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Variations in sea surface hydrology in the southern Makassar Strait over the past 26 kyr

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ABSTRACT

We present centennial-scale records of sea surface temperature and oxygen isotopes in a sediment core from Mandar Bay, offshore Sulawesi in the southern Makassar Strait, which provide new insights into the variability of Indonesian climate over the past 26 kyr. The age model for the core is constrained by 17 AMS radiocarbon ages, with a surface ocean reservoir age correction based on paired wood and foraminiferal samples. Small Holocene reservoir ages of 105 ± 180 years point to intense surface ocean-atmosphere interchange linked to increased monsoonal precipitation, whereas Last Glacial Maximum and deglacial reservoir ages are significantly higher. Mg/Ca derived sea surface temperature reconstructions based on *Globigerinoides ruber* (*s. s.*, white) exhibit an extended plateau during the Antarctic Cold Reversal, suggesting an atmospheric connection to high-latitude Southern Hemisphere climate and a seasonal bias on *G. ruber*. This is in agreement with southern hemisphere sites along the track of the Indonesian Throughflow and in contrast to Northern Hemisphere records from the South China Sea, Sulu Sea and Western Pacific (off Mindanao), which exhibit warming during the Bølling-Allerød. Ice-volume corrected $\delta^{18}O$ seawater ($\delta^{18}O_{sw}$) increased during Heinrich Stadial 1 and the Younger Dryas, whereas the Bølling-Allerød is characterized by low $\delta^{18}O_{sw}$. We attribute $\delta^{18}O_{sw}$ variability in the southern Makassar Strait during the Last Glacial Maximum and glacial termination to changes in provenance and seasonality of precipitation rather than to variability in the amount of local precipitation and runoff.

1. Introduction

The influence of high latitude climate change on precipitation and temperature in the Indonesian archipelago remains ambiguous on account of the high spatial variability exhibited by proxy records. For instance, speleothem records from Gunung Buda/Gunung Mulu caves in Borneo (Partin et al., 2007; Carolin et al., 2013) indicate drying on Borneo during Heinrich Stadial 1 (HS1, 18–14.8 ka). Seawater-$\delta^{18}O$ estimates from the Sulu Sea (Rosenthal et al., 2003), offshore Mindanao (Stott et al., 2002; Bolliet et al., 2011), Solomon Sea (Lo et al., 2014) and offshore Sumatra (Mohtadi et al., 2014) indicate reduced precipitation during HS1 and the Younger Dryas (YD, 12.8–11.7 ka) and show enhanced rainfall during the Bølling-Allerød interstadial (B-A, 14.8–12.8 ka). In contrast, speleothem data from Liang Luar cave in Flores (Ayliffe et al., 2013) exhibit significantly different precipitation patterns during the last glacial termination, suggesting wet stadials. High terrigenous flux during HS1 in the Flores Sea (Muller et al., 2012) points to enhanced precipitation in agreement with the Flores speleothem records. The records from Flores and NW Australia have been interpreted as reflecting Southern Hemisphere climate variability (Ayliffe et al., 2013; Reeves et al., 2013; Denniston et al., 2013). This regional heterogeneity has been related to various processes including latitudinal swings of the Intertropical Convergence Zone (ITCZ) driven by Northern or Southern Hemisphere climate variations (Broccoli et al., 2006; Ayliffe et al., 2013; Denniston et al., 2013; Gibbons et al., 2014; Mohtadi et al., 2014; Kuhnt et al., 2015), variability of the El Niño-Southern Oscillation (ENSO) and the Walker circulation (e.g., Stott et al., 2002; Mohtadi et al., 2016), and deglacial sea level changes impacting regional hydrology (Griffiths et al., 2009, 2013; DiNezio and Tierney, 2013).

A major obstacle in understanding the spatial heterogeneity of deglacial precipitation records is the large gap in high-resolution climate records between the region encompassing Flores, Timor

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Strait and NW Australia and the area including NW Borneo, Mindanao and the Sulu Sea. In particular, records from the Makassar Strait and the island of Sulawesi could help to better understand temporal and spatial changes in central Indonesian precipitation and their relations to high latitude forcings and meridional tropical climate dynamics. Sulawesi is located at the heart of the tropical convection in a central position within the Indonesian archipelago, close to the equator and approximately mid way between Borneo and Flores. Lake records from eastern Sulawesi (Russell et al., 2014) indicated dry conditions between 33 and 16 ka, when Northern Hemisphere ice sheets expanded and global temperatures cooled, followed by wetter conditions during the later part of the glacial termination and early Holocene. However, there is no matching, detailed marine record offshore Sulawesi, which allows to track changes in sea surface hydrology through the last termination. Previous records are either restricted to the late Holocene (Newton et al., 2006, 2011; Oppo et al., 2009), only extend back to the base of the B-A (Linsley et al., 2010), or have insufficient temporal resolution (Visser et al., 2003) to resolve spatial heterogeneity during the last glacial termination.

We present high-resolution sea surface temperature (SST) and surface seawater oxygen isotope composition ($\delta^{18}O_{sw}$) reconstructions, based on paired Mg/Ca and oxygen isotope measurements in near surface dwelling foraminifera from a new sediment core retrieved in the Mandar Bay, offshore Sulawesi in the southern Makassar Strait (Fig. 1). The record of core SO217-18515 spans the past 26 kyr with average sedimentation rates of ~40 cm/kyr (Kuhnt et al., 2011), allowing centennial resolution climate reconstructions over the last glacial termination. Our main objective is to investigate the timing and amplitude of changes in sea surface hydrology offshore Sulawesi in comparison with regional marine and terrestrial precipitation records over Termination I.

2. Material and methods

2.1. Material

Piston core SO217-18515 (3°37,791′ S, 119°21,601′ E, 688 m water depth) was retrieved from the southeastern Makassar Strait during RV "Sonne" cruise SO217 MAJA in 2011 (Kuhnt et al., 2011). The coring site is located in the Mandar Bay in proximity to the Sulawesi coastline (Fig. 1), which acts as a catchment basin for the Saddang River and other smaller tributaries off southwestern Sulawesi. This location was also chosen due to its position on a submarine promontory, reducing the probability of turbidite influence.

Core SO217-18515 is 12.18 m long and consists mainly of homogeneous silty clay to clay, interrupted by a layer of coarser particles (pteropod and shell fragments) between 6.37 and 6.45 m. Sediment colour changes from olive-brown in the upper 3 m to a lighter greenish-grey between 3 and 5 m and to a darker olive-grey between 5 and 12.18 m (Supplementary Fig. S1). Dark colour streaking and shell fragments are observed through the core.

Core SO217-18515 was initially sampled in 10 cm intervals, which is equivalent to a time resolution of 180–310 years in the upper part (0.1–3.1 m) and of 100–200 years in the lower part (8.1 m to base). From 3.1 to 8.1 m (~last glacial termination), the core was sampled in 1 or 2 cm intervals (time resolution of 30–110 years). Samples were oven dried at 40 °C and weighed prior to washing over a 63 μm sieve. Residues were oven dried at 40 °C on filter paper, then weighed and sieved into the following size fractions: >315 μm, 315–250 μm, 250–150 μm, 150–63 μm. In each sample, 35–45 well-preserved tests of *Globigerinoides ruber* (sensu stricto, white from the 315–250 μm size fraction) were selected and gently crushed between two glass plates. Crushed tests were divided into aliquots for stable isotope (~1/4) and Mg/Ca analysis (~3/4). For benthic stable isotopes we selected 3–6 well-preserved tests of the epibenthic species *Planulina wuellerstorfi* (>315 μm and 315–250 μm size fractions) from 40 samples in the interval 0.1–12 m.

2.2. AMS (accelerator mass spectrometry) ^{14}C dating

The chronology of core SO217-18515 is constrained by 22 accelerator mass spectrometry (AMS) radiocarbon ages (Table 1; Fig. 2; Supplementary Fig. S2). Fifteen ages were measured on planktonic foraminifera and seven on wood fragments. For each foraminiferal sample, ~1000 clean and well-preserved tests larger than 250 μm of either *Globigerinoides ruber* or *G. ruber* paired with *Globigerinoides sacculifer* or mixed surface-dwelling planktic foraminifera (when *G. ruber* and *G. sacculifer* were not sufficiently abundant) were selected. Samples were measured at the Leibniz Laboratory for Radiometric Dating and Isotope Research in Kiel, following the protocols of Nadeau et al. (1997) and Schleicher et al. (1998).

Foraminiferal conventional ages were corrected with variable surface ocean reservoir ages, derived from paired foraminiferal and wood samples (Fig. 2; see also Supplementary Fig. S2 and Supplementary Text 1). Reservoir ages were rounded to 200 years for samples younger than 12.1 ka, to 600 years for samples between 17.7 and 12.1 ka, to 1100 years for samples between 19 and 17.7, and to 750 years for samples older than 19 ka (Fig. 2). Errors in reservoir ages of paired wood and foraminiferal samples were estimated using a simplified Gaussian error propagation ("variance formula", Ku, 1966):

$$\sigma = \sqrt{\left(\sigma_a^2 + \sigma_b^2\right)}$$

where σ is the error of the reservoir ages, σ_a the error of the wood AMS ^{14}C samples and σ_b the error of the foraminiferal AMS ^{14}C samples. Errors are given in Table 1. For evaluation of the age model, we also applied a constant surface ^{14}C reservoir age correction of 474 years to our dataset (Table 1), following Southon et al. (2002).

All reservoir-corrected conventional ^{14}C ages were converted into calendar ages using *Calib 7.1* (Stuiver et al., 2005) with the *IntCal13.14c* calibration dataset (Reimer et al., 2013). Depth-age relationships were calculated using *KaleidaGraph 4.1.3*. An interpolated curve (Fig. 2b) was fitted to the age dating points using a Stineman function (smooth function in KaleidaGraph). The age model in the lower part of the core (11.75 m–12.05 m) is based on linear extrapolation from the last two ^{14}C ages to the base of the core.

2.3. Sea surface temperature reconstruction

The cleaning of 355 *G. ruber* samples for Mg/Ca-derived SST reconstruction followed the protocol of Martin and Lea (2002) and Barker et al. (2003), including oxidative and reductive steps, but excluding alkaline chelation using pentetic acid (DTPA). All cleaning steps were done on a class 100 (ISO 14644-1) clean bench to prevent contamination. Cleaned samples were fully dissolved in 0.1 N nitric acid (HNO_3). Samples were measured on a *Spectro Ciros SOP CCD* inductively coupled plasma optical emission spectrometer (ICP-OES) at the Institute of Geosciences, Christian-Albrechts-University, Kiel. In every seventh sample, the certified carbonate reference material ECRM 752-1 (Greaves et al., 2008) was routinely analysed to monitor analytical quality. Trace element ratios (Fe/Ca, Al/Ca, Mn/Ca) were evaluated to monitor cleaning efficacy, 7 samples showing a significant correlation between Fe/Ca, Al/Ca, Mn/Ca