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The Holocene environmental changes in southern Indonesia reconstructed from highland caldera lake sediment in Bali Island

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ABSTRACT

Diatom, pollen, geomagnetic and geochemical analyses were carried out on a 3.6 m long sediment core taken from Lake Buyan, a highland caldera lake in central Bali Island, to reconstruct the Holocene climate changes in equatorial southern Indonesia. The core represents ~8 thousand years sedimentation of organic-diatomaceous lake mud. Constant inclusion of benthic diatom fossils as main components indicated that suspension and inflow of littoral materials were the main sedimentary process. The core contained laminated sediments in two distinct intervals at 6.5–5.0 and 3.6–3.1 cal ky BP, and multi-proxy records showed generally drier climate in these sections especially at 3.6–3.1 cal ky BP. Lake bottom waters were more reducing condition in these laminated periods probably due to increased lake productivity by prolonged dry season and wind mixing. Laminae structures were made up of a layer composed of benthic diatoms and amorphous organic materials, and a layer made by only planktonic diatom fossils, each of which may represent rainy and dry period deposits. Although southern Indonesia shows clear Australian monsoon rainfall seasonality at present, counting of layer numbers showed interannual cycles of laminae formation. Prolonged dry seasons could obscured the rainfall seasonality in these periods, but precise depositional patterns were elusive. Unlaminated sections showed homogeneous sediment mixture of benthic, planktonic diatoms and more volume of terrigenous materials indicating wetter climate and seasonality similar to the present time. This was supported by the higher share of marsh environment pollens reflecting more stable lake level trends. The dry climate from 6.5 cal ky BP was in line with the general perception of stronger ENSO dynamics from the mid Holocene due to weaker than before boreal summer insolation, but the sporadic appearances of dry periods imply the influence of regional climate forcings such as temporal migrations of inter tropical convergence zone (ITCZ). It was, however, possible that temporal shifts of large climate mode occurred in equatorial Pacific and Indian Oceans. Wettest climate was inferred from 3.1 cal ky BP to the present and this might reflect increased importance of Austral hemisphere atmospheric convection and subsequent southerly position of ITCZ in Austral summer time.

1. Introduction

Archipelagoes of southern Indonesia are located at southern maritime continent and within the equatorial warm sea surface area called Indo-Pacific Warm Pool (IPWP) that range from central Pacific to eastern Indian Oceans. The year-round strong atmospheric convection in this area function as heat and moisture source to high latitudes and its thermodynamics are closely linked with El Niño Southern Oscillation (ENSO) in equatorial Pacific that affect global climates (Wang et al., 2000; McPhaden et al., 2006). Climate in southern Indonesia is characterized by Asian–Australian monsoon seasonality. This is accompanied by migration of inter-tropical convergence zone (ITCZ), a global atmospheric conversion belt of northern and southern trade winds. Interannual rainfall trend is influenced by ENSO dynamics with generally dry condition

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in El Niño years (Dai and Wigley, 2000; Aldrian and Susanto, 2003; Hendon, 2003) when moisture bearing low pressure moves eastward of the equatorial Pacific Ocean. Relative to central equatorial Pacific, southern Indonesia receive climatic influence from the austral hemisphere, but it is also linked with Indian Ocean thermal dynamics due to its boundary location of Pacific and Indian oceans (Abram et al., 2007; Aldrian and Djamil, 2008; Sahu et al., 2012).

The importance of understanding past climate changes in IPWP area is well recognized and accumulating paleoclimate archives are used for testing accuracy of climate modeling. Reconstructions of the Holocene environments were conducted mainly from ocean bottom cores and coral fossils, and general picture of Holocene climate trend was described (Stott et al., 2004; Donders et al., 2008; Reeves et al., 2013) represented by the early Holocene constant La Niña biased condition and subsequent active ENSO cycles in the mid-late Holocene. The first-order forcing of the climate trend was likely the boreal insolation trends driven by the precessional cycle of Earth's rotation axis. However, recent studies observed regional ENSO variability between the east and west part of Pacific Ocean (Reeves et al., 2013; Carré et al., 2014) and within IPWP area (Stott et al., 2004). Series of coral records across equatorial Pacific also showed no systematic trend during the Holocene (Cobb et al., 2013). These disagreements highlight the existence of ocean-atmospheric internal variability, but they also arise from technical difficulty in interpreting oceanic geochemical records and removing local environmental factors (Brijker et al., 2007; Russon et al., 2013). Terrestrial lacustrine deposits have potential to show more immediate data of rainfall variations that are most concerned issues for socioeconomics, but more numbers of sedimentary records are necessary as they are often discontinuous due to frequent episodic sedimentation events (Pirrung et al., 2004, 2005; Rodysill et al., 2012). Terrestrial archives could be also influenced by local climate features related to configuration of islands and regional topography (Rauniyar and Walsh, 2013; Dubois et al., 2014).

In this study, a sediment core taken from Lake Buyan in highland caldera area of central Bali Island was analyzed using multiple proxies and tried to infer the Holocene climate changes in southern Indonesia. On the same core, Li et al. (2013) conducted pollen analysis, XRF analysis and magnetic susceptibility measurement showing general wet/dry climate trend and vegetation changes with the possible influence of human settlement in the late Holocene. However, lake water dynamics and lamina formation patterns in relation to climate changes were left untouched as the pollen flora of tropical rainforest is rather insensitive to climate changes. Fossil diatom assemblages, on the other hand, are highly responsive to fine changes of lacustrine hydrology and climate by its rapid production rate and precise habitat segregations (Wolin and Stone, 2010). This study presents further environmental reconstruction with additional radiocarbon datings, diatom and chemical analyses with emphasis on diatom data. Microscopic observation of epoxy impregnated core samples and thin sections were also carried out to understand the nature of laminae structures.

2. Study site

Bali Island is one of the southern Indonesian volcanic arc islands with two large caldera structures in northern area: Batur caldera in the east of the island and Bratan caldera in the west (Fig. 1B). Lake Buyan (115° 07′ E, 8° 15′ S; 1214 m a.s.l.) is one of the three caldera lakes inside Bratan caldera of Batukau mountain complexes in Buleleng regency. It is elliptical shape with a surface area of 3.7 km^2 and a maximum depth of around 65 m (Fig. 1C). Northern lake shore is enclosed by more than 100 m high steep bluff of caldera rim. The geology of the lake surrounding is widely occupied by the parent product of the old Buyan–Bratan volcanoes mainly basalts-andesite breccia and tuff formed in the Pleistocene age (Ryu et al., 2013). There are no large inflow rivers and possible catchment areas are within 4 km distance from the lake shore (Shimano, 1994), and andosols are main soil types of the area (Delinom et al., 1997). There is no surficial outflow stream and main water loss is evoparation, but the existence of rivers and hot springs in lowland area imply underground percolation of lake water due to porous surrounding soils (Lehmusluoto and Mahbub, 1989; Delinom et al., 1997). Seasonal lake level change is as high as 1–1.5 m (Green et al., 1978; Kayane et al., 1992), but there has been an occasional wet season flooding with 3 m of lake level rise ("Inundation Not Caused", 2012). Lake water is oligo-mesotrophic with low nitrate and high silicate concentration (Lehmusluoto et al., 1997). The ratio of lake area with respect to its maximum water depth is one of the smallest in Indonesian lakes and anoxic water was observed at lower than 40 m depths in dry season (Green et al., 1978; Lehmusluoto et al., 1997). However, top to bottom lake water overturning could be occurring occasionally as hydrogen sulfide was not observed in hypolimnion waters in mixing dry season and oxidation-reduction potential of surface water showed rapid fluctuations in daily basis (Lehmusluoto et al., 1997) probably due to fragile thermal stratification and strong mixing by wind and nocturnal evaporative heat loss (Löffler, 1964; Lewis, 1987).

Climate of Bali Island show typical Asian–Australian monsoon seasonality (McBride and Frank, 1999) with clear dry and wet seasons. There is abundant rainfalls in austral summer (November–March: wet season) when ITCZ migrate southward and wet northwestern wind prevails, and dry southeastern wind prevails in austral winter (May–October: dry season). Annual air temperature ranges from 19.0 to 9.8 °C. There is large local variety of annual rainfall within Bali Island: 1500 mm in coastal lowland and more than 2500 mm in mountainous area including the study site (Kayane et al., 1992), due to abundant wet season rainfall in mountainous area (monthly rainfall reaches 400 mm in wet season at Candikuning Village adjacent of Lake Bratan) (Shimmi, 1993) and thus seasonal contrast of annual rainfall distribution is larger in mountainous area.

The rainfall pattern in southern Indonesia is strongly regulated by ENSO events and accompanying sea surface temperatures (Chang et al., 2004), and drought years are often associated with El-Niño events (Boer and Subbiah, 2005). Dry season rainfall is suppressed strongly in El-Niño years and elevated in La Niña years (Aldrian and Susanto, 2003; Hendon, 2003). Wet season rainfall could be less responsive to ENSO events (Haylock and McBride, 2001), but highly various in local scale (Qian et al., 2010). There were strong El-Niño events in historical ages that were comparable with or even stronger than recent 1982/83 and 1997/1998 El Niño events. Representative one was the severe dry spell in late 18th century which was stated in historical documents (Grove, 1998), and also detected in natural archives around Java Island such as tree rings (Poussart et al., 2004; D'Arrigo et al., 2006), coral fossils (Charles et al., 2003) and lacustrine sediments (Rodysill et al., 2012).

3. Materials and methods

3.1. Core sampling

For the selection of coring point, water depth was measured by echo sounding profiling in several transects of the lake basin. 3 sediment cores were collected from deepest basin at around 60 m water depth using piston coring (Fig. 1C) in December 2007. The three cores encased in polyvinyl chloride (PVC) tube were cut