Deep-Sea Research II 122 (2015) 131–141

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Differences in Late Quaternary primary productivity between the western tropical Pacific and the South China Sea: Evidence from coccoliths

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ARTICLE INFO

Available online 17 July 2015

Keywords:
Primary productivity
Florisphaera profunda
Western tropical Pacific
South China Sea
Milankovitch cycles

ABSTRACT

Changes in Late Quaternary oceanic primary productivity in the western tropical Pacific were reconstructed using coccolith counts from the improved SYRACO system in piston core MD01-2386 retrieved from the Halmahera Sea near northwest New Guinea. The calculated primary productivity exhibits cycles on obliquity and precession timescales over the last 192 ka. There are marked differences between primary productivity records from the western tropical Pacific and the South China Sea (SCS), with the former being dominated by precession, and the latter showing all three Milankovitch cycles (eccentricity, obliquity and precession). Empirical Orthogonal Function (EOF) analyses reveal two significant EOF modes in the western tropical Pacific and SCS records. EOF-1 accounts for 38% of the total variance and exhibits obvious precessional cycles corresponding to Northern Hemisphere summer insolation, while EOF-2 accounts for 22% of the total variance and exhibits strong 41-kyr periodicity, suggesting different biological responses to hydroclimate changes in the two regions. A more complex hydroclimate regime influenced by the East Asian monsoon and the large contrast in regional topography and circulation during glacial cycles are considered to be the primary drivers of the stronger temporal variability in productivity in the SCS compared to the relatively stable western tropical Pacific.

1. Introduction

The western tropical Pacific receives high solar radiation and high sea surface temperatures and experiences the most active monsoon circulation. Therefore, the western tropical Pacific is characterized by the largest magnitude of seasonal migration of the Intertropical Convergence Zone (ITCZ) (Wang, 2009). Because of the profound changes in atmospheric circulation and the shifts in precipitation zones associated with the meridional displacement of the ITCZ, ITCZ movement dictates seasonal changes in sea surface temperature, salinity, precipitation, land runoff, and land vegetation over the western tropical Pacific (Haug et al., 2001; Wang et al., 2004; Yancheva et al., 2007). Large amounts of precipitation and abundant terrigenous input make this area an ideal location in which to study global tropical climate. Previous studies in the western tropical Pacific have concentrated on sea surface temperature, salinity, and hydrological variability and, particularly, ocean currents (e.g., Lea et al., 2000; Rosenthal et al., 2003; de Garidel-Thoron et al., 2005; Tachikawa et al., 2011; Wu et al., 2012, 2013; Fan et al., 2013; Dang et al., 2015). The South China Sea (SCS) is the largest marginal sea in the western Pacific and has well-preserved hemipelagic sediments, making it the focus of paleoceanographic studies and hydrocarbon exploration in recent decades (Wang and Li, 2009; Wang et al., 1995, 2014). At present, the East Asian monsoon and the El Niño-Southern Oscillation (ENSO) respectively control the hydroclimate of the SCS and the equatorial Pacific, giving rise to different hydrological regimes. Various proxy records of past environmental change may similarly contain the signals of East Asian monsoon and ENSO dynamics. These records can help unravel the dominant climatic forces of the past in various areas.

Marine primary productivity has received a great deal of attention because of the possible link between atmospheric CO_2 concentrations and organic productivity in the oceans. Phytoplankton productivity in surface waters plays a central role in the global carbon cycle because of the effects of the biological pump. Variations in primary productivity also have a close relationship with glacial–interglacial atmospheric pCO_2 changes (Archer et al., 2000; Bopp et al., 2003). Although numerous

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http://dx.doi.org/10.1016/j.dsr2.2015.07.008
0967-0645/

paleoceanographic studies have examined primary productivity variations in the tropical Pacific Ocean (Beaufort et al., 2001, 2003, 2010; Zhang et al., 2007; Incarbona et al., 2008; Li et al., 2010, 2011; Ivanova et al., 2012; Tang et al., 2013), few have identified the major controls on phytoplankton productivity between regions.

Coccolithophores are one of the most important groups of marine primary producers. They secrete minute calcareous plates called coccoliths that are preserved in large quantities in many oceanic sediments. Coccoliths are widely used in paleoceanography and paleoclimatology as a reliable proxy for the nutricline and paleoproductivity (Molfino and McIntyre, 1990; McIntyre and Molfino, 1996; Beaufort et al., 1997, 2001). So far, only a few coccolithophore records with relatively low temporal resolution have been recovered from the western equatorial Pacific (Beaufort et al., 2001 and references therein). High-resolution records of Late Quaternary primary productivity dynamics in the region are scarce.

This study examines a high-resolution coccolith assemblage record in sediment core MD01-2386, retrieved from the western tropical Pacific. Based on the relative abundance of *Florisphaera profunda*, we reconstructed primary productivity changes over the past 192 ka. We also compared coccolith records from the western tropical Pacific and the SCS to identify the mechanisms that drive primary productivity variations in these two low latitude basins.

2. Modern hydroclimate setting

The western equatorial Pacific plays a key role in the establishment of ENSO events because it forms part of the so-called "great conveyor belt" linking the Pacific-to-Indian throughflow (e.g., Gordon, 1986; Hu et al., 2015). Modern surface currents in the study area are driven by the trade winds. Equatorward-flowing western boundary currents drive the two symmetrical gyres near the equator (Kessler and Taft, 1987). One gyre is entirely in the Northern Hemisphere whereas the other extends across the equator from its usual position in the Southern Hemisphere, forming a boundary marked by the North Equatorial Countercurrent at approximately 5°N (Fig. 1). The North Equatorial Countercurrent and the westward-flowing North Equatorial Current contribute to the zonal transfer of heat across the Pacific Ocean, and therefore influence the hydroclimate variability of the western tropical Pacific. Today, the North Equatorial Current splits into two branches near the east coast of the Philippine Islands (15°N) (Toole et al., 1990). While the northern branch forms the main part of the Kuroshio Current, the southern branch becomes the Mindanao Current, which transfers waters in the upper 300 m along the southeast Philippine coast, and ultimately contributes to the Indonesian Throughflow (Fig. 1). A similar situation occurs in the Southern Hemisphere, where the westward-flowing South Equatorial Current bifurcates (approximately 15°S) into a branch flowing northwestward and another flowing southward. Along the New Guinea coast the northwestward-flowing branch of the South Equatorial Current is usually recognized as the subsurface New Guinea Coastal Undercurrent and the surface New Guinea Coastal Current. The New Guinea Coastal Current flows to the east of Halmahera Island and joins the reflux of the Mindanao Current to flow eastward as the North Equatorial Countercurrent (Fig. 1). There are two semi-permanent eddies in the area of retroflection of the Mindanao and South Equatorial Currents (Fig. 1). The first, the Mindanao Eddy, is situated north of the North Equatorial Countercurrent (near 7°N, 128°E) and has cyclonic circulation, while the second, the Halmahera Eddy, is situated south of the North Equatorial Countercurrent (near 4°N, 130°E) and has anticyclonic circulation (Wyrtki, 1961).

The hydrological cycle in the study area is affected by both the Asian–Australian monsoon and ENSO (Webster et al., 1998; Wang et al., 2003). Northwest winds dominate from December to March (during the northwest monsoon) (Fig. 2C), and the ITCZ is positioned to the south (Fig. 1). From June to August, the wind direction reverses and the southeast winds are dominant (forming the southeast monsoon, Fig. 2C). Although the area is influenced by monsoonal variability with marked seasonality in the position of the ITCZ driving the local wind and rainfall patterns (Fig. 1), there is no true dry or wet season due to the relatively high amount of precipitation received by this area during the entire year (Rudolf et al., 2010).

The annual mean chlorophyll-a concentration in the West Pacific is shown in Fig. 1. We compared the monthly averaged 1998–2010 SeaWiFS and MODIS remote sensing estimates of chlorophyll-a concentration and the NCEP/NCAR mean surface wind speed from 0°N to 2.5°N and 127.5°E to 130°E (Fig. 2C). Seasonality is evident in the wind stress data with stronger winds during boreal summer and winter compared to the spring and fall. Satellite chlorophyll concentration in this region is positively correlated with greater wind stress during summer and winter (Fig. 2C). On interannual timescales, chlorophyll-a concentration and primary productivity are tightly linked to ENSO events, as shown by variations in the Niño 3.4 index (Fig. 2A) and rainfall (B). El Niño events correlate to sharp decreases in rainfall because of eastward migration of the convection and precipitation cells over the Pacific (Lyon et al., 2006). In contrast, La Niña periods are characterized by enhanced precipitation over the western equatorial Pacific Ocean and the surrounding land areas.

3. Materials and methods

3.1. Materials

Core MD01-2386 (01°07.80′N, 129°47.56′E, water depth 2816 m, total core length 32.84 m) was retrieved during the IMAGES VII WEPAMA cruise in May 2001 from the northern slope of the Halmahera Sea, within the Western Pacific Warm Pool northwest of New Guinea (Fig. 1). The recovered sediments consist of olive-gray calcareous ooze with slight bioturbation (Bassinot, 2002). The upper 20.1 m of core MD01-2386 was sampled with 2 cm spacing, except for a disturbed interval between 18.8 and 19.6 m, and the 20.1–27.6 m interval was sampled with 4–8 cm spacing. In total, 1109 samples were taken for this study.

3.2. Oxygen isotope stratigraphy and age model

The age model of core MD01-2386 was established using high-resolution $\delta^{18}O$ stratigraphy of the planktonic foraminifer *Globigerinoides ruber* (white) (Jiang, 2005; Fig. 3A). It was also constrained by five ^{14}C dates over the past 18 ka (Jiang et al., 2004). The planktonic $\delta^{18}O$ values were then tuned to the LR04 global benthic foraminiferal $\delta^{18}O$ stack (Lisiecki and Raymo, 2005) (Fig. 3A). The age model shows that the studied interval of core MD01-2386 goes back to 192 ka, with an average sedimentation rate of 14.2 cm ka^{-1} (Fig. 3B). The temporal resolution of the samples is approximately 140 yr for the upper 20.1 m (0–137 ka), 300 yr for the interval from 20.2 to 26.3 m (137–183 ka) and 620 yr for the interval from 26.3 to 27.6 m (183–192 ka).

3.3. Coccolith analysis

Smear slides were prepared for all 1109 samples. A fully automated polarizing microscope Leica DM6000 B (with 100× oil immersion objective) fitted with a SPOT Flex black-and-white