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Imprint of eastern Indian Ocean surface oceanography on modern organic-walled dinoflagellate cyst assemblages

Ines Hessler [a,c,*], Martin Young [b], Ulrike Holzwarth [c], Mahyar Mohtadi [c], Andreas Lückge [d], Hermann Behling [a]

[a] Department of Palynology and Climate Dynamics, Albrecht-von-Haller Institute, University of Göttingen, 37073 Göttingen, Germany
[b] CSIRO-Earth Science and Resource Engineering, North Ryde, NSW 2113, Australia
[c] MARUM-Center for Marine Environmental Sciences, University of Bremen, 28358 Bremen, Germany
[d] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 30655 Hannover, Germany

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ABSTRACT

Assemblages of organic-walled dinoflagellate cysts (dinocysts) from 116 marine surface samples have been analysed to assess the relationship between the spatial distribution of dinocysts and modern local environmental conditions [e.g. sea surface temperature (SST), sea surface salinity (SSS), productivity] in the eastern Indian Ocean. Results from the percentage analysis and statistical methods such as multivariate ordination analysis and end-member modelling, indicate the existence of three distinct environmental and oceanographic regions in the study area. Region 1 is located in western and eastern Indonesia and controlled by high SSTs and a low nutrient content of the surface waters. The Indonesian Throughflow (ITF) region (Region 2) is dominated by heterotrophic dinocyst species reflecting the region's high productivity. Region 3 is encompassing the area offshore north-west and west Australia which is characterised by the water masses of the Leeuwin Current, a saline and nutrient depleted southward current featuring energetic eddies.

1. Introduction

The eastern Indian Ocean is a key region in the global thermohaline circulation, thus of major climatic importance (e.g. Cane and Molnar, 2001; Wijffels et al., 2002; Karas et al., 2009). Minor changes in its sea surface temperature (SST) and salinity (SSS) potentially modify regional ocean current systems, the Asian monsoon and the global heat exchange (e.g. Gordon, 2005).

Analysing organic-walled dinoflagellate cyst (dinocyst) assemblages in marine surface sediments is a necessity to assess the modern relationship between their distribution and prevailing marine environmental conditions (e.g. Marret, 1994; de Vernal et al., 1997; Marret and de Vernal, 1997; Dale et al., 2002; Esper and Zonneveld, 2002; Kumar and Patterson, 2002; Matsuoka et al., 2003; Matthiessen et al., 2005; Holzwarth et al., 2007; Bouimetarhan et al., 2009). The knowledge gained from such studies can be applied to reconstruct palaeoenvironmental and palaeoceanographic conditions (e.g. Eynaud et al., 2000; Marret et al., 2006; González et al., 2008; De Schepper et al., 2009; Verleye and Louwye, 2010), which contributes significantly to our understanding of global climate change.

Within the south-east Asian region only a few studies exist that address the composition of dinocyst assemblages in marine surface sediments (Matsuoka, 1981; Kumar, 1996; Matsuoka et al., 1999; Azanza et al., 2004; Kawamura, 2004; Furio et al., 2006). In addition, those studies analysed a comparably low number of surface samples (n = 9–51) with a limited spatial coverage. Although the study of Matsuoka et al. (1999) covered a large part of the Indonesian Archipelago the very low number of data points (n = 9) restricts the interpretation considerably. Moreover, apart from Kumar (1996) all available studies are located in parts of the Indonesian Archipelago influenced by Pacific water masses. Since the prevailing oceanographic and environmental conditions in the Pacific and Indian Oceans differ (e.g. Wijffels et al., 2002; Gordon, 2005), the relationship between dinocyst distribution patterns and surface water parameters likely varies as well.

We present an extensive (n = 116) surface sample data set from the eastern Indian Ocean analysed for its organic-walled dinocyst assemblage composition. The geographical coverage extends from about 10°N to 30°S, and 93°E to 128°E (Fig. 1). Our overall aims are (1) to document the modern dinocyst composition of surface sediments from the eastern Indian Ocean and (2) to investigate the environmental control on the spatial distribution of dinocyst species. Relative abundance and statistical analyses have been used to determine the relationship between the regional distribution patterns and prevailing environmental as well as oceanographic conditions.

* Corresponding author at: Department of Biological Sciences, Macquarie University, North Ryde, NSW 2109, Australia. Tel.: +61 2 9850 8165.
E-mail addresses: ihessler@marum.de (I. Hessler), Martin.Young@csiro.au (M. Young), uholzwarth@marum.de (U. Holzwarth), mohtadi@uni-bremen.de (M. Mohtadi), Andreas.Lueckge@bgr.de (A. Lückge), Hermann.Behling@bio.uni-goettingen.de (H. Behling).

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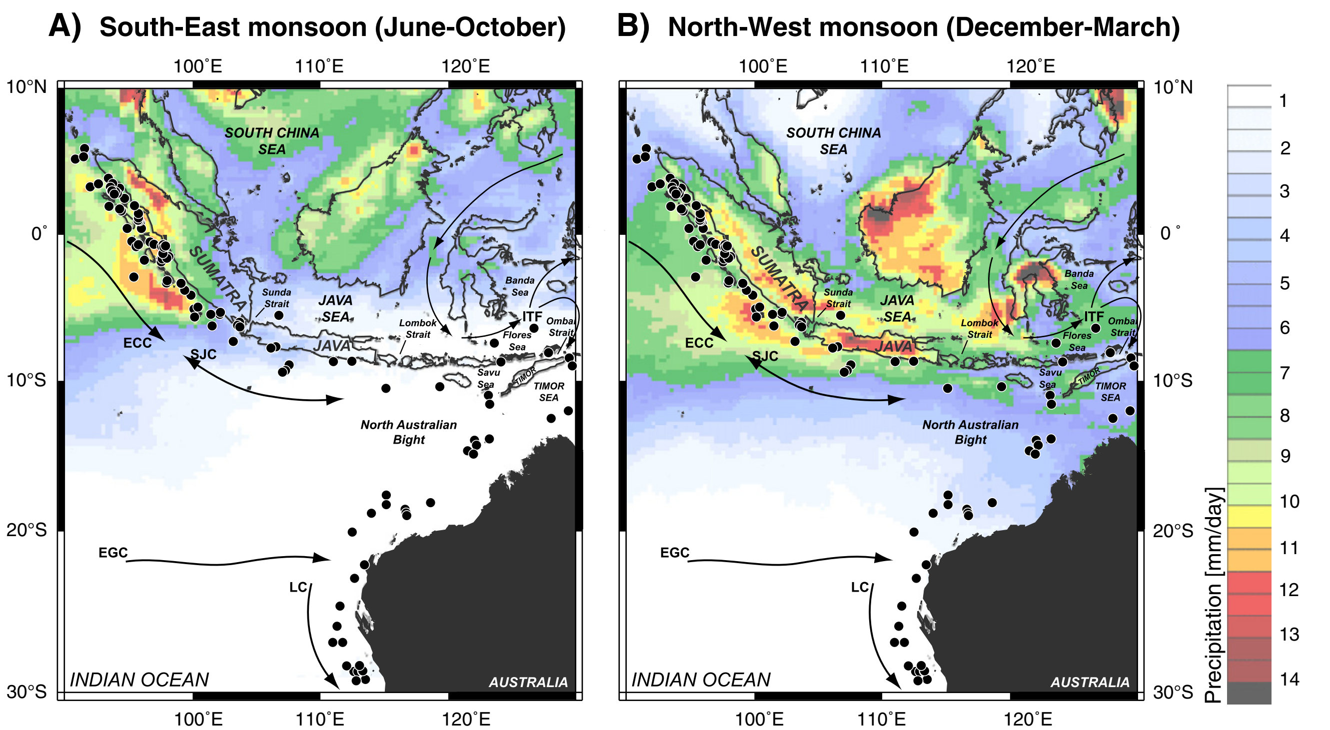

Fig. 1. Extension of the monsoon and oceanography of the eastern Indian Ocean. Map A) indicates precipitation during the SE monsoon and B) during the NW monsoon. The rainfall data set is based on TRMM satellites mixed with rain-gauge estimates (Huffman et al., 2007), at 0.25° resolution and was climatology computed for the period 1998–2010. Positions of investigated surface sediment samples are indicated with black circles. Arrows indicate oceanographic surface and subsurface currents. SJC = South Java Current, ECC = Equatorial Counter Current, EGC = Eastern Gyral Current, LC = Leeuwin Current, ITF = Indonesian Throughflow.

This study not only increases the available knowledge about environmental control of tropical organic-walled dinocysts but also reduces a geographical data gap as identified by Marret and Zonneveld (2003).

2. Regional setting

At present, the monsoonal circulation associated with the seasonal migration of the Inter Tropical Convergence Zone (ITCZ) dominates the climate of the eastern Indian Ocean. Between December and March, when the NW monsoon prevails and the ITCZ is in its southernmost position (Fig. 1), heavy rainfall occurs over the Indonesian Archipelago. In contrast, during the SE monsoon (June to October) warm and dry air is brought from Australia. On its way towards the north the SE monsoon takes up moisture from the Indonesian and south-east Asian seas, which is released when meeting the ITCZ that is situated in its northernmost position. The annual SST variations in the eastern Indian Ocean are only minor. The highest seasonal SST variability occurs off Sumatra and Java due to the influence of equatorial Indian Ocean waters and local upwelling (e.g. Qu et al., 2005).

Extreme climatic conditions on inter-annual timescales influencing the eastern Indian Ocean hydrography can be attributed to El-Niño Southern Oscillation (ENSO). During El-Niño (La-Niña) the Indonesian Throughflow (ITF) transport is weakened (strengthened) (Gordon, 2005), the SSTs in the eastern Indian Ocean are abnormally low (high) (Webster et al., 1999) and the coastal upwelling off Java and Sumatra is stronger (weaker) (Susanto et al., 2001). The Indian Ocean Dipole (IOD), another inter-annual phenomenon but independent from ENSO, also influences the Indonesian Archipelago and is accompanied by wind and precipitation anomalies (Saji et al., 1999; Webster et al., 1999). During a positive IOD event the surface water temperatures in the tropical eastern Indian Ocean are comparably low and lead to severe droughts in Indonesia. In contrast, a negative IOD event is characterised by high SSTs and increasing precipitation over the Indonesian Archipelago (Saji et al., 1999; Webster et al., 1999).

The oceanography of the eastern Indian Ocean is characterised by a complex system of surface currents (Fig. 1) that move according to the monsoon-dominated wind regime and have a pronounced seasonality (e.g. Wijffels et al., 1996, 2002; Gordon, 2005).

Between December and March (NW monsoon) the South Java Current (SJC), originating in the Equatorial Counter Current (ECC), flows towards the south-east to meet the Leeuwin Current (LC) (e.g. Tomczak and Godfrey, 1994). The high precipitation rates during this season result in a high run-off from Sumatra and Java. Together with the advection of fresher water from the Java Sea through the Sunda Strait this results in the build-up of a low-salinity "tongue" in the SJC (e.g. Wijffels et al., 1996).

The prevailing wind direction during the SE monsoon (July–October) leads to the establishment of an active upwelling system off Java and south-west Sumatra, characterised by lower SST and higher SSS (e.g. Tomczak and Godfrey, 1994). Due to the existence of a "barrier layer" this upwelling is rather weak (Sprintall and Tomczak, 1992; Du et al., 2005; Qu et al., 2005). The "barrier layer" is defined as the layer separating the top of the thermocline and the bottom of the mixed layer with features characteristic of the Indian Ocean Warm Pool (SST ≥ 28 °C) (Sprintall and Tomczak, 1992). In contrast to the boreal winter the SJC flows to the north-west between July and October, feeding the South Equatorial Current (SEC) without any significant contribution to the LC (e.g. Quadfasel and Cresswell, 1992). The SJC is characterised by a high variability in its current direction, reversing every three months (e.g. Wijffels et al., 1996).

Through various passages in the Indonesian Archipelago heat and freshwater from the Pacific enters the Indian Ocean (e.g. Gordon, 1986; Wijffels et al., 2002). This so-called ITF is the only low-latitude