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Abstract – The Canary Islands, east of the North Atlantic Ocean (27°N-29°N), are under the influence of the Canary Current, the descending branch of the North Atlantic Gyre, which is modulated by coastal upwelling off North-West Africa. They constitute strategic sites for palaeoclimatic reconstructions, especially for the Last Interglacial (LIG, 129 to 116 ky BP) estimated to be warmer than present. Seventy-four carbon and oxygen isotope bulk analyses and time series measurements were performed on 32 aragonitic mollusc shells from the LIG marine deposits on Lanzarote and Fuerteventura islands during a period of sea-level highstand that we estimated to occur between $\approx$125 and 119-116 ky BP. Our SST calculations, inferred from shell $\delta^{18}O$ values using available isotopic fractionation equations, provide a seasonal SST amplitude ranging from 3.5°C to 6.0°C, in agreement with the modern seasonal amplitude, along with a mean SST comprised between 20.4$\pm$1.3°C and 22.2$\pm$1.2°C. With respect to the pre-industrial times, we deduce a positive SST anomaly in the range of +1.0$\pm$1.4°C to +2.8$\pm$1.3°C, consistent with the presence of the species *Persististrombus latus*, typical of warm SSTs. Although this finding does not match with the zonal negative anomaly of a reconstructed SST at low latitudes of the North Atlantic, it is nevertheless corroborated by other climate reconstructions in the northeastern tropical Atlantic region. We attribute this trend to an excess of summer insolation during the LIG which warmed the Canary Current, enhanced by a weakening of the North African upwelling. The entire North Atlantic Gyre was probably warmer during the LIG.

Abbreviations used:

LIG : Last Interglacial period; GMST : Global Mean Surface Temperature; SST : Sea Surface Temperature; SL : Sea-level.

1. Introduction

Since pre-industrial times (middle of the 19th century) the global mean surface temperature (GMST) has increased by about 1°C due to the emission of anthropogenic greenhouse gases (IPCC, 2013). As these emissions will continue during the 21th century, global warming of between +2°C and +5°C is projected by the end of the century (IPCC, 2013). In such scenarios of large climate change, simulations of global warming must be performed with the highest precision possible. The confidence in the future climate simulations by models is tested through the ability of the same models to simulate past climates correctly, particularly climates warmer than the present. This calls for the most precise description of such past warm periods. Even though the cause of past warming differs from that of the present (i.e., not due to the greenhouse effect), it is of paramount importance that the state of the world in a warmer climate be accurately simulated.

Such findings are obtained from reconstitutions of regional and local climates, in which the temperature remains one of the key parameters. In the reconstitutions three criteria should be kept in mind : (1) a warmer than present context, (2) a geographical region, which, as far as possible, is consistent with the globally relevant climate mechanisms, and (3) a chronological framework that possesses sufficiently high precision for the data from the proxies used by the models.

The present study focuses on the sea surface temperature reconstruction during the Last Interglacial (LIG) in the Canary Islands (northeast tropical Atlantic) (Figure 1) from marine sediment deposits (Figure 2). It satisfies the above criteria in the following way :

(1) During the Quaternary glacial/interglacial oscillations, it is known that two interglacials were warmer than the present interglacial : the Marine Isotope Stage MIS11c, from ≈245 to ≈235 thousand years before present (ka BP), and the Last Interglacial (LIG) which covers approximately the time interval between ≈129 and ≈116 ka BP (Masson Delmotte et al.,

2013; Capron et al., 2017a). The LIG, i.e. the most recent, gives rise to a more detailed reconstitution. Moreover, of the last five Quaternary climate cycles, it appears to be the warmest interglacial (Jouzel et al., 2007; Past Interglacials Working Group of PAGES, 2016) by about +2°C with respect to the present interglacial.

(2) Temperature reconstructions during the LIG have recently been the subject of intense interest. Whereas many publications focus on the polar and mid latitude regions, temperature data from the tropics, particularly seawater surface temperature (SST) data, are much scarcer. The Canary Islands, located in the tropical northeast Atlantic along the west African coast, are exposed mainly to the southward marine Canary Current, the descending branch of the North Atlantic Gyre, and are also influenced by the cold coastal upwelling current off North-West Africa (Arístegui et al., 2009). The northeast tropical Atlantic region is particularly important from the point of view of ocean circulation because the North Atlantic Gyre, an essential component of the global circulation, participates directly in the climate equilibrium of the planet. At present, few LIG data exist for this region and those that do exist appear to be contradictory, some suggesting warming and others cooling. Reconstruction of the SST in this region is therefore of major importance.

(3) Over the last decades, the geology, sedimentology and chronology of the Canary Islands have been thoroughly investigated, as well as the composition of faunal taxa found in the marine fossil deposits and in paleosols (Meco and Stearns, 1981 ; Meco et al., 2002 ; Zazo et al., 2002 ; Meco et al., 2006 ; Meco et al., 2011 ; Muhs et al., 2014 ; Montesinos et al., 2014 ; Meco et al., 2018). This rich source of information is relevant to establishing the chronology of the deposits under study.

In this investigation, we used the oxygen and carbon isotope compositions of carbonate shells dating of the LIG in order to estimate not only the SST, but also the magnitude of seasonal temperature variations and the seasonal activity of the coastal upwelling. This method has not been applied in the region yet. In order to obtain qualitative indications of local warming/cooling of the SST, we also reconstituted the living environment of the faunal fossil record. These new data complement other SST results from the tropical northeast tropical Atlantic and afford a deeper understanding of regional ocean currents: the upwelling off the western African coast and the Canary Current.

2. Background

2.1. Geological setting

The Canary Islands comprise seven main volcanic islands and several islets. They are located in the Eastern Atlantic Ocean between 27°N and 30°N, forming a chain that extends about 450 km in latitude, with the easternmost point just over 100 km off the north-western African coast (Figure 1a). The islands have a complex geological history, with volcanic formations over 20 million years old (Carracedo et al., 2002), but they also include extensive sedimentary deposits (Meco and Stearns, 1981). As part of this study, two specific sites with sedimentary deposits were sampled in the easternmost Canary Islands, namely Fuerteventura and Lanzarote. While the eastern Canary Islands experienced some uplift during the last million years, discontinuous vertical movements with a reverse trend over the last hundreds of thousands of years have been observed (Zazo et al., 2002).

In the Canary Islands, the sedimentary deposits are related to the glacial–interglacial cycles and are characterized by a succession of four distinct climatic phases (Meco et al., 2011): (i) calcareous dune deposits, corresponding to a cold and arid glacial climate, (ii) paleosols, corresponding to a climate that became progressively warm and wet at the beginning of the interglacial period, (iii) marine sediments deposited during the sea-level highstand of the interglacial period, and (iv) pedogenic calcretes, marking the return to the next glaciation. These different phases were identified in the Eastern Canary Islands for the MIS11.3 interglacial period as well as for the MIS10–MIS9.3, MIS6–MIS5.5 (LIG) (Figure 2a), MIS2–MIS1 (Holocene) glacial–interglacial oscillations. In the Canary Islands, the warm and wet climate of phase (ii) that generated paleosol deposits is considered to be contemporaneous with the wet phase in West Africa ("African Humid Period"). The latter, evaluated through many proxies in different areas of North Africa, stems from the maximum summer insolation in the tropics (Rossignol-Strick, 1985; deMenocal et al., 2000).

LIG marine deposits are found in the Eastern Canary Islands. In Lanzarote, these deposits have outcrops mainly at the localities of La Santa, Matagorda and Punta Penedo (Meco et al., 2006; Muhs et al., 2014), whereas in Fuerteventura they occur at the localities of Matas Blancas, Las Playitas and La Guirra (Meco et al., 2002; Zazo et al., 2002; Meco et al., 2006; Montesinos et al., 2014; Meco et al., 2018) (Figure 1b). LIG marine deposits also occur in the central island of the archipelago in Las Palmas, Gran Canaria (Meco et al., 2002). In the present work two LIG marine deposits were studied: La Santa (Lanzarote) and Matas Blancas (Fuerteventura). The La Santa site (29°06’48,43’’N, 13°38’57,50’’W), which is located along the northwest coast of Lanzarote, is composed of fossiliferous marine sands overlying Middle Pleistocene basaltic lava flows at ~8 m above the present mean sea-level (Muhs et al., 2014). This sandy deposit developed in a foreshore environment. The same layer crops out at the Punta Penedo site, a few kilometers northeast of La Santa and shows the most complete section in the area (Figure 2a). The Matas Blancas site (28°10'26,60"N, 14°11'46,91"W) is located along the eastern coast of the Jandia Isthmus, in Southern Fuerteventura. The marine sedimentary deposit consists of an extensive fossiliferous marine conglomerate at -2 m to +3 m above the present medium sea-level, identified as a marine terrace (Meco et al., 2002). It is composed of coarse basaltic fragments and fossils with a calcareous sandy matrix and includes abundant specimens of *Persististrombus latus* (also named *Strombus bubonius*) (Figure 2b). It originally developed in a high energetic foreshore environment, forming part of a gravel berm or a beach of pebbles and sand. The deposit appears naturally cemented and can be considered as a beachrock.

2.2. Modern oceanic features

The eastern part of the North Atlantic Gyre is driven by the eastward Azores Current which partly feeds the Canary Current, a southward-flowing current along the Northwest African coast (Figures 3a and 1a). As it passes the Canary Islands archipelago, the current splits in two, with branches to the east and west of Lanzarote. The surface current is associated with a strong coastal upwelling regime along the north-west African coast, caused by the northeast trade winds (Figure 3b). Strengthening of the alongshore wind enhances upwelling and results in lower SST over the shelf (Figure 3b). In the latitude range 22°N to 30°N, where the Canary Islands are located, the coastal upwelling is permanent all year round, with the strongest activity occurring in summer and early fall (Pardo et al., 2011; Navarro-Pérez and Barton, 2001; Mittelstaedt, 1991).

The recent mean annual temperature of the eastern Canary Islands coastal waters has been estimated by different methods (Table 1). In the framework of this study we retain the combined satellite data and *in situ* SST datasets from the eastern Canary Islands, which give a sea surface temperature (SST) of 20.4°C from 2007 to 2017 (Meco et al., 2018). This finding is consistent with the other satellite measurements.

3. Materials

3.1. Sample collection

Thirty-two fossil marine mollusc shells belonging to 6 different species were collected in the eastern Canary Islands. The largest number of fossils was collected at La Santa site (Lanzarote) with 28 fossil mollusc shells belonging to 5 different species, whereas 4 fossil mollusc shells belonging to two different species were collected at Matas Blancas site (Fuerteventura). The fossils are either gastropods (*Cerithium vulgatum* Bruguière, 1792; *Stramonita haemastoma* Linnaeus, 1767; *Luria lurida* Linnaeus, 1758; *Persististrombus latus*, Gmelin 1791, usually refered to as *Strombus bubonius* Lamarck, 1822) or bivalves (*Loripes lacteus* Linnaeus, 1758 – *nomen nudum* ; *Cardium edule* Linnaeus, 1758, also named *Cerastoderma edule* Linnaeus, 1758) (Figure 4). Quite prevalent in the LIG sample deposits, they are representative of the sites, gastropods being more frequent than bivalves. They all lived in nearshore environments and shallow sea beds (Cuerda, 1987; Niclès, 1950; Rolán, 2011; Meco, 1977; Cosel von and Gofas, 2019; Cosel von and Gofas, 2019, respectively).

Among the 6 studied species, one lives in warm waters: *Persististrombus latus* (*Strombus bubonius*). This gastropod is currently found on the western African coasts from Dakar in Senegal to Angola, including the Cape Verde Islands. It belongs to the tropical Guinean/Senegalese faunal province (Muhs et al., 2014). In the Canary Islands, it is present only in the form of fossil species in the marine deposits of previous interglacials (LIG and MIS11) (Meco, 1977; Meco et al., 2002; Meco et al., 2007; Muhs et al., 2014). *Luria lurida* and *Stramonita haemastoma* live in an environment of warm to cooler waters : *Luria lurida* currently lives on the North-western African coasts from Morocco to Angola (Rolan et al., 2011), whereas *Stramonita haemastoma* currently lives on the western African coasts from Morocco to Angola, including the Canary Islands (Rolán, 2011). Finally, *Cardium edule*, *Loripes lacteus and Cerithium vulgatum* live in cooler marine waters. *Cardium edule*

(*Cerastoderma edule*) is present in the north-western Atlantic and in the north-eastern Atlantic, from Iceland and North Europe to Senegal, but rarely in the Canary Islands (Rolán, 2011; Nicklès, 1950). *Loripes lacteus* currently lives in the Eastern Atlantic from England and the North Sea to Senegal (Rolán, 2011; Nicklès, 1950). *Cerithium vulgatum* currently lives in the Atlantic from Portugal and Morocco to the Canary archipelago (Rolán, 2011). All the species except *Persististrombus latus* (*Strombus bubonius*), which at present lives far south of the Canary Islands, are now present at the latitude of the Canary archipelago in the eastern Atlantic (Figure 5).

The shells were directly sampled from the sedimentary marine beds at the sites where they outcrop, then labelled and put into plastic bags.

3.2. Age of the sampled deposits

The age of the marine deposits containing the mollusc shells has been estimated by three different approaches : the various LIG fossil datings in the eastern Canary archipelago, the sea-level history during interglacials, and the sedimentary successions during glacial-interglacial cycles in the Canary Islands.

U-series dating of two fragments of coral *Siderastraea radians*, Pallas 1766 coming from San Cristobal, Gran Canaria, and La Santa marine deposits, and which are ascribed to the LIG sea-level highstand, yields the ages 120.5±0.8 ka and 130.2±0.8 ka, respectively (Muhs et al., 2014). Five marine terraces cropping out in Lanzarote, which are considered to be contemporaneous with those of La Santa on the basis of stratigraphic arguments, provided U-series ages from the aragonitic shells of the gastropod *Patella* of 121±17 ka BP (n = 11) (Zazo et al., 2002). At the Matas Blancas site, the gastropods *Persististrombus latus* (*Strombus bubonius*) has yielded numerous radiometric ages based on the U/Th method, namely 106±7 and 112±7 ka BP according to Meco et al. (1992); 104±2 and 178±4 ka BP (Zazo et al., 2002); 115, 125 and 135 ka BP (Bard, personal communication in Meco et al., 2002). Dating of several mollusc shells from six other contemporaneous sites in Fuerteventura give mean U/Th ages of 118±11 ka BP (n = 22) (Zazo et al., 2002). Taken altogether, these results indicate that the La Santa and Matas Blancas marine deposits can be attributed to the LIG. Finally, the numerous U/Th datings at LIG sites in Lanzarote and Fuerteventura from Zazo et al. (2002) exhibit a first order normal distribution, thereby confirming the validity of the mean ages, despite the large standard deviation. According to these data, the marine sediments, aged 121±17 ka BP on Lanzarote and 118±11 ka BP on Fuerteventura, were probably deposited during the second part of the LIG.

As the shells analyzed in the present study were sampled from a marine deposit, the average age of the analyzed molluscan assemblage therefore corresponds to the average age of the deposit. Sedimentation took place during a steady period of sea-level highstand when sedimentary particles and shells could accumulate over a period of time long enough to generate substantial sedimentary formation, i.e., at least a few thousand years. To understand the general context in which our samples were deposited, we first present here the different reconstructions of sea-level evolution during the LIG. In order to reconstruct past sea-levels, many studies have relied on the oxygen isotope compositions of foraminifera tests trapped in marine sediments (Shackleton et al., 1987; McManus et al., 1999; Shackleton et al., 2000; Waelbroeck et al, 2002; Lisiecki and Raymo, 2005; Rohling et al., 2009; Sosdian and Rosenthal, 2009; Elderfield et al., 2012; Rohling et al., 2014; Shakun et al., 2015). In successive reviews the issue of sea-level and its relative variations during the LIG has received much attention in the scientific community. Different chronologies, deduced from proxy reconstructions and synthesis compilations, of the sea-level highstand during the LIG were compiled in Table 2. It should be noted that the diversity of chronological methods used to quantify paleo-sea-levels has sometimes led to substantial differences in the acquisition and appreciation of ages, a fact that may contribute to uncertainty in the chronology of sea-level changes. Dutton et al. (2015a) specified that sea-level during the LIG varied from +6 m to +9 m, with a peak occurring after 125 ka BP, probably between 122 and 119 ka BP. Capron et al. (2017a,b), on the basis of the work made by Dutton et al. (2015a), emphasized that most studies consider a two-phase sea-level change during the LIG, including a late event that peaked between 122 and 119 ka BP. We conclude from all these works that during the LIG the global sea-level rose by between +6 m and +9 m, with a maximum rise that very likely took place in the second part of the LIG, after ≈125 ka BP, and extended for a few thousand years until 119-116 ka BP. Secondly, the age estimation of the onset of sea-level highstand during the LIG is corroborated by the history of sea-level and that of global surface temperature during the last deglaciation and the Holocene. The timing of the changes in the global mean surface temperature can be documented by that of the evolution of the Antarctic temperature (see § 6.2.2) (Figure 6b,c). During the Holocene, the mean surface temperature has remained maximum and relatively steady since ≈12 ka BP (Marcott et al., 2013) (Figure 6b). From ≈18 ka to ≈7 ka BP, the sea-level has risen by more than 120 metres (Waelbroeck et al., 2002; Lambeck et al., 2014) (Figure 6d). Dutton et al. (2015a) note that at the beginning of the Holocene the global mean sea-level was still ≈60 m lower than today. The sea-level highstand has been steady only since ≈7 ka BP. The delay of about 5 ka between the establishment of the maximum of the mean temperature and the establishment of the maximum mean sea-level stemmed mainly from the melting dynamics of ice sheets from the northern hemisphere and Antarctica. It follows that a time lag of a few thousand years between the beginning of the LIG and the beginning of the global mean sea-level highstand during the LIG is consistent with the history of the Holocene global mean sea-level. Since during the LIG the mean surface temperature reached its maximum at ≈130 ka BP (Figure

6c), which marks the beginning of the interglacial stage, we infer that sea-level highstand began at ≈125 ka BP (Figure 6e). Therefore, based on the history of the last deglaciation and that of the Holocene it is very likely that the LIG marine deposits took place during the long time period of the sea-level highstand starting from ≈125 ka BP to 119-116 ky BP.

Finally, the chronology of the sea-level highstand during the LIG and the resulting estimate of the age of our samples is corroborated by the stratigraphic analysis performed by Meco et al. (2011) in the Canary Islands (see §2.1). The beginning of interglacials is characterized by a humid phase ("African Humid Period") with the development of a soil (labelled (ii)); as sea-levels rise, the soil is covered by seawater and marine sediments begin to form (labelled (iii)). During MIS1 or the Holocene, the two phases (ii) and (iii) are clearly identified: (ii) paleosols were mainly established between ≈10 ka and ≈8 ka BP, (iii) marine deposits between ≈5 ka and ≈1 ka BP, as dated from different samplings (Meco et al., 2011) (Figure 6a). The genesis of paleosols thus preceded that of marine sediments by a few thousand years. Such observations are consistent with the timing of the sapropel deposits in the Mediterranean (Rossignol-Strick, 1985) known to be correlated with the maximum intensity of the African wet phase between ≈10 ka and ≈8 ka BP (deMenocal et al., 2000; Lézine et al., 2011). As the sea-level has remained steady since ≈ 7 ka BP (Lambeck et al., 2014), the marine deposits are contemporaneous with the sea-level highstand. During the LIG, these two phases are well documented, the paleosol formation (ii) preceding the marine deposit (iii) (Figure 2a). Therefore, as pointed out by Meco et al. (2011), the stratigraphy of the paleosols and marine deposits indicate that the paleosol formation occurred during the first part of the LIG, and was followed by the sea-level highstand few thousand years after the beginning of the LIG, in the second part of the interglacial. It was during this sea-level highstand that the marine deposits were set down.

Finally, the three different approaches (deposit dating, the sea-level highstand history, and succession of paleosols and marine deposits) led to the same conclusion : the marine deposits from La Santa, Lanzarote, and Matas Blancas, Fuerteventura, date from the second part of the LIG, i.e. from ≈125 ka to ≈119-116 ka BP, at a time of sea-level highstand.

4. Methods

4.1. Analytical techniques

4.1.1. Raman spectroscopy and mineralogy of the sample shells

We used Raman spectroscopy in order to characterize the mineralogy of all the studied skeletal carbonates. The Raman Spectrometer X'plora, hosted by the Laboratoire de Géologie de Lyon at the University Claude Bernard Lyon 1, has been operated by using an objective x 1000, an optical network of 1800 lines per mm, a monochromatic laser (wavelength of 532 nm) filtered by 10% with ten acquisitions (15 s per acquisition) performed between 100 and 1600 cm^{-1}.

Aragonite was systematically identified from the low frequency part of the Raman spectra (Figure 7), and especially from the position and splitting of the symmetric bending mode which occurs as a doublet at 701-704 cm^{-1} according to Unvros et al. (1991) and Gillet et al. (1993). These analyses attest that the fossils shells studied consist of aragonite. It is known that the calcite to aragonite transition takes place at high pressure/high temperature (Gillet et al., 1987). As the mollusc shells precipitate at low pressure/low temperature, any polymorphism transformation from calcite to aragonite is *a priori* prevented during the shell growth. Thus the biogenic carbonates are considered to be originally aragonitic and the fossils pristine. This is confirmed by Raman spectroscopy on the modern bivalve *Cerastoderma edule* (or *Cardium edule*) species which forms an entirely aragonitic shell (Füllenbach et al., 2015). Also, Cornu et a. (1993) acknowledged that the inorganic part of the modern gastropod *Persististrombus latus* (*Strombus bubonius*) is composed exclusively of aragonite. Those two species are studied in the present work. Therefore, the results obtained by Raman spectroscopy, which indicate that the shell carbonate of the fossil specimens is aragonitic, are considered to be a reliable indicator of isotopic signal (O and C) preservation.

4.1.2. Oxygen and carbon isotope analysis of aragonite mollusc shells

Stable carbon and oxygen isotope compositions were measured on a total of 32 mollusc shells of 6 species. Selected samples were cleaned with double-deionized water, then placed in an ultrasonic bath to remove any trace of sediment, and finally dried in a dry-oven. Two types of sampling were performed : (1) bulk sampling, which delivers an average signal over the entire life of the specimen, and (2) incremental sampling, which delivers discrete signals during the ontogenic evolution of the specimen, i.e., sampling of different periods of the shell growth (younger to older periods). (1) For bulk shells, the entire sample was crushed with a hammer in a steel mortar to obtain a coarse powder, which we reduced to a fine powder (50 to 100 μm particle size) with a pestle and agate mortar. The aliquot size was about 300 μg of $CaCO_3$. Each shell represents one bulk sample. 30 shells from La Santa and Matas Blancas sites were selected for the bulk sampling, including 4 gastropods and 2 bivalves species. (2) For incremental sampling of the shells, first, as the surface of the outer shell layer is most often easily altered, the outermost part of the shell was gently removed using a diamond micro-drill (Dremel™). Second, after cleaning the shell with double-deionized water, the layer underneath the outermost surface of the shell was drilled at regular intervals along the growth direction. Two shells from La Santa (Lanzarote) and Matas Blancas (Fuerteventura) sites were selected for the incremental sampling: one bivalve specimen and one gastropod specimen, respectively. For the bivalve *Cardium edule* (*Cerastoderma edule*), 16 incremental samplings were performed along its main growth axis, one sampling every ≈3 mm (Figure S1a,b in the Supplementary materials). As the average growth rate of the *Cardium edule* shells ranges from ≈1.8 $mm.month^{-1}$ to ≈0.8 $mm.month^{-1}$ (Richardson et al., 1980; Eisma et al., 1965), and as the growth rates decrease with increasing age (Bourget and Brock, 1990), we estimated that we performed one sampling every ≈2 to ≈4 months. For the gastropod *Stramonita haemastoma*, 29 incremental samplings were carried out, one sampling every ≈5 mm, the sampling scheme precisely following the growth spiral of the shell according to the protocol of Cornu et al. (1993) (Figure S1c,d).

Stable isotope ratios were determined by using an auto sampler MultiPrep™ system coupled to a dual–inlet GV Isoprime™ isotope ratio mass spectrometer (IRMS). For bulk shells, aliquot size was about 300 μg of calcium carbonate while they were about 10–15 μg in the case of an incremental sampling strategy. All aliquots were reacted with anhydrous oversaturated phosphoric acid at 90°C during 20 minutes. By default, oxygen isotope ratios of calcium carbonate are computed assuming an acid fractionation factor $1000\ln\alpha(CO_2–CaCO_3)$ of 8.1 between carbon dioxide and calcite according to Swart et al. (1991) experimental data. However, acid fractionation factors differ between aragonite and calcite as shown by Kim and O'Neil (1997) and Kim et al. (2007a). At a temperature of 90°C, the mean difference in acid fractionation factors between calcite and aragonite is -0.41‰ (Kim et al., 2007a). Consequently, such offset value was applied to all mollusc oxygen isotope measurements as all the samples are made of aragonite. In addition, all sample measurements were duplicated and adjusted to the international reference NIST NBS19 ($\delta^{18}O_{V\text{-}PDB}$ = -2.20‰; $\delta^{13}C_{V\text{-}PDB}$ = +1.95‰) and NIST NBS18 ($\delta^{18}O_{V\text{-}PDB}$ = -23.2‰; $\delta^{13}C_{V\text{-}PDB}$ = -5.01‰). External reproducibility (2σ) is lower than ±0.10‰ for $\delta^{18}O$ and ±0.05‰ for $\delta^{13}C$. $\delta^{18}O$ and $\delta^{13}C$ of aragonite mollusc shells are expressed with respect to V-PDB.

4.2. Isotope fractionation equations for the aragonite-water system

The Raman spectra analyses indicate that the shell carbonate of the fossil specimens is aragonitic. As modern biogenic aragonites are precipitated close to oxygen isotope equilibrium with ambient water (Kim et al., 2007b), it is reasonable to assume that this condition was also met for past biogenic aragonites. Indeed, Grossman and Ku (1986) and Kim et al. (2007b) demonstrated that oxygen isotope fractionation between water and aragonite can be described by a well-constrained relationship with temperature, which is a necessary and sufficient condition for reconstructing marine paleotemperatures from aragonite fossils.

The sea surface temperatures were calculated using two oxygen isotope fractionation equations for the aragonite-water system. The first of these (Grossman and Ku, 1986) was determined by analyzing modern aragonitic molluscs, foraminifera and ambient water in the temperature range ≈ 3 to 22°C with $\delta^{18}O_{aragonite}$ ($\delta^{18}O_{ar}$) and $\delta^{18}O_{seawater}$ ($\delta^{18}O_{sw}$) relative to V-PDB:

$$T = 20.60 - 4.34(\delta^{18}O_{ar} - \delta^{18}O_{sw}) \quad (1)$$

where T (°C) is the temperature in which the shell grew. The second oxygen isotope fractionation equation (Kim et al., 2007b) was obtained from laboratory experiments with $\delta^{18}O_{ar}$ and $\delta^{18}O_{sw}$ relative to V-SMOW:

$$1000\ln\alpha_{ar-sw}=17.88\left(\frac{10^{3}}{T}\right)-31.14 \qquad (2)$$

T being the temperature in Kelvin, α the oxygen fractionation coefficient between synthetic aragonite and water:

$$\propto_{ar-sw}=\frac{\left(\frac{^{18}O}{^{16}O}\right)_{ar}}{\left(\frac{^{18}O}{^{16}O}\right)_{sw}}=\frac{\left(\delta^{18}O_{ar}+1000\right)}{\left(\delta^{18}O_{sw}+1000\right)} \qquad (3)$$

As we need the $\delta^{18}O$ of the aragonitic shell expressed relative to the V-SMOW (Eq.(2)) we use the following relationship between the V-PDB isotope scale and the V-SMOW scale established at 25°C by Coplen et al. (1983):

$$\delta^{18}O_{(V\text{-}SMOW)} = 1.03091\delta^{18}O_{(V\text{-}PDB)} + 30.91 \qquad (4)$$

The two temperature calibrations for the aragonite-water oxygen isotope fractionation have been tested on 50 modern shells, both gastropods and bivalves, in Crete, Greece, where present-day prevailing mean SSTs are similar to those of the Canary Islands (about 20°C) (Lécuyer et al., 2018). The SST calculated from the $\delta^{18}O$ values of those shells and $\delta^{18}O$ values of ambient seawater in Crete match the SST available from oceanic databases available for the Mediterranean Sea on using either the Kim et al. (2007b) equation or the Grossman and Ku (1986) equation. The best match between the present SST and calculated values was obtained by applying the Kim et al. (2007b) equation. Therefore it seems more appropriate to privilege the use of the Kim et al. (2007b) equation for calculating SST of Lanzarote and Fuerteventura coastal waters during the LIG. However, as Grossman and Ku (1986)'s equation was established from an *in situ* calibration and is predominantly used in the literature for SST reconstructions based on mollusc shells, we also present the results of this equation in order to allow comparisons of the results of this study with other publications.

4.3. $\delta^{18}O$ reconstruction of coastal seawater during the LIG

Reconstitution of marine paleotemperatures based on the $\delta^{18}O$ values of aragonite mollusc shells requires an estimate of the oxygen isotope composition of contemporaneous seawater of the living shells (Equations (1) and (2)). In this study, we therefore estimated the $\delta^{18}O$ of seawater during the LIG sea-level highstand in the coastal environment of sampling sites. Firstly, we considered the present-day coastal marine waters of the Canary Islands. Seawater sampled at 1 m to 5 m depth from Lanzarote and Fuerteventura (Figure 1b) has comparable $\delta^{18}O$ V-SMOW values, 1.09±0.04‰ and 1.08±0.07‰, respectively (Clauzel et al., 2019). Secondly, we calculated the oxygen isotope composition of the LIG global ocean by taking into account the sea-level change relative to present-days. Dutton et al. (2015a) assumed a mean seawater elevation of 7.6 m with respect to the Holocene level that was due to the melting of ice caps with a contribution of +2.0 m from Greenland + 4.6 m from Antarctica, +0.6 m from the glaciers, and +0.4 m from the thermal expansion of the oceans. Goelzer et al. (2016) proposed similar values of +1.4 m for Greenland, +4.4 m for the Antarctica, and +0.4 m for the thermal expansion of the oceans, the contribution of glaciers not being taken into account in this study. The $\delta^{18}O$ of ice in the Greenland Ice Core Project (GRIP) and North Greenland Ice Core Project (NGRIP) ice cores (North Greenland Ice Core Project members, 2004), located on the ice cap plateau, enable us to estimate for the Greenland ice cap an average $\delta^{18}O$ value of about -40.0±2‰. From the data of EPICA Dome C (EDC) and Dome F (Fuji) ice cores (e.g., Landais et al., 2007, and Dome Fuji Ice Core

Project Members, 2017, respectively), located on the ice cap plateau, we evaluate to a first approximation the mean $\delta^{18}O$ of the Antarctic ice sheet at about -57.5±2‰. Consequently, considering a sea-level higher by 7.6 m (Dutton et al., 2015a) during the highstand period of the LIG (±1.5 m), the present-day average ocean depth of 3682±44 m (Charette and Smith, 2010), and neglecting the glacier contribution, a mass balance calculation indicates that the contemporaneous seawater of the molluscs investigated was 0.09±0.02‰ lower than at present. Finally, as we consider that the melting of the ice caps is the main source of $\delta^{18}O$ variation in coastal seawater in the Canary Archipelago between the LIG and now, the $\delta^{18}O$ (V-SMOW) of Lanzarote and Fuerteventura coastal seawaters were likely close to 1.00±0.06‰ during the LIG sea-level highstand. In using Equation (1), a correction of -0.27‰ was applied to convert $\delta^{18}O$ of seawater from the V-SMOW to V-PDB scales according to Bemis et al. (1998) and established by Hut et al. (1987).

4.4. Estimation of the uncertainties

There are different sources of uncertainty associated with the calculation of the SST values. We shall consider first the uncertainties in the two equation variables, $\delta^{18}O_{ar}$ and $\delta^{18}O_{sw}$ (see Equations (1), (2) and (3)). The external reproducibility of $\delta^{18}O_{ar}$ measured from the mollusc shells (±0.10‰) gives an error of ±0.5°C. The error associated with $\delta^{18}O_{sw}$ of coastal seawater in the Canary archipelago during the LIG (≈±0.06‰) is ±0.3°C. Consequently, the uncertainty range in the SST reconstruction is ±0.6°C. This is the uncertainty stated in the results. It is calculated as follows:

$$\square_{total} = \sqrt{(\square_{ar})^2 + (\square_{sw})^2} = \sqrt{(0.5)^2 + (0.3)^2} 0.6 \quad (5)$$

We now consider the uncertainty associated with the linear regression of the empirical data (y = mx+b), which establishes the isotopic fractionation equation for oxygen in the aragonite-water system (Equation (1) and Equation (2)). This uncertainty is not available in the original publications. We used the "lm()" and "pred()" functions of R language (Chambers and Hastie, 1992) and obtained ±0.8°C for the Grossman and Ku (1986) equation (Eq.(1)) and ±0.3°C for the Kim et al. (2007b) equation (Eq.(2)).

5. Results

5.1. Oxygen isotope compositions of the mollusc shells

The bulk sampling method delivers an average signal over the entire life of the specimen. The bulk oxygen isotope data for the two sites of La Santa, Lanzarote (n = 27) and Matas Blancas, Fuerteventura (n = 3) range from -0.14 ‰ to 0.97 ‰ (V-PDB) with a mean value of 0.36±0.27 ‰ (Table S1, in the Supplementary materials).

Incremental sampling yields discrete signals of different periods of the shell growth (younger to older periods). Both the bivalve specimen (*Cardium edule* or *Cerastoderma edule*) from La Santa (n = 1) and the gastropod specimen (*Stramonita haemastoma*) from Matas Blancas (n = 1) show pseudo-cyclic variations of their oxygen isotope compositions recorded during shell growth. The *Cardium edule (Cerastoderma edule)* fossil shell has oxygen isotope ratios ranging from -0.11 ‰ to 2.54 ‰ with a mean value of 1.18±0.72 ‰ while the *Stramonita haemastoma* fossil shell has oxygen isotope ratios ranging from -0.52 ‰ to 0.66 ‰ with a mean value of 0.07±0.36 ‰ (Table S2). A signal drift is observed during the ontogenetic evolution of *Cardium edule (Cerastoderma edule)* with decreasing isotopic compositions from the younger (≈2‰) to the older (≈0.5‰) parts of the shell (Figure 8). The particularly high $\delta^{18}O$ values for the younger part of the record lies outside the range of variation of the other recordings, i.e., the 30 bulk samples and the *Stramonita haemastoma* incremental sample. No such drift is observed during the ontogenetic evolution of *Stramonita haemastoma.*

5.2. Carbon isotope compositions of the mollusc shells

The bulk carbon isotope data for La Santa and Matas Blancas sites (n = 30) range from 1.48 ‰ to 3.40 ‰ (V-PDB) with a mean value of 2.46±0.57 ‰ (Table S1).

For the incrementally-sampled specimens, $\delta^{13}C$ of *Cardium edule (Cerastoderma edule)* range from 0.51 ‰ to 3.02 ‰ with a mean value of 2.04±0.74 ‰ (n = 1), while $\delta^{13}C$ of *Stramonita haemastoma* range from 1.19 ‰ to 3.06 ‰ with a mean value of 1.98±0.50 ‰ (n = 1) (Table S2). For the mollusc *Stramonita haemastoma*, the two-tailed probability P calculated at a 95% level of confidence is 0.976 (n = 28; r = 0.0068) thus rejecting the null hypothesis that states there is a correlation between the $\delta^{13}C$ and $\delta^{18}O$ of shell aragonite while in the case of *Cardium edule (Cerastoderma edule)*, the two-tailed probability P calculated at a 95% level of confidence is 0.0014 (n = 16; r = 0.7275) confirming that both variables are significantly correlated (Figure 9).

5.3. Paleo-temperature reconstructions of coastal seawater

5.3.1. Mean annual SST during the LIG sea-level highstand

Marine molluscs living in tropical environments grow all year round and record variations in temperature or salinity at the daily scale (e.g. Frank, 1969). Lifespan for most marine molluscs, and especially bivalves, is lower than 11 years. The data compiled by Moss et al. (2016) reveal that populations of tropical (less than 30° in latitude) bivalves record a mean Maximum reported LifeSPan (MLSP) of 7.9 years, whereas those living under higher latitudes have a mean MLSP of 24.7 years. Therefore, the bulk sampling of mollusc shells delivers an average isotopic record integrated over the entire growth period of the specimen and whose duration is commonly several years. Finally, temperatures calculated from the $\delta^{18}O$ of bulk shells are considered to represent the mean annual SST. The data are listed in Table S1, in the Supplementary materials.

For La Santa and Matas Blanca sites taken altogether (30 samples), we obtain an average SST of 22.2±1.2°C according to the Grossman and Ku (1986) equation (Eq. (1)) and 20.4±1.3°C according to the Kim et al. (2007b) equation (Eq.(2)) (Figure 10). The standard deviation is ≤ ±1.3°C and the SST follow a normal distribution according to the use of normal probability plots with regression coefficients of 0.985. This indicates the sampling of a homogenous assemblage of molluscs, representative of their living environment during the sampling interval, which corresponds to the duration of the LIG sea-level highstand. In summary, values of 22.2±1.2°C (Eq. (1)) and 20.4±1.3°C (Eq. (2)) represent an average SST coming from 30 molluscs whose deposit extends over several thousand years (≈125 to 119-116 ky BP), each sample providing a mean annual SST value over a few years of life.

5.3.2. Seasonal SST during the LIG sea-level highstand

As the incremental sampling gives access to different periods recorded during the growth of the mollusc shell, it could potentially allow seasonal temperature variations to be reconstructed. Sclerochronological studies performed on modern bivalve molluscs show that they form patterns of periodic annual banding in their shell (Butler and Schöne, 2016).

Moreover, image processing by Scanning Electron Microscopy (SEM) on the outer surface of modern bivalve *Cerastoderma edule* shells from high latitudes (North Sea, 55°N) show that winter and summer growth lines are consistent with $\delta^{18}O$ variations from shell incremental measurements, higher $\delta^{18}O$ values corresponding to cold water conditions (≈10°C) and lower $\delta^{18}O$ values to warm water conditions (≈22°C) (Milano et al., 2015). Data from *Stramonita haemastoma* (Matas Blanca) (Figure 11) and *Cardium edule (Cerastoderma edule)* (La Santa) (Figure 12) (2 samples) show a pseudo-cyclical SST record, particularly obvious for *Stramonita haemastoma*. The variations, of sinusoidal type, are distorted in the ontogenic profiles since the exoskeleton growth mode of many molluscs follows a logarithmic law (Cornu et al., 1993; Roman-Roman et al., 2010). Mean temperatures reconstituted from the $\delta^{18}O$ of shell increments from the *Stramonita haemastoma* specimen collected at Matas Blanca, Fuerteventura, and the *Cardium edule (Cerastoderma edule)* specimen collected at La Santa, Lanzarote, are between 23.5±1.6°C and 21.8±1.8°C and between 18.7±3.1°C and 16.6±3.3°C, respectively, according to Equation (1) and Equation (2). The first set of temperatures is close to those obtained for the 30 bulk samples, while the second set is much lower and displays a wide distribution (standard deviation of more than 3°C) due to the $\delta^{18}O$ signal drift (§5.1).

For the gastropod *Stramonita haemastoma*, about 4 seasonal SST cycles are observed over a total length to apex of 16 cm (Figure 11) with variations in SST comprised between ≈3.5°C and ≈5.5°C. For the bivalve *Cardium edule (Cerastoderma edule)*, we observe SST fluctuations that mimic a seasonal-like signal recorded over two or more cycles, over a total length to umbo of 4.5 cm (Figure 12). Due to a signal drift (§5.1), we focus here on the oldest biological age of the mollusc shell. The average SST comprised between 21.1±1.6°C (Eq. (1)) and 19.2±1.8°C (Eq. (2)) is consistent with the average temperature reconstructed from the 30 bulk samples. The seasonal SST fluctuation is approximately 6.0°C. We note that this

SST amplitude is also observed for the youngest part of the mollusc shell. The low SST values recorded by the youngest part of the *Cardium edule (Cerastoderma edule)* shell, caused by the $\delta^{18}O$ signal drift, could result from an inter-annual fluctuation of the SST, with particularly cooler marine waters during the first period of life of the mollusc sample, a period that may last for 1 or 2 years. Finally, seasonal SST values during the LIG sea-level highstand, established from two samples with a lifespan of a few years, range from ≈3.5°C to ≈6.0°C.

6. Discussion

6.1. Interpretation of the fossil faunal record

The ecology of the species present in the LIG marine deposits indicates that they lived in different types of environments (§3.1) that can be designated as (a) warm water environments, (b) warm and cooler water environments and (c) cooler water environments (Figure 5).

The co-occurrence of these different faunal groups in the LIG fossil record can be understood as follows. The marine deposits accumulated throughout the second part of the LIG, a period when the warm climate became progressively cooler, similar to that observed during the second part of the Holocene (Marcott et al., 2013). The whole LIG marine deposit therefore consists of both "warm fauna", corresponding to the warm phase of the second part of the LIG, and "cooler fauna", corresponding to the end of the LIG, before the sea-level fell and the sediment accumulation stopped. Firstly, during the LIG warming, the "warm species" or extralimital southern species (Muhs et al., 2014) migrated from low latitudes up to latitudes as far as the Mediterranean sea (Muhs et al., 2014). Secondly, when the SST decreased, extralimital southern species disappeared in the Canary Islands. This scenario of faunal shifts during the LIG in the Canary Islands was also documented by Muhs et al. (2014), but whereas they deal with the whole of the LIG period, here, we consider only the sequence of sediment deposits, i.e., the second part of the LIG. It follows that in principle the first arrival of the "warm species" is not recorded in our marine deposits.

These faunal changes are illustrated by the presence of *Persististrombus latus (Strombus bubonius)*, known as a Guinean-Senegalese taxon, in the samples we collected in the Matas Blancas deposit, i.e., north of its present geographical distribution. This observation indicates that during the LIG the SST was higher than in the present interglacial, as already noted by Muhs et al. (2014). This finding is consistent with the particularly high and reproducible LIG SST values recorded for the 3 specimens of *Persististrombus latus* , namely 23.4±0.5°C (Eq.(1)) and 21.7±0.6°C (Eq.(2)) (see Table 2). These values are clearly higher by about +1.2°C than the mean temperature found for the total bulk sampling (30 samples, §5.3.1), which includes the cooling period at the end of the LIG.

6.2. Interpretation of the mean annual paleo-SST reconstructions

6.2.1. LIG SST anomaly with respect to pre-industrial times

As in the first step, where the mean annual SST was estimated from mollusc shell $\delta^{18}O$ values in the eastern Canary Islands during the LIG, in a second step we estimated the change in SST with respect to pre-industrial times, i.e., the middle of the nineteenth century.

We recall the SST value of 20.4°C in the eastern islands of Canary archipelago for the period from 2007 to 2017 (§2.2).

The recent evolution of air temperature has been evaluated by Martín et al. (2012) from meteorological measurements on Tenerife Island, Canary archipelago. A warming trend of

$0.09\pm0.04°C.decade^{-1}$ between 1944 and 2010 was observed, which increased to $0.17\pm0.04°C.decade^{-1}$ in the period 1970-2010. At Gran Canaria, Canary archipelago, Luque et al. (2014) observed similar trends over the same periods, respectively. Such acceleration in the temperature rise is consistent with the SST trends from Advanced Very High Resolution Radiometer (AVHRR) and *in situ* data in the eastern Canaries published by Gómez-Letona et al. (2017) who estimated this trend to be about $0.22°C.decade^{-1}$ during the period 1993–2014.

From the estimated SST warming of about $0.2\pm0.04°C.decade^{-1}$ since the seventies (Gómez-Letona et al., 2017; Martín et al., 2012; Luque et al., 2014), and the increase in SST of about 0.2±0.05°C between the beginning of the twentieth century to the nineteen seventies based on the GMST trend (IPCC, 2013), we assume that the SST increased by about 1.0±0.1°C in the eastern Canaries between the pre-industrial times and the 2010s. This estimate is based on the fact that that global temperature increase observed from the beginning of the pre-industrial until the beginning of the 20th century (IPCC, 2013) is negligible. We therefore assume a pre-industrial SST of the order of 19.4±0.1°C. This result is consistent with the calculated SST value of 19.8°C in 1986 (Borges et al., 2004), which implies a pre-industrial SST of about 19.3°C.

Consequently, with respect to pre-industrial times, our results show that the mean SST anomaly that prevailed during the LIG sea-level highstand is comprised between at least +1.0±1.4°C (Equation (2)) and +2.8±1.3°C (Equation (1)) at the two coastal sites of La Santa and Matas Blancas.

6.2.2. Global and regional LIG temperature distribution

A full understanding of the context in which the local SST warming took place in the eastern Canary Islands calls for a broad view of the temperature change both on a regional scale and on a global scale. Owing to coupling between the regional and local scale pattern and the global climate, it is possible to estimate the consistency of our results with the temperature pattern at the LIG. Two strong qualitative pieces of evidence show that the LIG was globally warmer than the Holocene : the amply documented Antarctic polar warming, and the sea-level rise and high-stand above that of the present (+6 to +9 m) (e.g., Table 2, Figure 6). How much warmer the LIG was on Earth at the regional and global scale remains an intensely discussed topic within the paleoclimate community. Nevertheless, some major aspects of this warming can be summarized as follows.

The Past Interglacials Working Group of PAGES (2016) recently published an overview of the climate patterns of the LIG. The different interglacial periods over the last 800 ka were described. The characteristics of the successive interglacials depend on seasonal and latitudinal insolation, which are determined by astronomical parameters (Milankovitch, 1941; Berger, 1988). The time dependence of these parameters explains the markedly warm climate of some interglacial periods, in particular the LIG (e.g., Mélières and Maréchal, 2015). The LIG appears to be the warmest of the last eleven interglacial stages: compared to the Holocene, it was warmer by between 0°C and +4°C depending on the latitude (Past Interglacials Working Group of PAGES, 2016). At the global scale, the LIG global mean surface temperature (GMST) can first be inferred independently from the $\delta^{18}O$ and δD temporal series measurements of ice cores located in the plateau of Antarctica. These ice core records allow us to reconstruct changes in air temperatures above the ice cap. We focus here on the Dome C ice core, which shows an air temperature record consistent with those of three other coring sites at Vostok, Dronning Maud Land and Dome F (see for example Capron et al., 2014). During the LIG, they indicate that, with respect to the mean Holocene temperature, the Antarctic air surface temperature record divides into two periods, in which a peak anomaly of about +4°C around ≈130 ka BP is followed by a plateau type signal of about

+2°C between ≈126 ka and ≈119 ka BP (Figure 6c). These local temperatures reflect the regional temperature because the Antarctic plateau is characterized by spatially-equalized climatic conditions. In different studies a linear relationship of GMST change for every 1°C change in Antarctic temperatures across glacial-interglacial cycles is inferred : between 0.5°C (Masson-Delmotte et al., 2010; Chylek and Lohmann, 2008; Hansen et al., 2008) and 0.6°C (Snyder et al., 2016). We can therefore estimate a maximum GMST anomaly of at least ≈+2°C around ≈130 ka BP, followed by a plateau type temperature signal of at least ≈+1°C between ≈126 ka and ≈119 ka BP. Our samples are therefore contemporaneous with a period defined by a GMST warmer than present by about +1°C relative to the mean Holocene temperature. These GMST anomalies are consistent with the estimates of Snyder et al. (2016) and Hansen et al. (2013), which are based on a broader time scale. Snyder et al. (2016) used a multi-proxy database compilation to reconstruct the GMST over the last 2 Ma: they found that during the LIG the GMST was +2°C warmer than in the late Holocene (0-5 ka BP). Finally, Hansen et al. (2013) reconstructed the GMST over the last 65 Ma and calculated that the LIG was +1.4°C higher than during the Holocene. Regarding exclusively the global sea surface temperature, a warming of +0.5°C±0.3°C at 125 ka with respect to the pre-industrial times has been reported by Hoffman et al. (2017).

Focusing now on regional changes, during the LIG the Arctic region was consistently warmer than today. The CAPE-Last Interglacial Project Members (2006) offered quantitative estimates of circum-Arctic LIG summer air and sea surface temperatures (SST), reconstructed from proxies inferred from terrestrial and marine records. These reconstructions indicate that Arctic summer air temperatures were on average about +4 to +5°C higher than at present for most of the Arctic, well above the planetary LIG average. A synthesis of temperature data obtained at different climatic time slices at 125 ka BP and 120 ka BP indicates that the highest temperature was about +4°C to +5°C warmer than present in central Greenland (Capron et al., 2015, 2014). Regarding continental data obtained at mid latitudes in the northern hemisphere, Kaspar et al. (2005) compared the anomalies between reconstructed January and July temperatures for a 125 ka time slice and present-day observed temperatures in Europe. Their reconstructions, based on pollen and plant macrofossils, indicate warming by a few degrees. Brewer et al. (2008) report climate reconstructions from across the European continent. Their results show a traditional three-part LIG, with an early optimum, followed by a slight cooling stage and finally a sharp drop in temperature. The climate anomalies were mapped for four periods (127 ka, 123 ka, 117 ka, 109 ka BP). Maximum warming took place at 127 ka BP, a period during which the climate anomalies ranged from +4°C in northern Europe to +1°C in the south of France.

Concerning the sea surface temperature, Capron et al. (2017a) published a critical evaluation of data compilation at high latitudes. These authors emphasise that all high-latitude regions experienced warmer conditions at the 125 ka time slice relative to the present-day, with temperature anomalies reaching +1.6±0.5°C and +0.8±0.5°C in the North Atlantic and in the Southern Ocean, respectively. In the last decades, global syntheses have been performed, first by Turney and Jones (2010) and by McKay et al. (2011). McKay et al. (2011) suggest a peak in the LIG global annual SST warming of +0.7±0.6°C with respect to Late Holocene (5 to 0 ka BP). Both compilations indicate a general warming at high and middle latitudes but, for the tropics, a less consistent pattern emerges in which SST cooling is identified in the tropical Atlantic Ocean. However, Capron et al. (2017b) suggest that these two LIG data syntheses may have major methodological limitations related to the chronology. Recently, Hoffman et al. (2017) published a new LIG SST compilation of global extent with a consistent temporal framework. The temperature anomalies with respect to 1870-1889 are estimated for three different time slices during the LIG (129, 125 and 120 ka BP). Three world maps of proxy-based mean annual SST anomalies at the LIG, based on 83 marine sediment core sites, were established using temperature estimates from Mg/Ca in planktonic foraminifera, $U^{K'}_{37}$ from alkenones, and microfossil reconstructions. For each time window, significant cooling by a few degrees at the LIG took place in the tropical north Atlantic Ocean and along the west African coast. At the global scale, as already noted, SSTs reached +0.5°C±0.3°C at 125 ka.

All the above estimates concur to show that the GMST at LIG was on average higher than during the Holocene. This warming was not uniform, but increased towards the poles. Some oceanic regions, however, did not follow this rule, as suggested by SST reconstitutions performed in the North Tropical Atlantic Ocean by Hoffman et al. (2017). In particular, the waters of the tropical Atlantic gyre, whose descending branch, the Canary Current, bathes the West African coast, appeared to be cooler.

Turning now to the regional scale, in the northeast tropical Atlantic area where the Canary Islands are located, a few studies aim to reconstruct the SST during the LIG (Figure 3b, Table 3). Sicre et al. (2000) analysed terrigenous and marine biomarkers from a core (SU94-20bK) that recorded the last 150 ka in the northeast Atlantic off Northwest Africa at 25°00.60'N, 16°23.40'W. Their results from $U^{K'}_{37}$ analyses revealed an annual SST of 23.3°C during the LIG (from ≈128 to ≈120 ka BP) and 21.8°C during the beginning of the Holocene, thereby indicating an anomaly of +1.5±0.3°C during LIG with respect to the core top (dated at ≈9 ka BP). Matsuzaki et al. (2011) studied a core (MD03-2705) retrieved off the Cape Verde Islands at 18°05.81'N, 21°09.19'W, spanning the last 220 ka. The annual SST anomaly estimated from planktonic foraminifera assemblages between LIG (from ≈122 to ≈118 ka BP) and the core top (dated at ≈10-8 ka BP) is +0.5±0.6°C. Castañeda et al. (2009) analysed a sediment core (GeoB9528-3) retrieved from the Guinea Plateau Margin at 09°09.96'N, 17°39.81'W, spanning the last 192 ka. The $U^{K'}_{37}$–based annual SST gives a LIG anomaly value of +1.0±0.5°C (from ≈125 to ≈120 ka) with respect to the core top (dated at

≈9 ka). The SST anomalies from these studies (Sicre et al. (2000), Matsuzaki et al. (2011), Castañeda et al. (2009)) with respect to the core top values are displayed in Figure 13a. These values can be expressed relative to pre-industrial times by taking into account the results of the two following investigations. Fischer et al. (2018) indicate a cooling of the global surface air temperature by ≈0.7±0.3°C between ≈9 ka BP and the period 1850-1900. The same order of magnitude is obtained from Arbuszewski et al. (2013). In order to obtain the SST anomalies with respect to the pre-industrial times, the value of 0.7°C must therefore be added to the core top values (Figure 13b). Turning now to the evidence from coastal molluscs, Muhs et al. (2014) noted a dramatic warming of marine waters around the Canary Islands during the LIG, on the basis of on the presence of 16 exclusively extralimital southern species found in their LIG deposits. At present, these species live between the Cape Verde Islands and south Angola and are members of the tropical Senegalese-Guinean faunal province. During the LIG one of the most celebrated Senegalese taxa, *Persististrombus latus (Strombus bubonius)* (Figure 4), was distributed between Cape Verde Islands and the Mediterranean region. The geographic extent of these extralimital southern species during the LIG indicates that these numerous mollusc species migrated northwards during the LIG, a situation that requires warmer waters than at present. Montesinos et al. (2014) estimated the SST anomaly around the Canary Islands by comparing the present geographical distribution of an extralimital southern warm-water species, *Harpa doris* Röding, 1798 (*Harpa rosea*), with that prevailing during the LIG. This estimate is based on the presence of *Harpa doris* in marine deposits from the Canary Islands (Gran Canaria, Lanzarote and Fuerteventura) during the LIG. This mollusc disappeared from the Canary Islands after the LIG and has not reappeared since. Today, *Harpa doris* lives far to the south in the Gulf of Guinea, from Angola to Senegal. Comparison between the annual SST of the present habitat of *Harpa doris* and the annual SST of the Canary Island coasts enabled Montesinos et al. (2014) to evaluate a surface temperature anomaly at LIG of at least +3.3°C higher than today. To relate this value to the pre-industrial period, we applied the correction method described in § 6.2.1. Since Montesinos et al. (2014) took the 2000s as the reference date for the present period, we assume the increase in SST in the Canary Islands from the pre-industrial to the 2000s to be about 0.8°C. The annual SST anomaly is therefore at least +4.1°C higher than in pre-industrial times. This value spans the LIG marine deposit period that we estimated to be between ≈125 and 119-116 ka BP (§ 3.2) (Figure 13b). Finally, the compilation work of Hoffman et al. (2017) includes three cores located in the tropical Northeast Atlantic region: GIK15637 (27°00.00’W, 18°58.80’W), M12392-1 (25°09.60’W, 16°51.00’W), and V22-196 (13°49.80’N, 18°58.20’W), where foraminiferal assemblage-based annual SST anomalies with respect to the pre-industrial times (1870-1889) for three different time slices during the LIG (129, 125 and 120 ka BP) are deduced from the three maps shown. The values range from -4.8±0.5°C to +0.3±0.5°C (estimated from the color code of the maps).

6.2.3. LIG SST data comparisons

Our results for the coastal surface waters during the second part of the LIG recorded in Lanzarote and Fuerteventura indicate a positive temperature anomaly comprised between +1.0±1.4°C and +2.8±1.3°C with respect to pre-industrial times. This positive anomaly, obtained from geochemical analyses of mollusc shells in LIG marine deposits, is congruent with data obtained from the northeast tropical Atlantic by two other methods, namely analyses of microfossils and alkenones in deep-sea cores (Sicre et al., 2000 ; Matsuzaki et al., 2011 ; Castañeda et al., 2009) and analyses of mollusc assemblages in LIG marine deposits (Muhs et al., 2014 ; Montesinos et al., 2014) (Figure 13b). The relatively strong SST anomaly in the Canary Islands reported by Montesinos et al. (2014) is consistent with the qualitative study of

Muhs et al. (2014), which covers a wider geographical area stretching as far as the Mediterranean and includes a larger number of taxa. All of these studies clearly indicate a warming in the second part of the LIG with respect to pre-industrial times.

However, such positive temperature anomalies appear to conflict with the compilation of Hoffman et al. (2017) for the North Atlantic tropical SST, where two of the three cores reported indicate colder surface waters during the LIG with respect to pre-industrial times. The amplitude of these negative temperature anomalies differs according to the LIG time slices studied. We exclude the beginning of the LIG (129 ka BP), which could be affected by glacial-interglacial transition mechanisms (e.g., Capron et al., 2014). At 125 ka BP, only one core (M12392) exhibits significant cooling of -3.0 ± 0.5°C. At 120 ka BP, two cores (M12392, V22-196) indicate negative SST anomalies of -3.0 ± 0.5°C and -1.5 ± 0.5°C, respectively. The SST anomalies from these cores are less convincing when the core-top SST value reconstructed for the Holocene is taken into account (Hoffman et al., 2017; Hessler et al., 2014) : the absence of original SST data in the core-top (CLIMAP, 1984) prevents accurate comparison of the SST with respect to the Holocene. For this reason, the few data points that display negative LIG temperature anomalies in the compilation by Hoffman et al. (2017) may not be reliable. Furthermore, they are inconsistent with the warmer surface waters documented by the other investigations in the region, as well as with the results of our present study.

Our evidence therefore points to a warming of the SST off Northwest Africa from $\approx$125 ka to $\approx$119-116 ka BP with respect to pre-industrial times. This warming, which only concerns the second part of the LIG, is in principle weaker than that of the first part of the interglacial, where the insolation was maximum. It therefore indicates a lower value of the temperature anomaly for the LIG (129 ka to 116 ka). One possible cause of this warming could have been weakening of the North African upwelling, which would increase the SST.

The warming could also be due to the high insolation during the LIG, thereby warming the Canary Current from the North Atlantic gyre.

6.2.4. Upwelling impact and insolation effect

To understand the potential impact of climate change on the coastal upwelling activity, further information is needed about how it changed during the different climatic alternations between recorded warming and cooling events in the past (interglacial and glacial periods, respectively). For the Holocene period, the summer insolation in the northern hemisphere slowly decreased, resulting in a slow diminishing of the GMST and a reduction in summer monsoon activity in the northern tropical regions of Africa (deMenocal et al., 2000; Shanahan et al., 2015; Collins et al., 2017), Asia and North America (Wang et al., 2009). The global Earth climate, which was initially warm and humid, became cooler and drier, with a transition at around 5 ka BP. Re-interpretation of two SST proxies at ODP Hole 658C, off Cape Blanc (20°45'N, 18°35'W, south of the Canary Islands, see Figure 1) combined with new data, provided a better understanding of the history of upwelling of North Africa (Adkins et al., 2006). These authors concluded that weaker upwelling activity coupled with stronger African monsoon activity occurred during the African Humid Period in the first part of the Holocene. A similar observation was made by Abrantes (1991) who documented a warming period in the region of the Canary Islands that spanned several millennia in the first part of the Holocene, accompanied by a reduction in the intensity of the northwest African upwelling. During the LIG, such a weakening of the upwelling is also suggested by Muhs et al. (2014) from the faunal record in the Canary Islands. The LIG may have been characterized by early insolation-forced warming along with northward migration of the intertropical convergence zone (ITCZ), and accompanied by weakened trade winds and diminished upwelling. This allowed the arrival of extralimital southern taxa from the tropical Senegalese faunal province. During the latter part of LIG, decreased insolation may have resulted in southward migration of the ITCZ, strengthened trade winds, and re-establishment of the upwelling. Such conditions may have brought about the local extinction of the Senegalese fauna. The change of the upwelling strength can also be documented in the framework of larger climate changes, such as glacial and interglacial oscillations. Those oscillations extend over millennia, the cyclic climate alternation driven by variations in the summer insolation at middle to high latitudes in the northern hemisphere. Although the boundary conditions of the climate in the LGM and the LIG were different, they were both the result of insolation changes, and these modulate atmospheric circulation and hence the upwelling strength. The global warming that took place from the LGM to the Holocene was of the order of +5°C (Masson-Delmotte et al., 2013; Snyder, 2016). Henderiks et al. (2002) estimated the changes in the Canary seasonal coastal upwelling from LGM to the Holocene : they documented stronger trade winds and enhanced productivity during the LGM, in good agreement with previous studies of the northwest African upwelling and trade wind-system (e.g., Sarnthein et al., 1982, 1988; Abrantes, 1991; Rognon and Coude-Gaussen, 1996). Similar observations, but spanning a larger time scale, were made by Freudenthal et al. (2002), who reconstructed changes in trade wind intensities over the last 250 ka at 4 sites close to the Canary Islands. Furthermore, from a sediment core in the Canary Basin, Nave et al. (2003) indicated that the glacial stages MIS4 and MIS2 were more productive than the interglacial intervals (LIG and Holocene). Moreno et al. (2002) analysed the primary productivity record from sediment cores over the last 250 kyr in the North Canary Basin (30°N). Their work demonstrates that productivity is lower during interglacials than during glacial periods. These observations corroborate the fact that in glacial times the northwest Africa coastal upwelling activity increased. All of the above observations indicate a weakening of upwelling activity during periods of global warming.

We therefore conclude that the North African upwelling was weaker during the LIG than during the Holocene. This finding implies warmer coastal seawater during the LIG relative to the Holocene.

The maximum increase in SST attributable to a weakened upwelling can be estimated from the present-day isotherms of the eastern Atlantic tropical gyre. Upwelling only decreases the SST along the coast (Figure 3b). According to recent data, in the eastern Canary Islands this cooling ranges from 0.75°C to 1°C (Gómez-Letona et al., 2017 ; Sousa et al., 2017 ; Santos et al., 2012 ; Arístegui et al., 2009 ; Muhs et al., 2014, after Conkright et al., 2002). It follows therefore that a weakening of the upwelling will lead to a warming by between 0.75°C and 1°C at the very most, since the cold deep waters never completely stop rising. However, the increase in SST with respect to pre-industrial times, indicated by proxies from the upwelling zone off northwest Africa (excluding the values of Hoffman et al., 2017) is significantly greater. It lies in the range +1°C to +4°C (Figure 13b). As such a temperature rise is too large to be attributed to a weaker upwelling alone, an alternative and additional mechanism, namely the insolation at the LIG, must therefore be examined.

Summer insolation in the northern hemisphere, the main driving force of the glacial-interglacial oscillations, was more pronounced during the LIG than in the Holocene, leading to an interglacial that was on average warmer (CAPE-Last Interglacial Project Members, 2006; Masson-Delmotte et al., 2013; Capron et al., 2014). Between 30°N and 90°N the insolation anomaly 125 ka ago exhibited a maximum in July between ≈+50 W/m^2 and ≈+70 W/m^2 with respect to pre-industrial times (Pedersen et al., 2016). These results are in agreement with those of Capron et al. (2017b). Not only the *summer insolation* but also the *annual insolation* anomaly was positive (between 0 and +2.5 W/m^2) (Pedersen et al., 2016). By contrast, the *annual insolation* anomaly observed in the tropical latitude belt between 30°N and 30°S displayed a slight decrease comprised between 0 and -0.2 W/m^2 (Pedersen et al., 2016). It is to this *annual insolation* decrease in the tropical latitudes that Hoffmann et al. (2017) attributed their estimated cooling of the SST in the tropical Atlantic. According to the latter authors, the simulations of Pedersen et al. (2016) at 125 ka “successfully simulate the weak cooling found in our tropical SST stack in response to reduced mean *annual insolation* at those latitudes”. However the simulations performed by Pedersen et al. (2016) revealed *annual cooling* of the air temperature only in the continental tropical zones of North Africa (5°N-20°N) and Asia (India). The tropical north Atlantic not only does not exhibit cooling but rather a *warming* of between +0.5°C and +3°C, and in particular a warming of between +1 and +3°C in its north-eastern part from 22°N to 30°N with respect to pre-industrial times. Pedersen et al. (2016) attribute the continental cooling to the impact of *summer warming* in the Northern hemisphere, which amplified the North African and Indian monsoons. Owing to this amplification, evaporation and spread of the cloud cover became more pronounced, consequently cooling the continental surface. The continental cooling was thus mainly caused by the increase in seasonal *summer insolation*, rather than being due to a reduction of the *annual insolation* in the tropics. Accordingly, in spite of the reduced *annual insolation* that took place in the tropics during the LIG, the simulation of Pedersen et al. (2016) did not reproduce the cooling indicated by Hoffman et al. (2017) in the north-east tropical Atlantic. On the contrary, it reveals warming of the surface water in the northern tropical Atlantic, in agreement with our own measurements as well as with the majority of compilations conducted in this zone. These results lend support to the impact of summer insolation in the Northern hemisphere on the SST of the Canary current water masses during the LIG. The warming by about +1°C to +4°C (Figure 13b) of the SST in the tropical northeast Atlantic, reported by all the data sets, apart from those reconstituted by Hoffman et al. (2017), thus stemmed principally from the excess *summer insolation* during the LIG and, to a lesser degree, from a weakening of the upwelling. Therefore this indicates a warming of the descending branch of the North Atlantic Gyre (Canary current), mainly engendered by the larger summer insolation. As the descending branch is part of the gyre, this implies that the warming extended over the whole of the gyre.

6.3 Seasonal variations in paleo-SST and paleo-Dissolved Inorganic Carbon (DIC) $\delta^{13}C$

6.3.1. Seasonal SST during the LIG sea-level highstand

According to the SST inferred from incremental sampling of two specimens with a lifespan of a few years, which are the gastropod *Stramonita haemastoma* sampled from Matas Blancas, Fuerteventura, and the bivalve *Cardium edule (Cerastoderma edule)* sampled from La Santa, Lanzarote, the pseudo-cyclic SST pattern observed along the growth direction of the shells can be attributed to the seasonality of the SST. Those two mollusc shells recorded seasonal SST variations ranging from ≈3.5°C to ≈6.0°C, with a mean value of about 4.8±1.2°C, during the LIG sea-level highstand (≈125 to ≈119-116 ka BP) in the eastern Canary archipelago. Other LIG seasonal SST values for the northeast Atlantic region may be deduced from the difference between the winter mean SST (JFM) and the summer mean SST (JAS) reconstructed from foraminifera assemblages, by a method that is complementary to our approach based on stable oxygen isotope compositions of carbonates. Indeed, Matsuzaki et al. (2011) estimated seasonal SST variations to be about 5.0±1.2°C during the second part of the LIG, from ≈122 to ≈118 ka BP, from the core MD03-2705 (Figure 3b) located in the northeast of Cape Verde Islands (18°05.81'N, 21°09.19'W). From the cores M12392-1 south of the Canary archipelago (25°09.60'W, 16°51.00'W) and V22-196 between the Cape Verde Islands and Senegal (13°49.80'N, 18°58.20'W) (Figure 3b) (CLIMAP Project Members, 1984), seasonal SST variations were estimated to be ≈5.0±2.4°C and ≈5.5±2.6°C during the

LIG, respectively. The core top of those two cores, which is not available, is not necessary for these calculations. All these LIG seasonal SST estimates in the northeast Atlantic region match our values.

Meco et al. (2018) reported a seasonal SST amplitude along the eastern coast of Fuerteventura ranging from 3.5°C to 6.7°C between 2007 and 2016. The seasonal temperature variations from ≈3.5°C to ≈6.0°C recorded by the two mollusc shells, *Stramonita haemastoma* and *Cardium edule (Cerastoderma edule)*, during the LIG sea-level highstand in the eastern Canary Islands are therefore comparable to those of modern times. Finally, our data obtained from mollusc samples and those coming from the cores MD03-2705, M12392-1 and V22-196 indicate that the SST seasonality of the northeast Atlantic waters was of the same order during the LIG as that of present-days.

6.3.2. Mean annual and seasonal DIC $\delta^{13}C$ during the LIG sea-level highstand

Coastal upwelling areas are important dynamic parts of the ocean carbon cycle. The bulk carbon isotope data for La Santa and Matas Blancas sites provide a mean $\delta^{13}C$ value of 2.46 ± 0.57 ‰ (Table S1, in the Supplementary materials). This value represents an average of 30 mollusc shells from a LIG sedimentary deposit that extends over several thousand years, each sample being characterized by a multiannual $\delta^{13}C$ value. Several authors (e.g. Mackensen et al., 1993; Rohling and Cooke, 1999; Maslin and Swann, 2005) have shown that the $\delta^{13}C$ value of biologically precipitated carbonate in seawater is very close to that of Dissolved Inorganic Carbon (DIC). Therefore the $\delta^{13}C$ values recorded in the aragonite mollusc shells should represent that of seawater DIC. As emphasized by Maslin and Swan (2005), the $\delta^{13}C$ values of planktonic carbonate foraminifera increase with higher biological productivity. This is due to isotope fractionation during the photosynthesis process where the lighter $^{12}CO_2$ is preferentially selected by the organic matter, thereby leaving the surface water DIC enriched in ^{13}C. Thus, the positive mean annual $\delta^{13}C$ values of carbonate shells from the eastern Canary archipelago reflect a high marine productivity of surface waters during the sea-level highstand, i.e., from ≈125 ky to 119-116 ky BP (Maslin and Swan, 2005).

The mollusc shells selected for isotopic ontogenetic profiles provide complementary information at the seasonal scale of the $\delta^{13}C$ values of DIC. We consider that the $\delta^{13}C$ fluctuations recorded in the aragonite mollusc shell represent the $\delta^{13}C$ fluctuations of seawater DIC. $\delta^{13}C$ values of the incrementally sampled shell of *Cardium edule (Cerastoderma edule)* sampled from La Santa sedimentary sequence show a pseudo-cyclic signal recorded over a few years, with $\delta^{13}C$ values ranging from 0.51 ‰ to 3.02 ‰ (Table S2, in the Supplementary materials). These values, obtained from one sample, range around a mean value (2.04 ± 0.74 ‰) similar to the mean annual $\delta^{13}C$ averaged over several thousands of years during the LIG (2.46 ± 0.57 ‰), which indicates highly productive marine waters. The $\delta^{13}C$ values of the incremental samples from the *Cardium edule (Cerastoderma edule)* shell are correlated with those of $\delta^{18}O$, the regression line having a positive slope of 0.73 and a regression coefficient R^2 of 0.51 (Figure 9). At the seasonal scale, these observations mean that the lowest shell $\delta^{13}C$ values correspond to the higher SST values during LIG (Figure S2, in the Supplementary materials). In upwelling areas, the superficial upwelled seawater is characterized by ^{13}C-depleted DIC generated by oxidation of organic matter. This is due to the fact that after the death of phytoplankton, the ^{12}C-enriched organic matter sinks into the deep ocean and is degraded and remineralized. As a result, upwelled deep waters are characterised by ^{13}C-depleted DIC (Peeters and al., 2002). The low values of shell $\delta^{13}C$ therefore indicate an enhanced seasonal upwelling activity. Owing to the recorded correlation between the shell $\delta^{13}C$ values and the SST, the LIG enhanced upwelling activity corresponded to high SST periods, i.e., to summer seasons (Meco et al., 2018). A more active upwelling in summer during the LIG sea-level highstand is consistent with the present enhanced upwelling during summer (Pardo et al., 2011; Navarro-Pérez and Barton, 2001; Mittelstaedt, 1991) (see §2.2). In one of the most active upwelling areas, the Peruvian upwelling, Sadler et al. (2012) noted the same relationship between δ^{13}C DIC recorded by fossil shell δ^{13}C values and the upwelled water season, i.e., low shell δ^{13}C values corresponding to maximum upwelling intensity. However, unlike the upwelling off western Africa, that off Peru is strengthened in winter, and accordingly, lower values of shell δ^{13}C correspond to lower SSTs. We note that as the Canary Current SSTs are highest during summer (Meco et al., 2018), the main factor controlling the seasonal variation of SST is the insolation. The thermal impact of upwelling, which decreases the SST particularly when it is active in summer, however, is only of second order.

The seasonal influence of the Canarian upwelling seems to be only recorded in La Santa, Lanzarote, and not in Matas Blancas, Fuerteventura, a difference that may be explained by the geographical location of these two sites. Lanzarote and Fuerteventura are both situated at the eastern end of the archipelago where the global influence of the upwelling is the strongest. However, La Santa lies on the western side of the island of Lanzarote while Matas Blancas is located east of the island of Fuerteventura. Local upwelling always takes place on the western sides of lands due to the westerly direction of the Trade Winds. The reconstitution of the pigment content of the surface seawater from satellite recordings (Nave et al., 2001, 2003; Borges et al. 2004), which is a signature of the primary oceanic productivity, indeed exhibits a local annual coastal upwelling on the western coasts of Lanzarote and Fuerteventura, and not along the eastern coasts.

Our results suggest seasonal variations in the oceanic surface water parameters of the Canary archipelago during the LIG related to the SST and to the North African coastal upwelling activity. These seasonal fluctuations resemble those of the present time.

7. Conclusion

The stable isotope study of aragonitic mollusc shells sampled from the sites of La Santa, Lanzarote, and Matas Blancas, Fuerteventura, in the eastern part of the Canary archipelago reveals several important findings about the climate during the Last Interglacial, the LIG :

(i) The sample collection investigated is composed of mollusc shells deposited during the sea-level highstand that occurred during the second part of LIG. Our sample collection is therefore contemporaneous with the second part of the LIG, and is dated between ≈125 and ≈119-116 ky BP.

(ii) From 30 mollusc shell $\delta^{18}O$ values, SST comprised between 20.4±1.3°C and 22.2±1.2°C is estimated during the LIG record in the eastern Canary marine sedimentary sequences. Two mollusc shells, sampled from La Santa and at Matas Blancas in order to obtain ontogenetic profiles, provide a seasonal SST amplitude comprised between about 3.5°C and 6°C, similar to that of the present. The $\delta^{13}C$ variations recorded within one of these two mollusc shells, reflecting those of seawater DIC, are correlated with the SST and indicate seasonal variations in the intensity of the upwelling off the African coast similar to those of the present.

(iii) According to the modern SST documented in the eastern part of the Canary archipelago and the warming gradient established in this zone, we deduce an average SST value of about 19.4±0.1°C during the pre-industrial times. This conclusion enables us to propose a SST anomaly ranging from +1.0±1.4°C to +2.8±1.3°C during the second half of the LIG with respect to pre-industrial times. This warming, which concerns only the second part of the LIG, is in principle weaker than that of the first part of the interglacial (≈129 ka to

≈125 ka), where the insolation was maximum and greater than in the Holocene. It therefore indicates a lower value of the temperature anomaly for the LIG (≈129 ka to ≈116 ka).

(iv) This positive anomaly is consistent with the composition of the faunal species recorded in the marine highstand deposit with a warm extra-limital southern species (*Persististrombus latus* or *Strombus bubonius*), typical of warm sea water, which shows that at the time of the LIG marine sediment deposits it was warmer than in the present interglacial, as already documented by Muhs et al. (2014). In fact, the SST recorded by the specimens of *Persististrombus latus* is definitely higher (≈+1.2°C) than that recorded by all 30 mollusc shells. The co-occurrence in the deposit of cooler species, nowadays present in the Canary Islands, illustrates the SST cooling that set in at the end of the LIG.

(v) This positive anomaly is also consistent with a global mean surface temperature during the LIG that was warmer than in the Holocene (a warming that we estimate to be ≈+2°C in the first part of the LIG (≈130 ka BP), followed by ≈+1°C in the second part (≈126 to ≈119 ky BP). By contrast, it does not accommodate with the zonal negative anomaly of reconstructed SST (cooler temperature) at low latitudes in the North Atlantic (Hoffman et al., 2017). The positive anomaly is nonetheless fully consistent with all the other existing regional reconstructions (Sicre et al., 2000; Matsuzaki et al., 2011; Castañeda et al., 2009; Muhs et al., 2014; Montesinos et al., 2014), as well as with the regional simulations of air temperature (Pedersen et al., 2016). This finding calls into question the reconstructed zonal cooling at low latitude in the North Atlantic proposed by Hoffman et al. (2017) as well as data in other studies that may be based on this work (e.g., Fisher et al., 2018).

(vi) We interpret the positive SST anomaly as resulting principally from warming of the descending branch of the North Atlantic Gyre (Canary current) due to the excess summer insolation during the LIG with respect to the Holocene and, to a lesser degree, from a weakening of the upwelling off the African coast. As the Canary current is part of the North Atlantic Gyre, this implies a warming that extended over the whole of the gyre.

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Tables captions

Table 1 : Present sea surface temperature (SST in °C) in the eastern Canary Islands. (*) Values and standard errors estimated from color codes indicated on the figures.

Table 2: Period of sea-level (SL) highstand(s) during the LIG, together with the sea-level anomaly relative to the modern period.

Table 3 : Different studies reconstructing the SST during the LIG in the northeast tropical Atlantic.

Figure captions

Figure 1: (a) Location of the Canary Islands and of the Canary Current (blue arrows). (b) Map of eastern Canary Islands and sites of the marine deposits from the Last Interglacial period (red circles) including the LIG marine terrace deposits studied here at La Santa, Lanzarote, and Matas Blancas, Fuerteventura (yellow squares). Sites of coastal water samplings in the eastern Canary Islands are indicated by blue stars (Clauzel el al., 2019). LPG = Las Palmas de Gran Canaria, MB = Matas Blancas, LP = Las Playitas, LG = La Guirra, LS = La Santa, PP = Punta Penedo, M = Matagorda, NGC = North Gran Canaria, NFV = North Fuerteventura, WLZ = West Lanzarote.

Figure 2 : (a) Stratigraphy of cliff sections at Punta Penedo site, a few kilometers north of the site at La Santa, Lanzarote, studied here, showing the most complete section in the area (adapted from Meco et al., 2006). The sedimentary deposits are characterized by a succession of four distinct climatic phases: (i) calcareous dune deposits, (ii) paleosols (with locust egg pods), (iii) marine sediments, and (iv) pedogenic calcretes (see text). (b) Marine deposits at the studied site at Matas Blancas (Fuerteventura) (Muhs et al., 2014) with well-preserved fossil specimens of *Persististrombus latus* (*Strombus bubonius)*.

Figure 3 : (a) Annual mean sea surface temperature (SST in °C) in the North Atlantic Ocean from Pathfinder satellite (adapted from Darfeuil et al., 2016, data from Armstrong and Vazquez-Cuervo, 2001). The surface circulation patterns are indicated by black arrows. AzC = Azores Current, CC = Canary Current, PC = Portugal Current. (b) SST (°C) in the northeast tropical Atlantic Ocean on 25 July 2007 from OSTIA satellite (adapted from Arístegui et al., 2009, data from Stark et al., 2007). Studies reporting a LIG SST record and discussed in the present work are indicated by filled circles (sediment cores) and by empty circles (marine deposits). Black arrows correspond to Trade Winds (from Nave et al., 2003).

Figure 4: Photographs of a selection of shells of the 6 studied molluscan species : gastropods (a) *Cerithium vulgatum*, (b) *Stramonita haemastoma*, (c) *Luria Lurida*, (d) *Persististrombus latus (Strombus bubonius)* and bivalves (e) *Loripes lacteus,* (f) *Cardium edule (Cerastoderma edule)*. The length of a rectangle corresponds to 1 cm.

Figure 5: Modern geographical distribution of the mollusc species studied in the la Santa, Lanzarote, and Matas Blancas, Fuerteventura, marine LIG deposits of the Canary Islands,

from south (red) to north (blue) of the archipelago (orange). The solid lines indicate the observed presence of the molluscs, the dashed lines their presumed presence.

Figure 6: (a) Sediments in the Canary Islands from the paleosols, corresponding to the African Humid Period, and from the marine deposits during the Holocene (Meco et al., 2011); (b) Antarctic temperature anomaly records (°C) from δD measurements of the ice at EPICA Dome C during the last 30 ky and (c) in the period 140-100 ky BP (Jouzel et al., 2007); (d) Sea-level variation (m) reconstructed from far-field coral and sediment data during the last 30 ky (grey circles) (Lambeck et al., 2014); (e) Sea-level variation (m) in the period 140-100 ky BP, reconstructed from combined field observations and glacial isostatic adjustment modeling (orange bar) (Dutton et al., 2015a) and from benthic foraminifera oxygen isotope ratios (grey curves) (adapted from Waelbroeck et al., 2002).The red and blue vertical lines correspond to the moment when the maximum temperature and the maximum sea-level, respectively, were reached during the interglacials. The green arrows indicate the lapse of several thousand years between these two moments. The blue dashed vertical line indicating the beginning of the highstand and the blue dashed curves describing the sea-level correspond to our interpretation (see text).

Figure 7: Raman spectra of selected mollusc shells sampled from La Santa, Lanzarote ((a) gastropod *Cerithium vulgatum* LAS-BULK-3 and (b) bivalve *Cardium edule (Cerastoderma edule)* LAS-INCR-14) and from Matas Blancas, Fuerteventura ((c) gastropod *Persististrombus latus (Strombus bubonius)* MAB-BULK-1 and (d) bivalve *Stramonita haemastoma* MAB-INCR-4). All these shells are made of aragonite that is characterized by the presence of relative intense peaks in the 150–250 cm^{-1} range, and a splitting of the

carbonate group bending mode yielding a doublet at 700–701 cm^{-1}. The peak located at 1080–1082 cm^{-1} is characteristic of the carbonate group stretching mode.

Figure 8: $\delta^{18}O$ (‰ V-PDB) of aragonitic shell increments of *Cardium edule* sampled from La Santa, Lanzarote, as a function of the distance from the umbo (cm) along the growth direction.

Figure 9: $\delta^{13}C$ (‰ V-PDB) as a function of $\delta^{18}O$ (‰ V-PDB) of aragonitic shell increments of (a) *Cardium edule* sampled from La Santa, Lanzarote and (b) *Stramonita haemastoma* sampled from Matas Blancas, Fuerteventura. (a) The regression line (red) is shown with its regression equation and coefficient ($R^2 = 0.51$).

Figure 10: Frequency histogram of reconstructed LIG SST from bulk mollusc shells sampled from La Santa, Lanzarote, and Matas Blancas, Fuerteventura, according to Equation (1) determined by Grossman and Ku (1986) (blue, on the left-hand side) and to Equation (2) determined by Kim et al. (2007b) (green, on the right-hand side).

Figure 11: Reconstructed LIG SST during the ontogenetic evolution of *Stramonita haemastoma* (Matas Blancas, Fuerteventura) according to Equation (1) determined by Grossman and Ku (1986) (blue) and to Equation (2) determined by Kim et al. (2007b) (green). The total length to apex is 16.0 cm.

Figure 12: Reconstructed LIG SST during the ontogenetic evolution of *Cardium edule* or *Cerastoderma edule* (La Santa, Lanzarote) according to Equation (1) determined by

Grossman and Ku (1986) (blue) and to Equation (2) determined by Kim et al. (2007b) (green). The total length to umbo is 4.5 cm.

Figure 13 : SST (°C) anomalies in the northeast tropical Atlantic relative (a) to core top values and (b) to the pre-industrial times. (1): Sicre et al. (2000), (2): Matsuzaki et al. (2011), (3): Castañeda et al. (2009), (1*) (2*) (3*): The same studies with SST anomalies estimated for the pre-industrial times (see text), (4): This study, (5): Adapted from Montesinos et al. (2014) (see text), (7), (8), (9): Hoffman et al. (2017) with cores GIK15637-1 (7), M12392-1 (8), V22-196 (9). See Figure 3(b) for the sites location.

Supplementary material captions:

Table captions

Table S1: Oxygen and carbon isotope compositions of bulk marine mollusc shells, listed together with calculated sea surface temperatures (SST) according to the oxygen isotope fractionation equations of Grossman and Ku (1986) (Eq.(1)) and Kim et al. (2007b) (Eq.(2)). Samples collected from La Santa, Lanzarote (LAS-BULK-1 to LAS-BULK-27) and from Matas Blancas, Fuerteventura (MAB-BULK-1 to MAB-BULK-3).

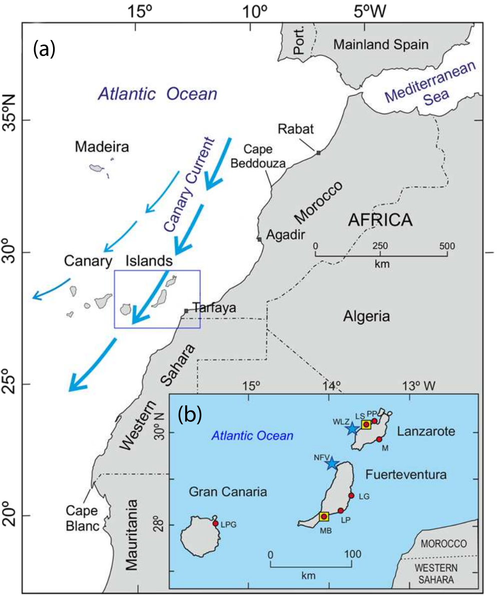
Table S2: Oxygen and carbon isotope compositions of marine mollusc shell increments and calculated sea surface temperatures (SST) according to the oxygen isotope fractionation equations of Grossman and Ku (1986) (Eq.(1)) and Kim et al. (2007b) (Eq.(2)). The *Cardium edule* specimen was collected from La Santa, Lanzarote (LAS-INCR-1 to LAS-

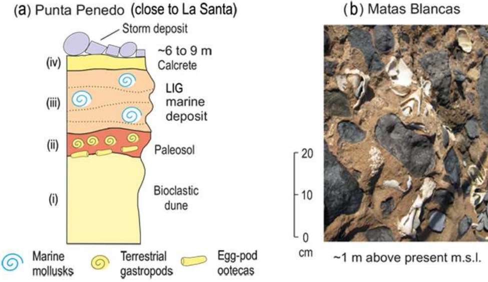
INCR-16) and the *Stramonita haemastoma* specimen from Matas Blancas, Fuerteventura (MAB-INCR-1 to MAB-INCR-29). Note: MAB-INCR-20 is missing.

Figure captions

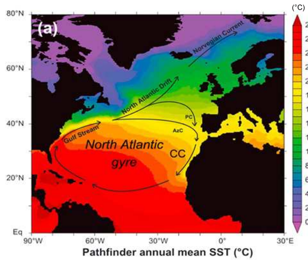
Figure S1: (a) Cross-section of a bivalve shell showing the growth direction of the shell from the umbo (adapted from Füllenbach et al., 2015). (b) Photomicrograph of the bivalve *Cardium edule (Cerastoderma edule)* with the incremental samplings carried out along the growth axis (drilling holes). (c) Diagram of a gastropod shell showing the growth spiral of the shell from the apex (frontal view). (d) Photomicrograph of the gastropod *Stramonita haemastoma* with the incremental samplings, represented by grey circles, made along the growth spiral. The length of a rectangle corresponds to 1 cm.

Figure S2: $\delta^{13}C$ (‰ V-PDB) as a function of reconstructed SST (°C) of aragonitic shell increments of *Cardium edule* sampled from La Santa, Lanzarote. The regression line (red) is shown with its regression equation and coefficient ($R^2 = 0.51$). High SSTs occur in summer (Meco et al., 2018) a season where the upwelling activity is the strongest (Pardo et al., 2011; Navarro-Pérez and Barton, 2001; Mittelstaedt, 1991).

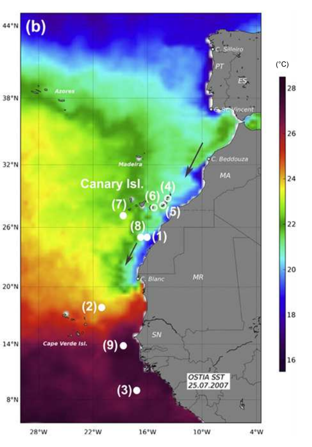

15º
10º
5ºW
35ºN
30º
25º
20º
(a)
Port.
Mainland Spain
Mediterranean Sea
Atlantic Ocean
Madeira
Canary Current
Rabat
Cape Beddouza
Morocco
AFRICA
Agadir
0
250
500
km
Canary Islands
Tarfaya
Algeria
Sahara
Western
Cape Blanc
Mauritania
15º
14º
13º W
30º N
28º
(b)
Atlantic Ocean
WLZ
LS
PP
Lanzarote
M
NFV
Fuerteventura
Gran Canaria
LG
LP
MB
LPG
0
100
km
MOROCCO
WESTERN SAHARA

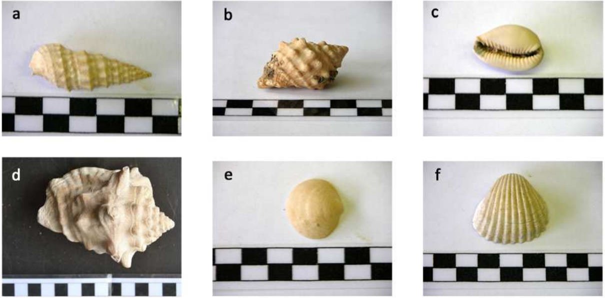


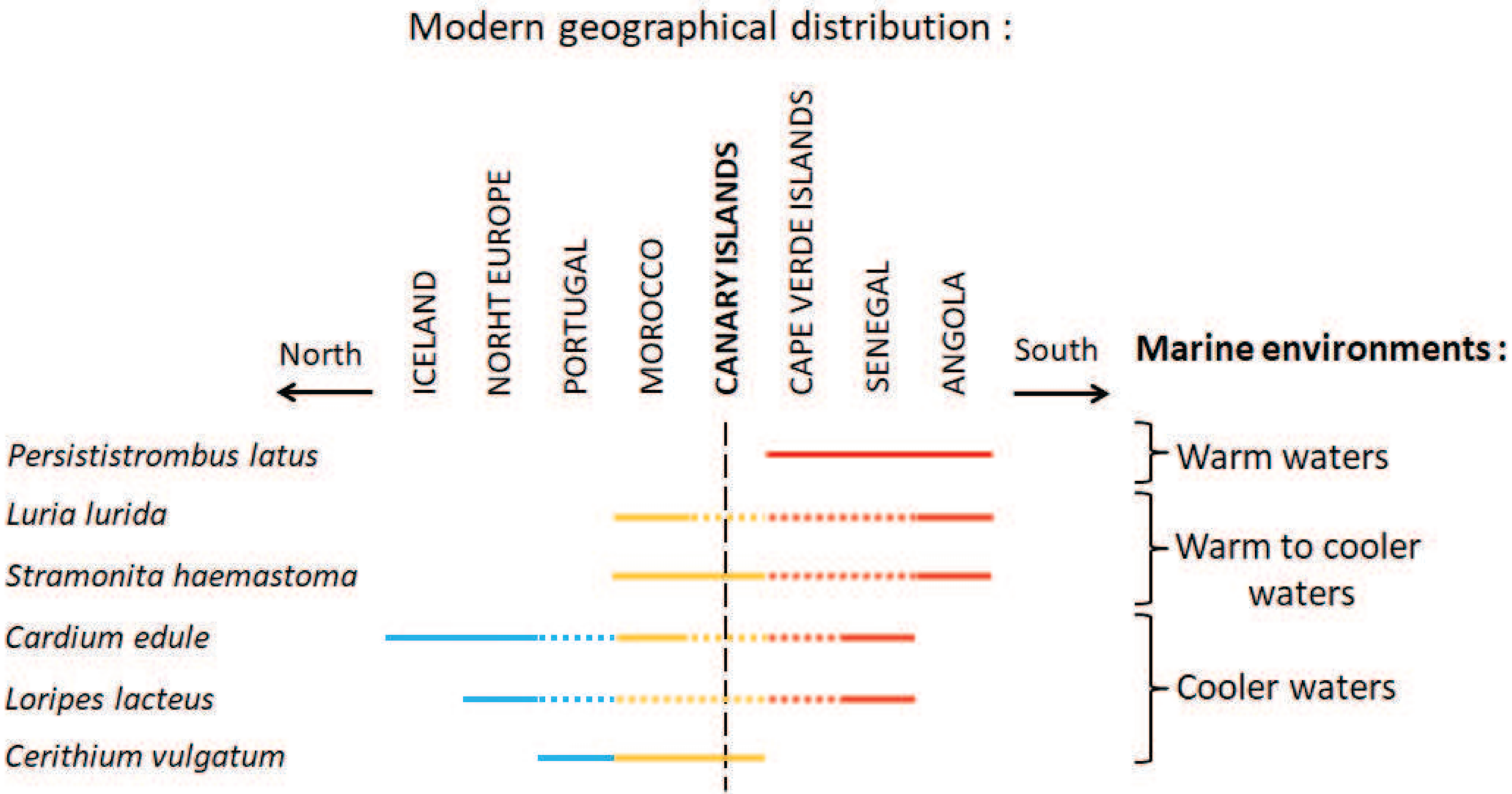
(a) Punta Penedo (close to La Santa)
Storm deposit
~6 to 9 m
(iv)
Calcrete
(iii)
LIG
marine
deposit
(ii)
Paleosol
(i)
Bioclastic
dune
Marine
mollusks
Terrestrial
gastropods
Egg-pod
ootecas
(b) Matas Blancas
20
10
0
cm
~1 m above present m.s.l.



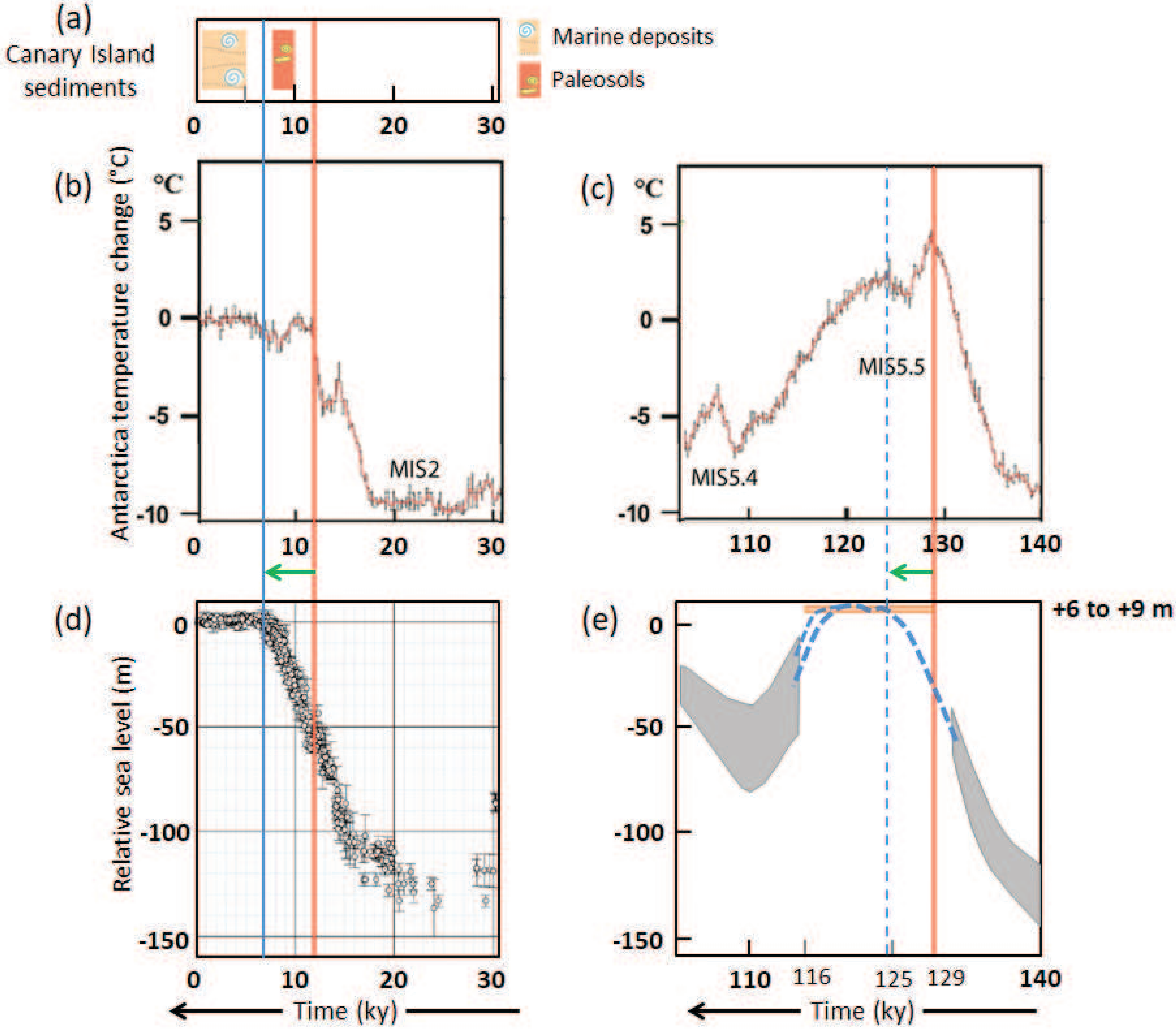
(b)
(1) Sicre et al. (2000)
(2) Matsuzaki et al. (2011)
(3) Castaneda et al. (2009) (7) GIK15637-1,
(4) This study (8) M12392-1,
(5) Montesinos et al. (2014) (9) V22-196,
(6) Muhs et al. (2014)
(7), (8), (9) in Hoffman et al. (2017)



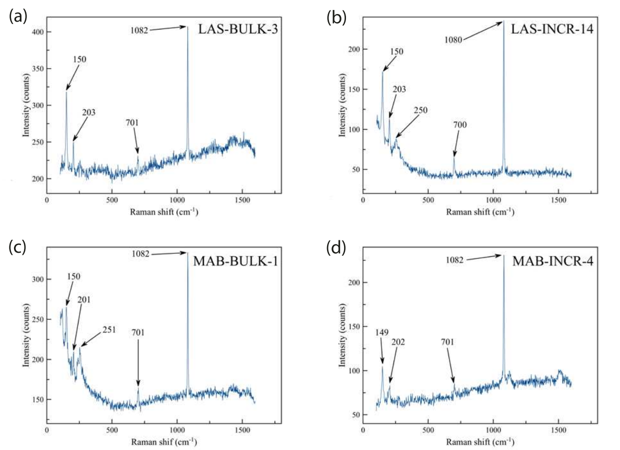

a
b
c
d
e
f

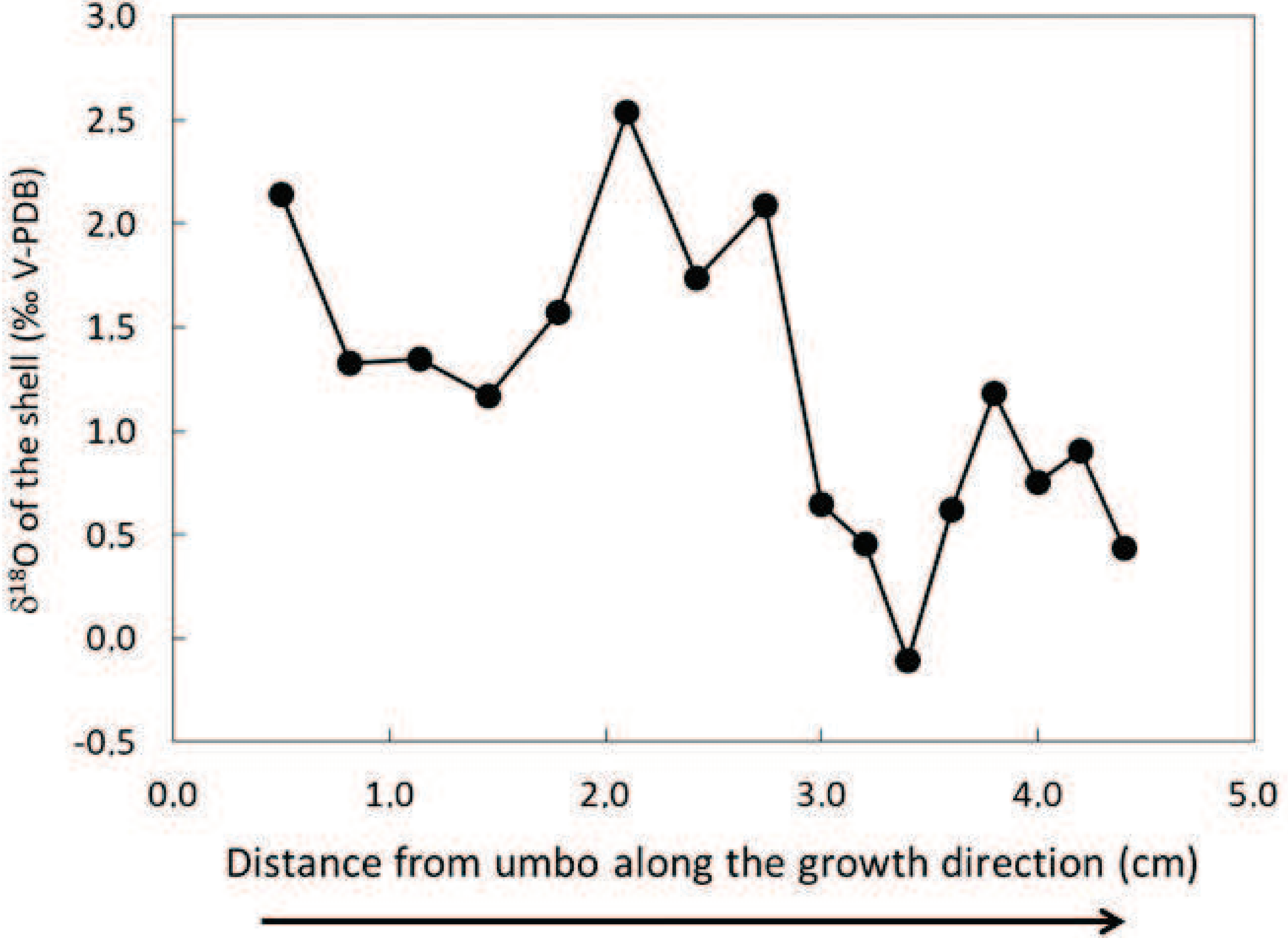


Modern geographical distribution :
North
ICELAND
NORHT EUROPE
PORTUGAL
MOROCCO
CANARY ISLANDS
CAPE VERDE ISLANDS
SENEGAL
ANGOLA
South
Marine environments :
Persististrombus latus
Luria lurida
Stramonita haemastoma
Cardium edule
Loripes lacteus
Cerithium vulgatum
Warm waters
Warm to cooler waters
Cooler waters



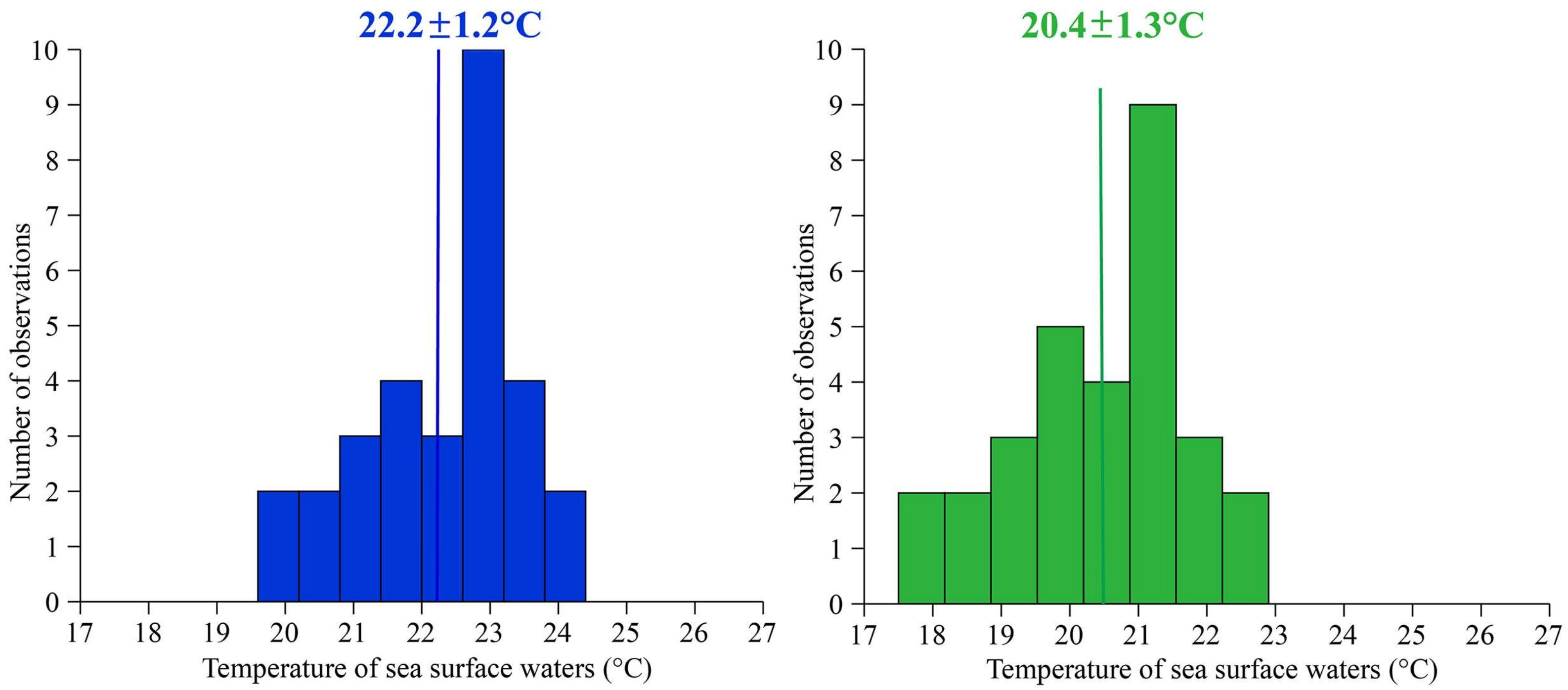
(a)
Canary Island sediments
Marine deposits
Paleosols
(b)
(c)
°C
Antarctica temperature change (°C)
MIS2
MIS5.5
MIS5.4
(d)
(e)
Relative sea level (m)
+6 to +9 m
116
125
129
Time (ky)

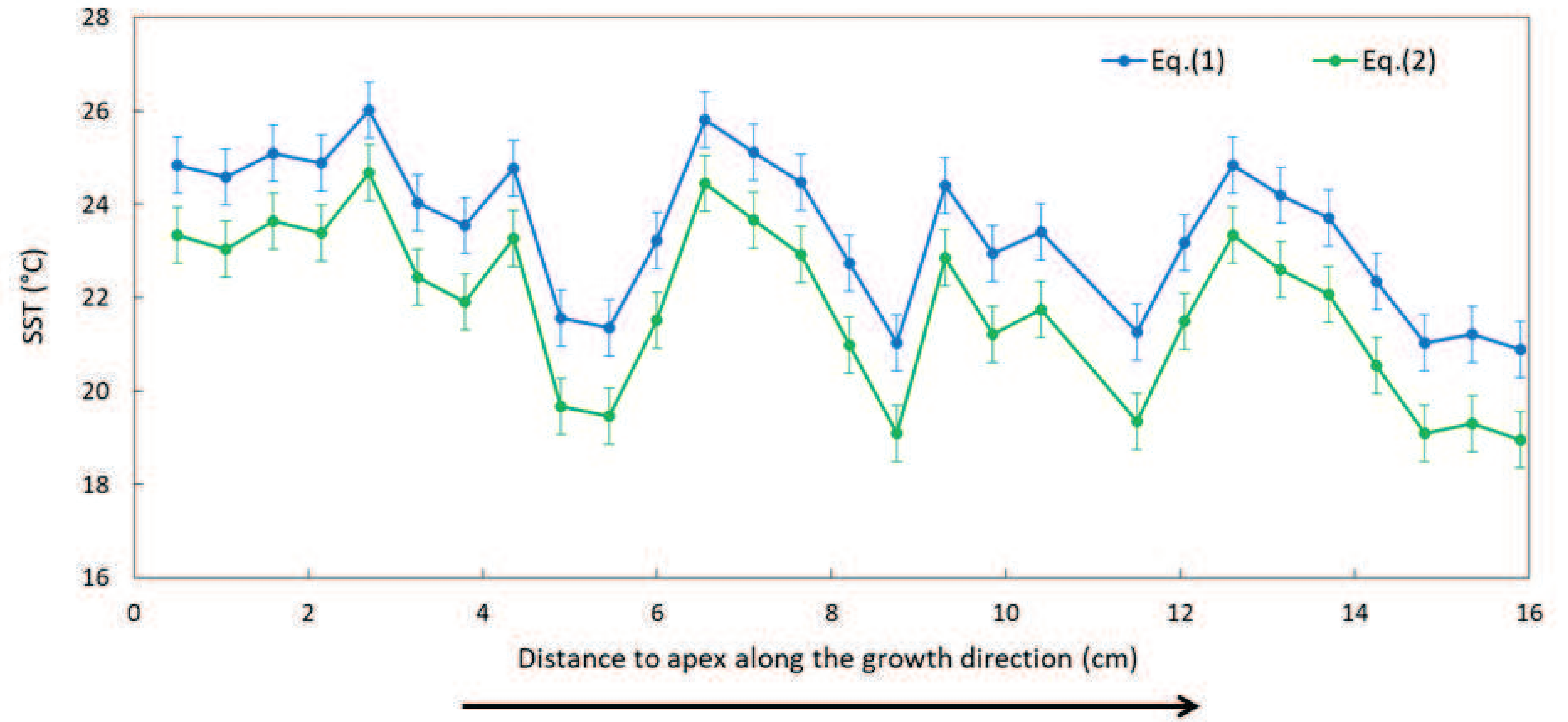

(a)
LAS-BULK-3
1082
150
203
701
Intensity (counts)
Raman shift (cm⁻¹)
(b)
LAS-INCR-14
1080
150
203
250
700
Intensity (counts)
Raman shift (cm⁻¹)
(c)
MAB-BULK-1
1082
150
201
251
701
Intensity (counts)
Raman shif (cm⁻¹)
(d)
MAB-INCR-4
1082
149
202
701
Intensity (counts)
Raman shift (cm⁻¹)



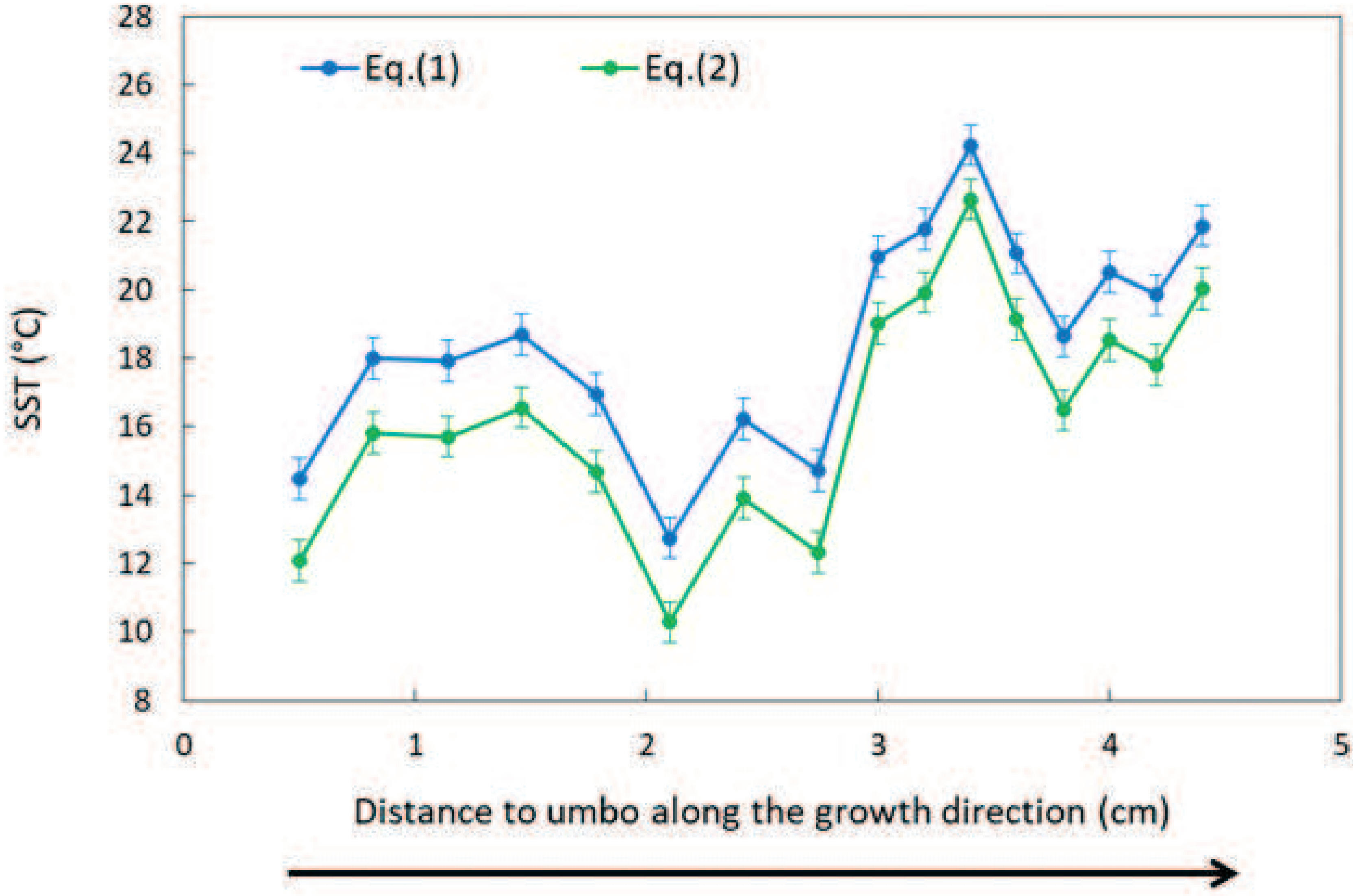
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
δ18O of the shell (‰ V-PDB)
0.0
1.0
2.0
3.0
4.0
5.0
Distance from umbo along the growth direction (cm)

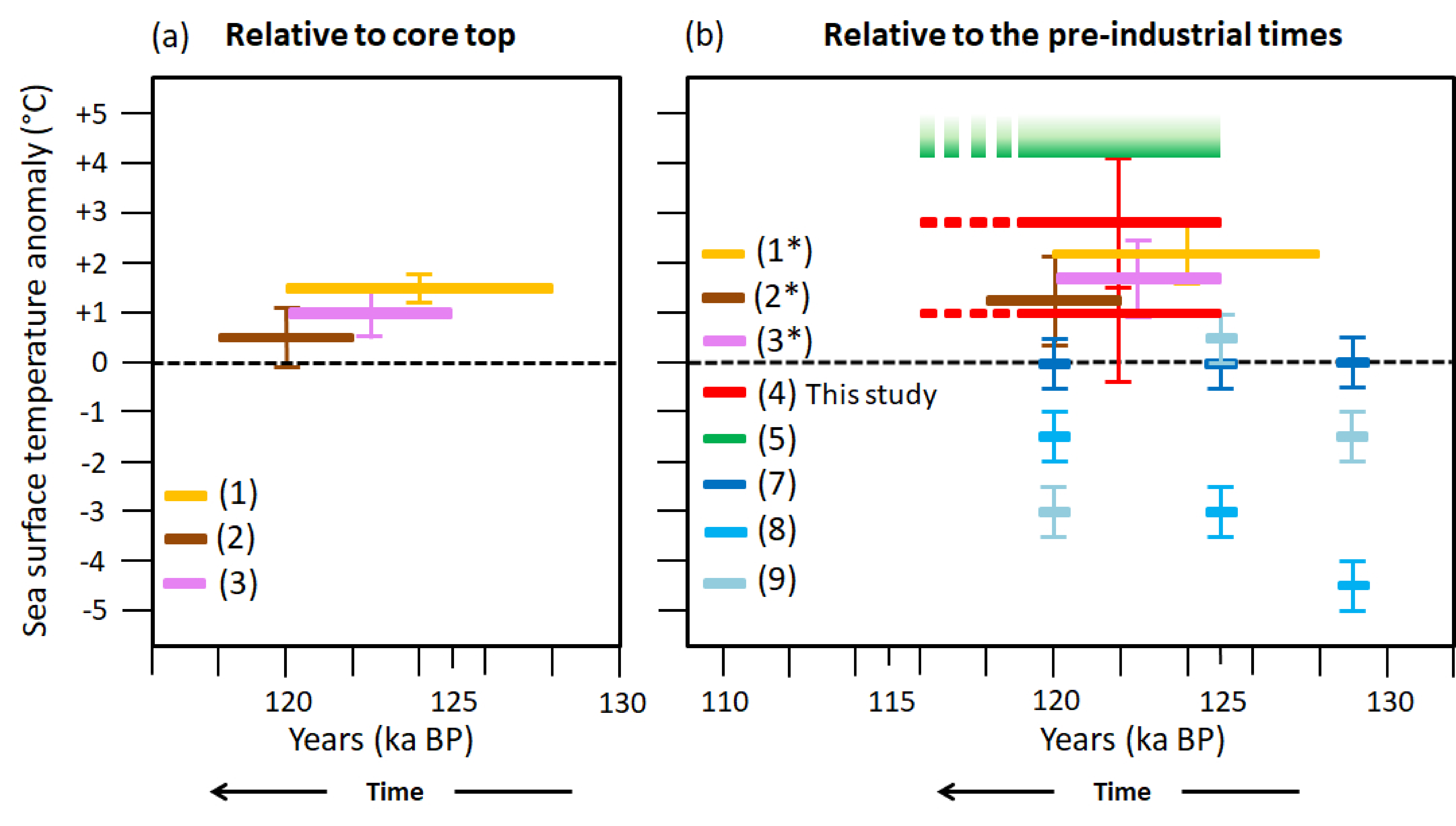
(a) Incremental series of Cardium edule
(b) Incremental series of Stramonita haemastoma
δ13C of the shell (‰ V-PBD)
δ18O of the shell (‰ V-PBD)
y = 0.73x + 1.18
R² = 0.51
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
-1.0
-0.5
0.0
0.5
1.0


22.2±1.2°C
Number of observations
0
1
2
3
4
5
6
7
8
9
10
17
18
19
20
21
22
23
24
25
26
27
Temperature of sea surface waters (°C)
20.4±1.3°C
Number of observations
0
1
2
3
4
5
6
7
8
9
10
17
18
19
20
21
22
23
24
25
26
27
Temperature of sea surface waters (°C)



Eq.(1)
Eq.(2)
SST (°C)
28
26
24
22
20
18
16
0
2
4
6
8
10
12
14
16
Distance to apex along the growth direction (cm)


Eq.(1)
Eq.(2)
SST (°C)
28
26
24
22
20
18
16
14
12
10
8
0
1
2
3
4
5
Distance to umbo along the growth direction (cm)


(a) Relative to core top
(b) Relative to the pre-industrial times
Sea surface temperature anomaly (°C)
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
-5
(1)
(2)
(3)
(1*)
(2*)
(3*)
(4) This study
(5)
(7)
(8)
(9)
120
125
130
110
115
Years (ka BP)
Time

Period	Mean SST (°C)	Method	Authors
2007-2017	20.44°C	Satellite data and *in situ* SST data	Meco et al. (2018)
1993-2014	20.5±0.2°C (*)	Satellite data and *in situ* SST data	Gómez-Letona et al. (2017)
1976-2005	18.5±0.2°C (*)	GCMs simulations	Sousa et al. (2017)
1982-2012	20.3±0.2°C (*)	Satellite data	deCastro et al. (2014)
≤ 2001	≤ 20°C	Atlas 2001	Muhs et al. (2014) from Conkright et al. (2002)
1982-2012	20.3±0.2°C (*)	Satellite data	Santos et al. (2012)

Authors	**Area**	**Proxy or Studies**	**SL anomaly**	**SL highstand(s)**	**Time-period**
Kopp et al. (2013)	47 sites worldwide	Probabilistic analyses on $\delta^{18}O$ of foraminifera	> + 6.6 m	2 highstands separated of +4m	125-116 ky
Spratt and Lisiecki (2016)	sites worldwide	Stack estimates from $\delta^{18}O$ of foraminifera	+6 to + 9m ±12 m		126-119 ky BP
Blanchon et al. (2009)	Yucatan, Mexico	Corals	+ 3 m : + 6m :		126-121 ky 120-117 ky
Thompson et al. (2011)	Bahamas	Corals	+4 m : + 6 m :		≈ 123 ky ≈ 119 ky
O'Leary et al. (2013)	Western Australia	Corals	+ 3-4 m : + 9.5 m :		127-119 ky < 118 ky
Dutton et al. (2015b)	Seychelles	Corals	rise : +7.6 m :		129-125 ky < 125 ky
Masson-Delmotte et al. (2013)	–	SL synthesis work	+ 6 m	2 highstands separated of +4m	129-116 ky
Dutton et al. (2015a)	–	SL synthesis work	+ 6 to + 9 m :	Peak :	129-116 ky < 125 ky (122-119 ky)
Capron et al. (2017a,b)	–	LIG studies	+ 6 to + 9 m :	2-phases, late peak :	122-119 ky

Reference	Material	SST Proxy
Sicre et al. (2000)	Sediment core	$U^{K'}_{37}$
Matsuzaki et al. (2011)	Sediment core	Planktonic foraminiferal assemblages
Castañeda et al. (2009)	Sediment core	$U^{K'}_{37}$
This study	Marine deposits	$\delta^{18}O$ from mollusk shells
Montesinos et al. (2014)	Marine deposits	Extralimital species
Muhs et al. (2014)	Marine deposits	Extralimital species
Hoffman et al. (2017)	Sediment cores	Planktonic foraminiferal assemblages