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Beyond the NAO: The East Atlantic Pattern's Role in Early 20th-Century Meteorological Droughts in Western Europe

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ABSTRACT

The North Atlantic Oscillation (NAO) and the East Atlantic (EA) pattern are the primary winter modes of large-scale atmospheric variability in the North Atlantic. While EA is generally considered secondary to NAO, recent studies have reported that during the early 20th century, EA was the leading mode of variability instead of NAO. This study builds on that finding to characterise North Atlantic winter atmospheric circulation during this period. The early 20th century was marked by an intensified Azores High coinciding with an extensive Icelandic Low (IL), which generated widespread negative SLP anomalies across the North Atlantic. This configuration elevated EA's role as a primary modulator of precipitation in Western Europe. Focusing on the Iberian Peninsula, we demonstrate that during this period, EA effectively captured precipitation variability both in the western sector—typically influenced by NAO—and in the eastern sector, where neither NAO nor EA generally exerts significant control. Our findings enhance the understanding of precipitation variability in this region and provide insights into the non-stationary relationship between EA and NAO. Finally, this study suggests the importance of internal climate variability in shaping those North Atlantic winter dynamics. Intense volcanic activity in the late 19th century likely contributed to ocean cooling and NAO intensifying. However, the mechanisms behind the exceptionally strong IL (e.g., EA−) remain unclear. Despite remaining uncertainties, advancing knowledge in this area will be crucial for improving medium-range weather prediction systems and long-term climate projections.

1 | Introduction

For decades, it has been known that winter climate variability in the North Atlantic and European regions is primarily driven by the North Atlantic Oscillation (NAO) and the East Atlantic (EA) pattern (Barnston and Livezey 1987). The NAO reflects fluctuations in the meridional pressure gradient between the Azores and Iceland, which directly influences the intensity and occurrence of the Greenland Blocking (GB) and the Azores High (AH) (Davini et al. 2012; Hanna et al. 2016; Sáez et al. 2025). Its positive phase (NAO+) strengthens the jet stream and shifts the storm track northward due to an anomalously intense AH and a weakened GB, leading to milder and wetter winters in northern Europe and colder and drier conditions in southern regions (Hurrell et al. 2003). This phase is typically associated with increased westerly flow, which enhances precipitation over northwestern Europe, particularly in the British Isles and Scandinavia, while simultaneously causing arid conditions in the Mediterranean basin. In contrast, the negative phase of the NAO (NAO−) induces opposite synoptic patterns, albeit with some asymmetries. During this phase, a weaker jet stream and a southward-displaced storm track lead to drier and colder, more severe winters across northern and central Europe, while southern Europe, especially the Iberian Peninsula, often experiences increased rainfall and storm activity, including heightened risks of flooding in the Mediterranean (Hurrell et al. 2003; Trigo et al. 2008).

The EA pattern is the second most significant mode of climate variability after the NAO (e.g., Trigo et al. 2008; Moore et al. 2013). Its spatial characteristics remain debated, with some studies describing it as a north–south dipole of pressure anomalies and others as a monopole of sea-level pressure (SLP) south of Iceland and west of Ireland (Comas-Bru and Hernández 2018; Cusinato et al. 2021). Despite these differences, the EA's primary centre of action consistently aligns along the NAO's nodal line, frequently shifting the storm track and jet stream southward. In its positive phase (EA+), it is marked by a centre of higher-than-average anomalies over Great Britain and the western European coasts (Trigo et al. 2008; Comas-Bru and McDermott 2014), reflecting an extension of the AH through the formation of an Atlantic Ridge (AR) blocking pattern (Hochman et al. 2021). In the EA− phase, the opposite SLP anomaly pattern leads to the development of the Atlantic Trough (Hochman et al. 2021), an extended form of the Icelandic Low (IL) over much of the North Atlantic. Consequently, the EA modulates storm tracks and influences regional precipitation and temperature patterns in Western Europe (Comas-Bru and Hernández 2018; Cusinato et al. 2021). Although its influence is generally weaker than that of the NAO, it can still contribute to meteorological extremes on seasonal timescales (Thornton et al. 2023; Baker et al. 2024).

The variability of NAO and EA, driven by complex interactions between atmospheric and oceanic components, underscores its importance in both short-term weather prediction and long-term climate projections (Cusinato et al. 2021; Schurer et al. 2023; Baker et al. 2024; Gu et al. 2024; Smith et al. 2025). Consequently, understanding its mechanisms and long-term fluctuations remains a key focus of contemporary climate research.

Research has already revealed substantial temporal and spatial variability in the NAO (Vicente-Serrano and López-Moreno 2008; Moore et al. 2013; Schurer et al. 2023), with notable multidecadal and centennial fluctuations (Ortega et al. 2015). These variations manifest as shifts in the latitude and longitude of its action centres (Börgel et al. 2020; Tao et al. 2023; Santolaria-Otín and García-Serrano 2024), prolonged dominance of specific phases (Hernández et al. 2020; Sáez et al. 2025), or significant changes in explained variance (EV) (Outten and Davy 2024).

In contrast, the spatiotemporal variability of the EA remains less explored (Baker et al. 2024; Hernandez and Comas-Bru 2025). Nevertheless, evidence suggests that the EA also undergoes cycles of intensification and weakening (Moore et al. 2013; Mellado-Cano et al. 2019) and, like the NAO, its relevance in capturing regional climate variability fluctuates over time (Outten and Davy 2024). Although often considered secondary, it provides valuable insight into the non-stationary relationship between the NAO and European climate (Comas-Bru and McDermott 2014; Mellado-Cano et al. 2019; Hu et al. 2022).

Notably, Halifa-Marín et al. (2025) recently highlighted that the EA was the primary mode of variability during the early 20th century, underscoring its potential significance in shaping European winter climates. This finding also presents critical challenges in interpreting historical climate records for the North Atlantic and European climate systems, as noted in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (Eyring et al. 2021 and references therein). A deeper understanding of the multidecadal behaviour of both the EA and NAO is crucial for studies focused on the Northern Hemisphere climate, particularly in Western Europe (Comas-Bru and Hernández 2018; Hu et al. 2022; Simpson et al. 2024; Hernandez and Comas-Bru 2025). In this region, these variability modes predominantly control winter precipitation, which directly affects water resource availability (Donegan et al. 2021; Rust et al. 2022; Lorenzo-Lacruz et al. 2022; Sánchez-García et al. 2022) and renewable energy production (Cionni et al. 2022), with cascading impacts on ecological and economic systems (e.g., Craig and Allan 2022; Georg et al. 2023).

Building on this evidence, this study examines winter precipitation variability in Europe during the early 20th century, a period when the EA emerged as the primary mode of variability, revealing an unparalleled regional atmospheric circulation since 1871. How unique was the North Atlantic climate system during this period? Did it significantly impact precipitation in Western Europe? Was the increased influence of the EA evident in its traditionally influenced regions? Did it serve as a better indicator of precipitation variability and affect a broader area? To address these questions, this study aims to:

1. Characterise the differences in North Atlantic winter atmospheric circulation during the early 20th century compared to other observed periods.
2. Analyse their impacts on precipitation variability in western Europe, particularly the Iberian Peninsula, where NAO and EA exert significant influence on human and natural systems.

2 | Data and Methods

2.1 | Data Sources

Monthly sea-level pressure (SLP), 850 hPa wind, and precipitation rate fields were obtained from the 20CRv3 reanalysis (80-member ensemble; Slivinski et al. 2021) for the period 1871–2015. This dataset represents the most temporally extensive surface-input reanalysis, incorporating the highest-quality SLP observations available and offering enhanced spatial resolution (T254; 1°×1° grid) compared to other reanalyses and observational datasets. This reanalysis product carries uncertainties related to the volume of assimilated data, particularly during the 19th and early 20th centuries. However, its ability to reproduce the tropospheric climate has been validated through comparisons with other comparable datasets (Slivinski et al. 2021; Halifa-Marín et al. 2025), and it is widely used for analysing winter climate variability modes in the North Atlantic region (Smith et al. 2025). Canonical winter (December–February) averages and accumulations were analysed for these variables.

Although 20CRv3 provides winter precipitation fields, this study primarily relies on a European monthly precipitation dataset compiled by Vicente Serrano et al. (2020), which includes 199 complete time series from 1871 to 2015. These series have undergone quality control and homogenisation, offering a significant number of observations across Western Europe during the Industrial Era.

While the SLP field is used to identify the spatiotemporal variability of the NAO and the EA pattern (see Section 2.2), observational versions of both modes were also considered. The station-based NAO index, based on winter SLP differences between Iceland and Gibraltar, is provided by CRU following Jones et al. (1997) methods. Additionally, SLP anomalies from Valentia (Ireland), provided by Comas-Bru and Hernández (2018), have been validated as an observational version of the EA index.

2.2 | Assessing the Influence of NAO and EA on the European Climate

NAO and EA were defined as the first two Empirical Orthogonal Functions (EOFs) using Singular Value Decomposition (SVD) applied to spatially weighted (i.e., square root of the cosine of latitude) detrended winter SLP anomalies. The SLP trend was removed to prevent the propagation of undesirable forcing effects inherent in 20CRv3, focusing on atmospheric dynamics variability. Anomalies were calculated by subtracting the full period mean. The analysis covered the spatial domain 90° W–40° E, 20° N–80° N, as proposed by Hurrell et al. (2003). These leading climate variability modes were identified using the metR R package (Campitelli 2021), which provided spatial patterns, principal component (PC) time series, and EV. In this study, the spatial patterns associated with EA and NAO were determined by regressing SLP onto the corresponding PC.

To track NAO and EA variability over time, EOF analysis was applied to overlapping 30-year windows from 1871–1900 to 1986–2015 (116 windows), following standard methodologies for assessing multidecadal variability in climate modes (Tao et al. 2023; Santolaria-Otín and García-Serrano 2024; Simpson et al. 2024). A 30-year scale was selected following the World Meteorological Organisation (WMO) standard for climatological normal and the typical timescale for defining North Atlantic climate variability modes (e.g., Santolaria-Otín and García-Serrano 2024). However, the analysis was also replicated using moving windows of 25 and 35 years, shifted year by year, consistently confirming the main findings of the study (Table S1).

For each window, the spatial patterns of the four leading modes were compared with those computed for the full period (referred to as canonical, 1871–2015) using Pearson correlation, after detrending the data. Spatial patterns were converted into time series by treating adjacent grid points as sequential records. To avoid biases from autocorrelation when testing correlation significance, we applied the method proposed by Núñez-Riboni et al. (2023), based on the Artificial Skill Method. The relevance of each variability mode is expressed in terms of the amount of variance explained by its corresponding PC. To assess whether the differences in explained variance between modes are statistically significant, we applied North's rule of thumb for EOF separation (North et al. 1982).

This study, informed by the findings of Halifa-Marín et al. (2025), focuses on the periods 1905–1934 and 1981–2010. The former corresponds to an unusual period where EA is detected as the leading mode of winter climate variability, while the latter represents a period characterised by intense positive NAO phases, which share this characteristic with the early 20th century. This selection enables a comparative analysis to assess the uniqueness of EA and NAO behaviour in the early 20th century. Additionally, the latter period serves as a reference for the late 20th-century NAO intensification, which has been extensively documented in the literature (Hernández et al. 2020; Smith et al. 2025).

To examine precipitation variations during the early 20th century, changes in the influence of EA and NAO were analysed. Correlations between detrended precipitation and these indices were quantified using Pearson's method and assessed for significance ($p \leq 0.05$) via *t*-test. To evaluate precipitation variations under different phases of these climate modes, relative precipitation changes were computed as the ratio of anomalies to their mean (expressed as a percentage) for winters with NAO and EA indices above the 70th or below the 30th percentile. By applying these thresholds, winters with near-neutral EA and NAO phases were excluded. The significance of precipitation changes was assessed using the Mann–Whitney test, which determines whether two independent samples exhibit significantly different distributions. As with the SVD/EOF analysis applied to 30-year moving windows, statistical analyses of NAO-EA and precipitation relationships were conducted using annually shifting windows from 1871 to 1900 onward.

3 | Results and Discussion

3.1 | Singular North Atlantic Winter Climate Variability During the Early 20th Century

The winter climate variability over the North Atlantic during 1905–1934 exhibited a state in which the EA pattern emerged as the first mode of variability rather than the NAO, as is typically assumed. Several indicators support this finding (Figures 1 and 2). First, the correlation between the temporal variability of the canonical NAO and EA—calculated over 1871–2015—with that of PC1 from this period reveals a stronger correlation with EA (0.81, Figure 1a) than with NAO. Similarly, PC2 correlates more closely with the canonical NAO (0.64, Figure 2a). This finding is further supported by their spatial patterns (Figures 1c and 2c). The spatial pattern associated with PC1 closely resembles the EA pattern, with an intense primary center of action centered

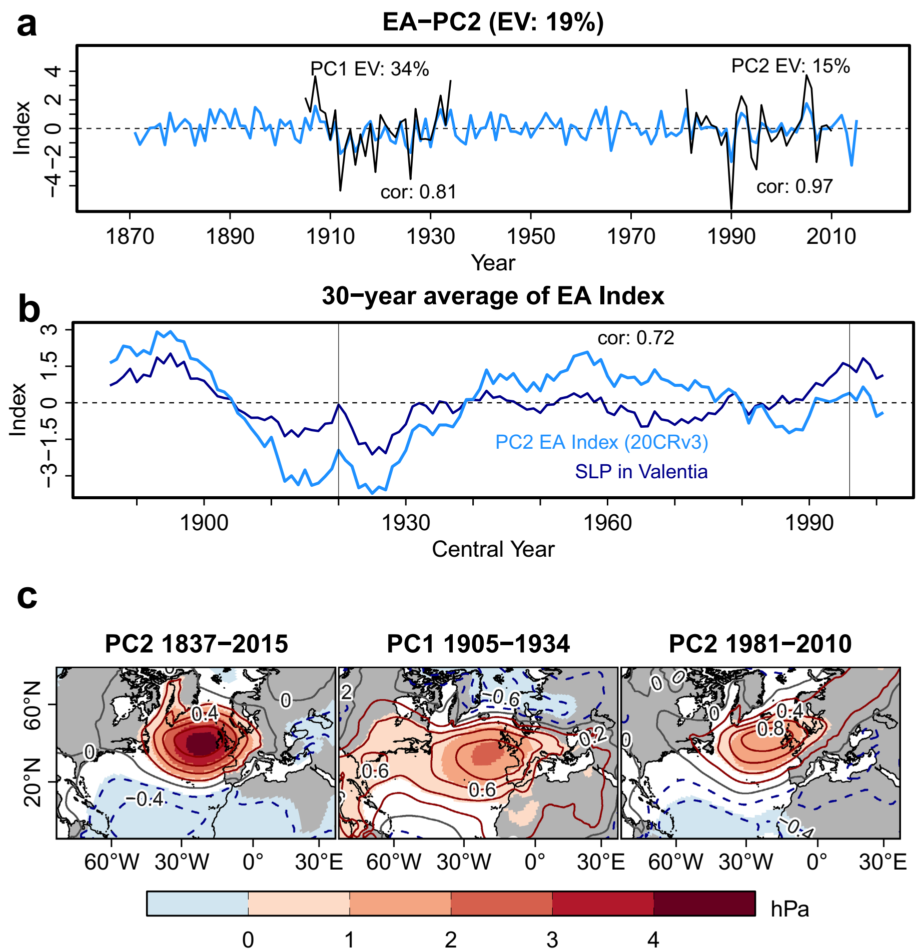

FIGURE 1 | Panels illustrate the spatiotemporal variability of the East Atlantic (EA) pattern over the study period. (a) The blue line represents the temporal variability of PC2 from 1871 to 2015. Black lines depict PC1 and PC2 variability during 1905–1934 and 1981–2010, respectively, reflecting the spatial EA pattern. Correlation coefficients between the canonical NAO variability (blue line) and these indices (black lines) are provided. The explained variance (EV) of EA—both in PC2 for 1837–2015 (title) and in PC1 and PC2 for the 30-year periods (panel)—is also specified. (b) The moving 30-year average of the PC2-EA index (1871–2015, blue) and mean winter SLP anomalies at Valentia, Ireland (dark blue), are shown. Valentia was identified as an observed-like EA variability site by Comas-Bru and Hernández (2018). The correlation between both series is noted. Vertical lines refer to the middle year of the two sub-periods analysed here, i.e., 1905–1934 and 1981–2010. (c) Panels display EA spatial patterns for 1871–2015 (PC2-derived, left), 1905–1934 (PC1, center), and 1981–2010 (PC2, right). Colours indicate significant regression of SLP anomalies onto these indices ($p \leq 0.05$). Contours represent correlations each 0.2, with solid red lines for positive coefficients, dashed blue lines for negative coefficients, and a solid grey line marking the zero contour. [Colour figure can be viewed at wileyonlinelibrary.com]

around 15°W–50°N (Comas-Bru and Hernández 2018; Cusinato et al. 2021; Hernandez and Comas-Bru 2025), while the pattern for PC2 exhibits a dipole structure characteristic of the NAO, with a disproportionately stronger northern center of action (Hurrell et al. 2003; Trigo et al. 2008).

Additionally, this period shows notable changes in the variance explained by PC1 and PC2, as also observed by Outten and Davy (2024). Unlike the 1871–2015 period, where PC1 explains roughly twice the variance of PC2, during 1905–1934, PC1 accounts for 34% of variability, while PC2 explains 25% (Figures 1a and 2a). The North's rule of thumb for EOF separation (North et al. 1982) shows that the difference in explained variance between PC1 and PC2 is not statistically significant (Figure S1); however, this results in both PCs contributing almost equally to variability, a feature not observed in any other 30-year period. Although NAO and EA are orthogonal in PC space, meaning their temporal variability is uncorrelated, a 30-year moving average reveals unique behaviour across those time windows. During 1905–1934, the EA-phase coincided with the persistence of NAO+ from the late 19th to early 20th century (Figures 1b and 2b). Additionally, this finding is consistently observed across all 80 ensemble members of the 20CRv3 reanalysis (Figure S2). Moreover, there is no evidence that changes in the volume of assimilated observations over the North Atlantic are responsible for the main findings described in this study (Figure S3). This suggests that the EA and NAO characteristics observed in this period are not merely artefacts of the EOF analysis for the period but instead represent genuine shifts in large-scale atmospheric dynamics.

This conclusion is further supported by NAO observations based on winter SLP from Gibraltar and Iceland (Jones et al. 1997) and from Ireland (Comas-Bru and Hernández 2018; Figures 1b and 2b). This finding highlights two major yet underexplored topics in the literature. The first concerns the EA and its multidecadal

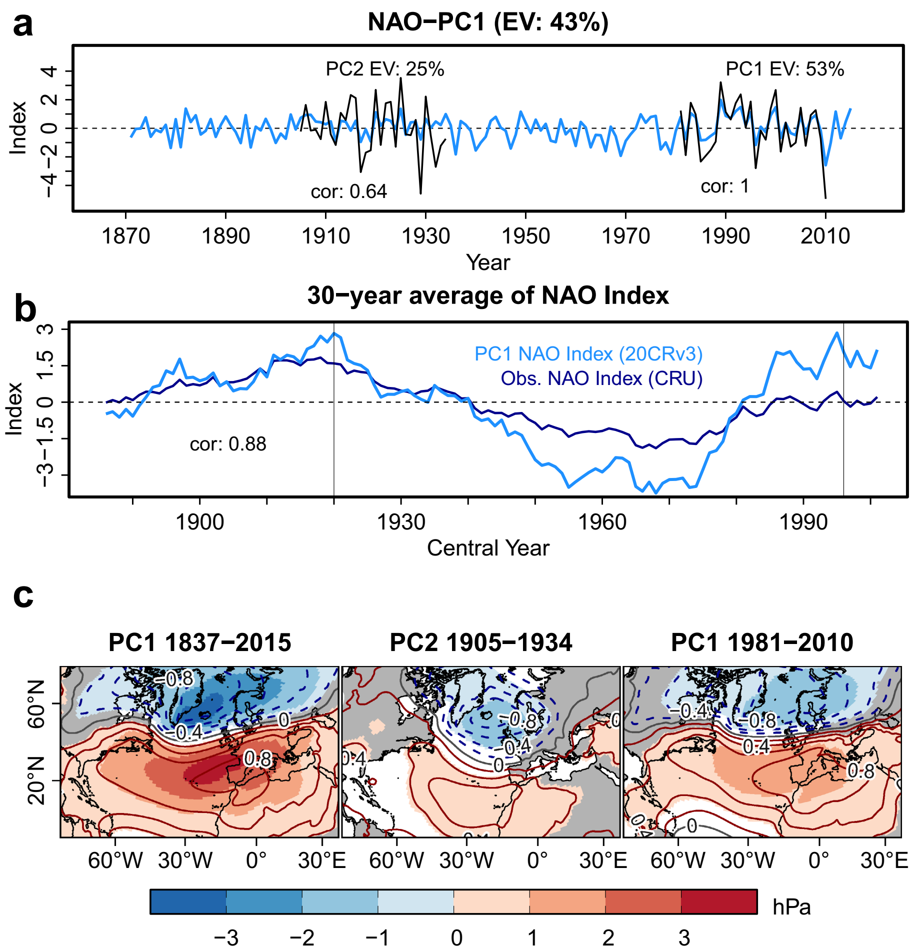

FIGURE 2 | Similar to Figure 1, albeit with some differences. In the case of (a) PC2 represents the NAO during 1905–1934, while PC1 corresponds to 1981–2010. (b) The NAO based on observed winter SLP is obtained from the Climate Research Unit (CRU), using data from Gibraltar and Iceland. [Colour figure can be viewed at wileyonlinelibrary.com]

variability. While the NAO has received significantly more scientific attention (Vicente-Serrano and López-Moreno 2008; Hernández et al. 2020; Smith et al. 2025), the EA has often been overlooked. Consequently, multidecadal circulation variability in the North Atlantic has traditionally been analysed through an NAO-centered perspective (Börgel et al. 2020; Tao et al. 2023; Santolaria-Otín and García-Serrano 2024), with few studies documenting persistent EA− and EA+ phases in reanalyses or reconstructions (Moore et al. 2013; Mellado-Cano et al. 2019).

The second issue relates to the NAO and its multidecadal variability. The early 20th-century intensification of the NAO has largely escaped scientific focus, either because it has been studied within centennial-scale reconstructions or because the more recent NAO+ dominance (e.g., in the late 20th century) has garnered significant attention due to its potential attribution to GHG forcing and a warming climate (Hurrell et al. 2003; Hernández et al. 2020; Smith et al. 2025).

In this study, the 1981–2010 period is used as a reference for this recent NAO+ dominance to facilitate comparison with 1905–1934. During this period, the NAO and EA follow their conventional roles as the first and second leading modes, respectively, capturing regional SLP variability (Figures 1a and 2a). This is confirmed by the high correlation between the PCs' temporal variability and the NAO and EA indices computed for 1871–2015 (both exceeding 0.97; Figure 1a) and by the spatial patterns (Figures 1c and 2c). Consistent with previous studies (Outten and Davy 2024), the explained variance of PC1-NAO increases to 53%, while that of PC2-EA decreases to 15%.

A comparative analysis between periods reveals two key insights into the uniqueness of 1905–1934. First, NAO intensifications do not necessarily align with a dominant EA-phase, as observed in the early 20th century (Figure 2). This suggests that the interplay between EA and NAO is not stationary at multidecadal scales. This finding aligns with previous literature indicating that the influence of NAO on European climate is non-stationary and mediated by EA (Moore et al. 2013; Comas-Bru and Hernández 2018; Mellado-Cano et al. 2019). Furthermore, it suggests that these NAO–EA relationships are not temporally stable.

For instance, the eastward shift of the NAO's northern centre has been linked to changes in its influence on European climate—an effect observed during both dominant NAO+ phases in the 20th century (Vicente-Serrano and López-Moreno 2008). However, the EA phase differs between these periods. This implies that analysing only one of these periods could lead to misleading conclusions, such as inferring

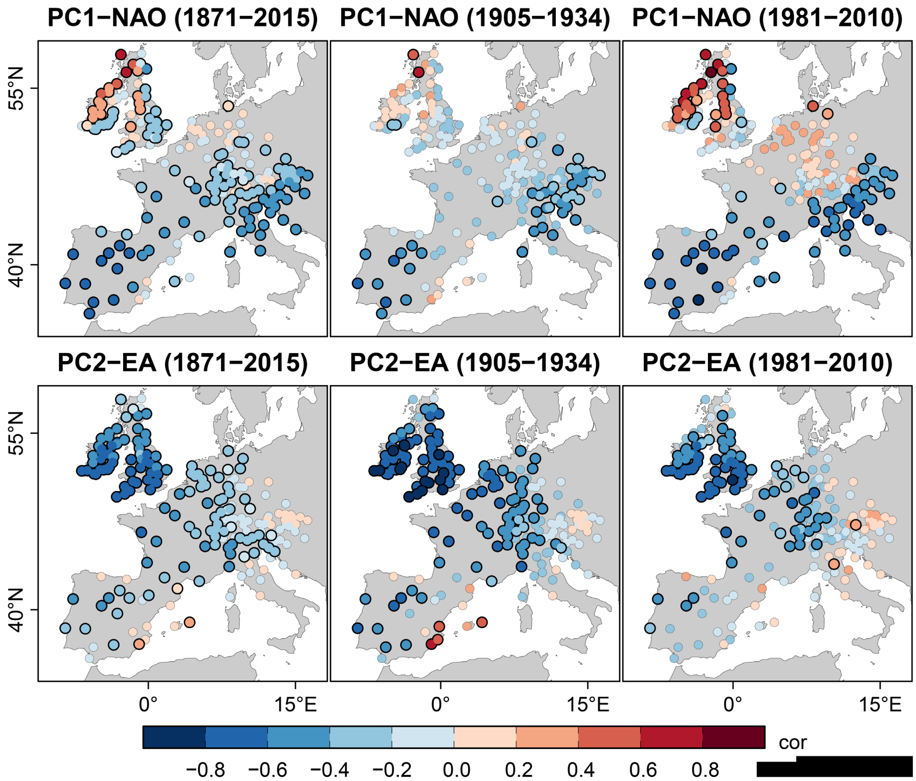

FIGURE 3 | Correlation between winter NAO and EA indices, derived from EOF analysis for 1871–2015, and observed winter precipitation series across Western Europe for the full 1871–2015 period (left column), 1905–1934 (central column), and 1981–2010 (right column). Statistically significant correlation coefficients are represented by larger symbols outlined in black. [Colour figure can be viewed at wileyonlinelibrary.com]

that EA is unrelated to NAO intensifications or, conversely, that EA weakened simultaneously in the early 20th century. Finally, our EOF-derived NAO variability closely aligns with observed pressure-based NAO indices (Jones et al. 1997). This reinforces that NAO intensification in the early 20th century was comparable to or stronger than in recent decades (1981–2010).

Second, a critical difference emerges when examining changes in the variance explained by NAO and EA. While NAO and EA had comparable importance during 1905–1934, by the late 20th century, NAO accounted for nearly four times the variance of EA (Figures 1a and 2a). This suggests that periods characterised by persistent EA and/or NAO states do not necessarily coincide with distinct frequencies of the synoptic patterns associated with each phase. This raises an important question regarding how precipitation regimes in European regions influenced by EA and NAO responded during 1905–1934—a topic explored in the following sections.

3.2 | Shifting Influence of NAO and EA on Winter Precipitation Across Western Europe

Significant shifts are observed in the teleconnections between the canonical EA and NAO indices and winter precipitation across Western Europe during 1905–1934 (Figure 3). The EA index generally shows a stronger correlation with precipitation, even in regions traditionally influenced by the NAO, such as southern France, Ireland, western Great Britain, and the Iberian Peninsula. In the Iberian Peninsula, EA also plays a more prominent role in shaping winter precipitation along the Mediterranean coast, where NAO influence is typically weak.

Meanwhile, the NAO index exhibits a weaker correlation with precipitation during 1905–1934. Its overall area of influence contracts, particularly over western Great Britain and the Iberian Peninsula. Notably, the NAO also loses its significant impact over northern Italy and central and southern France—regions that are generally less teleconnected to the NAO. In these areas, EA becomes the main driver of winter precipitation.

These changes in NAO and EA influence were not present during 1981–2010. During this period, EA's influence extends over fewer regions and weakens in traditionally well-teleconnected areas such as Ireland and northwestern Great Britain. Conversely, its impact remains stable or intensifies over southern England and Central Europe. A particularly striking shift occurs in the Iberian Peninsula, where both negatively correlated (Atlantic-influenced) and positively correlated (Mediterranean-influenced) regions lose statistical significance.

For the NAO, the spatial extent of its precipitation teleconnection during 1981–2010 closely resembles that observed over the full 1871–2015 period. Its influence strengthens over the western coast of Great Britain and Ireland (positive sign) and large areas of southern Europe (negative). Although some regions do not exhibit statistically significant correlations, a notable change is seen in Central Europe and along the northern slopes of the Alps, where correlations become positive. The most striking finding is observed in Scotland and western Iberia, where precipitation is strongly correlated with NAO, whose influence is more pronounced in 1981–2010.

Our results highlight several key scientific insights. First, the comparative analysis of 1905–1934 and 1981–2010 reveals substantial differences in how EA and NAO influence precipitation. A traditional NAO-centered perspective, commonly applied in the literature, would classify both periods as phases of persistent NAO+. However, their precipitation impacts across Western Europe are markedly different. This challenges the assumption that multidecadal NAO variability follows a binary pattern—one in which it behaves as conventionally understood and another in which it deviates from this state. Instead, our findings indicate that NAO variability is more complex, with multiple characteristics and underlying mechanisms. We show that 1905–1934 was not only a period of dominant NAO+ but also one in which EA played a primary role in modulating European climate. Yet, this aspect has been largely overlooked in previous studies, highlighting persistent uncertainties in understanding North Atlantic winter climate variability, despite decades of research advancements (e.g., Halifa-Marín et al. 2025 and references therein).

Second, the changing influence of EA and NAO on precipitation aligns with the increased relevance of EA during 1905–1934 and the dominance of the NAO during 1981–2010, as indicated by the explained variance. Although it is important to note that the difference in explained variance between the EA and NAO during 1905–1934 is not statistically significant (Figure S1), this underscores the scientific importance of tracking explained variance changes when using EA and NAO as indicators of European climate variability, in line with recent findings (Outten and Davy 2024).

Finally, our findings are particularly relevant for regions where NAO influence is typically dominant at other timescales such as the Iberian Peninsula. Notably, EA emerges as a stronger predictor of precipitation variability during 1905–1934 in the eastern Iberian Peninsula, where it shows a positive correlation with an intensity unmatched in any other period. Similarly, in western Iberia—traditionally under strong NAO influence—EA also becomes a key modulator. Given the critical role of winter precipitation in this region, where it largely determines water resource availability and has significant societal and ecological impacts (Vicente-Serrano and López-Moreno 2008; Trigo et al. 2008; Sánchez-García et al. 2022), the next section provides a focused analysis of these results for the Iberian Peninsula.

3.3 | EA Pattern Promoting the Drier Early 20th Century in the Iberian Peninsula

In this section, we analyse the changes observed in winter atmospheric circulation during the 1905–1934 period to better understand variations in the characteristics of EA and NAO and their influence on precipitation in Western Europe. To provide a more detailed assessment, we focus on the Iberian Peninsula, a region that has been shown to reflect the key findings described in the previous section, considering Lisbon as representative of Western Iberia and Murcia as the counterpart of Eastern Iberia.

In the western Iberian Peninsula, winter precipitation was anomalously low between 1905 and 1934 (Figure 4). Many stations recorded their most intense dry anomalies within this 30-year window, though dry conditions extended from 1871 to the mid-20th century. This aligns with the NAO+ phase but has a less clear connection with the prevailing EA− phase. Both EA and NAO exhibit a negative correlation with precipitation in the Atlantic sector. During 1905–1934, their correlation with Lisbon's precipitation—typically strongly linked to NAO—was similar (−0.6). No other period but the early 20th century shows this pattern (Figure 5a). This raises questions about the atmospheric dynamics behind the simultaneous occurrence of opposing EA and NAO phases, which appears inconsistent with their typical influence on regional precipitation (Hurrell et al. 2003; Trigo et al. 2008). Additionally, it prompts an investigation into the synoptic configuration driving this period of intensified winter drought. Between 1981 and 2010, a positive NAO phase re-emerged, but EA remained neutral to slightly positive, as previously discussed. Regarding precipitation in the Atlantic-influenced Iberian Peninsula, the late 20th and early 21st centuries marked a transition to drier conditions following the wetter decades of 1950–1980, when a weak EA+ and strong NAO-occurred. This dry period was shorter and less intense than in 1905–1934, as precipitation anomalies in Lisbon increased in subsequent periods after 1981–2010 (Figure 4a).

In the previous section, the eastern Mediterranean coast of the Iberian Peninsula was highlighted as a key region for understanding EA and NAO influences on precipitation. Here, EA exhibited an unusually strong positive correlation, unseen during 1871–2015 or 1981–2010 (Figure 3). In Murcia—the Iberian location with the highest significant long-term correlation between winter precipitation and EA—this correlation doubled from 0.4 to 0.8 during 1905–1934. EA's influence weakened after the mid-20th century, approaching zero. While a positive correlation with EA is evident in all 30-year windows, it significantly peaked in the early 20th century (Figure 5b). In contrast, NAO was not a reliable indicator of winter climate variability in Murcia. Between 1981 and 2010, this sector of the Iberian Peninsula experienced slightly wetter conditions, coinciding with a weak EA+ phase (Figure 4b).

Overall, Lisbon and Murcia display opposite trends in their moving averages of winter precipitation, particularly in the late 19th century and from the mid-20th century onward. This contrast is exemplified by the wet period in Lisbon (1950–1980), which coincided with dry conditions in Murcia (Figure 4). However, and crucially for this study, the only period when both the Atlantic and Mediterranean sectors experienced intense winter drought simultaneously was the early 20th century, particularly 1905–1934. This raises significant interest in understanding the atmospheric dynamics responsible for this precipitation anomaly, unparalleled in the 1871–2015 record, a topic explored in the following section.

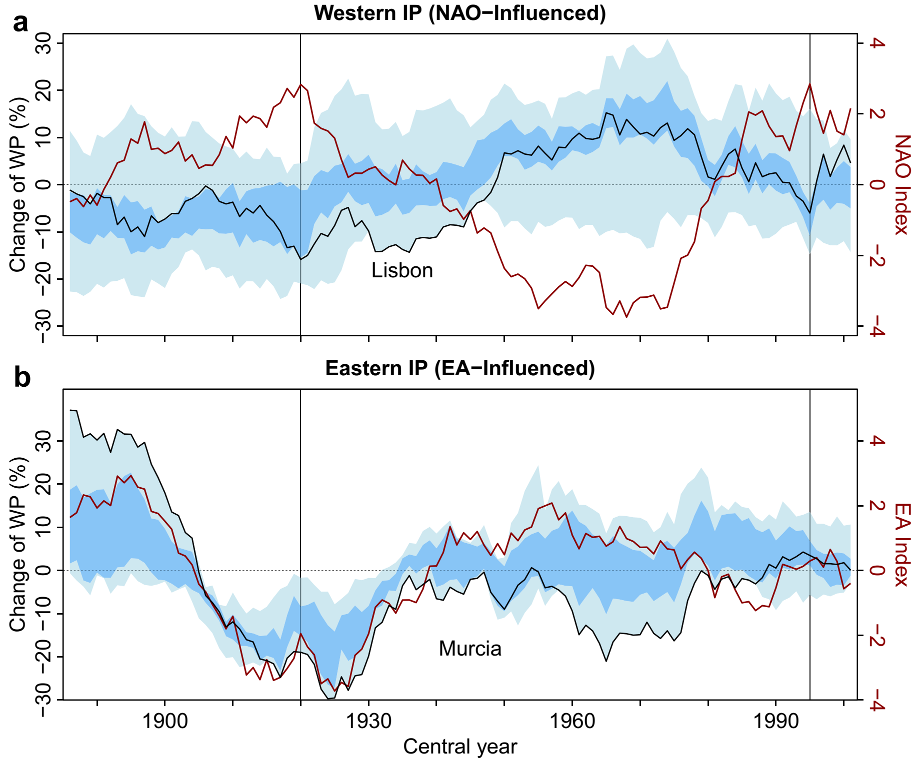

FIGURE 4 | (a) Time series of relative winter precipitation change in Lisbon over 30-year moving windows, referenced to the 1871–2015 mean. Light and dark blue shading represent the interquartile range and 5th–95th percentiles of relative precipitation change across stations significantly influenced by NAO (where NAO exhibits stronger correlations than EA, $n = 18$). The averaged NAO index is shown as a red line (right *Y*-axis). (b) Similar to (a), but for the EA index and precipitation change Murcia. In this case, the 5th–95th and 25th–75th percentile thresholds correspond to stations where precipitation is significantly influenced by EA ($n = 4$). Vertical lines refer to the middle year of the two sub-periods analysed here, i.e., 1905–1934 and 1981–2010. [Colour figure can be viewed at wileyonlinelibrary.com]

3.4 | Prevailing Winter North Atlantic Atmospheric Dynamics in the Early 20th Century

This section examines the synoptic patterns associated with EA and NAO phases across different study periods to explain why EA was a strong indicator of winter climate variability across the Iberian Peninsula only during 1905–1934. To this end, we compare it with the reference period 1871–2015 and with 1981–2010, the latter serving as a contrasting NAO+ phase.

The synoptic patterns linked to EA phases differ across these three periods (Figure 6). In general, EA+ induces positive sea level pressure (SLP) anomalies over the North Atlantic, centred west of Britain at ~50° N, extending into Central Europe. This configuration acts as an extension or northward shift of the AH, forming an expansive AR reaching as far as Iceland. Consequently, it displaces storm tracks northward, resembling NAO+ but with key differences. EA+ exerts stronger blocking over Ireland, Britain, and western France rather than southern Europe. This distinction is evident in winter precipitation: along Morocco's Atlantic coast, EA+ results in normal conditions, whereas NAO+ produces significant drying (Figures 6 and 7).

Similarly, in the Iberian Peninsula, standard EA+ pattern drives drought primarily in the northwest, while NAO+ exerts a stronger impact in the southwest (e.g., Lisbon). Another key contrast is that EA+ enhances winter precipitation in eastern Iberia, particularly around Murcia as shown in Figure 4. This occurs because the associated AR extends into Central Europe, promoting easterly winds that transport Mediterranean moisture inland (Figure 6, top panel). Conversely, EA− generally produces opposite precipitation effects, characterised by an intensified IL spanning the North Atlantic, predominantly affecting Ireland, Britain, and western France (Figure 6).

During 1905–1934, both EA phases were pronounced, though EA− was more intense. This period saw 27 winters with extreme EA index values—14 below the 30th percentile and 13 above the 70th percentile. Under EA+, the SLP anomaly centre shifted southward, blocking not only the regions affected during 1871–2015 but also Iberia and western Morocco, mirroring the broader influence of NAO+. EA+ also increased precipitation in Murcia and the eastern Iberian coast, but its extended AR influence intensified rainfall further east in the western Mediterranean Sea. Precipitation records from these regions could validate our findings based on 20CRv3 reanalysis. Under EA− conditions, which prevailed during this period (Figure 1b), the synoptic pattern exhibited a key difference: the IL was confined southward by an intensified AH, limiting its reach to ~44° N. This configuration increased precipitation in northwestern Iberia but intensified drying along the Mediterranean coast. The strengthened AH, consistent with NAO+ dominance, generated Atlantic westerlies toward Iberia that carried less moisture and induced

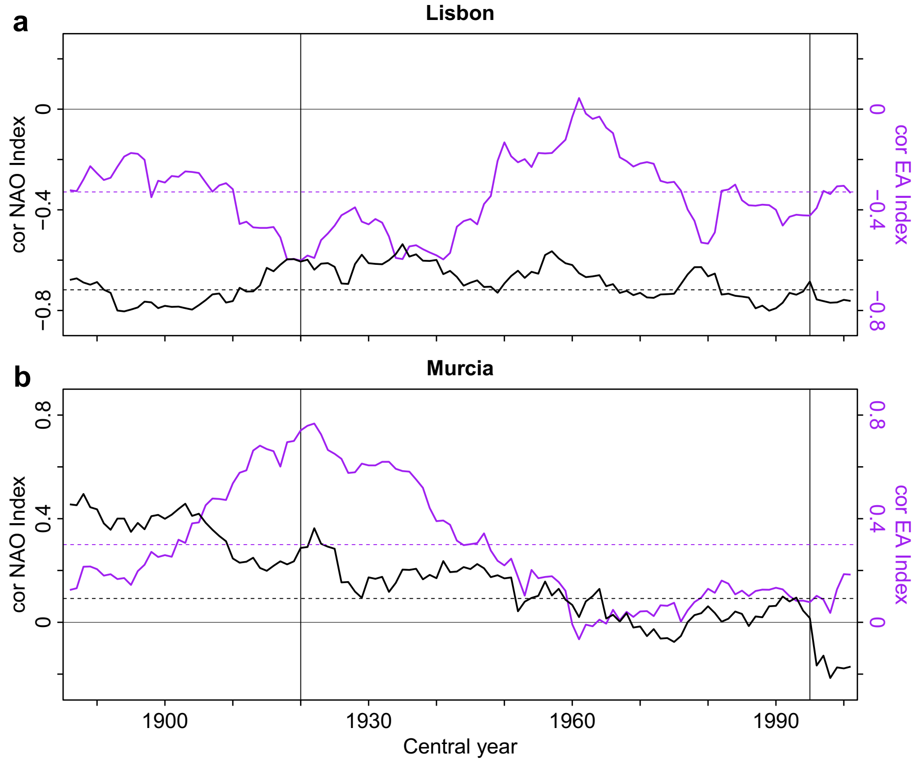

FIGURE 5 | 30-year moving correlation between winter precipitation in Lisbon (top) and Murcia (bottom) with NAO (black) and EA (purple) indices. The Y-axis represents the central year of each window, ranging from 1886 (for 1871–1900) to 2000 (for 1986–2015). In panel (b), black and purple lines indicate the correlation with NAO and EA over 1871–2015. Vertical lines refer to the middle year of the two sub-periods analysed here, i.e., 1905–1934 and 1981–2010. [Colour figure can be viewed at wileyonlinelibrary.com]

a Foehn-like effect along the Mediterranean coast, typically associated with NAO−.

Replicating this analysis for 1981–2010 reveals that these findings do not extend to another NAO+-dominated period. EA+ did not significantly block Iberian precipitation, nor did it generate substantial anomalies. Similarly, under EA−, positive SLP anomalies were not confined to the AH but extended across the western Mediterranean, shifting EA's influence northward toward southwestern Britain and western France.

From an NAO perspective, significant changes in the synoptic pattern associated with both phases occurred during 1905–1934. The most distinctive feature was the intensified and eastward-shifted AH during NAO+ winters (19), contributing to severe dryness along the Atlantic-facing Iberian Peninsula, as previously discussed for EA. The resulting blocking pattern closely resembled the AR configuration. During the rare NAO− winters (5 in total), the GB extended eastward, forming a SB. This shift displaced storm tracks northward, increasing their impact on Britain while reducing precipitation in Morocco, Iberia, and other southern European regions.

In contrast, during 1981–2010, NAO phases displayed different characteristics. Under NAO+, anomalous high pressure extended across the Mediterranean, directly blocking precipitation across the Iberian Peninsula. Under NAO-, the GB-to-SB transition observed in 1905–1934 reappeared but shifted farther south, allowing low-pressure systems to impact southwestern Iberia and Morocco more strongly. This period also exhibited a high frequency of intense NAO+ (15 winters) and NAO- (13 winters) phases, leading to alternating extreme dry and wet winters. Consequently, no 30-year period during this time was as dry as the early 20th century. This sequence of opposing extremes may: (1) directly result from the dynamic of atmospheric blocking over the North Atlantic, (2) be linked to broader climate variability observed in other regions, where severe droughts are followed by exceptionally wet periods, and (3) have significant implications for water resource management, ecosystem dynamics, agriculture, and other scientific fields.

3.5 | Internal Variability as a Key Driver of NAO-EA Interactions During the Early 20th Century

Having identified EA as a primary mode of variability with significant impacts on their interactions with NAO in controlling winter precipitation—and recognising that EA's traditionally secondary role depends on the study period—it is crucial to understand the physical mechanisms driving these changes in North Atlantic atmospheric dynamics. This section reviews the literature to discuss our results, identifying potential drivers of the anomalous atmospheric conditions observed during 1905–1934.

Different atmospheric blocking patterns significantly impact the European winter climate. In general, the Atlantic Ridge (AR) occurs in the absence of GB or SB, and vice versa (Rimbu et al. 2014). During 1905–1934, the reduced GB activity aligned

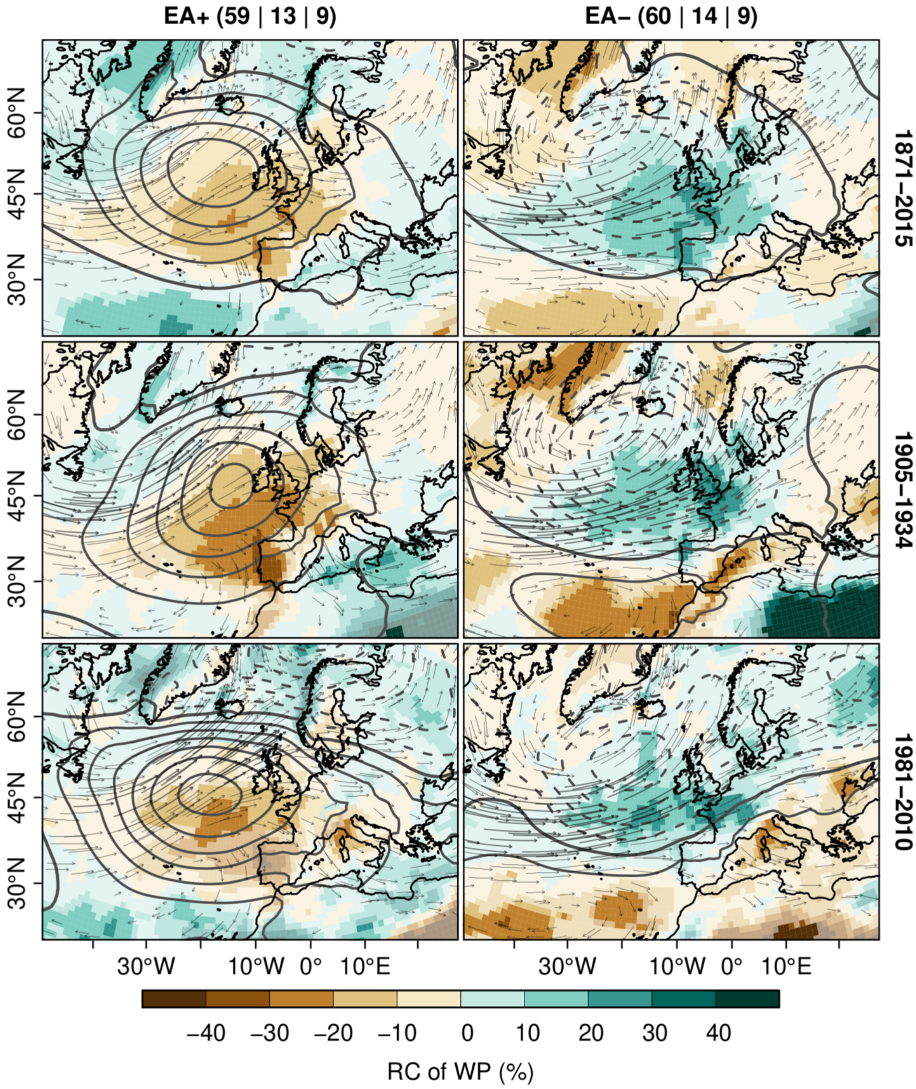

FIGURE 6 | Relative winter precipitation changes composites for EA+ (left) and EA− (right) phases across three periods: 1871–2015 (top), 1905–1934, and 1981–2010 (bottom). Precipitation deviations are expressed as a percentage relative to the mean (colour scale). Significant changes are highlighted with more intense colours. Dashed (negative) and solid (positive) contours indicate surface pressure anomalies at 10 hPa intervals. Mean 850 hPa wind direction is represented by arrows of three sizes corresponding to wind speed: small (2.5 m/s), medium (5 m/s), and large (> 15 m/s). The top-side panel titles indicate the number of winters analysed in each period. [Colour figure can be viewed at wileyonlinelibrary.com]

with the persistence of NAO+ but not with EA− (Figures 1b, 6, and 7). In this period, EA− is associated with a northward-displaced IL, driven by an intensified AR. A key question remains: what mechanisms explain this anomaly, and how does it differ from other periods of weak GB activity and dominant NAO+ (e.g., post-1980s)?

Oceanic variability appears to be the primary driver of atmospheric blocking over the North Atlantic. Börgel et al. (2020) identify the Atlantic Multidecadal Oscillation (AMO) as a key factor in multidecadal NAO variability, which modifies its climatic teleconnections (Vicente-Serrano and López-Moreno 2008; Hu et al. 2022). Kwon et al. (2020) demonstrated a one-way coupling in which SST anomalies influence atmospheric blocking but not the reverse. Warm SST anomalies in the western subpolar gyre, linked to AMO, reduce the meridional temperature gradient, weakening baroclinicity and synoptic eddy heat flux. This process promotes cyclonic wave breaking, shifts the eddy-driven jet southward, and enhances GB while reducing the intensity of the AH, ultimately favouring the NAO− phase. A similar but shorter-lag response occurs for cold AMO anomalies, reinforcing the inverse AMO-GB/NAO relationship proposed by previous studies (e.g., Birkel et al. 2018; Börgel et al. 2020).

However, the mechanisms underlying the prominence of EA in the early 20th century remain unclear. First, while volcanic forcing has been widely studied in relation to NAO (Birkel et al. 2018; Sáez et al. 2025; Smith et al. 2025), its influence on EA remains largely unexplored. Rimbu et al. (2014) provide evidence for AMO forcing on AR variability, but the scarcity of literature highlights the need for further research.

Second, the available observational record is too short to fully capture the multidecadal variability of EA and NAO, given their estimated 60–70-year cycles (Outten and Davy 2024). This limitation is even more pronounced for SST datasets, making

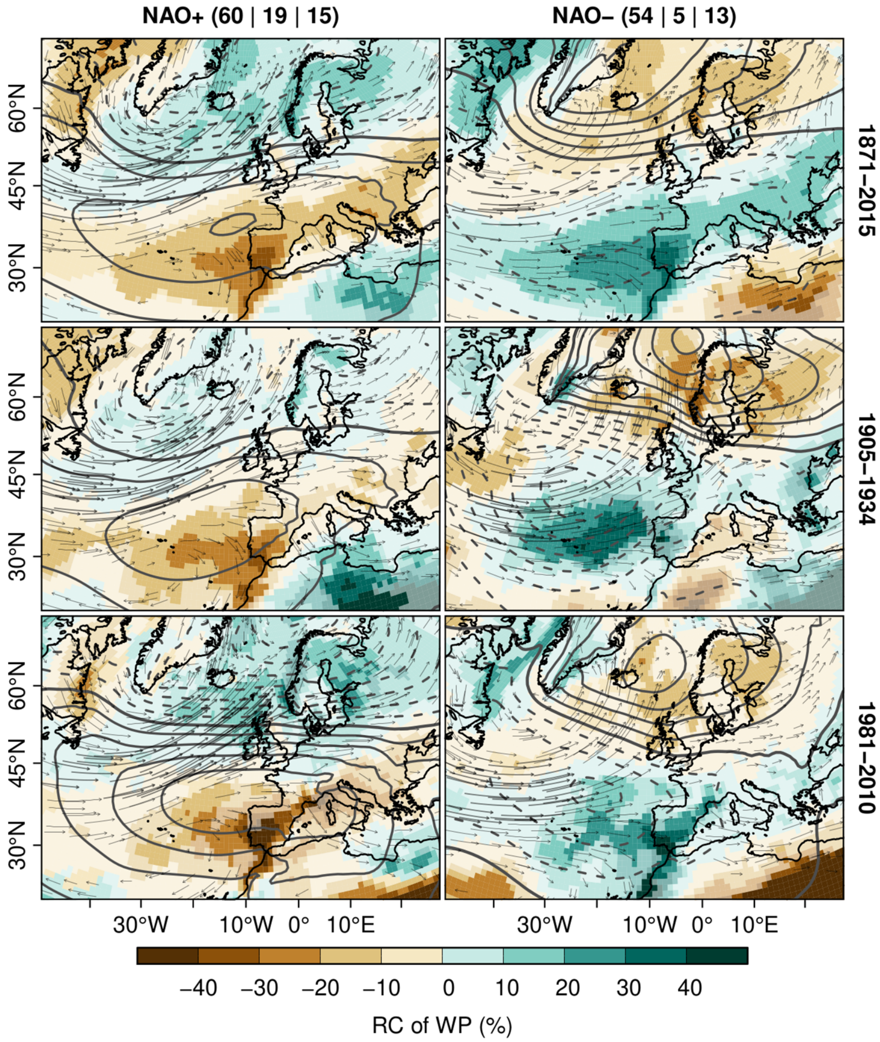

FIGURE 7 | Similar to Figure 5, for NAO index. [Colour figure can be viewed at wileyonlinelibrary.com]

it difficult to assess the uniqueness of EA activity during 1905–1934 or its recurrence. Additionally, the non-stationary relationship between NAO and EA complicates our understanding of why these modes sometimes exhibit similar phases and other times opposite phases (Mellado-Cano et al. 2019). For instance, while EA− and NAO+ characterised 1905–1934, this pattern differs from the NAO intensification observed in 1981–2010 (Figures 1b and 2b).

Reconstructing past climate conditions also poses challenges. The non-stationarity of NAO and EA complicates the extraction of their signals from climate proxies (Moore et al. 2013; Comas-Bru and McDermott 2014), and their interactions are not temporally stable (Halifa-Marín et al. 2025). Moreover, changes in westerly wind direction significantly affect climate records across Europe during the Holocene (Hu et al. 2022). While SST in the North Atlantic is consistently identified as a primary triggering factor, uncertainties persist. Consequently, it remains unclear whether past dry periods in Western Europe were primarily driven by EA variability, as observed during 1905–1934 (Figures 3 and 5).

Finally, current climate simulations fail to support divergent hypotheses regarding the evolution of the main modes of atmospheric circulation. State-of-the-art models struggle to capture the multidecadal variability of the North Atlantic climate system, as evidenced by the considerable spread in NAO variability both across and within models (Schurer et al. 2023; Gu et al. 2024; Smith et al. 2025). Additionally, models exhibit deficiencies in simulating NAO's centres of action (Tao et al. 2023; Santolaria-Otín and García-Serrano 2024), atmospheric blocking variability (Davini et al. 2012), ocean–atmosphere coupling (Börgel et al. 2020), polar jet intensity and trajectory (Bracegirdle 2022), and Northern Hemisphere Hadley Cell representation (Lionello et al. 2024). As long as these limitations persist, climate models remain inadequate for determining the contributions of various forcings to the anomalous behaviour of the AH and IL in the early 20th century.

4 | Conclusions

This study examines Iberian winter precipitation anomalies, focusing on the underlying synoptic mechanisms associated with NAO and EA phases during the long-term (1871–2015) and also during early and late 20th century periods. The period from 1905 to 1934 was assessed in detail after being identified as portraying a distinct phase of North Atlantic atmospheric dynamics. Unlike any other time in the Industrial Era, the EA pattern emerged as the first mode of winter climate variability, providing key insights into the multidecadal variability of both NAO and EA, as also highlighted by Halifa-Marín et al. (2025).

Our findings confirm that early 20th-century North Atlantic winter circulation was unprecedented within the Industrial Era. This is evident in the persistent positive NAO and strongly negative EA phases, a combination not observed at any other time. This confluence led to a synoptic pattern characterised by an intensified AH and a vast IL spanning much of the North Atlantic.

EA and NAO variability had significant climate impacts, particularly on Iberian precipitation (Figures 3 and 5). The pronounced influence of EA during 1905–1934, detectable even in long-term indices (1871–2015), highlights its role as a key precipitation modulator. During this period, EA+ conditions extended the AR toward Great Britain while preventing its penetration into Central Europe, generating easterly winds that enhanced precipitation in the western Mediterranean. Conversely, EA− conditions reduced precipitation by blocking Atlantic moisture, similar to NAO+. These impacts on precipitation were also evident across other regions influenced by these variability modes in Western Europe, including Ireland, Great Britain, France, and Central Europe (Figures 3, 6, and 7).

Furthermore, the persistence of a deep IL and a southward-shifted AH between 1905 and 1934 suggests a connection to natural variability, particularly volcanic forcing of SST, favouring AMO− and NAO+. However, the response of EA remains uncertain. A weakened GB plausibly intensified the IL, consistent with EA− dominance, yet the mechanisms governing EA's role in subsequent NAO+ or NAO− phases remain unresolved. Specifically, it is unclear why EA sometimes captures AR/IL activity over Great Britain rather than exhibiting the classical NAO dipole with GB or a displaced AH.

These findings challenge the conventional view of EA as secondary to NAO in multidecadal variability. Instead, EA may function as a primary mode shaping westerly dynamics over Europe (Hu et al. 2022). Despite its recognised role in modulating NAO's climatic influence (Comas-Bru and McDermott 2014), EA's variability and predictive potential remain underexplored. Recent studies emphasise EA's predictive skill for European climate (Thornton et al. 2023; Baker et al. 2024), suggesting that incorporating EA variability could enhance weather or seasonal forecasts across Western Europe. Consequently, climate monitoring services reliant on NAO should assess the added value of integrating EA into their predictive frameworks.

Although this study has not been able to precisely determine the mechanisms that caused EA to emerge as the primary mode of variability only in the early 20th century, further research on this matter could provide scientific insights to resolve some of the uncertainties related to ocean–atmosphere coupling in the North Atlantic climate system.

In conclusion, this study advances our understanding of North Atlantic winter climate variability by highlighting a previously underappreciated feature: the emergence of the EA pattern as the leading mode of variability during the early 20th century. Our results challenge the long-standing assumption that the NAO consistently dominates in terms of explained variance across all time periods. This finding not only prompts a reevaluation of the temporal stability of leading atmospheric modes but also opens new avenues for future research. These include assessing the influence of this anomalous configuration on extreme weather events in Europe and exploring the dynamics of NAO–EA interactions under past and future climate change scenarios.

Author Contributions

A. Halifa-Marín: conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review and editing, software, formal analysis, data curation, resources, supervision. **M. A. Torres-Vázquez:** writing – review and editing, visualization, validation. **R. Trigo:** conceptualization, investigation, methodology, supervision, writing – review and editing, project administration, resources. **S. M. Vicente-Serrano:** writing – review and editing, visualization, conceptualization, resources, supervision, formal analysis, validation. **M. Turco:** writing – review and editing, visualization, validation, methodology, funding acquisition. **P. Jiménez-Guerrero:** funding acquisition, project administration, resources, supervision. **J. P. Montávez:** conceptualization, investigation, funding acquisition, writing – review and editing, methodology, supervision, resources, project administration, visualization.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data used in this study are publicly available online. For 20CRv3 reanalysis data: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html (80-member ensemble mean), https://portal.nersc.gov/archive/home/projects/incite11/www/20C_Reanalysis_version_3/ (members data), and https://psl.noaa.gov/data/20CRv3_ISPD_obscounts/ (assimilated observations); for precipitation observations in Europa (Vicente Serrano et al. 2020, https://doi.org/10.1002/joc.6719; upon request); for observations-based NAO Index (https://www.uea.ac.uk/groups-and-centres/climatic-research-unit/data); and for monthly SLP anomalies from Valentia, Ireland (https://doi.org/10.1594/PANGAEA.892769).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.