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Holocene hydrography evolution in the Alboran Sea: a multi-record and multiproxy comparison

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ABSTRACT

A new high resolution deglacial and Holocene Sea Surface Temperature (SST) reconstruction is presented for the Alboran Sea (western Mediterranean), based on Mg/Ca ratios measured in the planktonic foraminifera *Globigerina bulloides.* This new record is evaluated by comparison with other Mg/Ca – SST and previously published alkenone-SST reconstructions from the same region for both Holocene and glacial period. In all cases there is a high degree of coherence between the different Mg/Ca-SST records but strong discrepancies when compared to the alkenone-SST records. We argue that these discrepancies are due to differences in the proxy-response during deglaciation which we hypothesize to reflect a resilience strategy of *G. bulloides* changing its main growth season. In contrast, short-term Holocene SST variability is larger in the Mg/Ca-SST than in the alkenone-SST records. It is proposed that larger Mg/Ca-SST variability to be the result of spring season variability, while the smoothed alkenone-SST variability represents average annual temperatures. Mg/Ca-SST record differentiates the Holocene in three periods (1) The warmest SST values occurred during the Early Holocene (11.7 – 9 kyr BP); (2) During the middle Holocene occurred a continuous cooling trend that culminated with the coldest Holocene SST in a double peak structure centred at around 4.2 kyr BP; (3) The Late Holocene (4.2 kyr BP to the present) did not follow any clear cooling/warming trend but millennial-scale oscillations were enhanced. This SST evolution is discussed in the context of changing properties in the Atlantic inflow associated to North Atlantic circulation conditions and also to local hydrographical and atmospheric changes. To conclude, we propose a tight link between North Atlantic circulation patterns and inflow of surface waters into the Mediterranean playing a major role in the controls of Holocene climatic variability of this region.

1. INTRODUCTION

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Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past
Discussions
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The Holocene climate evolution in general, and also in the Alboran Sea (11.7 kyr BP to present) is considered more stable than the last glacial period (Bond et al., 1997; Cacho et al., 1999; Martrat et al., 2014). However, there is an increasing number of Holocene climate records revealing significant changes in both long term patterns, orbital forcing (e.g. Marchal et al., 2002; Lorenz and Lohmann 2004; Tzedakis, 2007; Wanner et al., 2008; Tinner et al., 2009; Bartlein et al., 2011), and also to millennial and centennial-scale variability (e.g. Bond et al., 1997, 2001; Andrews et al., 2003; Marchitto and deMenocal, 2003; Moros et al., 2004; Debret et al. 2007 and 2009; Thornalley 2009; Giraudeau et al., 2010). In the ocean context and concretely over the North Atlantic Ocean, there are solid evidences about Holocene changes in several oceanographic parameters linked to Atlantic Meridional Overturning Circulation (AMOC) like the heat exchange within the subpolar gyre (SPG) and the subtropical gyre (STG) (Bond et al., 1997, 2001; Thornalley et al., 2009; Colin et al., 2010; Repschläger et al., 2017). Studies on Holocene atmospheric conditions over the North Atlantic region suggest the occurrence of northward and southward displacements of the winter storm tracks (Fletcher et al., 2012; Desprat et al., 2013; Chabaud et al., 2014; Zielhofer et al., 2017). The Western Mediterranean Sea is very sensitive to changes in the Atlantic Ocean conditions. These oceanic and atmospheric connections have been well documented and described for the last glacial period (Cacho et al., 1999; Moreno et al., 2002; Sierro et al., 2005; Frigola et al., 2008; Toucane et al., 2012) when intense millennial-scale variability occurred associated to major changes in the AMOC (the so-called Dansgaard-Oeschger cycles and Heinrich events). However, even though the Holocene climate variability over the western Mediterranean has also been extensively studied (i.e: Cacho et al., 2001; Frigola et al., 2007, Rodrigo-Gàmiz 2011; Ausin et al, 2015; Jalali et al., 2016), unlike the glacial periods, any potential connection with the changes occurred in the North Atlantic Ocean remains unclear.

One of the limitations in the study of Holocene climate variability relies on the sensitivity of our proxies. During this period, the natural range of variability for SST or $\delta^{18}O_{SW}$ are relatively short and, these natural changes are often below the magnitude of the proxy sensitivity. For this reason, to validate the climate value of proxy signals for the Holocene, it becomes critical to reproduce them in comparable records and ideally, with independent proxies. With this aim, here we present a new high resolution Holocene SST record based on the Mg/Ca ratio in the planktonic foraminifera *G. bulloides* in core ALB-2 from the Alboran Sea. The information of this record is also compared with other three Mg/Ca-SST records, two new (MD95-2043 and MD99-2343) and other previously published (ODP 976; Jimenez-Amat and Zahn 2015) and all of them are from the Western Mediterranean Sea and based on *G. bulloides*. The Western Mediterranean Sea has been intensively studied previously and several SST records exist mostly based in the application of the U^{K}_{37} index measured on alkenones (Cacho et al., 2001; Martrat et al., 2004; Rodrigo-Gámiz 2014; Ausin et al., 2015). This multi-core and multi-proxy approach comparison lets into the discussion of the proxy limitations to identify some SST changes with discrepancies between the two considered proxies. The new high-resolution Mg/Ca-SST let us to discuss the Holocene-SST evolution in this region and hypothesize some potential connection with changes in the North Atlantic Ocean.

2. REGIONAL SETTINGS

Climate in the western Mediterranean region is characterized by warm and dry summers while autumn and winter are mild and humid. During winters, westerly winds are predominant displacing the storm tracks to southern positions and thus supplying humid conditions over the western Mediterranean region. (Trigo et al., 2002; Combourieu Nebout et al., 2009; Fletcher et al., 2012; Roberts et al., 2012; Nieto-Moreno et al., 2013). At the end of summer and the early autumn the temperature differences between the air

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions
Open Access

masses and the surface Mediterranean can produce violent precipitation events (Lionello et al., 2006 Sabatier et al., 2012).

The Alboran Sea oceanography is controlled by the water masses exchange between the Mediterranean and the Atlantic Ocean. The low-salinity Atlantic waters enter to the Mediterranean Sea as a surface layer while high salinity waters from the Mediterranean outflow into the Atlantic Ocean as a deeper-water mass (Mediterranean Outflow Water, MOW). Surface waters at the Alboran Sea are typically defined as Modified Atlantic Water (MAW), composed mainly by a mixing of Surface Atlantic Water (SAW) and the Eastern North Atlantic Central Water (ENACW) (Bray et al., 1995; Millot, 2009) (Fig.1a and b). This ENACW has been characterized by central waters from two different sources areas converging in the northwest of the Iberian Peninsula. One source has a subpolar origin (ENACWsp) which is formed near 46ºN around the Celtic Sea (McCarteney and Talley, 1982). The other source has a subtropical origin (ENACWst) formed near 35ºN around the Azores Islands (Fiúza, 1984) (Fig. 1a). Hydrographic properties of these water masses are related to changes in heat and salt transport through the STG – SPG that ultimately modulate the AMOC (ie: Cléroux et al., 2012; Thornalley., 2009; Gao and Yu 2008; Böning et al., 2006). MAW describes two anticyclonic gyres at the Alboran Sea (Western and Eastern Alboran Gyres, WAG and EAG) when it progresses eastwards changing its proprieties (Fig 1b). The ALB-2 core is located in the center of the WAG. Sediment fluxes based in sediments traps from the same location showed relatively high values attributed to a funneling effect by the gyre capturing particles from the edges toward the center (Fabres et al., 2002).

3. MATERIALS AND METHODS

Core HER-GC-ALB2 (here abbreviated as ALB-2) was retrieved from the Alboran Sea (Lat: 36°0’44.80”N; Log: 4°16’24.38”W; 1313 mwd) during the HERMESIONE cruise in

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Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

2009 (Fig.1b), on board of BIO Hespérides. Core ALB-2 was drilled with a gravity core system and covers a continuous sequence of 337 cm length.

Geochemical analysis were performed on the planktonic foraminifera *Globigerina bulloides*. The individual specimens were hand-picked between 250 – 355 µm size fractions in order to obtain a homogenous population. The selected specimens presented apparently well-preserved and clean shells.

3.1 Stable Isotopes

Around 10 specimens of *G. bulloides* per sample were crushed between two glasses under the binocular microscope in order to open the chambers and allow the cleaning of the shells interior. Samples were cleaned with 500 µl of methanol in an ultrasonificated bath during 30 seconds in order to mobilize the clay residues. The residual methanol was removed and samples dried prior to analysis. The analyses were performed with an isotope-ratio mass spectrometry (IRMS) Finnigan-MAT 252 linked online to a single acid bath CarbonKiel-II carbonate preparation device at Scientific and Technological Centre (CCiT) of the University of Barcelona. The analytical precision of laboratory standards for $\delta^{18}O$ was better than 0.08 ‰. Calibration to Vienna Pee Dee Belemnite (VPDB) was carried out by means of NBS-19 standards (Coplen, 1996).

Seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) was obtained after removing the temperature effect, with the Shackleton paleotemperature equation (Shackleton, 1974) on the *G. bulloides* $\delta^{18}O$ signal using the *G. bulloides* Mg/Ca–SST values. The results are expressed in the SMOW (Standard Mean Ocean Water) water standard ($\delta^{18}O_{sw}$) after the correction of Craig (1965).

3.2 Chronologies

Chronology from core ALB-2 is based on fourteen ^{14}C AMS dates measured in planktonic foraminifera samples handpicked from the 215 – 355 µm fraction (8 – 33 mg). The top

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

ten radiocarbon dates are based on monospecific samples of *Globigerina inflata,* and the four older dates are based on multispecific samples of planktonic foraminifera (Supplement Table S1). Radiocarbon ages were calibrated with the MARINE13 calibration curves (Reimer, et al., 2013). The age model was build using the Bayesian statistics software Bacon with the statistical package R (Blaaw and Christien, 2011) for marine sediments (Supplementary Figure S2). From the core top to the first ^{14}C AMS date (10 cm), the age model was performed by a linear regression assuming the age of the core top to be that of the sediment core recovery (2009 yr CE or -59 yr BP). The chronology at the base of the core was established by isotopic stratigraphy by correlating a well-expressed positive excursion in the $\delta^{18}O$-ALB2 to a well dated comparable structure in the $\delta^{18}O$-MD95-2043 measured in both cases on *G. bulloides* (Supplementary Table S1 and Supplementary Figure S2). According to the generated age model, core ALB-2 covers the last 15 kyr BP with an average sedimentation rate of 22 cm/kyr that provides a time resolution of about 45 yr for the applied sampling interval (1 cm).

Age model for MD99-2343 was improved from that originally published by Frigola et al. (2007) in base to nine new ^{14}C AMS dates incorporated to the previous age model (Supplement Table S3). The updated age model is provided with nineteen ^{14}C AMS recovering the last 17 kyr BP. This age model update was built using the Bayesian statistics software Bacon with the statistical package R (Blaaw and Christien, 2011) for marine sediments (Supplementary Figure S4). The age of the core top was assumed to be the recovered year (1999 yr CE or -49 yr BP). The chronology during the deglaciation was improved by adding two tie points by correlating a marked $\delta^{18}O$ structure in both the Menorca core MD99-2343 and the Alboran core MD95-2043 (Supplementary Table S3 and Supplementary S4).

3.3 *G. bulloides* Mg/Ca ratios and Sea Surface Temperatures estimates

Mg/Ca measurements in core ALB-2 were done over samples containing 50-60 specimens of *G. bulloides,* gently crushed between two glasses under the binocular in order to open the chambers and allow the removal of contaminant phases from the shell interior. The cleaning protocol for the foraminifera shells was based on the full procedure described by Pena et al. (2005) which includes the reductive step. Once cleaned each sample was dissolved in ultra-pure acid nitric 1% with Rh as an internal standard. After dissolution, samples were centrifuged to remove any potential un-dissolved mineral particles. Procedural blanks were routinely produced to detect any potential contamination problem during the sample cleaning and dissolution process.

Instrumental analysis were performed in an ICP-MS Perkin-Elmer Elan-6000 at the CCiT-UB. Every four samples, a standard solution was analysed. The standard solution was prepared gravimetrically with known concentrations of Mg, Ca, Mn, and Al, and produced with a ratio (element/Ca) comparable to that expected for the samples. Analytical reproducibility obtained in base to the gravimetric standard samples was 98.38% for the Mg/Ca ratio. Moreover, all Mg/Ca ratios in this core were corrected using the same gravimetric standard for each ICP-MS round using a sample-standard bracketing (SSB) method providing a valid solution with high-precision and accuracy of every sample measurement.

The obtained *G. bulloides* Mg/Ca ratios were then compared with other analysed ratios, i.e. Al/Ca and Mn/Ca, in order to identify potential contaminations of remaining manganese oxides and/or aluminosilicates in the samples (Barker et al., 2003; Pena et al., 2005). Such potential contamination could provide anomalous high *G. bulloides* Mg/Ca ratios and therefore, overestimating the inferring SST values. In the ALB-2 record, Mn/Ca ratios above 2σ (0.29 mmol/mol) were removed (Supplementary Figure S5a). The Al/Ca ratio was considered to potentially indicate presence of un-removed silicates (likely clays) and those samples with values above 2σ (1.74 mmol/mol) were also removed (Supplementary Figure S5b).

G. bulloides Mg/Ca records from cores MD95-2043 and MD99-2343 were produced following a comparable procedure to that described for the ALB-2 core but, for these cores, the data to estimate analytical reproducibility and the Mn/Ca and Al/Ca ratios to evaluate the potential interference of contamination phases were not available. Consequently, the uncertainties associated with these complementary SST-records are larger than those associated with the ALB-2 sediment core, which is the main focus of this study. *G. bulloides* Mg/Ca ratios from core ODP 976, also included in the discussion, were already published by Jiménez-Amat and Zahn (2015).

The *G. bulloides* Mg/Ca ratios of the four discussed sediment cores have been transferred to SST applying the calibration from Cisneros et al. (2016). This calibration is based on those *G. bulloides* Mg/Ca ratios available from core top samples of the North Atlantic Ocean (Elderfield and Gansen, 2000) and the addition of core top samples from the western Mediterranean Sea. These Mediterranean samples enhance the temperature range of the original calibration toward the warmer edge and thus, the obtained calibration covers better the oceanographic conditions of the western Mediterranean Sea. This calibration provides realistic SST for the *G. bulloides* bloom season around April-May over the western Mediterranean Sea (Cisneros et al., 2016).

4. RESULTS AND DISCUSSION

4.1 Holocene evolution in western Mediterranean *G. bulloides* – $\delta^{18}O$ records

The new $\delta^{18}O$ record from ALB-2 is compared with other previously published high resolution $\delta^{18}O$-records from the western Mediterranean Sea (Cacho et al., 1999; Frigola et al., 2007; Jiménez-Amat and Zahn 2015) in order to evaluate the regional significance of the recorded signal (Fig. 2). The main patterns in the $\delta^{18}O$ records show an extraordinary resemblance between them and even several centennial scale structures can be correlated through the cores, taking into account the individual core chronological

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions Open Access

uncertainties. The isotopic depletion associated with the last termination ends in all four records at around 9 kyr BP. Along the Holocene all the *G. bulloides* $\delta^{18}O$ records are rather stable, with several short oscillations (0.2-0.3‰) and a slight enrichment trend toward the late Holocene (Fig. 2). This comparison supports the regional value of the captured paleoceanographical signal and the robustness of the individual age models.

In terms of absolute values of *G. bulloides* $\delta^{18}O$ records, clear differences can be detected between the different cores. Both ALB-2 and ODP976 cores, located in the westernmost part of the Alboran Sea, display the lightest values (note that curves in Fig. 2b are plotted with independent y axis). While core MD95-2043 located in the eastern part of the Alboran Sea show heavier $\delta^{18}O$ values than the other two Alboran records (Fig. 2b). Finally, core MD99-2343, located north of Minorca Island, shows the heaviest $\delta^{18}O$ values. Such isotopic pattern is consistent with the regional oceanography, showing the lightest $\delta^{18}O$ values in those sites with stronger influence of North Atlantic surface inflow while $\delta^{18}O$ values become heavier along its path into the Mediterranean Sea. This situation reflects the excess of evaporation of the Mediterranean Sea (Béthoux, 1980; Lacombe et al., 1981) that results in an enhancement of the salinity but also of the marine water $\delta^{18}O$ values. It is interesting to note that the presented isotopic records show a strong gradient between the western and eastern Alboran Sea (of about 0.5‰), probably due to a strong surface mixing with the underlying Mediterranean waters originated by the two anticyclonic gyres (Tintore et al., 1988; Millot., 1999), and supporting that the Atlantic Inflow became rapidly modified along the Alboran Sea. The isotopic change from the eastern Alboran Sea core (MD95-2043) and the Menorca core (MD99-2343) is even larger (of about 0.7‰) reflecting the long path of these inflowing Atlantic waters through the western Mediterranean Sea until reaching the Menorca location.

4.2 Sea Surface Temperatures: Multi-record and multi-proxy comparison

According to the ALB-2 Mg/Ca-SST record, the Holocene maximum temperatures (18.3±1.4°C; uncertainties of average values represent 1σ; uncertainties of absolute

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions

values are those derived from the Mg/ Ca–SST calibration) were reached at the onset of the Holocene ~11.0 kyr (Fig. 3b) and a general cooling trend until the present characterizes the record, punctuated by several short term oscillations (maximum of 2ºC). However, the ALB-2 SST record can be divided in three main intervals. The first interval correspond to most of the Early Holocene (11.7 – 9 kyr BP) when SST were warmest and relatively stable (no significant trend) oscillating at around an average value of ~16.2±1.3°C (Fig. 3b). The second interval displays a general cooling trend of ~4°C ending at around 4.2 kyr BP when minimum Holocene SSTs were reached (~12.8±1.1°C) (Fig. 3b). The last and most recent interval does not show any clear warming/cooling trend although shows warmer SST than previous interval (average SST of ~14±1.2°C) and intense SST oscillations (~1.2°C) of longer duration than those recorded during previous intervals (Fig. 3b).

The ALB-2 *G. bulloides* Mg/Ca-SST record has been compared to other three SST records from the western Mediterranean Sea that were calculated following the same Mg/Ca-SST procedure (Fig. 3b-e). The chronologies of the four compared records are very robust (Fig. 2c) and totally independent for the Holocene period (ALB-2 and MD99-2343: This study; ODP976: Combourieu Nebout et al., 2002; MD95-2043: Cacho et al., 1999). The sampling resolution of the ALB-2 record is higher than in the other sites, but the main patterns agree well between all the compared records. Maximum SST occurred around 11 kyr BP in all records, and also a general cooling trend can be observed during Early-Mid Holocene ending in all cases before the Late Holocene (Fig. 3b-e). Absolute values also show a good agreement, when the resolution is high enough, some millennial scale structures can even be correlated between the four records. This multi-core comparison strongly supports the value of *G. bulloides* Mg/Ca in this region as a SST proxy, and gives confidence that the obtained SST records reflect true regional environmental conditions. Nevertheless, these Mg/Ca-SST reconstructions show evident differences with the previous published SST reconstructions based on alkenones

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

measurements that needs a further discussion (Fig.3f; Cacho et al., 2001; Martrat et al., 2004 and 2014; Jiménez-Amat and Zahn 2015).

Alkenones-SST reconstructions are based on the relative abundance of di and tri-unsaturated C_{37} alkenones mostly produced in the Alboran Sea by the marine coccolithophore *Emiliania huxleyi* (Valkman et al., 1980; Prahl et al., 2000; Ausin et al., 2015). The comparison between *G. bulloides* Mg/Ca-SST and alkenones-SST (also studied by Jiménez-Amat and Zahn 2015) shows remarkable differences in both absolute values and main patterns, even when both proxies are measured on the same core, as it can be observed in core MD95-2043 and also ODP 976 (Fig. 3d and f). For the Holocene period, maximum SST in the alkenones record was reached latter (~10 kyr BP) than in Mg/Ca-SST records, and thenceforth the alkenones-SST record shows a rather flat pattern for the whole Holocene, with a slight cooling trend of about 1ºC. In contrast, ALB-2 *G. bulloides* Mg/Ca-SST (Fig. 3b) show larger variability in the long term but also in the short term variability. Holocene absolute SST values in the alkenones record are warmer (20-18ºC) than those recorded by the Mg/Ca record (18-13ºC).

Alkenones-SST records have been interpreted to reflect an annual average (Prahl, et al., 2000; Cacho et al., 2001, Martrat et al., 2004, 2014) although slightly biased toward the colder values since cocccolith productivity during the very stratified and oligotrophic summer months of the Mediterranean Sea is limited (Ternois et al., 1996; Sicre et al., 1999; Bárcena et al., 2004; Versteegh et al., 2007; Hernández-Almeida et al., 2011). In contrast, the Mg/Ca-SST record in the western Mediterranean Sea has been argued to show a narrower seasonal window, in particular during spring months (April-May) (Bárcena et al., 2004; Cisneros et al., 2016). This observation agrees with the preferential habitat of *G.bulloides* that needs nutrient supply by vertical missing (Rao et al., 1988; Hemleben et al., 1989; Kemle-von Mücke and Hemleben, 1999; Bárcena et al., 2004). Moreover maxima foraminifera fluxes in sediment traps from the western Mediterranean Sea are concentrated in April-May, even that in autumn months

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past
Discussions
Open Access

(November-December) a second small increase can also occur (Bárcena et al., 2004; Rigual-Hernańdez, 2012). Current SSTs in the Alboran Sea are on average 17.9 ºC, 18.3 ºC and 18.7ºC, for spring months, autumn and on annual average, respectively (Shaltout and Omstedt., 2014). Consequently, alkenones-Mg/Ca SST offset may reflect both seasonal but also depth differences between *E. huxleyi* and *G. bulloides* habitats. The rather smooth behaviour of the alkenone signal, in contrast to the Mg/Ca signal, has previously been recognised and attributed to the intrinsic characteristics of the proxy measurements (Laepple and Huybers, 2013). The number of individuals that integrates the SST signal in a single measurement is of several orders the magnitude larger in the alkenones than in the Mg/Ca analyses (Laepple and Huybers, 2013). This situation favours the integration of several seasons and years in the alkenone-SST signal while Mg/Ca-SST signal will be more sensitive to seasonal and inter-annual variability (Jiménez-Amat and Zahn 2015) In base to these observations, we interpret that the Mg/Ca-SST appears to represent better spring season variability, allowing to characterise better the short and long term SST variability during the relatively stable Holocene period.

But the most remarkable difference between the Mg/Ca and alkenones SST reconstructions corresponds to the deglacial period (at the end of GS-1 or Younger Dryas - YD). Both alkenones and Mg/Ca SST records show a cooling of about ~3 – 4ºC at the onset of the GS-1 (YD) but the big difference occurs at the end of this interval. Both alkenones and Mg/Ca records show an intra-YD first warming (Cacho et al., 2001) and then alkenones SST continues the deglacial warming while Mg/Ca record shows a cooling. In order to explore better this proxy discrepancies we have also compared these two records for the glacial period in Figure 4. *G. bulloides* Mg/Ca-SST during the last glacial period record the same oscillations and absolute values than alkenones-SST, they both agree in the first warming of the deglaciation but clearly, the second warming phase of the deglaciation does not appears in the Mg/Ca record (Fig. 4). The absence of SST warming during the second phase of the deglaciation can be observed in the four Mg/Ca records presented in Figure. 3. Thus, this is a proxy characteristic that may reflect the limited capacity of *G. bulloides* to adapt to the large temperature change occurring during the deglaciation. *G. bulloides* has different genotypes adapted to different ranges of water temperatures, from transitional to subpolar water (Kucera and Darling 2002; Kucera et al., 2005) but they start to be scarce in water with temperatures over 18ºC. This agrees with the maximum temperatures recorded during both glacial and interglacial periods in the Mg/Ca records (Fig. 4). Consequently we interpret that *G. bulloides* has a resilient capacity to change the growth season in order to survive the large deglacial-SST changes in the region. We propose that during the glacial period and the first part of deglaciation *G. bulloides* could have had its maximum representation during the autumn bloom when upwelling conditions reappear after the warm sea summer stratification. That could have allowed *G. bulloides* to grow in a relatively mild upwelling season during the glacial period. Nowadays autumn SST values are comparable to the annual average SST values and that could explain the comparable SST values of both alkenones and Mg/Ca proxies. However the second deglacial warming could have been too extreme for *G. bulloides* and they would have moved to the spring upwelling bloom with colder SSTs than those during autumn. Consequently we hypothesize that the absence of the second deglacial warming in the *G. bulloides*-Mg/Ca record may reflect a resilience strategy to change its habitat. Upon entering the Holocene, when SST variability was shorter and within its habitat tolerance, *G. bulloides* became a good sensor of interglacial SST variability (Fig. 3 and 4).

4.3 Holocene evolution in Alboran surface hydrography

The overall Holocene SST evolution in the Alboran Sea is described in three different phases (Fig. 5c): (a) maximum SST during the early Holocene (11 - 9 kyr BP); (b) cooling trend across the middle Holocene (9 – 4.2 kyr BP); (c) relatively colder temperatures with intense millennial-scale oscillations for the late Holocene (4.2 – 0 kyr BP). This general

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions
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SST pattern also agrees well with that described for the North Atlantic and Western Mediterranean Sea in base to regional data compilation (Marchal et al., 2002; Kim et al., 2004; Rimbu et al., 2004; Wanner et al., 2008) and with the expected Holocene redistribution of solar energy by the changing orbital configuration according to atmosphere-ocean general circulation model (Fig. 5a and c; Lorenz and Lohmann 2004). Nevertheless, the intensity of the Holocene SST changes in the Alboran Sea (over 5ºC) exceeds that expected by simply orbital changes in insolation (~1.6ºC in atmosphere) (Lorenz and Lohmann 2004), therefore other factors need to be considered to explain the magnitude of the recorded SST.

The period of maximum SST in the Alboran Sea (11 – 9 kyr BP) occurred while the North Atlantic ocean was still under the influence of meltwater pulses from the Laurentide ice sheet (Fig. 5b) that injected fresh-water in to the surface north Atlantic Ocean. This situation induced a stratification in the north Atlantic and consequently a weakening the SPG circulation (Thornalley et al., 2009). At lower latitudes, it has been proposed that the heat transport from the STG toward the north Atlantic was reduced (Repschläger et al., 2017). The consequent heat accumulation in the STG could have contributed to form a warmer inflow into the Mediterranean Sea and thus lead to the observed maximum SST in the Alboran Sea (Fig. 5c). But it is also relevant to note that this early Holocene warm period (11 – 9 kyr BP) in the Alboran Sea corresponds to the last stage of an organic rich layer (ORL) formation (Fig. 5e). This ORL has been associated to a strong western Mediterranean stratification phase lead by the deglacial sea level rise reducing the vertical mixing. (Cacho et al., 2002; Rogerson et al., 2008). As a consequence of this situation, the modification of Atlantic inflow through its path into the Mediterranean could be reduced and thus favouring the persistence of the warm conditions of the inflowing subtropical waters.

At around 9 kyr BP, the Alboran SST record (Fig. 5c) starts a progressive cooling trend that culminates reaching the minimum values at around 4.2 ka BP. The onset of this

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

cooling trend is coincident with the development of a well-mixed surface layer (Fig. 5b) in the North Atlantic due to the reduction of the deglacial melting (Thornalley et al., 2009). This situation would have allowed an enhanced transport of subtropical waters towards higher latitudes, releasing the previous heat accumulation in the STG and potentially, leading to the entrance of a cooler inflow into the Mediterranean Sea. In addition, 9 kyr BP also marked the end of the Western Mediterranean stratification phase that led the formation of the last ORL in the Alboran Sea (Fig. 5e). This end occurred at the time of a strong increase in the speed of deep water currents (Fig. 5d) associated with the formation of the Western Mediterranean Deep Waters (Frigola et al., 2007). The reduction in surface stratification in the Alboran Sea would have led to an increased water mixing of the inflowing Atlantic waters that could contribute to the observed cooling trend. This situation was apparently also linked to an increase in the local upwelling conditions developed by the establishment of the western anticyclonic gyre of the Alboran Sea that, according to cocccolith assemblages, occurred after 7.7 kyr BP (Ausin et al., 2015). In addition, the described SST cooling trend for this period, could also be promoted by some additional atmospheric forcing. Several authors have suggested a southward displacement of North Atlantic westerlies during this period, inducing a southern penetration of winter storm tracks (Desprat et al., 2013; Fletcher et al., 2012; Chabaud et al., 2014; Zielhofer et al., 2017). Therefore, a combination of factors, internal and external to the Alboran Sea could have accounted for the observed SST cooling trend after 9 kyr and until 4.2 kyr BP, when a change occurred in both long and short term variability.

At about 4.2 kyr BP a double peak structure of minimum SST occurred (Fig. 5c) reaching ~12.8°C and representing the minimum values of the record. After this event, the long term cooling trend ceased while an intense millennial-scale variability developed, involving SST oscillations over 2°C. This event is apparently synchronous with a peak in the record of deep water current intensity (Fig. 5d) suggesting that deep convection

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions

was strengthened in the Western Mediterranean Sea during this 4.2 event, but not more than during other previous and later Holocene events of this record (Frigola et al., 2007). On another hand, the North Atlantic record (Fig. 5b) indicates that the 4.2 cold SST over the Alboran Sea correspond to one of the millennial scale stratification events that occurred along the Holocene, interpreted as a weak mode of SPG circulation (Thornalley et al., 2009). This situation contrasts with that observed during the early Holocene period, when weak SPG circulation coexisted with maximum SST in the Alboran Sea. Interestingly, after the 4.2 event, during the late Holocene, both the Alboran record and also the North Atlantic record show an intense millennial-scale variability, with minimums in Alboran SST occurring systematically during periods of weak SPG circulation (Fig 5b and c). However, further information would be required to establish a mechanism that could potentially link these apparent changes in late Holocene AMOC and properties in the Atlantic inflow in the Alboran Sea.

A further insight into the Holocene evolution of the inflowing Atlantic water into the Mediterranean Sea comes from the observation of the obtained ALB-2 $\delta^{18}O_{sw}$ reconstruction (Fig. 5f). This record also differentiates three Holocene periods consistent with those defined in base to the SST record (Fig. 5c). The ALB-2 $\delta^{18}O_{sw}$ record is compared with another $\delta^{18}O_{sw}$ record (Fig. 5g) that reflects conditions of the subsurface waters from the subtropical gyre (Repschläger et al., 2017). Interestingly, the relation between these two records change for the three defined Holocene intervals (Fig. 5f and g). During the early Holocene Alboran waters were heavier than those from the STG as should be expected for an inflowing modified water after mixing with Mediterranean source isotopic heavier water masses. During the middle Holocene phase, while Alboran-SST followed a cooling trend, the $\delta^{18}O_{sw}$ record oscillates around its lightest values, even lighter than those from the STG during the same period, and this difference became larger across the interval (Fig. 5f and g). Such a situation could suggest that the inflowing waters into the Mediterranean Sea are also feeding by some lighter water mass

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

likely from a higher latitude source. This is consistent with the previous discussed enhanced transport of subtropical waters towards higher latitudes during this period that would have led, to a stronger southward influence SPG source waters that would ultimately get into the Atlantic inflowing waters. This situation would be coherent with the described intensification of the SPG by Thornalley et al. (2009) and the dominant influence of subpolar source central waters at intermediate depths of the mid-latitude North Atlantic (Colin et al., 2010). After the 4.2 event the STG and Alboran $\delta^{18}O_{sw}$ records converge to similar values (Fig. 5f and g). This supports a reduced southward influence of SPG waters during the late Holocene, consistent with the interpreted STG source of intermediate waters in the mid-latitude North Atlantic (Colin et al., 2010) and the end of the mid Holocene SST cooling trend described previously for the Alboran Sea. The late Holocene millennial scale variability is difficult to characterise in this Atlantic-Mediterranean $\delta^{18}O_{sw}$ comparison (Fig. 5f and g) due to uncertainties in the relative chronologies and errors in the proxy reconstruction. Thus further information needs to be explored to ultimately determine the nature of a potential late Holocene Atlantic-Mediterranean millennial scale connection.

5. CONCLUSIONS

The analysis of Mg/Ca derived SST and the $\delta^{18}O$ from the ALB-2 record have allowed the reconstruction of the paleoceanography of the Alboran Sea during the Holocene and its possible interactions with the Atlantic Ocean. The comparison of new generated oxygen isotopes ($\delta^{18}O$) and Mg/Ca-SST records from ALB-2 with the others western Mediterranean records confirms a common oceanographic signal and evidences the fast modification of the Atlantic Water Inflow in to a more Mediterranean signal likely reflecting surface mixing with the underlying Mediterranean waters.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions
Open Access

This multi-core comparison of the Western Mediterranean *G. bulloides* Mg/Ca-SST signal, strongly supports the value of this proxy to reconstruct true regional environmental conditions. However, when Mg/Ca-SST records are compared with the previously published alkenone-SST records significant differences emerge. This proxy comparison is extended to the glacial period, observing a major proxy difference during the deglaciation, particularly during the second warming phase occurring after the YD period, which is almost absent in all the Mg/Ca-SST records. We interpret that this damped warming in the Mg/Ca record reflects a resilient capacity of *G. bulloides* to change the growth season in order to compensate the large SST deglacial warming (above 8ºC according to the alkenone-SST record). In this regard, we argued that during the last glacial period and the first part of the deglaciation, *G. bulloides* would had mostly grown during the milder upwelling season (autumn) while, after the YD, *G. bulloides* minimized the impact of the warming by developing mostly during the colder upwelling season, (spring) which is also the current situation. In contrast, during the Holocene, the SST variability is far larger in the Mg/Ca-SST record (~5ºC) than in the alkenone-SST record (~2ºC). We interpreted this Mg/Ca-SST variability as a true climate evolution of a single season, spring, while the reduced variability in the alkenone-SST responds to a well averaged annual signal.

The new high resolution Holocene Mg/Ca-SST record differentiates three intervals according to its main patterns: (1) The warmest SST values occurred during the Early Holocene (11.7 – 9 kyr BP); (2) During the middle Holocene occurred a continuous cooling trend that culminated with the coldest Holocene SST in a double peak structure centred at around 4.2 kyr BP; (3) The Late Holocene (4.2 kyr BP to the present) did not follow any clear cooling/warming trend but millennial-scale oscillations were enhanced. This general Holocene SST evolution matches to some extend solar energy redistribution by the changing orbital configuration, nevertheless, the intensity of the changes and the short term variability requires of the action of some other factors.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions
Open Access
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The warmest SST of the Early Holocene (11 – 9 kyr BP) occurred while intense meltwater pulses from the Laurentide ice sheet could have led to a reduction in the northward heath transport from the STG towards north Atlantic, the consequent heat accumulation could have contributed to the warm inflow in to the Mediterranean Sea. These warm conditions could also be favoured by the enhanced surface stratification in the Western Mediterranean that lead the last ORL formation.

The onset of the cooling trend occurred at 9 kyr BP and was coincident with the re-establishment of well-mixed surface and deep water layers that ended the ORL deposition in the Alboran Sea. This long term cooling trend is also coincident with the increase of the upwelling conditions on the Alboran Sea and with a described southward displacement of the North Atlantic westerlies. The relative evolution of the $\delta^{18}O_{sw}$ records from Alboran sea and the STG suggest the arrival through Gibraltar of light waters from northern latitudes, supporting a enhance influence of high latitudes north Atlantic conditions in the inflowing waters to the Mediterranean Sea. In summary, the described middle Holocene SST-cooling trend could reflect a complex interaction of external and internal factors into this Mediterranean region.

The 4.2 kyr BP event is recorded in the Mg/Ca-SST as a double peak event, reaching the lowest SST of the Holocene, and it ended the cooling trend of the previous interval. This 4.2 event marks the onset of an intense millennial-scale variability that dominated during the Late Holocene and that coincides with an event of intense WMDW formation. A comparable millennial-scale variability has been previously described further north in the North Atlantic Ocean, in relation to the intensity of the SPG. The ultimate connections between these North Atlantic changes and Alboran Sea need of further information to be fully understood but our observations highlight that the Atlantic-Mediterranean connections through the inflow operated in a different way during the Early and Late Holocene.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

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Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

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Climate of the Past
Discussions
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Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Figure Capture

Figure 1: Schematic modern surface and central hydrography of the North Atlantic currents. Basic map obtained by © 2008-2018, Marine Geoscience Data System - All Rights Reserved. Warm surface currents are shown by red dashed arrows. Central currents are shown by light-blue dashed arrows. Oceanographic gyres are represented by blue/red soft colored circles. Abbreviations are: NAC, North Atlantic Current; AC, Azores Current; PC, Portugal Current; ENACWsp, East North Atlantic Central Water Subpolar; ENACWst, East North Atlantic Central Water Subtropical; SPG, Subpolar Gyre; STG, Subtropical Gyre; WMDW, Western Mediterranean Deep Water; AI, Atlantic Inflow; MAW, Modified Atlantic Water. Red dots black circled indicates the cores locations.

Figure 2: Comparison of $\delta^{18}O$ (VPDB) records and their ^{14}C calibrated dates from the western Mediterranean sea along the last 17 cal. kyr BP. (a) $\delta^{18}O$ ‰ NGRIP record. (b) From the top to the base in green color ranges $\delta^{18}O$ ‰ (VPDB) records from the cores ALB2, ODP976 (Combourieu-Nebot et al., 2002), MD95-2043 (Cacho et a., 1999) and MD99-22343 (Minorca Drift). Note ALB2 $\delta^{18}O$ ‰ (VPDB) record is plotted with an independent y axis from the others in order to help on the figures compression. (c) ^{14}C calibrated dates with the available errors from each record shown above. Each date is colored with the same color as the record excluding the yellow dots which represents the tie-points.

Figure 3: Western Mediterranean SST multi-record comparison for the last 17 cal. kyr BP. (a) In red, summer insolation at 40°N. (b) Mg/Ca – SST (°C) from the ALB2. Light-blue dots correspond to each SST result and in dark bold blue the 3 points average. Dark blue arrows above the record correspond to the three Holocene intervals described in the text. (c, d and e) Mg/Ca – SST (°C) from ODP976 (Jiménez-Amat and Zahn 2015), MD95-2043, and MD99-2343 respectively (blue bold colored) compared with ALB-2 3 points average Mg/Ca – SST (°C) (black line underneath). Note that both records from each plot are plotted in the same y axis. (f) Alkenones - SST (°C) from MD95-2043 (Cacho et al., 1999).

Figure 4: Western Mediterranean SST from alkenones and *G. bulloides* Mg/Ca multi-comparison for the last interglacial and the following present interglacial period. Note that the each following comparison have the same y axis. (a) In blue lines (ALB-2; this study and ODP976; Jiménez-Amat and Zahn 2015) *G. bulloides* Mg/Ca – SST compared with alkenones SST (Martrat et al., 2014) from the same ODP976 record. (b) In blue lines (ALB-2 and MD95-2043; both in this study) *G. bulloides* Mg/Ca – SST compared with alkenones SST from the same MD95-2043 record (Cacho et al., 1999). (c) In blue lines (ALB-2 and MD99-2343; both in this study) *G. bulloides* Mg/Ca – SST compared with alkenones SST from the MD95-2043 record (Cacho et al., 1999).

Figure 5: Holocene evolution in the Alboran Sea surface hydrography related with oceanographic processes in the North Atlantic Ocean. (a) In red, thr summer insolation at 40°N. (b) In purple, 3 points average of density differences (kg/m^3) between *G. bulloides* and *G. inflate* from the North Atlantic record RAPiD-12-1K (Thornalley et al., 2009). (c) The new Mg/Ca – SST (°C) presented in this work from the ALB2 (Alboran

Sea). Light-blue dots correspond to each SST result and in dark bold blue the 3 points average. (d) In brown, the UP10 fraction (%) from the Minorca drift core MD99-2343 (Frigola et al., 2007). (e) In grey filled line, the concentration of C_{37} alkenones in the Alboran Sea record MD95-2043 (Cacho et al., 2002). (f) In green, the new $\delta^{18}O$ ‰ (SMOW) presented in this work from the ALB2 (Alboran Sea). (g) In orange, the calculated $\delta^{18}O$ ‰ (SMOW) from the south Azores record GEOFAR-KF16 (Repschläger et al 2017). Vertical bar centered: 8.4 – 9 cal kyr BP correspond to the Alboran Sea and North Atlantic synchrony in oceanographic changes; 4.2 cal. kyr BP correspond to the double peach structure observed in ALB-2 Mg/Ca – SST. The four vertical grey bars during the Late Holocene correspond to cold events of ALB-2 Mg/Ca – SST.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions

Figure 1

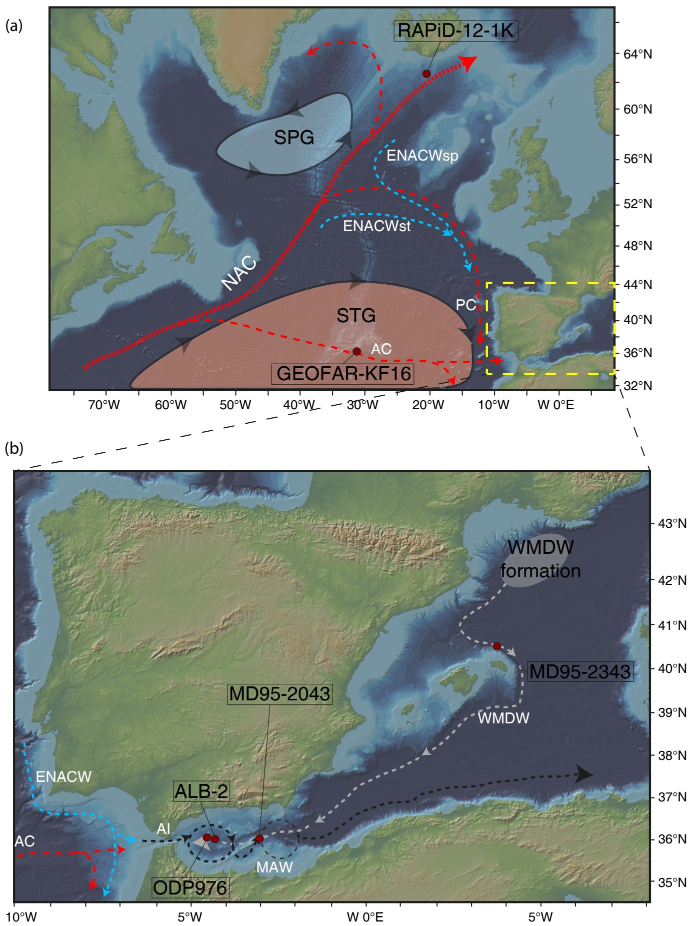
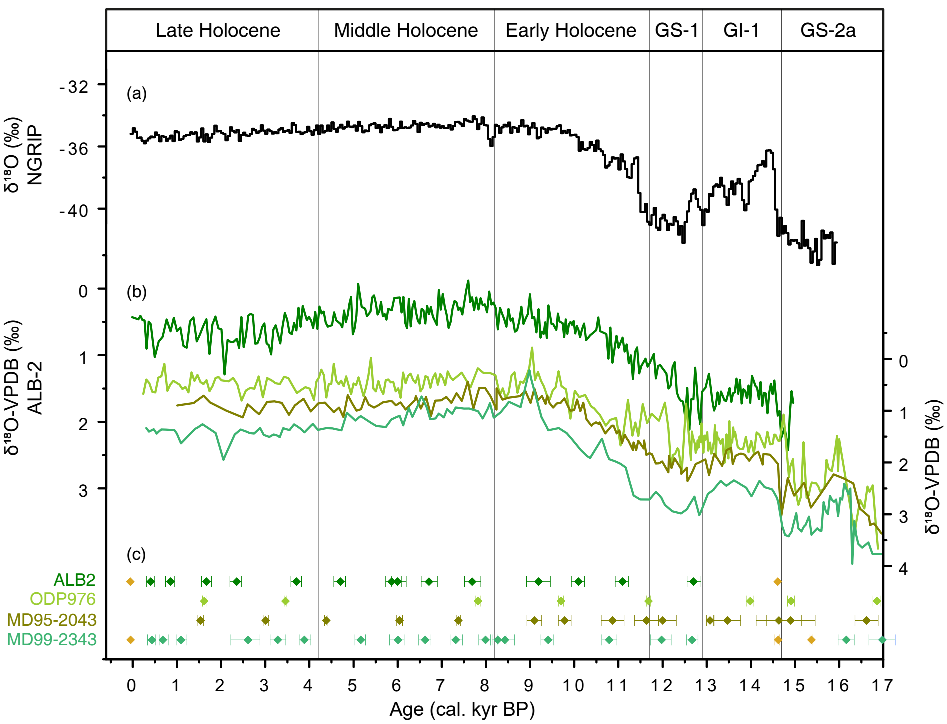
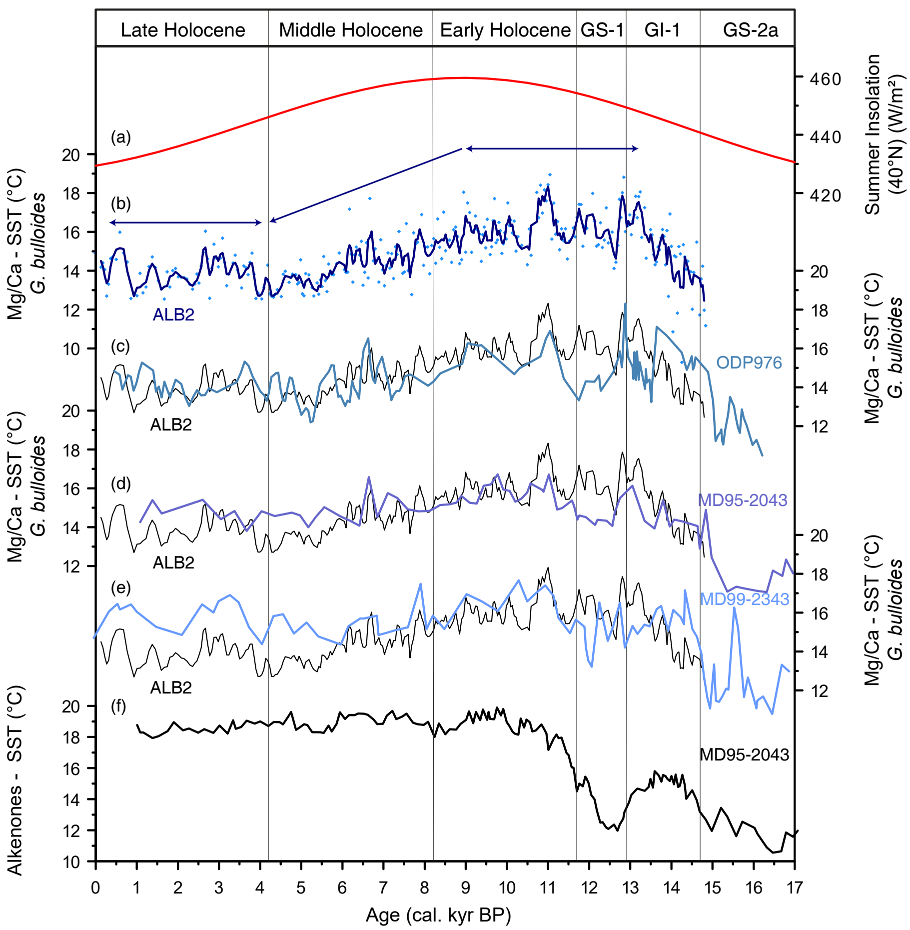


Figure 2


Late Holocene
Middle Holocene
Early Holocene
GS-1
GI-1
GS-2a
(a)
δ18O (‰) NGRIP
(b)
δ18O-VPDB (‰) ALB-2
δ18O-VPDB (‰)
(c)
ALB2
ODP976
MD95-2043
MD99-2343
Age (cal. kyr BP)

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

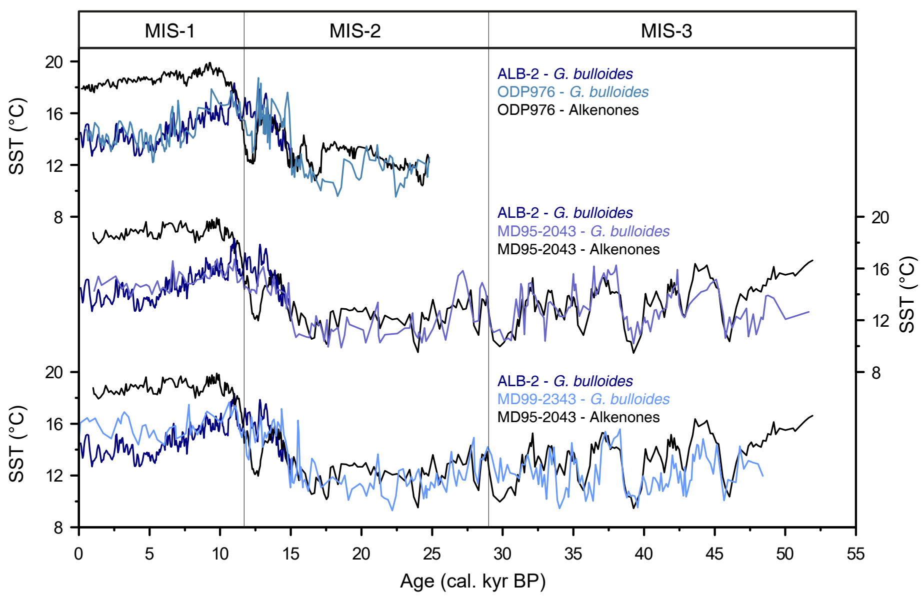
Figure 3



Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Climate of the Past Discussions

Figure 4



Clim. Past Discuss., https://doi.org/10.5194/cp-2018-163
Manuscript under review for journal Clim. Past
Discussion started: 29 November 2018

Figure 5