External forcing mechanisms controlling the North Atlantic coastal upwelling regime during the mid-Holocene

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ABSTRACT

Nearshore upwelling along the eastern North Atlantic margin regulates regional marine ecosystem productivity and thus impacts blue economies. While most global circulation models show an increase in the intensity and duration of seasonal upwelling at high latitudes under future human-induced warmer conditions, projections for the North Atlantic are still ambiguous. Due to the low temporal resolution of coastal upwelling records, little is known about the impact of natural forcing mechanisms on upwelling variability. Here, we present a microfossil-based proxy record and modeling simulations for the warmest period of the Holocene (ca. 9–5 ka) to estimate the contribution of the natural variability in North Atlantic upwelling via atmospheric and oceanic dynamics. We found that more frequent high-pressure conditions in the eastern North Atlantic associated with solar activity and orbital parameters triggered upwelling variations at multidecadal and millennial time scales, respectively. Our new findings offer insights into the role of external forcing mechanisms in upwelling changes before the Anthropocene, which must be considered when producing future projections of midlatitude upwelling activity.

INTRODUCTION

Coastal upwelling regions are the most productive marine areas in the world. Current human-induced greenhouse warming influences the intensity of upwelling because it is strongly connected with the increase in land-sea temperature differences (Bakun et al., 2010). In response to future warming, the upwelling season is expected to start earlier, end later, and last longer by the end of this century, particularly at high latitudes (Wang et al., 2015). An exception is the Iberian North Atlantic margin (INAM), where the recent upwelling dynamics are more strongly influenced by climate modes of variability (MoV; Sydeman et al., 2014). The North Atlantic Oscillation (NAO) is the leading mode over the eastern North Atlantic European sector at interannual time scales (Pinto and Raible, 2012). However, other MoV, such as the East Atlantic pattern, play a larger role in wind-intensity variability across this region (Trigo et al., 2008).

On decadal to millennial time scales, MoV partly control the link between atmospheric and oceanic dynamics (Hernández et al., 2020), which is also sensitive to solar changes (Meehl et al., 2008). Studies arguing for a solar impact on MoV invoke a top-down mechanism related to the ultraviolet irradiance pattern (Gray et al., 2010). Changes in ultraviolet radiation due to solar activity would lead to an altered stratospheric circulation that propagates poleward and downward, affecting tropospheric jet streams and thus atmospheric circulation (Ineson et al., 2011). Specifically, low solar irradiance promotes the development of frequent and persistent atmospheric blocking events over the eastern North Atlantic as the result of an atmospheric configuration compatible with negative East Atlantic phases (Mofa-Sánchez et al., 2014). Moreover, Häkkinen et al. (2011) showed that there is a correlation between the occurrence of Atlantic blocking events and the North Atlantic sea-surface temperature (SST).

Thus, further information on the role played by atmospheric patterns and SSTs in the duration and intensity of upwelling, as well as their external forcing mechanisms, is crucial when considering the control of upwelling on marine ecosystem processes and their impact on blue economies (Barth et al., 2007).

The temporal heterogeneity of the upwelling regimes and their drivers makes observational data and simulated projections unsatisfactory for determining the role of forcing mechanisms in the long-term evolution of coastal upwelling (Tim et al., 2016). More reliable reconstructions from periods prior to industrial human influence are therefore necessary to provide long-term analogous scenarios for the evaluation of the role of nonanthropogenic external forcing mechanisms in the upwelling regimes. The Holocene Climate Optimum (HCO) was a warm interval covering the period from ca. 9 to 5 ka with high summer insolation in the Northern Hemisphere (Bergen and Loutre, 1991). These background conditions (warm temperatures and high land-sea temperature differences) make the HCO a candidate period for evaluating the role of nonanthropogenic external forcing mechanisms in the upwelling regimes, comparable in some aspects to the impacts of future warming on ocean-atmosphere climate dynamics over the North Atlantic.

Here, we present a new multidecadal resolved coastal upwelling record during the HCO based on calcareous nanofossil records (Alday et al., 2006) from the sediment sequence of the paleo-ria sector of the Mira estuary (Iberian margin; Fig. 1). We reassessed the data set by (1) subdividing the assemblages into two clusters of distinct paleoecological affinity; (2) analyzing...
and interpreting their distinct patterns of cyclicality in relation to external forcing mechanisms; and (3) using five climate model simulations from the third phase of the Paleoclimate Modelling Intercomparison Project (PMIP3, https://pmip.lsce.ipsl.fr/) forced with mid-Holocene conditions (ca. 6 ka) to study the forcing drivers in the long-term upwelling fluctuations in comparison to preindustrial climatic conditions.

**DATA AND METHODS**

The INAM is located at the northern limit of the North Atlantic Upwelling System, one of the major upwelling areas in the world, which is predominantly modulated by the seasonal (winter/summer) wind direction cycle (deCastro et al., 2008). The subtropical high-pressure system migrates northward in spring and summer, enhancing northerly winds and upwelling conditions (Fig. 1A). During winter, the northerly winds weaken, resulting in prevailing coastal downwelling (Fig. 1B). However, this pattern shows a north-south gradient, with higher seasonality at higher latitudes (42°N) and an extended upwelling season at lower latitudes (37°N; Ramos et al., 2013).

The Mira estuary is a small mesotidal system located on the INAM (37°40′N, 8°40′W), and its sedimentary infill (24.5 m depth) covers the entire Holocene section (see the Supplemental Material). For this study, a high-resolution set of 192 samples (5 cm sampling interval) was selected between core depths of 4 and 16 m (Alday et al., 2006). The sedimentation rate was 0.3 ± 0.04 cm yr⁻¹, providing a sample resolution of 16.2 ± 0.2 yr between 9 and 5 ka (see the Supplemental Material). This time period corresponds to full marine conditions responding to the sea-level rise after the Last Glacial Maximum.

A data set of 10 variables and 192 samples was employed to perform a factor analysis with varimax rotation. The two main factors (F1/F2) accounted for 48% of the total variance (Fig. 2A). The cyclicity of the studied time series was investigated by performing spectral analyses on the scores from the factor analysis (see the Supplemental Material). We also used data from five atmosphere-ocean coupled global climate models (GCMs) that contributed to the third phase of the PMIP3 (Braconnot et al., 2012). These models were (1) BBC-CSM1 (Beijing Climate Center, China), (2) CCSM4 (U.S. National Center for Atmospheric Research), (3) IPSL-CM5A-MR (Institut Pierre Simon Laplace, France), (4) MIROC-ESM (Atmosphere and Ocean Research Institute, Japan), and (5) MRI-CGCM3 (Meteorological Research Institute, Japan) (see the Supplemental Material). We used the last 100 yr of each model run for the...
following idealized simulations: the 6 ka period (mid-Holocene), and the preindustrial control period. These simulations had steady (constant) forcings (including solar) without considering postindustrial greenhouse gases. To obtain the ensemble means, we regridded the different model data sets to a common horizontal regular grid. The resulting ensemble is presented in a grid with a 1° × 1° horizontal resolution for atmospheric variables and 0.5° × 0.5° resolution for oceanic variables.

**RESULTS AND DISCUSSION**

**Nannoliths as Indicators of Iberian North Atlantic Margin Dynamics**

As one of the highest producers of nannoliths, coccolithophores are traditionally interpreted to represent typical oceanic oligotrophic conditions, but they are also important indicators of neritic coastal marine environmental conditions when affected by upwelling (Cachão and Moita, 2000). Coccolithophores are thus sensitive proxies for marine and associated atmospheric circulation regimes (Ziveri et al., 2004; Giraudou et al., 2010). In addition, the Mira samples revealed a high content of another nannolith, ascidian spicules (Didemnidae), which are usually indicators of shallow-marine waters and high-nutrient concentrations on the continental shelf (Łukowiak et al., 2016).

Factor analysis applied to the matrix assemblage of the nannoliths allowed us to separate and classify variables into two main clusters (A/B; Fig. 2A). Coccolith species of cluster A are more independent from nutrient-rich waters and preferentially tend to develop in oligotrophic offshore waters outside the direct influence of upwelling (Silva et al., 2008). In contrast, coccolith species of cluster B typically indicate the presence of a summer upwelling front in persistent high-productivity coastal waters (Guerreiro et al., 2015), which also explains their association with the ascidian spicules. The seasonal nature of the upwelling system in the INAM indicates that F1 scores are a proxy for downwelling conditions in winter, whereas F2 scores can be considered a direct indicator of an enhanced summer upwelling regime (Fig. 2B).

**INAM Upwelling Regime during the Holocene Climate Optimum**

**Multidecadal Time Scale Forcing Mechanisms**

Although increased INAM summer upwelling has been associated with more positive NAO phases at different time scales (Santos et al., 2005), it is controlled by the seasonal intensity and duration of the northerly winds, which result from intensified atmospheric blocking events west of the British Isles, mainly linked to negative East Atlantic phases (Häkkinen et al., 2011). Thus, increased upwelling is associated with more negative East Atlantic phases and, to a lesser extent, with positive NAO phases (deCastro et al., 2008).

The Mira record shows two main periods (7.4–6.8 ka and 6.5–6.1 ka) of intensified upwelling activity at multidecadal to centennial time scales and some events between 8.5 and 7.5 ka at shorter time scales (Fig. 3). To evaluate the potential forcing mechanisms controlling the upwelling regime, we applied a time-frequency (T-F) wavelet analysis on the F2 scores (summer upwelling indicator), which revealed periodicities with significant power at ∼40 and 250 yr during specific times of the HCO (Fig. 3). To better constrain the most prominent frequencies, we also performed periodogram analyses that identified pairs of significant frequencies with compatible values for 226 and 42–35 yr scores exceeding the 95% confidence level (Fig. 3). Thus, multidecadal and centennial cycles in the Mira sediments seem to approximately correspond to well-constrained solar variability periodicities such as the Brückner (∼35 yr) and the Suess/Vries (∼210 yr) cycles. Wavelet diagrams denote that periodicities did not have the same intensity (energy) during the entire studied period, remaining strong at centennial time scales (226 yr). High power for intensified summer upwelling conditions occurred at 8.4–8.2, 7.4–6.8, and 6.5–6.1 ka at decadal time scales and 7.6–7.1 ka at centennial time scales (Fig. 3), broadly coinciding with episodes of low solar activity (Figs. S4–S5; Wu et al., 2018). This pattern of low solar activity during the HCO was favorable for the development of stronger...
upwelling conditions at decadal to centennial time scales resulting from enhanced northwest-southeast pressure gradients in the eastern North Atlantic, which have been associated with low solar irradiance conditions and negative East Atlantic phases (Moffa-Sánchez et al., 2014).

**Orbital Forcing Mechanisms**

The ensemble mean of the idealized climate model experiment also showed an increase in summer upwelling activity during the HCO over the INAM in comparison with the preindustrial period (Fig. 4A), forced by orbital parameters. Higher Northern Hemisphere summer insolation increased the surface radiative budget over terrestrial areas, resulting in a stronger east-west sea-level pressure (SLP) gradient over the eastern North Atlantic (Figs. 4B and 4C). This asymmetric heating of the continent versus the ocean is related to the different heat storage capacities of both surface layers and is responsible for the asymmetric SLP anomaly and northerly winds. Interestingly, this stronger SLP gradient due to asymmetric heating of the continent versus ocean is also observed presently as a result of the greenhouse gas effect (Wang et al., 2015).

High Northern Hemisphere summer insolation also led to intensified thermal lows, a northerly position of the Intertropical Convergence Zone, and warm Atlantic Multidecadal Oscillation (AMO) and positive NAO phases (Wanner and Brönnimann, 2012). Accordingly, models show high SSTs within the North Atlantic region (Fig. 4D), supported by previous proxy-based reconstructions (e.g., Cléroux et al., 2012; Jiang et al., 2015). At present, warm North Atlantic SSTs are associated with more frequent summer blocking conditions in the northern North Atlantic (Häkkinen et al., 2011) and a pattern of summer lengthening at a multidecadal scale (Peña-Ortiz et al., 2015). Hence, prolonged summers controlled by higher North Atlantic SSTs result in enhanced northerly winds and longer upwelling periods.

**CONCLUSIONS**

Our results demonstrate the solar impact on the North Atlantic upwelling regime during the HCO at different time scales. At millennial time scales, increased Northern Hemisphere insolation due to orbital forcing mechanisms resulted in long-term positive warm-water anomalies in the North Atlantic (Perner et al., 2018), whereas at decadal-to-centennial time scales, lower solar activity triggered the development of an anomalous high-pressure system over the eastern North Atlantic (Häkkinen et al., 2011; Moffa-Sánchez et al., 2014). Both driving mechanisms resulted in an ocean-atmosphere feedback provoking strong SLP gradients with intensified northerly winds, leading into more intense and longer upwelling conditions at different time scales.

The present work provides evidence for the influence of solar and orbital forcing on the North Atlantic upwelling regime and the associated MoV that affect this upwelling region. Summer negative East Atlantic conditions associated with blocking conditions, modulated by solar activity, are responsible for short-term intensified upwelling conditions. In turn, positive AMO- and NAO-like conditions forced by orbital parameters triggered upwelling variations at longer time scales. The combination of proxy-based and model evidence for the HCO emphasizes the finding that solar and orbital forcing has influenced extratropical ocean-atmosphere dynamics at different time scales, with important effects on regional upwelling in the

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![Figure 4. Ensemble of considered PMIP3 models (Paleoclimate Modelling Intercomparison Project, https://pmip.lsce.ipsl.fr) comparing mid-Holocene to preindustrial control period. (A) Anomalies in upward mass transport of water in 0–150 m layer (shaded) and in surface wind (vectors). (B) Anomalies in surface radiative budget (circles), mean sea-level pressure (SLP; shaded), and surface wind (vectors). (C) Anomalies in 2 m temperature. (D) Anomalies in sea-surface temperatures (SSTs). White stippling denotes areas where high robustness was found for ensemble simulated changes.](http://pubs.geoscienceworld.org/gsa/geology/article-pdf/doi/10.1130/G48112.1/5189764/g48112.pdf)
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REFERENCES CITED
Alday, M., Cearreta, A., Cachão, M., Freitas, M.C., Andrade, C., and Gama, C., 2006, Micropaleoceanographic record of Holocene estuarine and marine stages in the Çorgo do Porto rivulet (Mira River, SW Portugal): Estuarine, Coastal and Shelf Science, v. 66, p. 532–543, https://doi.org/10.1016/j.ecss.2005.10.010.
Bakun, A., Field, D.B., Redondo-Rodriguez, A., and Weeks, S.J., 2010, Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems: Global Change Biology, v. 16, p. 1213–1228, https://doi.org/10.1111/j.1365-2486.2009.02094.x.
Barth, J.A., Menge, B.A., Lubchenco, J., Chan, F., Bakun, A., Field, D.B., Redondo-Rodriguez, A., and Jansen, E., 2010, Millennial-scale variability in Atlantic water advection to the Nordic Seas derived from Holocene coccolith concentration records: Quaternary Science Reviews, v. 29, p. 1276–1287, https://doi.org/10.1016/j.quascirev.2010.02.014.
Gray, L.J., et al., 2010, Solar influences on climate: Reviews of Geophysics, v. 48, RG4001, https://doi.org/10.1029/2009RG000282.
Guerreiro, C., Cachão, M., Pawłowsky-Glahn, V., Oliveira, A., and Rodrigues, A., 2015, Compositional data analysis (CoDA) as a tool to study the (paleo)ecology of coccolithophores from coastal-neritic settings off central Portugal: Sedimentary Geology, v. 319, p. 134–146, https://doi.org/10.1016/j.segeo.2015.01.012.
Häkkinen, S., Rhines, P.B., and Worthen, D.L., 2011, Atmospheric blocking and Atlantic multidecadal ocean variability: Science, v. 334, p. 655–659, https://doi.org/10.1126/science.1205683.
Hernández, A., et al., 2020, Modes of climate variability: Synthesis and review of proxy-based reconstructions through the Holocene: Earth-Science Reviews, v. 209, p. 103286, https://doi.org/10.1016/j.earscirev.2020.103286.
Ineson, S., Scaife, A.A., Knight, J.R., Manners, J., Dunstone, N.J., Gray, L.J., and Haigh, J.D., 2011, Solar forcing of winter climate variability in the Northern Hemisphere: Nature Geoscience, v. 4, p. 753–757, https://doi.org/10.1038/ngeo1282.
Jiang, H., et al., 2015, Solar forcing of Holocene summer sea-surface temperatures in the northern North Atlantic: Geology, v. 43, p. 203–206, https://doi.org/10.1130/G36377.1.
Łukowiak, M., Dumitruiu, S.D., and Ionesi, V., 2016, First fossil record of early Sarmatian didemnid ascidian species (Tunicata) from Moldova: Geobios, v. 49, p. 1–8, https://doi.org/10.1016/j.geobios.2016.01.020.
Meehl, G.A., Arblaster, J.M., Braunstator, G., and van Loon, H., 2008, A coupled air-sea response mechanism for solar forcing in the Pacific region: Journal of Climate, v. 21, p. 2883–2897, https://doi.org/10.1175/2007JCLI1776.1.
Moffa-Sánchez, S., Born, A., Hall, I.R., Thornalley, D.J.R., and Barker, S., 2014, Solar forcing of North Atlantic surface temperature and salinity over the past millennium: Nature Geoscience, v. 7, p. 275–278, https://doi.org/10.1038/ngeo2094.
National Oceanic and Atmospheric Administration, 2020, NOAA OI SST V2 High Resolution Dataset: https://psl.noaa.gov/data/griddata/data.noaa.oisst.v2.highres.html (accessed September 2020).
Peña-Ortiz, C., Barriopedro, D., and Garcia-Herrera, R., 2015, Multidecadal variability of the summer length in Europe: Journal of Climate, v. 28, p. 5375–5388, https://doi.org/10.1175/JCLI-D-14-00429.1.
Perner, K., Moros, M., Jansen, E., Kuijpers, A., Troelstra, S.R., and Prins, M.A.A., 2018, Subarctic Front migration at the Reykjaness Ridge during the mid- to late Holocene: Evidence from planktic foraminifera: Boreas, v. 47, p. 175–188, https://doi.org/10.1111/bor.12263.
Pinto, A.M., Fires, A.C., Sousa, P.M., and Trigo, R.M., 2013, The use of circulation weather types to predict upwelling activity along the western Iberian Peninsula coast: Continental Shelf Research, v. 69, p. 38–51, https://doi.org/10.1016/j.csr.2013.08.019.
Santos, A.M.P., Kazmin, A.S., and Peliz, A., 2005, Decadal changes in the Canary upwelling system as revealed by satellite observations: Their impact on productivity: Journal of Marine Research, v. 63, p. 359–379, https://doi.org/10.1357/0022240053693673.
Silva, A., Palma, S., and Moita, M.T., 2008, Coccolithophores in the upwelling waters of Portugal: Four years of weekly distribution in Lisbon Bay: Continental Shelf Research, v. 28, p. 2001–2013, https://doi.org/10.1016/j.csr.2008.07.009.
Sydeman, W.J., García-Reyes, M., Schoenhofer, D.S., Rykaczewski, R.R., Thompson, S.A., Black, B.A., and Bograd, S.J., 2014, Climate change and wind intensification in coastal upwelling ecosystems: Science, v. 345, p. 77–80, https://doi.org/10.1126/science.1251635.
Tim, N., Zorita, E., Hänicke, B., Yi, X., and Emesz, K.-C., 2016, The importance of external climate forcing for the variability and trends of coastal upwelling in past and future climate: Ocean Science, v. 12, p. 807–823, https://doi.org/10.5194/os-12-807-2016.
Trigo, R.M., Valente, M.A., Trigo, I.F., Miranda, P.M.A., Ramos, A.M., Paredes, D., and García-Herrera, R., 2008, The impact of North Atlantic wind and cyclone trends on European precipitation and significant wave height in the Atlantic: Annals of the New York Academy of Sciences, v. 1146, p. 212–234, https://doi.org/10.1196/annals.1464.014.
Wang, D., Gouhier, T.C., Menge, B.A., and Gagliudy, A.R., 2015, Intensification and spatial homogenization of coastal upwelling under climate change: Nature, v. 518, p. 390–394, https://doi.org/10.1038/nature14235.
Wanner, H., and Brönnimann, S., 2012, Is there a global Holocene climate mode?: PAGES News, v. 20, p. 44–45, https://doi.org/10.22498/pages.20.1.44.
Wu, C.J., Usoskin, I.G., Krivova, N., Kovaltsov, G.A., Baroni, M., Bard, E., and Solanki, S.K., 2018, Solar activity over nine millennia: A consistent multi-proxy reconstruction: Astronomy & Astrophysics, v. 615, p. A93, https://doi.org/10.1051/0004-6361/201731892.
Ziveri, P., Baumann, K.-H., Böckel, B., Bollmann, P., and Jansen, E., 2005, The first fossil record of early Sarmatian didemnid ascidian species (Tunicata) from Moldova: Geobios, v. 49, p. 1–8, https://doi.org/10.1016/j.geobios.2005.01.012.