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Mid-Holocene climate in New Caledonia (southwest Pacific): coral and PMIP models monthly resolved results

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ABSTRACT

The mid-Holocene climate is characterized by an insolation seasonality decrease in the Southern Hemisphere but measurements of its actual impact on monthly resolved sea surface temperature (SST) in the southwest Pacific region are still insufficient. A New Caledonian 5.5 ka cal BP coral provides a 20-year-long seasonally-resolved record of ocean surface conditions as inferred from coral Sr/Ca and Ba/Ca. Results were compared to monthly series of Paleoclimate Modeling Intercomparison Project phase 2 (PMIP2) model simulations. Anomalous stable isotope and U/Ca values are observed in a restricted area of the skeleton related to dissolution features. The mid-Holocene SST seasonal amplitude mean and variability are higher than presently in New Caledonia, the increased seasonal amplitude in the mid-Holocene being most probably due to the occurrence of colder winters. Other southwest Pacific mid-Holocene coral data showed also such an increased seasonal amplitude. This could mean that the South Pacific Convergence Zone (SPCZ) was weaker or reached locations more northerly than at present, which could fit with northward shifts of the inter-tropical convergence zone (ITCZ) during South Hemisphere winter. Inversely, strong rainfalls during the summer, deduced from the Ba/Ca signal and reconstructed sea surface salinity (SSS), were interpreted as reflecting pronounced southwestward shifts of the SPCZ in summer, as those occurring today during La Niña events. None of the six PMIP2 models used reproduce the proxy-based mid-Holocene increase of SST seasonal amplitude. Model maps show a less intense SPCZ in winter that would be consistent with higher SST seasonal amplitude. Finally, we stress the need for more seasonally-resolved data to validate this enhanced mid-Holocene SST seasonal amplitude in the southwest Pacific region and to better understand the underlying mechanisms.

1. Introduction

The strong ocean–atmosphere interactions that take place in the tropical Pacific give birth to two convergence zones, the Inter-Tropical (ITCZ) and the South Pacific Convergence Zone (SPCZ), and to the El Niño Southern Oscillation (ENSO). ENSO is characterized by cold (La Niña) and warm (El Niño) phases which have worldwide consequences (e.g., Webster and Yang, 1992; Janicot et al., 1996; Neelin et al., 1998; Paegle and Mo, 2002; Tozuka and Yamagata, 2003). The seasons have a strong influence on the activity and zonal/latitudinal position of the convergence zones (Meehl, 1987; Delcroix and Henin, 1991; Vincent, 1994; Delcroix et al., 1996). Since El Niño events generally start at the end of the calendar year (this is termed "phase locking"), the seasonal cycle plays a critical role in the ENSO dynamic (Tziperman et al., 1997; An and Wang, 2001). The underlying mechanisms are, however, complex and still debated (e.g., Tziperman et al., 1997; An and Wang, 2001; Lengaigne et al., 2006; Yan and Wu, 2007).

Coupled ocean–atmosphere models forced by the Holocene insolation change show that ENSO is dependent on the mean state of the tropical Pacific Ocean and that its amplitude and/or its frequency was reduced during the early- to mid-Holocene period (Clement et al., 2000; Liu et al., 2000; Otto-Bliesner et al., 2003; Cane et al., 2006; Zheng et al., 2008). Paleoclimate data indicate that ENSO was indeed reduced during that period (Rodbell et al., 1999; Tudhope et al., 2001; Moy et al., 2002; McGregor and Gagan, 2004; Koutavas et al., 2006). Various hypotheses are advanced to explain this ENSO damping: an increased heating of the western equatorial Pacific in boreal summer and autumn (Clement et al., 1999, 2000), a general warming of the equatorial

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Pacific (Rodbell et al., 1999), an interaction with the Asian Monsoon (Liu et al., 2004; Marzin and Braconnot, 2009; Luan et al., 2012), or a northward shift of the ITCZ (Koutavas et al., 2006). To our knowledge, monthly-resolved proxy data on mid-Holocene are rare, or at least not used neither in studies dealing with mid-Holocene ENSO or in studies describing the mean climatological state for that period. More data on Holocene tropical Pacific Ocean, including seasonal data, are thus needed.

For several decades, the aragonitic skeletons of massive *Porites* sp. coral colonies appear as reliable archives of past tropical climates and environments (Weber, 1973; Smith et al., 1979; Beck et al., 1992; Gagan et al., 2000; Corrège, 2006). Indeed, the incorporation of various trace elements and of the Oxygen (O) and Carbon (C) stable isotopes in its biogenic aragonite skeleton depends on environmental conditions and may thus document on both past climates and anthropogenic disturbances. Numerous studies using element/Ca ratios as sea surface temperature (SST)-related proxies were published. Magnesium/Calcium (Mg/Ca) ratio has tentatively been used for SST reconstructions (Mitsuguchi et al., 1996; Wei et al., 2000) but the Mg/Ca–SST relationship is strongly questioned, if not dismissed (Yu et al., 2005; Inoue et al., 2007; Mitsuguchi et al., 2008). The Uranium/Calcium (U/Ca) can also be used to reconstruct past SSTs (Weber, 1973; Emiliani et al., 1978; Min et al., 1995; Corrège et al., 2000; Gagan et al., 2000; Corrège, 2006; Felis et al., 2009). Nevertheless, the element/Ca ratio the most used to reconstruct past SST from *Porites* sp. colonies is certainly the Sr/Ca (e.g., McCulloch et al., 1996; Corrège et al., 2000; Ayling et al., 2006; Azmy et al., 2010). Indeed, even if some limitations about the relationship between Sr/Ca and SST have been pointed (de Villiers et al., 1994; de Villiers et al., 1995; Y. Sun et al., 2005), the Sr/Ca in coral skeleton remains the more robust SST-proxy (e.g., Beck et al., 1992; Fallon et al., 2003; Corrège, 2006), with a high inter-colony reproducibility (Stephans et al., 2004; DeLong et al., 2007, 2013; Inoue et al., 2007).

While the Sr/Ca incorporation in coral skeleton is mainly controlled by SST variations, the $\delta^{18}O$ is influenced by both the SST and the $\delta^{18}O$ of the seawater (Weber and Woodhead, 1969; Aharon, 1991). Depending on the local settings, $\delta^{18}O$ coral records were thus used to reconstruct SST and/or precipitation/evaporation balance (Kuhnert et al., 1999; Ayliffe et al., 2004; D. Sun et al., 2005; Ayling et al., 2006; Azmy et al., 2010; Duprey, 2012).

Along a Barium/Calcium (Ba/Ca) coral profile, the presence of Ba/Ca peaks documents on upwelling occurrences and river runoffs (Lea et al., 1989; Abram et al., 2001; Alibert et al., 2003; McCulloch et al., 2003; Montaggioni et al., 2006). In addition, mean Ba/Ca values, issued from coral bulk sampling data or from high-resolution profiles with removed peaks (i.e., Ba/Ca background) were used as indicative of upwelling-related environmental conditions (Montaggioni et al., 2006; Inoue et al., 2010).

However, corals are living organisms and the coral skeleton growth is a complex biochemical process, depending on several environmental and physiological parameters (Le Tissier, 1991; Lough and Barnes, 2000; Cohen and McConnaughey, 2003; Cuif and Dauphin, 2005a, 2005b). Moreover, both submarine and freshwater diagenesis can affect the coral skeleton microstructure and chemistry. The submarine diagenesis is mainly characterized by the occurrence of secondary aragonite (MacIntyre, 1977) and the freshwater diagenesis is characterized by skeleton's aragonitic dissolution and low-magnesian calcite precipitation (Pingitore, 1976). Both diagenesis types affect both the trace element ratios and the stable isotope values of the coral skeleton (e.g. Bar-Matthews et al., 1993; Zazo et al., 2002; McGregor and Gagan, 2003; Allison et al., 2007; Hendy et al., 2007; Hathorne et al., 2011). Therefore, environmental reconstructions based on such diagenetically-altered skeleton are false (Bar-Matthews et al., 1993; McGregor and Gagan, 2003; Quinn and Taylor, 2006; Allison et al., 2007; Hendy et al., 2007). Negative SST anomalies reconstructed from Sr/Ca, U/Ca, Mg/Ca, and $\delta^{18}O$ data were indeed observed within corals presenting secondary aragonite and dissolution (Enmar et al., 2000; Müller et al., 2001; Allison et al., 2005; Quinn and Taylor, 2006; Allison et al., 2007; Hendy et al., 2007). While the effects of secondary aragonite are now well constrained, the effects of dissolution on the geochemical composition of coral skeletons are poorly known mainly because corals affected by this kind of diagenesis are rarely analyzed. Once potential diagenetic effects are excluded, or identified, corals can provide seasonally-resolved quantitative records of past climate which can, in addition, be compared with model outputs.

A feature of coupled ocean–atmosphere models mid-Holocene (6 ka) runs in the South Pacific region is a cooling of the tropical Pacific SST (Zheng et al., 2008) related to the reduction of insolation from January to March (Braconnot et al., 2000; Liu et al., 2000). This change is more pronounced in PMIP2 models, where ocean and atmosphere are coupled, than in PMIP1 models with fixed SST or oceans reduced to a single mix-layer (Ohgaito and Abe-Ouchi, 2007; Braconnot et al., 2007a). The cooler tropical Pacific SST in PMIP2 models indicates that this feature is related to a change in ocean dynamics, confirming the strong ocean–atmosphere interactions in the tropical Pacific. The change in amplitude of the SST seasonal cycle follows the change in insolation characterized by a weakening in the southern hemisphere and a strengthening in the northern hemisphere. The maximum change of seasonality is observed in the east equatorial region (Luan et al., 2012).

For most proxies, it is difficult to distinguish between seasonal and inter-annual variability. This paper focuses on mid-Holocene seasonally-resolved changes in the southwest tropical Pacific as documented in both coral data and model simulations. A mid-Holocene coral from New Caledonia is used to reconstruct paleoceanographic parameters in the southwest tropical Pacific where variations are related to SPCZ displacements. The proxy-based results are compared with several model simulations.

2. Area of the study

New Caledonia is a group of islands located from 20°S to 23°S and 163°E to 168°E in the southwest Pacific (Fig. 1). The main island, "La Grande Terre", is surrounded by one of the largest coral reef barrier in the world, enclosing also one of the largest lagoon system in the world (Guilcher, 1988; Andréfouët et al., 2009). The

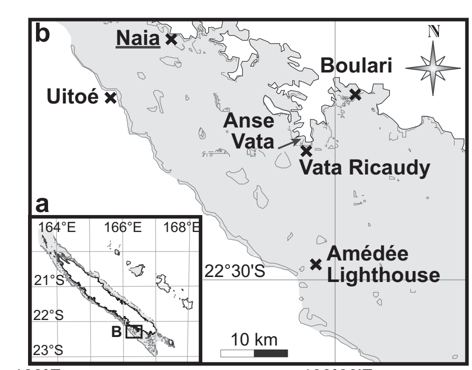

Fig. 1. Location of the New Caledonian sites cited in this study. (a) Global map of New Caledonia and, in the box, area where this study was done. (b) Enlargement of the south eastern part of the Nouméa lagoon showing the location of the Naia site (this study) and of the various modern sites were modern data (corals or SST measurements) are issued from (see Table 1 and text for details). Gray areas: lagoon environments; thin gray lines: coral reefs. Maps: copyright IRD – Cartography department.