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Hydrological and vegetation shifts in the Wallacean region of central Indonesia since the Last Glacial Maximum

Satrio A. Wicaksono [a, *], James M. Russell [a], Ann Holbourn [b], Wolfgang Kuhnt [b]

[a] Department of Earth, Environmental, and Planetary Sciences, Brown University, Box 1846, Providence, RI, 02912, USA
[b] Institute of Geosciences, University of Kiel, Ludewig-Meyn-Str 10, Kiel, 24118, Germany

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ABSTRACT

Precipitation is the most important variable of Indonesian climate, yet there are substantial uncertainties about past and future hydroclimate dynamics over the region. This study explores vegetation and rainfall and associated changes in atmospheric circulation during the past 26,000 years in Wallacea, a biogeographical area in central Indonesia, wedged between the Sunda and Sahul shelves and known for its exceptionally high rainforest biodiversity. We use terrestrial plant biomarkers from sediment cores retrieved from Mandar Bay, off west Sulawesi, to reconstruct changes in Wallacean vegetation and climate since the Last Glacial Maximum (LGM). Enriched leaf wax carbon isotope ($\delta^{13}C_{wax}$) values recorded in Mandar Bay during the LGM, together with other regional vegetation records, document grassland expansion, implying a regionally dry, and possibly more seasonal, glacial climate. Depleted leaf wax deuterium isotope (δD_{wax}) values in Mandar Bay during the LGM, and low reconstructed precipitation isotope compositions from nearby sites, reveal an intensified Austral-Asian summer monsoon circulation and a southward shift of the mean position of the Intertropical Convergence Zone, likely due to strong southern hemisphere summer insolation and the presence of large northern hemisphere ice sheets. Mandar Bay $\delta^{13}C_{wax}$ was anti-correlated with δD_{wax} during the LGM and the last deglaciation, but was positively correlated during most of the Holocene, indicating time-varying controls on the isotopic composition of rainfall in this region. The inundation event of the Sunda Shelf and in particular the opening of the Java Sea and Karimata Strait between 9.4 and 11.1 thousand years ago might have provided new moisture sources for regional convection and/or influenced moisture source trajectories, providing the trigger for shifts in atmospheric circulation and the controls on precipitation isotope compositions from the LGM to the Holocene.

1. Introduction

Alterations in modern-day rainfall patterns over the Indonesian archipelago influence the stability of its rich and diverse tropical rainforests (Underwood et al., 2014) and impact the livelihoods of more than a quarter billion people living in the region (Naylor et al., 2007; Oktaviani et al., 2011). However, there is relatively weak agreement among Intergovernmental Panel on Climate Change climate models on the trend and magnitude of future precipitation changes over Maritime Southeast Asia (Knutti and Sedlacek, 2013), reflecting substantial uncertainty about hydroclimate dynamics in the archipelago under future climate boundary conditions. Similarly, there is a long-running debate on changes in Maritime Southeast Asian hydroclimate during the Last Glacial Maximum (LGM), when atmospheric CO_2 concentrations were approximately 80 ppm lower than pre-industrial values and Sundaland and Sahul were two, separate contiguous landmasses (Fig. 1). Nearly all terrestrial- and marine-based climate records indicate cooler temperatures in the Indonesian archipelago during the LGM, but regional precipitation patterns are still poorly understood (Reeves et al., 2013 and references therein) and vegetation responses to regional climate change are even less clear (Wurster and Bird, 2014). Given the importance of LGM climate to climate model validation and testing (e.g. DiNezio and Tierney, 2013), new reconstructions of precipitation and vegetation response during the LGM are needed to close these knowledge gaps.

At the heart of the Indonesian archipelago lies Wallacea, a

* Corresponding author. Present address: World Resources Institute Indonesia, Jalan Wijaya 1 No. 63, Jakarta, 12170, Indonesia.
E-mail address: satrio.wicaksono@wri.org (S.A. Wicaksono).

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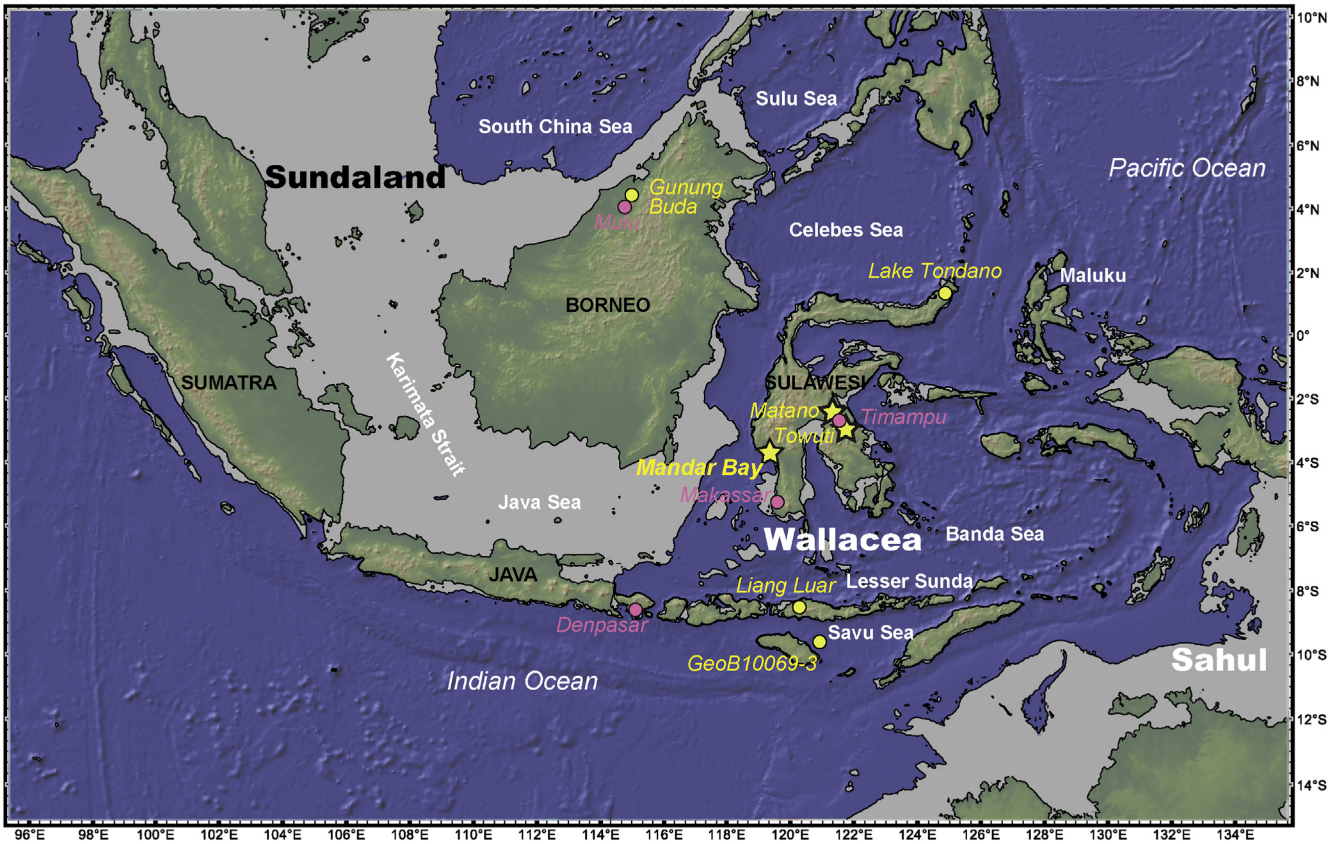

Fig. 1. Map of Maritime Southeast Asia indicating locations discussed in the text. During the Last Glacial Maximum, the exposed Sundaland was separated from Sahul by deep and narrow straits, along with a group of islands termed Wallacea, comprised of Sulawesi, Maluku islands, and Lesser Sunda Islands (from GeoMapApp, bathymetric data from General Bathymetric Chart of the Ocean, 2008). Locations of our study site (Mandar Bay) and other paleoclimate records as well as rainfall isotope stations discussed in the text are marked on the map.

biogeographical region comprised of Sulawesi, the Maluku Islands, and the Lesser Sunda Islands (Fig. 1, Whitten et al., 1987; Monk et al., 1997). Although the biogeographical lines delineating Wallacea have been the subject of much academic debate (e.g. Mayr, 1944; Simpson, 1977), the widely accepted delineation of Wallacea at present defines it as the region separating Sundaland (the Malay Peninsula, Sumatra, Borneo, Java, and Bali) to the west and Sahul (Papua and Australia) to the east, while excluding the Philippines. Wallacea is separated from Sundaland and Sahul by deep seaways, and thus had a different environmental history from the neighboring islands connected to the Sunda and Sahul shelves, which were exposed during the LGM. Wallacea is a global biodiversity hotspot due to its high species diversity, yet is also at high risk of habitat loss due to changes in land use and climate (Myers et al., 2000). Here we present new reconstructions to assess Wallacean climate and vegetation within the larger context of climate changes in Maritme Southeast Asia since 26 kyr BP to improve our understanding of regional vegetation and climate history, with a particular emphasis on the LGM.

The LGM climate of Maritime Southeast Asia has proved challenging to understand, due to significant disagreement among reconstructions in the direction and magnitude of regional precipitation change. This uncertainty could be partly due to the use of different precipitation proxies in different archives, which are sensitive to different elements of paleohydrologic change. For example, records of precipitation isotopes such as speleothem oxygen isotopic compositions (e.g. Griffiths et al., 2009; Ayliffe et al., 2013) and seawater oxygen isotope data derived from foraminifera (Mohtadi et al., 2011) have been interpreted to reflect changes in the amount of annual precipitation. The interpretation of foraminiferal $\delta^{18}O$ is underpinned by the dilution of isotopically-enriched seawater with isotopically-depleted rainfall, which is itself influenced by the so-called “amount effect”, in which local rainfall amount is considered as the primary control of rainfall isotopes (e.g. Dansgaard, 1964; Rozanski et al., 1992). However, recent modeling studies and observations of modern precipitation isotope data indicate that precipitation isotopes can record a range of atmospheric circulation processes including moisture sources and trajectories (e.g. LeGrande and Schmidt. 2009; Kurita et al., 2009; Lewis et al., 2010; Moerman et al., 2013). Better constraints on the interpretation of rainfall isotope data through comparisons of multiple climate indicators will therefore help to elucidate not only the regional hydroclimate sensitivities to global climate forcings, including atmospheric greenhouse gas levels (e.g. Tachikawa et al., 2013), orbital variations (e.g. Holbourn et al., 2005; Kershaw et al., 2011; Tierney et al., 2012; Carolin et al., 2013), ice volume changes (e.g. Lee et al., 2014; Russell et al., 2014; Wicaksono et al., 2015), and aerial exposure of the Sunda and Sahul Shelves (Griffiths et al., 2009; Partin et al., 2007; DiNezio and Tierney, 2013; Dubois et al., 2014; Niedermeyer et al., 2014), but also the atmospheric circulation changes that govern the regional climate response.

Here we employ stable isotope analyses of terrestrial plant biomarkers to reconstruct paleoclimate and paleovegetation in Wallacea. Carbon and hydrogen isotope ratios of terrestrial plant leaf wax compounds (e.g. *n*-alkanes, *n*-acids, and others) can record changes in vegetation type and the isotopic composition of precipitation, providing valuable paleoclimate data (Sachse et al.,