



Investigation of sea surface temperature changes from replicated coral Sr/Ca variations in the eastern equatorial Pacific (Clipperton Atoll) since 1874

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ARTICLE INFO

Article history:

Received 21 March 2014

Received in revised form 11 July 2014

Accepted 30 July 2014

Available online 8 August 2014

Keywords:

Sea surface temperature

Sea surface salinity

Porites lobata

El Niño/Southern Oscillation

ABSTRACT

Sub-seasonally resolved and replicated coral Sr/Ca time series at Clipperton Atoll (10°18'N, 109°13'W) in the eastern Pacific are assessed as a sea surface temperature (SST) proxy in this region with small seasonal SST variability. The composite coral Sr/Ca time series is a partially replicated record of three live and one sub-modern colony of *Porites lobata* extending back to 1874. Large inter-colony coral Sr/Ca offsets equate to relative SST differences of 0.6 to 4.3 °C and limit the ability to reconstruct absolute SST changes. Moreover, the replication method revealed a 12-year section of growth in one colony where mean Sr/Ca was anomalously low (~1 °C higher SST) relative to the other colonies without evidence of diagenesis or other significant skeletal alterations. The presence of this anomalous interval supports the need for multi-coral Sr/Ca replication in specific sites or regions. The Clipperton Composite Sr/Ca anomaly record is significantly coherent ($r = 0.71\text{--}0.76$, $p < 0.001$) with gridded instrumental SSTs but with larger amplitude decadal variance that appears to more accurately represent actual SST variability at Clipperton. The amplitude of the secular warming trend during the last century at Clipperton is 0.3 to 0.6 °C larger (~twice as large) than the trend in the poorly “ground-truthed” instrumental SST records for the region. The interannual and decadal variability in Clipperton coral Sr/Ca demonstrates strong coherence to the Pacific Decadal Oscillation and the El Niño/Southern Oscillation (ENSO) with reduced ENSO variability from 1920 to late 1930s and enhanced variability in the late twentieth century.

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1. Introduction

Understanding natural trends and variability of tropical sea surface temperature (SST) over the last century remains an important objective in climate change research (Solomon et al., 2007). To assist future climate change predictions, it is important to identify the different modes of naturally occurring climate variability forcing temporal and spatial SST patterns (Solomon et al., 2011). Known natural modes of climate variability in the Pacific Ocean include the interannual El Niño/Southern Oscillation (ENSO) (Enfield and Mestas-Núñez, 2000) and decadal-scale Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; Mantua and Hare, 2002). Interpolated SST databases (Reynolds et al., 2002; Rayner et al., 2003) are now available based on a variety of records (e.g. shipboard bucket/engine intake measurements, historical documents) that allow some limited assessment of temporal changes in ENSO and the PDO. However, in constructing these databases, large assumptions are made about the spatial pattern of SST variability and,

in addition, each SST data product also contains observational bias corrections (Rayner et al., 2003) or uncertainties from irregular spatial/temporal representation (Deser et al., 2010a). These limitations are even more pronounced in the eastern equatorial Pacific where recent studies found significant disagreement in the twentieth century trend (positive/negative) between multiple SST databases (Deser et al., 2010b). Here we evaluate Sr/Ca in massive hermatypic (*Porites lobata*) corals from Clipperton Atoll at 10°N in the eastern Pacific as a SST proxy and evaluate this unique archive as a means of verifying instrumental SST databases in the region and to investigate the different modes of eastern Pacific SST variability.

Porites spp. corals growing in the surface mixed layer of the tropics and subtropics contain geochemical evidence in their skeletons of past variations in environmental conditions (e.g. Dunbar and Cole, 1993; Druffel, 1997; Gagan et al., 2000; Corrège, 2006). One proxy of SST found in *Porites* corals is the trace element ratio of strontium to calcium (Sr/Ca) (Weber, 1973; Smith et al., 1979). Studies have employed this tool to reconstruct records of SST where the Sr/Ca ratio of the coral skeleton decreases (increases) in response to increases (decreases) of SST (Beck et al., 1992; Guilderson et al., 1994). Fundamental to the

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reconstruction of past SST using Sr/Ca ratios is the assumption that seawater Ca^{2+} and Sr^{2+} concentrations are constant over space and time. However, it has been shown that seawater Sr/Ca can vary by location (de Villiers et al., 1994; Shen et al., 1996) and over long time periods (Stoll and Schrag, 1998). Despite these possible limitations, many studies have provided robust evidence on the SST dependence of Sr/Ca ratios in corals (Alibert and McCulloch, 1997; Linsley et al., 2000a; Corrège et al., 2001; Hendy et al., 2002; Quinn et al., 2006; Wu et al., 2013). Examples include the reconstruction of ENSO events (Alibert and McCulloch, 1997; Ourbak et al., 2006; Nurhati et al., 2009) as well as decadal-scale changes in SST (Linsley et al., 2000a; Hendy et al., 2002; Calvo et al., 2007; DeLong et al., 2007, 2012; Nurhati et al., 2011).

Although studies using *Porites* corals from the Pacific indicate robust SST reconstructions, non-climatic impacts on Sr/Ca variability have been reported. The impacts on coral Sr/Ca-SST reconstructions include: growth rate effects (de Villiers et al., 1994, 1995; Meibom et al., 2003; Allison and Finch, 2004; Grove et al., 2013), photosynthetic related kinetic effects (Cohen et al., 2001), and elemental partitioning efficiency effects during aragonite precipitation from seawater (Gaetani and Cohen, 2006). In addition, Gagan et al. (2012) reported significant bio-smoothing of geochemical tracers in *Porites* leading to the over-estimation of the true amplitude of water temperature and/or salinity variability over time. Studies have also described sampling issues (Alibert and McCulloch, 1997; DeLong et al., 2007), local environmental condition differences (e.g. water-depth) (Weber, 1973; Fallon et al., 2003), and differences in analytical instrumentation or proxy calibration techniques that produced discrepancies in absolute SST reconstructions (Corrège, 2006). Post-depositional coral skeletal alterations including diagenesis (McGregor and Gagan, 2003; McGregor and Abram, 2008; Sayani et al., 2011), micro-dissolution and secondary aragonite formation (Hendy et al., 2007) can result in anomalous Sr/Ca-SST reconstructions. These wide-ranging potential impacts on coral Sr/Ca-SST thermometry highlight the concern of using a single coral colony for climate

reconstruction. To reduce the non-climatic variability of Sr/Ca-SST reconstructions, Lough (2004) recommended the routine replication of coral proxy records from a single reef or region. Recent studies following the above recommendations have examined the reliability of *Porites* spp. Sr/Ca ratios in multi-colony reproducibility studies (DeLong et al., 2007, 2013; Pfeiffer et al., 2009; Grove et al., 2013; Wu et al., 2013).

Here we present a new near-monthly resolved 120-year composite multi-coral Sr/Ca record (1874–1994) generated from four *Porites lobata* colonies at Clipperton Atoll ($10^{\circ}18' \text{ N}$, $109^{\circ}13' \text{ W}$; Fig. 1). As there are no other islands north of the equator in the eastern Pacific between Clipperton and the Line Islands (2° N , 157° W), coral proxy records from this location contain valuable and unique paleo-environmental information (Linsley et al., 2000b). The primary goal of this study is to examine the reproducibility of inter-colony *P. lobata* Sr/Ca values and assess the fidelity of Sr/Ca as a proxy of SST in the eastern equatorial Pacific. The Sr/Ca record from this study is combined with the coral $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_c$) records (Linsley et al., 1999, 2000b) to reconstruct variations of seawater $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{sw}$) that has been shown to be linearly related to sea surface salinity (SSS) at least at some tropical sites (Fairbanks et al., 1997). The proxy reconstructions will allow for the investigation of interannual to longer-term decadal variability in addition to the secular trends from this location.

2. Materials and methods

2.1. Climatic setting of the study area

Clipperton Atoll is situated in the eastern tropical Pacific and experiences a seasonal SST range of $1.5 \pm 0.28^{\circ} \text{ C}$ with an annual mean SST of $27.9 \pm 0.23^{\circ} \text{ C}$ (Fig. 1A) (Locarnini et al., 2010). Based on the 2° by 2° gridded Extended Reconstructed Sea Surface Temperature version 3b (ERSST) for the grid centered on 10° N , 110° W (Smith et al., 2008), the annual SST maxima for the 100-year period from 1894 to 1994 is

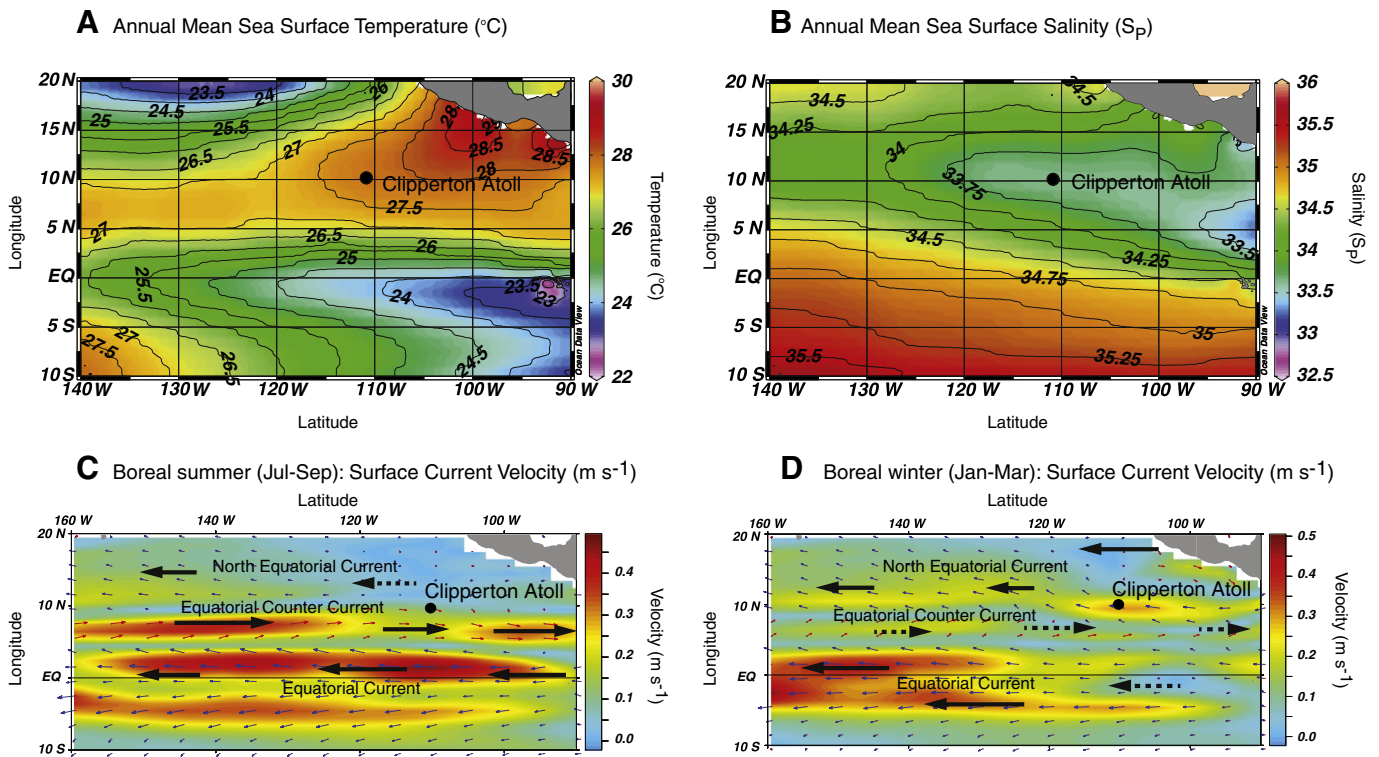


Fig. 1. The mean annual (A) sea surface temperature ($^{\circ} \text{ C}$) and (B) sea surface salinity (S_p) surrounding Clipperton Atoll ($10^{\circ}18' \text{ N}$, $109^{\circ}13' \text{ W}$) in the eastern tropical Pacific. The seasonally varying strength of surface currents velocity (m s^{-1}) is shown for (C) boreal summer (Jul–Sep) and (D) boreal winter (Jan–Mar).

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