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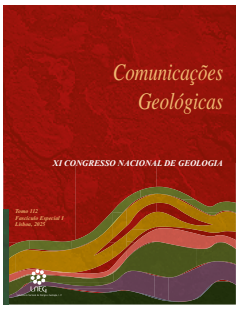
Sea surface temperature variations revealed by planktonic foraminifera at the Portuguese margin during the Holocene

Foraminíferos planctónicos revelam variações na temperatura da superfície do mar da margem portuguesa durante o Holocénico



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Abstract: Global warming, resulting from increasing human emissions of greenhouse gases, is raising ocean temperatures, projecting an increase of 2.6 °C by the end of this century. With the aim of refining climate models and predicting future regional climate conditions more accurately, this study reconstructs sea surface water temperature during the current interglacial period, the Holocene, off the southwest coast of Portugal, through the analysis of associations of planktonic foraminifera. During this period, surface waters in the region south of Sines exhibited higher and more stable temperatures compared to those detected further north, in the Estremadura spur. The northern region, due to its geographical position, more prominently highlights short-duration cold events associated with polar ice melting and marine circulation.

Keywords: Sea Surface Temperature, Paleoceanography, Planktonic Foraminifera, Holocene, Bond Events.

Resumo: O aquecimento global, devido ao aumento das emissões de gases de efeito estufa resultantes das atividades humanas, está elevando as temperaturas dos oceanos, projetando-se um aumento de 2,6 °C até o final deste século. Com o objetivo de aprimorar os modelos climáticos e prever com maior precisão as condições climáticas regionais futuras, este estudo possibilitou a reconstrução da temperatura da água superficial do oceano durante o presente período interglacial, o Holocénico, na costa sudoeste de Portugal, através da análise de associações de foraminíferos planctónicos. Durante esse período, as águas superficiais na região ao sul de Sines apresentaram temperaturas mais elevadas e estáveis em comparação com as reconstruídas mais ao norte, no Esporão da Estremadura. A região mais ao norte, devido à sua posição geográfica, evidencia de maneira mais proeminente os eventos frios de curta duração associados à fusão dos gelos polares e à circulação marinha.

Palavras-chave: Temperatura da superfície do oceano, Paleoceanografia, Foraminíferos Planctónicos, Holocénico, Eventos Bond.

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1. Introduction

Marine heatwaves, *i.e.*, high values of sea surface temperature (SST), have become more frequent, intense, extensive, and longer-lasting over the 20th century. It is projected that the global mean SST will increase up to 2,6°C by the year 2100 (IPCC, 2019). The SST is one of the factors that control the dissolution of atmospheric CO_2 at the ocean surface, as solubility decreases with increasing temperature. Pre-industrial atmospheric CO_2 concentrations oscillated in phase with glacial-interglacial cycles, featuring lower levels during glacial periods and higher concentrations during interglacial periods (Petit *et al*., 1999). However, this natural variability has been significantly disrupted due to the perturbation caused by the rise of anthropogenic CO_2 emissions over the last decades (Lüthi *et al*., 2008). Such a scenario would have dramatic impacts as already observed in the marine realm, in particular carbonate calcifying organisms like planktonic foraminifera (Bijma *et al*., 2013). Planktonic foraminifera are single celled protists that synthesize calcium carbonate shells. Their shells contain valuable information about the chemical and physical conditions of the seawater where these organisms lived, making them a valuable tool to investigate past environmental conditions such as SST (Schiebel *et al*., 2018). The impact on the planktonic foraminifera calcification will affect diversity, abundance, and assemblage composition (Bijma *et al*., 2013). The main goal of this study is to reconstruct the SST during the present interglacial, the Holocene, a warm period partially influenced by anthropogenic activities. The acquisition of high-resolution paleo-data for this period is important to reduce uncertainties within regional climatic models.

2. Study area

The Portuguese margin is part of the Canary Eastern Boundary Upwelling System. This region experiences a high sedimentation rate, making it a key area for paleoceanographic studies (*e.g.* Abrantes, 2000). The regional modern oceanographic circulation is characterized offshore by the cooler southward-flowing Portugal Current (PC), which is a southward branch of the North Atlantic Drift, and the warm Azores Current (AzC) (Peliz *et al*., 2005). Near the coast, during spring and summer, northeasterly winds, and bathymetry lead to seasonal southward flow of the Portugal Coastal Current (PCC) and the occurrence of coastal upwelling. The type of upwelled water depends on the strength of the winds and can consist of either the cold and nutrient-rich Eastern North Atlantic

Central Water of subpolar origin (ENACWsp), transported by the PC or the Eastern North Atlantic Central Water of subtropical origin (ENACWst), transported by the AzC (*e.g.* Fiúza *et al.*, 1998; Peliz *et al.*, 2005). During winter, near to the coast, the Iberian Poleward Current (IPC), a branch of the AzC, flows northward (Fiúza *et al.*, 1998) and replaces the PCC.

3. Material and Methods

We analyzed samples from deep-sea sediment cores with a temporal resolution of ±300 years retrieved from two sites along the SW Portuguese margin, each characterized by different oceanographic conditions: MD03-2699 (39°02.20′N, 10°39.63′W, 1895m water depth) located at the Estremadura spur (northern site), and Shak-03-6K (37º42.45'N, 10º29.542'W, 3735m water depth) situated off Sines (southern site) (Figura 1). Age models of MD03-2699 and Shak-03-6K records were established through stable isotopes ($\delta^{18}O$) analyses and AMS ^{14}C ages (Rodrigues *et al.*, 2010; Skinner *et al.*, 2020). The planktonic foraminifera fauna was identified in the >150 µm sediment fraction, using the identification criteria of Salgueiro *et al.* (2010), and were grouped into three ecological categories according to Kucera (2007): tropical and subtropical species, transitional species, and polar and subpolar species. Summer SST were reconstructed using the planktonic foraminifera fauna, the non-distance weighted option of the SIMMAX transfer function (Pflaumann *et al.*, 1996) and the updated modern analog database of Salgueiro *et al.* (2010, 2014). The obtained SST display high similarity ranging from 0.80 to 0.98 for both cores. To identify sudden shifts in SST during cold events, we also show the relative abundances of the polar foraminifera species *Neogloboquadrina pachyderma*, and the coldest subpolar foraminifera species *Turborotalia quinqueloba*.

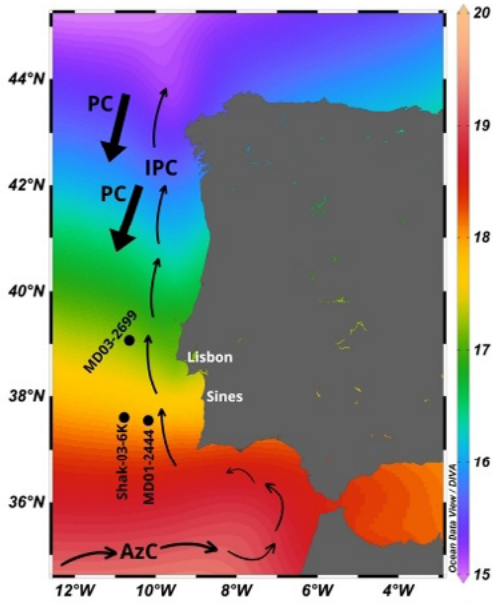

Figure 1. Location of the sediment records used in this study: MD03-2699, Shak-03-6K, and MD01-2444. Black arrows represent the surface circulation: PC (Portugal Current); IPC (Iberian Poleward Current); AzC (Azores Current). The background gradient color represents annual mean Sea Surface Temperature (°C), data from the World Ocean Atlas (2013).

Figura 1. Localização dos registos sedimentares utilizados neste estudo: MD03-2699, Shak-03-6K e MD01-2444. As setas pretas representam a circulação superficial: PC (Corrente de Portugal); IPC (Corrente Polar Ibérica); AzC (Corrente dos Açores). As cores do fundo representam a temperatura média anual da superfície do mar (°C), dados retirados do World Ocean Atlas (2013).

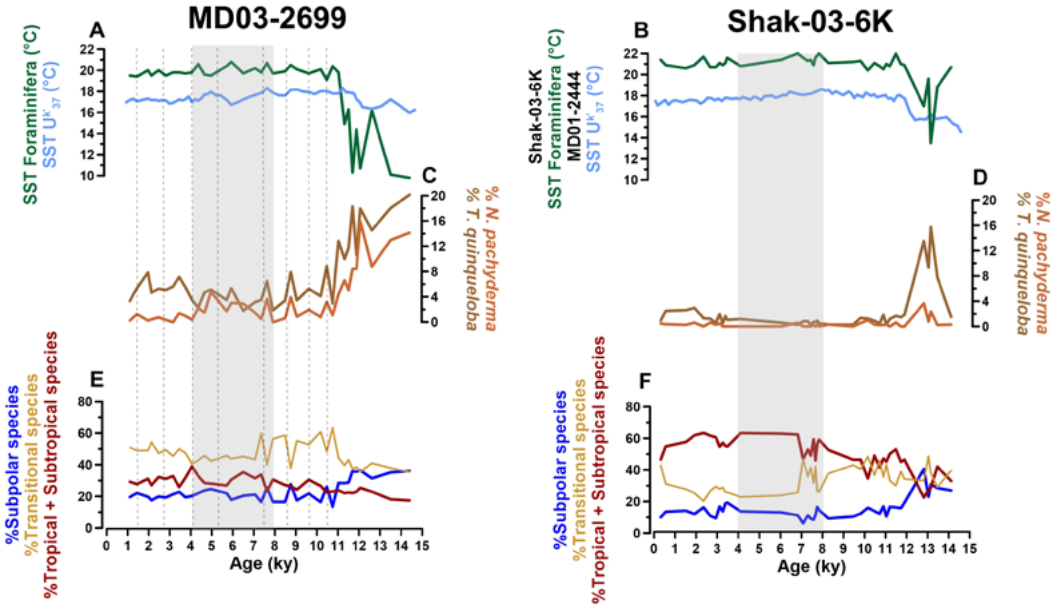

Figure 2. A: Sea surface temperature reconstruction at Site MD03-2699 using planktonic foraminifera and alkenones ($U^{k'}_{37}$) (Rodrigues *et al.*, 2010). B: Sea surface temperature reconstruction at Site Shak-03-6K using planktonic foraminifera and at Site MD01-2444 using alkenones ($U^{k'}_{37}$) (Martrat *et al.*, 2007). C and D: Abundance of subpolar species *Turborotalia quinqueloba* and polar species *Neogloboquadrina pachyderma* at both sites. E and F: Abundance (%) of subpolar species, transitional species, and the sum of tropical and subtropical species at both sites. Gray bars indicate the warmest period of the Holocene, while dotted lines mark cold events.

Figura 2. A: Reconstrução da temperatura da superfície do mar no local MD03-2699 utilizando foraminíferos planctónicos e alquenonas (Uk'_{37}) (Rodrigues et al., 2010). B: Reconstrução da temperatura da superfície do mar no local Shak-03-6K utilizando foraminíferos planctónicos e no local MD01-2444 utilizando alquenonas (Uk'_{37}) (Martrat et al., 2007). C e D: Abundância das espécies subpolar Turborotalia quinqueloba e polar Neogloboquadrina pachyderma nas duas áreas de estudo. E e F: Abundância (%) das espécies subpolares, espécies transicionais e soma das espécies tropicais e subtropicais nas duas áreas de estudo. A barra cinza indica o período mais quente do Holocénico, enquanto as linhas pontilhadas marcam os eventos frios.

4. Results

Twenty-four species were identified in 78 sediment samples from both cores across the entire Holocene. The transitional species compose the most abundant group, with a mean value of 47.6% during the Holocene at the northern site and 33% at the southern site. Followed by the tropical and subtropical species with mean values of 28.4% in the north and a higher value of 53.8% at the southern site. Meanwhile, the polar and subpolar group represented 23.9% at the northern and 13.2% at the southern site throughout the Holocene (Figura 2). The Estremadura Spur and Sines sites record an average summer SST of 19.1 °C and 21.2 °C, respectively. The SST at the northern site experienced intermittent disruption of the summer SST by short cold events when the abundance of the cold planktonic foraminifera species was higher relatively to the warm species (Figura 2).

5. Discussion

The Holocene begins with an increase in SST by approximately 8ºC during the last glacial-interglacial transition, coinciding with an abrupt decrease in the relative abundance of *N. pachyderma* and *T. quinqueloba*, at both sites. The alkenone derived SST reconstructions in the same northern core (Rodrigues *et al*., 2010) and nearby southern core (MD01-2444, 37°34 N, 10°09 W; Martrat *et al*., 2007) record smaller temperature increases during this transition than that estimated by the planktonic foraminifera transfer function. However, both methods show a colder northern site relatively to the southern site during the Holocene.

The warmest SST were registered during the warmer and stable phase of the Holocene between 8 and 4 kyr. At the northern site, during this period the average SST reached 20ºC (foraminifera) and 17.5ºC (alkenoneswhereas for the southern site, average SST reached 21.4ºC (foraminifera) and 18ºC (alkenones). The abundance of tropical and subtropical planktonic foraminifera species was relatively stable in this interval in both sites, with 30% at the northern site and 60% at the southern site. Palumbo *et al*. (2013), at the same time also registered an increase in the warm species of coccolithophores in the northern core.

While the southern site maintained relatively stable SST throughout the Holocene, experiencing small variations, the northern site exhibited a series of short cold events when temperatures were below average by approximately 0.4 to 1.3ºC. These events coincide with an increase in the abundance of cold planktonic foraminifera species and may be related with some of the quasi-periodic cooling events known as Bond (B) events (Bond *et al*., 2001).

The first cold event observed at both sites occurred at 10.3kyr (B7), with SST decreasing by only 1 ºC. Subsequently, at 9.6 kyr (B6) we observed a 0.4 ºC drop in SST. In contrast, the southern site exhibited stable SST at 21ºC during this period. These cold events coincided with an increase in the abundance of polar species *N. pachyderma* and subpolar species *T. quinqueloba*.

The subsequent cold event, at 8.5 kyr corresponding to B5, led to SST of 19.9ºC at the northern site, while at the southern site, SST dropped by only 0.5 ºC. This event, extensively documented in the North Atlantic (Rush *et al*., 2023), has been associated with the discharge of meltwater from the Laurentide Ice Sheet (Thomas *et al*., 2007).

A brief SST drop of 0.9ºC at the southern site around 7.4 kyr was also recorded at the nearby site Shak-06-5K. Cutmore *et al*. (2022) identified a rapid and significant decline in thermophilous woodland pollen possibly related to the decline of solar activity at that time.

During the 5.2 kyr event, in the mid-Holocene transition, SST at the northern site reached 19.5ºC. This event was globally reported and associated with changes in ocean circulation and solar activity (Magny *et al*., 2006).

The more recent cold events, at 4.2 kyr (B3), 2.8 kyr (B2), and 1.4 kyr (B1), are also evident in the SST reconstruction of both sites, but resulted in only minor cooling, with SST decreasing by no more than 1ºC.

When comparing SST reconstruction and planktonic foraminifera fauna of this study with the coccolithophores results from Palumbo *et al*. (2013) for the northern site, the co-occurrence of those cold Bond events becomes clear. During these events, peaks of the subpolar subspecies *Coccolithus pelagicus pelagicus* correspond with peaks of the cold species *T. quinqueloba* and *N. pachyderma*.

6. Conclusion

This study provides a detailed perspective on the SST variations along the offshore Portuguese margin during the Holocene, shedding light on the region's response to significant global climatic events. In general, the Estremadura spur site, in the north, records colder and more variable SST relatively to the southern site offshore Sines, reflecting the cold (sub)surface oceanographic conditions mirrored by the increase in the relative abundance of polar and subpolar planktonic foraminifera species. The cold events recorded at both sites, mainly in the MD03-2699 site, may be synchronous with the Bond events and other previously documented cold events in the North Atlantic. These findings emphasize the complex interconnections between various climatic factors and oceanic processes, in the North Atlantic region.

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