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DATABASES FOR SEA SURFACE PALEOTEMPERATURE BASED ON GEOCHEMICAL PROXIES FROM MARINE SEDIMENTS: IMPLICATIONS FOR MODEL-DATA COMPARISONS

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Clara BOLTON¹ & Camille CONTOUX¹

ABSTRACT

The Paleoclimate Model Intercomparison Project (PMIP) aims to simulate the response of Earth's climate system to changes in different climate forcing factors, focusing on six key intervals of the geological past (the mid-Piacenzian Warm Period at ~3.3-3.0 Ma, the last interglacial period at ~127 ka, the last glacial maximum at ~21 ka, the mid-Holocene at ~6 ka, the last millennium i.e. the 850-1850 Common Era (CE) time window, as well as the last glacial termination, i.e. the ~21-9 ka time window). Model evaluation is ultimately achieved via model-data comparison exercises, and such diagnoses rely on databases of proxy-based paleoclimate reconstructions available in the literature. In this context, we provide a review of the main geochemical sea surface temperature (SST) proxies (namely foraminiferal Mg/Ca ratio, the $U^{K_{37}}$, and the TEX_{86}) that are routinely used to aliment databases used in model-data comparisons, focusing on proxy systematics and specificities that may affect or bias SSTs reconstructed with each of these proxies. We then go on to discuss notorious mismatches between SST estimates derived from different proxies for all periods studied in PMIP, and aim to provide guidance for a better interpretation of these model-data mismatches. This review is deliberately aimed at helping the paleoclimate modeling community to better appraise how information on past SST variability is transferred to the marine geological record. In particular, when SST estimates based on different proxies provide contrasting SST signals, we stress the importance of looking at those contrasting signals through the prism of the ecology of the organisms at the origin of the SST proxies.

Keywords : Paleoclimate Model Intercomparison Project (PMIP), Sea Surface Temperature (SST), Databases, foraminiferal Mg/Ca, Alkenone unsaturation index ($U^{K_{37}}$), Tetraether index 86, (TEX_{86})

RÉSUMÉ

BASES DE DONNÉES DES PALÉOTEMPÉRATURES DE L'Océan DE SURFACE ISSUES DES PROXIES GÉOCHIMIQUES ANALYSÉS SUR LES SÉDIMENTS MARINS : IMPLICATIONS POUR LES COMPARAISONS MODÈLES-DONNÉES

Le Projet d'intercomparaison des modèles des paléoclimats (PMIP) vise à simuler la réponse du système climatique terrestre aux changements des différents facteurs de forçage du climat, en se concentrant sur six intervalles clés du passé géologique : la période chaude du Plaisancien moyen il y a environ 3,3-3,0 Ma, la dernière période interglaciaire à ~127 ka, le dernier maximum glaciaire à ~21 ka, l'Holocène moyen à ~6 ka, le dernier millénaire, c'est-à-dire la fenêtre de temps 850-1850 Common Era (CE), ainsi que la dernière terminaison glaciaire, c'est-à-dire la fenêtre de temps entre 21 et 9 ka. L'évaluation des modèles est réalisée par des comparaisons modèles-données, et de tels diagnostics reposent sur des bases de données de reconstructions paléoclimatiques basées sur les traceurs disponibles dans la littérature. Dans ce contexte, nous passons en revue les principaux traceurs géochimiques pour l'estimation des températures de surface de la mer (SST), à savoir le rapport Mg/Ca des foraminifères, l' $U^{K_{37}}$ et le TEX_{86} qui sont couramment utilisés pour alimenter les bases de données utilisées dans les comparaisons modèles-données. En se concentrant sur les spécificités des traceurs qui peuvent affecter ou biaiser les reconstructions de SST, nous discuterons ensuite des principales disparités entre les estimations de SST dérivées de différents traceurs et des modélisations des SST pour toutes les périodes étudiées dans le programme PMIP, et tenterons de fournir des indications pour mieux interpréter ces différences. Cette revue de l'état de l'art a pour objectif d'aider la communauté des modélisateurs à mieux comprendre les principales sources d'incertitudes des estimations de paléotempératures dérivées des archives sédimentaires océaniques. En particulier, lorsque les estimations de SST basées sur des traceurs différents fournissent des signaux SST divergents, nous soulignons l'importance de regarder ces signaux contrastés au travers du prisme de l'écologie des organismes à l'origine des traceurs de SST.

Mots-clés : Projet d'intercomparaison de la modélisation des paléoclimats (PMIP), températures océaniques de surface (SST), bases de données, Mg/Ca des foraminifères, index d'insaturation des alcénones ($U^{K_{37}}$), index tetraether 86 (TEX_{86})

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1 - INTRODUCTION

Since the middle of the 19th century, anthropogenic activities have driven the Earth's climate away from its pre-industrial background state (Abram *et al.*, 2016; IPCC, 2013). In this context, assessments of population or ecosystem vulnerability and adaptation strategies exclusively rely on climate model projections driven by different emissions scenarios. Over the last two decades, the climate modelling community has been working to evaluate the performance of climate models in the framework of the Paleoclimate Model Intercomparison Project (PMIP), through simulations of past climate background states and comparison of the modelling outputs to paleoclimate reconstructions (see Kageyama *et al.*, 2016 for an introduction of the fourth PMIP phase). The ongoing PMIP4 project will ultimately provide model outputs for 5 time slices: the Mid-Piacenzian Warm Period (mPWP, i.e. at ~3.3-3.0 Ma), the last interglacial period (LIG, i.e. at ~127 ka), the last glacial maximum (LGM, i.e. at ~21 ka), the mid-Holocene (MH, i.e. at ~6 ka) and the last millennium (LM, i.e. the 850-1850 CE time window) (Kageyama *et al.*, 2016), as well as a series of transient simulations of the last glacial termination (LGT, i.e. the ~21-9 ka time window) (Ivanovic *et al.*, 2016).

The model evaluation step requires researchers to compare model outputs to quality-controlled paleoclimatic databases compiling different metrics of past climates. Such paleoclimatic databases provide benchmarks for assessing climate models' skills. In those databases, the measurements of past oceanic changes are based on "proxies", that can be defined as "measurable descriptors for desired but unobservable environmental variables", such as SST in the case considered here (Wefer *et al.*, 1999). The main metric of past climatic change in the ocean is the sea surface temperature (SST), which has been the focus of many studies. Over the last few decades, numerous databases were assembled to reconstruct global continental temperature and SST fields during the relevant PMIP time-slices. Although the modelling community has made a sustained effort to perform this model evaluation (see e.g. Kageyama *et al.*, 2013), paleoceanographers are lagging behind in terms of producing extensive evaluation of databases with respect to geochemical and micropaleontological proxies for SST. Such a lag in paleoclimate database evaluation is partly due to the difficulties involved in compiling data from a mosaic of different proxies, each with their own specificities which are not always easy to objectively evaluate within a single database. For example, paleothermometers based on biomarkers such as the C₃₇ alkenone unsaturation index (U^K₃₇) and the Tetraether indEX with 86 carbon atoms (TEX₈₆) cannot easily be assigned to specific seasons and/or water depths because the biomarkers used in those two proxies are synthesized by different species of phytoplanktonic algae (for the U^K₃₇) and of archaea (for the TEX₈₆). In contrast, the seasonal and water depth preferences embedded in species-specific foraminiferal Mg/Ca can often be evaluated in the modern ocean using sediment traps that collect

particles sinking through the water column (Jonkers & Kucera, 2015), or with ecophysiological models that take into account the ecology of foraminifers (Lombard *et al.*, 2011). Besides ecological preferences, different geochemical proxies have also their own specific biases (see discussion in Chapter 2), complicating the comparison of multiproxy databases to model outputs.

Here we provide a brief overview of geochemical SST proxies used in SST compilations for some selected time windows relevant to the PMIP project. The objective is to provide guidance for model-data comparison studies, in particular to the modeling community who might lack a deep understanding on how and why individual SST estimates might deviate from the mean-annual SST estimate often provided in SST databases. We will highlight some notable model-data mismatches and suggest possible scenarios to reconcile them in light of each geochemical proxy's specificities.

2 - A BRIEF OVERVIEW OF GEOCHEMICAL SST PROXIES

Paleoceanographic proxies for SST derived from marine sediments exclusively rely on organic or inorganic remains of marine organisms (archaea, phytoplankton or zooplankton) that are assumed to have lived at the ocean surface (*i.e.* the mixed layer), or slightly below the ocean surface (*i.e.* in subsurface). After the death of these organisms, their remains sink to the seafloor (often inside fecal pellets or in the form of aggregates called "marine snow") and are buried in the sediments, making sedimentary sequences suitable archives for past SST reconstruction once a chronology is available.

The first attempts to estimate past SST were based on planktonic microfossil assemblages. As different planktonic species have different ecological niches, their spatial distributions in the ocean depend on environmental parameters such as temperature, salinity and food availability. In such approaches, near-modern assemblages of planktonic organisms counted in surface sediments are calibrated against one or several chosen surface or subsurface ocean properties. Because SST is the main factor controlling modern assemblages in the global ocean, it is possible to infer past SST by reconstructing downcore changes in species' abundances through the use of statistical methods (Imbrie & Kipp, 1971; see also Mix *et al.*, 1999 and Kucera *et al.*, 2009 and references therein for more details on faunal assemblage techniques). Although extremely valuable, the main pitfall of statistical estimates of past temperatures based on assemblages is the occurrence of species or assemblages in the fossil record that have no modern analogs – the so-called no-analog problem. Geochemical proxies, often based on thermodynamic processes, do not suffer from this problem and can therefore be used to extrapolate past conditions outside of the modern ocean range once they are carefully calibrated. Moreover, geochemical proxies can be calibrated *in vitro*, whereas this is not possible for assemblage-based proxies.

Since the 1980s, new geochemical tools have been developed to reconstruct past SST that do not rely on assemblages. These proxies do not always provide the same SST estimates as faunal or floral assemblages techniques (see Bard, 2000), and have subsequently increasingly been incorporated into SST databases. Now that geochemical SST proxies are widely integrated in databases, comparing different SST estimates based on different proxies in contrasting oceanic regimes can help refine our understanding of both paleotemperatures and SST proxy specificities. Below, we concisely review the three most commonly used geochemical proxies for past SST derived from marine sediments.

2.1 - FORAMINIFERAL MG/CA

Planktonic foraminifera are unicellular zooplankton protists that precipitate shells – or tests – made of calcium carbonate (CaCO_3). Ca can be substituted by Mg in the carbonate lattice, and early suggestions of a thermo-dependence of Mg incorporation were first made in the early 1970s (Kilbourne & Sen Gupta, 1973; Bender *et al.*, 1975). Two decades later, analysis of foraminifera cultured at laboratory unambiguously demonstrated that foraminiferal test Mg/Ca is thermo-dependent, paving the way to the use of foraminiferal Mg/Ca as a paleothermometer (Nürnberg *et al.*, 1996). Later, further culture experiments complemented by core-top analyses and sediment trap studies demonstrated that Mg/Ca exponentially increases with the ambient temperature at which planktonic foraminifera calcify (see Dekens *et al.*, 2002; Anand *et al.*, 2003 among many others). Since the mid 1990s, a wealth of calibration equations has been published, which vary significantly with ocean basin and foraminifera species used for paleotemperature reconstructions (see e.g. McConnell & Thunell, 2005, Regenberg *et al.*, 2009). Those calibration efforts further refined the accuracy of SST estimates, even though most calibration equations use a similar slope within the calibration uncertainty. Such a variety of calibrations poses a challenge in assembling SST databases since they may contribute to increase SST heterogeneities or require to re-calibrate raw Mg/Ca values when new calibrations become available.

Other effects, such as salinity and foraminiferal dissolution have been identified as secondary effects on the Mg/Ca signature of planktonic foraminifera. For example, high salinity may increase Mg/Ca independently of temperature (Kisakürek *et al.*, 2008; Mathien-Blard & Bassinot, 2009; Arbuszewski *et al.*, 2010), but a more recent work indicates that such bias may not be as critical as originally thought (Hönisch *et al.*, 2013). Also, post-depositional foraminiferal test dissolution occurring in sedimentary environments where the carbonate saturation state is low is thought to artificially decrease foraminiferal Mg/Ca (Brown *et al.*, 1995; Dekens *et al.*, 2002; Regenberg *et al.*, 2006). This effect can be monitored by weighing foraminifera tests to detect significant downcore weight loss associated with dissolution (Lea *et al.*, 2006), or corrected for by applying depth-dependent calibrations

(Dekens *et al.*, 2002). Finally, the Mg/Ca ratio of seawater itself is known to have changed over time on timescales longer than 1 Ma, and some correction should be applied to account for this, e.g. when Pliocene SSTs are estimated with Mg/Ca (see for a recent review Evans *et al.*, 2016).

The foraminifera cleaning steps that need to be undertaken prior to analysis constitute another potential source of uncertainty because different chemical cleaning protocols can introduce significant deviations from the original pristine foraminiferal Mg/Ca (Lea *et al.*, 2000; Barker *et al.*, 2003). Interlaboratory comparisons of Mg/Ca analysis indicate that intralaboratory precision is much better than interlaboratory standard deviation of Mg/Ca measurements (Greaves *et al.*, 2008). This dispersion in interlaboratory accuracy implies that one has to be careful in interpreting raw temperature changes in databases, that are built by assembling SST estimates based on Mg/Ca measured in different laboratories.

One key advantage of Mg/Ca paleothermometry is that the foraminiferal species used to derive temperatures can be studied in the modern marine realm when extant (see e.g. Jonkers & Kucera, 2015 for a recent review). Thus, further insight into the ecology of the species used, or even at the pseudo-cryptic species level (Regoli *et al.*, 2015), can be taken into account when interpreting foraminifera-based paleotemperatures.

2.2 - C₃₇ ALKENONE UNSATURATION INDEX

C₃₇ alkenones are lipids synthesized in the modern ocean by certain haptophyte algae, notably a few species of coccolithophorids. Coccolithophorids are unicellular, phytoplanktonic algae. In the modern ocean, *Emiliania huxleyi* and *Gephyrocapsa oceanica* thrive in the upper ocean photic zone and are thought to be the main C₃₇ alkenone producers (Conte *et al.*, 1994; Volkman *et al.*, 1995). The C₃₇ alkenone unsaturation index (U^K₃₇) measures the proportion of di- and tri-unsaturated C₃₇ alkenones. To explain the U^K₃₇ thermodependance, it was first proposed that alkenone unsaturation may regulate the cell membrane rigidity to adapt to ambient water temperatures (Brassel *et al.*, 1986), but more recent work failed to confirm that alkenones were located in coccolithophorids' cell membranes (Conte & Eglinton, 1993), leaving the unsaturation thermodependence unexplained. The two most commonly used calibrations, which are based on laboratory cultures (Prahl & Wakeham, 1987) and on surface sediments (Müller *et al.* 1998), provide linear calibration equations that are nearly identical. It has since been shown that for both the warm and cold temperature extreme ranges (i.e. for temperatures $>24^\circ\text{C}$ and $<4^\circ\text{C}$), the slope of calibration may be reduced, leading to specific calibrations using either a reduced slope for the warm water range (Sonzogni *et al.*, 1997) or a polynomial calibration that, once computed, asymptotically converges towards the temperature extremes (Conte *et al.*, 2006). This implies that alkenone thermometry is not well suited to very warm or cold waters, in particular in equatorial regions where tri-unsaturated C₃₇ alkenones are often absent from sediments.

Even though the $U^{K_{37}}$ index is largely thought to produce values close to mean-annual SST (Müller *et al.*, 1998; Conte *et al.*, 2006), coccolithophorid blooms (usually associated with enhanced export production relative to primary production) often occur over a short period of time (days to weeks), such that SST estimates may diverge from the mean-annual SST and hence be skewed towards particular seasons (Bijma *et al.*, 2001; Leduc *et al.*, 2010a; Prahl *et al.*, 2010; Schneider *et al.*, 2010; Lohmann *et al.*, 2013; Kaiser *et al.*, 2014). Water column and sediment trap studies also indicate that alkenone-producing coccolithophore species might integrate some subsurface as well as surface temperature signal (Ternois *et al.*, 1997; Andruleit *et al.*, 2003). It is difficult to quantify such subsurface bias but, as coccolithophorids are photosynthetic organisms, they must live in the euphotic zone and may hence record the SST integrated over the surface mixed layer depth range in a given area. For example, *Gephyrocapsa* and *Emiliania* reach their maximum of abundance between 150 and 200 meters in the oligotrophic stratified waters of the central Pacific, where the chlorophyll maximum occurs significantly deeper than in well-mixed regions of the ocean (Beaufort *et al.*, 2008).

In comparison with relatively fast sinking foraminifera tests, alkenones are more prone to lateral advection, both during their descent to the seafloor and once deposited by bottom currents (Benthien & Müller, 2000). Radio-carbon age measurements performed on alkenones often produce substantially older age estimates than co-occurring foraminifera (Mollenhauer *et al.*, 2003; Ohkouchi *et al.*, 2002). Such age differences imply lateral advection and/or sediment re-suspension or focusing, suggesting that alkenones might not always represent local SST signals. To a lesser extent, such bias is probably also true for foraminiferal Mg/Ca in regions where fast-flowing surface currents exist, for example in the Agulhas region (van Sebille *et al.*, 2015). Thus, SST records based on marine sediments should be interpreted with care since advective processes act to spatially smooth the SST signal from an area much broader than the section of ocean directly overlying the core site.

2.3 - TETRAETHER INDEX 86

Tetraether indEX with 86 carbon atoms (TEX_{86} ; Schouten *et al.*, 2002) is a recently developed temperature proxy based on isoprenoid glycerol dialkyl glycerol tetraether (GDGT) lipids (Schouten, 2002, Schouten 2013). Isoprenoid GDGTs are cell membrane lipids characteristic of archaea (mainly *Thaumarchaeota*) that are thought to adapt the rigidity of their membrane structures by altering the number of cyclopentane rings in response to environmental stressors such as temperature.

TEX_{86} has been calibrated empirically with respect to sea surface temperature using modern surface sediments from the global ocean for temperatures ranging from -3 to 30°C (Schouten *et al.*, 2002; Kim *et al.*, 2008). However, the initial TEX_{86} calibration does not appear to accurately reconstruct temperatures below ca. 5°C, which later led

to the use of two different versions of TEX_{86} , one for low temperature (TEX_{86}^L ; SST < 15°C), and one for higher temperature (TEX_{86}^H ; SST > 15°C) (Kim *et al.*, 2010).

Several recent studies suggest that, in the open ocean, the TEX_{86} index reflects subsurface temperature rather than surface temperature (Huguet *et al.*, 2007; Lopes dos Santos *et al.*, 2010; Kim *et al.*, 2012a,b; Ho & Laepple, 2016), and both TEX_{86}^H and TEX_{86}^L were re-calibrated against subsurface (0-900 meters of water depth) temperatures (Kim *et al.*, 2012a,b; Ho & Laepple, 2016). Furthermore, since the relationship between TEX_{86} and temperature may vary regionally, Tierney & Tingley (2014) developed a new calibration model allowing regional calibrations for the global ocean. Trommer *et al.* (2009), Kabel *et al.* (2012) and Kaiser *et al.* (2015) published regional calibrations for, respectively, the Red Sea, the Baltic Sea, and the southeast Pacific region. In order to address the impact of depth habitat, Schouten *et al.* (2013) further proposed a calibration based on suspended particulate matter and in situ water temperature from the upper 100 m of the global ocean. Kim *et al.* (2010) provided the first calibration curve derived from cultures of *Thaumarchaeota* – the most important archaeal group synthesizing isoprenoid GDGTs – that compares well with the TEX_{86}^H global ocean calibration. Recently, cultures using purer archaea strains have revealed that TEX_{86} values of several thaumarchaeotal strains respond to temperature stress, but without a consistent pattern, and only the *Nitrosopumilus maritimus* strain responds linearly to temperature (Elling *et al.*, 2015; Qin *et al.*, 2015). Therefore, while the relationship between $U^{K_{37}}$ and SST is relatively robust, global and uniform, many different relationships exist for the TEX_{86} temperature proxy, which appears to be more sensitive to regional parameters.

Indeed, factors other than temperature also affect the TEX_{86} proxy. First, isoprenoid GDGTs are also produced by *Thaumarchaeota* and other archaea that thrive in soils (Weijers *et al.*, 2006; Sinninghe Damsté *et al.*, 2011), thus the input of soil and peat organic matter to marine sediments may bias TEX_{86} towards overestimated temperatures, especially in coastal environments. Second, an additional contribution of GDGTs from groups other than *Thaumarchaeota*, such as methanotrophic archaea, can influence TEX_{86} values resulting in biased SSTs (Pancost *et al.*, 2001; Blumenberg *et al.*, 2004). Seasonality of the *Thaumarchaeota* bloom can also influence TEX_{86} temperature. In marine systems, *Thaumarchaeota* are generally abundant in surface waters when the phytoplanktonic activity is low (Galand *et al.*, 2010; Hollibaugh *et al.*, 2011), and thus TEX_{86} temperatures estimates may be skewed towards this period of the year (Kaiser *et al.*, 2014).

3 - A BRIEF OVERVIEW OF SST DATABASES

Earliest attempts at mapping past SST were focused on the LGM and date back to the mid 1970s (CLIMAP, 1976). Initially, the CLIMAP SST data were mainly based on assemblages of fossil planktonic organisms (CLIMAP, 1976). As the amount of LGM SST data

increased exponentially over the last decades, further refinements were made to LGM SST mapping efforts. For example, geochemical paleothermometers such as the $\text{U}^{237}_{\text{K}}$ and foraminiferal Mg/Ca are now used in the revised version of the CLIMAP SST database (MARGO, 2009).

Other databases also rely on a multitude of different types of proxy. Depending on which time window is studied, certain SST records may also have different kinds of biases. For example, Pliocene sedimentary sequences are often retrieved in marine environments where low sedimentary accumulation rates prevail, such as at abyssal sites situated away from the coastlines (fig. 1). As a comparison, core sites targeting Pliocene sedimentary sequences are on average located at $\sim 3300\text{m}$ water depth, compared with an average depth of $\sim 1100\text{m}$ for cores included in the Late Holocene (Ocean2k) database (fig. 1). Such deep sites might have been located below the lysocline during long periods of time, which is a crucial source of uncertainties for Mg/Ca paleothermometry because it causes partial dissolution of foraminiferal tests (White & Ravelo, 2015). On much shorter timescales, such as the last millennium (fig. 1), suitable high-resolution sedimentary sequences are mainly located very close to the coastline, where terrigenous sediment delivery is highest, and might subsequently lead to a strong imprint of land-sea interactions on the overall SST database (see McGregor *et al.*, 2007; Leduc *et al.*, 2010b).

In general, SST databases are built by data producers and are quality checked, and detailed guidance may be found in the original publications of the databases. As the final product is ultimately used in model-data comparisons such as in the framework of the PMIP exercises, we now review some key aspects of model-data mismatches

for each time interval studied in the PMIP4 project. We have opted to group the LIG and the MH time periods as well as the LGM and the last deglaciation. Since the LIG and MH scientific objectives and methodologies are similar in many aspects, we discuss both time slices in a single section. Also, the LGM and the last deglaciation directly follow each other in time, but as the onset of the last deglaciation might not be detected in SST records synchronously depending on sites and/or on proxies, it is also advantageous to treat those two time slices in a single section.

3.1 - THE MID-PIACENZIAN WARM PERIOD (3.3-3.0 MA)

The mid-Piacenzian Warm Period (mPWP, sometimes referred to as the mid-Pliocene warm period), which occurred between 3.3 and 3.0 Ma during the late Pliocene, is a time interval during which climate was globally warmer than today. With CO_2 concentrations around 400 ppm, this period is considered as a potential analogue for future climate and is studied in the framework of the PlioMIP subgroup of the PMIP3 and PMIP4 networks (Haywood *et al.*, 2013; Haywood *et al.*, 2016). A SST database in the framework of the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) effort has existed for that time window since the early 1990s, but SST proxies other than foraminiferal assemblage-based ones were added and considered only a decade later (see Dowsett, 2007 for a review of earlier PRISM evolution). The PRISM SST reconstruction now reports interpolated global SST anomalies for each month, with an estimated level of confidence for each SST record considered in the PRISM SST database (Dowsett *et al.*,

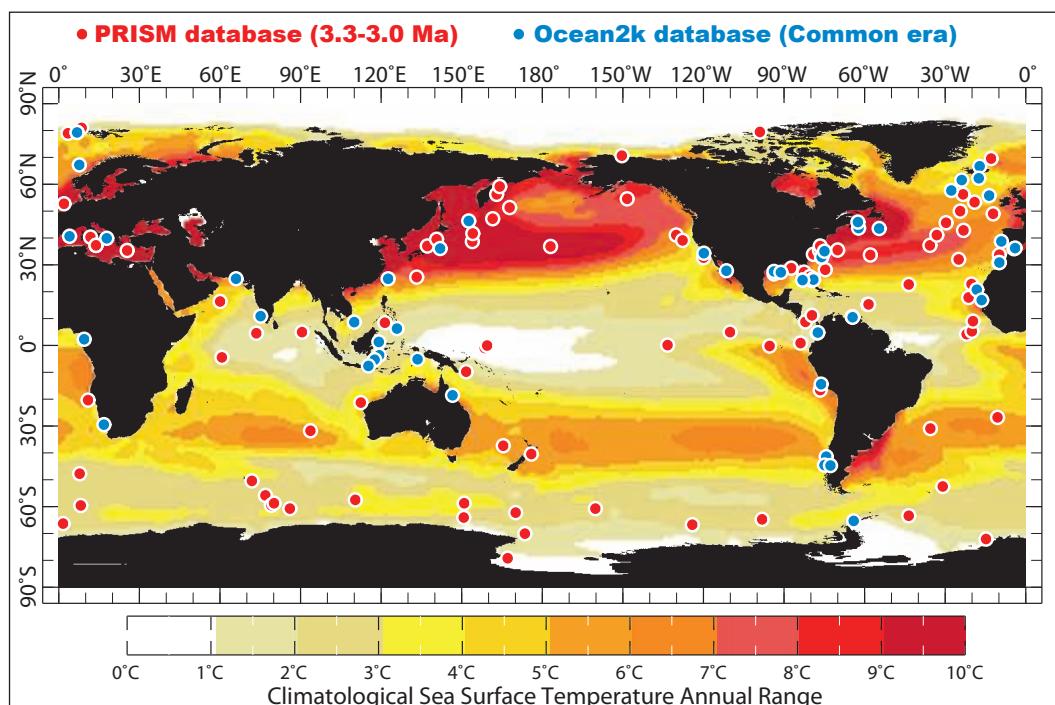


Figure 1: Annual range of the monthly mean SST in the 1971-2000 climatology (Reynolds & Smith, 1995).

Red and blue dots localize sites used in the PRISM (Dowsett *et al.*, 2012) and Ocean2k (McGregor *et al.*, 2015) databases.

Figure 1 : Amplitude saisonnière des SST pour la période 1971-2000 (Reynolds & Smith, 1995). Les points rouges et bleus localisent les sites utilisés dans les bases de données PRISM (Dowsett *et al.*, 2012) et Ocean2k (McGregor *et al.*, 2015).

2012). The last extensive model-data comparison study highlighted the largest mismatches for sites close to the equator, in the North Atlantic at mid and high latitudes, and to a lesser extent in the western boundary currents of the Atlantic and Pacific Oceans (Dowsett *et al.*, 2013). While the use of extinct foraminiferal species in transfer functions might have contributed to errors in faunal SST estimates at some locations (Robinson *et al.*, 2008), an independent Pliocene SST review using exclusively geochemical proxies for SST essentially drew the same picture (Fedorov *et al.*, 2013).

According to both Mg/Ca and alkenone-based SST estimates, temperatures in equatorial regions excluding the eastern equatorial Pacific varied little over the last 5 Ma, ranging between 27 and 29°C (Fedorov *et al.*, 2013), such that most of the temperature anomalies computed for the late Pliocene time interval are essentially the same as today. On the other hand, all models suggest moderate but significant warming of 1 to 2°C in the Pliocene relative to the modern (Dowsett *et al.*, 2013). As alkenone-based SST cannot be applied in oceans warmer than ~28 to 29°C, other proxies are needed to quantify the western equatorial Pacific warm pool during the Pliocene warmth. To address this bias in tropical alkenone records, Zhang *et al.* (2014) derived SST estimates using the TEX_{86} index, and their data suggest that late Pliocene warm pool temperatures were systematically 1 to 2°C warmer than contemporary alkenone-based SST estimates for the same region. Subsequently, a re-evaluation of warm pool Mg/Ca-derived SST confirmed that previous estimates, which did not account for secular changes in seawater Mg/Ca, underestimated Pliocene warm pool SSTs by ~2°C (O'Brien *et al.*, 2014). Both TEX_{86} and Mg/Ca data hence brought those new warm pool SST estimates much closer to the values derived from multi-model ensembles.

The largest Pliocene SST anomalies derived from alkenones occur in the mid-latitude western boundary upwelling systems. All available records from the Californian, Peruvian, Benguela and North African margins indicate large SST anomalies ranging from 4 to 10°C warmer during the late Pliocene compared to today (Fedorov *et al.*, 2013). In the eastern Pacific, such extreme Pliocene warmth recorded in mid-latitude upwelling areas implies reduced meridional SST gradients between the equator and the subtropics, analogous to those occurring during El Niño events (Brierley *et al.*, 2009). An eastern Pacific SST pattern with reduced meridional gradients was in turn used as a benchmark for defining SST fields used as a boundary condition in some Pliocene modelling experiments using atmosphere-only models (Brierley *et al.*, 2009; Haywood *et al.*, 2013). In the Benguela upwelling system, alkenone-derived late Pliocene SSTs were ~25°C, i.e. up to 8°C warmer than the modern mean-annual SST values (Etourneau *et al.*, 2009). Interestingly, Mg/Ca-derived SST from the same site using *Globigerina bulloides*, a species well-known to increase its abundance during intensified upwelling at those latitudes, produced SST estimates much colder than alkenones – by up to 7°C (Leduc *et al.*, 2014). One valid explanation for such inter-proxy differences in SST is that the

two proxies do not record the same season, with Mg/Ca recording winter SST when upwelling intensifies and alkenones recording SST when upwelling ceases and the water column becomes less turbulent (Uitz *et al.*, 2010). If this hypothesis is correct, then it implies that the full range of the annual SST cycle cannot be appropriately captured if SST proxies sensitive to the upwelling season are not used in these specific environments (Leduc *et al.*, 2014). Thus, taking into account these considerations with respect to seasonality, it may be possible to better evaluate climate models that supposedly underperform in upwelling systems (Dowsett *et al.*, 2013).

Another region where models fail to simulate the pronounced Pliocene warmth inferred from proxy data is the North Atlantic (Dowsett *et al.*, 2013). Multiproxy SST estimates were generated over a series of meridional transects in the North Atlantic at mid (Robinson *et al.*, 2008) and high (Robinson, 2009) latitudes. Various explanations for such pronounced warmth in the mid-Pliocene North Atlantic have been suggested, such as episodic pulses of warm water intrusion in the Arctic and seasonality of proxy carriers (Dowsett *et al.*, 2013), and changes in Arctic gateways (Otto-Btiesner *et al.*, in press). Seasonality is perhaps an overlooked factor that has the potential to explain such model-data deviations. For example, fluxes of the planktonic foraminifera species *G. bulloides* tend to broadly increase during seasons when temperatures are slightly warmer than the mean-annual value (Jonkers *et al.*, 2015), i.e. during spring-summer. Coccolithophorid fluxes north of Iceland may also be skewed towards warm seasonal extremes, with sediment trap studies showing fluxes spiking from near-zero flux to a single period of bloom occurring during August-September, i.e. during the warmest two months of the year (Bijma *et al.*, 2000). Thus, alkenone-based temperature estimates seem to record the warmest summer months exclusively in the North Atlantic high latitudes. This warm bias in high northern latitude alkenone-based SST estimates is even greater than that for *G. bulloides* Mg/Ca-based SSTs, which are also skewed towards periods warmer than mean-annual SST (Robinson *et al.*, 2008). Thus, seasonality may at least partly be a valid explanation for why such warm mid-Pliocene SSTs are recorded in the North Atlantic.

As the seasonal regimes are far from being a linear response to a sine insolation curve (Laepple & Lohmann, 2009), monthly SST fields in the PRISM database could also be refined by taking into account the hierarchy of seasonal information provided by multiple proxies (Dowsett *et al.*, 2012). Re-examined in this way, regional SST reconstructions based on multiple proxies suggest that models capture the most notable SST features for the mid-Pliocene warm period better than previously thought. The next generation of model simulations during the PlioMIP2 initiative will attempt to better constrain the Earth system sensitivity by targeting the Marine Isotope Stage KM5c time slice (dated at ~3.205 Ma) which has a similar orbital configuration to the present but with higher CO₂ concentrations (Haywood *et al.*, 2016). Although age model uncertainties will probably be the most challenging issues to tackle, it will also be essential

to evaluate the new set of model simulations keeping in mind all the uncertainties embedded in the new version of the PRISM SST database (Dowsett *et al.*, 2016).

3.2 - TWO INTERGLACIALS: THE LAST INTERGLACIAL PERIOD (LIG) AND THE MID-HOLOCENE (MH)

Comparing climate simulations for the LIG (dated at ~ 127 ka) and the MH (dated at 6 ka) is ideal to better understand the impact of orbital forcing on the global climate state, when atmospheric CO₂ concentrations and continental configuration were similar to those observed under pre-industrial climatic background conditions (Otto-Bliesner *et al.*, 2016). At low latitudes insolation is high year-round, yet the precession of the equinoxes induces substantial long-term insolation changes for a given month, with out-of-phase insolation changes for months that are opposite within the annual cycle (such as March and September, fig. 2). At high latitudes, seasonal insolation changes are massive, ranging from very low values in winter to values surpassing those recorded at the equator for June (fig. 2). The long-term (multi-millennial) changes in seasonal insolation will also be twice as large for the LIG compared to the MH period because the magnitude of the precessional forcing is shaped by eccentricity, which was much larger during the LIG than the Holocene (fig. 2). Mean-annual insolation changes at a given latitude are solely induced by obliquity, and are negligible when compared to seasonal insolation changes induced by precession (fig. 2). This implies that any record that contains variability at the precessional periods – potentially including some SST records for the Holocene and the Last Interglacial period – must be skewed towards certain months of the year (Huybers &

Wunsch, 2003). This could have important implications when comparing different SST records skewed towards contrasting seasons.

The LIG is a period during which global temperatures are thought to have been warmer than preindustrial temperatures by $\sim 1^\circ\text{C}$ (Dutton *et al.*, 2015). The LIG PMIP experiments target the 127 ± 1 ka time slice, corresponding to a time window during which the orbital configuration led to maximum insolation at northern high latitudes during the summer solstice (fig. 2). Such a precise time slice implies that the main source of uncertainties in model-data comparison will depend on the precision and the accuracy of the age model of individual SST records (see Govin *et al.*, 2015 for a review). The available SST databases for the LIG are not yet able to provide age models that meet these quality requirements, since they either integrate SST anomalies over long (multi-millennial) time periods, or target the LIG peak warmth (Turney & Jones, 2010; McKay *et al.*, 2013; Past Interglacials Working Group of PAGES, 2016). A set of high-resolution SST records for the LIG with refined age models has been published by Capron *et al.* (2014), but was focused on high-latitude sites exclusively. The construction of a global LIG SST database for the 127 ka time slice is underway, however, and will allow model-data comparisons with minimal age uncertainties (Capron *et al.*, submitted).

The mid-Holocene (MH) is another period thought to have been warmer than the pre-industrial background climate by $\sim 0.5^\circ\text{C}$ (Marcott *et al.*, 2013), and is documented by a wealth of well-dated SST records. Such abundance in high-quality marine records theoretically makes this time interval easier to study than the LIG. However, the reported SST anomalies during the MH are often smaller than those reported for the LIG (see e.g. Leduc *et al.*, 2010a), which given the proxy uncer-

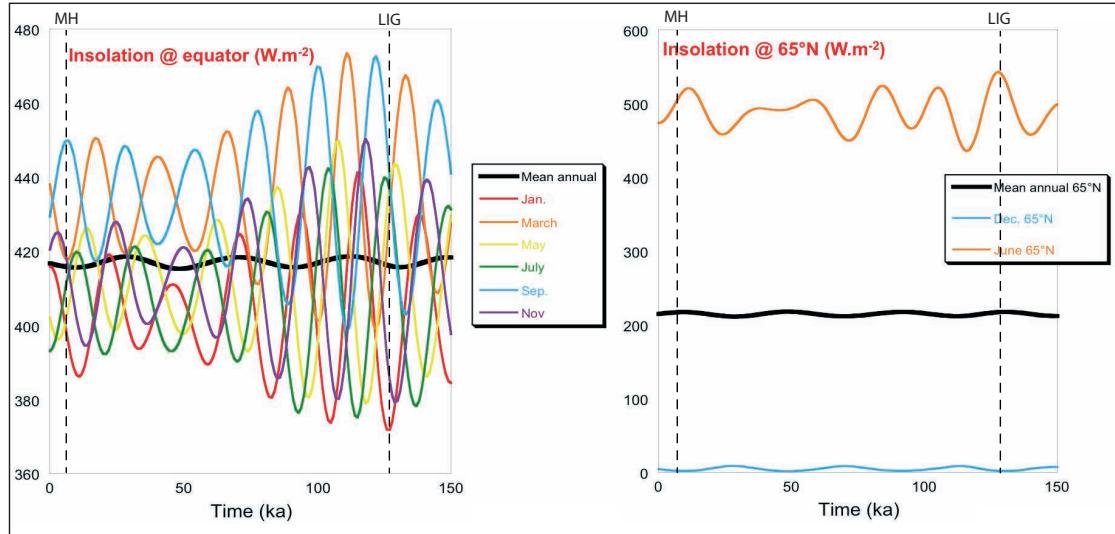


Figure 2: Changes in insolation forcing at the equator (left panel) and at 65°N (right panel) over the last 150 ka for some selected months of the year (data from Laskar, 2004).

Dotted lines indicate the 6 and 127 ka time slices targeted for the MH and the LIG model simulations, respectively (see text for details). Note that the effect of daylight duration at high latitudes surpasses that of the angle of incoming solar radiation to explain higher insolation values at high latitudes as compared to the equator in June.

Figure 2 : Changements d'insolation à l'équateur (panneau de gauche) et à 65°N (panneau de droite) sur les 150 derniers ka pour une sélection de certains mois de l'année (d'après Laskar, 2004). Les lignes pointillées repèrent les intervalles à 6 et 127 ka ciblés pour les simulations du MH et du LIG, respectivement (voir le texte pour plus de détails). Il est à noter que l'effet de la longueur de l'ensoleillement journalier à 65°N explique les valeurs d'insolation plus élevées à ces latitudes par rapport à celles reportées pour l'équateur au mois de juin.

tainties makes this time interval harder to study than the LIG. An overview of the uncertainties associated with SST anomalies for the MH indicates that the methodological uncertainties are indeed often larger than the reported climate anomalies themselves, suggesting that a precise and accurate model-data comparison is difficult to achieve (Hessler *et al.*, 2014).

For both interglacials, further evaluations of depth habitat and/or seasonal artifacts that may contribute to biases in the SST reconstructions are warranted. It is, however, extremely challenging to assign one SST proxy to a specific season since proxy sensitivity changes from one region to another. Schneider *et al.* (2010) combined satellite data for monthly changes in SST and primary productivity – the latter was assumed to reflect coccolithophorid productivity and used to infer seasonal changes in alkenone synthesis on a global scale. They defined a seasonality index to map the relationship between seasonal changes in SST and productivity for the global ocean (Schneider *et al.*, 2010). At high latitudes, the seasonality index is positive, reflecting the fact that

photosynthesizing organisms such as coccolithophorids usually thrive during summer, when both insolation and SSTs reach their maximum (Bijma, 2000; Schneider *et al.*, 2010). At low latitudes, where the open-ocean is permanently stratified and solar irradiance is high year-round, surface nutrients that limit phytoplankton growth are mostly replenished in the photic zone during winter, when mixing of the surface ocean increases (Behrenfeld *et al.*, 2006). Here, the seasonality index is negative, i.e. productivity tends to be greatest during months when SST is below the mean-annual SST (Schneider *et al.*, 2010).

At first order, changes in Holocene SST relative to modern as estimated from alkenones suggest Holocene warming and cooling trends at low and high latitudes, respectively (Kim *et al.*, 2004; Leduc *et al.*, 2010a; fig. 3). Such a pattern is not captured by climate models used in the PMIP simulations of the MH (Lohmann *et al.*, 2013). Following the global pattern of the above-described seasonality index, modelled Holocene SST trends can be reconciled with alkenone records in the northern hemisphere when high and low latitude records are assumed to

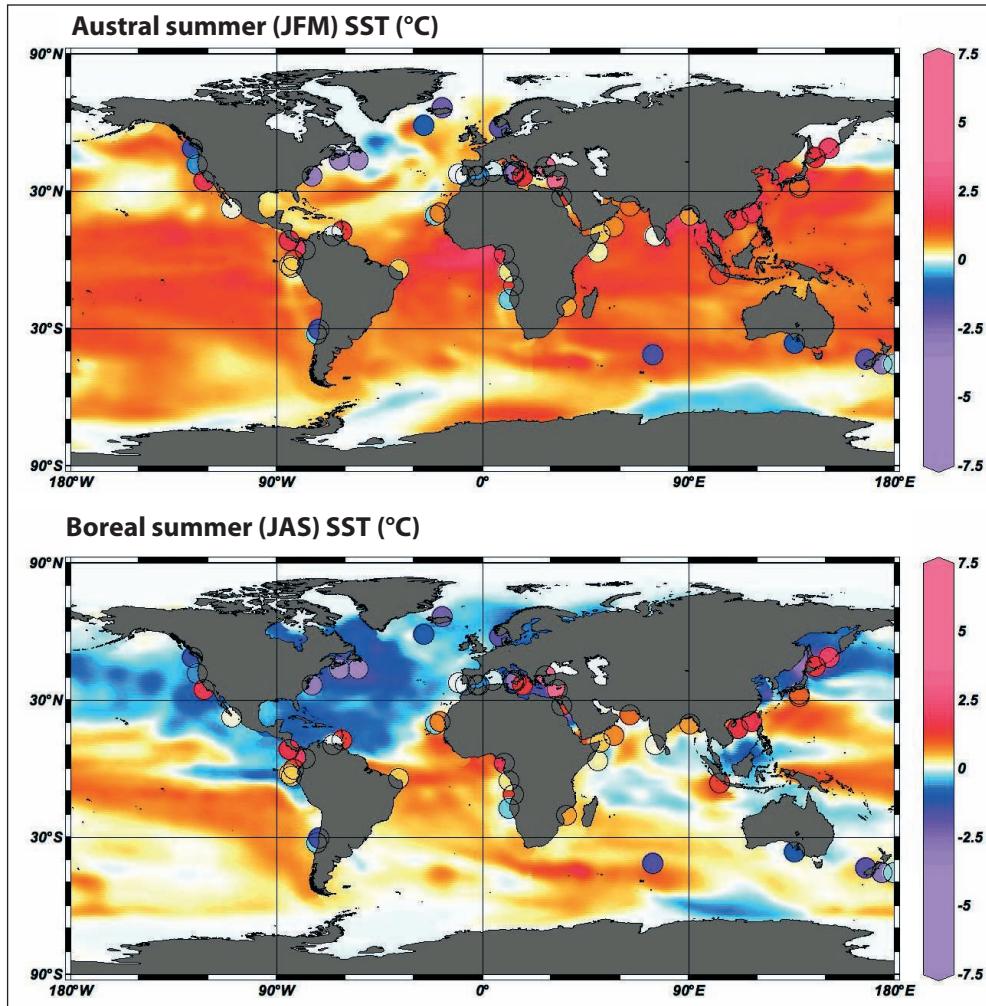


Figure 3: Model-data comparison of Holocene SST trends as simulated by the Kiel Climate Model for two different seasons (coloured map, Schneider *et al.*, 2010) and reconstructed using alkenone-based SST records (coloured dots, Leduc *et al.*, 2010).

SST anomalies are presented as the SST difference between the early Holocene (i.e. a 9.5 ka time slice simulation for the Kiel Climate Model and the 10 +/- 1ka alkenone data) and modern (core top) simulated (estimated) SST value. fig. reproduced using the data presented in Schneider *et al.* (2010). *Figure 3 : Comparaison modèles - données des changements de SST pendant l'Holocène tels qu'il sont simulés par le modèle climatique de Kiel pour deux saisons différentes (carte colorée, Schneider *et al.*, 2010) et reconstruits à l'aide des enregistrements de SST à partir des alkenones (points colorés, Leduc *et al.*, 2010). Les anomalies de SST reportées représentent la différence de SST entre l'Holocène précoce (centrée sur 9,5 ka pour le modèle climatique de Kiel et les données d'alkenone datées à 10 +/- 1ka) et la valeur de SST simulée (estimée) pour la période préindustrielle (pour les valeurs de SST estimées pour le dernier millénaire). La fig. reproduit les résultats présentés dans Schneider *et al.* (2010).*

reflect boreal summer and winter, respectively (Schneider *et al.*, 2010; Lohmann *et al.*, 2013; fig. 3). This suggests that accounting for the basic ecological requirements of primary producers such as coccolithophorids in model-data comparisons holds the key to reducing at least parts of the model-data mismatches for the MH.

While alkenone-based MH records generally do not agree with Mg/Ca-based records, potentially because the relevant organisms thrive during different seasons and/or record different water depths, Holocene records of SST based on Mg/Ca and TEX₈₆ generally agree with each other, suggesting that the emerging TEX₈₆ proxy can help to fill gaps in MH databases (Hertzberg *et al.*, 2016). TEX₈₆ can be particularly useful in locations where Mg/Ca and alkenones cannot be easily applied, such as in the Southern Ocean (Ho *et al.*, 2014), here again with a strong summer bias (Shevenell *et al.*, 2011). Yet, the coherence between TEX₈₆ and Mg/Ca Holocene SST estimates does not always hold beyond the Holocene time window since it may be overprinted by a subsurface signal (Hertzberg *et al.*, 2016), challenging the applicability of the TEX₈₆ SST proxy under climate backgrounds that are fundamentally different such as the LGM.

A comparison of Holocene and LIG SST trends as estimated from alkenones and Mg/Ca indicates that SST trends are generally of the same sign, but with larger magnitudes estimated for the LIG compared to the Holocene (Leduc *et al.*, 2010a, fig. 4). Those SST trends match the magnitude and sign of the hypothesized orbital forcing relevant for the individual records (Leduc *et al.*, 2010a, fig. 4). It is worth noting that modern fluxes of alkenones to the seafloor, based on measurements of export using sediment traps, are generally inconsistent with the sea-

nality index presented in Schneider *et al.* (2010) based on satellite estimations of primary productivity (see e.g. Rosell-Mélé & Prahl, 2013; Richey & Tierney, 2016), and this conundrum still needs to be resolved. Given that the modern annual range of SST is greater than the reported MH SST anomaly in many regions (fig. 1 and 3), and considering that mixed layer temperature lags the orbitally-induced changes of the shortwave radiation forcing by several months (Timmermann *et al.*, 2013), it is crucial for the study of interglacials to consider the seasonality embedded in each proxy since many of them – if not all – are likely skewed towards some particular season.

3.3 - THE LAST GLACIAL MAXIMUM AND THE LAST DEGLACIATION

The Last Glacial Maximum (LGM), by definition, is the last time when continental ice sheets reached their maximum volume, and eustatic sea level subsequently reached a low stand (EPILOG, 2001; Clark *et al.*, 2009). The EPILOG project (Environmental Processes of the Ice age: Land, Oceans, Glaciers) defined the LGM time window as the 19-23 ka time interval (EPILOG, 2001). Even though more recent eustatic sea level reconstructions document an earlier onset of the glacial maximum dated at 30 ka (Lambeck, 2014), PMIP experiments use boundary conditions as defined for 21 ka (Braconnot, 2007). The LGM time interval is immediately followed by the onset of the last deglaciation, which runs through the entire 21-9 ka time interval in the PMIP4 experimental design (Ivanovic *et al.*, 2016). Modelling this 11 kyr-long time window allows us to study climate variability under constantly changing boundary condi-

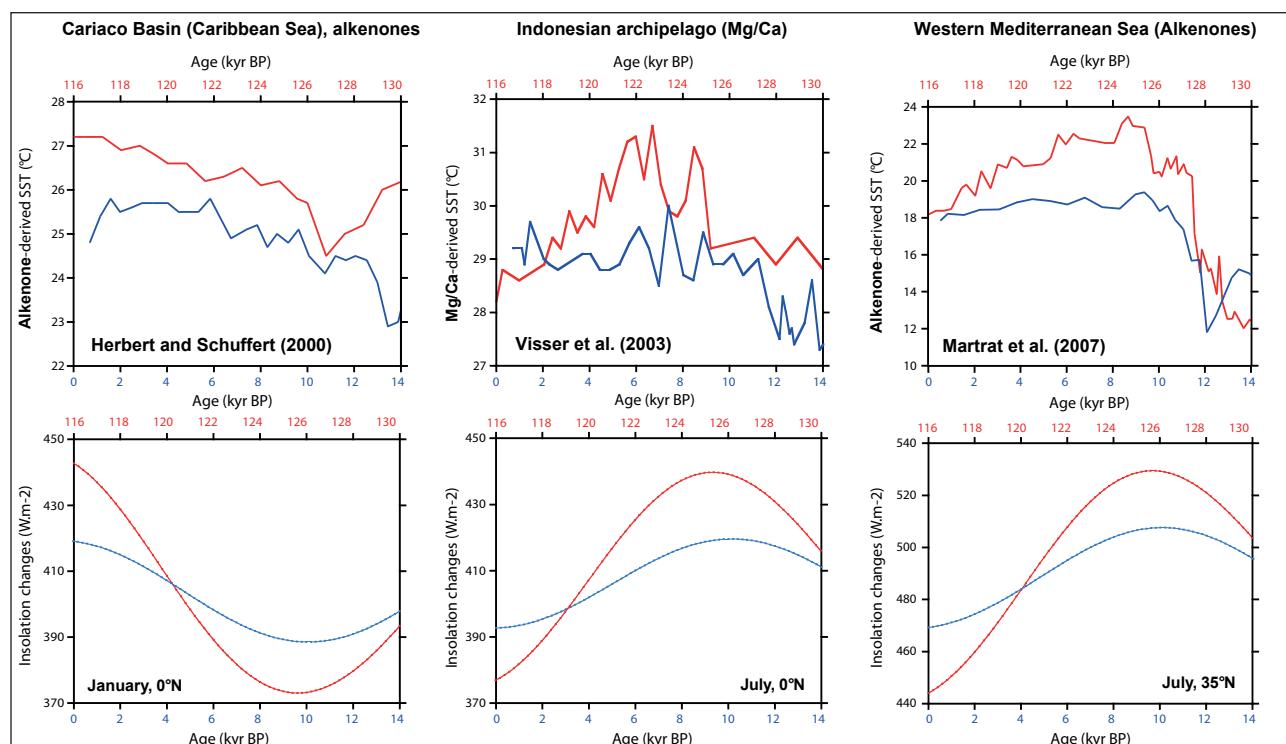


Figure 4: Comparison of SST trends for the Holocene and the last interglacial period for some selected regions and proxies (Leduc *et al.*, 2010).
Figure 4 : Comparaison des changements de SST reconstruits pour l'Holocène et pour la dernière période interglaciaire pour certaines régions et proxy sélectionnés (Leduc *et al.*, 2010).

tions, including the severe climate changes that occurred at the millennial timescale associated with North Atlantic freshwater fluxes (Ivanovic *et al.*, 2016).

The most recent extensive SST database available for the LGM is the MARGO database (MARGO, 2009). Since the publication of this database, model-data comparisons have used it to constrain climate sensitivity (Schmittner *et al.*, 2011; Hargreaves *et al.*, 2012). The MARGO database reports much more heterogeneous SST results than climate model simulations (Kageyama *et al.*, 2013), in particular in the tropics. Such heterogeneity may in part be embedded in the multitude of proxy types employed to reconstruct LGM SST. That aspect was addressed in the framework of the initial results of the COMPARE working group, that reported tropical SST cooling of 2°C for alkenone-based SST vs. a 3°C cooling estimated with Mg/Ca (Lea *et al.*, 2014). After substantial incorporation of high-quality records and a thorough data quality-control exercise, the Sensitivity of the Tropics (SENSETROP) working group has refined the LGM cooling for low latitudes, and reported comparable SST cooling of -2.3 ± 0.8 °C and -2.4 ± 0.8 °C for alkenone and Mg/Ca-based SST records, respectively (de Garidel-Thoron *et al.*, 2016; Lea *et al.*, 2016). In contrast to alkenone and Mg/Ca results, tropical SST anomalies for the LGM based on the TEX₈₆ paleothermometer are much larger, suggesting that it is representative of deep subsurface water temperature (Lopes dos Santos *et al.*, 2010; Ho & Laepple, 2015; Hertzberg *et al.*, 2016). Thus, although combining TEX₈₆ with other SST proxies might help track changes in water column stratification (see e.g. Tierney *et al.*, 2016), its use as a SST proxy for the LGM time window should be avoided (Hertzberg *et al.*, 2016).

To date, the most comprehensive SST database for the last deglaciation based on geochemical proxy records is probably the one published in Shakun *et al.* (2012). During most of the deglaciation time interval, a succession of rapid swings in temperatures, named Heinrich Event 1 (HE1, ~18-15 ka), the Bolling-Allerod (BA, ~15-13 ka) and the Younger Dryas (YD, ~13-11.7 ka), occurred in the northern hemisphere at mid and high latitudes (Shakun *et al.*, 2012). The bipolar thermal seesaw is a climate mechanism associated with the efficiency with which the interhemispheric redistribution of heat takes place when the Atlantic Meridional Overturning Circulation (AMOC) is turned on (such as during the BA) and off (such as during the HE1 and the YD). It predicts that temperatures in the southern hemisphere will increase during cold North Atlantic spells because the collapse of the AMOC leads to temperature buildup in the southern hemisphere (Stocker & Johnsen, 2003). During the last deglaciation, the thermal seesaw is most apparent when Greenland and Antarctic ice cores temperature records are compared: while temperatures increased in Antarctica during the cold North Atlantic intervals of HE1 and the YD, Antarctic warming ceased during the warm period of the BA in Greenland (fig. 5).

While such a seesaw is clearly seen at mid to high latitudes in the ocean (Lamy *et al.*, 2007; Shakun *et al.*, 2012), SST changes in the tropics over the last degla-

ciation are more puzzling. It has been recognized for a decade that, in the tropics, different proxies do not track synchronous deglacial SST warming (de Garidel-Thoron *et al.*, 2007), with UK_{37}' warming generally lagging Mg/Ca temperature records (Shakun *et al.*, 2012). A number of processes have been put forward to explain this complex response. It was first suggested that differences in the water depth habitat of planktonic foraminifera and coccolithophores combined to calcite dissolution changes could be responsible for this mismatch (de Garidel-Thoron *et al.*, 2007). As the number of available records of Mg/Ca and alkenone-based SST for sites located close to the equator increased, it became apparent that many alkenone records mimic the temperature evolution seen in the northern hemisphere. On the other hand, Mg/Ca records, including sites where dissolution did not impact foraminiferal Mg/Ca, mimic the warming sequence observed in the southern hemisphere (Kiefer & Kienast, 2005 ; Wang *et al.*, 2013, fig. 5), with the exception of the Arabian Sea (Tierney *et al.*, 2016). The effect of seasonality has been proposed to account for this deglacial equatorial pattern: for those regions where the Intertropical Convergence Zone (ITCZ) passes overhead twice a year, a marine core location could be under the alternate influence of climate variability in both the northern and southern hemispheres, given that the ITCZ represents the meteorological equator (Wang *et al.*, 2013). In this case, if different proxies are sensitive to different seasons, multiple proxies could theoretically track temperatures under seasonal situations sensitive to the northern or the southern hemisphere. Model-data comparison of equatorial Pacific sites highlighted that model-data matching is achieved only when alkenones – that mimic Greenland temperatures – are compared to modelled boreal winter SSTs, and Mg/Ca – that mimic Antarctic temperatures – are compared to boreal summer SSTs (Timmermann *et al.*, 2014). It is also likely that contrasting water depth habitats of different *Globigerinoides ruber* morphotypes mixed in the same Mg/Ca record might also blur the deglacial hydrological structure changes (Steinke *et al.*, 2001; Regoli *et al.*, 2015). It would imply that surface and subsurface temperatures are not sensitive to the same hemisphere. The proxy-dependent dynamics of the deglaciation are likely a combination of the different processes highlighted here: in the Shakun *et al.* (2012) database, within the tropical latitudinal band, 21 out of 36 SST records are based on Mg/Ca, suggesting that the overall warming of the tropics reconstructed during HE1 and the YD in the northern hemisphere could at least partly be an artifact of the over-representation of Mg/Ca relative to alkenone records in the database. Regardless of the exact timing of SST changes during the last deglaciation, the reasons why alkenone- and Mg/Ca-based data are not in phase is a conundrum that still needs to be resolved.

3.4 - THE LAST MILLENNIUM

Model experiments focused on the last millennium (i.e. the 850-1850 years of the Common Era (CE), as defined in Jungclaus *et al.*, 2016) aim to study natural climate varia-

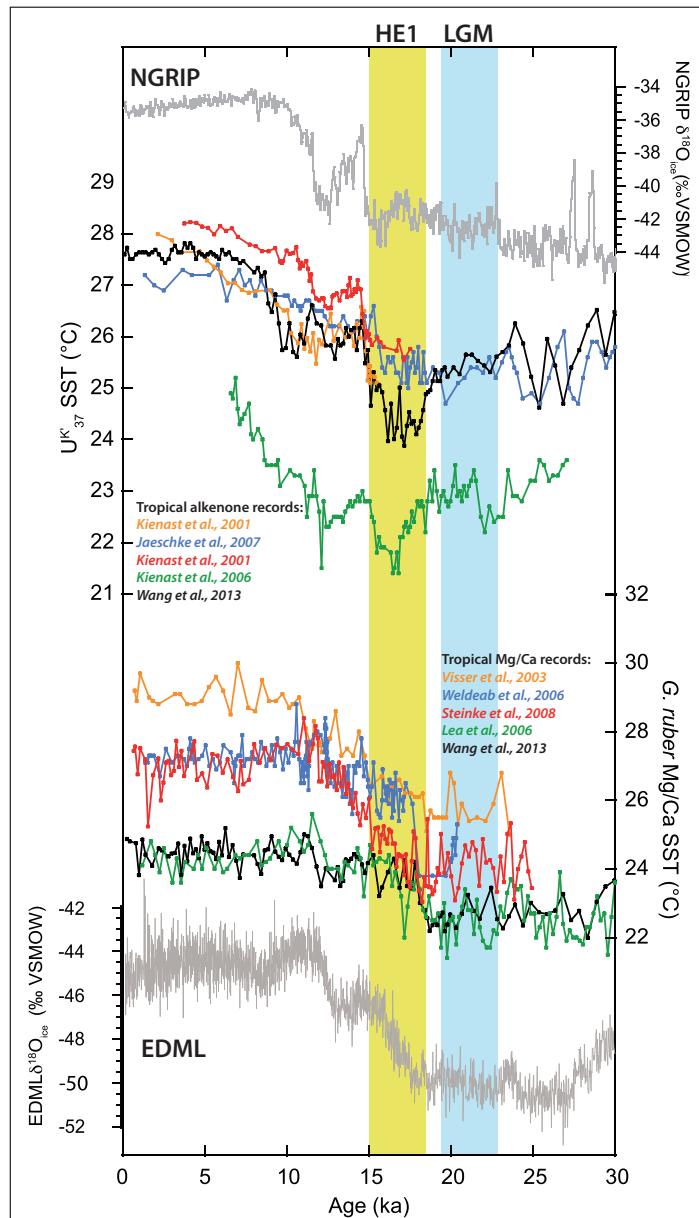


Figure 5: Upper curves: comparison of a selection of alkenone records compared to Greenland (NORTHGRIP, 2004) temperatures. Lower panels: comparison of a selection of Mg/Ca records compared to Antarctic temperatures (EPICA, 2006).
 SST records are coloured in green for the eastern equatorial Pacific sites, in blue for the western equatorial Atlantic sites, in black for the western tropical Indian Ocean (Mozambique channel) site, and red and yellow for the Indonesian archipelago. Blue and green vertical bars indicate the LGM and HE1 chronozone, respectively. Note the contrast of alkenones and Mg/Ca SST changes that either increase rapidly at the end of the HE1 or decrease progressively during the full HE1 chronozone, respectively, as predicted by the interhemispheric thermal seesaw model of Stocker and Johnsen (2003).
Figure 5 : Courbes supérieures: comparaison entre une sélection d'enregistrements d'alkenone aux températures du Groenland (NORTHGRIP, 2004). Panneaux inférieurs: comparaison d'une sélection d'enregistrements de Mg/Ca par rapport aux températures antarctiques (EPICA, 2006). Les enregistrements en vert proviennent du Pacifique Est-équatorial, en bleu de l'Atlantique Ouest-équatorial, en noir de l'océan Indien Ouest-tropical (canal du Mozambique) et rouge en jaune l'archipel indonésien. Les barres verticales bleues et vertes indiquent respectivement les périodes du dernier maximum glaciaire et l'événement Heinrich 1 (HE1). Notons le contraste des changements de SST estimés avec les alkenones et le Mg/Ca qui, respectivement, augmentent rapidement à la fin du HE1 et décroissent progressivement pendant le HE1, à l'image du modèle de balançoire thermique inter-hémisphérique de Stocker et Johnsen (2003).

bility on decadal to millennial timescales. The last millennium period encompasses two periods often referred to as the “Medieval Climate Anomaly” (MCA) and the “Little Ice Age” (LIA), that have recently been extensively documented in the framework of the PAGES2k group (see PAGES2k, 2013; McGregor *et al.*, 2015 among others). Although the exact subdivision of those two periods is often vaguely defined in the literature, there is increasing evidence that the first part of the MCA was particularly stable because of the lack of important changes in natural

climate forcing until ~1025 CE (Bradley *et al.*, 2016). Similarly to the MCA, the LIA time window is often not clearly defined, but the recent literature tends to date the beginning of the LIA to the mid 13th century when a series of clustered explosive volcanic eruptions and solar irradiance minima led to a departure from the previous unperturbed climate forcing factors (note that the PAGES2k consortium labeled the continental temperature cooling periods that started in the mid-1250s as being triggered by “volcanic-solar turndowns”, PAGES2k, 2013).

In marine sediments, available high-quality SST data have clearly detected the onset of a cooling acceleration associated with the LIA (McGregor *et al.*, 2015). Yet, various technical difficulties associated with geochemical proxies hinder the precise and accurate detection in space and time of this onset in individual SST records (McGregor *et al.*, 2015). First, marine sequences are particularly difficult to precisely date for the last millennium, and contrarily to other types of archives commonly used to study the recent past – such as corals or tree rings – it is almost impossible to achieve annual resolution because bioturbation acts to smooth the sedimentary signal. Second, the magnitude of SST changes over the last millennium is often within the range of the proxy uncertainty, which makes it challenging to infer significant changes in SST. Third, sediment retrieval during coring is imperfect, and the uppermost sediment layer is often missing. Ideally, a combination of long cores and shorter multicores taken at the same site would be used, to preserve the marine-sediment interface and ensure proper recovery of the uppermost few centimeters of the sedimentary sequence.

Yet despite these problems, when all proxies are collated into a single standardized SST record hypothesized to be representative of the global ocean, a significant cooling acceleration associated with the onset of the LIA can be extracted from standardized SST data (McGregor *et al.*, 2015). Interestingly, the sign of SST change does not seem to depend on whether alkenones, Mg/Ca or TEX_{86} were employed to estimate SST, unlike what was recognized earlier for the Holocene period (McGregor *et al.*, 2015). During the Holocene, the largest forcing at play for explaining SST trends is probably orbital forcing, which has opposite signs of change for opposite seasons at a given location. If, as suggested by McGregor *et al.* (2015), the clustering of explosive volcanic eruptions is the most likely first-order forcing factor for the LIA cooling, the nature of the forcing itself might explain why all types of SST proxies respond in the same manner. During volcanic eruptions, and despite significant warming that occurs in the northern hemisphere during the winter immediately following the largest tropical eruptions, the net impact of the aerosol atmospheric loading following large eruptions is a global cooling that could last several years, independent of the season and/or the hemisphere (Zanchettin *et al.*, 2016). This may explain why collating and aggregating different kinds of geochemical proxies that are sensitive to contrasting seasons and/or marine environment types may not be as problematic as for other periods over which different climate forcing factors drive variability.

4 - CONCLUSIONS

Geochemical proxies for SST such as the U^{237} , the Mg/Ca and the TEX_{86} paleothermometers are now relatively well-established paleoclimate tools, however, it should be kept in mind that refining the understanding of these SST proxies is an ongoing process that

involves a large community in the field of paleoceanography and proxy refinement. SST databases, which are built, quality-controlled and provided to the modeling community by paleoceanographers, should not be seen as static tools. They must be compared to SST model outputs with some basic understanding of the processes behind how proxies record and integrate the SST signals in a given location. In particular, geochemical SST proxies should be interpreted through the prism of the carrier organisms' ecology, as well as other sources of uncertainty such as oceanic and sedimentary mixing processes. Statistical models accounting for those processes can achieve significant advances in interpreting proxy discrepancies (Laeppe & Huybers, 2013; Ho & Laeppe, 2016). In such a way, it might be feasible to go a step further towards better understanding why models do not reproduce SST as estimated from geochemical proxies, providing further room for evaluating and calibrating climate models outside of the historical period (Braconnot *et al.*, 2012; Laeppe & Huybers, 2014).

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