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ORIGINAL ARTICLE

Causal oceanic feedbacks onto the winter NAO

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Abstract
Of the climate variability patterns that influence the weather in the North Atlantic region in winter, the North Atlantic Oscillation (NAO) is the most dominant. The effects of the NAO span from cold air outbreaks to unseasonably warm conditions and unusual precipitation, with significant impacts on human activities and ecosystems. While a connection between the NAO and antecedent sea surface temperature (SST) conditions has been recognised for decades, the precise causal interaction between the ocean and the atmosphere remains enigmatic. In this study we uncover a robust statistical relationship between North Atlantic SSTs in November and the NAO throughout the subsequent winter in the extended ERA5 reanalysis back to 1940. We apply a well-established causal inference technique called mediation analysis, commonly used in social science and now adopted in climate research. This analysis highlights the roles of low-level baroclinicity, latent heat fluxes, and latent heat release in mediating the effect of November SSTs on the NAO in January and February. It is important to recognise that these mediators are interrelated. Moreover, our analysis reveals bidirectional relationships, where the NAO reciprocally mediates the effects of the November SSTs on these variables. This is evidence of a complex web of feedback mechanisms which collectively contribute to the response of the winter NAO to late autumn/early winter SSTs.

Keywords North Atlantic Oscillation · North Atlantic Ocean · Feedback mechanisms · Mediation analysis · Causal inference

1 Introduction

In the mid-to-high latitudes of the North Atlantic, the North Atlantic Oscillation (NAO), an indicator of the strength and location of the storm track over this region (e.g., Hoskins and Valdes 1990; Hoskins and Hodges 2002; Hurrell et al. 2003), is generally considered to be the dominant climate variability pattern. Because the circulation anomalies associated with the NAO influence the weather in large parts of Eurasia and North America (Hurrell et al. 2003), prediction of the phase and strength of the NAO, from sub-seasonal (Albers and Newman 2021; Feng et al. 2021) and seasonal (Athanasiadis et al. 2017; Parker et al. 2019) to decadal (Smith et al. 2019; Athanasiadis et al. 2020) time scales, has been an active topic of research for decades (Stephenson et al. 2003). The predictability and persistence of the NAO has been linked to diverse climatic features, including the stratospheric polar vortex (Charlton-Perez et al. 2018; Domeisen 2019; Kolstad et al. 2020), the El Niño–Southern Oscillation, or ENSO (Domeisen et al. 2014), Arctic sea ice (Warner 2018), volcanic activity (Kelly et al. 1996), and North Atlantic SSTs.

It is well-known that the NAO influences North Atlantic SSTs through changes in surface winds, which generate anomalous turbulent heat fluxes at the ocean surface, anomalous Ekman transport and temperature advection (e.g., Marshall et al. 2001). In response to this NAO forcing, a distinct pattern of SST anomalies which resembles a tripole emerges in the North Atlantic (e.g. Deser et al. 2010; their Fig. 1). In the positive phase of the NAO, it consists of anomalously cold SSTs south of Greenland, anomalously warm SSTs along the Gulf Stream extension into the Nordic Seas, and cold SST anomalies further south (while opposite anomalies tend to occur in the negative NAO phase).

A longstanding debate revolves around whether North Atlantic SSTs also exert an influence on the NAO, potentially giving rise to a bidirectional feedback mechanism

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between the ocean and the atmosphere. Statistical evidence supporting such an effect was identified by Czaja and Frankignoul (1999) and Czaja and Frankignoul (2002), who analysed observational data and found that early winter NAO anomalies could be traced back to an SST pattern resembling this pattern several months earlier. Wang et al. (2017) found a similar SST pattern during autumn, which was found to be associated with skilful predictions of the NAO during the subsequent winter. These findings provide empirical evidence that North Atlantic SSTs may indeed wield a meaningful lagged impact on the NAO.

However, it is worth noting a key difference between the pattern identified by Deser et al. (2010) and the ones found by Czaja and Frankignoul (2002) and Wang et al. (2017). As mentioned, the SST anomaly pattern highlighted by Deser et al. (2010), which reflects the zero-lag relationship between the NAO and SSTs during winter, has a tripole-like structure. In contrast, the SST anomaly pattern identified by Czaja and Frankignoul (2002) and Wang et al. (2017), which represents SSTs leading the NAO, resembles a horseshoe. In the horseshoe pattern, SST anomalies extend from the subpolar North Atlantic (south of Iceland), proceed south-eastwards via the British Isles, and then curve south-westwards toward the Caribbean.

In addition to observational evidence, several studies have employed experiments using prescribed SSTs to force atmosphere-only models. Generally, these studies support the notion of a lagged effect of North Atlantic SSTs on the NAO (e.g., Peng et al. 2002; Paeth et al. 2003). However, some researchers, such as Sutton et al. (2000), have emphasised that the impact of SSTs may be weaker than the influence of internal atmospheric variability. This could be attributed to the limitations of using models where the SSTs are prescribed. An issue with these simulations is that the coupling between the ocean and atmosphere is broken, and SST anomalies directly generate anomalous heat fluxes to the atmosphere. In reality, and within a coupled model, the heat fluxes often act as a forcing mechanism for these SST anomalies and work in the opposite direction (Bretherton and Battisti 2000).

An early example of studies using prescribed SSTs is the work by Rodwell et al. (1999), who conducted experiments where an atmospheric model was forced with positive and negative SST anomaly patterns. These were derived from an SST/NAO correlation analysis. The authors argued that, as the ocean surface conditions were fixed, any influence on the NAO must be attributed to the SSTs. They suggested that North Atlantic SST anomalies can lead to local changes in surface evaporation, precipitation, and atmospheric heating, and that these changes tend to reinforce the thermal and geopotential structure of the NAO, indicating a potential feedback mechanism. Subsequent studies have further refined and expanded upon this proposed mechanism.

For instance, it has been suggested that eddy-feedback mechanisms (e.g., Lorenz and Hartmann 2003) may be important for the interactions between the NAO and the ocean (Peng et al. 2003; Nie et al. 2019; Wu et al. 2022). SST gradients along the Gulf Stream front, which influence the low-level atmospheric baroclinicity, have also been highlighted as a key influence on the North Atlantic storm track and consequently the NAO (e.g., O'Reilly et al. 2017; Famooss Paolini et al. 2022).

In this study we use data from the ERA5 reanalysis (Hersbach et al. 2020), which has recently been extended back to 1940, to investigate the role of late autumn/early winter North Atlantic SST anomalies in forcing the winter NAO. As mentioned, many of the previous studies on this topic have relied on simulations with prescribed SST boundary conditions. In ERA5, the ocean surface is also prescribed, but an indirect coupling between the ocean and the atmosphere is obtained by forcing the model with the dynamic oceanic reanalysis ORAS5 (Zuo et al. 2019).

As the climate system is complex, with a large range of variables influencing each other, it is often challenging to assign causality in an explicit manner. Using statistical methods to address causality and not just correlations is often referred to as *causal inference* (e.g., Pearl et al. 2016; Runge et al. 2019). While such methods provide a valuable framework for assessing the causal validity of relationships between climate variables, it is essential to apply a fundamental scientific understanding when interpreting the results of such an analysis. Causal inference methods are increasingly used to enhance the understanding of linkages between different parts of the climate system (e.g., Mosedale et al. 2006; Ebert-Uphoff and Deng 2012; Kolstad et al. 2017; Barnes et al. 2019; Kretschmer et al. 2021). Here we make use of a subset of causal inference theory focused on *mediation* (MacKinnon et al. 2007; Preacher 2015) to study the lagged relationship between SSTs and the NAO.

There are four parts to the research presented in this paper. First, we assess the linkages between the NAO and a set of diagnostic variables, including SSTs, low-level baroclinicity, latent heat fluxes between the ocean and the atmosphere, and convective precipitation. Second, we conduct a lagged correlation analysis to test whether specific North Atlantic SST patterns in November have a significant influence on the NAO in the subsequent winter months. In the third part we explore the dynamical pathways for this influence by studying the evolution of a set of diagnostic variables from early to late winter. Finally, we use mediation analysis to check whether these evolutions and their associated dynamics mediate the impact of North Atlantic SSTs on the NAO in a causal sense. The paper concludes with a discussion of the findings.

2 Data and methods

2.1 Data

From ERA5, we made use of monthly means of sea level pressure (SLP), SST, sea ice cover, convective precipitation, surface latent heat flux, and temperature, wind and geopotential height at low levels (700 and 850 hPa). The study period is 1940–2022. Convective precipitation is treated as a proxy for latent heat release through condensation. Such diabatic heating is a well-known potential positive feedback mechanism on cyclones (e.g., Hawcroft et al. 2017, and references therein). The pressure-level data were used to calculate the maximum Eady growth rate (denoted EGR hereafter) between 700 and 850 hPa, following Hoskins and Valdes (1990).

The analysis was performed for the region north of 20°N, the 'midlatitudes' region in Czaja and Frankignoul (2002). Including areas further south had little influence on the results on this timescale. This does not mean that tropical SSTs do not influence the NAO, only that the focus in this paper is on the midlatitude feedback mechanisms between SSTs and the NAO.

2.2 Indices

For each of the ERA5 winters, we calculated the December–February (DJF) mean SLP anomalies and used these to compute an NAO index as the Principal Component (PC) of the first Empirical Orthogonal Function (EOF) inside the standard NAO domain between 20°N and 80°N and from 90°W to 40°E, using the *eofs* software package for Python (Dawson 2016). The leading EOF was found to explain 48% of the variance of the SLP.

By regressing time series of standardised anomalies in the diagnostic variables in each grid point onto the DJF NAO index time series, we computed 'loading patterns' which reveal the spatial signature of these variables associated with the winter NAO. These patterns are shown in Fig. 1, which will be discussed more in Sect. 3.1.

We used both seasonal and monthly mean data, the latter to explore evolutions within the winter season. To obtain a separate NAO index for each month between November and March, we projected monthly mean SLP anomalies inside the NAO reference region onto the SLP loading pattern shown in Fig. 1a, and then we standardised the resulting time series.

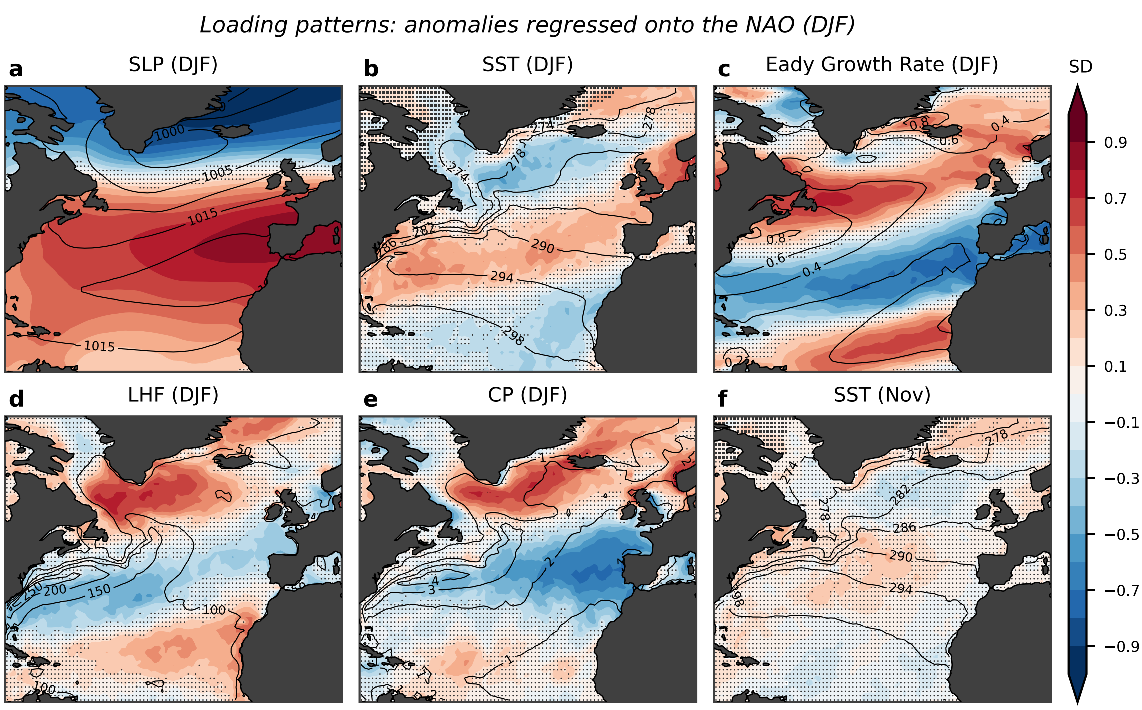

Fig. 1 Filled contours: Anomaly loading patterns associated with the DJF NAO index. The variables are: SLP during DJF (**a**); SST during DJF (**b**); the EGR during DJF (**c**); latent heat flux during DJF (**d**); convective precipitation during DJF (**e**); SST during November (**f**). The grey squares in the SST panels indicate grid points with a mean sea ice cover above 50%. Dots indicate regressed anomalies which are not significantly different from zero at the 5% level, and the unit for the anomalies is standard deviation (SD). Contours: Climatological means with the following units: SLP: hPa; SST: K; EGR: day^{-1}; latent heat flux: W m^{-2}; precipitation: mm day^{-1}

This was done to ensure that the NAO index for each month refers to the same spatial pattern. The alternative would be to compute the EOFs separately for each month, but as these would each have had slightly different spatial signatures, the results would have been more difficult to interpret. For the same reason, we computed an index which we will refer to as the November 'SST index' henceforth. This was done by projecting November monthly mean SST anomalies in all the oceanic grid points inside the 'midlatitude' region in Czaja and Frankignoul (2002) (20°N–70°N, and 100°W–20°E) onto the November SST loading map, which is shown in Fig. 1f, and then standardising the resulting time series. The results of the analysis were not sensitive to the choice of reference region.

2.3 Impact of trends

While we acknowledge the discernible trends in our dataset throughout the study period, it is important to note that some of these trends are intertwined with multidecadal cycles. Applying linear detrending across the entire period may not be the most suitable approach, as demonstrated in Appendix 1. Considering the intricacy of these variabilities on multiple time scales, our analysis relies on non-detrended data.

2.4 Mediation and suppression

We adopt the terminology used in Eqs. 1, 2, 3 in MacKinnon et al. (2000), dropping intercepts and error terms for clarity. To understand *mediation* and the related concept of *suppression*, we start from a known relationship between a 'predictor' or 'independent variable' X and a 'predictand' or 'outcome variable' Y:

$$Y = \tau X. \tag{1}$$

In Fig. 2, the total effect τ is illustrated by the solid, directed line at the bottom of the diagram. The direction from left to right indicates that X precedes Y in time, or that for a sound physical reason it is clear that X causes Y. If one suspects that there is a third variable Z that influences the relationship between X and Y, one can check for mediation. This can be done using two more linear regressions:

$$Y = \tau' X + \beta Z, \tag{2}$$

where $\tau\prime$ is the effect of X on Y when accounting for Z, and β is the effect of Z on Y when accounting for X. The next regression is:

$$Z = \alpha X, \tag{3}$$

where α is the effect of X on Z. We follow the heuristics outlined by Baron and Kenny (1986), which state that τ, α and β must all be significantly different from zero for Z to be a mediator of the effect of X on Y. For $\tau\prime$ there are several possibilities:

1. If $\tau\prime$ is not significantly different from zero, the effect of X on Y becomes negligible when accounting for Z. In this case there is no direct causal relationship between X and Y. The reason that the total effect τ is significant in this case is that Z fully (or completely) mediates the effect of X on Y.

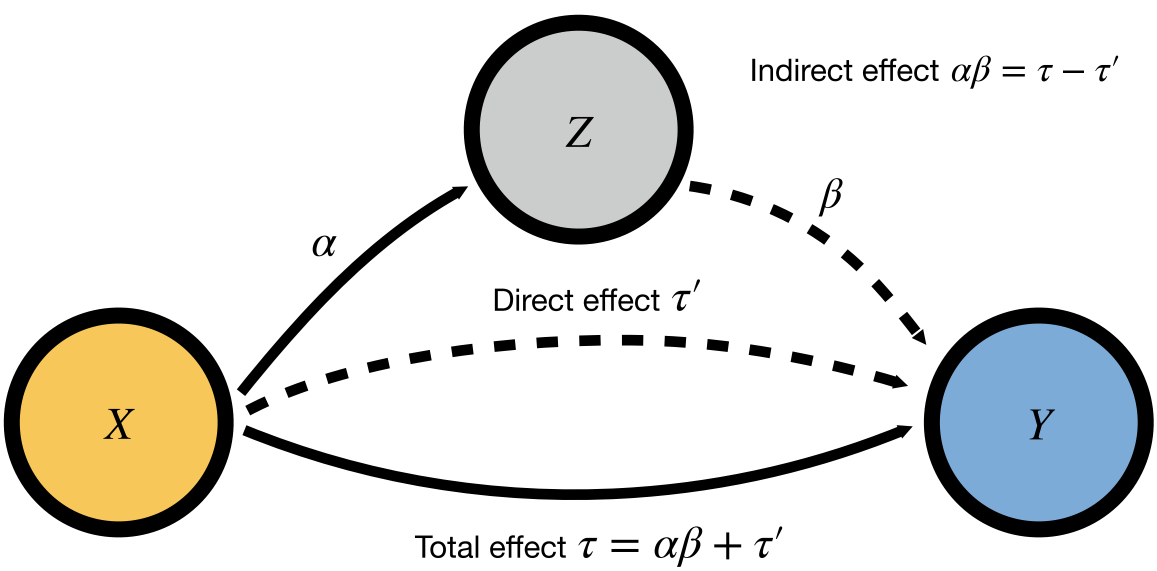

Fig. 2 An illustration of the effect of X on Y and the mediation of this effect by Z. See the text for details

2. If $\tau\prime$ is significantly different from zero, but its magnitude is less than the total effect ($|\tau\prime| < |\tau|$), Z partially mediates the effect of X on Y.
3. If $\tau\prime$ is significantly different from zero and its magnitude is greater than the total effect ($|\tau\prime| > |\tau|$), Z is a 'suppressor' of the effect of X on Y. A suppressor has been defined by Conger (1974) as 'a variable which increases the predictive validity of another variable by its inclusion in a regression equation'. In practice this means that the influence of X on Y would have been larger if it were not for the relationship between X and the suppressor Z and the relationship between Z and Y.
4. Cases where $\tau\prime$ has the opposite sign of τ are known as 'inconsistent mediation'.

As noted in Fig. 2, $\tau = \alpha\beta + \tau\prime$ (MacKinnon et al. 1995), which means that $\alpha\beta = \tau - \tau\prime$. The strength of the mediation or suppression is therefore proportional to $\alpha\beta$ (also known as the 'indirect' or 'mediated' effect). When the indirect effect $\alpha\beta$ is negative, there is suppression.

An issue to consider upfront is that since we are employing mediation analysis to explore feedback mechanisms, there is not necessarily a unique causal direction. In practice, the criteria for complete or partial mediation may be met not only for the causal chain X—> Z—> Y, which is illustrated in Fig. 2, but also for the causal chain X—> Y—> Z. The literature is replete with examples of such bidirectional relationships, which are often referred to as 'feedback loops' (e.g., Moody and Zhao 2020; McDonald et al. 2021). As statistical methods cannot definitively determine whether one of the causal chains is more valid than the other (MacKinnon et al. 2000; Thoemmes 2015; Lemmer and Gollwitzer 2017), causal inference approaches are only appropriate when they can be backed up by expert knowledge about physical mechanisms (Ebert-Uphoff and Deng 2012; Kretschmer et al. 2021).

Finally, we emphasise that mediation or suppression by Z does not necessarily mean that Z is the only mediator or suppressor of the effect of X on Y (e.g., Fiedler et al. 2011; VanderWeele and Vansteelandt 2014). In the analysis that follows, we find multiple full and partial mediators/suppressors of the effect of North Atlantic SSTs on the NAO.

2.5 Significance testing

A significance level of 5% was applied throughout. Unless specified, conventional techniques integrated into the SciPy Python library (Virtanen et al. 2020) were used to calculate the statistical significance of the parameters. The p-values for both correlation coefficients and linear regressions in this software library were determined through two-sided t-tests.

However, an exception is noted for the significance analysis in Fig. 1, for which a two-sided bootstrapping test was conducted. This involved generating a set of 1000 synthetic NAO time series, wherein the original data points were replaced with random data from the original NAO time series (with replacement). Subsequently, the anomalies in the diagnostic variables were regressed onto these 1000 synthetic time series. The key criterion was whether the regressed anomalies fell outside the range defined by the 2.5th and 97.5th percentiles of the synthetic regressions. If they did, the anomalies were considered to be significantly different from zero.

3 Results

3.1 NAO relationships

We start our analysis by investigating the simultaneous and lagged relationships between the NAO in winter and a set of diagnostic variables in Fig. 1. The zero-lag relationship between the NAO and SLP, shown in Fig. 1a, is included for reference and shows a typical positive NAO pattern. When considering the relationship between the NAO and SSTs (Fig. 1b), we note that the spatial signature resembles the North Atlantic SST tripole (Deser et al. 2010). Of special interest are the gradients between the SST anomalies, as these are linked to the EGR, a measure of low-level baroclinicity. Notably, there are gradients in the SST anomaly field between Newfoundland and the entrance to the Nordic Seas (Fig. 1b), in the area between cold SST anomalies between Newfoundland and Iceland and warm SST anomalies further south. This is an area where the climatological SST field exhibits a gradient between cold SSTs in the north and warm SSTs in the south (as indicated by the contours in Fig. 1b). These gradients are enhanced by the SST anomalies in Fig. 1b, reflecting colder SSTs where these are already cold in the north and warmer SSTs in the south where they are already warm. This area with enhanced gradients coincides with positive EGR anomalies (Fig. 1c). It is probable that these EGR anomalies emerge due to a combined influence of the underlying SST gradients and the NAO (temperature advection from anomalous winds). Conversely, beneath the band marked by negative EGR anomalies in the southern North Atlantic, the SST gradients diminish between the warm SST anomalies to the north and cold SST anomalies to the south of the negative EGR anomalies. When considered collectively, the pattern of positive EGR anomalies in the north and negative EGR anomalies further south seen in Fig. 1c is consistent with a northward shift and strengthening of the storm track during positive NAO winters and a southward shift during negative NAO winters.

The latent heat flux anomaly pattern shown in Fig. 1d exhibits a maximum to the north of the storm track region. This is a signature of high wind speeds and intensified fluxes from the ocean to the atmosphere during the positive phase of the NAO and weaker winds and suppressed fluxes when the NAO is negative. To the north of Iceland, positive latent heat flux anomalies are found in areas with decreased sea ice extent during positive NAO winters. This reduced sea ice is not shown explicitly, but it is implicitly evident from the positive SST anomalies in this area (Fig. 1b). When looking at the convective precipitation pattern in Fig. 1e, we see positive anomalies above and downstream of the positive latent heat flux anomalies.

Lastly, in Fig. 1f we show the regression of November SST anomalies onto the NAO index in DJF to check whether there is a systematic relationship between the late autumn/early winter SST pattern and the subsequent NAO. The loading pattern is only significant in a few areas: to the northeast and southwest of Iceland, as well as further south near the middle of the North Atlantic. As shown in Appendix 2, a similar pattern is seen already in September and October. This demonstrates that, on average, an SST anomaly pattern is in place already in November when the NAO later in the winter is non-neutral. In the next section we investigate this pattern in time series form through the SST index, which is the projection of November SST anomalies onto the pattern in Fig. 1f.

3.2 Lagged correlation analysis

Figure 3 provides an opportunity to study the strength and intraseasonal evolution of the link between the November SST index on the NAO index later in the winter. It also allows a comparison with the autocorrelation of the November NAO index. This figure presents the coefficients for a multivariate linear model in which the NAO and SST indices

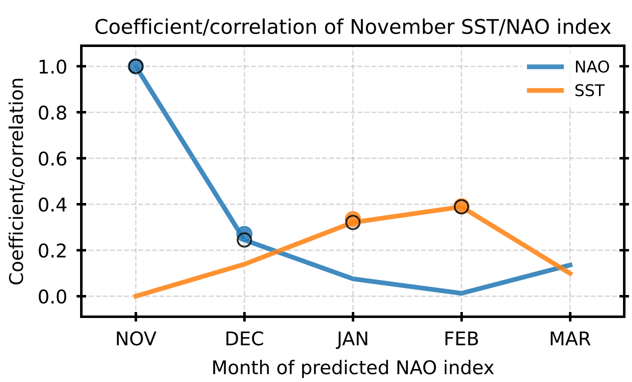

Fig. 3 Lines: Regression coefficients for a linear model where the indicated indices in November are predictors and the NAO index in subsequent months (denoted on the x-axis) is the response variable. The black circles indicate coefficients that are significantly different from zero (at the 5% level). Filled circles: Lagged correlations between the indices in November and the NAO index in subsequent months. Correlations that are not significantly different from zero (at the 5% level) are not shown

in November are the predictors, and where the response variable is the NAO index spanning the entire winter. For the sake of comparison, we also display the lagged correlation coefficients between the November indices and the subsequent NAO index when these are statistically significant.

We break down the results for the NAO coefficients first. For November, the correlation and regression coefficient are both 1, which is expected as the NAO perfectly predicts itself, and the SST index adds no additional information. Moving to December, the coefficients differ. The correlation (depicted with a filled circle) is slightly higher than the regression coefficient. This discrepancy arises because the regression coefficient accounts for the SST index, which begins contributing to the regression in December. After December, neither the correlations nor the regression coefficients are statistically significant.

We now turn to the SST index coefficients. In November, the regression coefficient is zero because the NAO index itself is a predictor, while the correlation is weakly positive but not significant at the 5% level. Both coefficients are also non-significant when predicting the December NAO index (the correlation is still weakly positive). When predicting the January and February NAO index, both the correlation and the regression coefficients of the November SST index are significant.

A notable feature in Fig. 3 is that the SST index coefficients increase with each passing month until February. This suggests that the feedback mechanisms linking the November SSTs and the NAO gain in strength as the winter progresses. However, the non-significant coefficients predicting the March NAO index indicate a sharp decline in the lagged effect of the November SST index as winter transitions to spring. We also note that the regression coefficients for predicting the January and February NAO index are almost identical to the correlation coefficients. This aligns with the non-significance of the coefficients of the November NAO index when predicting the NAO index in these same months.

Referring back to the discussion on trends in Sect. 2.3, it is worth mentioning that we generated an iteration of Fig. 3 by employing linearly detrended SST and NAO indices. Although not shown here, the correlation and regression coefficients remained statistically significant for the same months as in the analysis based on non-detrended data. Furthermore, the magnitude of these coefficients did not change appreciably. This implies that the findings presented in this study are not disproportionately affected by the linear trends observed in the SST and NAO indices.

Essentially, the findings presented in Fig. 3 confirm that when it comes to predicting the January and February NAO index, the November NAO index provides no meaningful information. In contrast, the November SST index exhibits significant predictive power for the NAO index during these same months. Consequently, the remaining sections focus on

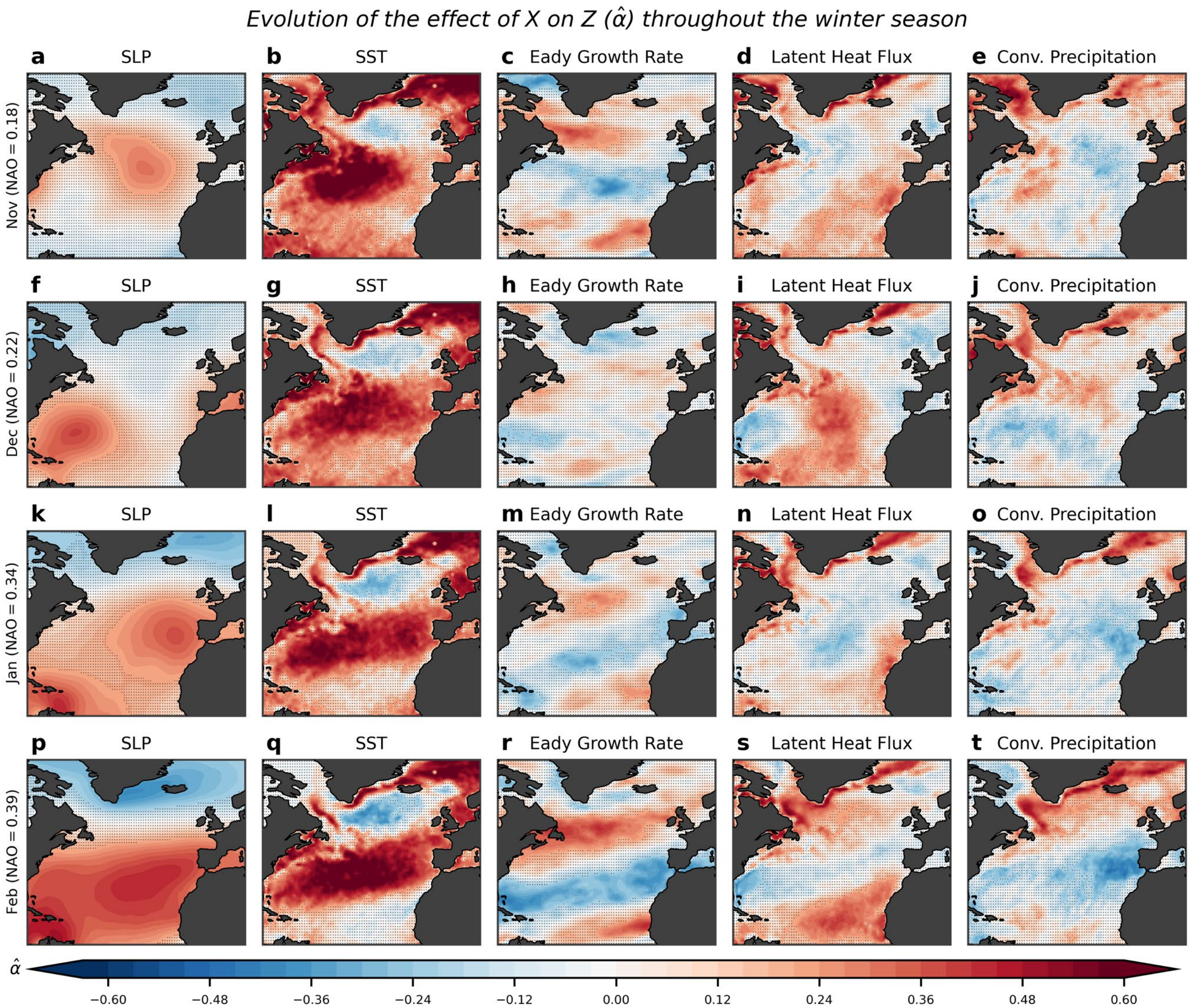

Fig. 4 Sample ERA5 $\hat{\alpha}$ coefficients for the case when X in Eq. 3 is the SST index in November and Z is the indicated diagnostic variable in November (top row), December (second row), January (third row), and February (bottom row). The expected NAO index starting with an SST index value of 1 SD in November is indicated to the left of each row. Grid points with non-significant (at the 5% level) are identified with dots

the lagged correlation between the November SST index and the NAO index in subsequent months.

3.3 Pathways for an oceanic influence on the NAO

We extend our investigation from the previous section by examining the mechanisms by which North Atlantic SSTs in November impact the NAO throughout the winter. To do this, we use the SST index in November as X in Eq. 3 and present the sample coefficient $\hat{\alpha}$ for each of the diagnostic variables Z (SLP, SST, EGR, latent heat flux, and convective precipitation) for each month between November and February in Fig. 4.

In our analysis, we take a $+1$ standard deviation (SD) anomaly of the SST index in November as a reference point. This means that the $\hat{\alpha}$ coefficients can be understood as the expected average standardised anomalies in the diagnostic variables during each of the subsequent months given these initial conditions. As the same holds for the correlations in Fig. 3, starting from this reference point the NAO index gradually approaches a value of 0.39 in February, which is indicated to the left of each row in Fig. 4. The progression of the $\hat{\alpha}$ coefficients for SLP in the first column aligns with this anticipated development. In February, we observe a distinct and positive NAO pattern, as depicted in Fig. 4p.

In parallel, the SST anomalies shown in the second column of Fig. 4 depict a transition from a pattern characterised by unusually warm conditions in the western central part of the North Atlantic in November (Fig. 4b) to a dipole-like structure in February (Fig. 4q), in which the warm area is more elongated and cold anomalies have emerged in the subpolar North Atlantic.

For the EGR anomalies in Fig. 4r, a configuration which is consistent with the gradients in the SST anomalies is seen. Between Newfoundland and the entrance of the Nordic Seas, there is a region with enhanced baroclinicity because the climatological gradients between cold SSTs in the north and warm SSTs in the south are strengthened (see also Fig. 1c). Conversely, to the south of the warm SST anomalies there is a large area with suppressed baroclinicity because the SST gradients are weakened in that area. In essence, the structure presented in Fig. 4r signifies a concentration and strengthening of the storm track in the primary storm track region when the NAO is positive (and a shift towards the south when the NAO is negative).

In the area to the north of the enhanced baroclinicity (i.e., to the south of Greenland), stronger wind speeds and anomalous cold air advection from the Labrador Sea yield positive latent heat flux anomalies (Fig. 4s). Additionally, north of Iceland, there is a small area with positive latent heat flux anomalies due to reduced sea ice cover (not shown, but evident from the positive SST anomalies in Fig. 4q). Both above and downstream of these positive flux anomalies, above-average convective precipitation indicates an intensified release of latent heat in the northern branch of the NAO, which in turn represents a positive feedback which reinforces the positive NAO pattern (Fig. 4t). The negative precipitation anomaly in the eastern part of the subtropical North Atlantic can be linked to the reduced baroclinicity upstream (Fig. 4r), which implies a suppressed storm track. Consequently, the reduced diabatic heating reinforces the positive SLP anomalies in the southern branch of the NAO.

In summary, Fig. 4 has illustrated an evolution from near-neutral NAO conditions in November to positive NAO conditions in February, given a 1 SD anomaly in the SST index in November. This agrees with the evolution in Fig. 1a. SSTs, baroclinicity, wind speed, latent heat fluxes and convective precipitation/latent heating have been found to be affected by the shift towards a positive NAO, but they also appear to contribute to positive feedbacks onto the SLP anomalies in both branches of the NAO. In the next section we will examine mediators and suppressors to gain a deeper understanding of these feedback mechanisms.

3.4 Mediation analysis

In this section we go through the steps of checking for mediation and suppression as described in Sect. 2.4. Our aim is to check whether the diagnostic variables mediate or suppress the lagged relationship between the SST index in November and the NAO index in January and February. We focus on these months because Fig. 3 demonstrated a significant relationship for this period. The procedure entails calculating the sample coefficients $\widehat{\tau}$, $\widehat{\alpha}$, $\widehat{\tau\prime}$ and $\widehat{\beta}$, as well as their significance. This was done separately for each diagnostic variable and for each grid point. In Eqs. 1, 2, 3, we let the predictor X be the SST index in November, Y the NAO index in first January and subsequently February, and Z each of the diagnostic variables in turn during those same months.

To check for meditation or suppression, we use the following heuristic approach. First, we know already that $\widehat{\tau}$ is significant for both January and February (see Fig. 3). Second, we check if $\widehat{\alpha}$ is significant. Third, we check if $\widehat{\beta}$ is significant. Fourth, we check if $\widehat{\tau\prime}$ is significant.

We have previously presented the January and February sample $\widehat{\alpha}$ coefficients in the last two rows of Fig. 4. These coefficients represent the lagged effect of X (the November SST index) on the diagnostic variables Z during these months. The sample $\widehat{\beta}$ coefficients (which are not shown here) are the effect of Z on Y (the NAO index) when accounting for the SST index in November. Wherever both $\widehat{\alpha}$ and $\widehat{\beta}$ are significant and share the same sign, the product $\widehat{\alpha}\widehat{\beta}$, referred to as the indirect effect, will be positive. Conversely, when both coefficients are significant but have opposite signs, the product $\widehat{\alpha}\widehat{\beta}$ becomes negative. In such cases, the third variable Z acts as a suppressor, dampening the impact of X on Y.

Prior to describing the results of the mediation analysis, we point out that the diagnostic variables Z are not independent. For instance, latent heat fluxes have a significant relationship with convective precipitation. Additionally, the heat fluxes and baroclinicity are both linked through their mutual association with the underlying SSTs. Consequently, the subsequent analysis uncovers instances of mediation and suppression involving multiple variables. It is important to emphasise that these variables do not compete but instead illuminate different facets of mediation and suppression, with a substantial portion of these phenomena ultimately stemming from the evolution of the North Atlantic SST pattern.

We also emphasise that the indirect effects investigated here represent feedback loops. Although we do not show this explicitly, we verified that the criteria for partial or full mediation were satisfied not only for the causal chain X—> Z—> Y, which is depicted in Fig. 2, but also for the causal chain X—> Y—> Z. This means that there is a bidirectional relationship between the diagnostic variables and the NAO index.

In Fig. 5 the sample indirect effect $\widehat{\alpha}\widehat{\beta}$ is shown for all the diagnostic variables, excluding SLP and SST, as they are too closely linked to X and Y to serve as meaningful mediators. We start by analysing the indirect effects of baroclinicity, represented by the EGR. Beginning with Fig. 5d, it shows

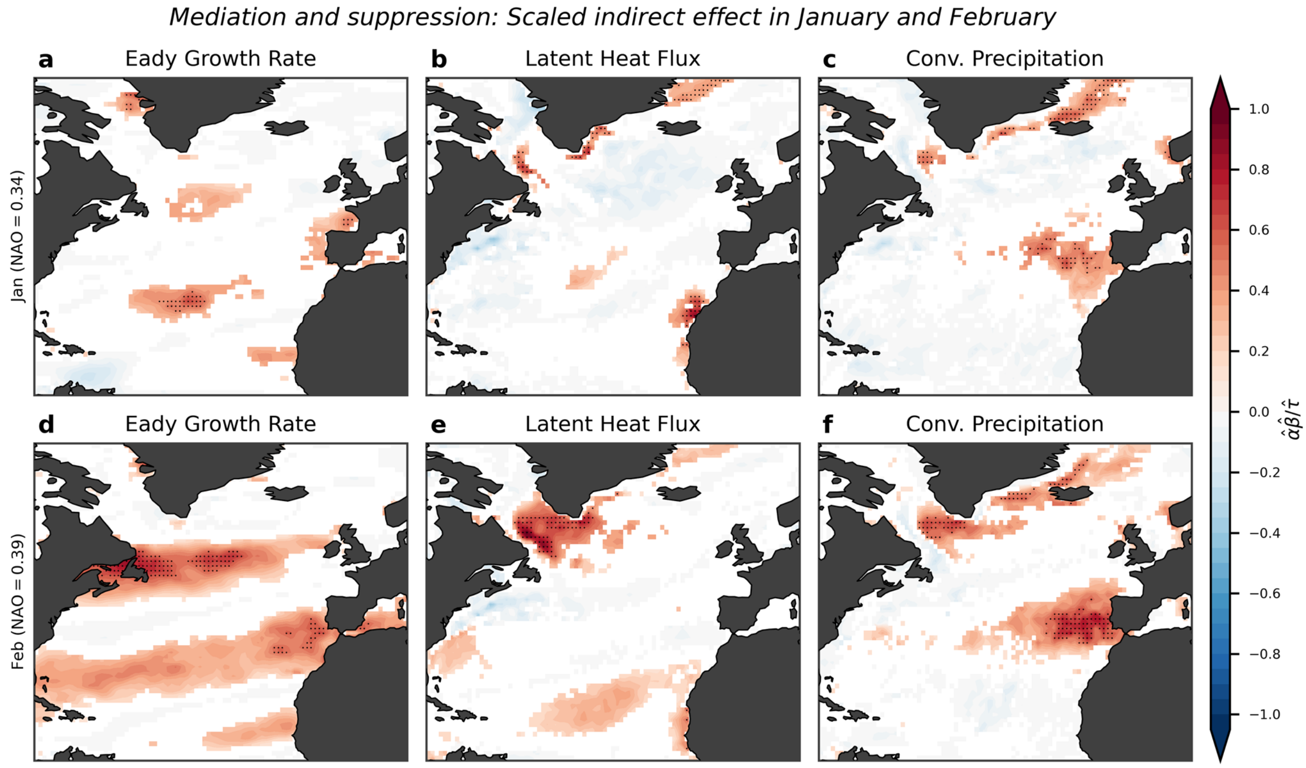

Fig. 5 Sample indirect effect $\widehat{\alpha}\widehat{\beta}$ (scaled by the total effect $\widehat{\tau}$) for the cases when X in Eq. 3 is the SST index in November and the specified diagnostic variable Z and the NAO index Y are both evaluated in January (top row) and February (bottom row). The expected NAO index starting with an SST index value of 1 SD in November is indicated to the left of each row. Masked grid points indicate the absence of both mediation and suppression. Full mediation is illustrated with black dots

that $\widehat{\alpha}\widehat{\beta}$ for the EGR is positive, not only within the primary storm track region where $\widehat{\alpha}$ was previously identified as positive (Fig. 4r), but also in the southern region where $\widehat{\alpha}$ was found to be negative. In both regions, baroclinicity is a complete mediator. One month earlier, in January, a weaker version of this pattern is seen in Fig. 5a.

These observed patterns in the EGR align with earlier studies suggesting that heating associated with the SST pattern generates anomalous temperature gradients, which in turn contribute to a positive NAO response (e.g., Rodwell et al. 1999; Peng et al. 2003). This underscores the crucial role of low-level baroclinicity. It is also worth noting that a few areas have slightly negative values of $\widehat{\alpha}\widehat{\beta}$. In these areas, the EGR rate acts as a modest suppressor, which means that the effect of November SSTs contributes to a negative feedback on the NAO index later in the winter.

We now turn to the latent heat fluxes and the convective precipitation, for which the indirect effects are shown in the middle and right columns of Fig. 5. Starting with the northern NAO branch, these variables play a mediating role, with the strongest mediation occurring south of Greenland in February (Fig. 5e–f) and north of Iceland in January (Fig. 5b–c).

In the region south of Greenland, enhanced fluxes and precipitation (accompanied by latent heating) during positive NAO conditions are linked to a reinforced flow from the northwest. This relationship can be both a consequence of and a contributor to the NAO. Conversely, during negative NAO conditions, the fluxes and diabatic heating are subdued due to a weakening of the westerly flow over the area. Notably, in January, when the baroclinicity upstream of the northern NAO branch is relatively weak compared to February, the latent heat fluxes have a modest suppressing effect in the subpolar North Atlantic (Fig. 5b). This is likely attributed to the negative SST $\widehat{\alpha}$ coefficients in this area (Fig. 4l), which suppress the heat fluxes during positive NAO conditions. This is a negative feedback onto the NAO. In February, the SST $\widehat{\alpha}$ coefficients in this area are even more negative than in January (Fig. 4q), but the strengthened baroclinity and NAO signal during this month likely leads to stronger wind speeds during positive NAO conditions, which in turn enhance the surface heat fluxes. Because of these opposite influences, the suppressing role of the latent heat fluxes seen in January (Fig. 5b) is neutralised in February (Fig. 5e).

To the north of Iceland, a correlation exists between reduced sea ice extent during positive NAO cases and increased sea ice extent during negative NAO cases. While the sea ice extent is not explicitly displayed here, this relationship is evident from the positive SST $\widehat{\alpha}$ coefficients in both January (Fig. 4l) and February (Fig. 4q). The sign of these anomalies aligns with the role of the heat fluxes and precipitation as mediators in this region.

Inside the southern NAO branch, convective precipitation, and consequently latent heating, plays an important mediating role in the eastern North Atlantic, off the coast of the Iberian Peninsula. This pattern is very clear in February (Fig. 5f) and somewhat less pronounced in January (Fig. 5c). The association to the NAO is that there is enhanced precipitation during negative NAO cases, when there is enhanced cyclone activity in this region due to enhanced baroclinicity upstream. Conversely, there is reduced cyclone activity during positive NAO cases. The latent heat fluxes appear to play a less important role in the southern NAO branch compared to the northern branch.

4 Discussion

As described in the Introduction, a large body of research has investigated linkages between North Atlantic SST patterns and the NAO. It is clear that the NAO influences the ocean surface through cooling/heating and wind stress. Several studies have suggested that North Atlantic SSTs also influence the NAO, but to the best of our knowledge, no causally robust evidence of the latter relationship has been presented. One significant reason for the absence of such evidence is the limited availability of reliable observational data. However, now that the ERA5 reanalysis has been extended back to 1940, it is possible to perform a robust causal investigation.

Our results show that North Atlantic SST anomalies during late autumn/early winter (November) exert a significant influence on the NAO in January and February. Furthermore, we have presented evidence for the mediation of this lagged influence by a few selected diagnostic variables through a mediation analysis, which is a novel approach in studies of climate dynamics. We also performed a 'reverse' mediation analysis, which, although we did not delve into its results in detail, revealed that the NAO mediates the lagged influence of the November SSTs on the diagnostic variables. This is evidence of a bidirectional relationship, or feedback loop, between the diagnostic variables and the NAO. The main feedback mechanisms identified through our analysis are as follows.

Baroclinicity in the lower troposphere. The November SST pattern which is most favourable for the subsequent development of the NAO has slightly below-normal SSTs over the subpolar North Atlantic and strongly above-normal SSTs further south for the positive phase of the NAO. Over the course of the winter, this pattern evolves into a structure that resembles the North Atlantic tripole pattern (e.g., Deser et al. 2010). At the boundary between the cold SST anomalies to the north and the warm SST anomalies to the south, which coincides with the primary storm track area of the North Atlantic, above-normal maximum Eady growth rates are found. These anomalies play a role in bolstering the formation of low-pressure systems within the storm track region and consequently lower pressure in the northern branch of the NAO. At the same time, a distinct weakening of the baroclinicity is seen upstream of the southern NAO branch. This leads to less cyclone activity during the positive phase of the NAO. Conversely, during negative NAO cases, the baroclinicity within the main storm track region weakens, while it is strengthened in the southern part of the North Atlantic.

These results align with modelling studies with prescribed SST boundary conditions, which found that strengthened SST gradients exert an influence across the Gulf Stream region in high-resolution models (e.g., O'Reilly et al. 2017; Famooss Paolini et al. 2022). In these studies, the SST gradients strengthen the low-level baroclinicity, which in turn strengthens the storm track and reduces the frequency of high-latitude blocking over Greenland (e.g., Athanasiadis et al. 2020), resulting in strengthened westerlies and a positive NAO-like anomaly over the North Atlantic. While the specific results can vary depending on the model, our study identifies similar dynamic responses within the real-world coupled system using a causal framework.

Latent heat fluxes and precipitation/latent heat release. During the positive NAO phase, there are positive anomalies in both latent heat flux and convective precipitation (used as a proxy for latent heating) within the northern NAO branch. These anomalies are primarily a result of increased westerly flow to the south of Greenland and reduced sea ice extent to the north of Iceland. In contrast, during negative NAO conditions, the sea ice extent to the north of Iceland expands, and the westerly flow south of Greenland weakens. Both of these factors lead to reduced fluxes and precipitation, resulting in decreased diabatic heating. In the southern NAO branch, convective precipitation in the eastern part of the North Atlantic is a significant mediator. This mediation is connected to the upstream baroclinicity. When the NAO is positive, there is less latent heat release than usual, and conversely, there is more diabatic heating during negative NAO phases. In both scenarios, these effects contribute as positive feedback mechanisms on the NAO. The role of the surface heat fluxes and the downstream diabatic heating rates are consistent with the feedback mechanism proposed by Rodwell et al. (1999).

These results have potentially important implications for winter weather predictability in the North Atlantic sector, which has historically been relatively low (Johansson 2007; Baker et al. 2018). Our results reinforce the conclusions drawn by numerous prior studies, underscoring the predictability associated with the SST pattern in the North Atlantic. While we did not explicitly explore this in our study, there is clear potential for incorporating information about late autumn/early winter SSTs as a predictor in statistical NAO prediction models. This approach was pursued by Wang et al. (2017), who identified a North Atlantic SST anomaly pattern in September as one of the most useful predictors of the winter NAO.

However, we propose an alternative application of our findings: to investigate whether there is a link between the ability of dynamical seasonal forecasting model systems to accurately represent the intricate ocean–atmosphere feedbacks identified here and their skill in predicting the winter NAO. We have conducted initial work attempting to perform the mediation analysis using hindcast data from one such system. While we did identify a lagged effect of November SSTs on the winter NAO, this effect was substantially weaker than what we found using ERA5 data. A preliminary analysis suggests that certain dynamical models may be representing mechanisms that are positive feedbacks between North Atlantic SSTs and the NAO in the real world as negative feedbacks. Should this hold true in further investigations, it would serve as a critical indicator of model deficiencies, which in turn could adversely impact the forecasting skill of these models at intraseasonal time scales.

Finally, we note that our study does not necessarily (or even probably) define the upper limit for predictability of North Atlantic circulation based on SSTs. From the start, we focused on the leading circulation pattern (the NAO) and the associated SST pattern. There may well be strong links between other weather regimes/patterns (such as Scandinavian blocking or Mid-Atlantic ridging) and other SST configurations. The methodology used here can be used to explore some of these potential relationships.

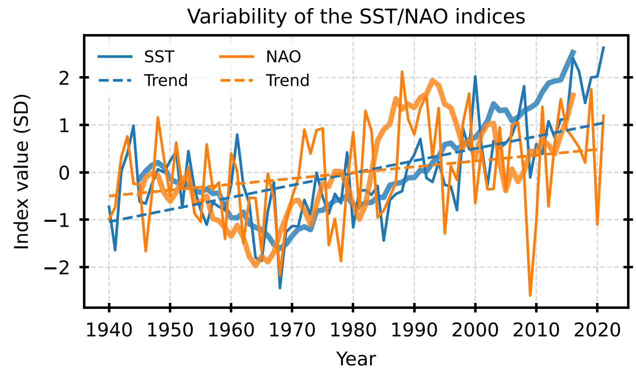

Fig. 6 Thin solid lines: interannual values of the November SST index (blue) and the DJF NAO index (orange). Dashed lines: linear trends, both of which are significant at the 5% level. Thick lines: 11-year running means of the interannual values

Appendix 1

Figure 6 shows that both SST and NAO indices underwent significant linear trends over the study period. As it is probably influenced both by global warming and Atlantic Multidecadal Variability (AMV; e.g., Zhang et al. 2019), the SST index increased by 0.26 SD per decade, but the index also manifests signs of multidecadal variability. Simultaneously, the NAO index, which also exhibits multidecadal variability (e.g., Schurer et al. 2023) and has been linked to the AMV on long time scales (e.g., Delworth et al. 2017), increased by 0.12 SD per decade. It is important to note that these linear trends, which are both positive, introduce correlation between the indices.

Appendix 2

Figure 7 shows the spatial structure of the regression of SST anomalies from September to February onto the DJF NAO index. As mentioned in Sect. 3.1, a pattern similar to the one in November (Fig. 1f and Fig. 7c) is found already in September (Fig. 7a). It is also noteworthy how the pattern evolves from one with weak anomalies in autumn (Fig. 7a–c), through a

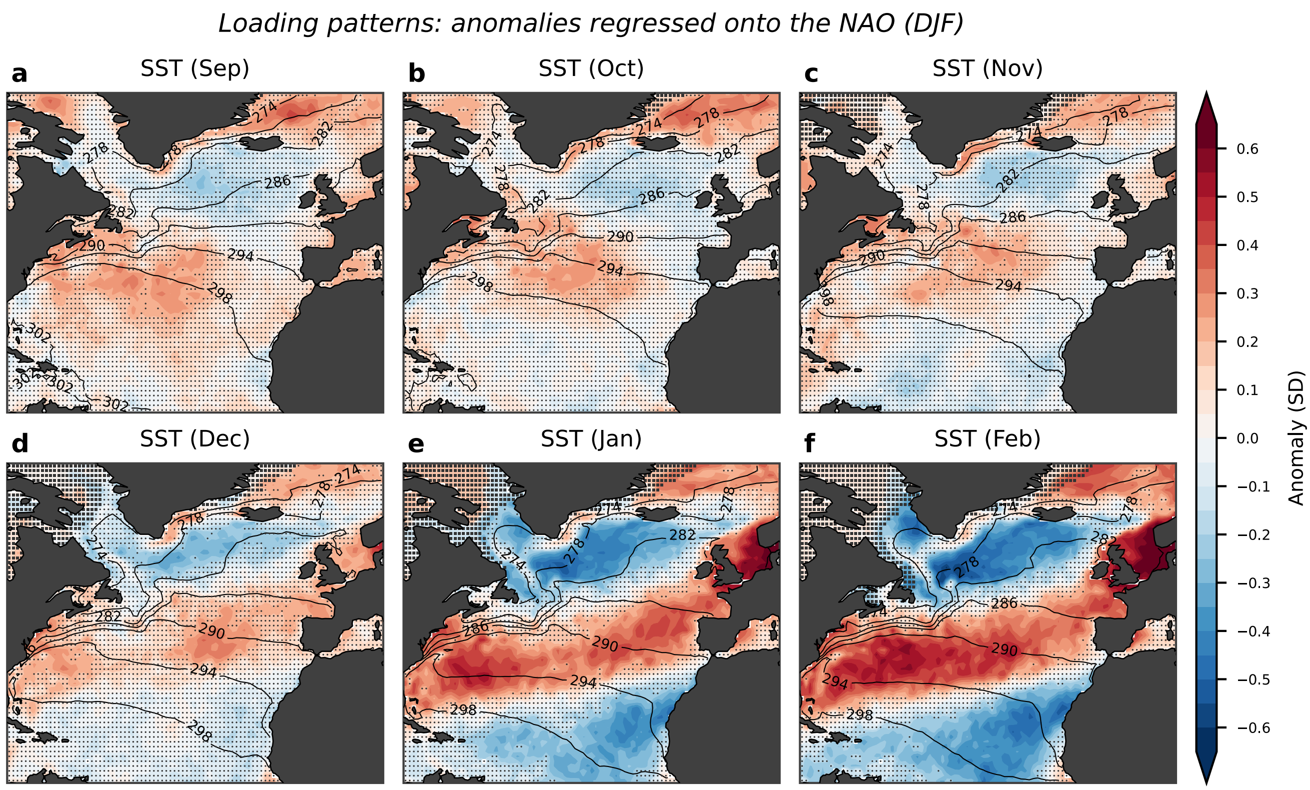

Fig. 7 As Fig. 1, but for SST anomalies from September (a) to February (f)

pattern that starts to resemble the North Atlantic tripole in December (Fig. 7d), to a strong tripole pattern in January and February (Fig. 7e,f).

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Author contributions Both authors developed the ideas for the research together and both contributed to the writing. EWK produced the figures.

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Data availability The ERA5 data are available from the Copernicus Climate Data Store.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

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