AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL084350

**Key Points:**
- Atlantic ocean-atmosphere circulation links drought in North America, Europe, and the Mediterranean
- Coupled modes of drought variability can be used to infer atmospheric circulation and ocean temperature anomalies
- Coupled terrestrial drought patterns reveal the start of the Little Ice Age to be characterized by a negative NAO and cold Atlantic SSTs

**Supporting Information:**
- Supporting Information S1
- Figure S1
- Figure S2

**Correspondence to:**
K. J. Anchukaitis,
kanchukaitis@email.arizona.edu

**Citation:**
Anchukaitis, K. J., Cook, E. R., Cook, B. I., Pearl, J., D'Arrigo, R. D., & Wilson, R. (2019). Coupled modes of North Atlantic ocean-atmosphere variability and the onset of the Little Ice Age. *Geophysical Research Letters*, *46*. https://doi.org/10.1029/2019GL084350

Received 1 JUL 2019
Accepted 23 SEP 2019
Accepted article online 16 OCT 2019



# Coupled Modes of North Atlantic Ocean-Atmosphere Variability and the Onset of the Little Ice Age

**Kevin J. Anchukaitis[1,2,3,4], Edward R. Cook[3], Benjamin I. Cook[3,5], Jessie Pearl[2,4], Rosanne D'Arrigo[3], and Rob Wilson[3,6]**

[1]School of Geography and Development, University of Arizona, Tucson, AZ, USA, [2]Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, USA, [3]Lamont-Doherty Earth Observatory, Palisades, NY, USA, [4]Department of Geosciences, University of Arizona, Tucson, AZ, USA, [5]NASA Goddard Institute for Space Studies, New York, NY, USA, [6]School of Earth and Environmental Sciences, University of St Andrews, St Andrews, UK

**Abstract** Hydroclimate extremes in North America, Europe, and the Mediterranean are linked to ocean and atmospheric circulation anomalies in the Atlantic, but the limited length of the instrumental record prevents complete identification and characterization of these patterns of covariability especially at decadal to centennial time scales. Here we analyze the coupled patterns of drought variability on either sides of the North Atlantic Ocean basin using independent climate field reconstructions spanning the last millennium in order to detect and attribute epochs of coherent basin-wide moisture anomalies to ocean and atmosphere processes. A leading mode of broad-scale moisture variability is characterized by distinct patterns of North Atlantic atmosphere circulation and sea surface temperatures. We infer a negative phase of the North Atlantic Oscillation and colder Atlantic sea surface temperatures in the middle of the fifteenth century, coincident with weaker solar irradiance and prior to strong volcanic forcing associated with the early Little Ice Age.

## 1. Introduction

Hydroclimate extremes including droughts and floods in North America, Europe, and the Mediterranean are linked to Northern Hemisphere ocean and atmosphere anomalies across a range of time scales. In the North Atlantic, these events are associated with changes in both atmospheric pressure and wind patterns (Barnston & Livezey, 1987; Rodríguez-Fonseca et al., 2006) including the North Atlantic Oscillation (NAO; Hurrell, 1995; Hurrell et al., 2003; Kingston et al., 2006; Marshall et al., 2001; Zanardo et al., 2019) and coherent large-scale interdecadal (Kushnir, 1994) and multidecadal sea surface temperature (SST) anomalies, including the Atlantic Multidecadal Oscillation (AMO; Enfield et al., 2001; Knight et al., 2006). Thus, hydroclimate anomalies and extremes on both sides of the North Atlantic are linked via their origins in the dynamics of the coupled ocean-atmosphere system.

A challenge to understanding internal and forced climate system variability and ocean-atmosphere circulation in the North Atlantic is the limited length of the instrumental period as well as evidence for substantial decadal and multidecadal variability (Wang et al., 2017). Paleoclimate reconstructions provide the potential to observe these systems over a longer period in order to better characterize time scales of variability as well as the response to radiative forcing due to volcanic eruptions and solar variability (Driscoll et al., 2012; Shindell et al., 2003; Sjolte et al., 2018). However, terrestrial paleoclimate proxies like tree rings do not directly record the atmospheric pressure or wind anomalies associated with the NAO nor the SSTs used to characterize the AMO but can reflect these indirectly via their influence on precipitation or temperature at the location of the tree-ring chronology. Marine records from sediments or corals may be used to reconstruct SSTs, but only some have the temporal resolution, age model precision, and length to do so at decadal time scales over the last millennium in the North Atlantic itself (Moffa-Sánchez et al., 2014a; Moffa-Sánchez et al., 2014b; Moffa-Sánchez et al., 2019; Thirumalai et al., 2018). A common approach to reconstructing the NAO or AMO is therefore to directly target indices of these modes as predictands in a statistical regression model where tree-ring chronologies are the potential predictors (cf. Cook et al., 2002; Cook et al., 2019; D'Arrigo et al., 2011; Gray et al., 2004; Ortega et al., 2015). If local and regional patterns of terrestrial temperature and precipitation variability consistently reflect the influence of large-scale modes of atmospheric circulation, tree-ring chronologies and other high-resolution proxies that record local climate variability may be used to estimate large-scale but distal patterns of wind, pressure, or SST anomalies (Evans et al., 2001; Fritts et al., 1971).

Here, we use an alternative approach to infer the past and long-term behavior of these coupled ocean-atmosphere modes. We use two independent terrestrial drought reconstructions from both sides of the North Atlantic spanning the last millennium and isolate their common behavior through time. We identify a persistent leading mode of North Atlantic basin drought variability over the last millennium that is associated with coherent atmosphere and ocean temperature anomalies, although the latter with greater uncertainty. The most anomalous period in the North Atlantic drought record occurs in the midfifteenth century, and we can therefore infer the likely state of the North Atlantic ocean-atmosphere system at that time. Our findings provide new insight and support for interpretation of independent proxies of North Atlantic climate and suggest a dynamical contribution to pronounced cooling in the fifteenth century.

## 2. Materials and Methods

### 2.1. Drought Atlases

We analyze coupled North Atlantic drought patterns using the Living Blended Drought Atlas update (LBDA2010) of the North American Drought Atlas (NADA; Cook et al., 2004; Cook et al., 2010) and the Old World Drought Atlas (OWDA; Cook et al., 2015, 2016). The atlases are 0.5° gridded reconstructions of the Palmer Drought Severity Index (hereafter PDSI; Dai et al., 2004; van der Schrier et al., 2013; Wells et al., 2004) from two independent networks of moisture-sensitive tree-ring chronologies using the Point-by-Point Regression climate field reconstruction approach (Cook et al., 1999, 2004, 2013, 2015). We conduct our analyses over a common period of 1000 to 2005 CE, which reflects a compromise between the temporal length of the comparison and the domain of continuous spatial reconstruction coverage.

### 2.2. Climate Data

In order to identify and interpret the atmosphere and ocean phenomena associated with coupled patterns of North Atlantic drought variability, we use gridded observational and reanalysis data. We extract atmospheric data fields including surface pressure, geopotential height, and winds from the NOAA-CIRES 20th Century Reanalysis (v2C; Compo et al., 2011), while SST data are from the Hadley Centre ISST version 1.1 (HadISST; Rayner et al., 2003). In order to compare drought patterns with radiative forcing over the last millennium, we used time series of total solar irradiance (TSI) data compiled by Schmidt et al. (2012) and the most recent estimate of Common Era volcanic forcing from Toohey and Sigl (2017). For comparison between our coupled drought modes and last millennium temperatures, we use the Northern Hemisphere summer temperature reconstruction from Wilson et al. (2016).

### 2.3. Analyses

We identified coupled patterns of North Atlantic PDSI covariance using the singular value decomposition (SVD) described by Bretherton et al. (1992) and Cherry (1996). We calculated the cross-covariance of the two independent fields over the common period 1000 to 2005 CE. We then decomposed this matrix into eigenvectors (or loadings) and the associated singular values. For each mode, we calculated the corresponding time series expansion (or scores) by multiplying the eigenvectors and the centered data matrix from each drought field. The procedure therefore produces eigenvectors and their associated time series for each of the two domains used in the analysis. Homogeneous correlations were calculated as the correlation between the time series expansion for each drought atlas and the corresponding original field (Bretherton et al., 1992). We assessed the interpretability and significance of these coupled modes using a Monte Carlo approach. We repeatedly ($n = 1,000$) randomized the temporal order of both fields independently, disrupting their temporal relationship but maintaining the spatiotemporal covariance in each individual atlas. We then compared the variance accounted for by each of the SVD modes against those from the randomized fields. We measured the coherence of the temporal expression of each mode using the multitaper method (Chave et al., 1987; Huybers, 2004; Lall & Mann, 1995; Thomson, 1982).

We analyzed the association between the leading modes of drought variability and large-scale climate using composite analysis. Composite analysis has two advantages here: First, it does not require that opposite sign anomalies have a symmetrical spatial structure or magnitude, which is a concern for North Atlantic climate (Cassou et al., 2004; Hurrell & Deser, 2010). Second, composite analysis can be used to identify years and analyze the corresponding mean fields when both the NADA and OWDA regions have the same-sign time series anomalies. To create the composite fields, we identified those years in which the SVD1 time series

10.1029/2019GL084350

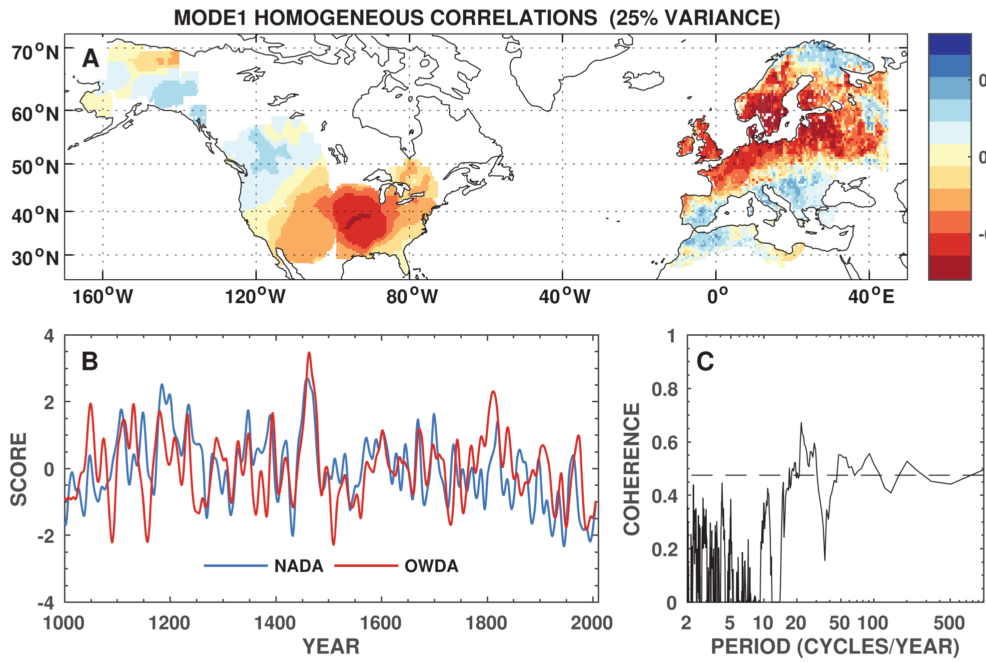


**Figure 1.** The leading mode (SVD1) of coupled North Atlantic terrestrial drought variability. This coupled spatiotemporal pattern accounts for 25% of the total North Atlantic drought variability over the last millennium. (a) The spatial pattern of homogeneous correlations suggests opposite sign Palmer Drought Severity Index anomalies in the Mediterranean versus those in Northern and western Europe and the central and eastern United States. (b) The temporal expression of this mode smoothed with a 21-year spline to emphasize coherent variability at multidecadal-to-centennial time scales shown in (c).

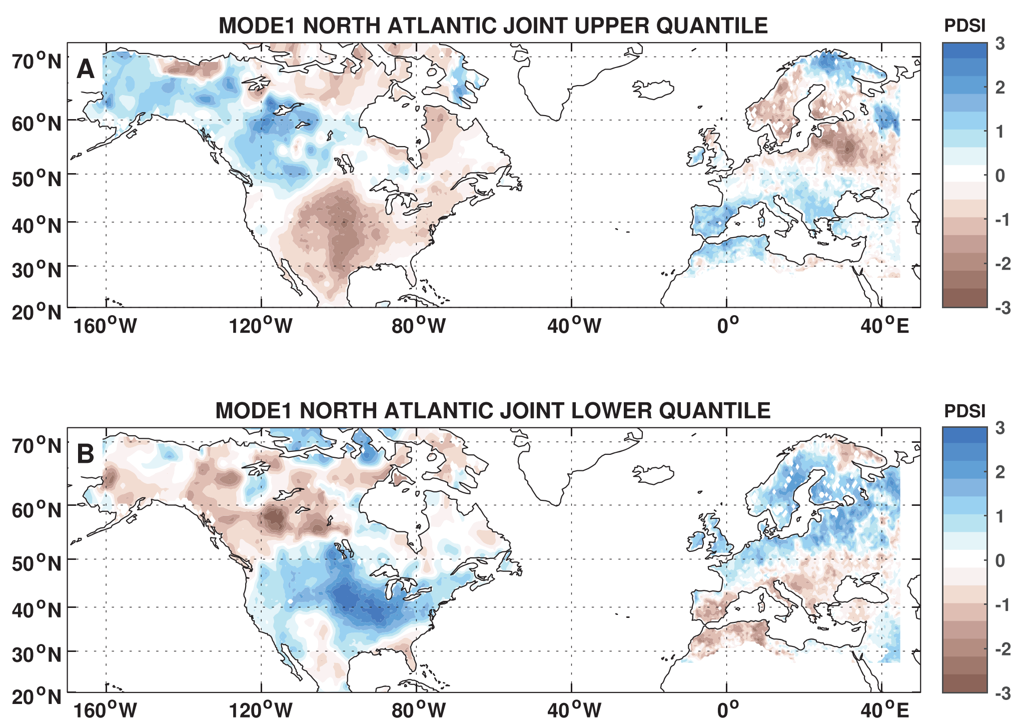


**Figure 2.** Composite Palmer Drought Severity Index (PDSI) for the North American Drought Atlas and Old World Drought Atlas when their time series expansion for the leading mode (SVD1) are both in the (a) upper quantile and (b) lower quantile during the period 1900 to 2005.

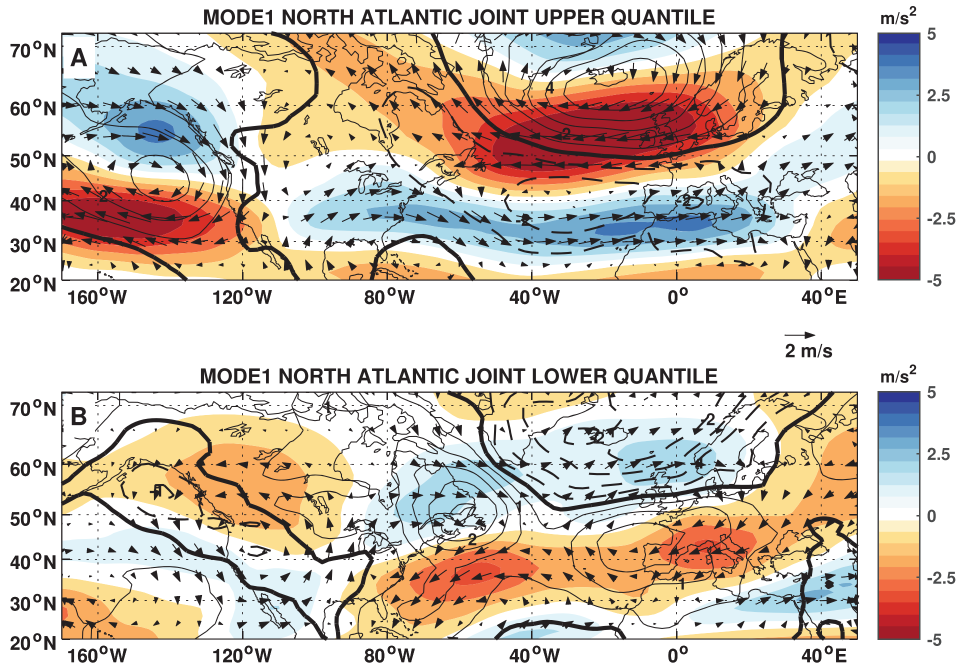


**Figure 3.** Composite winter (January–March) 250-mb geopotential height zonal wind speed (filled contours) and wind magnitude and direction (vectors) anomalies from the 20th Century Reanalysis (1850–2014; Compo et al., 2011) when the time series expansion of the North American Drought Atlas and Old World Drought Atlas in SVD1 are both in their (a) upper quantile and (b) lower quantile. Line (unfilled) contours show the corresponding surface pressure anomalies, with dashed lines showing negative anomalies and solid lines showing positive anomalies. The zero line is shown by a heavy black line.

were both above or below their respective 25th and 75th quantiles. For our decadal-scale SST analyses, we further identified those epochs where the smoothed (21-year spline) SVD time series were both above or below their respective medians. For correlation analysis of smoothed series, we use the method described by Ebisuzaki (1997) to account for the reduced degrees of freedom.

## 3. Results and Discussion

Coupled SVD of the NADA and OWDA reveal two leading patterns that account for 25% (SVD1; Figure 1) and 17% (SVD2, not shown) of the total North Atlantic drought variance during the last millennium. Our Monte Carlo randomization procedure indicates that only these first two modes are significant at the 99% level. We focus on the leading mode of variability (SVD1) for the remainder of this paper, as it is linked to North Atlantic ocean-atmosphere variability.

The leading mode of coupled hydroclimate variability (SVD1) is characterized by same-sign PDSI anomalies over the continental United States and northern and western Europe and the opposite sign over the Mediterranean and North Africa (Figure 1). At annual time scales, the NADA and OWDA SVD1 time series (1000 to 2005 CE) are weakly but significantly correlated at $r = 0.28$ ($p < 0.001$). Greater similarity is observed at decadal to centennial time scales (Figure 1b), and the two series are significantly coherent at time periods longer than ~15 years (Figure 1c) and correlated at $r = 0.49$ ($p < 0.001$). The homogeneous field correlations and composite PDSI fields indicate that over the last millennium when the Mediterranean is dry, much of the United States and northern and western Europe are wet and vice versa (Figures 1a and 2). The leading coupled mode in the OWDA domain is similar to the leading mode when OWDA is considered in isolation (Cook et al., 2015), while the coupled pattern in the NADA domain is distinct from any of its individual leading empirical orthogonal functions (Cook et al., 2011).

Years when both SVD1 time series are in their respective upper quantile are characterized by a weaker North Atlantic meridional surface pressure gradient, similar to the negative phase of the NAO (Figure 3a). These years are associated with a wetter Mediterranean and drier Northern Europe and show stronger and southerly displaced upper level (250 mb) westerly winds. Conversely, dry years in the Mediterranean and

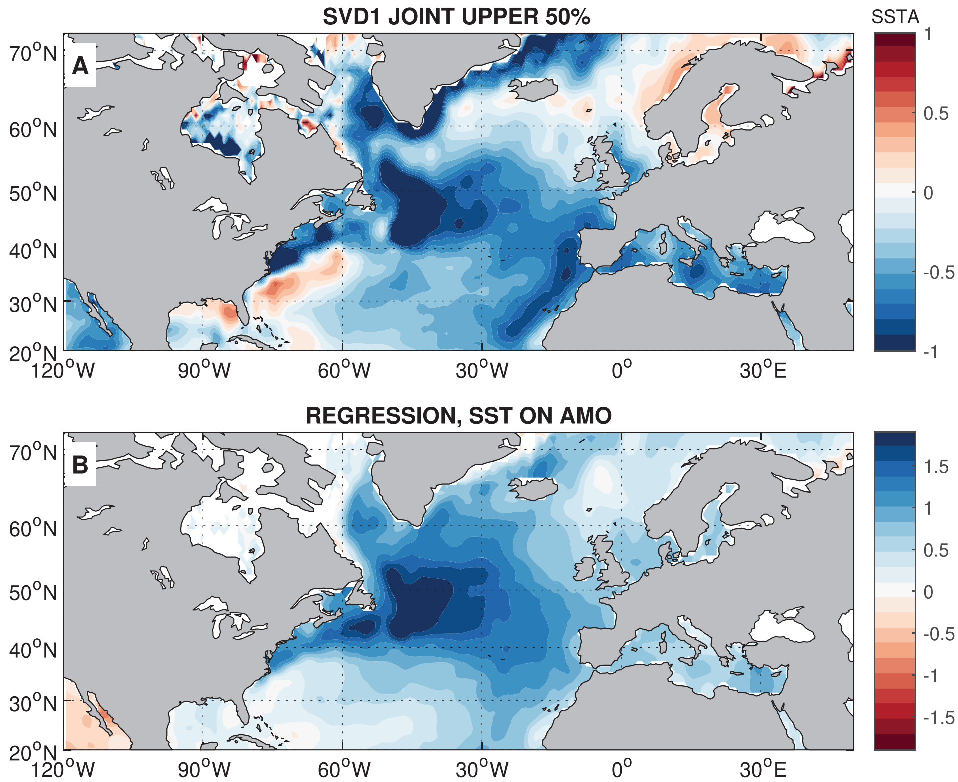


**Figure 4.** (a) Annual mean (January–December) sea surface temperature anomaly (SSTA) composites (Rayner et al., 2003) for when the SVD1 time series expansion of both the North American Drought Atlas and Old World Drought Atlas are greater than their median value over the period from 1900 to 2015 and (b) the regression of the HadISST field on the Atlantic Multidecadal Oscillation (AMO) index calculated from the field (the mean SSTA from the global mean over the region from 25° to 60°N and 7° to 75°W).

wet years in Northern Europe have a stronger North Atlantic surface pressure gradient, and upper level winds are shifted to the north (Figure 3b), a pattern similar to that associated with the positive phase of the NAO. The covariability of the temporal expressions of the circum-Atlantic drought modes can therefore be used to infer the state of atmospheric circulation at any time during the last millennium, including changes in the position and strength of the upper level jet.

SSTs during epochs when both the NADA and OWDA SVD1 series are above their median value (Figure 4a) are characterized by widespread cold anomalies in the Atlantic although warmer SSTs are observed around Fennoscandia and in the Gulf Stream, the latter likely because of the link between Gulf Stream position and North Atlantic climate (McCarthy et al., 2018; Thirumalai et al., 2018). In the Atlantic, the pattern is similar to the regression of the SST field on the AMO index (Figure 4b), including the large anomalies in the Labrador Sea and weaker anomalies in the western subtropical Atlantic. Using ERSST (v5; Huang et al., 2017) results in similar patterns (supporting information Figure S1). Anomalies in the OWDA series and indices of North Atlantic atmospheric circulation are coincident, while correlations with the AMO are lagged by up to a decade (Figure S2). This lag is consistent with both observations and modeling indicating the atmosphere leads the Atlantic SST response (Clement et al., 2015; Li et al., 2013). SSTs are influenced not only by atmospheric dynamics but also directly by radiative forcing, and therefore, the inferred patterns and magnitude of past SST anomalies should be interpreted cautiously.

This persistent and coherent mode of decadal-to-centennial coupled climate variability throughout the last millennium may reflect a combination of a forced response and internal variability (Deser et al., 2014; Goosse et al., 2005; Luterbacher et al., 2002; Moffa-Sánchez et al., 2014b; Semenov et al., 2008). Solar minima in the eleventh (Oort), fifteenth (Spörer), and eighteenth centuries (Dalton) are associated with inferred negative phases of the NAO and colder SSTs but not in the thirteenth (Wolf) or sixteenth (Maunder) centuries, and we observe no consistent response to volcanic eruptions. Multidecadal internal ocean-atmosphere variability is an important control on North Atlantic climate during the Common Era (Luterbacher et al., 1999, 2002), and

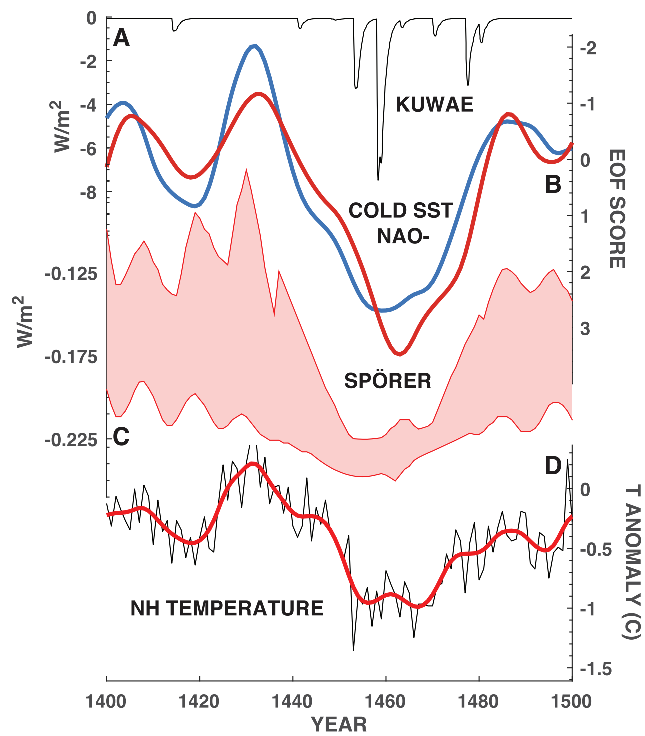


**Figure 5.** Inferred state of the North Atlantic ocean-atmosphere in the fifteenth century. (a) Northern Hemisphere (NH) volcanic forcing from Toohey and Sigl (2017) scaling aerosol optical depth to estimated forcing based on Hansen et al. (2005); (b) the leading (SVD1) time series expansions from North American Drought Atlas (blue) and Old World Drought Atlas (red), as in Figure 1. Note the axis here is inverted, and the inferred ocean-atmosphere state during the middle fifteenth century is labeled; (c) the range of total solar irradiance anomalies compiled by Schmidt et al. (2012) and indicating the Spörer minimum; (d) Northern Hemisphere summer temperature reconstructed by Wilson et al. (2016), with annual values in black and a 30-year Gaussian smoothed series shown in red.

successful simulation of this in climate models is therefore important for projections of the future change and investigation of past variability (Osborn, 2004; Parker et al., 2007).

While multidecadal variability in this leading mode is persistent throughout the last millennium, the largest and most coherent coupled feature across the North Atlantic drought reconstructions is the positive anomalies in the fifteenth century (Figures 5 and 1b), indicating dry conditions in North America and western Europe and wetter conditions in the Mediterranean. This event occurs during the beginning of the Little Ice Age (LIA) in the 1450s (Masson-Delmotte et al., 2013; Matthews & Briffa, 2005), and we interpret it as a decadal-scale period of sustained colder SSTs and atmospheric anomalies similar to the negative phase of the NAO, consistent with multiproxy NAO reconstructions (e.g., Cook et al., 2002; Ortega et al., 2015; Trouet et al., 2009) and reconstruction of colder North Atlantic SSTs (Moffa-Sánchez et al., 2014a, 2014b). This event in the terrestrial drought records is coeval with several large volcanic eruptions (Figure 5a; Toohey & Sigl, 2017), reduced TSI during the Spörer Grand Solar Minimum (Figure 5c; Schmidt et al., 2012), and colder Northern Hemisphere summer temperatures (Figure 5d; Wilson et al., 2016). The precise chronology and annual resolution of the drought reconstructions and their coupled modes allow us to observe the timing of the ocean-atmosphere anomalies relative to radiative forcing.

Inferred cooler SSTs and negative NAO conditions actually begin in the early 1400s, prior to the large volcanic eruptions of the 1450s and before the start of the LIA as defined in Masson-Delmotte et al. (2013). Drijfhout et al. (2013) showed that sustained enhanced blocking over the North Atlantic could cause rapid shifts in the southward extension of sea ice, colder SSTs, and LIA-type conditions. The occurrence of atmospheric blocking patterns would be greater during the negative phase of the NAO we infer for the early and middle fifteenth century, and therefore, unforced variability of the NAO itself may have been important in initiating and sustaining LIA conditions (cf. Camenisch et al., 2016; Cook et al., 2019; Croci-Maspoli et al., 2007; Luterbacher et al., 2001; Mellado-Cano et al., 2018). Alternatively, the Spörer Grand Minimum may also have played a preconditioning role. That is, cooling, a negative NAO, and enhanced initially caused by reductions in TSI allowed for sustained cold anomalies and feedbacks when large eruptions occurred in the 1450s and 1460s (e.g., Ineson et al., 2011; Lockwood et al., 2010; Moffa-Sánchez et al., 2014b). Glacier advances and the onset of LIA conditions in the early fifteenth century have been linked to indicate sustained sea ice and ocean feedbacks leading to North Atlantic cooling (Andres & Peltier, 2016; Lehner et al., 2013; Massė et al., 2008; Miller et al., 2012; Moffa-Sánchez et al., 2019; Zhong et al., 2010), and Slawinska and Robock (2018) observed that in the Community Earth System Model Last Millennium Ensemble simulations, the model runs using all forcings caused a more sustained LIA than in runs forced only with volcanic eruptions and concluded that the solar forcing amplified the volcanic cooling. However, Yoshimori et al. (2005) demonstrated that even during periods of strong radiative forcing, internal variability at multidecadal significantly modulate the response of the climate system. The lack of similar strongly coherent events during other solar minima (Figure 1) suggests that either the co-occurrence of reduced TSI, large volcanic eruptions, or a sea ice feedback is important for creating the strong coupled responses we observe in the fifteenth century (Slawinska & Robock, 2018) or that unforced variability plays an important role (Luterbacher et al., 2001; Palastanga et al., 2011; Zanchettin et al., 2012).

Ocean sediment cores suggest the early LIA was characterized by a weakened Gulf Stream, reduced Atlantic surface-ocean circulation, and colder SSTs (Lund et al., 2006; Moffa-Sánchez et al., 2014a, 2014b, 2019, Thirumalai et al., 2018). While model simulations show that an abrupt weakening of the subpolar gyre can cause LIA conditions in the Atlantic (Moreno-Chamarro et al., 2016), in agreement with ocean sediment proxies (Moffa-Sánchez et al., 2014b), models are inconsistent on the forced response of the gyre (e.g., Lehner et al., 2013; Schleussner & Feulner, 2013). Similarly, the modeled response of AMOC to forcing depends on the background state, volcanic eruption characteristics, and model configurations (Andres & Peltier, 2016; Mignot et al., 2011; Palastanga et al., 2011; Slawinska & Robock, 2018; Zanchettin et al., 2012). Our coupled North Atlantic drought mode is diagnostic of a negative NAO and consistent with colder SSTs in the North Atlantic (Moffa-Sánchez et al., 2014b, 2019), but from our terrestrial data alone, we cannot determine to what extent these inferred SST anomalies were caused by endogenous ocean circulation changes, a response to NAO forcing, or the direct radiative response.

## 4. Conclusions

We have demonstrated that analysis of independent terrestrial hydroclimate reconstructions associated with North Atlantic climate variability can be used to infer the state of the ocean-atmosphere system and complement climate modeling, temperature reconstructions, and marine proxy studies. Internal decadal-to-centennial scale variability is a persistent feature of North Atlantic climate of the last millennium. Although the majority of this record appears to be independent of changes in radiative forcing, we do find that a decadal-scale negative phase of the NAO and cold North Atlantic are most consistent with proxy reconstructions of drought on both sides of the Atlantic during the onset of the LIA in the fifteenth century. While decadal-scale coupling emerges as a robust feature of North Atlantic terrestrial climate variability, there is no indication in our analysis here of persistent multicentennial-scale phases of the NAO (Trouet et al., 2009), in agreement with models and reconstructions (Cook et al., 2019; Landrum et al., 2013; Lehner et al., 2012; Ortega et al., 2015; Palastanga et al., 2011; Touchan et al., 2011). Rather, decadal-to-centennial variability is present throughout the last millennium. Nor do the coupled drought patterns reveal significant multicentennial variability as reconstructed using temperature proxies (Wang et al., 2017). These observations suggest both caution and opportunities when interpreting multiproxy Northern Hemisphere networks whose records may comprise a mix of different components of the forced and internal climate variability in both temperature and hydroclimate with a range of characteristic time scales.

**Acknowledgments**
This research was funded by grants from the U.S. National Science Foundation P2C2 program (AGS-1501856 and AGS-1502224). B. I. C. was supported by the NASA Modeling, Analysis, and Prediction program (NASA 80NSSC17K0265). We thank Mukund Rao for helpful discussion. Both drought atlases are available from the NCEI World Data Service for Paleoclimatology (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data). The 20th Century Reanalysis data are available from NOAA-CIRES (https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.html), and HadISST data are available from the U.K. Met Office (https://www.metoffice.gov.uk/hadobs/hadisst/). This is Lamont contribution #8358.

## References

Andres, H. J., & Peltier, W. R. (2016). Regional influences of natural external forcings on the transition from the Medieval Climate Anomaly to the Little Ice Age. *Journal of Climate*, *29*(16), 5779–5800. https://doi.org/10.1175/jcli-d-15-0599.1

Barnston, A. G., & Livezey, R. E. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review*, *115*(6), 1083–1126.

Bretherton, C. S., Smith, C., & Wallace, J. M. (1992). An intercomparison of methods for finding coupled patterns in climate data. *Journal of Climate*, *5*, 541–560.

Camenisch, C., Keller, K. M., Salvisberg, M., Amann, B., Bauch, M., Blumer, S., et al. (2016). The 1430s: A cold period of extraordinary internal climate variability during the early Spörer Minimum with social and economic impacts in north-western and central Europe. *Climate of the Past*, *12*(11), 2107–2126.

Cassou, C., Terray, L., Hurrell, J. W., & Deser, C. (2004). North Atlantic winter climate regimes: Spatial asymmetry, stationarity with time, and oceanic forcing. *Journal of Climate*, *17*(5), 1055–1068.

Chave, A. D., Thomson, D. J., & Ander, M. E. (1987). On the robust estimation of power spectra, coherences and transfer functions. *Journal of Geophysical Research*, *92*, 633–648.

Cherry, S. (1996). Singular value decomposition analysis and canonical correlation analysis. *Journal of Climate*, *9*(9), 2003–2009.

Clement, A., Bellomo, K., Murphy, L. N., Cane, M. A., Mauritsen, T., Rädel, G., & Stevens, B. (2015). The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science*, *350*(6258), 320–324.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R., Yin, X., et al. (2011). The Twentieth Century Reanalysis project. *Quarterly Journal of the Royal Meteorological Society*, *137*(654), 1–28.

Cook, B. I., Anchukaitis, K. J., Touchan, R., Meko, D. M., & Cook, E. R. (2016). Spatiotemporal drought variability in the Mediterranean over the last 900 years. *Journal of Geophysical Research: Atmospheres*, *121*, 2060–2074. https://doi.org/10.1002/2015JD023929

Cook, B. I., Cook, E. R., Anchukaitis, K. J., Seager, R., & Miller, R. L. (2011). Forced and unforced variability of twentieth century North American droughts and pluvials. *Climate Dynamics*, *37*(5-6), 1097–1110. https://doi.org/10.1007/s00382-010-0897-9

Cook, E. R., D'Arrigo, R. D., & Mann, M. E. (2002). A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since AD 1400. *Journal of Climate*, *15*, 1754–1764.

Cook, E. R., Krusic, P. J., Anchukaitis, K. J., Buckley, B. M., Nakatsuka, T., & Sano, M. (2013). Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 CE. *Climate Dynamics*, *41*(11-12), 2957–2972.

Cook, E. R., Kushnir, Y., Smerdon, J. E., Anchukaitis, K. J., & Wahl, E. R. (2019). A Euro-Mediterranean tree-ring reconstruction of the winter NAO index since 910 CE. *Climate Dynamics*, *53*, 1567. https://doi.org/10.1007/s00382-019-04696-2

Cook, E. R., Meko, D. M., Stahle, D. W., & Cleaveland, M. K. (1999). Drought reconstructions for the continental United States. *Journal of Climate*, *12*(4), 1145–1162.

Cook, E. R., Seager, R., Heim, R. R., Vose, R. S., Herweijer, C., & Woodhouse, C. A. (2010). Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science*, *25*(1), 48–61.

Cook, E. R., Seager, R., Kushnir, Y., Briffa, K. R., Büntgen, U., Frank, D., et al. (2015). Old World megadroughts and pluvials during the Common Era. *Science Advances*, *1*(10), e1500561. https://doi.org/10.1126/sciadv.1500561

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., & Stahle, D. (2004). Long-term aridity changes in the western United States. *Science*, *306*(5698), 1015–1018.

Croci-Maspoli, M., Schwierz, C., & Davies, H. C. (2007). Atmospheric blocking: Space-time links to the NAO and PNA. *Climate Dynamics*, *29*(7-8), 713–725. https://doi.org/10.1007/s00382-007-0259-4

D'Arrigo, R., Anchukaitis, K. J., Buckley, B., Cook, E. R., & Wilson, R. (2011). Regional climatic and North Atlantic Oscillation signatures in West Virginia red cedar over the past millennium. *Global and Planetary Change*, *84–85*, 8–13. https://doi.org/10.1016/j.gloplacha.2011.07.003

Dai, A., Trenberth, K. E., & Qian, T. (2004). A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, *5*(6), 1117–1130.

Deser, C., Phillips, A. S., Alexander, M. A., & Smoliak, B. V. (2014). Projecting North American climate over the next 50 years: Uncertainty due to internal variability. *Journal of Climate*, *27*(6), 2271–2296.

Drijfhout, S., Gleeson, E., Dijkstra, H. A., & Livina, V. (2013). Spontaneous abrupt climate change due to an atmospheric blocking-sea-ice-ocean feedback in an unforced climate model simulation. *Proceedings of the National Academy of Sciences*, *110*(49), 19,713–19,18. https://doi.org/10.1073/pnas.1304912110

Driscoll, S., Bozzo, A., Gray, L. J., Robock, A., & Stenchikov, G. (2012). Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. *Journal of Geophysical Research*, *117*, D17105. https://doi.org/10.1029/2012JD7607

Ebisuzaki, W. (1997). A method to estimate the statistical significance of a correlation when the data are serially correlated. *Journal of Climate*, *10*(9), 2147–2153.

Enfield, D. B., Mestas-Nunez, A. M., & Trimble, P. J. (2001). The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letters*, *28*, 2077–2080.

Evans, M. N., Kaplan, A., Cane, M. A., & Villalba, R. (2001). Globality and optimality in climate field reconstructions from proxy data. In V. Markgraf (Ed.), *Interhemispheric climate linkages* pp. 53–72). Cambridge, UK: Cambridge University Press.

Fritts, H. C., Blasing, T. J., Hayden, B. P., & Kutzbach, J. E. (1971). Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. *J. Appl. Meteorol.*, *10*, 845–864.

Goosse, H., Renssen, H., Timmermann, A., & Bradley, R. S. (2005). Internal and forced climate variability during the last millennium: A model-data comparison using ensemble simulations. *Quaternary Science Reviews*, *24*(12-13), 1345–1360.

Gray, S., Graumlich, L., Betancourt, J., & Pederson, G. (2004). A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. *Geophysical Research Letters*, *31*, L12205. https://doi.org/10.1029/2004GL019932

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G., et al. (2005). Efficacy of climate forcings. *Journal of Geophysical Research*, *110*, D18104. https://doi.org/10.1029/2005JD005776

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended reconstructed sea surface temperature, version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. *Journal of Climate*, *30*(20), 8179–8205.

Hurrell, J. W. (1995). Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science*, *269*(5224), 676–679. https://doi.org/10.1126/science.269.5224.676

Hurrell, J. W., & Deser, C. (2010). North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems*, *79*(3-4), 231–244. https://doi.org/10.1016/j.jmarsys.2009.11.002

Hurrell, J. W., Kushnir, Y., Ottersen, G., & Visbeck, M. (2003). An overview of the North Atlantic Oscillation, *The North Atlantic Oscillation: Climatic significance and environmental impact* pp. 1–35). Washington: American Geophysical Union. https://doi.org/10.1029/134gm01

Huybers, P. (2004). Comment on 'Coupling of the hemispheres in observations and simulations of glacial climate change' by A. schmittner, O. A. Saenko, and A. J. Weaver. *Quaternary Science Reviews*, *23*(1-2), 207–210. https://doi.org/10.1016/j.quascirev.2003.08.001

Ineson, S., Scaife, A. A., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray, L. J., & Haigh, J. D. (2011). Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geoscience*, *4*(11), 753.

Kingston, D. G., McGregor, G. R., Hannah, D. M., & Lawler, D. M. (2006). River flow teleconnections across the northern North Atlantic region. *Geophysical Research Letters*, *33*, L14705. https://doi.org/10.1029/2006gl026574

Knight, J. R., Folland, C. K., & Scaife, A. A. (2006). Climate impacts of the Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, *33*, L17706. https://doi.org/10.1029/2006GL026242

Kushnir, Y. (1994). Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *Journal of Climate*, *7*(1), 141–157.

Lall, U., & Mann, M. (1995). The great salt lake: A barometer of low-frequency climatic variability. *Water Resources Research*, *31*(10), 2503–2515.

Landrum, L., Otto-Bliesner, B. L., Wahl, E. R., Conley, A., Lawrence, P. J., Rosenbloom, N., & Teng, H. (2013). Last millennium climate and its variability in CCSM4. *Journal of Climate*, *26*(4), 1085–1111.

Lehner, F., Born, A., Raible, C. C., & Stocker, T. F. (2013). Amplified inception of European Little Ice Age by sea ice–ocean-atmosphere feedbacks. *Journal of Climate*, *26*(19), 7586–7602. https://doi.org/10.1175/jcli-d-12-00690.1

Lehner, F., Raible, C. C., & Stocker, T. F. (2012). Testing the robustness of a precipitation proxy-based North Atlantic Oscillation reconstruction. *Quaternary Science Reviews*, *45*, 85–94.

Li, J., Sun, C., & Jin, F.-F. (2013). NAO implicated as a predictor of Northern Hemisphere mean temperature multidecadal variability. *Geophysical Research Letters*, *40*, 5497–5502. https://doi.org/10.1002/2013GL057877

Lockwood, M., Harrison, R. G., Woollings, T., & Solanki, S. K. (2010). Are cold winters in Europe associated with low solar activity? *Environmental Research Letters*, *5*(2), 024,001.

Lund, D. C., Lynch-Stieglitz, J., & Curry, W. B. (2006). Gulf Stream density structure and transport during the past millennium. *Nature*, *444*(7119), 601–604. https://doi.org/10.1038/nature05277

Luterbacher, J., Rickli, R., Xoplaki, E., Tinguely, C., Beck, C., Pfister, C., & Wanner, H. (2001). The late Maunder minimum (1675–1715)—A key period for studying decadal scale climatic change in Europe. *Climatic Change*, *49*(4), 441–462.

Luterbacher, J., Schmutz, C., Gyalistras, D., Xoplaki, E., & Wanner, H. (1999). Reconstruction of monthly NAO and EU indices back to AD 1675. *Geophysical Research Letters*, *26*(17), 2745–2748.

Luterbacher, J., Xoplaki, E., Dietrich, D., Rickli, R., Jacobeit, J., Beck, C., et al. (2002). Reconstruction of sea level pressure fields over the eastern North Atlantic and Europe back to 1500. *Climate Dynamics*, *18*(7), 545–561.

Marshall, J., Kushnir, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., et al. (2001). North Atlantic climate variability: Phenomena, impacts and mechanisms. *International Journal of Climatology*, *21*(15), 1863–1898. https://doi.org/10.1002/joc.693

Massė, G., Rowland, S. J., Sicre, M.-A., Jacob, J., Jansen, E., & Belt, S. T. (2008). Abrupt climate changes for Iceland during the last millennium: Evidence from high resolution sea ice reconstructions. *Earth and Planetary Science Letters*, *269*(3-4), 565–569. https://doi.org/10.1016/j.epsl.2008.03.017

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., Rouco, J. G., et al. (2013). Information from paleoclimate archives, in climate change 2013: The physical science basis. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. Midgley (Eds.), *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* pp. 383–464). Cambridge United Kingdom and New York, NY, USA: Cambridge University Press.

Matthews, J. A., & Briffa, K. R. (2005). The 'Little Ice Age': Re-evaluation of an evolving concept. *Geografiska Annaler Series A – Physical Geography*, *87A*, 17–36.

McCarthy, G. D., Joyce, T. M., & Josey, S. A. (2018). Gulf Stream variability in the context of quasi-decadal and multidecadal Atlantic climate variability. *Geophysical Research Letters*, *45*, 11257–11264. https://doi.org/10.1029/2018GL079336

Mellado-Cano, J., Barriopedro, D., García-herrera, R., Trigo, R. M., & Álvarez-Castro, M. C. (2018). Euro-Atlantic Atmospheric Circulation during the Late Maunder Minimum. *Journal of Climate*, *31*(10), 3849–3863.

Mignot, J., Khodri, M., Frankignoul, C., & Servonnat, J. (2011). Volcanic impact on the Atlantic Ocean over the last millennium. *Climate of the Past*, *7*(4), 1439–1455. https://doi.org/10.5194/cp-7-1439-2011

Miller, G. H., Geirsdóttir, A., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., et al. (2012). Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophysical Research Letters*, *39*, L02708. https://doi.org/10.1029/2011GL050168

Moffa-Sánchez, P., Born, A., Hall, I. R., Thornalley, D. J., & Barker, S. (2014b). Solar forcing of North Atlantic surface temperature and salinity over the past millennium. *Nature Geoscience*, *7*(4), 275.

Moffa-Sánchez, P., Hall, I. R., Barker, S., Thornalley, D. J., & Yashayaev, I. (2014a). Surface changes in the eastern Labrador Sea around the onset of the Little Ice Age. *Paleoceanography*, *29*, 160–175. https://doi.org/10.1002/2013PA002523

Moffa-Sánchez, P., Moreno-Chamarro, E., Reynolds, D., Ortega, P., Cunningham, L., Swingedouw, D., et al. (2019). Variability in the Northern North Atlantic and Arctic Oceans across the Last Two Millennia: A review. *Paleoceanography and Paleoclimatology*, *34*, 1399–1436. https://doi.org/10.1029/2018PA003508

Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., & Jungclaus, J. H. (2016). An abrupt weakening of the subpolar gyre as trigger of Little Ice Age-type episodes. *Climate Dynamics*, *48*(3-4), 727–744. https://doi.org/10.1007/s00382-016-3106-7

Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., Casado, M., & Yiou, P. (2015). A model-tested North Atlantic Oscillation reconstruction for the past millennium. *Nature*, *523*(7558), 71–74. https://doi.org/10.1038/nature14518

Osborn, T. J. (2004). Simulating the winter North Atlantic Oscillation: The roles of internal variability and greenhouse gas forcing. *Climate Dynamics*, *22*(6-7), 605–623.

Palastanga, V., Van der Schrier, G., Weber, S., Kleinen, T., Briffa, K., & Osborn, T. (2011). Atmosphere and ocean dynamics: Contributors to the European Little Ice Age?. *Climate Dynamics*, *36*(5-6), 973–987.

Parker, D., Folland, C., Scaife, A., Knight, J., Colman, A., Baines, P., & Dong, B. (2007). Decadal to multidecadal variability and the climate change background. *Journal of Geophysical Research*, *112*, D18115. https://doi.org/10.1029/2007JD008411

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(D14), 4407. https://doi.org/10.1029/2002JD002670

Rodríguez-Fonseca, B., Polo, I., Serrano, E., & Castro, M. (2006). Evaluation of the North Atlantic SST forcing on the European and Northern African winter climate. *International Journal of Climatology*, *26*(2), 179–191.

Schleussner, C. F., & Feulner, G. (2013). A volcanically triggered regime shift in the subpolar North Atlantic Ocean as a possible origin of the Little Ice Age. *Climate of the Past*, *9*(3), 1321–1330. https://doi.org/10.5194/cp-9-1321-2013

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., et al. (2012). Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1). *Geoscientific Model Development*, *5*(1), 185–191. https://doi.org/10.5194/gmd-5-185-2012

Semenov, V. A., Latif, M., Jungclaus, J. H., & Park, W. (2008). Is the observed NAO variability during the instrumental record unusual? *Geophysical Research Letters*, *35*, L11701. https://doi.org/10.1029/2008GL033273

Shindell, D. T., Schmidt, G. A., Miller, R. L., & Mann, M. E. (2003). Volcanic and solar forcing of climate change during the preindustrial era. *Journal of Climate*, *16*, 4094–4107.

Sjolte, J., Sturm, C., Adolphi, F., Vinther, B. M., Werner, M., Lohmann, G., & Muscheler, R. (2018). Solar and volcanic forcing of North Atlantic climate inferred from a process-based reconstruction. *Climate of the Past*, *14*(8), 1179–1194.

Slawinska, J., & Robock, A. (2018). Impact of volcanic eruptions on decadal to centennial fluctuations of Arctic Sea ice extent during the last millennium and on initiation of the Little Ice Age. *Journal of Climate*, *31*(6), 2145–2167. https://doi.org/10.1175/jcli-d-16-0498.1

Thirumalai, K., Quinn, T. M., Okumura, Y., Richey, J. N., Partin, J. W., Poore, R. Z., & Moreno-Chamarro, E. (2018). Pronounced centennial-scale Atlantic Ocean climate variability correlated with Western Hemisphere hydroclimate. *Nature Communications*, *9*(1), 392. https://doi.org/10.1038/s41467-018-02846-4

Thomson, D. J. (1982). Spectrum estimation and harmonic analysis. *Proceedings of the IEEE*, *70*, 1055–1096.

Toohey, M., & Sigl, M. (2017). Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. *Earth System Science Data*, *9*(2), 809–831. https://doi.org/10.5194/essd-9-809-2017

Touchan, R., Anchukaitis, K. J., Meko, D. M., Sabir, M., Attalah, S., & Aloui, A. (2011). Spatiotemporal drought variability in northwestern Africa over the last nine centuries. *Climate Dynamics*, *37*(1–2), 237–252. https://doi.org/10.1007/s00382-010-0804-4

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., & Frank, D. C. (2009). Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly. *Science*, *324*(5923), 78–80. https://doi.org/10.1126/science.1166349

van der Schrier, G., Barichivich, J., Briffa, K. R., & Jones, P. D. (2013). A scPDSI-based global data set of dry and wet spells for 1901–2009. *Journal of Geophysical Research: Atmospheres*, *118*, 4025–4048. https://doi.org/10.1002/jgrd.50355

Wang, J., Yang, B., Ljungqvist, F. C., Luterbacher, J., Osborn, T. J., Briffa, K. R., & Zorita, E. (2017). Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years. *Nature Geoscience*, *10*(7), 512–517. https://doi.org/10.1038/ngeo2962

Wells, N., Goddard, S., & Hayes, M. J. (2004). A self-calibrating Palmer Drought Severity Index. *Journal of Climate*, *17*(12), 2335–2351.

Wilson, R., Anchukaitis, K., Briffa, K. R., Büntgen, U., Cook, E., D'Arrigo, R., et al. (2016). Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context. *Quaternary Science Reviews*, *134*, 1–18. https://doi.org/10.1016/j.quascirev.2015.12.005

Yoshimori, M., Stocker, T. F., Raible, C. C., & Renold, M. (2005). Externally forced and internal variability in ensemble climate simulations of the Maunder Minimum. *Journal of Climate*, *18*(20), 4253–4270.

Zanardo, S., Nicotina, L., Hilberts, A. G. J., & Jewson, S. P. (2019). Modulation of economic losses from European floods by the North Atlantic Oscillation. *Geophysical Research Letters*, *46*, 2563–2572. https://doi.org/10.1029/2019GL081956

Zanchettin, D., Timmreck, C., Graf, H.-F., Rubino, A., Lorenz, S., Lohmann, K., et al. (2012). Bi-decadal variability excited in the coupled ocean–atmosphere system by strong tropical volcanic eruptions. *Climate Dynamic*, *39*(1-2), 419–444. https://doi.org/10.1007/s00382-011-1167-1

Zhong, Y., Miller, G. H., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Schneider, D. P., & Geirsdottir, A. (2010). Centennial-scale climate change from decadally-paced explosive volcanism: A coupled sea ice-ocean mechanism. *Climate Dynamics*, *37*(11-12), 2373–2387. https://doi.org/10.1007/s00382-010-0967-z