

# Relationship between NAO and wind climate over Norway

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**ABSTRACT:** This study investigates the strength of the relationship between the large-scale atmospheric phenomenon known as the North Atlantic Oscillation (NAO) and the Norwegian winter wind climate. The relationship is measured through spatial and temporal correlations of wind climate measures derived from reanalysis datasets and the winter NAO index for the time period 1920 to 2010. Wind speeds exceeding specific thresholds, percentile wind speeds, and wind direction frequencies are correlated with the NAO index. The results show strong and significant correlations for median and strong wind speeds over southern Norway and along the western coast to about 68°N. The results also indicate that a positive NAO is strongly associated with increased frequencies of winds from the southwest and decreased frequencies of winds from the northeast. There is no significant relationship between wind climate and the NAO for the northernmost part of the country. Time series reflect a temporal variability in the strength of the relationship with the NAO, where a stronger relationship is found during time periods containing the most extreme NAO phases. Due to the lack of correlations in northern Norway, a correlation analysis with the Barents Oscillation, which is a dominating mode of variability over the Barents region, was also conducted, but yielded no strong and significant correlation at any point across Norway. The implications of the variation in correlations, particularly those associated with geography and choice of wind climate metric for wind energy production, are discussed.

**KEY WORDS:** Wind climate · North Atlantic Oscillation · Reanalysis · Wind energy · Norway · Barents Oscillation · Gale days

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## 1. INTRODUCTION

The North Atlantic Oscillation (NAO) is the leading mode of variability in the Northern Hemisphere atmosphere (Hurrell et al. 2003). It is characterised by a fluctuation in sea-level pressure (SLP) between the Arctic Basin and the mid-latitudes, traditionally measured between stations in Iceland and in the Azores, Gibraltar or Lisbon (Jones et al. 1997). Its index (NAOi) is a measure of the normalised difference in the strength of these pressure systems, where a positive (negative) NAOi represents a characteristically strong (weak) Azores High pressure system and a deep (weak) Icelandic Low (Hurrell 1995). The index can be described by principal component (PC) analysis, which identifies NAO variability through the leading empirical orthogonal function (EOF) of SLP

anomalies over the Atlantic sector (Rogers 1990). The NAO varies over interannual to decadal time scales, with no particular pattern, and is most pronounced during the winter months when the Northern Hemisphere atmosphere is most active. The definition of Northern Hemisphere winter varies throughout the literature (e.g. DJF: Rogers 1984, Dickson et al. 2000; DJFM: Hurrell 1995, 1996, Ely et al. 2013; NDJFM: Jones et al. 1997), but always includes December and January (Burningham & French 2013).

Shifts in the NAO produce large changes in air temperature, winds, storminess and precipitation across the Atlantic Ocean and surrounding continents during the winter months (Hurrell & Deser 2010). These climatic signatures are connected with the strength and location of the North Atlantic storm track, which, to a large extent, is controlled by the

NAO. A positive NAOi is associated with a north-eastward-displaced storm track, enhanced storm activity from Newfoundland into northern Europe (Rogers 1990, 1997, Hurrell & van Loon 1997), and more intense and frequent storms in the vicinity of Iceland and the Norwegian Sea (Serreze et al. 1997, Deser et al. 2000). Generally, the positive phase is associated with stronger-than-average surface westerlies across the Atlantic onto northern Europe. During negative index conditions, the storm track typically takes on a more east–west oriented path, leading to less frequent storm events and generally calmer winter-averaged wind conditions for northern Europe. The NAOi varies from month to month and winter to winter, but has shown a pronounced low-frequency behaviour over the longer record (Visbeck et al. 2001).

The Arctic Oscillation (AO) resembles the NAO in many respects and has been shown to be highly correlated with the NAO (Walker & Bliss 1932). However, the NAO pattern is restricted to the Atlantic region, whereas the AO's primary centres of action cover more of the Arctic, giving it a more zonally symmetric or 'annular' structure (Thomson & Wallace 1998, 2000). This mode of variability is a result of modulations in the strength of the polar vortex, and has also shown to be strongly coupled to zonal winds, surface air temperature and SLP fluctuations over the Northern Hemisphere. There has been some debate about its distinction from the NAO, and it has been suggested that the NAO is the regional manifestation of the AO (Hurrell 2003). Considering that the present study investigates climate restricted to Norway, we have chosen to focus on the NAO and to exclude the AO.

Several studies have explored the connections between wind climate, storminess and the NAO across Europe. Dickson et al. (2000) noted changes in wind conditions during the evolution from the extreme negative phase in the 1960s to the extreme positive phase in the early 1990s. Northeastward extension of the Atlantic storm track to Greenland, Iceland, and the Norwegian and Barents Seas (Serreze et al. 1997, Alexandersson et al. 1998) resulted in an extreme increase in the number of deep Atlantic storms observed. Pryor et al. (2005) investigated records of wind speeds over the Baltic and found significant increases in wind speed (and in particular the upper quartile) in the mid- to late 20th century, coinciding with the prevalent positive phase of the NAO. Pirazzoli et al. (2010) analysed wind records back to the 1950s along the westernmost European border between 44° and 64°N and found that average wind speed is the most significant for correlation with the

NAO, but that the degree of correlation changes spatially and temporally. Donat et al. (2010) used gale-day frequency (days on which wind speed exceeds a threshold of 34 knots [ $17.5 \text{ m s}^{-1}$ ]) as a measure of storm frequency, and showed that the majority of storm days are associated with westerly flow regimes and a positive NAO phase, and none with a strongly negative NAOi value. This concurs with findings from other similar studies (Busch et al. 1998, Raible 2007, Pinto et al. 2009), but Burningham & French (2013) showed that choice of wind climate measure and winter period had a significant impact on the extent to which wind climate and the NAOi are correlated. Using instrumental wind records from the British Isles, a range of wind measures (e.g. gale-day frequency, wind rose and percentile wind speeds), and different winter periods, they found that positive NAO phases are associated with an increased frequency of winds from the SW and a decreased frequency of winds from the NE, but that the connection with wind speed and storminess is far weaker, particularly in terms of extreme wind speeds. Of the winter periods they tested, DJFM and DJF yielded the largest number of strong and significant correlations.

The connection between NAO and climate variables in Norway is described in part in some Europe-wide analyses. Temperature and precipitation patterns forced by the NAO over northern Europe, including Norway, are characterised by warm and wet winters during positive phases of the NAO, and cold and dry winters during negative phases (see e.g. Hurrell 1995, Hurrell et al. 2003). Stenseth et al. (2002) described how this influences ecological patterns and processes in Norway (among other regions) through controls on growth, reproduction and migration. Uvo (2003) investigated the regional variability of the influence of the NAO on winter precipitation, and correlation analysis showed that precipitation along the length of Norway is strongly affected by the moist westerly Atlantic winds, which in turn are strongly related to the NAO. The strongest correlations were observed over SW Norway, whereas the northernmost region is only intermediately influenced by the NAO because the westerly winds reach this area less directly. Stenevik & Sundby (2007) noted that there is a high correlation between the NAOi and temperatures in Norwegian waters, where a high NAOi is associated with increased ocean temperatures, which they found to strongly influence productivity and distributions of fish stocks. Cherry et al. (2005) investigated the impact of the NAO on Scandinavian hydropower production, and showed that the early-to-mid-1990s concurred with a record

high electricity production (at that time), followed by a drop in 1996 (EIA 2013), coinciding with the shift from extreme positive to extreme negative phases between 1995 and 1996. In 1998, the NAO returned to a strong positive phase, and electricity production followed, with the highest number on record in 2000 (EIA 2013). This highlights the strong NAO impact on precipitation and temperature, and indeed energy production, in Norway.

Few publications focus explicitly on the relationship between the NAO and the Norwegian wind climate. Liléo et al. (2013) conducted a brief analysis comparing a spatially averaged wind index (variability of wind speeds compared to the long-term average) for Norway, based on reanalysis data from 1920 to 2010, with the NAOi over the same time period. Extended phases of positive or negative NAOi coincided with high or low wind speeds, respectively. The period 1976–1981 had unusually low annual wind speeds, coincident with a dip in the NAOi, the period 1989–1995 was characterised by unusually high annual mean wind speeds, associated with a large positive peak in the NAOi, and a decrease to the long-term mean occurred between 1990 and 2005, coinciding with a declining NAOi after the mid-1990s maximum. Thomas et al. (2009) also found that trends in wind speed indices in northern Europe from 1990 to 2008 compare well with the NAOi. Given the physical mechanisms of the NAO—how it affects the path and intensity of the North Atlantic storm tracks and the westerly wind belt—one can make assumptions of how it affects wind climate over Norway. During positive NAO phases, the northeastward shift of storm tracks, carrying more intense storms, would indicate increased frequency and intensity of westerly winds onto Norway, and especially the west coast. During negative NAO phases, the typically weaker weather systems of the storm tracks take on a more east–west oriented path, indicating generally calmer wind conditions over the whole of Norway.

The Barents Oscillation (BO), another wintertime atmospheric circulation pattern in the Northern Hemisphere, is also known to exert an influence on a geographical area that includes the north of Norway (Skeie 2000). The NAO is the leading mode defined by the first principal component (PC 1) of SLP variability over the North Atlantic sector. When considering this restricted region, Chen et al. (2013) found the BO to be the second PC, with its primary centres of action over the Barents Region and the North Atlantic Ocean and a centre with opposite sign over Greenland. The PC 2 showed a high and stable temporal correlation with the geostrophic zonal wind

over the Barents Sea, whereas correlation with the PC 1 (the NAO) was weak in this area.

Large swings in wind climate over longer timescales have important implications for wind energy production. A variation in annual mean wind speed of 3–7% equates to a variation in annual energy production of a wind farm of about 8–18% (Liléo et al. 2013). Longer periods of above- or below-average wind speeds do not only affect direct energy production, but also the estimation of future energy production, which is important for wind farm planning and operation.

The main questions in the present study are how and to which degree wind climate is connected with the NAO over Norway. A systematic correlation analysis between the NAOi and a range of metrics representing the Norwegian wind climate is undertaken at 30 locations across Norway. The primary objectives are 2-fold: first, to establish which metrics of winter wind climate are directly associated with shifts in the NAO, and second, to evaluate the spatial patterns in these relationships across the extensive latitudinal gradient of Norway. The relationship with the BO is also briefly investigated. Given that the NAO, and also the BO, produce large swings in wind climate over longer timescales, which most likely will affect wind conditions at coastal, non-complex sites in Norway ideal for wind energy production, the results obtained in this study are considered in the context of wind energy. The direct effects of the NAO on wind energy production will be further investigated in a follow-up paper.

## 2. DATA AND METHODS

The wind data used for analysis is extracted from NOAA's Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES) Twentieth Century Global Reanalysis version II (20CRv2) dataset (Compo et al. 2009). This spans about 140 yr, from 1 November 1869 to 31 December 2010, with 6 h temporal resolution on a global grid with  $2 \times 2^\circ$  resolution. The data are available at different pressure levels: at the 0.995 sigma level (42 m above ground level), and at tropopause height. Here, the 0.995 sigma level is used because it most closely corresponds to typical wind turbine heights. The 20CRv2 dataset has 56 ensemble members, and the ensemble mean is used in this study. Further information on this dataset may be found in Compo et al. (2011). Data from 30 evenly distributed grid points across Norway (see Fig. 3) were used to represent Norwegian wind climate.

The use of reanalysis data to represent long-term wind climate and to estimate long-term wind farm energy production, is a common practice (Liléo et al. 2013). As long-term local wind measurements from meteorological stations are often rather sparse and affected by inhomogeneities, reanalyses data were used here due to higher consistency, better quality and better spatial and temporal resolution. Intercomparison with independent radiosonde data indicated that the 20CRv2 data are generally of high quality, and Compo et al. (2011) concluded that the quality in the extratropical Northern Hemisphere throughout the century is similar to that of current 3 d operational numerical weather prediction forecasts. However, it should be noted that weaker synoptic variability was found in the ensemble-mean analysis for the earlier 61 yr (1887–1947) than for the later (1948–2008) period. This is due to the lower observational density as one goes back in time, and therefore caution is needed when using the ensemble mean for investigations of interannual variability and trends. The same was stated by Ferguson & Villarini (2012), who found evidence of inhomogeneities in the early record (prior to 1960) over the central USA. Looking at the homogeneity of the 20CR data globally (between 60° S and 60° N), Ferguson & Villarini (2014) found that 10 m wind speed is the climate variable most affected by non-climate breaks, but that northern Europe is the least affected. They do state though, that of the inhomogeneous records, often the last (most modern) homogeneous segment extends back to a very early date. Krueger et al. (2013) also found inconsistencies in the 20CR data for the first half of the 19th century when analysing long-term storm trends over the NE Atlantic, and support the argument that increasing station density over time has caused inhomogeneities during the earlier decades of the reanalysis. There is an ongoing debate concerning storm trends in the 20CR ensemble data, where Wang et al. (2014) state that the storm record is in fact homogeneous back to about 1893, where the 20CR cyclone trends are in agreement with observation-based geostrophic wind extremes (see also Wang et al. 2013). Liléo et al. (2013) found somewhat suspicious data for some grid points over Norway in the 20CR record, where the wind index was significantly lower prior to 1920 compared to the rest of the record and to other grid points. Those authors chose to exclude these data from their analysis. For the reasons discussed above, and the fact that Norway is the study region, we have chosen to focus on the 20CRv2 data between 1920 and 2010 in the present analysis.

Both the PC and the reanalysis station-based winter NAOi are used for analysis. The PC index was acquired from the Climate Data Guide at the National Center for Atmospheric Research (NCAR), and is calculated from SLP anomalies over the North Atlantic region defined by 20°–80° N and 90° W–40° E (NCAR 2014). The 20CR NAOi was acquired from NOAA's Earth System Research Laboratory, and is derived from the 20CR pressure data at grid points closest to Lisbon, Portugal and Reykjavik, Iceland (ESRL 2014). The BO index (BOi) calculated from the 20CRv2 data was acquired from H. W. Chen (pers. comm.). Chen et al. (2013) derived the BOi using NCEP/NCAR Reanalysis 1 data and PC analysis of SLP over the region 30°–90° N and 90° W–90° E. The same method has been applied here to the 20CRv2 data. All indices are evaluated for the DJF winter period and over the same time period as the reanalysis wind data (1920–2009).

In order to explore the relationship between winter wind climate and the NAO and BO, a selection of parameters representing time-averaged windiness and extremes were defined for correlation analysis (see Table 1). Initial analyses were undertaken on both DJF and DJFM winter periods. There was little difference in the pattern of correlations, but the DJF period exhibited a stronger association overall with the NAOi, and is therefore presented here, defined by the December year. Wind data was analysed to calculate 4 main metric types: (1) wind direction frequency distribution (i.e. wind rose), (2) percentile wind speeds, (3) speed-limited frequency (i.e. proportion of winter that a specific speed was achieved or exceeded) and (4) gale-day frequency (i.e. the number of days gale force winds were recorded). Wind speed thresholds used here are 4, 14, 17.5 and 25 m s<sup>-1</sup>. The values of 4, 14 and 25 m s<sup>-1</sup> were chosen for their association with the wind power industry; the cut-in and cut-out speeds for turbines are turbine-specific, but normally lie around 4 and 25 m s<sup>-1</sup>. Their maximum potential is achieved at the rated output speed, typically around 14 m s<sup>-1</sup> (WindPower program 2013). The value 17.5 m s<sup>-1</sup> was used as contextual comparison to related studies; it corresponds to the definition of a gale force wind (34 knots), a measure widely used in the literature to define storminess or very strong winds (e.g. Jenkinson & Collison 1977, Dawson et al. 2002, Donat et al. 2010).

A wind rose (directional frequency distribution) was calculated for specific wind direction quadrants (NE, SE, SW and NW). The 50th, 90th and 99th percentile wind speeds were calculated to provide measures of average and strong to extreme wind speeds (Pirazzoli

et al. 2010). These percentile wind speeds were also calculated for each wind rose quadrant. Analysis of the frequency of winds at or exceeding turbine-related speeds (4, 14 and 25 m s<sup>-1</sup>) was undertaken by calculating the proportion of wind data in each winter period that was at or above each speed threshold. Gale-day frequency is a standard measure representing the number of days (here within each winter period) when a gale force wind ( $\geq 17.5$  m s<sup>-1</sup>) is recorded (Limbert & Farman 1976). This is different to the speed-limited frequencies we also calculate here, which reflect the proportion of the wind data (here within each winter period) when specific wind speed thresholds (at 4, 14 and 25 m s<sup>-1</sup>) are exceeded. For all measures other than those associated with the wind rose quadrants, the westerly (vector mean wind direction from 0° to 180° N) and easterly (vector mean wind direction from 0° to 180° N) components were also evaluated. Correlation coefficients ( $r$ , supported by  $p$ -values) were calculated between all paired wind measures and the NAOi and BOi values for each of the 30 grid points. Both Pearson's linear and Spearman's rank correlations were calculated and compared to account for the varied nature of metrics and populations. The difference in the resulting correlation metrics was negligible, and subsequent analyses focused on Pearson's linear correlation results. Strong ( $|r| > 0.71$ ) and significant ( $p < 0.01$ ) cases were identified (Burningham & French 2013). Choice of the correlation coefficient limit for the identification of 'strong correlations' is application- and situation-dependent. The critical values for  $|r|$  (Pearson's) for this sample size (NAO pairs,  $n = 90$ ; BO pairs,  $n = 62$ ) are 0.21 and 0.27 at the 95 and 99% significance levels for

the NAOi tests and 0.25 and 0.32 for the BOi tests, but these coefficients correspond to weak associations (Fig. 1A). Strong relationships are usually associated with  $|r| > 0.5$  or  $|r| > 0.71$  (Weinberg & Abramowitz 2008, Jackson 2013), but the lower of these limits still includes a high degree of scatter (Fig. 1B), so here,  $|r| > 0.71$  is used to identify those sites where a well-defined relationship is evident (Fig. 1C); this limit is significant at both the 95 and 99% levels.

### 3. RESULTS

Given the expressed concern about the validity of the 20CRv2 data prior to 1920 (see Section 2), the analysis was originally carried out both with and without these data. Inclusion of the pre-1920 data led to a reduction in correlation significance, and given the concern of Liléo et al. (2013) and other authors, these data were excluded from the analysis throughout the rest of our study. Analysis was also initially carried out using both the 20CR station-based and PC-derived NAO indices (Fig. 2). The 20CR NAO yielded just one strong, significant correlation, but the pattern and distribution of correlation coefficients closely followed that of the PC-derived NAOi (Fig. 2A,B). As the PC-derived NAOi exhibited an overall improved correlation (across all metrics), subsequent analyses focused on this NAOi. A summary of the results of the wind climate correlations can be seen in Table 1, which lists the number of stations exhibiting a strong and significant ( $|r| > 0.71$ ,  $p < 0.01$ ) correlation between the climate indices (NAOi and BOi) and wind climate metrics. No strong and signif-

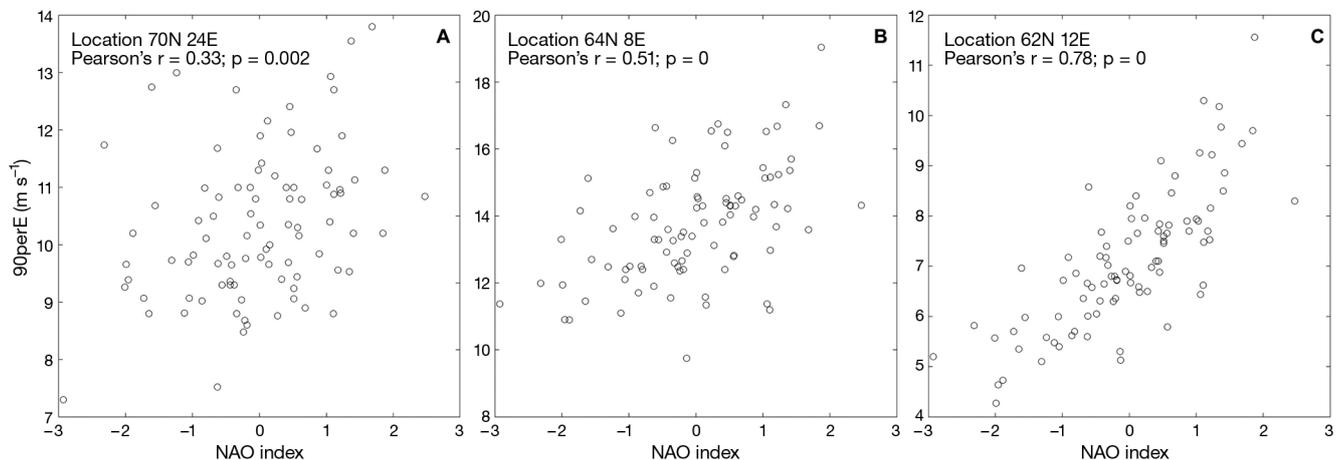


Fig. 1. Relationship between NAO index and the easterly component of the 90th percentile wind speeds (90perE) associated with different levels of Pearson's correlation coefficient, all significant at the 95% level. No relationship is evident in (A) which is defined by  $r = 0.33$ , while only a moderate relationship is evident in (B), defined by  $r = 0.51$ . A clear and strong relationship is illustrated in (C), defined by  $r = 0.78$

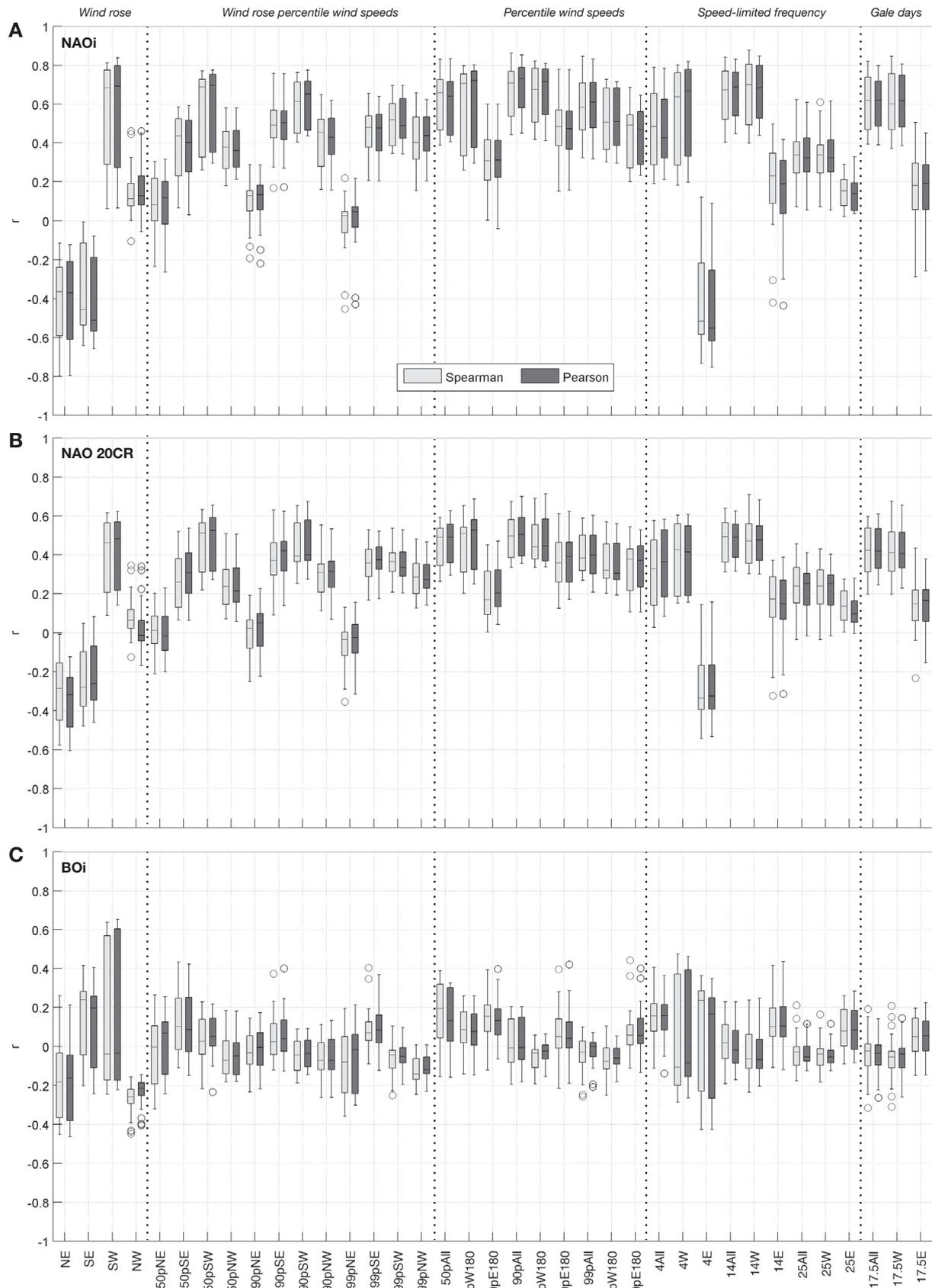


Fig. 2. Distribution of spatial correlation values (Pearson's and Spearman's  $r$ ) for association between climate indices and wind climate metrics across Norway (see Table 1). (A) Principal component (PC)-derived NAO index (NAOi). (B) Twentieth Century Global Reanalysis (20CR) station-based NAOi. (C) 20CR PC-derived Barents Oscillation index (BOi). The boxplots reflect the median (middle bar), interquartile range (box), minimum and maximum excluding outliers (error bars) and outliers (circles) in the correlation results

Table 1. Wind climate measures and the number of stations exhibiting a strong and significant correlation (Pearson's  $r$ ) between the NAO (1920–2009) and Twentieth Century Global Reanalysis Version II (20CRv2) data (–ve indicates negative correlation). There were no significant correlations between the Barents Oscillation (BO) index and 20CRv2 data

Variable code	Description	No. of stations with strong and significant correlation
<b>Wind direction frequency</b>		
NE	Wind frequency 0°–90° N	5 (–ve)
SE	Wind frequency 90°–180° N	0
SW	Wind frequency 180°–270° N	13
NW	Wind frequency 270°–360° N	0
<b>Wind direction percentile speeds</b>		
50pNE	50th percentile wind speed 0°–90° N	0
50pSE	50th percentile wind speed 90°–180° N	0
50pSW	50th percentile wind speed 180°–270° N	12
50pNW	50th percentile wind speed 270°–360° N	0
90pNE	90th percentile wind speed 0°–90° N	0
90pSE	90th percentile wind speed 90°–180° N	1
90pSW	90th percentile wind speed 180°–270° N	9
90pNW	90th percentile wind speed 270°–360° N	0
99pNE	99th percentile wind speed 0°–90° N	0
99pSE	99th percentile wind speed 90°–180° N	0
99pSW	99th percentile wind speed 180°–270° N	0
99pNW	99th percentile wind speed 270°–360° N	0
<b>Percentile wind speeds</b>		
50pAll	50th percentile wind speeds	11
50pW180	Westerly component of 50pAll	16
50pE180	Easterly component of 50pAll	0
90pAll	90th percentile wind speed	16
90pW180	Westerly component of 90pAll	16
90pE180	Easterly component of 90pAll	1
99pAll	99th percentile wind speed	8
99pW180	Westerly component of 99pAll	2
99pE180	Easterly component of 99pAll	0
<b>Speed-limited frequency</b>		
4All	Proportion of winter record $\geq 4 \text{ m s}^{-1}$	4
4W	Westerly component of 4All	12
4E	Easterly component of 4All	2 (–ve)
14All	Proportion of winter record $\geq 14 \text{ m s}^{-1}$	11
14W	Westerly component of 14All	13
14E	Easterly component of 14All	0
25All	Proportion of winter record $\geq 25 \text{ m s}^{-1}$	0
25W	Westerly component of 25All	0
25E	Easterly component of 25All	0
<b>Gale-day frequency</b>		
17.5All	Frequency of days when wind speeds $\geq 17.5 \text{ m s}^{-1}$	8
17.5W	Westerly component of 17.5All	9
17.5E	Easterly component of 17.5All	0

icant correlations were found between the BOi and wind climate measures, and the distribution of correlation values was much closer to zero than those found with the NAOi (Fig. 2C). The focus of the following analyses is therefore on the associations with the NAOi.

The NAOi is strongly associated with wind direction frequencies at around a third of the grid points analysed (Table 1). Fig. 3 shows the spatial pattern of correlation ( $r$ -value) strength for the wind rose direction quadrants (where the gradient from dark blue through white to dark red illustrate strong positive, through weak to strong negative correlations): stations with a significant correlation are marked with a white star. Wind direction frequency (wind rose) analysis shows that winds from the SW, followed by winds from the NE, are most strongly correlated with the winter NAOi. Winds from the SW are positively correlated (13 grid points exhibit significant correlations), whereas winds from the NE are negatively correlated (5 grid points exhibit significant correlations), which agrees well with the expectation that a positive NAO phase is linked to increased frequencies of winds from the SW and reduced frequencies of winds from the NE (e.g. Burningham & French 2013). Strong correlations for the NE quadrant are found mostly at points in the south or east (58°–62° N and 8°–12° E), whereas strong correlations for the SW quadrant reach further north up the western coast (58°–64° N and 6°–12° E). No strong significant correlations exist within the Arctic Circle.

Percentile wind speeds (50th, 90th and 99th) associated with these direction quadrants predominantly display positive correlations; stronger correlations are found in the SW quadrant and very weak correlations (close to zero) in the NE quadrant (not shown). Only the 50th and 90th percentile wind speeds exhibit significant correlations (positive), and these are only associated with winds from the SW, except for one point (62° N, 12° E) which also exhibits a strong correlation for the 90th percentile SE quadrant. The 99th percentile wind speeds in each quadrant show no strong and significant correlations, indicating that extreme wind speeds are poorly correlated with the NAOi. Spatially, there is a trend of weaken-

ing correlation with increasing latitude, and no significant correlations exist north of the Arctic Circle.

The temporal relationship between wind rose measures and the NAOi reveals that the wind climate of northern latitudes is more stable and rather more dominated by southwesterlies than in the south (Fig. 4).

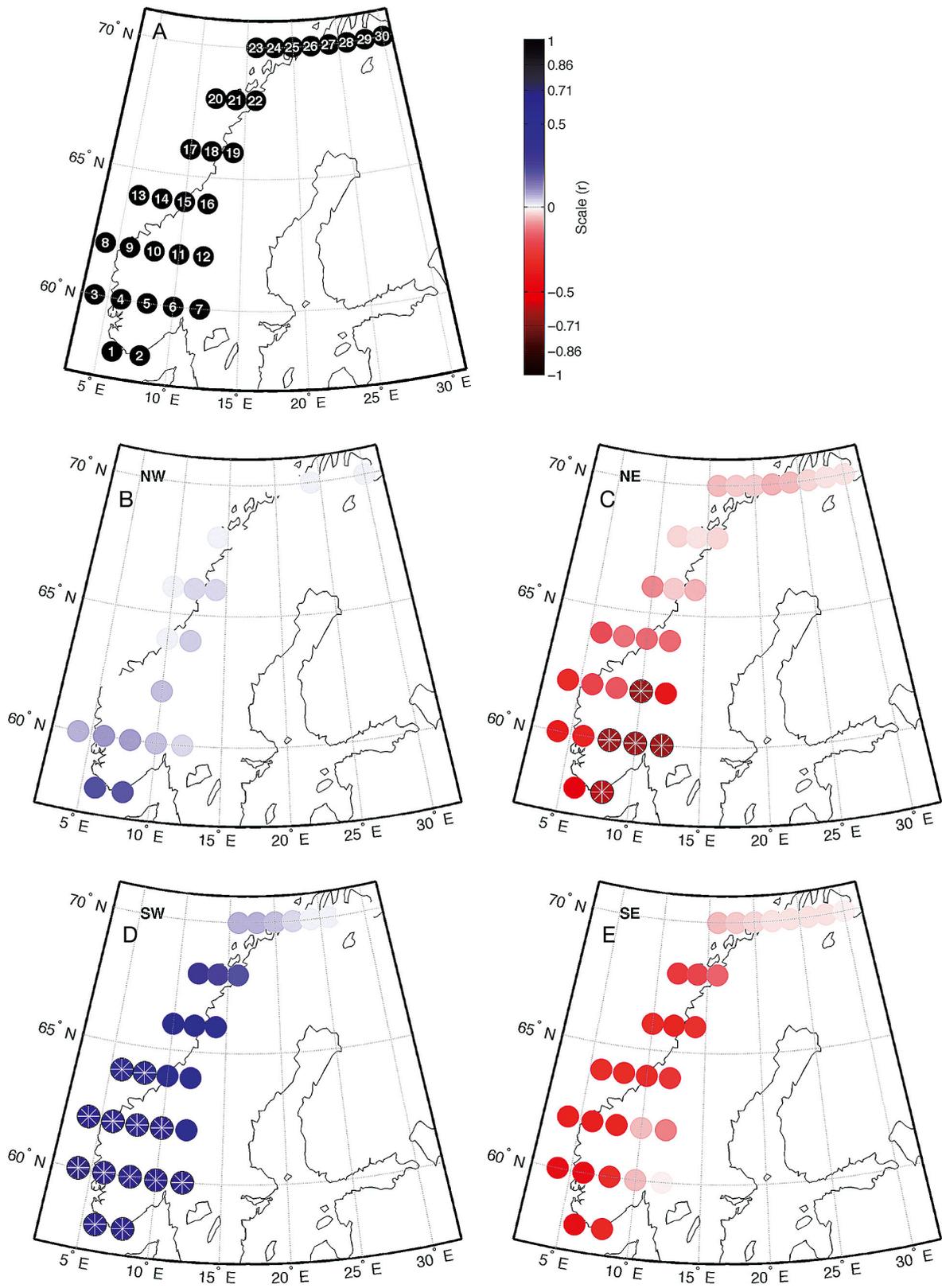


Fig. 3. (A) Location of grid points used to represent the Norwegian wind climate. (B–E) Spatial variation in the correlation between the NAO index and wind direction frequency (NW, NE, SW and SE). Starred grid points show a significant ( $p < 0.01$ ) correlation

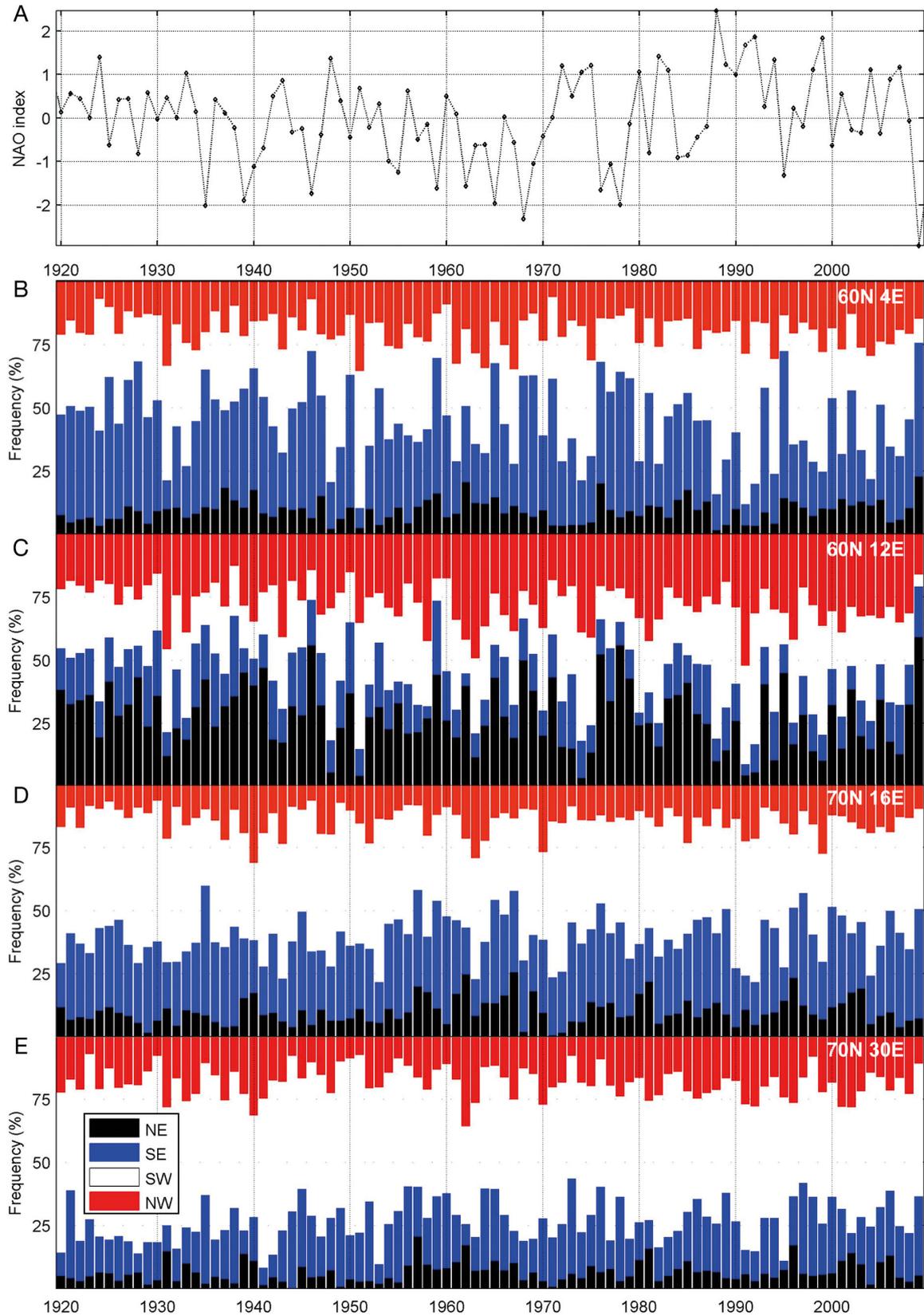


Fig. 4. Time series of (A) the NAO index, and (B–E) wind direction frequency (% of year) for 4 different grid points representing the far SW ( $60^{\circ}$  N,  $4^{\circ}$  E), SE ( $60^{\circ}$  N,  $12^{\circ}$  E), NW ( $70^{\circ}$  N,  $16^{\circ}$  E) and NE ( $70^{\circ}$  N,  $30^{\circ}$  E) of Norway. Wind directions are NE, SE, SW and NW

In the south, positive phases of the winter NAOi are matched with increased frequencies of winds from the SW and decreased frequencies of winds from the NE (such as the peaks around 1948 and 1974, and the strong positive phase of the late 1980s to early 1990s). Negative phases of the winter NAOi (such as the lows of the 1960s, late 1970s, 1995 and 2009) are associated with a significant reduction in winds from the SW, and an increase in wind from the SE (in the west) and NE (in the east). Frequencies of winds from the NW do not display an obvious connection with the NAOi for any region.

Within the Arctic Circle (68°–70° N), southwesterlies account for an average of 43–55% of the wind climate, in comparison to 28–38% in the south (58°–60° N) (Kruskal-Wallis test showed a significant difference,  $p < 0.01$ ). Conversely, northeasterlies account for 8–28% of the wind climate in the south in comparison to 6–11% in the north (Kruskal-Wallis test showed a significant difference,  $p < 0.01$ ). There is no significant latitudinal difference in the proportion of winds from the SE and NW across Norway. This difference in wind climate corresponds to a significant reduction in the temporal variability in wind direction frequency with increasing latitude, suggesting that the association between wind direction frequency and the NAO is stronger in regions that have a multi-direction wind climate. No statistically significant long-term trends are expressed, but the proportion of southeasterlies has exhibited a slight decrease (and relative increase in other wind directions) at locations south of the Arctic Circle, while to the north, it is the proportion of southwesterlies that are in decline.

Exploring the percentile wind speeds across all directions, as a more integrated measure of relative wind energy, shows that significant correlations exist for 27–53% of grid points (Fig. 5). The 90th percentile wind speed exhibits the highest number of significant correlations, shown at 16 grid points for both the 'all directions' metric and the westerly metric. The westerly median wind speed is also significantly correlated at 16 grid points; 13 of these grid points are common between these 3 metrics, covering the south-mid-latitudes (60°–66° N) and westerly longitudes (4°–12° E). For the median wind speed, the number of correlations decreases when considering all wind directions. Significant correlations are fewer for the more extreme 99th percentile, with 8 and 2 points for the overall and westerly component respectively. The easterly components of the wind speed measures do not exhibit any strong correlations for the 50th and 99th percentile, but do show a

positive, strong correlation at one point (62° N, 12° E) for the 90th percentile wind speeds. The general geographical pattern exhibited within the quadrant-based metrics is evident again, where significant correlations are more strongly associated with SW Norway. But there is no general trend of decreasing correlations from the west coast to inland, and correlations do not necessarily disappear in the easternmost part of the country. The 50th and 90th percentile wind speed correlations do not extend north of 66° N, and the most extreme 99th percentile correlations are restricted to 58°–62° N.

The temporal relationship with the NAO changes notably across the country. Comparison of the far SW with the far NE (Fig. 6) reveals a distinctly different temporal signature. Percentile wind speeds from the east and west are comparable magnitudes in the SW (Fig. 6A–D), but in the NE (Fig. 6E–H), easterly wind speeds are distinctly slower. In the SW, where significant correlations exist with the NAOi, there is clear conformity in the timing of peaks in wind speed with positive NAOi extremes; discrete negative extremes in NAOi are not particularly well aligned with low wind speeds, but broader phases of negative NAOi (e.g. 1960s and mid-1980s) do correspond to lower wind speeds. In the far NE, some of the phases in the NAOi correspond with higher wind speeds, for example the late 1940s and early 1980s. But higher wind speeds lead the extended positive phase of the early 1970s and lag that of the late 1980s–early 1990s. A similar situation occurs for negative phases of the NAOi and lower than average wind speeds; the wind speed lows of 1948 across most metrics coincide with negative NAOi phases, but low wind speeds in the late 1960s lag the NAOi negative extreme of 1968, and the negative NAOi corresponds to low easterly wind speeds, but peaks in westerly and 'all' wind speeds. It is this discordance in phase that diminishes the net correlation. These results generally show that the median and strong wind speeds correlate relatively well with the NAOi, and that the relationship is weaker for extreme wind speeds, which indicates that the positive phase of the NAO is more strongly associated with a higher frequency of median and strong winds than of the extreme cases.

Gauging the frequency of occurrence of specific wind speed thresholds is an alternative way to examine both change in the historical wind climate and links to the NAO. Here, the wind speed thresholds of 4 and 14  $\text{m s}^{-1}$  show some correlation with the NAOi, but no significant correlation is found with the 25  $\text{m s}^{-1}$  threshold (Table 1, Fig. 2), primarily due to the infrequency of this extreme wind speed. This re-

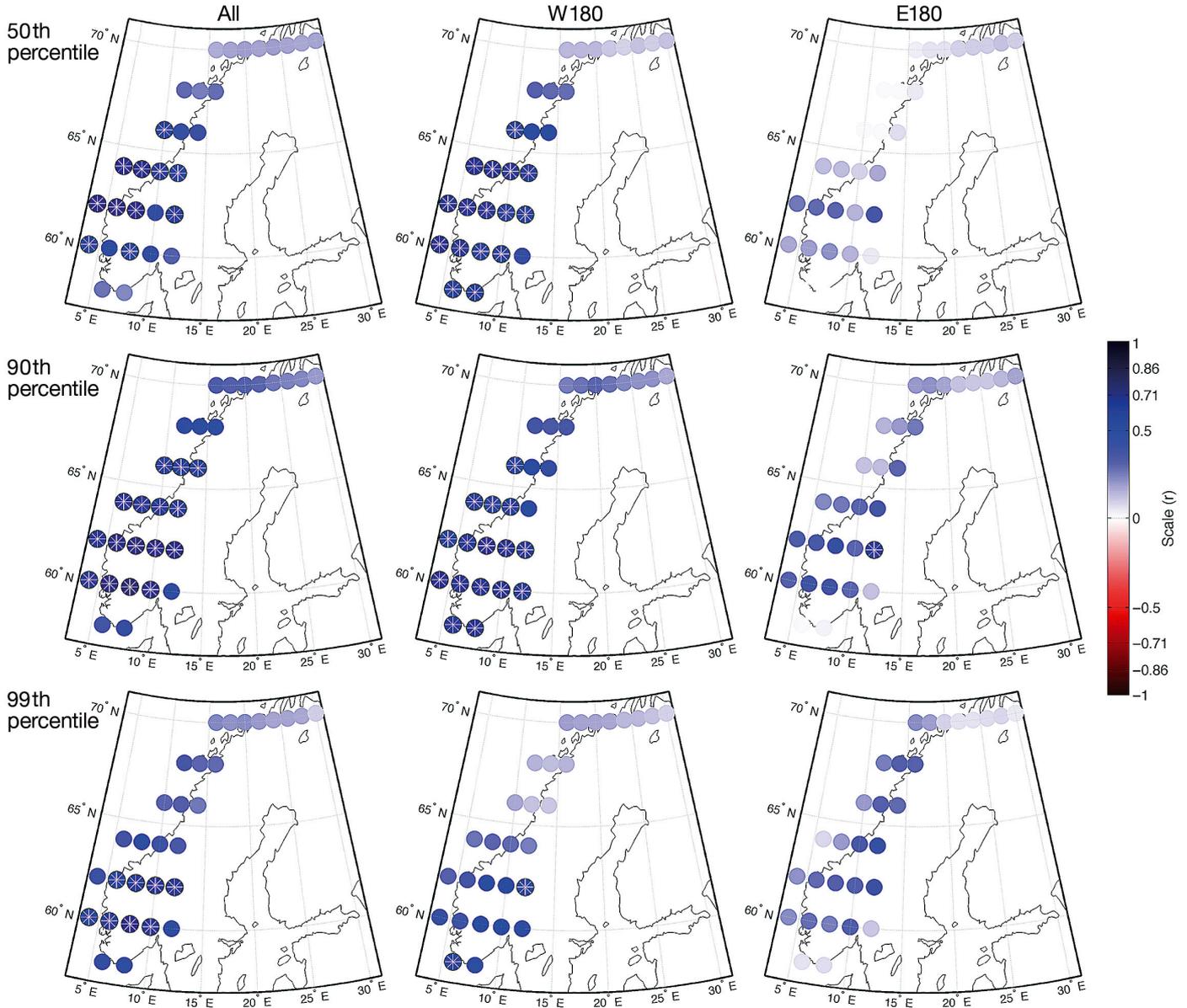


Fig. 5. Spatial variation in the correlation between the NAO index and wind speed percentiles (50th, 90th and 99th; see Table 1). Starred grid points show a significant ( $p < 0.01$ ) correlation

inforces the outcome of the percentile-based analysis that the NAOi expresses variability in the average and strong wind climate, but not the extremes. Interestingly, when considering winds from all directions (Fig. 7), the  $14 \text{ m s}^{-1}$  threshold is far more strongly associated with the NAOi than the  $4 \text{ m s}^{-1}$  threshold, with significant correlations at 11 grid points (at a wide range of westerly grid points,  $60^{\circ}$ – $66^{\circ}$  N) versus 4 for the lower threshold (only found at  $62^{\circ}$  N) (Fig. 7A,B). When westerly winds are considered, the number of correlations increases slightly for the  $14 \text{ m s}^{-1}$  threshold (to 13 grid points), and considerably for

the  $4 \text{ m s}^{-1}$  threshold (to 12 grid points); in both cases, these correlated grid points are located in the south and west. Easterly winds are only correlated at the  $4 \text{ m s}^{-1}$  threshold (2 grid points, both in the far south).

Wind speeds of  $4 \text{ m s}^{-1}$  and above occur, on average, around 80% of the winter, and only grid points far inland show a drop below 70%. Temporal variability is relatively small, but this increases when considering just westerly or easterly winds. Winter to winter variability in the frequency of wind speeds exceeding the  $14 \text{ m s}^{-1}$  threshold is greater (Fig. 8). In the south-westerly region, the variability in the  $14 \text{ m s}^{-1}$  thresh-

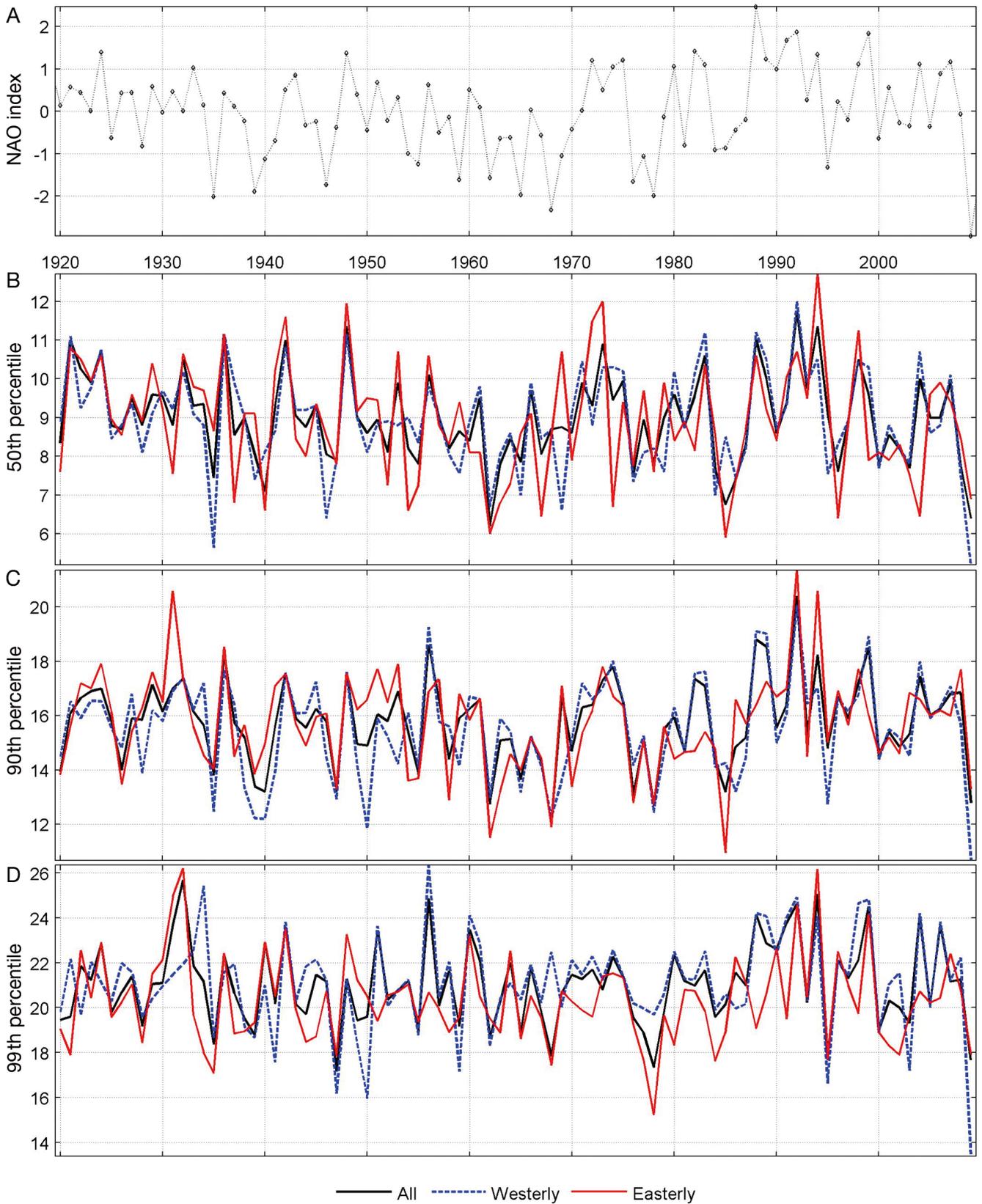
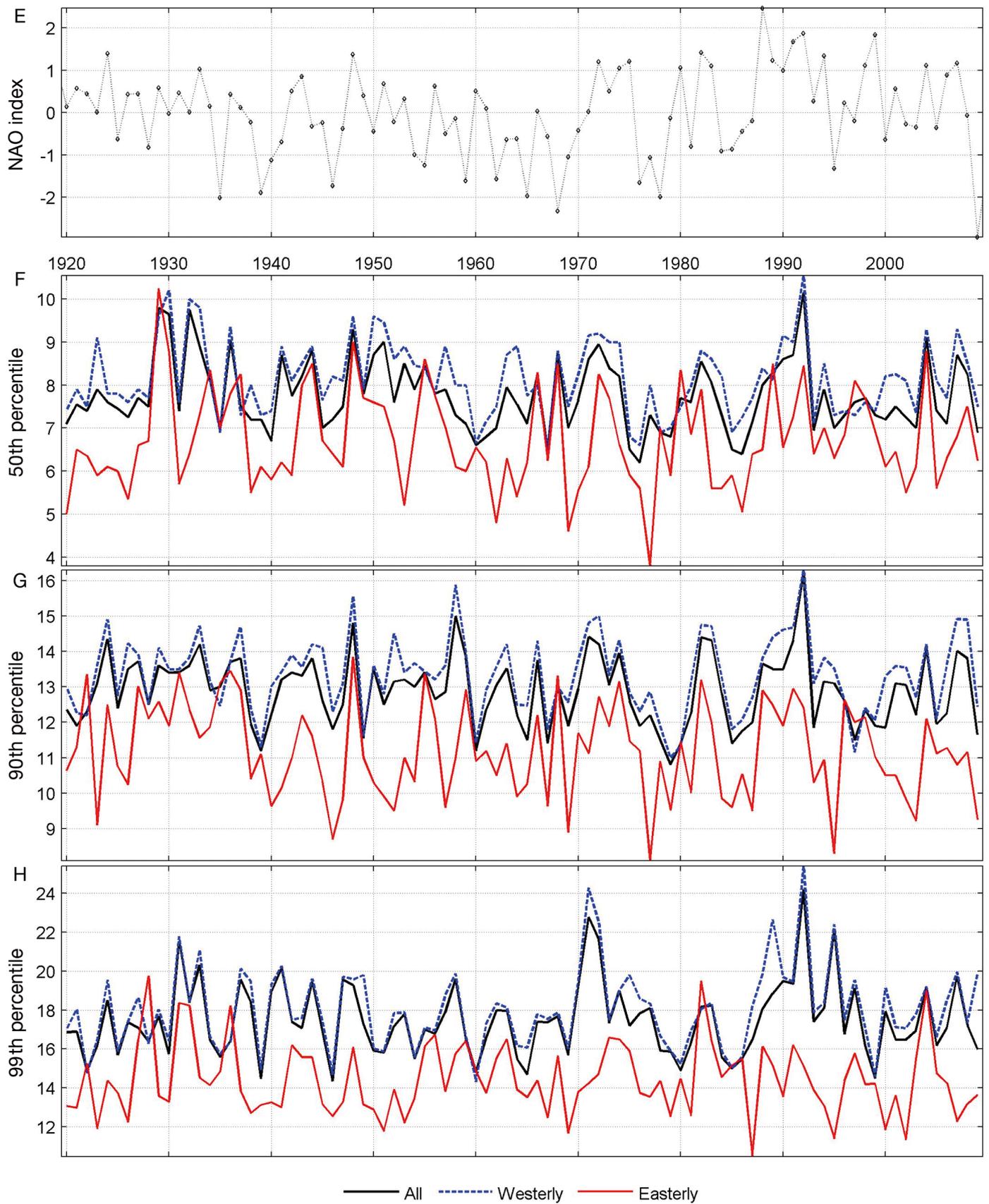


Fig. 6. Time series of the NAO index and 50th, 90th and 99th percentile wind speeds in (A–D) the far SW (60° N, 4° E) and (E–H) the far NE (70° N, 30° E) of Norway



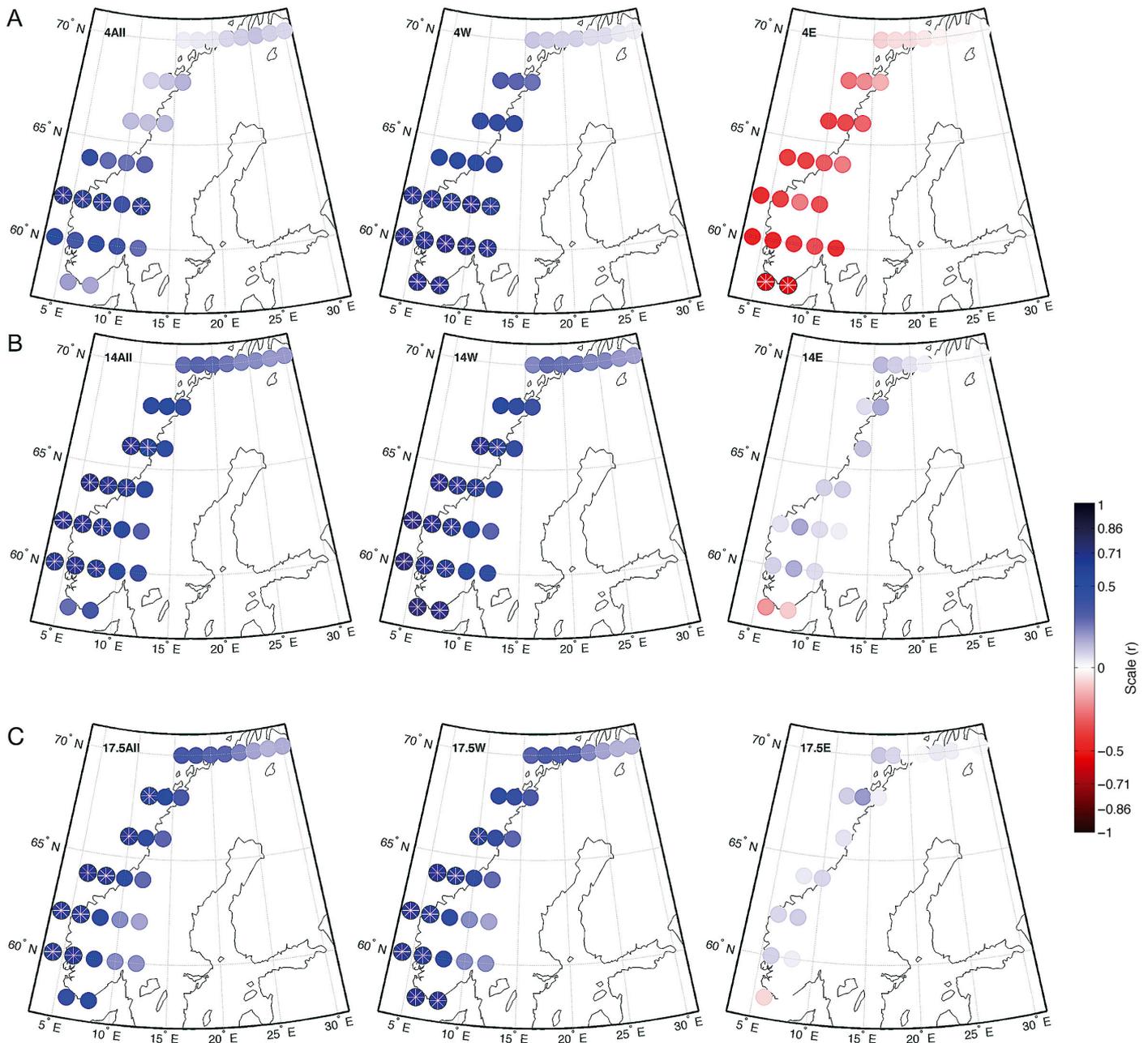


Fig. 7. Spatial variation in the correlation between the NAO index and (A,B) speed-limited frequency at 4 and 14  $\text{m s}^{-1}$ , and (C) gale-day frequency (see Table 1). Starred grid points show a significant ( $p < 0.01$ ) correlation

old matches that of the winter NAOi: positive peaks in 1948, the early 1970s, late 1980s to early 1990s and late 1990s all correlate with larger proportions of wintertime. Negative extremes of NAOi also align with smaller proportions of time. But at locations away from the SW, this connection becomes markedly complicated, where some peaks and troughs correlate while others do not. The 1948 (positive NAOi) and 2009 (negative NAOi) winters stand out as strongly

connected to high and low frequencies across all locations, and there are some broader agreements when considering phases of positive (early 1970s) or negative (mid-1960s) NAOi which align with some discrete peaks and troughs (relatively) in the proportion of time that 14  $\text{m s}^{-1}$  wind speeds are achieved. But there is structure in these time series that cannot be explained by the NAOi, for example the peak in 1953 and low in 1960 at northerly grid points.

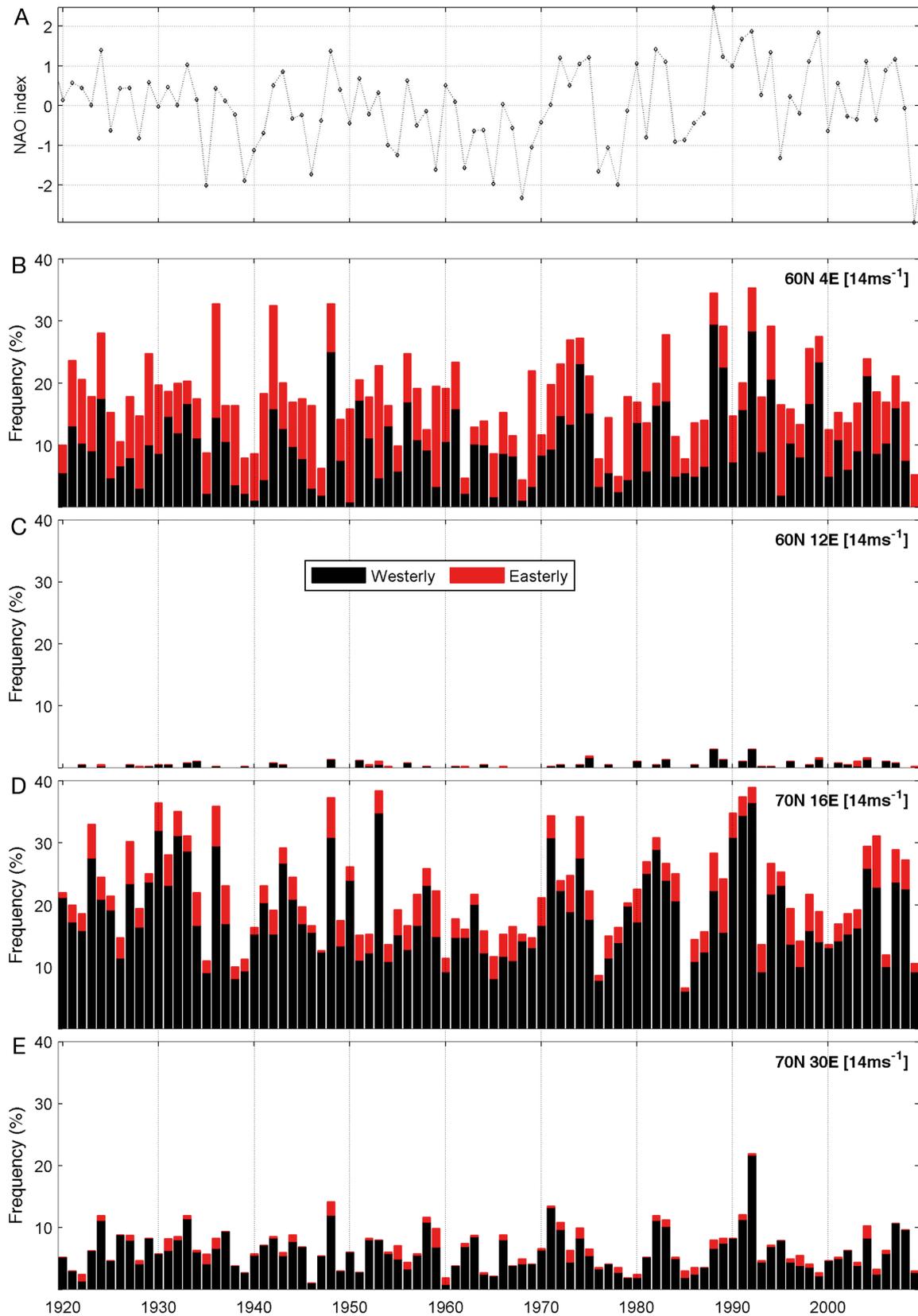


Fig. 8. Time series of (A) the NAO index, and (B–E) speed-limited frequency at  $14 \text{ m s}^{-1}$  for 4 stations representing the far SW ( $60^\circ \text{ N}$ ,  $4^\circ \text{ E}$ ), SE ( $60^\circ \text{ N}$ ,  $12^\circ \text{ E}$ ), NW ( $70^\circ \text{ N}$ ,  $16^\circ \text{ E}$ ) and NE ( $70^\circ \text{ N}$ ,  $30^\circ \text{ E}$ ) of Norway

Only less than a third of the stations exhibited a strong and significant correlation between NAOi and gale-day frequency (Fig. 7C). When just westerly gales are considered, the number of grid points with significant correlation rises by one grid point, but easterly gales show no strong correlations. Significant correlations are associated with a full range of latitudes ( $58^{\circ}$ – $68^{\circ}$  N) along the west coast of Norway, and correlations decrease in strength from the coast to inland. In Fig. 9, the temporal signature shows that reduced correlations are primarily associated with a reduction in gale-day frequency, and is particularly well evidenced in southeasterly grid points (e.g.  $60^{\circ}$  N,  $12^{\circ}$  E) and by easterly gale-day frequency (at all grid points). In northwestern latitudes, however, gale-day frequency is comparable to that experienced in the SW, and yet no significant correlations with the NAOi are observed. Peaks in the NAOi in the 1940s, early to mid-1970s, and late 1980s to early 1990s concur with peaks of gale-day frequency in most places outside the SE. The extreme negative NAOi of 1946, 1968, 1976–1978 and 2009 also concur with low frequencies.

Gale-day frequency is a measure often used to describe storminess (e.g. Dawson et al. 2002), and in Norway there are strong, positive correlations between gale-day frequency and the winter NAOi along the western coast of Norway, consistent with the fact that positive phases of the NAO tend to steer the storm tracks with strong westerly winds into northern Europe. Stronger winds occur more frequently during such phases, which is also reflected in the time series of these wind climate measures. The results indicate that such strong westerly winds associated with a positive NAOi do not reach eastern (inland) parts of Norway as frequently, and that the NAO relationship is weaker for these longitudes.

#### 4. DISCUSSION

The results of this study confirm that there is a strong relationship between winter wind climate over southern and western Norway and the NAO, reflected through strong and significant correlations between the NAOi and wind direction frequencies, percentile wind speeds, and wind speed thresholds. These results agree well with previous research, and were somewhat expected from our knowledge of how the pressure variability of the NAO affects the storm track systems crossing the North Atlantic (e.g. Rogers 1990, 1997, Hurrell & van Loon 1997, Serreze et al. 1997, Deser et al. 2000). They are consistent

with the findings of Burningham & French (2013) that the NAO is strongly associated with wind direction frequency from the SW (positively) and NE (negatively). The weak correlations with median wind speeds at sites across the British Isles and Ireland are not reflected in Norway, however, where this metric was significantly correlated at a third of locations; Pirazzoli et al. (2010) also found strong correlations with the average wind speed at some west European locations. Pryor et al. (2005) found the strongest association with the 90th percentile wind speeds over the Baltic region, which is also relatively consistent with the results obtained here. Fewer and weaker correlations are found for the 99th percentile wind speeds, as found in Burningham & French (2013), indicating that the NAOi is not as good a measure for the frequency of more extreme wind conditions in Norway.

The consideration of the frequency of the exceedance of specific wind speed thresholds during winter is shown here to express stronger associations with the NAOi at low to medium-high wind speeds, and weaker associations with extreme wind speeds. It should be noted here that specific wind speeds at a site will be influenced by local terrain effect, which is typically not represented well in reanalysis data. Our point is merely to express that indeed a strong relationship exists with the NAOi and wind speed. The wind turbine cut-in speed of  $4 \text{ m s}^{-1}$  corresponds to a threshold that is attained on average 80% of the wintertime, and is best connected with the NAOi when considering westerly winds only. The persistence of winds of  $4 \text{ m s}^{-1}$  means that this metric describes a little more of the nature of wind climate, or its association with the NAO, than the wind direction frequency. The wind turbine-rated speed of  $14 \text{ m s}^{-1}$  is correlated with the NAOi at almost all points in the mid-latitudes ( $60^{\circ}$ – $66^{\circ}$  N) of Norway. This shows the significant association between stronger winds and the NAO, complementing the results for the 90th percentile wind speeds. It is unsurprising then that the time- (1920–2009) and space- (selected grid points used here) averaged 90th percentile winter wind speed is  $14.6 \text{ m s}^{-1}$ . The cut-out speed threshold ( $25 \text{ m s}^{-1}$ ) shows very little connection with the NAO, again confirming the weak association between the NAO and extreme wind climate in Norway. In some instances, the weak correlations associated with the high wind speed metrics is related to the limited occurrence of high-speed 'events'. Statistically, this specifically relates to the threshold-based metrics (e.g.  $25 \text{ m s}^{-1}$  threshold and gale-day frequency) at sites in the far north and east (e.g. Fig. 9 showing very few gale days in the SE, at  $60^{\circ}$  N,  $12^{\circ}$  E). But in

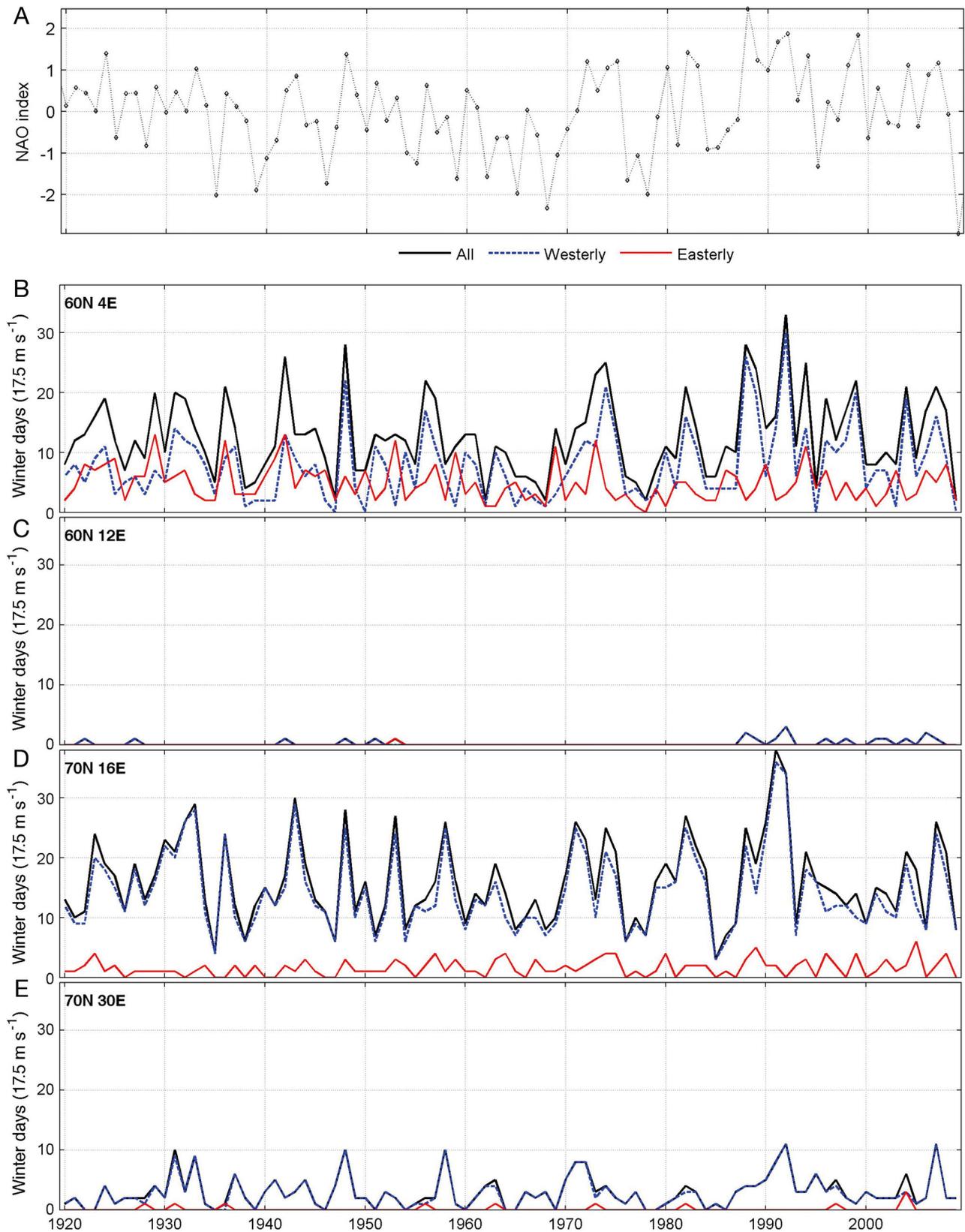


Fig. 9. Time series of (A) the NAO index, and (B–E) gale-day frequency for 4 grid points representing the far SW ( $60^\circ \text{ N}$ ,  $4^\circ \text{ E}$ ), SE ( $60^\circ \text{ N}$ ,  $12^\circ \text{ E}$ ), NW ( $70^\circ \text{ N}$ ,  $16^\circ \text{ E}$ ) and NE ( $70^\circ \text{ N}$ ,  $30^\circ \text{ E}$ ) of Norway

many of these cases, the few occurrences of high wind speed 'events' are not directly associated with positive phases in the NAO. Furthermore, the use of the 99th percentile as a measure of extremes avoids any reduced sample size issue, and it is clear that the highest wind speeds are poorly correlated with the NAO in east and north Norway.

Pinto et al. (2009) demonstrated that strong positive NAO phases are related to the occurrence of more extreme cyclones. As noted earlier, NAO theory in general states that positive phases of the NAO force more intense and frequent Atlantic storms to northern Europe. So why do we not see the association with extreme events in our analysis? This could potentially be related to the data issues we highlighted regarding the homogeneity of the earlier record of our data. Several studies state that the ensemble mean 20CR data record is inconsistent prior to 1950 (Compo et al. 2011, Ferguson & Villarini 2012, 2014, Krueger et al. 2013), and we chose to exclude data prior to 1920 only, due to the findings of the Norway-specific study by Liléo et al. (2013). The ongoing debate regarding inconsistencies is mainly related to trends in storminess and wind extremes over the North Sea area (see Krueger et al. 2013, 2014, Wang et al. 2013, 2014). A comparison of a cyclone activity index (CAI) derived from 20CR pressure data and 95th winter percentiles of geostrophic wind speed derived from observations in Wang et al. (2013, 2014), showed that linear trend estimates are consistent with each other, but not low-frequency variability. A correlation with the NAOi was carried out which implied that wind extremes from observations were a better fit than the 20CR CAI ( $R = 0.79$  and  $R = 0.11$  respectively). Further clarification of the nature of the difference between observations and 20CR-derived wind extreme metrics is needed to fully explore the role this has in associations with the NAO.

Another explanation could simply be linked to the scale and calculation of the measures used. Similar to what Burningham & French (2013) noted, the results presented here may only reflect the extent to which the datasets are matched in terms of their temporal scale and resolution. Our analysis has shown that, although the NAO might control the delivery of extreme cyclones to NW Europe, it is mainly the southern part of Norway that is directly aligned with the higher-density storm track, and this is where we do see significant correlations with extreme winds.

The close relationship between the NAO and median to strong wind speeds, which are within the

operating range of a standard wind turbine, have important implications for the wind power industry. The interannual to decadal variability of the NAO causes large swings in wind climate over longer timescales. Longer periods of above- or below-average wind speeds do not only affect direct energy production, but also the estimation of future energy production, which is important for wind farm planning and operation. In the wind energy industry, it is normally assumed that the future wind climate will vary in a similar way as in the past, and it is common practice to use a past period of wind speed measures—a reference period—to be representative of future variations (Liléo et al. 2013). If, for example, a period of unusually high annual wind speeds is chosen to represent a future period where the average wind climate is more 'normal', it will lead to an over-estimation of the future wind climate, and thereby the energy production. Understanding how and why wind climate varies on interannual and decadal time scales is therefore crucial for wind farm planning and long-term power generation.

The results of our analysis also show a distinct northern limit of the extent of a strong NAO signal in the wind climate of Norway, and thereby indicate the limit of the northerly extent of the storm tracks; grid points in the  $58^{\circ}$ – $66^{\circ}$ N latitudes exhibit a distinctly different wind climate than those to the north of the Arctic Circle. Meridional differences in the influence of the NAO over Norway have not directly been investigated in previous literature. Uvo (2003) did find that the correlations between winter precipitation and the NAO are strong over the SW coast of Norway and that the northernmost part is only intermediately influenced. This relationship is strongly connected to the westerly Atlantic winds and agrees well with the findings here.

Chen et al. (2013) found that the BO showed a high and stable temporal correlation with the geostrophic zonal wind over the Barents Sea, whereas correlation with the NAO was weak. This is consistent with the results obtained here that there are no strong and significant correlations with the NAO over the north of Norway, but implies that the BO could exert a larger influence on the wind climate at these latitudes. However, when running the same correlation analysis across Norway with the BOi, no strong and significant correlations were found at any location. This could be due to the fact that the present study investigates winds relatively close to ground level, whereas Chen et al. (2013) analysed geostrophic winds, which are located at substantially higher levels of the atmosphere.

## 5. CONCLUSIONS

By the use of simple correlations of wind climate measures with the winter NAOi, it is shown that there is a strong relationship between the Norwegian wind climate and the NAO over most of southern Norway and along the western coast to about 66°–68° N. No strong and significant correlations are found north of this latitude. Correlation analysis with the BOi yielded no strong and significant correlations for any of the wind climate metrics at any grid point across Norway.

Correlations with wind direction frequencies indicate that the winter NAOi is strongly associated with increased frequencies of winds from the SW and decreased frequencies of winds from the NE. Directional percentile wind speeds also exhibit most strong correlations in the SW quadrant, where correlations for the 50th and (to a lesser extent) the 90th percentile wind speeds are more and stronger than for the 99th percentile. More generally, the 50th and 90th percentile wind speeds have more and stronger correlations than 99th percentile wind speeds, indicating that the more extreme part of the wind speed distribution is not that strongly connected with the NAO, whereas median to strong winds have a rather close relationship.

The proportion of wintertime met or exceeded by the wind turbine cut-in speed threshold ( $4 \text{ m s}^{-1}$ ) correlates well with the winter NAOi in the south and west, but it is actually the rated speed threshold ( $14 \text{ m s}^{-1}$ ) that is most strongly correlated with the NAOi. This threshold is very close to the time- and space-averaged 90th percentile wind speed of  $14.6 \text{ m s}^{-1}$ , which is also well correlated with the winter NAOi in south and west Norway. No significant correlations exist at the cut-out threshold ( $25 \text{ m s}^{-1}$ ), but gale-day frequency is well correlated in the SW.

These results are consistent with the expectations of how the NAO affects the path and intensity of the North Atlantic storm tracks and thereby the Norwegian winter wind climate. During positive, or 'high' NAO phases, the increased pressure gradient across the North Atlantic typically shifts the path of the storm tracks northeastward, with a general increase in the number and intensity of cyclonic weather systems hitting the south and western coast of Norway. These systems do not reach the very north of the country as directly or frequently, and thereby do not affect the wind climate of northern Norway to the same extent. During negative, or 'low' NAO phases, the typically weaker weather systems of the storm tracks take on a more east–west oriented path, lead-

ing to generally calmer winter-averaged wind conditions in Norway. It is clear that average and relatively high-energy wind climates are more strongly associated with the NAO than extremes.

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