An investigation of the regional correlation gradients between Euro-Atlantic atmospheric teleconnections and winter solar short wave radiation in northwest Europe

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Abstract
Increased use of solar photovoltaic electricity requires a better understanding of the impact of large-scale atmospheric teleconnections on incident short wave (SW) solar radiation. Our focus is on the relationship between winter (December to February) SW radiation in northwest Europe and the dominant Euro-Atlantic atmospheric teleconnection patterns using multiple multi-decadal observational and gridded reanalysis datasets, with a focus on the islands of Ireland and Britain. Our study reveals that the previously reported west–east seesaw in the correlation pattern between the winter North Atlantic Oscillation (NAO) index and winter SW radiation across the United Kingdom is complex, involving several zonal changes in the sign of the NAO–SW correlations (multiple seesaws). By comparison with the NAO, the east Atlantic pattern exerts only a weak control on winter SW radiation across the United Kingdom and Ireland, although in the western part of the Iberian Peninsula and adjacent Atlantic Ocean significant positive correlations occur. High values of the Scandinavian pattern index result in higher than average winter SW radiation in much of northern Europe, although it is evident that some regions (e.g. northeast England, east Scotland and the adjacent North Sea area) exhibit the opposite behaviour. Inter-seasonal variations in the dominant atmospheric flow and moisture transport directions, steered by large-scale atmospheric pressure patterns, combined with orographic uplift and rainout effects on the windward side of hills and mountains are interpreted to be the physical drivers of the observed zonal variations and correlation sign reversals between winter SW anomalies and the NAO index.

KEYWORDS
east Atlantic (EA) pattern, Euro-Atlantic sector, North Atlantic Oscillation (NAO), Scandinavian (SCAND) pattern, solar energy, zonal gradients
1 | INTRODUCTION

Greenhouse gas emission reductions will require continued decarbonization of the global energy system and a switch to renewable sources. However, increased penetration and diversification of renewables (e.g. wind, solar) in power systems gives rise to multiple challenges, linked to their inherent intermittency on a range of spatiotemporal scales (Widén et al., 2015; Engeland et al., 2017). Prediction of wind and solar resources on timescales beyond the approximately 10 day limit of numerical weather prediction is currently impossible, but significant progress has been made recently with regard to seasonal-scale prediction of some large-scale atmospheric pressure patterns in the North Atlantic–European sector such as the winter North Atlantic Oscillation (NAO) (Dunstone et al., 2017; Scaife et al., 2017) and the summer east Atlantic (EA) pattern (Wulff et al., 2017). Because solar and wind resources are linked to large-scale atmospheric circulation patterns (Pozo-Vázquez et al., 2004; Brayshaw et al., 2011; Jerez et al., 2013; Colantuono et al., 2014; Clark et al., 2017; Cradden et al., 2017; Krakauer and Cohan, 2017), improved predictability of these may permit enhanced energy supply balancing in the future at regional (Colantuono et al., 2014) and even continental scales (Grams et al., 2017; Santos-Alamillos et al., 2017).

Most previous investigations of the connections between large-scale atmospheric patterns, particularly the NAO, and renewable energy resources have focused on wind speeds and directions (e.g. Suselj et al., 2010; Brayshaw et al., 2011; Ely et al., 2013; García-Bustamante et al., 2013; Correia et al., 2017; Krakauer and Cohan, 2017), but fewer studies (Pozo-Vázquez et al., 2004; Colantuono et al., 2014; Krakauer and Cohan, 2017) have assessed their impact on incident short wave (SW) solar radiation, of relevance to the solar energy industry.

Here the focus is on the links between large-scale atmospheric circulation patterns and incident winter SW radiation in the Euro-Atlantic sector, with a particular focus on the United Kingdom and Ireland. In this sector, atmospheric teleconnections such as the NAO, the EA and the Scandinavian (SCAND) patterns reflect regional-scale sea level pressure anomalies (Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Hurrell and Deser, 2009). The effects of these patterns on renewable energy resources on various time-scales remain a topic of active research (Brayshaw et al., 2011; Jerez et al., 2013; Kriesche and Adam Schlosser, 2014; François, 2016; Commin et al., 2017; Correia et al., 2017; Cradden et al., 2017). In this regard, recent work has shown that the interactions between the various teleconnection patterns may also be important in determining their impacts on meteorological variables locally (Moore et al., 2013; Comas-Bru and McDermott, 2014) and in assessment of their effects on renewable energy resources on long-term planning timescales (François, 2016; Cradden et al., 2017; Zubiate et al., 2017). Our study builds on the work of Colantuono et al. (2014), but extends both the spatial and temporal data coverage to gain new insights into the effects of large-scale atmospheric pressure patterns, particularly the NAO, on SW solar radiation, which in turn has implications for optimal exploitation of solar energy resources in the region. In recent years solar power deployment has increased substantially in the region, particularly in the United Kingdom which had a cumulative installed collar capacity of approximately 13 GW at the end of 2019, representing roughly 15% of the United Kingdom’s total electrical power generation capacity (~85 GW) (Dukes, 2019).

The important findings of this study are as follows: (i) the zonal gradient in the correlation between the winter NAO index and incident SW solar radiation is not a single unidirectional west–east (seesaw) trend across northwest European mid-latitudes, but instead exhibits multiple zonal reversals in the sign of the correlation from west to east across Ireland, through the United Kingdom and into continental Europe, and (ii) land surface elevation strongly influences the magnitude and sign of the NAO–SW radiation correlations, probably linked to NAO-driven changes in the dominant atmospheric moisture transport directions (e.g. westerlies versus easterlies) and regional-scale orographically driven rainout that influences cloudiness and therefore incident SW radiation.

2 | DATA AND METHODS

2.1 | Large-scale atmospheric teleconnection indices

The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre’s indices for the NAO, EA and SCAND patterns were used in this study. These are obtained by applying the rotated principal component analysis method on 500 hPa geopotential height anomalies for the study region (latitude 20 °N–90 °N; longitude 180 °W–180 °E) to compute the monthly winter (December–January–February) indices for the three teleconnection patterns of interest (NAO, EA and SCAND). In this study, principal component analysis derived teleconnection indices were preferred over station based indices, because the former are less sensitive to temporal migrations in the locations of the centres of action of the teleconnections that can affect the calculation of NAO indices if a fixed station based
approach is used (Hurrell and Deser, 2009; Moore et al., 2013; Comas-Bru and McDermott, 2014; Wang et al., 2014). It should be noted that the sign of the EA teleconnection pattern follows the convention of Barnston and Livezey (1987), and so positive phases of the EA pattern occur when there are positive sea level pressure anomalies in the subtropical North Atlantic (Comas-Bru and McDermott, 2014; Zubiate et al., 2017). Similarly, high SCAND indices reflect anomalously high sea level pressures over southern Scandinavia (Comas-Bru and McDermott, 2014).

2.2 | Solar radiation data

Three sources of global solar radiation observations and three reanalysis products focusing on the winter months (December–January–February) were used in the present study. The three observational datasets comprise hourly pyranometer recordings from meteorological stations operated by Ireland’s meteorological service (Met Éireann), monthly pyranometer data from the United Kingdom (World Radiation Data Centre) and satellite SW radiation measurements for Europe from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT; https://www.eumetsat.int/). The three reanalysis products used are the ECMWF’s ERA-interim (Dee et al., 2011; https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim), NASA’s MERRA-2 (Gelaro et al., 2017; https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/) and Met Éireann’s recently released MÉRA Regional Climate Reanalysis (Gleeson et al., 2017; https://www.met.ie/climate/available-data/mera). By contrast with the ERA-Interim (0.75° × 0.75°, ~78 km) and MERRA-2 products (0.5° × 0.625°, ~50 km), the MÉRA dataset is a high resolution (2.5 km horizontal grid) reanalysis product for a restricted domain comprising the island of Ireland, the UK mainland and adjacent seas.

For consistency in our use of the reanalysis datasets, the time period considered here was restricted to the period 1982–2015 (34 years), more than double the time period considered in a previous station based study (Colantuono et al., 2014). The available pyranometer datasets for the United Kingdom and Ireland typically have shorter durations than those provided by the reanalysis products, but seven pyranometer stations provide approximately 30 years of hourly data (Tables 1 and 2, Figure 1) for Ireland. Data from some weather stations that provide monthly recordings of incident SW radiation in the east and west coast of the UK mainland were also considered, as these have sufficient time resolution and duration to validate the reanalysis products (Table 2).

In addition, station based sunshine hour observations were considered, as these provide supplementary observations that are independent of both the gridded climate reanalysis products and the station based SW radiation pyranometer measurements. For Ireland, sunshine hour

| TABLE 1 | Summary of datasets used in this paper |
|-------------------|-------------------|-------------------|-------------------|
| **Climate reanalysis datasets** | **Provider** | **Spatial coverage** | **Spatial resolution** |
| ERA-interim | ECMWF | Global | 0.75 × 0.75 ( ~78 km) |
| MERRA-2 | NASA | Global | 0.5 × 0.625 ( ~50 km) |
| MÉRA climate reanalysis | Met Éireann | Regional | 2.5 km × 2.5 km |

| **Observational datasets** | **Provider** | **Spatial coverage** | **Spatial resolution** |
|-------------------|-------------------|-------------------|-------------------|
| SW radiation Ireland | Met Éireann | Regional | Seven stations |
| SW radiation United Kingdom | World Radiation Data Centre | Regional | Five stations |
| Sunshine hours Ireland | Met Éireann | Regional | Nine stations |
| Gridded dataset from sunshine hours observations | Met Office | Regional | ~5 km × 5 km for sunshine hours |

| **Satellite products** | **Provider** | **Spatial coverage** | **Spatial resolution** |
|-------------------|-------------------|-------------------|-------------------|
| AVHRR – PATMOS-x CDR (clouds) | NOAA | Global | 10 km × 10 km |
| MSG (SW radiation) | EUMETSAT | Global | 0.05° × 0.05° |

The upper three rows refer to the reanalysis products. The middle four rows refer to the various observational datasets. The time period of analysis is 1982–2015 for all datasets apart from Met Éireann’s sunshine hour data which represent the period 1981–2007. The lower two rows show details of the satellite products employed.
observations from nine stations were used (1981–2007; Table 3). For the United Kingdom, a gridded dataset produced by spatial interpolation from the UK Met Office’s network of historical observations of sunshine hours (Perry and Hollis, 2005b) for the period 1982–2015 was used.

In this study, all SW radiation data (reanalysis, satellite and pyranometer derived) were aggregated to monthly averages in order to explore linkages to the monthly defined atmospheric teleconnection indices discussed above, followed by a normalization for each calendar month of the winter season (December–January–February). This normalization was performed by dividing each month’s SW radiation mean by the climatological SW radiation mean for that calendar month (e.g. aggregated SW radiation for February 1983 was divided by the average aggregated SW radiation of all Februays in the dataset). This normalization procedure removes the effect of higher absolute SW radiation levels in some months (e.g. February) that might otherwise dominate and bias the overall December–January–February anomaly. This normalization process was also applied to the sunshine hour data.

| SW                | 1982–2015 | NAO $r_{sp}$ | EA $r_{sp}$ | SCAND $r_{sp}$ | Years covered | Lat  | Lon  |
|-------------------|-----------|--------------|-------------|----------------|---------------|------|------|
| Ireland           |           |              |             |                |               |      |      |
| Belmullet         | −0.71 (0.0) | 0.04 (0.81) | 0.55 (0.0)  | 1982–2015      | 54.22         | −10.01 |
| Malin head        | −0.69 (0.0) | 0.18 (0.31) | 0.38 (0.03) |                | 55.37         | −7.34  |
| Valentia          | −0.58 (0.0) | 0.20 (0.26) | 0.39 (0.02) |                | 51.93         | −10.23 |
| Clones            | −0.43 (0.01)| −0.01 (0.97) | 0.31 (0.07) |                | 54.18         | −7.23  |
| Birr*             | −0.56 (0.0) | −0.08 (0.65) | 0.17 (0.33) | 1982–2012      | 53.09         | −7.89  |
| Kilkenny*         | −0.07 (0.7) | −0.08 (0.67) | −0.16 (0.35) | 1982–2009      | 52.66         | −7.27  |
| Dublin            | 0.20 (0.27) | 0.08 (0.64) | −0.11 (0.53) | 1982–2015      | 53.43         | −6.24  |
| United Kingdom    |           |              |             |                |               |      |      |
| Camborne (Cornwall)| −0.38 (0.04)| −0.12 (0.55) | 0.42 (0.02)  | 1986–2016      | 50.22         | −5.33  |
| Aberporth (Wales) | −0.80 (0.0) | −0.21 (0.27) | 0.49 (0.01) | 1982–2016      | 52.13         | −4.57  |
| Dunstaffnage (west Scotland) | −0.29 (0.15) | −0.06 (0.77) | 0.38 (0.05) | 1981–2016      | 56.57         | −5.43  |
| Bracknell (central south England) | 0.22 (0.24) | 0.02 (0.91) | −0.11 (0.55) | 1971–2003      | 51.38         | −0.78  |
| Aberdeen (east Scotland) | 0.28 (0.12) | −0.24 (0.20) | −0.22 (0.23) | 1981–2016      | 57.20         | −2.22  |

**FIGURE 1** Locations in Ireland for which data from pyranometers and sunshine hour recorders (filled circles) or sunshine hour recorders only (open circles) were used. For the UK mainland, an observation based sunshine hours gridded dataset (Perry and Hollis, 2005b) was used, along with pyranometer data from sites shown by the filled squares. Additionally, the colour scale refers to the average total incident short wave radiation over the whole year (a) and over the winter only (b), produced using the MÉRA dataset.
Spatially, SW radiation variability was explored in two geographical domains. A large domain comprising all of the North Atlantic sector (latitude 30°N–67°N; longitude 100°W–40°E) was explored to provide a broad regional-scale context, but our study focuses mainly on a more restricted geographical domain comprising the United Kingdom and Ireland for which the recently released high-resolution MÉRA reanalysis dataset is available and station based observations are accessible to validate our results.

Autocorrelation is known to occur in some weather and climate time series observations that exhibit temporal memory effects (e.g. Angell and Korshover, 1981) and must be taken into account when computing correlations between time series datasets. In the present study the approach of Angell and Korshover (1981) was followed to calculate the number of “effective” independent observations for lags of 1–5 years. This analysis showed that none of the analysed time series that were used to calculate correlations exhibits strong autocorrelation effects, reflecting the low inter-annual “memory” of atmospheric dynamics. For lags between 1 and 5 years, the number of effective observations never decreased below 27, and statistical significance levels for the correlation maps were computed on the basis of the effective observations calculated from a nominal 34 years of data.

### 2.3 | Cloud cover data

Besides direct solar radiation data, indirect estimates of solar radiation such as cloud cover data were also considered in the present study. The Advanced Very High Resolution Radiometer (AVHRR) Cloud Properties – Pathfinder Atmospheres Extended (PATMOS-x) Climate Data Record dataset, a 10 km spatial resolution gridded dataset, contains data on several variables linked to cloud properties (https://www.ncdc.noaa.gov/cdr/atmospheric/avhrr-cloud-properties-nasa). Because this study focused on solar radiation, the “cloud fraction” variable was analysed, which refers to the fraction of the sky in the domain of interest that is covered by clouds at a given time. As described above for the other datasets, the data were normalized and aggregated as winter December–January–February means, producing 36 years (1982–2016) of gridded time series data covering Ireland and the United Kingdom.

### 3 | RESULTS

#### 3.1 | North Atlantic sector

Figure 2 shows the Spearman correlation coefficients between the NAO (Figure 2a,b), the EA (Figure 2c,d) and the SCAND (Figure 2e,f) indices and incident winter (December–January–February) SW radiation derived from both the ERA-Interim and MERRA-2 reanalysis products for this sector. In all correlation maps (Figures 2–5), stippled areas denote correlations that are statistically significant at the 95% confidence level having taken account of the very weak autocorrelation effects described above. As expected (Pozo-Vázquez et al., 2004), the relationship between incident SW radiation and the winter NAO index (Figure 2a,b) shows a strong latitudinal variability. Across most of the high latitude North Atlantic, the correlation between SW radiation and the NAO pattern is predominantly negative, meaning that positive phases of the NAO are associated with negative SW radiation anomalies in winter. However, the

| Sunshine hours | 1981–2007 | NAO \(r_{sp}\) | EA \(r_{sp}\) | SCAND \(r_{sp}\) | Lat | Lon |
|----------------|-----------|----------------|----------------|----------------|-----|-----|
| Ireland        |           | −0.80 (0.0)    | 0.22 (0.26)    | 0.49 (0.01)    | 54.22 | −10.01 |
| Belmullet      |           | −0.67 (0.0)    | 0.41 (0.04)    | 0.50 (0.01)    | 55.37 | −7.34 |
| Malin head     |           | −0.61 (0.0)    | 0.32 (0.1)     | 0.30 (0.13)    | 51.93 | −10.23 |
| Valentia       |           | −0.51 (0.01)   | 0.08 (0.71)    | 0.34 (0.08)    | 52.69 | −8.92 |
| Shannon        |           | −0.39 (0.05)   | 0.02 (0.93)    | 0.26 (0.19)    | 54.18 | −7.23 |
| Clones         |           | −0.49 (0.01)   | 0.23 (0.26)    | 0.20 (0.32)    | 53.09 | −7.89 |
| Birr           |           | −0.18 (0.36)   | 0.29 (0.15)    | 0.01 (0.97)    | 52.66 | −7.27 |
| Kilkenny       |           | 0.04 (0.86)    | 0.20 (0.33)    | −0.23 (0.25)   | 53.43 | −6.24 |
| Dublin         |           | 0.02 (0.93)    | 0.22 (0.28)    | 0.03 (0.9)     | 52.25 | −6.33 |
correlation between the NAO index and SW radiation anomalies in the mid-latitudes of northern Europe is complex and patchily developed. Crucially, the sign of the correlations switches zonally across the United Kingdom into the North Sea, and again close to the western margin of Norway, the Baltic and into Finland, regardless of whether the ERA-Interim or MERRA-2 reanalysis product is considered (Figure 2a,b). The latter result provides a broader, northwest European continent-scale context within which the apparently simpler single switch in the sign of the correlation (seesaw) inferred previously for Northern Ireland and the UK mainland was detected (Colantuono et al., 2014). By contrast, in southern Europe (south of about 45 ° N), both reanalysis datasets indicate relatively uniform positive correlations between the NAO index and SW radiation anomalies, with no evidence for the zonal switches in the sign of the correlation scores (Figure 2a,b).

Aside from a region in northern Europe (Denmark and part of Sweden), the western margin of the Iberian Peninsula and the adjacent sub-tropical Atlantic, continent-scale winter SW radiation correlations with the EA pattern are not as strongly developed as those with the NAO index (Figure 2c,d). Correlation scores over
Ireland and the United Kingdom, for example, are not statistically significant.

Stronger correlations between the winter SW radiation and the Scandinavian SCAND pattern are evident in much of the mid-latitude EA sector, particularly in the MERRA-2 reanalysis (Figure 2e,f). There is some evidence for a switch to negative correlations in part of the northeast coastal region of the United Kingdom and the western North Sea. Overall, however, like the NAO correlation scores, the clearest change in the correlation sign with regard to the SCAND pattern is from positive to negative between northern and southern Europe. South of approximately 45° N, the correlation maps show uniformly negative values that extend from the mid-Atlantic, through the Iberian Peninsula, across much of southern Europe to the northern part of the Mediterranean basin (Figure 2e,f).

3.2 | Ireland and the UK region

3.2.1 | Reanalysis datasets

A more restricted Ireland/UK domain is now considered in more detail, using the MÉRA dataset to understand better the physical drivers for the observed correlation gradients and the zonal switches in the sign of the NAO–SW radiation correlations. Figure 3 illustrates the Spearman correlation coefficients between the NAO, EA and SCAND indices respectively and the incident winter SW radiation for the ERA-Interim, MERRA-2 and MÉRA products for this restricted domain (Ireland and the United Kingdom). An important result, outlined above in the context of the wider northwest European region, is that the strength of the NAO–winter SW correlation changes zonally from west to east across Ireland and the United Kingdom (Figure 3a–c), a feature observed in all three reanalysis products. At this spatial resolution, incident SW radiation is negatively correlated with the NAO index for most of Ireland (except for the east and southeast coastal areas of Ireland), the western Scottish isles and for much of the western part of the UK mainland. By contrast, the eastern seaboard of the UK mainland, in particular the region around East Anglia and the North Sea coastline, exhibits a positive correlation between the winter NAO index and incident SW radiation (Figure 3a–c). It is also noteworthy that, in the correlation map produced using the MÉRA dataset (Figure 3c), the zonal west–east gradient of NAO–SW radiation correlation for the island of Ireland is stronger than in the ERA-interim and MERRA-2 dataset (Figure 3a,b), with some regions in the east and southeast of Ireland showing no significant correlation with the NAO index. While our NAO–SW radiation correlation results are broadly consistent with those of Colantuono et al. (2014), they are based on an extended analysis period (34 versus 16 years) and use a range of datasets such as ERA-interim, MERRA-2 and MÉRA, as well as station based observations. The highly resolved (2.5 km grid) MÉRA product indicates that the zonal gradient in the NAO–SW radiation correlation is not a simple monotonic pattern across the British Isles and Ireland, but instead shows a change in the gradient across the island of Ireland (Figure 3c) from the northwest to the southeast, verified by independent sunshine hour observations, as discussed below.

Similarly, zonal gradients in correlation patterns are evident for the SCAND maps (Figure 3g–i), although the sign of the correlation is reversed compared with the NAO correlation maps. For the EA pattern (Figure 3d–f), no statistically significant (95% confidence) correlated areas are found for Ireland, and positive correlation areas occur sporadically across the UK mainland and into the North Sea, although all signals are relatively weak. In general, the correlation maps with the EA index exhibit only weak signals over the whole region of Ireland and the United Kingdom and its most obvious effect appears to be confined to Iberia and the adjacent sub-tropical North Atlantic (Figure 2c,d).

Across all three reanalysis datasets, correlation patterns are replicated with a high level of similarity, including the zonal gradients that are evident mainly for the NAO and SCAND patterns. As a further check, correlation scores were computed based on satellite derived SW radiation data (Figure S1). Although only 32 years of satellite data could be obtained (winters 1984–2015), the correlation scores are very similar to those obtained with the reanalysis products.

3.2.2 | Observational records

To further verify the correlation patterns discussed above the correlation scores were recalculated using two types of station based observations (global SW radiation and sunshine hour observations) for Ireland and the United Kingdom. Figure 4a illustrates the correlation coefficients between the NAO index and winter SW radiation as derived from the MÉRA high resolution climate reanalysis (as in Figure 3a), but the numbers shown on the maps are the correlation coefficients between the same variables based on global SW measurements from pyranometers at the Irish meteorological stations for which there is good temporal coverage. These pyranometer based NAO–SW radiation correlation coefficients vary from highly negative (−0.71) values in northwest Ireland to low negative and weakly positive values
in the southeast (Table 2), a geographical gradient that is consistent with that based on the MÉRA reanalysis. Regarding the SCAND pattern (Figure 4c), although the pyranometer data mirror the zonal gradient verified in Figure 3g–i, these station based scores indicate a weaker signal. For the EA pattern, similarly, the observational record confirms no significant correlations across the whole of Ireland.

To further assess the robustness of the west–east change in the relationships between incident SW radiation and the NAO and SCAND indices, correlation scores were also computed using independent sunshine hour datasets. For Ireland, sunshine hour observations are available for a widely distributed array of stations across the island. For the United Kingdom, a sunshine hours gridded dataset (Perry and Hollis, 2005b) was used. In Figure 5a,b, correlation patterns between solar radiation variability based on sunshine hour data and the NAO index emerge that are consistent with those based on the gridded reanalysis products. Importantly, zonal changes in correlation strength are apparent in Ireland (Figure 5a) and the United Kingdom (Figure 5b), based
on the sunshine hour data. Regarding the EA index, correlation scores with the winter SW radiation are once again weak. In summary, pyranometer based data (Table 2) and sunshine hour based data (Table 3) provide verification of the spatial correlation patterns detected in the reanalysis products discussed above.

The preceding paragraphs emphasized spatial patterns in the correlation scores between the various teleconnection indices and measures of solar energy resources (incident SW radiation and sunshine hours). From a solar energy perspective, however, it is instructive to examine the magnitude of the absolute changes in incident SW radiation that are linked to variations in the teleconnection indices.

SW radiation data from three pyranometer stations located close to the Atlantic coastline in Ireland, namely Malin Head in the north, Belmullet in the northwest and Valentia island in the southwest, are highly correlated with the NAO index. Mean SW radiation anomalies from these stations are shown as the red curve in Figure 6, highlighting the strongly negative correlation between winter SW radiation at these coastal stations and the NAO index (blue curve, Figure 6). In this figure, the relative change (%) in winter SW radiation as a function of the NAO index is shown, indicating that the magnitude of the changes is relatively large (up to approximately ±20% around the mean, Figure 6).

In summary, strong zonal gradients in the correlations between winter SW radiation and the winter NAO and SCAND indices across Ireland and the United Kingdom are indicated. The new high resolution MÉRA gridded reanalysis dataset, along with station based pyranometer and sunshine hour datasets, indicate that zonal changes in
the strength of the NAO–winter SW radiation correlations
occur within the island of Ireland, from the northwest to
the southeast. In effect, this means that there are two
NAO–winter SW radiation correlation seesaws, a weaker
one within the island of Ireland and another stronger see-
saw across the UK mainland. The strongest negative corre-
lations are observed on and close to the western margins of
both islands and neutral/weak positive to strongly positive
correlations are observed on the eastern or southeastern
coasts of Ireland and the UK mainland respectively.

To understand the physical mechanisms responsible
for these zonal correlation gradients, and to assess the mag-
nitude of the SW radiation anomalies, winter NAO indices
less than or greater than one standard deviation around
the long-term mean were selected. Thus, five winters with
unusually negative (1985, 1987, 1996, 2010, 2011) and posi-
tive (1989, 1995, 2000, 2012, 2015) NAO indices were
selected for further detailed analysis, representing about
30% of available data. For illustrative purposes, the winter
SW radiation anomalies for these 10 winters were plotted
as a function of longitude for an exemplar latitude (a west–
east transect at 54.20° N through Ireland, the Isle of Man
and England) (Figure 7a), together with the corresponding
land surface elevation from the MÉRA dataset. Assessing
the role of orography in modulating the west–east geo-
graphical SW radiation anomaly gradients is important,
since this influences meteorological variables such as pre-
cipitation that may in turn link to atmospheric water
vapour transport, cloudiness and potentially to SW radia-
tion anomalies.

Figure 7b,c illustrates how the magnitude of the win-
ter SW radiation anomaly varies zonally, based on the
MÉRA reanalysis dataset and satellite data respectively.
Figure 7b shows the winter SW radiation anomalies
along the 54.20° N transect for the mean of the five
most negative (bold red curve) and the mean of the five
most positive (bold blue curve) based on the MÉRA
reanalysis dataset. The faint red and blue curves in
Figure 7b represent the SW radiation anomalies for each
of the five extreme NAO– and NAO+ winters described
above. Anomalies range from nearly zero to approxi-
mately ±20% of the long-term mean winter values, with
a clear link to land surface elevation (black curve in
Figure 7b). Figure 7c also shows the satellite based SW
radiation anomalies (thin red and blue curves) for com-
parison, highlighting that the anomaly pattern is similar
to that derived from the MÉRA reanalysis dataset,
although the absolute values are lower in the satellite
observations.

In the case of NAO+ winters (blue curves), for example,
SW radiation anomalies increase (become more negative) on
the western (windward) side of topographic barriers,
reaching local minima to the west of the peak elevation
(black curves), with local maxima reached to the east of the
local topographic peak (summit elevation). In general, for
NAO+ winters, SW radiation anomalies are negative (blue
curves generally plot below the horizontal dashed “zero
anomaly” lines in Figure 7b,c). It is noteworthy, however,
that at several points along the transect (e.g. the east coast
of Ireland, Isle of Man, Pennine barrier at around 2° W in
northwest England), the NAO+ SW radiation anomaly
(blue curve) crosses the “zero anomaly” dashed line
(Figure 7b), consistent with the notion of multiple zonal
seesaws. For NAO– winters (red curves) the opposite rela-
tionships are observed, resulting in a bilateral symmetry
of SW radiation anomalies around the local climatological
mean. Thus, winter SW radiation anomalies are typically
positive (red curves generally plot above the horizontal

FIGURE 6 Times series of
aggregated short wave mean
December–January–February
radiation anomalies for the three
Irish stations close to the Atlantic
coastline (red filled circles and red
curve), alongside the December–
January–February North Atlantic
Oscillation index (blue curve,
inverted axis). These time series are
strongly correlated (Spearman
correlation −0.72). Also shown for
comparison are the data points for all
other Irish meteorological stations
(open symbols) for which
pyranometer data are available.
dashed “zero anomaly” lines), the region to the east of the high elevation topographic barrier at around 2°W again being an obvious exception along this exemplar transect. Furthermore, the anomaly gradients as a function of longitude tend to be lower across the sea regions, while steeper gradients occur across the land masses, especially in the elevated regions.

4 | DISCUSSION

It is well known that moisture-bearing air masses tend to rain out on the windward slopes of orographic barriers due to orographic uplift, resulting in drier, clearer atmospheric conditions on the lee side of topographic barriers. Rain-shadow effects occur worldwide, including across
relatively low elevation mountains (Bonacina, 1945; Roe, 2005; Houze, 2012). Orography is known to play a key role in establishing precipitation rain-shadows over the United Kingdom, specifically over parts of the northeast UK mainland (Wheeler, 2013). This effect occurs in both high (e.g. Scotland; McClatchey, 2014) and low elevation regions (e.g. Cornwall; Perry, 2014). Some studies (e.g. Mayes, 1996; 2000; 2013; Wilby et al., 1997) have discussed the role of orography in controlling the precipitation spatial gradients across the United Kingdom, and have discussed the intensification of spatial gradients linked to the NAO state and its control on the mid-latitude westerly flow. Mayes (2000), for example, argued that the more active westerlies seen in the 1980s and 1990s have “coincided with increased regional gradients of rainfall, temperature and sunshine between north-western and south-eastern Britain”. The fact that orographic driven gradients are manifest not only in rainfall but also in temperature and sunshine duration is consistent with the range of physical mechanisms that characterize the Foehn effect (Elvidge and Renfrew, 2016). In a broader context, the interplay between the NAO and orography has also been explored with respect to precipitation variables in central Italy (Vergni et al., 2016) as well as in the United Kingdom (Burt and Howden, 2013). The latter study demonstrated a NAO modulation of local rain-shadow effects due to interaction with orography, and both studies detect local zonal gradients in the relationship between precipitation and the teleconnection pattern.

The SW radiation anomaly patterns illustrated in Figure 7b,c are interpreted to reflect NAO driven changes in the dominant atmospheric moisture transport direction (predominantly west to east advection in NAO+ winter), coupled with topographically driven orographic rainout effects. Windward/leeward differences in SW radiation anomalies are noticeably present even for relatively small distances across relatively low elevation features in both the MÉRA (Figure 7b) and satellite data (thin lines in Figure 7c).

To illustrate the NAO control on wind direction, and therefore on the predominant moisture transport direction, wind roses were constructed for two exemplar locations on the western and eastern land margins of the 54.2 °N latitude transect (Figure S2). The western location is at Belmullet, northwest Ireland, and the eastern location is in northeast England. Wind roses to the left (Figure S2a,c) refer to Belmullet (54.2 °N, 10 °W). Wind roses to the right (Figure S2b,d) refer to the location in northeast England (54.2 °N, 0.33 °W). As in Figure 7, only years whose December–January–February NAO indices are greater or less than one standard deviation around the long-term mean were considered, which correspond to approximately 30% of the time series. Each wind rose is built up from the daily means of wind directions (and speeds, m s⁻¹) within the selected winters.

The dominance of westerly flow during NAO+ conditions is evident, whereas for NAO– conditions a marked increase in the frequency of the other wind directions (e.g. easterlies) and a reduction in westerly flow occurs (Figure S2c,d). Thus, during NAO+ conditions west-facing slopes are typically on the windward side, whereas during NAO– conditions these slopes are more likely to be on the leeward side. The SW radiation anomaly patterns seen in Figure 7 were therefore interpreted to reflect the interplay between the NAO–modulated dominant moisture transport direction and land surface elevation.

The tendency for local SW radiation anomaly minima and maxima to be centred either to the west or east of the topographic barriers to zonal flow, depending on the NAO phase, is further highlighted in Figure 8. Figure 8 shows the results of a peak-lag analysis, in which the geographical position of local SW radiation peaks and troughs for each NAO phase is assessed based on the MÉRA data. For NAO+ (NAO–) winters, SW radiation maxima are typically located to the east (west) of topographic highs (Table 4). Thus, the blue (red) circles denoting the longitudinal position of NAO+ (NAO–) local maxima in SW radiation typically plot below (above) the horizontal dashed line in Figure 8b because they occur to the east (west) of the local topographic high (summit elevation). These longitudinal differences between local minima and maxima correspond approximately to geographical distances in the range 10–100 km. Similarly, for NAO+ (NAO–) winters, SW minima are generally located on or to the west (east) of the topographic peaks.

A Student’s t test on the latitudinal values of the NAO– and NAO+ SW radiation maxima confirmed that they are significantly different from each other (t = 5.61; p = 0.00012). The same test for the SW radiation minima produced a similar result (t = 5.73; p = 9.45 x 10⁻⁵). Figure 8c presents a similar, albeit lower amplitude, peak-lag analysis based on the satellite derived SW radiation anomalies only, indicating that this result is not simply an artefact of the MÉRA reanalysis product (Table S1).

These results are likely to have applications in the assessment of renewable energy (solar) resources and their local sensitivity to the state of large-scale atmospheric teleconnection patterns. The identified longitudinal SW radiation anomaly gradients may offer potential opportunities for local- and regional-scale renewable energy generation balancing, particularly in the context of enhanced seasonal-scale prediction of the NAO (Dunstone et al., 2017). Conversion of SW radiation
anomalies to solar power output is beyond the scope of this contribution and would require a similar analysis for other seasons when absolute values of incident radiation are higher. The relationship between the teleconnection patterns and direct incident SW radiation (as distinct from global, analysed here) also merits further investigation in the context of solar energy because a previous study (Colantuono et al., 2014) demonstrated stronger correlations between the NAO index and direct SW radiation. Other studies (Monforti et al., 2014; Miglietta et al., 2017) have assessed local complementarities between solar and wind power generation for Europe and Italy, showing that while wind and solar power are generally anti-correlated (in the winter season) in both regions,
locally significant positive correlation between these two renewable resources can occur. These effects may in part reflect zonal correlation signal inversions discussed here for incident solar radiation that can manifest themselves over relatively small distances, attributable to Foehn-like effects on the lee side of mountain chains as outlined in this work.

Finally, the Spearman correlation scores were also computed between the NAO index and independent satellite derived December–January–February cloud cover data for the UK and Ireland region (Figure 9) and the North Atlantic sector (Figure S3), for the 1982–2016 period. Figure 9 shows that the same west–east zonal gradients detected using SW radiation data for the UK and Ireland region also emerge when the satellite derived cloud cover data are used.

In contrast with the NAO, the EA pattern exerts only a weak influence on SW radiation, and only some regions such as the Iberian Peninsula, the region of the North Atlantic to the west of Iberia and parts of Scandinavia exhibit consistent correlation patterns in both the ERA-Interim and MERRA-2 datasets with respect to the EA pattern. On this large spatial scale, correlations between winter SW radiation and the SCAND index are patchily developed, but strong and statistically significant positive correlations occur over parts of Scandinavia, the United Kingdom and Ireland in both the MERRA-2 and the ERA-interim datasets.

5 | CONCLUSIONS

Inter-annual winter short wave (SW) solar radiation anomalies in the North Atlantic domain examined here...
are linked strongly to the North Atlantic Oscillation (NAO), the Scandinavian (SCAND) pattern and the east Atlantic (EA) pattern on a range of spatial scales. On a large scale (e.g. the eastern North Atlantic/northwest European domain), meridional (north–south) contrasts in the NAO–SW radiation correlation are dominant. Negative correlations are evident between winter SW radiation and the NAO index over much of the North Atlantic domain, extending eastwards into continental Europe, north of approximately 45° N, with contrasting, generally positive correlations to the south.

On the smaller regional scale of the United Kingdom and Ireland, three reanalysis and multiple observational datasets reveal that considerable west to east complexity exists in the sign of the correlation and magnitude of the anomalies, particularly with respect to the NAO. For example, across the land masses of Ireland and the United Kingdom, multiple zonal shifts in the sign of the NAO–winter SW radiation correlations occur, and the data are not consistent with a simple zonal “seesaw” across the United Kingdom and Ireland. Instead, separate zonal gradients in the NAO–winter SW radiation correlations exist across the land masses of both the island of Ireland and the UK mainland, with the western sectors of both islands showing significant negative NAO–SW radiation correlations. Thus, in a west to east direction, the correlations change zonally from negative to neutral/marginally positive (within the island of Ireland), to strongly negative scores (west of the UK mainland) to positive scores (east of the UK mainland and western North Sea). These results may have implications for the optimal siting of solar generation capacity in the future, but further analysis is required to explore the extent to which these latitudinal variations in these spatial relationships with the NAO and other teleconnections extend to seasons for which the absolute value of incident solar energy is higher than the December–January–February season considered here.

An important finding is that the zonal winter SW radiation anomalies are strongly amplified locally by topographic barriers to zonal flow and atmospheric moisture transport. In strongly NAO+ winters, SW radiation anomalies decrease by up to about 20% in a west to east direction as elevation increases through the west-facing slopes of mountains, interpreted to reflect orographic uplifting of moisture-bearing air masses in the predominantly westerly flow, progressive rainout and less cloudy conditions with increasing elevation. Local maxima in SW radiation anomalies tend to occur close to or marginally to the east (leeward side) of summits, whereas local minima under these NAO+ conditions occur on or marginally to the west of the summits (windward side). Conversely, in the case of strongly NAO– winters, maxima in SW radiation (positive anomalies) occur to the west of mountain summits (more frequent easterly flow) and minima occur at or to the west of summits.

These observations are interpreted to reflect orographic uplift and rainout effects, with generally clearer sky and positive SW radiation anomalies on the lee-side of mountainous terrain. These effects are evident even for relatively modest topographic features (e.g. hills with an elevation of less than a few hundred metres) that occur along the studied transect. The sign of the correlations can switch over relatively short distances, of the order of 10–100 km.

As the solar energy industry expands, greater attention should be paid to assessing the spatiotemporal variability of the incident SW radiation because this may be important for local balancing of solar energy resources, particularly in negative NAO winters when wind capacity factors are low and energy demand is high.

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