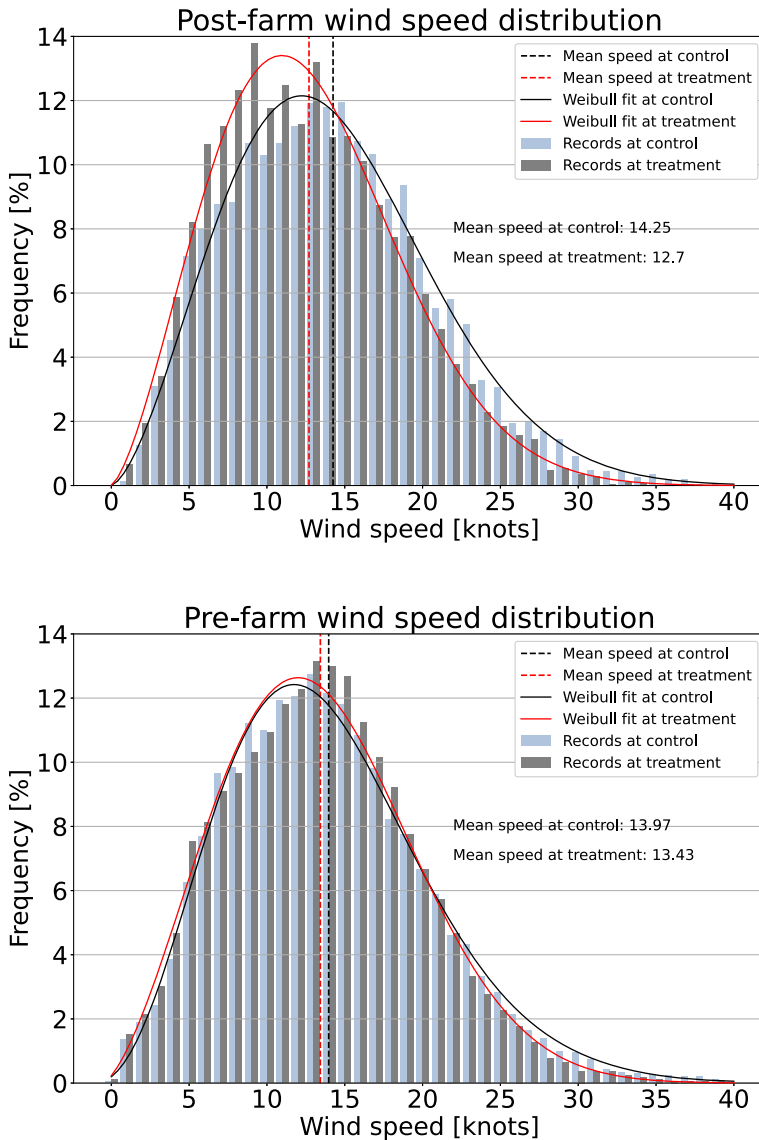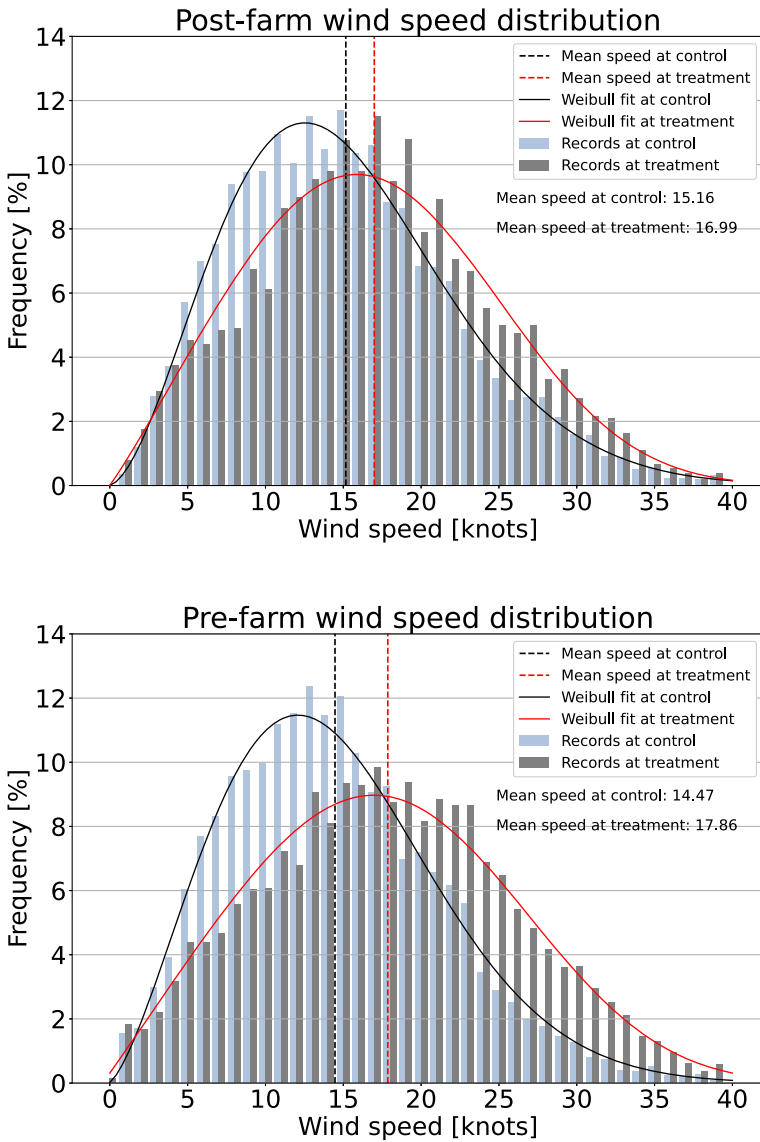
Fig. 8 Pre-farm (bottom) and post-farm (top) frequency distributions of hourly wind speed at Crosby and at its control station (Saint Bees)

trends in the NAO index over the western part of the UK has revealed an increased frequency of winter (and yearly) average negative index values, often correlated with enhanced precipitation.

At Walney (Fig. 9), the average hourly positive precipitation increases by 8% (from 0.73 mm/h pre-farm to 0.79 mm/h post-farm), while its control experiences a 19% increase (from 0.72 to 0.86 mm/h) over the same period. Similarly, at Crosby (Fig. 10), such average

Post-farm precipitation distribution

Pre-farm precipitation distribution

Fig. 9 Pre-farm (bottom) and post-farm (top) frequency distributions of hourly positive precipitation at Walney site and at its control station for the wind directions within the angle of influence of the Walney wind farms

increases by 2.6% (from 0.77 to 0.79 mm/h), while its control experiences a 15% increase (from 0.61 to 0.70 mm/h) over the same period. The fact that the increase in precipitation post-farm is greater at the control site than at both treatment sites is an indication that the wind farm might be indeed reducing the precipitation at the treatment sites, although less than the increase due to the NAO trends. A DiD approach will be able to isolate the effect of the farm, as described in the next section.
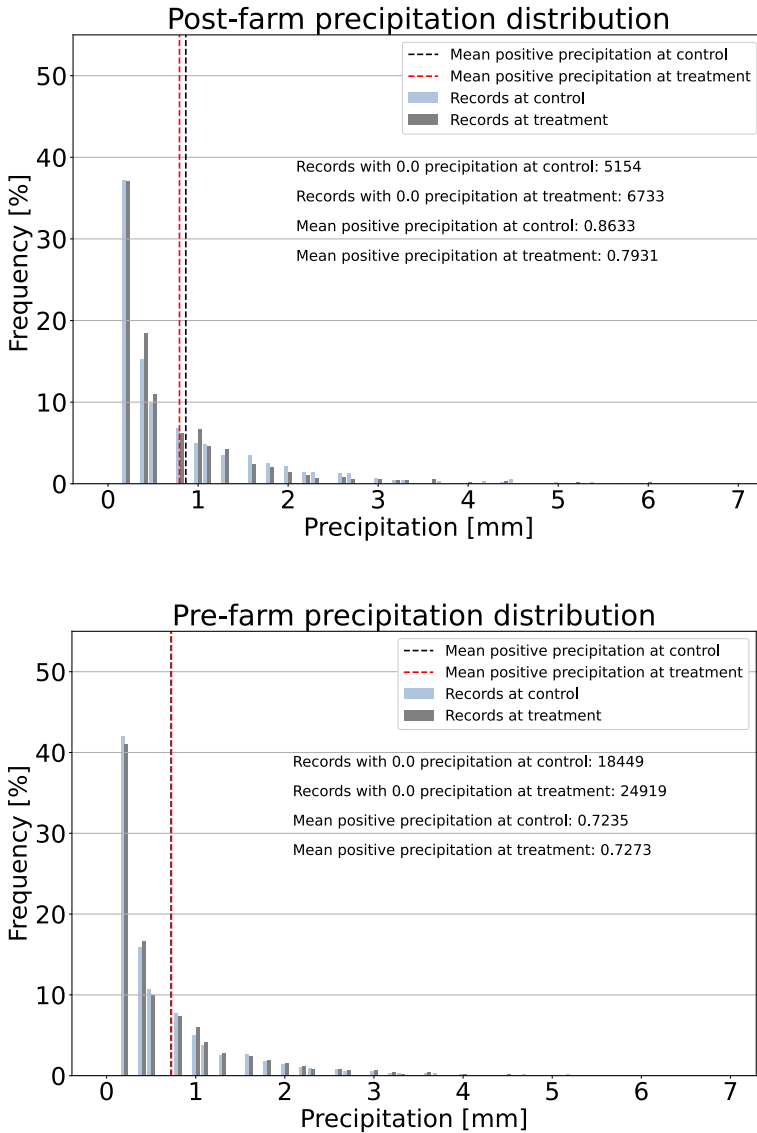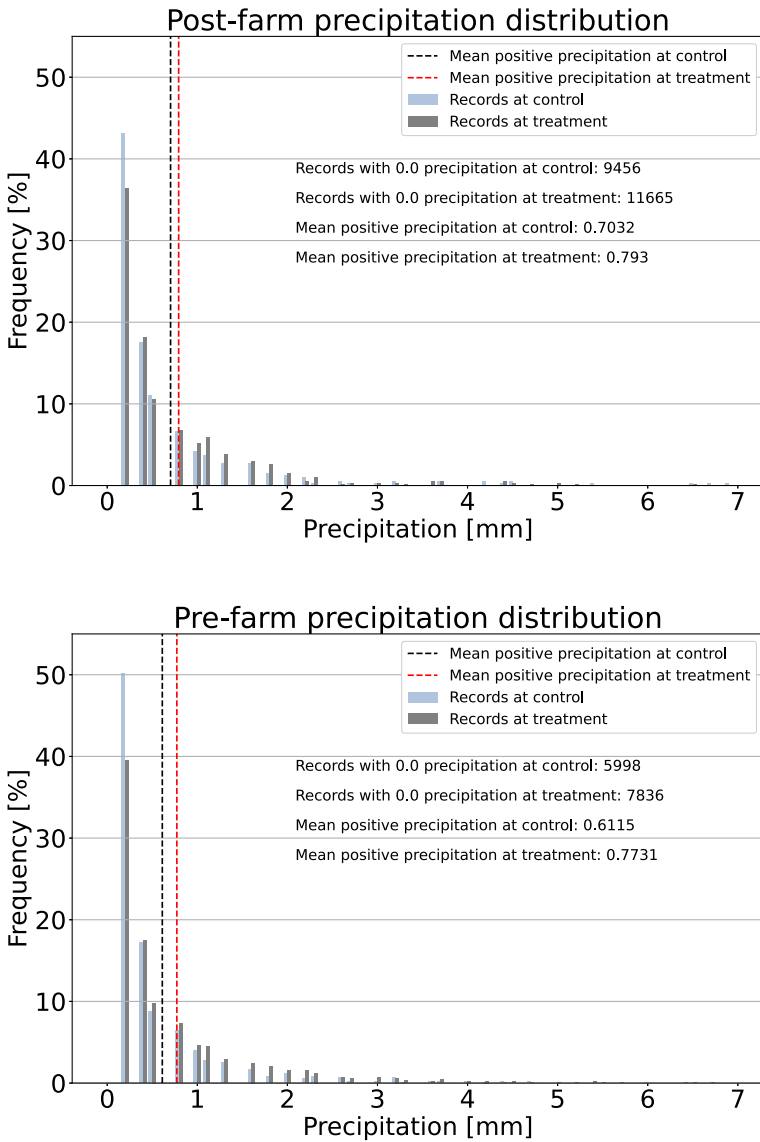
Fig. 10 Pre-farm (bottom) and post-farm (top) frequency distributions of hourly positive precipitation at Crosby site and at its control station for the wind directions within the angle of influence of the Burbo Bank wind farms

3.3 Difference-in-Differences

Following Table 3, we computed pre- and post-farm averages for treatment and control stations (Tables 4 and 5). At Walney, each pre-farm subperiod of four consecutive years is compared with the entire post-farm period (also 4 years). At Crosby, each one of the eight post-farm subperiods is compared to each one of the five pre-farm subperiods.

At Walney (Table 4), the treatment subsample contains systematically more observations than its control counterpart for every pre- and post-farm subperiod. The discrepancy between the sample size of each pair is maintained over the time series, which is an indication that the treatment does not significantly affect the wind direction. Such an assumption is necessary in the context of DiD as proper analysis design requires for the treatment to only affect one characteristic of the data, hence controlling for all other parameters. In other words, the treatment is here assumed to either affect wind speed or precipitation but not the wind direction, which determines data point selection and sample size. Therefore, it is assumed, and supported by the computed sample sizes, that the construction of the wind farms does not redistribute meteorological records around the wind roses of the treatment. It is worthwhile noting however that for the two precipitation variables, post-farm averages are larger for both the treatment and control, which here, again, provides evidence of an upward trend in precipitation amounts in Western UK in the recent years.

At Crosby (Table 5), visual inspection of the calculated average values is made difficult due to the existence of more than one post-farm subperiod. Yet, it can be observed that, for the treatment, the three highest wind speed averages are associated with three (out of five) pre-farm subperiods while the five lowest ones all correspond to post-farm subperiods. Yet, four of the five highest values observed at the control station are associated with pre-farm years. On the other hand, the presence of an upward trend in the precipitation variables is less clear at Crosby than at Walney—the range of average values for the two precipitation variables is similar before and after the farm was built.

The net effect of the treatment on all three variables studied was calculated for each pre- and post-farm pair of subperiods at both sites by subtracting the post-/pre-farm difference in the variables mean at control from the post-/pre-farm difference in the mean at the treatment. Results are reported in Tables 6 and 7 for Walney and Crosby, respectively.

At Walney (Table 6), the construction of the farm led to a decrease in wind speed during post-farm years ranging from -1.276 to -0.577 knots, regardless of the pre-farm subperiod used for the computation. As for precipitation, the calculated DiD coefficients indicate a negative net effect of the treatment (construction of offshore wind farms) for a great majority of cases, regardless of the variable studied and for the majority of the subperiods among the pre-farm years. In fact, the only exceptions are three subperiods (2001–2004, 2002–2005, and 2003–2006) for average hourly precipitation. Incidentally, these subperiods are associated with three of the five lowest wind speed DiD coefficients (all three being less than 1 knot in absolute value).

At Crosby (Table 7), the results of the DiD analysis are clear for wind speed but somewhat less coherent for precipitation. The 4-year wind speed averages recorded after the farm was built are lower than those recorded before. A total of 5 (pre-farm subperiods) × 8 (post-farm subperiods) pairs were compared as part of the study. All 40 DiD coefficients calculated for speed were negative with a magnitude ranging from -0.916 knots for the lowest bound (2000–2003 vs. 2011–2014) to -2.08 knots for the highest (1997–2000 vs. 2015–2018).

Yet, the signal of an effect of the farm on hourly precipitation amounts is more diluted than at Walney. For $\overline{P}$, 14 coefficients out of 40 were negative and in the order of a thousandth to a hundredth of a millimeter drop; 26 coefficients were positive but with value in the same order of magnitude. Regarding $\overline{PP}$, 28 coefficients came out negative, among which, all five coefficients calculated for post-farm years 2010–2013, 2011–2014, 2012–2015, and 2013–2016. For the remaining five post-farm subperiods, coefficients were negative only when compared with pre-farm years 1997–2000 and 1998–2001.

Table 4 Pre- and post-farm averages (with number of records reported in parentheses) of wind speed ($\overline{U}$), hourly precipitation ($\overline{P}$), and positive precipitation ($\overline{PP}$) for treatment and control at Walney

Period	$\overline{U}$ Walney	Control	$\overline{P}$ Walney	Control	$\overline{PP}$ Walney	Control
Post-farm:						
2015–2018	12.703	14.249	0.109	0.133	0.793	0.863
	(7810)	(6093)	(7810)	(6093)	(1077)	(939)
Pre-farm:						
2006–2009	14.355	14.336	0.091	0.108	0.696	0.729
	(8433)	(6780)	(8433)	(6780)	(1104)	(1006)
2005–2008	13.387	14.355	0.094	0.114	0.706	0.768
	(8295)	(6461)	(8295)	(6461)	(1101)	(963)
2004–2007	13.204	14.147	0.098	0.112	0.732	0.723
	(7887)	(6119)	(7887)	(6119)	(1051)	(944)
2003–2006	12.977	13.772	0.090	0.116	0.707	0.748
	(7671)	(5812)	(7671)	(5812)	(981)	(897)
2002–2005	13.082	13.696	0.092	0.118	0.742	0.783
	(7746)	(5761)	(7746)	(5761)	(960)	(871)
2001–2004	13.022	13.300	0.097	0.123	0.750	0.787
	(7611)	(5579)	(7611)	(5579)	(980)	(875)
2000–2003	13.194	13.564	0.099	0.120	0.750	0.777
	(7528)	(5809)	(7528)	(5809)	(991)	(897)
1999–2002	13.614	13.981	0.101	0.120	0.743	0.774
	(7994)	(5858)	(7994)	(5858)	(1084)	(910)
1998–2001	13.754	14.060	0.103	0.126	0.748	0.673
	(7853)	(5743)	(7853)	(5743)	(1081)	(1073)
1997–2000	13.708	14.143	0.106	0.124	0.763	0.651
	(7625)	(5850)	(7625)	(5850)	(1063)	(1110)
1996–1999	13.467	13.783	0.098	0.113	0.720	0.624
	(7103)	(5177)	(7103)	(5177)	(964)	(936)
1995–1998	13.534	13.804	0.099	0.117	0.738	0.636
	(6560)	(5030)	(6560)	(5030)	(882)	(923)

The absence of a clear signal of a negative impact of the treatment on precipitation at Crosby motivated the conduction of t tests on the distribution of calculated DiD coefficients for all three variables at both sites. To evaluate the statistical significance of these coefficients, we tested, for each variable at each site, the null hypothesis $\overline{X} = \mu_0 = 0$ (i.e., the mean DiD coefficient is 0 for variable X) versus the alternate hypothesis that $\overline{X} < \mu_0$ (i.e., negative mean DiD coefficient indicating a negative impact of the treatment on variable X). The results of these tests are reported at the bottom of Tables 6 and 7 for Walney and Crosby, respectively.

At Walney, the null hypothesis was rejected for all three variables with p values lower than 0.02 at 5% significance (Table 6), which indicates strong support for a net negative impact of the treatment on both precipitation and wind speed. At Crosby, the t test results support evidence of a significant negative impact of the treatment (with 95% confidence)

Table 5 Pre- and post-farm averages (with number of records reported in parentheses) of wind speed ($\overline{U}$), hourly precipitation ($\overline{P}$), and positive precipitation ($\overline{PP}$), for treatment and control at Crosby

	$\overline{U}$		$\overline{P}$		$\overline{PP}$	
Period	Crosby	Control	Crosby	Control	Crosby	Control
Post-farm:						
2015–2018	16.841	15.325	0.096	0.075	0.793	0.703
	(4741)	(3797)	(4741)	(3797)	(575)	(405)
2014–2017	15.292	15.625	0.116	0.100	0.770	0.692
	(4611)	(3727)	(4611)	(3727)	(599)	(416)
2013–2016	17.535	15.853	0.097	0.075	0.738	0.709
	(4475)	(3720)	(4475)	(3720)	(588)	(394)
2012–2015	17.377	15.611	0.109	0.087	0.768	0.787
	(4628)	(3829)	(4628)	(3829)	(659)	(423)
2011–2014	17.482	15.385	0.112	0.100	0.746	0.829
	(4759)	(3941)	(4759)	(3941)	(716)	(476)
2010–2013	16.818	15.010	0.120	0.100	0.801	0.802
	(4693)	(3888)	(4693)	(3888)	(701)	(484)
2009–2012	16.809	15.014	0.111	0.098	0.827	0.776
	(5082)	(4032)	(5082)	(4032)	(684)	(509)
2008–2011	17.066	15.145	0.101	0.083	0.835	0.681
	(5251)	(4078)	(5251)	(4078)	(636)	(496)
Pre-farm:						
2001–2004	17.142	13.874	0.096	0.090	0.757	0.707
	(4652)	(3355)	(4652)	(3355)	(591)	(426)
2000–2003	17.237	14.223	0.100	0.090	0.799	0.748
	(4312)	(3553)	(4312)	(3553)	(542)	(427)
1999–2002	17.860	14.632	0.113	0.095	0.791	0.756
	(4448)	(3672)	(4448)	(3672)	(634)	(461)
1998–2001	17.970	14.922	0.118	0.098	0.813	0.619
	(4558)	(3766)	(4558)	(3766)	(661)	(593)
1997–2000	18.616	15.011	0.111	0.085	0.785	0.529
	(4395)	(3653)	(4395)	(3653)	(620)	(584)

on only wind speed (p value $< 10^{-10}$) and positive precipitation (p value $< 10^{-3}$). The alternative hypothesis of a negative mean DiD coefficient must be rejected for $\overline{P}$, as the calculated t-statistic is positive for this variable.

By construction, the presence of a small signal is harder to detect by studying variations in $\overline{P}$ than by studying variations in $\overline{PP}$. The fact that the null hypothesis could be rejected for both variables at Walney, while only for $\overline{PP}$ at Crosby is evidence that the magnitude of the effect of the treatment is stronger at Walney.

3.4 Location of the divergence zone

It is worthwhile noting that the measured drops in wind speed are greater at Crosby than at Walney ($-$ 1.45 knots vs. $-$ 1.09 knots, Tables 6 and 7). We suspect that such observable

Table 6 Net effect of the wind farm on precipitation at Walney for all pre-farm subperiods, including the values of the relevant parameters for the *t* test

Period	$\Delta \overline{U}$ (knots)	$\Delta \overline{P}$ (mm/h)	$\Delta \overline{PP}$ (mm/h)
Pre-farm:			
2006–2009	−1.732	−0.007	−0.037
2005–2008	−0.577	−0.003	−0.009
2004–2007	−0.604	−0.010	−0.079
2003–2006	−0.751	0.001	−0.029
2002–2005	−0.932	0.003	−0.029
2001–2004	−1.268	0.003	−0.033
2000–2003	−1.176	−0.002	−0.043
1999–2002	−1.180	−0.004	−0.039
1998–2001	−1.240	−0.001	−0.145
1997–2000	−1.111	−0.006	−0.182
1996–1999	−1.230	−0.009	−0.167
1995–1998	−1.276	−0.006	−0.172
t test:			
$\overline{X}$	−1.09	−0.003	−0.080
t	−2.791	−2.885	−2.703
t_{crit}	−1.685	−1.685	−1.685
p value	$< 10^{-7}$	0.010	$< 10^{-3}$
$\overline{X} < 0$?	Yes	Yes	Yes

difference is due the difference in the distance separating the farms from the weather station at each site. Indeed, the wind farms are located closer to shore at Crosby ($\sim$ 8 km for the first row of turbines) than at the Walney ($\sim$ 11 km for Ordmonde farm and $>$ 15 km for Walney farms). Consequently, we interpret the relatively greater drops in wind speeds observed at Crosby as resulting from the closer proximity between the recording station and the farm itself, as the wind speed deficit is likely stronger and the wake recovery limited, closer to the wind farm.

The divergence mechanism that is assumed to cause precipitation reduction onshore, however, requires that the wind accelerates after the wind farm and partially recovers some of its speed. Given this, sufficient distance between the farm and the shore is needed for the divergence zone to develop. To complicate the matter further, the high turbulence associated with the wind farm wake may interfere with the formation of the divergence zone, especially at high wind speeds, and push the divergence zone further downstream. Additionally, the impact of the underlying convergence mechanism (Fig. 1a) at the sea–land boundary may differ from one site to the other as the farm/shore distance at the two sites also differs. We suspect that the divergence zone cannot always form within the first $\sim$ 8 km past the farm and therefore cannot always be properly captured at Crosby, while it can at Walney.

To initialize an understanding of the relationship between divergence and distance from the farm, we repeated the DiD analysis presented above while restricting both the treatment and control samples (at both sites) to only records with speed greater than a threshold of 8 knots. The reason for a minimum threshold resides in the fact that a wake can only form downstream of a turbine if the wind speed at hub height is greater than the cut-in

Table 7 Net effect of the wind farm on wind speed and precipitation at Crosby for all pre- and post-farm subperiod pairs, including the values of the relevant parameters for the *t* test

Period	$\Delta \overline{U}$ (knots)	$\Delta \overline{P}$ (mm/h)	$\Delta \overline{PP}$ (mm/h)
Pre-farm (post-farm 2015–2018):			
2001–2004	−1.752	0.015	0.040
2000–2003	−1.497	0.011	0.040
1999–2002	−1.712	0.003	0.054
1998–2001	−1.532	0.001	−0.104
1997–2000	−2.089	−0.005	−0.166
Pre-farm (post-farm 2014–2017):			
2001–2004	−1.600	0.016	0.028
2000–2003	−1.346	0.012	0.028
1999–2002	−1.560	0.005	0.042
1998–2001	−1.380	0.002	−0.115
1997–2000	−1.938	−0.003	−0.178
Pre-farm (post-farm 2013–2016):			
2001–2004	−1.586	0.016	−0.020
2000–2003	−1.331	0.012	−0.020
1999–2002	−1.546	0.004	−0.006
1998–2001	−1.366	0.002	−0.164
1997–2000	−1.923	−0.004	−0.226
Pre-farm (post-farm 2012–2015):			
2001–2004	−1.501	0.016	−0.069
2000–2003	−1.247	0.012	−0.069
1999–2002	−1.462	0.005	−0.055
1998–2001	−1.281	0.002	−0.212
1997–2000	−1.839	−0.004	−0.275
Pre-farm (post-farm 2011–2014):			
2001–2004	−1.171	0.006	−0.133
2000–2003	−0.916	0.002	−0.133
1999–2002	−1.131	−0.006	−0.118
1998–2001	−0.951	−0.008	−0.276
1997–2000	−1.508	−0.014	−0.339
Pre-farm (post-farm 2010–2013):			
2001–2004	−1.460	0.013	−0.051
2000–2003	−1.205	0.009	−0.051
1999–2002	−1.420	0.002	−0.037
1998–2001	−1.240	−0.001	−0.194
1997–2000	−1.797	−0.006	−0.257
Pre-farm (post-farm 2009–2012):			
2001–2004	−1.473	0.007	0.002
2000–2003	−1.218	0.003	0.002
1999–2002	−1.433	−0.005	0.016

Table 7 (continued)

Period	$\Delta\overline{U}$ (knots)	$\Delta\overline{P}$ (mm/h)	$\Delta\overline{PP}$ (mm/h)
1998–2001	−1.253	−0.007	−0.142
1997–2000	−1.810	−0.013	−0.204
Pre-farm (post-farm 2008–2011):			
2001–2004	−1.346	0.012	0.103
2000–2003	−1.092	0.008	0.103
1999–2002	−1.307	0.000	0.117
1998–2001	−1.126	−0.002	−0.040
1997–2000	−1.684	−0.008	−0.103
t test:			
$\overline{X}$	−1.45	0.003	−0.080
t	−33.959	2.130	−4.394
t_{crit}	−1.685	−1.685	−1.685
p value	$< 10^{-10}$	0.020	$< 10^{-4}$
$\overline{X} < 0$?	Yes	No	Yes

wind speed. Looking at Table 1, the cut-in wind speeds varied by turbine model from 3 to 4 m/s. Also, weak wind speeds tend to form weak wakes, which are shorter and less likely to create a sufficiently coherent divergence field. As such, we used 5 m/s at hub height as the minimum threshold, which corresponds to approximately 4 m/s (8 knots) at 10 m, the height at which winds are measured, assuming a shear coefficient of 0.1. However, it should be noted that weather stations at selected sites can only record post-farm wind speeds which are likely to be lower than pre-farm speeds offshore as illustrated by Fig. 1.

Indeed, restricting the data to only the records with wind speed greater than 8 knots:

– Did not significantly alter the DiD coefficients for wind speed (variation of at most 0.2 knots with no changes in coefficient signs at both sites);
– Significantly improved the coefficients for $\overline{PP}$ at Walney (all coefficients remained negative with values gaining up to one order of magnitude depending on the cases);
– Significantly worsened the precipitation coefficients at Crosby (some coefficients previously negative became positive, with estimated values losing up to one order of magnitude for the majority of the cases).

This suggests that, at higher wind speeds, the location of the divergence zone moves further away from the farm (toward the shore), as a consequence of the longer, more turbulent wake. Vice versa at lower speeds, the turbulence is weak and the divergence zone is closer to the wind farm. At Walney, the distance from the farm is sufficient for the divergence zone to form near the shore for most wind speeds, but may lie too far from the shore at lower speeds. At Crosby on the other hand, the farm is much closer to the shore. Therefore, at high speeds, the weather station may still be located within the high-turbulence zone of the wake. For low wind speeds, the divergence zone is more likely to form near the shore; thus, the signal is clearer under such conditions than at high speeds.

4 Conclusions and future work

The results of the DiD analysis conducted at two sites located in western England—Walney and Crosby—have revealed evidence of a dual impact of constructed offshore wind farms on local (i.e., downstream and onshore) weather. First of all, as predicted by the theory, a drop in wind speed can be measured onshore at both study sites. The magnitude of the wind speed drop ranges from − 0.6 knots (measured at Walney for years 2015–2018 vs. 2005–2008) to − 2.1 knots (measured at Crosby for years 2015–2018 vs. 1997–2000), with an average value of − 1.1 knots at Walney (− 8% from a pre-farm wind speed average of 13.4 knots) and − 1.5 knots at Crosby (− 8% from a pre-farm wind speed average of 17.8 knots). Such outcomes confirm the slowing down of the wind after blowing through the farm. These observed post-farm decreases in wind speed affect onshore precipitation as a divergence zone is formed downstream from the farms.

Although wind accelerates past the wind farm, it may or may not completely recover its original speed (i.e., the undisturbed wind speed upstream of the farm) when it reaches the shore. We hypothesize that the divergence effect caused by such an acceleration enhances downward vertical motion which, in turn, suppresses precipitation. We found supporting evidence for this mechanism at Walney, where positive precipitation decreased by 0.080 mm/h on average, which represents a drop of 11% from a pre-farm precipitation average of 0.727 mm/h. At Crosby, positive precipitation decreased by 0.080 mm/h, corresponding to a 10.35% drop. Hourly precipitation decreased significantly at Walney, but not at Crosby.

The results of the DiD analysis conducted on this restricted sample are interesting as they tend to confirm the effect of the distance of the farms from shore on the location of the divergence zone relatively to the weather station. We propose that it takes about 10 km downwind of the farm for the divergence zone to form and the precipitation effects to be observed.

Future work should identify more treatment and control pairs, not only in the UK, but also in other countries. A larger sample is necessary to solidify the findings on wind speed and precipitation reduction and to possibly confirm the hypothesis of the minimum distance of ∼ 10 km for the divergence zone formation.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

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