

LETTER • OPEN ACCESS

The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate

To cite this article: Florian Börgel *et al* 2020 *Environ. Res. Lett.* **15** 104025

View the [article online](#) for updates and enhancements.

Environmental Research Letters



The Atlantic Multidecadal Oscillation controls the impact of the North Atlantic Oscillation on North European climate

OPEN ACCESS

RECEIVED

21 May 2020

REVISED

17 July 2020

ACCEPTED FOR PUBLICATION

24 July 2020

PUBLISHED

22 September 2020

Original Content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Florian Börgel¹, Claudia Frauen², Thomas Neumann¹ and H E Markus Meier^{1,3}¹ Leibniz Institute for Baltic Sea Research, Warnemünde, Rostock² German Climate Computing Centre, Hamburg, Germany³ Swedish Meteorological and Hydrological Institute, Norrköping, SwedenE-mail: florian.boergel@io-warnemuende.de**Keywords:** Atlantic Multidecadal Oscillation, North Atlantic Oscillation, Regional climate

Abstract

European climate is heavily influenced by the North Atlantic Oscillation (NAO). However, the spatial structure of the NAO is varying with time, affecting its regional importance. By analyzing an 850-year global climate model simulation of the last millennium it is shown that the variations in the spatial structure of the NAO can be linked to the Atlantic Multidecadal Oscillation (AMO). The AMO changes the zonal position of the NAO centers of action, moving them closer to Europe or North America. During AMO+ states, the Icelandic Low moves further towards North America while the Azores High moves further towards Europe and vice versa for AMO- states. The results of a regional downscaling for the East Atlantic/European domain show that AMO-induced changes in the spatial structure of the NAO reduce or enhance its influence on regional climate variables of the Baltic Sea such as sea surface temperature, ice extent, or river runoff.

1. Introduction

The North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) are two of the most prominent modes of climate variability in the North Atlantic sector as European climate is heavily affected by these two modes (Peings and Magnusdottir 2014). The NAO describes a sea level pressure (SLP) difference between the subpolar Icelandic Low (IL) and the subtropical Azores High (AH) (Hurrell *et al* 2003). It affects regional climate and weather patterns in the Northern Hemisphere and is responsible for more than 80% of the annual SLP variability over the North Atlantic and Europe and explains about 40% of the annual SLP variability for the whole Northern Hemisphere during winter (Kauker and Meier 2003). As a result the NAO is the most important pattern of atmospheric variability in the Northern Hemisphere (Hurrell 1995). Typical time scales cover intra-seasonal to decadal variability (Visbeck *et al* 2001).

Often, the NAO is discussed under the assumption that the spatial structure of both centers of action — IL and AH — does not change. However, several studies found that both the IL and the AH exhibit a change in their spatial structure over time (Hilmer and Jung 2000, Jung and Hilmer 2001, Jung *et al* 2003, Johnson *et al* 2008). Hilmer and Jung (2000)

found that the zonal position of both pressure centers influences regional climate conditions in the Arctic region. Further, Lehmann *et al* (2011) showed that an eastward shift of the NAO changes the number and pathways of deep cyclones influencing the wind patterns over the Baltic Sea. Beranová and Huth (2008) summarized that the correlation between the NAO index and surface air temperature and precipitation changes across Europe. They concluded that the changes in correlation are linked to the longitudinal position of the IL and the AH. When the NAO centers of action are located further east, the correlation between the NAO and European climate increases. Different physical causes have been identified to influence zonal shifts of the NAO pattern: increasing greenhouse gas concentrations (Ulbrich and Christoph 1999) or an increase of mean westerlies in the Atlantic basin (Peterson *et al* 2002). Further, Peterson *et al* (2003) argued that the spatial pattern of the NAO exhibits an eastward shift during the transition from a negative to a positive NAO phase. Luo *et al* (2010) proposed that an eastward shift of the Atlantic storm track activity, associated with an increase of the mean westerly flow, is likely causing an eastward shift of the whole NAO pattern.

In addition to the impact of the NAO on the climate of the Northern Hemisphere, several studies have shown that the AMO impacts the climate of the

Northern Hemisphere as well. It influences regional climate such as European summer climate, precipitation over Europe, Africa, and North America and cold weather episodes in Europe during winter (Enfield *et al* 2001, Knight *et al* 2006, Börgel *et al* 2018, Sutton and Hodson 2005, Ting *et al* 2011, Casanueva *et al* 2014, Ruprich-Robert *et al* 2017, Peings and Magnúsdóttir 2014). The AMO describes an alternation between warm and cold sea surface temperature (SST) anomalies in the North Atlantic (Knight *et al* 2006), with a periodicity of about 50 to 90 years (e.g. Knight *et al* 2006, Knudsen *et al* 2011).

In the past, the AMO and the NAO have mostly been discussed separately. More recently, studies started to investigate how these two climate modes interact with each other. By analyzing observational data Li *et al* (2013) showed that multidecadal fluctuations of the NAO lead the AMO signal by approximately 15 to 20 years. Peings and Magnúsdóttir (2014) found that multidecadal fluctuations of the wintertime NAO and the AMO are positively correlated when the NAO is leading the AMO by 10 to 20 years. Further, positive NAO anomalies lead to a strengthening of the Atlantic Meridional Overturning Circulation (AMOC) (e.g. Sun *et al* 2015). Wills *et al* (2019) discussed these interactions between the NAO, the AMO, and the AMOC by applying a low-frequency component analysis (LFCA). They showed that the interaction between the NAO and the AMOC plays a key role in the AMO variability, which confirms studies of Sun *et al* (2015), Delworth and Zeng (2016), and Delworth *et al* (2017). Further, they propose a mechanistic understanding of the AMO. During the growth phase of an AMO warm event, strong zonal winds over the North Atlantic (associated with NAO variability) lead to anomalous heat loss from the Labrador Sea, which in turn triggers deep water formation and strengthens the AMOC. The AMOC needs several years to respond to these NAO heat-flux anomalies. This response causes the AMOC to vary on multidecadal time scales. During the peak of an AMO warm event a basin-wide low-pressure anomaly forms over the North Atlantic accompanied by a weakly negative NAO in the following years. This atmospheric circulation anomaly weakens the AMOC and terminates the AMOC-driven warming. This suggests that the ocean circulation provides the main source of inertia in the climate system that sustains SST anomalies over a longer period of time (Wills *et al* 2019, their figure 7). In contrast Clement *et al* (2015) found that the AMO is the response to stochastic forcing from the mid-latitude atmospheric circulation, i.e. NAO. By analyzing a suite of slab ocean models they showed that the ocean does not play an important role for AMO variability. However, Wills *et al* (2019) presented evidence that the mechanism of the AMO in a slab ocean model does not agree with observational data.

It is evident that a better understanding of the complex relationship between the AMO and the NAO is necessary to understand the climate of the Northern Hemisphere. Therefore, this study aims to assess the impact of the AMO on the spatial structure of the NAO. Using the example of the Baltic Sea region, we show the importance of this spatial change for the North European climate.

In the following, first the relationship between the AMO and the NAO is analyzed based on a pre-industrial period of the last millennium using a global circulation model. Then the shift of the NAO pattern is identified and linked to the AMO. Further, the impact of the AMO on the mean position of the storm tracks over Northern Europe is evaluated. Lastly, the influence of the spatial position of the NAO on regional climate patterns in the Baltic Sea region is discussed.

2. Material and methods

2.1. Model description

This study is based on the model results as described by Schimanke and Meier (2016). In their study they used a multi-centennial paleoclimate simulation based on the global circulation model (GCM) ECHO-G, focusing on the last millennium. ECHO-G consists of an atmospheric component with a horizontal resolution of approximately $3.75^\circ \times 3.75^\circ$ and 19 vertical levels and an ocean component with a horizontal resolution of about $2.8^\circ \times 2.8^\circ$ and 20 vertical levels. The ECHO-G Holocene simulation is forced with variations in orbital parameters, solar irradiance, and greenhouse gases and covers 7000 years BP (Hünicke *et al* 2010).

The spatial resolution of ECHO-G is too coarse to analyze regional impacts such as local wind patterns. To overcome this problem a dynamical downscaling was performed for the European region with the regional circulation model RCA3 (Rossby Centre Atmosphere model). The downscaling covers the period 950 to 1800 and was forced with the ECHO-G Holocene simulation at the lateral boundaries. RCA3 has a horizontal resolution of $0.44^\circ \times 0.44^\circ$ with 24 vertical levels and a 30 minute time step. It covers nearly the whole area of Europe, ranging from Northern Africa to Northern Scandinavia (33.0°W to 58.52°E ; 26.0°N to 71.76°N). A detailed model description of RCA3 is given by Samuelsson *et al* (2011). The resulting atmospheric fields were used to force the regional ocean model Rossby Centre Ocean Model (RCO), simulating the Baltic Sea from 950 to 1800. RCO is a Bryan-Cox-Semtner primitive equation circulation model and has a resolution of $3.7\text{ km} \times 3.7\text{ km}$. It consists of 83 vertical layers, each with a thickness of 3 m. A detailed description of RCO is given by Meier *et al* (2003). This simulation has also been analyzed by Börgel *et al* (2018) to study the impact of the AMO on Baltic Sea variability and has

proven to be suitable to analyze the role of the AMO for Northern European climate. Studies by Zhang and Wang (2013) showed that the spatial and temporal representation of the AMO varies among every GCM. Medhaug and Furevik (2011) analyzed the representation of the AMO in 24 different GCMs. They showed that ECHO-G performs reasonably well within the model spread and captures the AMO variability to a satisfying degree. Further, ECHO-G was one out of ten GCMs that matched the mean observed overturning circulation and showed a significant correlation between the AMO and the AMOC. The representation of the NAO generated by ECHO-G is sufficient. Its variability matches the variability of observations and captures regional correlations with precipitation and surface air temperature (Min *et al* 2005).

2.2. Modes of variability

In this study the AMO is defined as area-weighted average SST across the North Atlantic domain (0°W to 80°W ; 0°N to 60°N). Further, the global signal is removed by subtracting the global mean SST (Trenberth and Shea 2006). Zanchettin *et al* (2013) showed that it is difficult to separate between low-frequency variability and forced global changes when discussing the AMO. They showed that the AMO is strongly influenced by volcanic eruptions, which are not included in this simulation. In addition, they stressed that the AMO definition of Trenberth and Shea (2006) may cause some variability loss in the North Atlantic, but it also removes the impact of external forcing. Hence, we argue that the impact of forced global changes on the AMO as discussed in this study is rather small. The NAO is defined as the first empirical orthogonal function (EOF) of the monthly SLP anomalies (20°N to 70°N ; 90°W to 40°E) of the winter season (DJFM). The NAO pattern is mainly associated with a north-south dipole, and the centers of action are referred to as IL and AH in this study. Since RCA3 covers only the European domain, the SLP and SST fields are taken from ECHO-G.

2.3. EOF analysis with overlapping time windows

A reference NAO pattern is defined by calculating the first EOF of the period from 950 to 1800 simulated by ECHO-G. To analyze the change of the spatial position of the NAO an EOF analysis with overlapping time windows is performed. The idea of this concept is similar to a centered moving average. For each time step t an EOF is calculated considering $[t-n, t+n]$ time steps of the SLP anomalies, with $n = 60$ months. It should be noted that the anomalies are calculated relative to the mean of that segment, without any detrending. The next EOF is calculated with the same window length $[t-n, t+n]$ but t is now shifted by the time increment $dt = 1$ month. This creates a series of EOFs, one for each time step. For every time step the first four EOFs are calculated to ensure that the

NAO pattern is captured. To identify the NAO pattern, they are compared to the reference NAO pattern by applying a spatial correlation.

Based on this series of NAO patterns the movement of the NAO centers of action (IL and AH) is tracked by applying a k-means cluster algorithm which is related to the algorithm proposed by Lloyd (1982). The cluster algorithm finds k cluster centroids that minimize the distance between data points and the nearest centroid. The cluster algorithm is a robust way to identify the minimum and maximum of the NAO pattern. The center of each cluster is obtained by calculating its mean position.

The idea of an EOF analysis with overlapping time windows has also been applied by Lehmann *et al* (2011) to track the spatial shift of the NAO centers of action. They performed an EOF analysis for the time period 1958 to 1997 with time windows of 20 years with each period overlapping by 10 years. However, in the present study the overlapping EOF is constructed separately for each time step.

2.4. Wavelet transformation

A continuous wavelet transform (CWT) is used to analyze the power spectrum of the AMO signal. Similar to a common power spectrum, CWT expands a time series into frequency space, but without losing the time information. This allows analyzing time-localized oscillations in the signal (Torrence and Compo 1998). To find a relationship between the AMO and the NAO, wavelet coherence (WTC) is used. WTC compares two CWTs and finds locally phase-locked behavior of two signals. By using Monte Carlo simulations, the statistical significance level of the WTC is tested. A large ensemble of $n = 300$ surrogate dataset pairs with the same AR1 coefficients as the input datasets is created. For each scale of the CWT the significance level is estimated by calculating the wavelet coherence with each pair of datasets (Grinsted *et al* 2004).

2.5. Storm tracks

To evaluate the impact of the AMO on the storm tracks a calculus-based cyclone identification (CCI) method is used. CCI uses multiple least square regressions to a truncated series of sinusoids to estimate the coefficients of the Fourier approximation. Solving the first and second derivative along the north-south and east-west profiles of the SLP searching for zero crossings and positive values respectively results in the local minima. A detailed description is given by Benestad and Chen (2006).

3. Results

To analyze the relationship between the AMO and the NAO in ECHO-G we use CWT and WTC (see figure 1). The AMO and the NAO alternate between

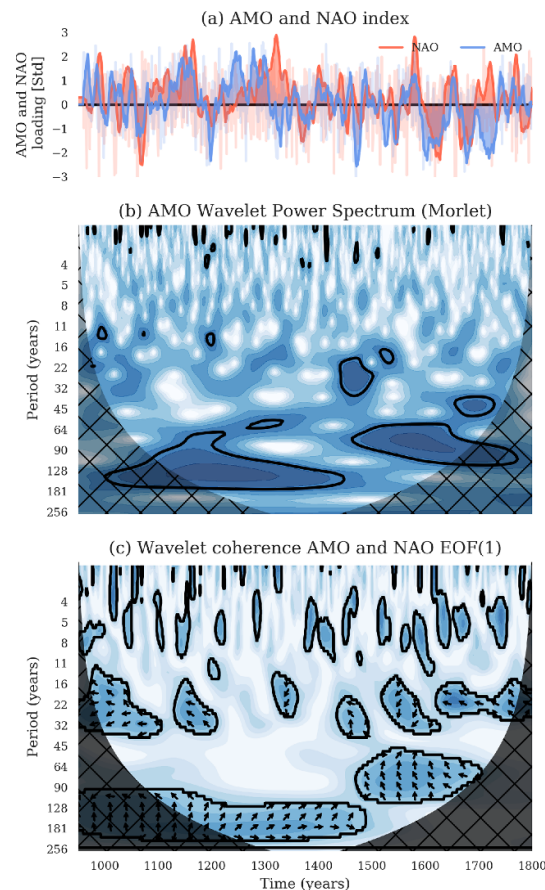


Figure 1. Calculated AMO and NAO index for the period 950 to 1800 (a), wavelet power spectrum of the AMO (b) and the wavelet coherence of the AMO and the NAO (c). The black contour lines show statistical significance according to Grinsted *et al* (2004). The cone of influence where edge effects might influence the results is hatched (Grinsted *et al* 2004). The arrows in the significant regions indicate the phase relationship between the signals: pointing up (down) in phase (antiphase), and AMO leading (lagging) right (left). AMO = Atlantic Multidecadal Oscillation; NAO = North Atlantic Oscillation.

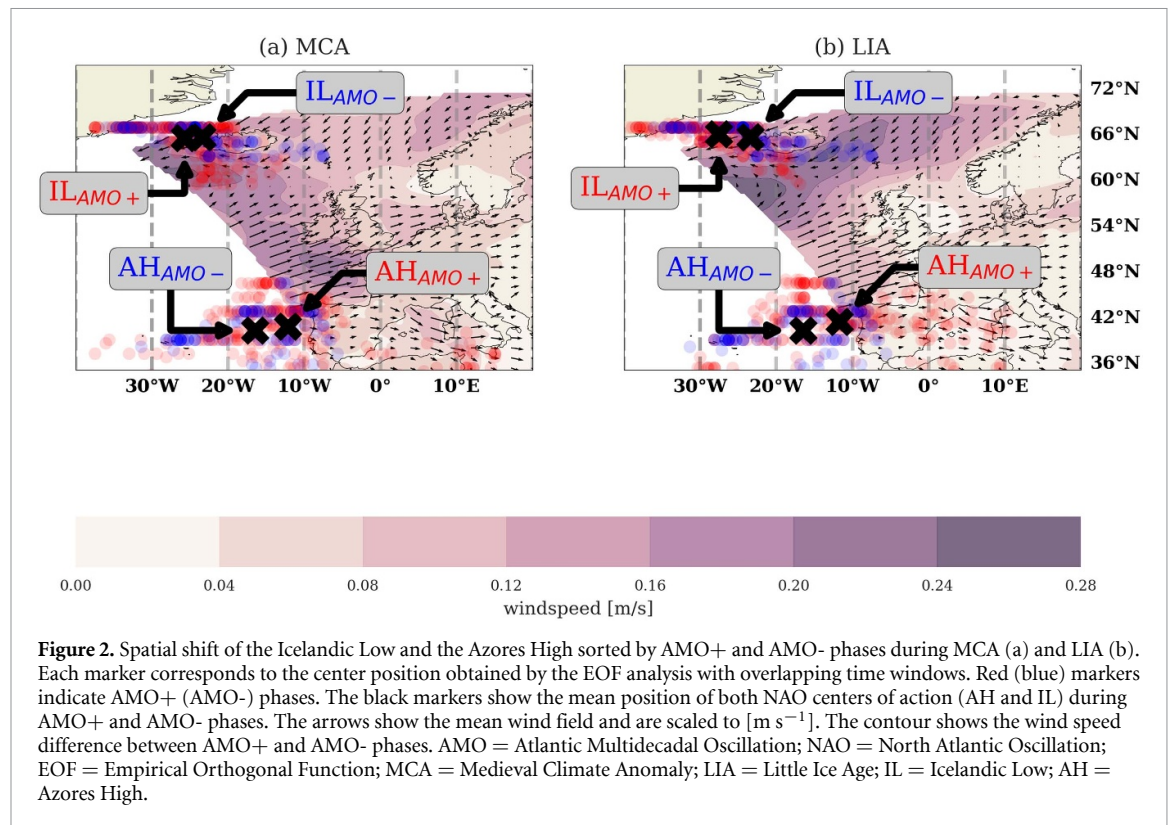
positive and negative states. During the Medieval Climate Anomaly (MCA) from 950 to 1300, the AMO and the NAO are predominantly positive. During the transition to the Little Ice Age (LIA; 1400 to 1700), AMO- and NAO- states appear more frequently and the number of positive and negative states is more balanced (figure 1 (a)). The CWT reveals that the AMO has two persistent low-frequency components (figure 1 (b)). From 1150 to 1400 the AMO has significant power in the frequency band from 90 to 180 years. During the LIA the power distribution changes and significant power is found in the frequency band from 60 to 90 years. As the power of the AMO signal is not stationary in time and changes between the MCA and the LIA, we use WTC to reveal a non-stationary, low-frequency coherence between the AMO and the NAO (figure 1 (c)). The WTC shows that the AMO and the NAO have a significant coherence in the time span from 1150 to 1450 in the frequency range from 90 to 180 years. During the LIA from approximately 1450 to 1700, a significant coherence is found in the frequency range from 60 to 90 years. For the phase relationship we find that the AMO is leading the NAO by roughly 12 years during the MCA. As the dominant frequency shifts from 90 to 180 years to 60 to 90 years

during the LIA, the phase relationship changes with the NAO leading the AMO by 6 years on average.

To capture the spatial variability of the NAO, we perform an EOF analysis with overlapping time windows of 30 years (see figure 2). As the CWT revealed that the dominant frequency of the AMO changes between the MCA and the LIA, we analyze both climate states separately, to see if the frequency of the AMO impacts the spatial shift of the NAO.

Figure 2 (a) shows the spatial variability of the IL and AH during the MCA. We find that the mean position of the IL is shifted westwards (eastwards) during AMO+ (AMO-) phases. In contrast, the mean position of the AH is shifted eastwards (westwards) during AMO+ (AMO-) phases. The wind fields are extracted from RCA3 and therefore do not cover the whole domain. However, matching the observed shift of the IL and AH, we find increased westerlies at the location of the AH and increased easterlies at the location of the IL. The distance between the mean position during AMO+ and AMO- phases is greater for the AH than for the IL.

Figure 2 (b) shows the spatial variability of the IL and AH during the LIA. Again, we find that the mean position of the IL is shifted westwards (eastwards)



during AMO+ (AMO-) phases. The AH is shifted in the opposite direction as during AMO+ (AMO-) phases the AH is located further east (west). The wind difference between AMO+ and AMO- phases shows stronger westerlies at the location of the AH and stronger easterlies at the location of the IL. The distance between the mean position during AMO+ and AMO- phases is slightly greater for the AH than for the IL.

Comparing the MCA and the LIA we find that both time periods show similar results. The IL is located further west during AMO+ phases and further east during AMO- phases. The opposite relationship is found for the AH. While the impact on the AH remains similar during the MCA and the LIA, the distance between the mean position of the IL during AMO+ and AMO- increases during the LIA. Since both centers are moving away from each other, we observe a tilting of the axis between the IL and the AH. It should be noted that the results are independent of the selected time window for the EOF analysis (see figure 3).

During AMO+ phases the IL and the AH are located further west and east, respectively (figure 2). The position of both NAO centers of action is likely related to the position of the storm tracks (Luo *et al* 2010). Therefore, we analyze the impact of the shift on the storm track density.

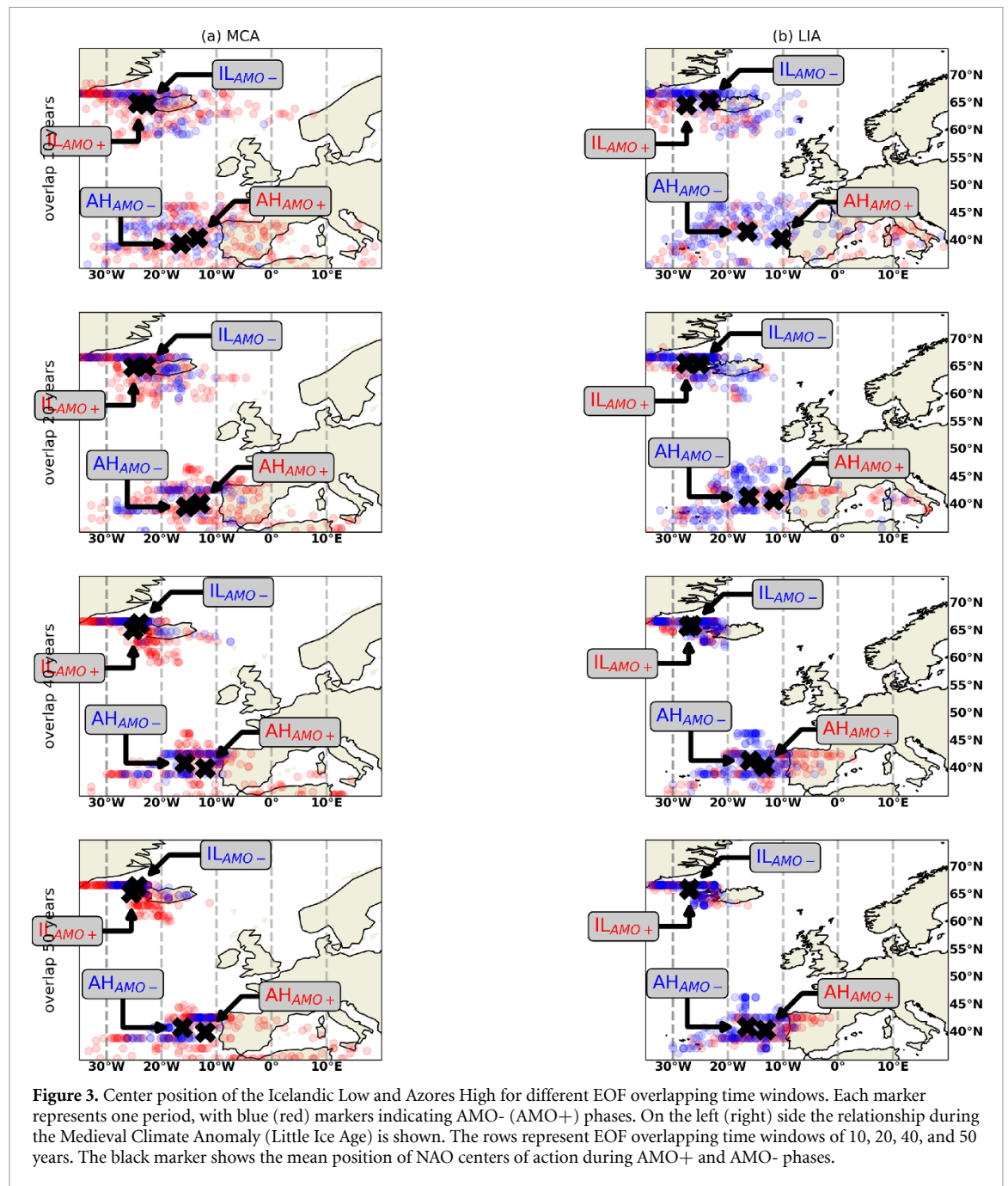
Figure 4 (a) shows the mean storm track activity over Northern Europe for the period 950 to 1800. The center of the mean storm track density is located at approximately 22°W and ranges from 54°N

to 66°N. Further, we find that the storm track density stretches east across Northern Scandinavia. Figure 4 (b) shows the storm track density difference associated with zonal shifts of the IL for the period 950 to 1800. The shifts of the IL are defined as the deviation from its mean position. We find that the storm track density decreases in the northern part of the model domain, starting west of Iceland and stretching east across Northern Scandinavia. Further, we find a slight decrease at 20°W and 54°N west of Great Britain. A slight increase is found east of Great Britain at 0°E and 60°N. However, only the decrease near Iceland stretching east is statistically significant.

Next, the regional importance of the NAO for Northern Europe is analyzed using the example of the Baltic Sea (figure 4 at 9°E to 30°E; 54°N to 66°N). Figure 5 (a) shows the 30-year running correlation between the NAO and regional climate variables — mean SST, sea ice extent, and runoff of the Baltic Sea, respectively — and the longitudinal position of the IL.

The SST shows a positive correlation with the NAO of up to 0.8 from 960 to 1090 but decreases to 0.0 at around 1750. The correlation between the NAO and the sea ice extent is negative and varies between -0.2 to -0.8. Lastly, the correlation between the NAO and runoff amounts to 0.5 from 1000 to 1100 but then changes sign with about -0.2 during 1120. All variables exhibit strong multidecadal variability.

The longitudinal position of the IL deviates between -12° and +20° from its mean position. Similar to the three regional variables it also exhibits multidecadal fluctuations. To analyze the importance of



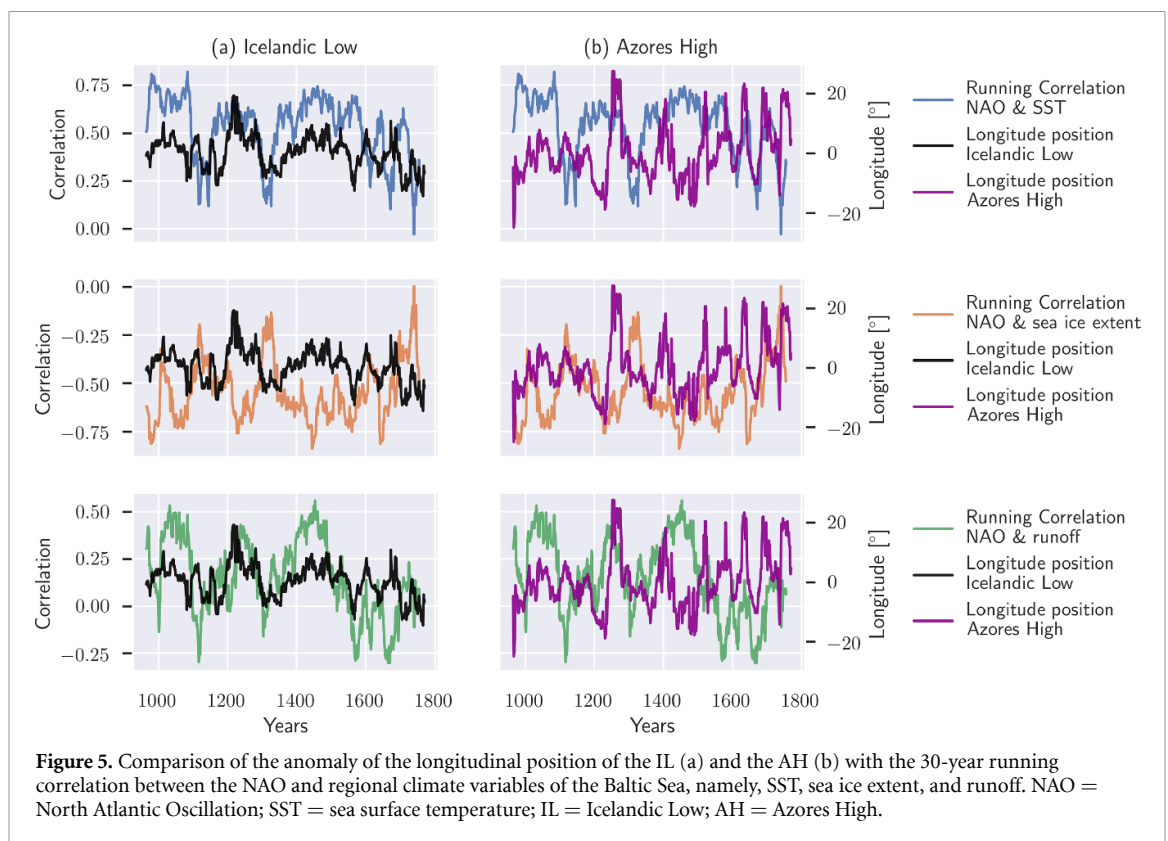
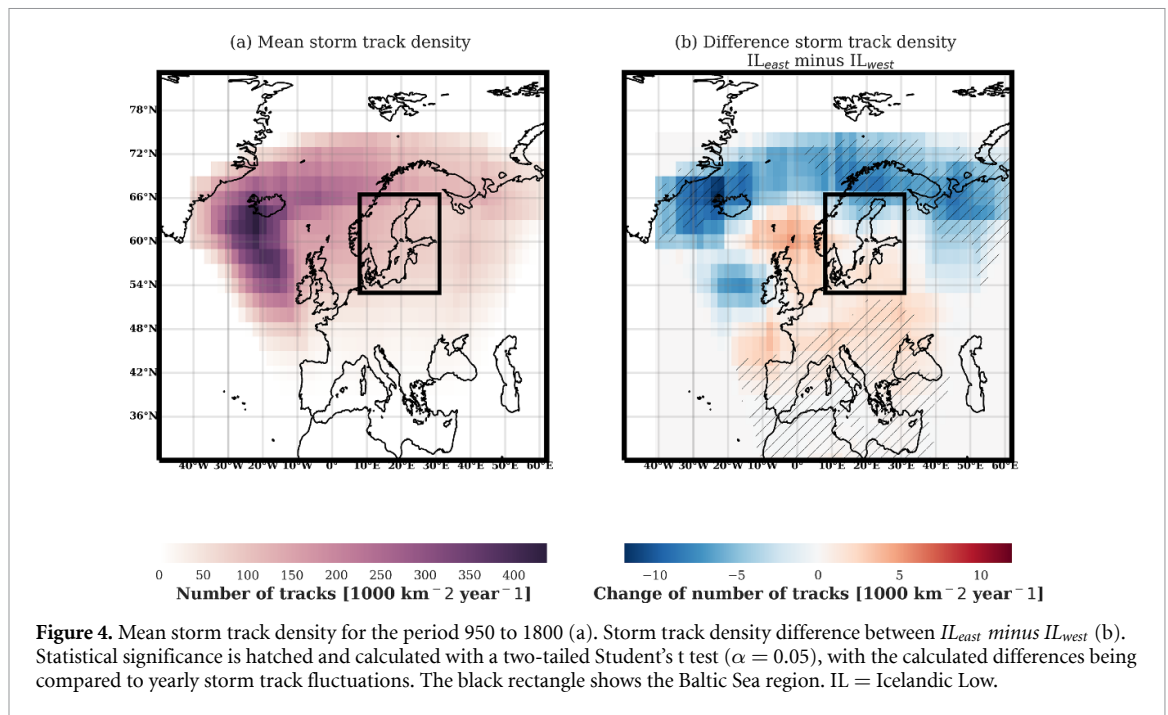
the IL for the regional climate of the Baltic Sea, the correlation between the position of the IL and all three running correlations is computed. Considering the time lag due to the inertia of the ocean, we find a correlation of 0.5 for the SST, a correlation of 0.42 for the sea ice extent, and a correlation of 0.35 for the runoff.

The same analysis is repeated for the AH (see figure 5 (b)). Just like the IL, the AH exhibits multi-decadal variability. Its position deviates between -20° and $+22^\circ$ from its mean position. Again, we compute the correlation between the running correlations of the regional climate variables with the NAO and the longitudinal position of the AH. For SST, sea ice extent, and runoff we find correlations of up to -0.1, 0.05, and -0.14 respectively. In summary, the position

of the IL plays a more important role for the climate of the Baltic Sea, as the position of the AH does not have a significant impact on the climate of the Baltic Sea.

4. Discussion

According to the ECHO-G simulation, the climate mode AMO influences the spatial pattern of the NAO. This connection is revealed by the EOF analysis with overlapping time windows (figure 2). We find that the state of the AMO influences the zonal position of the IL and the AH. AMO+ states cause a westward shift of the IL which in turn reduces the regional importance of the NAO for the North European climate.



To analyze the characteristics of the AMO in ECHO-G and its relationship with the NAO we use CWT and WTC (figure 1). The frequency of the AMO varies from 90 to 180 years during the MCA and from 60 to 90 years during the LIA. The simulated AMO tends to stay in a positive phase during the MCA, which is in agreement with studies by Mann *et al* (2009), Wang *et al* (2017), and Landrum *et al* (2013). Frequency shifts of the AMO appear throughout the

entire 7000 years of the ECHO-G Holocene simulation. There are several studies discussing possible reasons for these shifts of the AMO on centennial time scales: By analyzing seven Holocene climate proxies Knudsen *et al* (2011) revealed changes in the dominant frequency and regional importance of the AMO over a period of 8000 years. Further, Frankcombe *et al* (2010) proposed that the AMO can be viewed as a damped oscillatory internal ocean mode that is

excited by atmospheric noise, modulating its dominant frequency. In addition, changes of the dominant frequency of the AMO were also found by Wang *et al* (2017). They found that the reconstructed AMO changes its dominant frequency. While it ranges from 90 to 180 years during the period 1200 to 1500, during the recent 100 years a frequency of 30 to 90 years is observed. A similar change in the AMO frequency has also been found in a Greenland ice core record (Chylek *et al* 2012). The simulated NAO in ECHO-G tends to stay in a positive state during the MCA as well, which is also found by Trouet *et al* (2009). They argued that the climate transition between MCA and LIA was coupled to prevailing La Niña-like conditions which were amplified by an intensified AMOC during the MCA. These studies are in good agreement with the dynamical interpretation of the AMOC and the NAO interplay proposed by Wills *et al* (2019) or Delworth and Zeng (2016) as they described the frequency of the AMO as a result of the interaction between atmosphere, i.e. NAO, and the ocean.

The WTC between the AMO and the NAO reveals a significant coherence in a frequency range that can be attributed to the AMO. We find that the phase relationship between the AMO and the NAO changes between the MCA and the LIA. However, with a frequency of 50 to 90 years during the LIA the AMO lags the NAO as discussed by e.g. Delworth and Zeng (2016), Sun *et al* (2015), and Wills *et al* (2019). We argue that the changing phase relationship is also caused by the previously described climate transition between the MCA and the LIA. It should be noted that the phase relationship between the AMO and the NAO in ECHO-G is roughly matching the observation-based relationship found by Li *et al* (2013). Further, by analyzing the relationship between a tree-ring based reconstruction of the AMO since 1567 (Gray *et al* 2004) and an NAO reconstruction based on proxy data from all over Eurasia covering the period 1659 to 1995 (Luterbacher *et al* 2001) we found a constant significant coherence between the AMO and the NAO, too (not shown).

The impact of the AMO on the spatial position of the NAO is analyzed in figure 2 and distinguishes between MCA (a) and LIA (b). However, independent of both climate states we find similar results for both periods as the AMO causes a westward shift of the IL and an eastward shift of the AH during AMO+ phases. Previous studies argued that the change of the mean flow causes a zonal shift of the IL and AH (Jung *et al* 2003, Luo and Gong 2006, Luo *et al* 2010). Hence, the observed shift of both pressure centers is likely related to the difference in the wind fields between AMO+ and AMO-. Further, Luo *et al* (2010) found that the position of the Atlantic storm track likely influences the positions of both NAO centers of action. However, we find that the position of the IL and of the AH as influenced by the AMO are not

affecting the position of the mean storm track density. Instead of an increased storm track density during an eastward shift of the IL, we find a lower number of storms (figure 4 (b)). By analyzing the SLP fields we find that the state of the AMO is influencing the number of storm tracks instead of the position of both centers. A westward or eastward shift of the IL corresponds to AMO+ and AMO- states respectively (figure 2). The SLP difference between westward and eastward shifts of the IL shows negative values at the location of the IL and positive values at the position of the AH, resembling an NAO+ pattern (figure 6). This results in a higher SLP gradient and a higher number of storms (not shown). Further, the difference between eastward and westward shifts of the AH, corresponding to AMO+ and AMO- states, results in the same SLP pattern as for the IL. It is found that during AMO+ phases the SLP gradient between the IL and the AH is higher than for AMO- phases, increasing the number of storms.

Nevertheless, the shift of the IL and the AH is of particular importance when studying the impact of the NAO on, e.g. local precipitation patterns. Studies discussing global climate such as Landrum *et al* (2013) neglected that the correlations of the NAO and regional climate variables change over time. However, a few regional climate studies considered that the influence of the NAO on regional climate variables in Europe changes over time (Vihma and Haapala 2009, Omstedt and Chen 2001, Hunicke and Zorita 2006, Chen and Hellström 1999, Meier and Kauker 2002, Beranová and Huth 2008). The Baltic Sea has been shown to respond very sensitively to external forcing (Belkin 2009). Further, studies by Börgel *et al* (2018) and Kniebusch *et al* (2019) revealed a significant impact of the AMO on the Baltic Sea region (i.e. Northern Europe). It is exposed to a variety of anthropogenic pressures such as agricultural, industrial, and urban activities. In this study we are investigating the impact of natural variability on the environmental state of the Baltic Sea because this impact may be even more important than anthropogenic climate change in the near future, as 58% of the decadal variability in the Baltic Sea mean SST can be explained by the AMO (Kniebusch *et al* 2019).

Using the Baltic Sea as an example for the impact of the NAO on regional climate (figure 5), we find that the correlation between regional climate variables and the NAO varies on multidecadal time scales. The correlation between the NAO and SST varies immensely with correlations ranging from 0.0 to 0.8. Beranová and Huth (2008) found a higher correlation between the NAO and the European climate when the NAO centers of action are located farther east. While our findings support their claims, we find that only the position of the IL is relevant for the regional correlation with the NAO in Northern Europe.

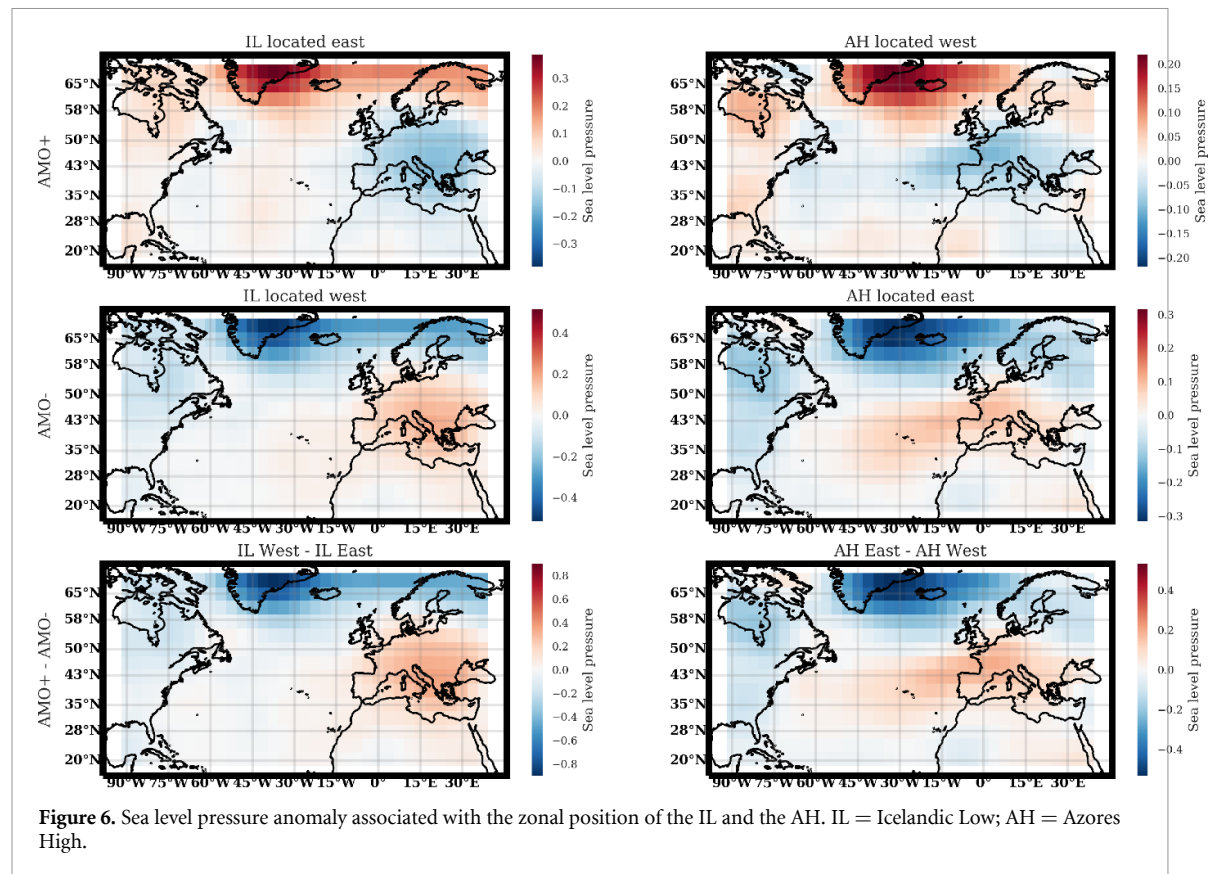


Figure 6. Sea level pressure anomaly associated with the zonal position of the IL and the AH. IL = Icelandic Low; AH = Azores High.

Previous studies have focused on the stationary relationship between the AMO and the NAO. The present study is the first showing an influence of the multidecadal variability of the AMO on the spatial structure of the NAO over longer periods of time. As presented in this study, the AMO influences the east-west position of the IL and the AH, with a NW-SE shift during AMO+ phases. We find that it is important to consider the respective state of the AMO since it indicates whether the correlation between the NAO and regional climate will increase or decrease.

Acknowledgments

The research presented in this study is part of the Baltic Earth program (Earth System Science for the Baltic Sea region, see <http://www.baltic.earth>). Eduardo Zorita and Semjon Schimanke are acknowledged for providing ECHO-G and RCA3/RCO data, respectively. We thank two anonymous reviewers whose constructive comments greatly improved an earlier draft of the manuscript.

ORCID iDs

Florian Börgel  <https://orcid.org/0000-0003-3294-667X>

Claudia Frauen  <https://orcid.org/0000-0002-8615-5702>

References

- Belkin I M 2009 Rapid warming of Large Marine Ecosystems *Prog. Oceanogr.* **81** 207–13
- Benestad R E and Chen D 2006 The use of a calculus-based cyclone identification method for generating storm statistics *Tellus A* **58** 473–86
- Beranová R and Huth R 2008 Time variations of the effects of circulation variability modes on European temperature and precipitation in winter *Int. J. Climatol.* **28** 139–58
- Börgel F, Frauen C, Neumann T, Schimanke S and Meier H E M 2018 Impact of the Atlantic multidecadal oscillation on Baltic Sea variability *Geophys. Res. Lett.* **45** 9880–8
- Casanueva A, Rodríguez-Puebla C, Frías M D and González-Reviriego N 2014 Variability of extreme precipitation over Europe and its relationships with teleconnection patterns *Hydrol. Earth Syst. Sci.* **18** 709–25
- Chen D and Hellström C 1999 The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations *Tellus A* **51** 505–16
- Chylek P, Folland C, Frankcombe L, Dijkstra H, Lesins G and Dubey M 2012 Greenland ice core evidence for spatial and temporal variability of the Atlantic multidecadal oscillation *Geophys. Res. Lett.* **39** L09705
- Clement A, Bellomo K, Murphy L N, Cane M A, Mauritsen T, Rädel G and Stevens B 2015 The Atlantic Multidecadal Oscillation without a role for ocean circulation *Science* **350** 320–4
- Delworth T L and Zeng F 2016 The Impact of the North Atlantic Oscillation on Climate through Its Influence on the Atlantic Meridional Overturning Circulation *J. Clim.* **29** 941–62
- Delworth T L, Zeng F, Zhang L, Zhang R, Vecchi G A and Yang X 2017 The central role of ocean dynamics in connecting the North Atlantic oscillation to the extratropical component of the Atlantic multidecadal oscillation *J. Clim.* **30** 3789–805
- Enfield D B, Mestas-Núñez A M and Trimble P J 2001 The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.* **28** 2077–80

- Frankcombe L M, von der Heydt A and Dijkstra H A 2010 North Atlantic Multidecadal Climate Variability: An Investigation of Dominant Time Scales and Processes *J. Clim.* **23** 3626–38
- Gray S T, Graumlich L J, Betancourt J L and Pederson G T 2004 A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophys. Res. Lett.* **31** L12205
- Grinsted A, Moore J C and Jevrejeva S 2004 Application of the cross wavelet transform and wavelet coherence to geophysical time series *Nonlinear Processes Geophys.* **11** 561–6
- Hilmer M and Jung T 2000 Evidence for a recent change in the link between the North Atlantic oscillation and Arctic Sea ice export *Geophys. Res. Lett.* **27** 989–92
- Hurrell J W 1995 Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation *Science* **269** 676–9
- Hurrell J W, Kushnir Y, Ottersen G and Visbeck M 2003 The North Atlantic oscillation: climatic significance and environmental impact *Geophys. Monograph Ser.* **134** 279
- Hünicke B, Zorita E and Haeseler S 2010 Baltic holocene climate and regional sea-level change: A statistical analysis of observations, reconstructions and simulations within present and past as analogues for future changes *GKSS Reports*
- Hünicke B and Zorita E 2006 Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century *Tellus A* **58** 141–53
- Johnson N C, Feldstein S B and Tremblay B 2008 The continuum of Northern Hemisphere teleconnection patterns and a description of the NAO shift with the use of self-organizing maps *J. Clim.* **21** 6354–71
- Jung T, Hilmer M, Ruprecht E, Kleppek S, Gulev S K and Zolina O 2003 Characteristics of the recent eastward shift of interannual NAO variability *J. Clim.* **16** 3371–82
- Jung T and Hilmer M 2001 The link between the North Atlantic oscillation and Arctic Sea ice export through Fram Strait *J. Clim.* **14** 3932–43
- Kauker F and Meier H E M 2003 Modeling decadal variability of the Baltic Sea: 1. Reconstructing atmospheric surface data for the period 1902–1998 *J. Geophys. Res. Oceans* (1978–2012) **108** 3267
- Kniebusch M, Meier H E M, Neumann T and Börgel F 2019 Temperature variability of the Baltic Sea since 1850 and Attribution to atmospheric forcing variables *J. Geophys. Res. Oceans* **124** 4168–87
- Knight J R, Folland C K and Scaife A A 2006 Climate impacts of the Atlantic Multidecadal Oscillation *Geophys. Res. Lett.* **33** L17706
- Knudsen M, Seidenkrantz M-S, Jacobsen B and Kuijpers A 2011 Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years *Nat. Commun.* **2** 178
- Landrum L, Otto-Bliesner B L, Wahl E R, Conley A, Lawrence P J, Rosenbloom N and Teng H 2013 Last millennium climate and its variability in CCSM4 *J. Clim.* **26** 1085–111
- Lehmann A, Getzlaff K and Harlaß J 2011 Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009 *Climate Res.* **46** 185–96
- Li J, Sun C and Jin F-F 2013 NAO implicated as a predictor of Northern Hemisphere mean temperature multidecadal variability *Geophys. Res. Lett.* **40** 5497–502
- Lloyd S 1982 Least squares quantization in PCM *IEEE Trans. Inf. Theory* **28** 129–37
- Luo D and Gong T 2006 A possible mechanism for the eastward shift of interannual NAO action centers in last three decades *Geophys. Res. Lett.* **33** L24815
- Luo D, Zhu Z, Ren R, Zhong L and Wang C 2010 Spatial pattern and zonal shift of the North Atlantic oscillation. Part I: A dynamical interpretation *J. Atmos. Sci.* **67** 2805–26
- Luterbacher J et al 2001 Extending north Atlantic oscillation reconstructions back to 1500 *Atmospheric Sci. Lett.* **2** 114–24
- Mann M E, Zhang Z, Rutherford S, Bradley R S, Hughes M K, Shindell D, Ammann C, Faluvegi G and Ni F 2009 Global signatures and dynamical origins of the little ice age and medieval climate anomaly *Science* **326** 1256–60
- Medhaug I and Furevik T 2011 North Atlantic 20th century multidecadal variability in coupled climate models: sea surface temperature and ocean overturning circulation *Ocean Sci.* **7** 389–404
- Meier H E M, Döscher R and Faxén T 2003 A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow *J. Geophys. Res. Oceans* **108** 3273
- Meier H E M and Kauker F 2002 Simulating Baltic Sea climate for the period 1902–1998 with the Rossby Centre coupled ice-ocean model *Rep. Oceanography* **30** 111
- Min S-K, Legutke S, Hense A and Kwon W-T 2005 Internal variability in a 1000-yr control simulation with the coupled climate model ECHO-G—I. Near-surface temperature, precipitation and mean sea level pressure *Tellus A* **57** 605–21
- Omstedt A and Chen D 2001 Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea *J. Geophys. Res. Oceans* **106** 4493–500
- Peings Y and Magnusdottir G 2014 Forcing of the wintertime atmospheric circulation by the multidecadal fluctuations of the North Atlantic ocean *Environ. Res. Lett.* **9** 034018
- Peterson K A, Greatbatch R J, Lu J, Lin H and Derome J 2002 Hindcasting the NAO using diabatic forcing of a simple AGCM *Geophys. Res. Lett.* **29** 50–1–50–4
- Peterson K A, Lu J and Greatbatch R J 2003 Evidence of nonlinear dynamics in the eastward shift of the NAO *Geophys. Res. Lett.* **30** 1030
- Ruprich-Robert Y, Msadek R, Castruccio F, Yeager S, Delworth T and Danabasoglu G 2017 Assessing the climate impacts of the observed Atlantic multidecadal variability using the GFDL CM2.1 and NCAR CESM1 global coupled models *J. Clim.* **30** 2785–2810
- Samuelsson P et al 2011 The Rossby centre regional climate model RCA3: model description and performance *Tellus A* **63** 4–23
- Schimanke S and Meier H E M 2016 Decadal-to-centennial variability of salinity in the Baltic sea *J. Clim.* **29** 7173–88
- Sun C, Li J and Jin F-F 2015 A delayed oscillator model for the quasi-periodic multidecadal variability of the NAO *Clim. Dyn.* **45** 2083–99
- Sutton R T and Hodson D L R 2005 Atlantic ocean forcing of North American and European summer climate *Science* **309** 115–18
- Ting M, Kushnir Y, Seager R and Li C 2011 Robust features of Atlantic multi-decadal variability and its climate impacts *Geophys. Res. Lett.* **38** L17705
- Torrence C and Compo G P 1998 A Practical Guide to Wavelet Analysis *Bull. Am. Meteorol. Soc.* **79** 61–78
- Trenberth K E and Shea D J 2006 Atlantic hurricanes and natural variability in 2005 *Geophys. Res. Lett.* **33** L12704
- Trouet V, Esper J, Graham N E, Baker A, Scourse J D and Frank D C 2009 Persistent positive North Atlantic oscillation mode dominated the medieval climate anomaly *Science* **324** 78–80
- Ulbrich U and Christoph M 1999 A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing *Clim. Dyn.* **15** 551–9
- Vihma T and Haapala J 2009 Geophysics of sea ice in the Baltic Sea: A review *Prog. Oceanogr.* **80** 129–48
- Visbeck M H, Hurrell J W, Polvani L and Cullen H M 2001 The North Atlantic oscillation: past, present and future *Proc. Natl Acad. Sci.* **98** 12876–7
- Wang J, Yang B, Ljungqvist F, Luterbacher J, Osborn T, Briffa K and Zorita E 2017 Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years *Nat. Geosci.* **10** 512–17
- Wills R C J, Armour K C, Battisti D S and Hartmann D L 2019 Ocean–atmosphere dynamical coupling fundamental to the Atlantic multidecadal oscillation *J. Clim.* **32** 251–72
- Zanchettin D, Bothe O, Graf H F, Lorenz S J, Luterbacher J, Timmreck C and Jungclauss J H 2013 Background conditions influence the decadal climate response to strong volcanic eruptions *J. Geophys. Res. Atmos.* **118** 4090–106
- Zhang L and Wang C 2013 Multidecadal North Atlantic sea surface temperature and Atlantic meridional overturning circulation variability in CMIP5 historical simulations **118** 5772–91