Examining the North Atlantic Oscillation, East Atlantic Pattern, and Jet Variability since 1685

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(Manuscript received 18 February 2019, in final form 20 June 2019)

ABSTRACT

Recent studies have stressed the key role of the east Atlantic (EA) pattern and its interactions with the North Atlantic Oscillation (NAO) in Euro-Atlantic climate variability. However, instrumental records of these leading patterns of variability are short, hampering a proper characterization of the atmospheric circulation beyond the mid-nineteenth century. In this work, we present the longest (1685–2014) observational-based records of winter NAO and EA indices as well as estimates of the North Atlantic eddy-driven jet stream speed and latitude for the same period. The time series display large variability from interannual to multidecadal time scales, with, for example, positive (negative) EA (NAO) phases dominating before 1750 (during much of the nineteenth century). By identifying winters with different combinations of NAO/EA phases in the twentieth century, our results highlight the additional role of EA in shaping the North Atlantic action centers and the European climate responses to NAO. The EA interference with the NAO signal is stronger in precipitation than in temperature and affects areas with strong responses to NAO such as Greenland and the western Mediterranean, which prevents simplistic relationships of natural proxies with NAO. The last three centuries uncover multidecadal periods dominated by specific NAO/EA states and substantial interannual-to-centennial variability in the North Atlantic jet stream, thus providing new evidence of the dynamics behind some outstanding periods. Transitions in the NAO/EA phase space have been recurrent and pin down long-lasting anomalies, such as the displacement of the North Atlantic action centers in the late twentieth century, besides some disagreements between NAO indices.

1. Introduction

The North Atlantic eddy-driven jet stream governs the atmospheric circulation in the Euro-Atlantic sector and has a mediating role between the large-scale patterns of

atmospheric variability, synoptic weather regimes, and ultimately regional climates. The North Atlantic Oscillation (NAO) is the main pattern of atmospheric variability in the Euro-Atlantic sector (e.g., [Pinto and Raible 2012](#), and references therein). With the exception of the high summer (July–August; [Folland et al. 2009](#)), the spatial pattern of the NAO is characterized by a meridional

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DOI: 10.1175/JCLI-D-19-0135.1

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dipole in the pressure field between the Azores high and Icelandic low, also referred to as the North Atlantic action centers. Positive phases of the NAO are associated with warm and wet conditions in central and northern Europe as well as precipitation deficits in southern Europe, while the opposite pattern is observed during negative phases (e.g., [Trigo et al. 2002](#)). However, climatic anomalies in other European regions are not properly accounted for by the NAO (e.g., [García-Herrera and Barriopedro 2018](#), and references therein). Besides the NAO, other large-scale patterns of atmospheric circulation variability are also known to play a significant role in the European climate, particularly the east Atlantic (EA) and Scandinavian (SCAND) patterns ([Comas-Bru and McDermott 2014](#); [Jerez and Trigo 2013](#); [Trigo et al. 2008](#)). In addition, previous studies have shown that the NAO signal in surface climate cannot be considered stationary (e.g., [Vicente-Serrano and López-Moreno 2008](#); [Raible et al. 2014](#)). Sources of nonstationary NAO signals include migrations and intensity changes in the North Atlantic action centers (e.g., [Barriopedro et al. 2014](#); [Comas-Bru and McDermott 2014](#)). These limitations to characterize the European climate variability can be partially overcome by complementing the NAO with other patterns of variability.

The second pattern of climate variability in the region is the EA pattern ([Wallace and Gutzler 1981](#); [Barnston and Livezey 1987](#)) traditionally described as a dipole in the pressure field, whose centers of variability are shifted southeastwards and more zonally oriented as compared to those of the NAO. However, recent works characterize it as a well-defined sea level pressure (SLP) monopole south of Iceland and west of Ireland (e.g., [Moore et al. 2013](#); [Comas-Bru and McDermott 2014](#); [Comas-Bru and Hernández 2018](#)). These works have indicated that the EA also modulates the location of the North Atlantic action centers and can shape the surface responses to the NAO. For example, the EA played a key role in determining the climate anomalies during the outstanding negative NAO episodes associated with the extremely cold European events of December 2010 and winter 2006/07 ([Moore et al. 2011](#); [Moore and Renfrew 2012](#)). Besides, [Bastos et al. \(2016\)](#) show that both patterns influence European land CO₂ sink, underscoring the necessity of characterizing better their joint effects.

The variability of the North Atlantic eddy-driven jet stream can be largely described using a combination of NAO and EA. These indices reflect winter changes in the latitude and speed of the North Atlantic jet stream ([Woollings et al. 2010](#); [Woollings and Blackburn 2012](#)). In turn, these parameters of the jet are strongly related to the location of the North Atlantic storm tracks (e.g., [Pinto et al. 2007](#)) and the occurrence of wavelike weather

regimes (e.g., [Woollings et al. 2018](#)). The latitude and waviness of the North Atlantic jet also modulate the occurrence of midlatitude weather extremes in observational and model studies ([Mahlstein et al. 2012](#); [Röthlisberger et al. 2016](#)). Indeed, future regional changes in European climate strongly depend on the responses of the jet stream to climate change, which are subject to large uncertainties (e.g., [Zappa and Shepherd 2017](#); [Peings et al. 2018](#)). This limited understanding of the jet stream variability is partially hampered by the short observational record of wind measurements in the historical period, which are mostly constrained to the twentieth century ([García-Herrera et al. 2018](#), and references therein).

In recent decades, much work has been done to extend NAO indices back in time. The longest high-resolution series are based on indirect proxy records (e.g., [Cook et al. 1998](#); [Appenzeller et al. 1998](#); [Ortega et al. 2015](#); [Sjolte et al. 2018](#), and references therein), which tend to show notable discrepancies in the pre-industrial period ([Schmutz et al. 2000](#); [Schultz et al. 2015](#)), while those relying on observations only reach the eighteenth century (e.g., [Jones et al. 1997](#); [Luterbacher et al. 2001](#)). As a consequence, the variability of the NAO further back in time remains only partially answered ([Hurrell et al. 2003](#)). Less effort has been made to extend the EA backward beyond the instrumental record. [Moore and Renfrew \(2012\)](#) derived an EA index since 1870 based on historical SLP data, which have recently been updated and extended back to 1851 by [Comas-Bru and Hernández \(2018\)](#). However, the evolution of the EA before the mid-nineteenth century remains unknown, and the few existing studies considering the NAO, EA, and their interactions are limited to the twentieth century. The integrated assessment of these indices and their joint exploitation to infer the variability of the eddy-driven jet in the historical period is also missing.

In this paper we use the directional indices (DIs) built from wind direction observations over the English Channel ([Mellado-Cano et al. 2018, 2019](#), manuscript submitted to *Climate Dyn.*) to extend back current records of NAO and EA, analyze their multiple combinations and exploit them to reconstruct the variability of the North Atlantic jet stream since the end of the seventeenth century. The derived winter series constitute powerful tools to characterize the Euro-Atlantic climate variability from high to low frequencies, since they are based on observations and cover the 1685–2014 period, extending current records beyond the industrial period.

2. Data

We employ the time series of the DIs ([Mellado-Cano et al. 2018, 2019](#), manuscript submitted to *Climate Dyn.*),

TABLE 1. Performance of the first (SVD1) and second (SVD2) singular vectors of the DIs with respect to traditional NAO and EA indices, as diagnosed by the Pearson correlation coefficient and RMSE for 1951–2001. Significant correlations at $p < 0.01$ are highlighted in bold. All indices are standardized for the 1951–2001 period.

Index	Definition	Period	R : SVD1/SVD2	RMSE: SVD1/SVD2
NAO				
CPC NOAA	First rotated PC of standardized geopotential height anomalies at 500 hPa for (20°–90°N)	1950–2014	0.61 /–0.22	0.88/1.54
Hurrell (1995)	First PC of SLP anomalies over the Atlantic sector (20°–80°N, 90°W–40°E)	1901–2014	0.49 /–0.18	1.00/1.52
Jones et al. (1997)	Normalized pressure difference between Azores [Ponta Delgada (37.7°N, 25.7°W)] and Iceland [Akureyri (65.7°N, 18.1°W) and Stykkisholmur (65.0°N, 22.8°W)]	1824–2014	0.74 /–0.17	0.72/1.51
Luterbacher et al. (2002)	Standardized SLP difference between Azores and Iceland, each region defined as the mean of four grid points on a 5° × 5° grid	1685–2001	0.77 /–0.24	0.68/1.56
EA				
CPC NOAA	Second rotated PC of standardized geopotential height anomalies at 500 hPa for (20°–90°N)	1950–2014	0.34/0.54	1.14/0.95
Second EOF SLP ERA-20C	Second PC of the monthly standardized area-weighted SLP anomaly over (10°–80°N, 100°W–40°E)	1901–2010	–0.37/0.71	1.64/0.75
Comas-Bru and Hernández (2018)	Composite of EA series constructed from two historical records (Bergen Florida and Valentia) and five reanalyses	1852–2014	0.18/ 0.70	1.27/0.77

which have monthly resolution and cover the 1685–2014 period, with only some missing months. They are derived from daily wind direction observations obtained over the English Channel, mostly kept in ships' logbooks (García-Herrera et al. 2018) and measure the persistence of the wind (in percentage of days in the month) in the four main cardinal directions: northerly, southerly, easterly, and westerly. The reader is referred to Mellado-Cano et al. (2019, manuscript submitted to *Climate Dyn.*) for further information on data sources and the construction of the DIs. These indices have been shown to provide additional information to that of the NAO (Vicente-Serrano et al. 2018; Mellado-Cano et al. 2019, manuscript submitted to *Climate Dyn.*), also capturing unusual periods in the recent (Barriopedro et al. 2014) and preindustrial (Mellado-Cano et al. 2018) eras. Therefore, they should be considered as optimal benchmarks to characterize the Euro-Atlantic climate variability of the last three centuries.

The DIs are herein employed to construct NAO and EA indicators for the 1685–2014 period, from which the North Atlantic jet stream speed and latitude can be inferred. We have focused on winter [December–February (DJF)] means, when NAO and EA are more active dynamically and explain the largest variance of atmospheric circulation (Hurrell et al. 2003; Trigo et al.

2008; Comas-Bru and Hernández 2018). For comparative purposes, we have also used other NAO and EA indices, obtained from different data sources, fields, domains and methodologies. They include (Table 1): the principal component (PC) NAO index of Hurrell (1995) and the station-based indices of Jones et al. (1997) and Luterbacher et al. (2001), all derived from SLP data; the EA index of Comas-Bru and Hernández (2018), obtained from a multireanalysis PC-based approach; the EA index defined as the second PC from SLP data of the twentieth-century ECMWF Re-Analysis (ERA-20C; Poli et al. 2016); the NAO and EA indices provided by the Climate Prediction Center (CPC) of the NOAA (<https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>) based on a rotated PC analysis of geopotential height at 500 hPa (Z500) from the NCEP–NCAR reanalysis (Kalnay et al. 1996).

To explore the surface signatures of NAO and EA indices we used monthly near-surface temperature from the CRU TS3 database of the Climatic Research Unit (Harris et al. 2014) and total monthly precipitation from the Global Precipitation Climatology Centre (GPCC; Schamm et al. 2014). They are provided on a grid of 1° × 1° longitude–latitude over land for 1901–2014. In addition, monthly Z500 and SLP data were obtained from the ERA-20C reanalysis with 2.5° × 2.5° spatial resolution.

Finally, daily parameters of the North Atlantic jet stream were computed from zonal wind data of the ERA-20C reanalysis for the 1901–2010 period, based on the methodology of Woollings et al. (2010). The low-level (925–700 hPa) mean zonal wind was first smoothed with a low-pass (10-day) filter and averaged from 0° to 60°W. For each day, the jet location corresponds to the latitude between 15° and 75°N where this zonal-mean zonal wind maximizes, and the jet speed is defined as the zonal wind at that latitude. These daily series were averaged to obtain winter means.

3. Results

a. NAO and EA indices

A singular value decomposition (SVD) analysis (Wilks 2011) was applied to the 1685–2014 winter series of the four DIs, retaining the two first singular vectors, which explain 44% and 35% of the total variance, respectively. Similar results were obtained by applying the same analysis to the DIs series of each calendar month separately (December: 45%, 34%; January: 43%, 36%; February 44%, 35%). Figure 1 shows the regression patterns of SLP (shading) and Z500 (contours) onto these singular vectors. Despite their regional character, the singular vectors are associated with substantial atmospheric circulation anomalies over large areas of the Euro-Atlantic sector, including changes in the location/intensity of the North Atlantic action centers. The first (second) singular vector reflects a meridional (almost zonal) dipole that resembles the NAO (EA) pattern. Overall, their signatures in near-surface climate fields (temperature and precipitation) also agree well with those reported elsewhere for traditional NAO (e.g., Trigo et al. 2002) and EA (Comas-Bru and McDermott 2014) indices (not shown). Divergences with instrumental indices could be due to differences in their underlying dynamical information (e.g., ageostrophic component of the wind missed by indices based on pressure gradients) and the target region (an eastern location of the English Channel with respect to the centers of variability of the NAO). However, in general, they are not substantially larger than the discrepancies obtained between different instrumental indices (not shown).

To further explore this question, Table 1 shows the Pearson correlation coefficients and the root-mean-square errors (RMSEs) between these singular vectors and different NAO and EA indices for the 1951–2001 common period of all indices. All NAO (EA) indices display significant correlations at $p < 0.01$ with the first (second) singular vector of the DIs

FIG. 1. Regression coefficients of the winter SLP (shading) and Z500 (contours) anomaly fields onto (a) the first and (b) the second singular vector of the DIs for the period 1901–2010.

and insignificant or very weak correlations with the second (first) one. The same result is obtained if we analyze the full period of each reference index (not shown). The highest correlation with the first singular vector corresponds to the NAO index of Jones et al. (1997), and remains constant with time (e.g., $r = 0.67$, $p < 0.01$ for their common overlapping period 1824–2014). Similar correlation coefficients are obtained between the second singular vector and the EA index of Comas-Bru and Hernández (2018) for the 1950–2014 period. However, in this case, the relationship tends to weaken back in time ($r = 0.48$, $p < 0.01$ for their common overlapping period 1852–2014), arguably because of methodological issues in the definition of that EA index, which involves a multireanalysis ensemble mean. Still, the correlations observed with the second singular value are of similar magnitude to those obtained between other EA indices (e.g., $r = -0.58$ for the EA indices of CPC and Valencia SLP series), stressing the differences between its multiple definitions.

On the other hand, the RMSE of the first and second singular vectors with respect to the aforementioned NAO and EA indices, respectively, is ~ 0.7 , slightly higher than those obtained between some canonical indices of the NAO [~ 0.6 , e.g., for the NAO indices of Jones et al. (1997) and CPC], and within the range of the values retrieved among traditional EA indices [e.g., ~ 0.8 for the EA indices of Comas-Bru and Hernández (2018) and CPC]. As compared to the reference values derived from the intercomparison of instrumental indices for the 1951–2001 period, the skill of the second singular vector is slightly better than that of the first one. This is partially explained by the large diversity (and hence performances) of EA indices, as compared to those of NAO, and the fact that the first singular vector performs worse for PC-based than station-based NAO indices. Indeed, if the comparison is limited to station-based NAO definitions, we obtain similar skills for the two singular vectors. Therefore, the first and second singular vectors of the DIs can be considered good indicators of the NAO and EA, respectively, and hereafter they will be referred to as NAO_{DI} and EA_{DI} .

Figures 2a and 2b show the standardized (1685–2014) winter series of NAO_{DI} and EA_{DI} for the last 330 years (black lines), with red (blue) colors indicating 7-yr running mean values above (below) zero. NAO_{DI} captures the most outstanding anomalous periods reported in previous studies, including the dominant positive phases during 1900–30 and 1970–2000 as well as the persistent negative phase between 1820 and 1845 and the 1960s (Jones et al. 1997; Visbeck et al. 2001; Slonosky and Yiou 2001; Luterbacher et al. 2001; Trouet et al. 2009; Cornes et al. 2013). The NAO_{DI} series also displays extreme negative values for the well-known cold winters of 1916/17 ($\text{NAO}_{\text{DI}} = -1.97$ SD) and 1962/63 ($\text{NAO}_{\text{DI}} = -2.30$ SD) (Cornes et al. 2013; Greatbatch et al. 2015). The same level of agreement applies to the EA_{DI} index, which captures the predominance of positive phases at the end of the nineteenth century and the subsequent reversal at the beginning of the twentieth century (Comas-Bru and Hernández 2018). It also reflects extreme episodes on different time scales, such as the recurrent negative values in the 1950s reported by the CPC EA index or the extreme 2004/05 winter ($\text{EA}_{\text{DI}} = -1.40$ SD). Therefore, our indices are excellent indicators of outstanding periods associated with prominent anomalies of the two leading patterns of atmospheric variability over the Euro-Atlantic sector, as reported by the instrumental record. They provide the longest observational-based series of NAO and EA, extending current records by more than 150 years in the case of EA. Superimposed on the aforementioned signatures, our series also show large variability on very

FIG. 2. Winter standardized series of: (a) NAO_{DI} and (b) EA_{DI} for 1685–2014 (in SD, black line) and a 7-yr running mean (gray line), with red (blue) shading indicating periods above (below) the 1695–2014 mean. Vertical gray shading identifies periods of missing data.

low frequencies (multidecadal and longer). The EA_{DI} negative phase dominated during the 1750–1950 period (blue in Fig. 2b), while the positive phase prevailed before 1750 and after 1950. The NAO_{DI} shows a more alternating behavior until 1800, with a certain prevalence of the negative phase along the nineteenth century.

b. The combined role of NAO and EA in Euro-Atlantic climate

To determine the joint effects of the NAO_{DI} and EA_{DI} (Fig. 1) on the Euro-Atlantic climate we have partitioned the 2D $\text{NAO}_{\text{DI}}/\text{EA}_{\text{DI}}$ phase space, thus defining four combinations of the NAO_{DI} and EA_{DI} indices (Fig. 3): $\text{NAO}_{\text{DI}}+/\text{EA}_{\text{DI}}+$, $\text{NAO}_{\text{DI}}+/\text{EA}_{\text{DI}}-$, $\text{NAO}_{\text{DI}}-/\text{EA}_{\text{DI}}+$, and $\text{NAO}_{\text{DI}}-/\text{EA}_{\text{DI}}-$. The analysis is restricted to the period of available data in the reanalysis and observational datasets (1901–2014). These groups only contain winters with absolute values of NAO_{DI} and EA_{DI} larger than 0.5 SD. This criterion provides a balanced and sufficient number of cases (see the left bottom corner of each panel in Fig. 3), excluding winters with weak signals of either NAO_{DI} or EA_{DI} . The resulting composites for each combination are weaker but qualitatively similar if the above threshold is omitted, therefore cataloguing all winters in one of the four groups (not shown). Our approach is similar to that adopted by Comas-Bru and McDermott (2014), except that they only considered two groups formed by winters

FIG. 3. Winter composites of: (a)–(d) near-surface temperature (shading, in $^{\circ}\text{C}$) and geopotential height at 500 hPa (contours, in dam) anomalies; (e)–(h) precipitation (shading, in percentage of normals) and SLP (contours, hPa) anomalies for different combinations of NAO_{DI} and EA_{DI} indices with absolute values larger than 0.5 SDs: (a) $\text{NAO}_{\text{DI}}^{+}/\text{EA}_{\text{DI}}^{+}$, (b) $\text{NAO}_{\text{DI}}^{+}/\text{EA}_{\text{DI}}^{-}$, (c) $\text{NAO}_{\text{DI}}^{-}/\text{EA}_{\text{DI}}^{+}$, and (d) $\text{NAO}_{\text{DI}}^{-}/\text{EA}_{\text{DI}}^{-}$. Anomalies are computed with respect to 1901–2010. Numbers in the left bottom corner of each panel represent the number of cases employed in each composite. Only temperature and precipitation anomalies that are significantly different ($p < 0.05$) from the climatology are shown, after a 5000-trial bootstrap test. Horizontal red arrows and vertical purple lines summarize the composited winter anomalies of the jet speed and latitude respectively, with the length being proportional to the anomaly. Eastward (westward) red arrows indicate a strengthening (weakening) of the jet. Purple lines pointing upward (downward) indicate a poleward (equatorward) shift of the jet.

with equal and opposite phases of NAO and EA, thus disregarding asymmetric responses between positive and negative phases, as those reported for the NAO (e.g., Cornes et al. 2013).

To lend further support to our results, this analysis was repeated for the same period of the NAO and EA indices of Jones et al. (1997) and Comas-Bru and Hernández (2018), respectively (Fig. 4). Note that differences

FIG. 4. As in Fig. 2, but for the NAO of Jones et al. (1997) and the EA of Comas-Bru and Hernández (2018).

between Figs. 3 and 4 can be due to discrepancies between indices and/or the resulting number of winters employed in the composites. Still, these differences mainly concern to the areal extent of statistical significance rather than the sign of the anomalies, and are not dramatically larger than those observed between the indices of Fig. 4 and other instrumental series of the NAO and EA (not shown).

Figure 3 shows the composites of winter anomalies in atmospheric circulation (Z500 and SLP, contours) and near-surface (2-m temperature and precipitation, shading) fields for each combination of indices. All NAO_{DI}/EA_{DI} combinations display a pressure dipole, but exhibit differences in

its location, intensity, and spatial extension. When the NAO_{DI} and EA_{DI} are in the same phase (Figs. 3a,e,d,h), the southern center of action shifts eastward toward Europe, while the northern center retreats toward the Atlantic (see also Figs. 4a,e,d,h). As a consequence, the North Atlantic jet stream displays changes in the typical southwest–northeast tilt. This can occur at expense of the westerlies (i.e., a wavier pattern; Figs. 3d,h, NAO_{DI}−/EA_{DI}−) or be accompanied by a stronger jet (i.e., an enhanced southwest–northeast tilt of the jet; Figs. 3a,e, NAO_{DI}+ /EA_{DI}+). This is supported by the corresponding composites of jet speed anomalies, which show a reinforced jet for NAO_{DI}+ /EA_{DI}+ and the opposite for NAO_{DI}−/EA_{DI}− (horizontal red arrows in

Figs. 3a,d), with relatively weaker anomalies in the jet latitude. On the other hand, when the NAO_{DI} and EA_{DI} have opposite phases (Figs. 3b,f,c,g) the northern and southern anomaly centers shift toward Europe and the Atlantic, respectively, as compared to winters of equal phases, resulting in a meridionally oriented dipole (see also Figs. 4b,f,c,g). In this case the anomalies in the jet latitude are larger than those obtained when both indices are in the same phase, with a poleward shift of the jet for NAO_{DI+}/EA_{DI-} (vertical red arrows in Figs. 3b,f) and equatorward migrations for NAO_{DI-}/EA_{DI+} (Figs. 3d,h).

Overall, our results indicate that NAO_{DI} and EA_{DI} induce anomalies of the same sign in the jet speed but have opposite effects in the jet latitude. The role of EA_{DI} seems to occur through the tilt of the jet, with the positive phase favoring a stronger and reinforced southwest–northeast tilt (i.e., southward displacements in the North Atlantic and the opposite in the exit region of Europe). Using daily data, Woollings et al. (2010) identified three nodal locations for the North Atlantic jet stream in northern, central, and southern latitudes. According to our results, winters with a central jet position tend to occur when NAO_{DI} and EA_{DI} display the same sign, while meridional displacements dominate in winters of opposite phases, being poleward (equatorward) for NAO_{DI+}/EA_{DI-} (NAO_{DI-}/EA_{DI+}).

We next turn attention to the composites of surface climate anomalies for the different partitions of the NAO_{DI}/EA_{DI} phase space. The sign of the temperature anomalies is largely determined by the NAO_{DI} , with warmer winters in most of continental Europe for all combinations with positive NAO_{DI} phases (Figs. 3a,b) and relatively colder conditions for winters of negative NAO_{DI} (Figs. 3c,d). However, the EA_{DI} shapes this overall picture by modulating the regions with significant temperature anomalies, which tend to shift from central to northeastern Europe when the EA_{DI} changes from positive (Figs. 3a,c) to negative (Figs. 3b,d) phases. Analogously, Greenland exhibits larger anomalies when the EA_{DI} phase is opposite to that of NAO_{DI} (Figs. 3b,c and 4b,c). In addition, there are areas where the additional role of one of the indices is able to alter the expected temperature response to the other. For example, under NAO_{DI+} , southwestern Europe tends to exhibit warming if EA_{DI} is in a positive phase (Fig. 3a), but no significant signals for EA_{DI-} (Fig. 3b). Therefore, the reported signatures of EA in Iberian winter temperature (Sáenz et al. 2001; Toreti et al. 2010; Hernández et al. 2015; Sánchez-López et al. 2016) change under the additional effects of NAO. Similarly, Greenland warming, typically associated with pervasive blocking conditions during negative NAO phases (Davini et al. 2012; Hanna et al. 2016), is more pronounced for EA_{DI+} (Fig. 3c) but

substantially damped and even reversed under EA_{DI-} (Fig. 3d).

On the other hand, precipitation anomalies (Fig. 3, right panels) are overall more sensitive to the concomitant state of NAO_{DI} and EA_{DI} than temperature, although the areas displaying significant responses are comparatively reduced (see also Fig. 4, right panels). Widespread precipitation responses occur in winters with opposite phases of NAO_{DI} and EA_{DI} (Figs. 3f,g), since these combinations reflect the largest anomalies in the jet latitude, which largely controls the trajectories of the moisture transport into Europe. As such, when acting together, the EA_{DI} substantially alters the precipitation responses prompted by the NAO_{DI} . For example, NAO_{DI-}/EA_{DI+} (Fig. 3g) is the only combination leading to significant precipitation increases in the Iberian Peninsula. Surprisingly, this region is among the areas with the strongest responses to the NAO (e.g., Trigo et al. 2002), meaning that the EA_{DI} can even overwhelm the NAO effects, even in canonical regions of important NAO fingerprints. These unexpected results are in agreement with the opposite effects of NAO_{DI} and EA_{DI} on the jet latitude. During NAO_{DI-}/EA_{DI+} both patterns contribute to a southward shift of the jet and enhanced storminess in southern Europe (Fig. 3g). Precipitation increases are particularly pronounced in southwestern Europe and weaken eastward, the latter being in agreement with the extension of high-pressure anomalies toward central and eastern Europe. In contrast, the NAO_{DI-}/EA_{DI-} combination is less efficient in displacing the jet because of their competing effects in the jet latitude (Figs. 3d,h). In this case, positive pressure anomalies are confined to eastern Atlantic midlatitudes, impeding the entrance of storm tracks to the westernmost sector of southern Europe (see also Figs. 3d,h). The resulting weaker and wavier jet allows storm tracks to be diverted northward or southward of the high-pressure center (not shown). This configuration leaves a corridor of low pressure through northern Africa toward eastern Mediterranean that has also been associated with anomalies in the African jet (Gaetani et al. 2011). These results indicate that the Mediterranean precipitation responses in NAO– composites arise from mixing winters with larger precipitation signals in either western or eastern Mediterranean, which are influenced by the additional role of EA. A similar behavior is found for positive NAO_{DI} phases (Figs. 3e,f). As such, under active EA phases, the canonical precipitation signature attributed to NAO in southwestern Europe only manifests when EA is in the opposite phase. If EA is in phase with the NAO, the signal shifts eastward, leading to weaker precipitation responses in that region (see also Fig. 4). This west–east shift of the canonical NAO signal

TABLE 2. Stepwise regression model of the (top) jet speed and (bottom) latitude standardized anomalies onto the NAO_{DI} and EA_{DI} indices for the 1945–2010 calibration period (first two columns) and the 1901–44 validation period (last two columns). For the calibration period, the first two rows indicate the regression coefficients for each index with their p values in parentheses (based on a t test with null hypothesis of zero coefficient). The last row shows the multiple correlation coefficient of the SRM (i.e., explained variance by the selected predictors) with the p value of the goodness-of-fit F statistic in parentheses. For the validation period, the following diagnostics of the reconstructed series are shown: Pearson correlation coefficient (R , with the p value in parentheses), RMSE (in SD) and RE (dimensionless)/CE (dimensionless).

Predictand	Predictor	Calibration	Diagnostic	Validation
Jet speed	NAO_{DI}	0.68 (<0.01)	R	0.79
	EA_{DI}	0.22 (<0.02)	RMSE	0.59
	All	0.66 (<0.01)	RE/CE	0.65/0.61
Jet latitude	NAO_{DI}	0.30 (<0.01)	R	0.38
	EA_{DI}	−0.37 (<0.01)	RMSE	0.89
	All	0.43 (<0.01)	RE/CE	0.12/0.11

induced by the EA may explain the reported anti-correlation in drought severity between western (Iberia) and eastern (Turkey) Mediterranean for the twentieth century (Sousa et al. 2011)

c. NAO, EA, and jet stream since 1685

In the previous section we have reported how different combinations of NAO_{DI} and EA_{DI} have profound implications in the Euro-Atlantic climate variability through their effects in the latitude and speed of the eddy-driven jet. Herein, we explore the whole 1685–2014 record to address the relative frequencies of NAO_{DI}/EA_{DI} combinations and their relevance to explain anomalous periods of the last three centuries. To further exploit the complementary information of these indices on the jet stream, we performed a stepwise regression model (SRM; Wilks 2011; Bruce and Bruce 2017) using either the latitude or speed of the jet as the dependent variable and the NAO_{DI} and EA_{DI} as the predictors. SRM finds the optimal combination of predictors by proceeding forwards and backward in the selection of predictors (i.e., adding and removing explanatory variables), and retaining only those that increase significantly the explained variance of the predictand. The SRM is calibrated over the 1945–2010 period, which samples enough the NAO_{DI}/EA_{DI} phase space (similar results are obtained for the full 1901–2010 period). The regression coefficients of the selected predictors are then employed to reconstruct the latitude and speed of the jet stream for the 1685–2014 period, using the correlation coefficient, RMSE, reduction error (RE; e.g., Luterbacher et al. 2004), and coefficient of efficiency (CE; Briffa et al. 1988; Cook et al. 1999) as diagnostics over the 1901–44 validation period.

The SRM is able to explain a significant amount of the jet variance, being more skillful for the jet speed ($r = 0.66$) than for the jet latitude ($r = 0.43$) in the validation period (Table 2). Similar results are obtained for the other diagnostics, with positive RE and CE (i.e., better

predictions than climatology). The performance of our SRM is also similar to that obtained from instrumental NAO and EA indices (not shown). For both jet parameters, the NAO_{DI} and EA_{DI} enter in the SRM, confirming their independent influences on the jet. As inferred from the regression coefficients of the SRM, NAO_{DI} and EA_{DI} have opposite (equally signed) effects on the jet latitude (speed), but with different loadings.

Figure 5a shows the frequency of the dominant NAO_{DI}/EA_{DI} combination for each 7-yr interval of the 1685–2014 period, with the color identifying the specific pair: $NAO_{DI}+/EA_{DI}+$, $NAO_{DI}+/EA_{DI}-$, $NAO_{DI}-/EA_{DI}+$, or $NAO_{DI}-/EA_{DI}-$. Herein, all winters are catalogued in one of these four groups based on the sign of the indices. Moreover, Fig. 5b displays the 7-yr mean standardized anomalies of the jet latitude reconstructed from NAO_{DI} and EA_{DI} , with orange (blue) colors indicating strengthening (weakening) of the jet for the same 7-yr mean periods. When the whole period is considered, there is a balanced frequency of NAO_{DI}/EA_{DI} combinations, with $NAO_{DI}-/EA_{DI}+$ displaying slightly lower frequencies (22.4%) than the rest. For the whole period, and independently of the combination considered, the EA_{DI} is the dominant pattern (i.e., it displays absolute values larger than NAO_{DI}) in nearly 50% of the winters, indicating that the last three centuries cannot be properly described by the state of the NAO_{DI} alone. Accordingly, the jet displayed substantial variability from interannual to centennial time scales, both in terms of intensity and latitudinal location. In spite of this, there are no hints of long-term trends or exceptional values for the last decades in the context of the last 330 years.

In addition, there are some periods that stand out from the dominance of a given NAO_{DI}/EA_{DI} combination. For example, 1720–40 was characterized by recurrent positive phases of NAO_{DI} and EA_{DI} (Fig. 5a) as well as large anomalies in the jet (i.e., a stronger and

FIG. 5. (a) Frequency and type of the dominant winter $\text{NAO}_{\text{DI}}/\text{EA}_{\text{DI}}$ combination for each 7-yr interval of the 1685–2014 period, with the black color indicating intervals without a dominant combination. Vertical gray shading identifies periods of missing data; (b) reconstructed jet latitude anomaly (in SD with respect to 1685–2014) with a 7-yr running mean (gray line). The corresponding 7-yr running mean of the jet speed anomalies are shown in color, with orange (blue) colors shading denoting a strengthening (weakening) of the jet.

equatorward shifted jet, Fig. 5b), involving warm (cold) winters in north-central Europe (Greenland and eastern Mediterranean basin), as well as relatively dry (wet) conditions over Mediterranean (northern European) regions. This result provides a dynamical evidence of the reported shift toward increased precipitation in northern Europe (Jacobeit et al. 2003; Pauling et al. 2006) as well as the drought conditions in the south (Domínguez-Castro et al. 2008) that followed the Late Maunder Minimum (LMM, 1700–15). Our time series also allow explaining individual extreme years. For example, the winter of 1783/84 that followed Laki's eruption was extremely cold around the circum-North Atlantic. D'Arrigo et al. (2011) suggested that the unusual conditions were caused by a negative NAO phase and a warm El Niño–Southern Oscillation event. Our results confirm the former ($\text{NAO}_{\text{DI}} = -1.54$ SD) event but also uncover a key role of the EA_{DI} , which was also in its negative phase (-1.04 SD), both contributing to an extreme weakening of the jet.

Now, we turn attention to periods of contrasting phases between the NAO_{DI} and EA_{DI} , which are those displaying the largest displacements of the jet stream. There were recurrent periods of $\text{NAO}_{\text{DI}}-/ \text{EA}_{\text{DI}}+$

through 1685–2014 (Fig. 2) characterized by southward excursions of the jet stream (Fig. 5b), including some decades of the LMM (Mellado-Cano et al. 2018). Although the period 1825–75 was mostly dominated by negative phases of NAO_{DI} and EA_{DI} , the EA_{DI} was in a positive phase during the 1840s (blue shading in Fig. 5b). Interestingly, Cornes et al. (2013) and Luterbacher et al. (2001) reported negative phases of the NAO during the 1830s, but their indices disagree on the 1840s. Our results indicate that a shift in the phase of the EA_{DI} prompted circulation changes (similar to those observed from Fig. 3d to Fig. 3c), which are not captured in the same way by the different NAO indices. On the other hand, Santos et al. (2013) described two recent and exceptional winters in the North Atlantic sector (2009/10 and 2011/12) with a contrasting behavior in the jet stream. In addition to the extreme negative (positive) NAO phase reported therein, our series evidence a measurable influence of $\text{EA}_{\text{DI}}+$ ($\text{EA}_{\text{DI}}-$) in the southwardly (northwardly) shifted jet of 2009/10 (2011/12).

The combination $\text{NAO}_{\text{DI}}+/ \text{EA}_{\text{DI}}-$ dominated several intervals of the 1685–2014 period, most notably the beginning of the twentieth century (Fig. 5a), which was characterized by poleward excursions of the jet stream

(Fig. 5b). This was followed by a strengthening and more frequent southward migrations of the jet at the end of the twentieth century, coinciding with a transition toward EA_{DI+} winters during 1975–2000. This shift from EA_{DI-} to EA_{DI+} (Figs. 3e,f) is timely with the well-reported migration of the North Atlantic action centers (e.g., Jung et al. 2003; Vicente-Serrano and López-Moreno 2008). Similar transitions have been recurrent in the last three centuries (e.g., from NAO_{DI+}/EA_{DI+} to NAO_{DI+}/EA_{DI-} at the beginning of the twentieth century, or from NAO_{DI-}/EA_{DI+} to NAO_{DI-}/EA_{DI-} in the mid-nineteenth century). Therefore, our results stress that long-lasting anomalies (e.g., shifts) in the North Atlantic action centers can to a large extent be explained by different combinations of these indices and have occurred frequently in the last three centuries.

4. Summary and discussion

We present an almost continuous observational-based record of winter NAO, EA, and North Atlantic jet stream estimates for the last 330 years. These are the longest observational times series of the North Atlantic atmospheric circulation currently available and constitute a valuable tool to study the European climate variability beyond the industrial era, when only proxy-based NAO indices can be found. They are obtained from the DIs (Mellado-Cano et al. 2019, manuscript submitted to *Climate Dyn.*), which measure the persistence of the wind in the four cardinal directions based on wind direction observations over the English Channel. This strategic area (at the exit zone of the jet stream) and the dynamical links between wind persistence and pressure gradients make the DIs optimum indicators of the circulation signatures on larger spatial scales and surface climate anomalies over large areas of Europe, particularly when considered altogether (Mellado-Cano et al. 2019, manuscript submitted to *Climate Dyn.*).

Our indices are significantly correlated with traditional NAO and EA series, with comparable skill to that obtained between some instrumental indices (particularly of the EA), also capturing their main signatures on European temperature and precipitation and outstanding periods of the instrumental record. The combined influence of NAO and EA on the Euro-Atlantic climate variability is addressed for the twentieth century by partitioning the NAO/EA phase space into four groups of winters. When both indices are in the same phase the southern action center extends toward Europe, while winters of opposite phases are characterized by the westward retreat of the southern node. Therefore, in addition to the NAO, we evidence an important role of EA in modulating the geographical

location of the North Atlantic action centers (Azores high and Icelandic low). Our results demonstrate that the joint effects of the NAO and EA cause European surface climate anomalies that can substantially differ from their canonical signatures. Although the sign of the temperature responses is largely determined by the NAO, the EA modulates the spatial pattern of the anomalies (magnitude and location). Precipitation responses are more sensitive to the concomitant state of the EA and NAO, and there are regions where the EA can dampen and even reverse the NAO-related precipitation signal. For example, when both indices act together, the canonical NAO precipitation signal in western Mediterranean is mainly confined to winters with an out-of-phase EA, but it weakens when EA is in phase with the NAO because of an eastward shift of the precipitation response toward eastern Mediterranean. This has implications for the robustness of some widely reported fingerprints of the NAO and previous proxy-based reconstructions.

Furthermore, our results indicate that winter NAO and EA have significant complementary fingerprints in the North Atlantic jet stream on seasonal time scales, extending previous studies based on daily diagnostics (e.g., Woollings et al. 2010). The jet speed is more affected by the NAO, with the EA acting on the same direction, while NAO and EA are of comparable importance but have opposite effects in the jet latitude. As such, the largest departures in jet speed (latitude) tend to occur in winters with equal signed (opposite) phases of NAO and EA. Using historical (1960–2000) model simulations, Woollings and Blackburn (2012) found that meridional shifts of the jet are largely due to the NAO, while NAO and EA are of roughly equal importance in describing jet speed anomalies. These discrepancies with our results could be due to model biases in the jet, differences between our indices and those considered therein and/or nonstationary influences of NAO and EA on the jet.

The evolution of the NAO and EA indices and their interactions through the last three centuries provide evidences of the dynamics behind some anomalous periods and extreme episodes and unveil substantial interannual to centennial variability in the North Atlantic jet stream. Recent changes in the Euro-Atlantic circulation such as the displacement of the North Atlantic action centers during the last decades of the twentieth century agree with temporary transitions between preferred NAO/EA states on decadal time scales. Similar transitions have been recurrent in the last three centuries, explaining some disagreements between historical NAO indices and pointing the EA as a potential source of nonstationary signatures of the NAO. This has implications for NAO reconstructions based on proxy records, whose climatic signals are

calibrated against the NAO alone, therefore assuming stationary relationships. As climate anomalies are often affected by the concomitant state of NAO and EA (even in canonical spots of the NAO), the blurring effect of EA can lead to weak and sometimes misleading NAO-proxy relationships (Sánchez-López et al. 2016), affecting the skill of the NAO reconstruction. For example, when acting together, the Greenland cooling (warming) attributed to NAO+ (NAO−) is largely restricted to EA− (EA+) phases. In addition, the precipitation NAO signal identified in Iberian and the Atlas proxies is related to winters with an out-of-phase EA, while over Turkey, precipitation responses are only relevant when both indices are in the same phase. This problem can be partially circumvented by performing reconstructions that rely on proxies from regions where the conflicting interferences of NAO and EA can be compensated. Notwithstanding, improved calibration and reconstructions of the atmospheric circulation would be better obtained by considering the joint effects of these indices. This is supported by the fact that nearly half of the winters in the last three centuries were dominated by the EA, meaning that a proper characterization of the Euro-Atlantic atmospheric circulation cannot be achieved by the NAO alone.

Our results also stress the need of additional efforts to delve further into the past evolution of the EA (in addition to that of the NAO). In this sense, a significant step forward could be achieved by fully integrating marine observations with instrumental series on land, thus yielding improved sea level pressure reconstructions and spatially coherent patterns that allow more detailed insights into the past climate variability than regional indices. This would also make it possible to better pin down the long-term variability of the North Atlantic jet stream. Further studies are also required to disentangle its internal variability from externally forced responses. This idea gains special relevance in the context of the ongoing climate change and the large uncertainty in future climate change projections of the jet stream (e.g., Peings et al. 2018). Although jet speed and latitude are herein inferred from linear regression models with different skills, our results indicate that they are largely independent and may thus respond differently to changes in external forcings (including rising concentrations of greenhouse gases). Therefore, prospective studies should also distinguish future changes in jet speed and latitude, which have different impacts on European regional climates.

Acknowledgments. This work is a contribution to UID/GEO/50019/2019—Instituto Dom Luiz. Javier Mellado-Cano was supported by the Portuguese Science Foundation (FCT) through the PhD fellowship PD/BD/106028/2014, and by the Spanish Ministry of Economy and

Competitiveness through the PALEOSTRAT (CGL2015-69699-R) project through the contract PAII18/19/2/2019/14. Ricardo M. Trigo and Armand Hernández were founded through the HOLMODRIVE (PTDC/CTA-GEO/29029/2018) project. Ricardo M. Trigo was also funded by project INDECIS, part of the European Research Area for Climate Services (ERA4CS). The authors are particularly thankful to the NOAA for providing the ICOADS 3.0 dataset (<http://icoads.noaa.gov/>). Temperature data and precipitation were provided by the CRU (<http://www.cru.uea.ac.uk>) and the GPCC (<http://gpcc.dwd.de>), respectively. Support for the ERA-20C dataset is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). We thank two anonymous reviewers for their valuable comments, which helped to improve the manuscript.

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