ENSO and monsoon variability during the past 1.5 kyr as reflected in sediments from Lake Kalimpaa, Central Sulawesi (Indonesia)

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Abstract

The climate of Sulawesi is driven by the monsoon system as well as the El Niño–Southern Oscillation (ENSO). Until now, mechanisms and long-term variations of these complex interacting climate processes have been poorly understood. This paper uses a sediment record from Lake Kalimpaa to investigate long-term rainfall trends of the past ~1500 years. Granulometric and geochemical data provide indications for an increasingly wetter climate (higher rainfall intensities and/or mean rainfall) on centennial to millennial time scales from approximately AD 560 to the 20th century. Highest rainfall intensities probably occurred at the end of the ‘Little Ice Age’ (LIA). The trend towards wetter conditions during this time could also be detected in other palaeoclimatic studies from the region. A plausible explanation for these observations is the southward displacement of the Intertropical Convergence Zone (ITCZ) associated with changes in monsoon dynamics. However, comparison of the results with other proxy and model data indicates that the long-term rainfall variability in Central Sulawesi is also determined by variations in ENSO. During the 20th century, the climate signal in the Kalimpaa record is superimposed by human impact. Moreover, the data suggest that two periods of disturbance occurred within the lake catchment between about AD 1090–1190 and AD 1450–1620. Comparison with fire frequency derived from macro-charcoal analysis indicates that these events were caused by forest fires which likely took place during periods of drought. Broadly simultaneous drought periods have been detected in records from East Java suggesting a regional drought occurrence affecting at least East Java and Sulawesi.

Keywords

El Niño–Southern Oscillation, fire history, Intertropical Convergence Zone, lake sediments, monsoon, palaeorainfall

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Introduction

Sulawesi belongs to the Greater Sunda Islands located in the Indo-Pacific warm pool (IPWP), which is the largest storage of warm surface ocean water globally (Gagan et al., 2004; Oppo et al., 2009). Consequently, this area is a substantial source of latent heat and has a great importance for understanding modern climate dynamics (Hope, 2001).

Several rainfall regimes occur in Indonesia in response to, for example, variations in the monsoon system and the El Niño–Southern Oscillation (ENSO; Aldrian and Susanto, 2003). The seasonal rainfall in eastern Indonesia is mainly driven by the intensity of the Australian–Indonesian summer monsoon (Griffiths et al., 2010), whereas the ENSO cycle (Diaz and Kiladis, 1992) is responsible for the complex interannual climatic variability in this region. While ENSO cold events (La Niña) enhance the rainfall in Sulawesi, ENSO warm events (El Niño) result in dry periods, which occasionally have led to extreme droughts in the past (D’Arrigo et al., 2006; Keil et al., 2008; Salafsky, 1994). These drought events facilitated the occurrence of forest fires in tropical rainforests, as recorded in Borneo and Sulawesi during the strong El Niño of 1997/1998 (Rowell and Moore, 2000; Sastry, 2002; Siegert and Hoffmann, 2000).

The annual influence of the monsoon is dominant in most parts of Sulawesi, where the wet season coincides with the

Australian–Indonesian summer monsoon from October to March and the dry season with the Asian summer monsoon from April to September (Aldrian and Susanto, 2003; Gunawan, 2006; Figure 1b–c). An ‘anti-monsoonal’ rainfall pattern has been observed in the northeast of Sulawesi. This area representing only a vast minority of the island is characterized by inverse occurrences of wet seasons from April to August and dry seasons from September to March as well as a more pronounced impact of ENSO (Aldrian and Susanto, 2003; Aldrian et al., 2004; Gunawan, 2006). The mechanism underlying this pattern is the strong influence of the ocean and its sea surface temperatures (SST) in this region. Due to the Indonesian throughflow (ITF), marine currents from a Pacific warm pool northeast of New Guinea can enter the Indian Ocean

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Figure 1. (a) Map of the research area showing the location of Lake Kalimpa on the island of Sulawesi. Also depicted are the locations of other study sites mentioned in the text: (1) Makassar Strait (Oppo et al., 2009; Tierney et al., 2010); (2) Halmahera: Kau Bay (Langton et al., 2008); (3) East Java: Lake Lamongan (Crausbay et al., 2006), Lake Logung (Rodysill et al., 2012), Lake Lading (Konecky et al., 2013); (4) Makassar Strait (Newton et al., 2006); (5) South Sulawesi: Wanda site near Lake Matano (Hope, 2001); (6) North Sulawesi: Lake Tondano (Dam et al., 2001); (7) Besoa Valley, Central Sulawesi (Kirleis et al., 2011). The grey solid arrows represent the sea currents of the Indonesian throughflow (ITF) referring to Godfrey (1996) and Morey et al. (1999), whereas the dashed arrows depict further possible pathways. (b) The generalized main wind directions over Sulawesi during the Australian-Indonesian summer monsoon (DJF: December-January-February) and (c) during the Asian summer monsoon (JJA: June-July-August). The basic map was created using MapCreator 2.0.

(Godfrey, 1996; Morey et al., 1999). These currents not only mainly pass the Makassar Strait but also influence the SST in the Molucca Sea northeast of Sulawesi (Figure 1a). During the boreal winter, the ITF brings cooler water from the warm pool to the Molucca Sea inhibiting the formation of a convective zone in the northeastern part of Sulawesi (wet season in the monsoonal regions of Indonesia). In contrast, during the boreal summer, warmer water supplied from the warm pool promotes the formation of a

convective zone in northeastern Sulawesi (dry season in most parts of Sulawesi; Aldrian and Susanto, 2003; Godfrey, 1996; Gordon et al., 1999; Gunawan, 2006; Morey et al., 1999). According to Gunawan (2006), Central Sulawesi is characterized by a mixture of both monsoonal and 'anti-monsoonal' types of rainfall and by the strong influence of ENSO.

Topography also influences rainfall and causes substantial variations over short distances. In the mountainous regions of the

Figure 2. (a) The age-depth model for the Lake Kalimppaa record based on calibrated radiocarbon ages which are presented as medians referring to the 2σ ranges (Haberzettl et al., 2013). The grey data points are regarded as outliers and have been excluded from the final age-depth model (Haberzettl et al., 2013). (b) Comparison of declination and inclination of the Lake Kalimppaa record (Haberzettl et al., 2013) with the CALS3k.4 model output for the location of Lake Kalimppaa (Korte and Constable, 2011).

Lore Lindu National Park, rainfall is mainly generated orographically (Gunawan, 2006). During boreal winters, the Australian–Indonesian summer monsoon brings moist air masses to Central Sulawesi reaching the island from the northwest. In the mountains around Palu Valley, the ascending air leads to orographic rainfall with a strong correlation between altitude and precipitation totals. In contrast, dry air masses reach Sulawesi during austral winters, when precipitation is lower and solely generated orographically (Gunawan, 2006).

Thus far, neither the mechanisms nor the long-term variations of these complex interacting climate processes have been completely understood. Palaeoenvironmental data are needed to achieve more detailed knowledge of palaeoclimatic changes in Sulawesi; there are only a few palaeoclimatic studies from this region covering the past millennia. Marine records are available from Makassar Strait (Newton et al., 2006; Oppo et al., 2009; Tierney et al., 2010; Figure 1a) and Kau Bay (Halmahera; Langton et al., 2008); lacustrine sediments from East Java (Lake Lamongan: Crausbay et al., 2006; Lake Lading: Konecky et al., 2013; Lake Logung: Rodysill et al., 2012) provide terrigenous archives with a suitable temporal resolution. Palynological evidence is available from two sites in the Besoa Valley, Central Sulawesi, and the pollen data of one of these exhibit a cooling trend during the ‘Little Ice Age’ (LIA; Kirleis et al., 2011). However, palaeoclimatic studies from Sulawesi are rare and cover longer time frames with lower temporal resolutions (Lake Tondano: Dam et al., 2001; Wanda site near Lake Matano: Hope, 2001; Figure 1a). Therefore, it is necessary to carry out further investigations on palaeoenvironmental archives from Sulawesi to enhance the spatial and temporal resolution of proxy data.

This study aims to contribute to a better understanding of palaeoclimatic changes in Sulawesi during the past 1500 years. The main objective is to investigate various sedimentological characteristics of a core from Lake Kalimppaa (Central Sulawesi; Figure 1a) in order to provide indications for long-term rainfall trends, palaeoenvironmental changes and fire history in the lake catchment.

Site description

Lake Kalimppaa ($1^{\circ}19'34.8''\text{S}$, $120^{\circ}18'31.9''\text{E}$; Figure 1a), sometimes also referred to as Danau Tambing, is located at 1660 m

a.s.l. in the Lore Lindu National Park in Central Sulawesi, Indonesia. It occupies an area of 6.5 ha and has a maximum water depth of 6.6 m. The lake is surrounded by small reed belts and a swamp area to the north (Haberzettl et al., 2013); it has an inflow from the northeast and an outflow to the southwest.

Lake Kalimppaa is located in a mountain pass at the end of a side valley of the Palu Valley. Surrounding mountaintops in the northeast and southwest exceed altitudes of 2000 m a.s.l. The lake’s catchment area of approximately 1.8 km² extends mainly to the north. The geological setting is characterized by the Pliocene Kambuno Granite (Leemhuis, 2005; Priadi et al., 1994; Simandjuntak et al., 1991) and its weathering products. Regional vegetation is characterized by montane rainforest which in the Lore Lindu National Park is presently characterized by a 90% intact canopy cover (Kirleis et al., 2011) and is dominated by Fagaceae, mostly represented by the two genera *Lithocarpus* and *Castanopsis* (Culmsee et al., 2010).

There is no representative meteorological station in the vicinity of Lake Kalimppaa itself, but there are records for the mountains of western Central Sulawesi, and these can be used as representative of the catchment. Because of the close proximity to the equator, temperatures are almost constant throughout the year. Daytime temperatures at higher altitudes range from 16°C to 22°C; annual precipitation is around 2000–3000 mm (Weber, 2006).

Materials and methods

A 211-cm-long composite sediment record consisting of three overlapping sections (KAL 1-1, KAL 1-2, KAL 1-3) was recovered from Lake Kalimppaa using a Livingstone piston corer (Livingstone, 1955). Palaeomagnetic analyses showed that only KAL 1-1 and KAL 1-2 (153 cm composite length) were suited for palaeoenvironmental reconstruction since no reliable chronology could be established for the oldest part of the core (Haberzettl et al., 2013). Each section was split, photographed and described lithologically. The composite profile was compiled based on macroscopic marker layers. The chronology was adapted from Haberzettl et al. (2013; Figure 2a). Several sets of bulk samples which had been sent for radiocarbon dating revealed inconsistencies, that is, ages were not in stratigraphic order. Since hard-water effects can be excluded for Lake Kalimppaa, another kind of

reservoir effect is assumed. Probably, the dated material of the bulk samples comprised both autochthonous and allochthonous organic matter. Therefore, only the youngest ages were used for the age-depth model that is based on linear interpolation (Haberzettl et al., 2013; Figure 2a). Despite these dating uncertainties, the created age-depth model seems to be a first-order approximation which is corroborated by magnetostratigraphy. The comparison of palaeosecular variation data of the Kalimpaa record with the output of the CALS3k.4 model (Korte and Constable, 2011) shows many isochronic similarities for inclination as well as for declination (Figure 2b). Therefore, the age-depth model can be used as basis for further multi-proxy approaches on the Lake Kalimpaa record. A marked increase in sedimentation rate is obvious for the most recent sediments. While the mean sedimentation rate between 151 and 44 cm is about 0.8 mm/yr, for the youngest sediments between 44 cm and the top of the core, the age-depth model provides a sedimentation rate of ~9.2 mm/yr on average.

After palaeomagnetic measurements, u-channels of KAL 1-1 and KAL 1-2 were subsampled for subsequent geochemical and granulometric analyses. Grain size distribution was measured at an interval of 1 cm ($N=153$) with a Laser Diffraction Particle Size Analyser (Beckman Coulter LS 13320) utilizing the Aqueous Liquid Module and 10 s ultrasonic for dispersion. The Fraunhofer diffraction theory was used for optical modelling of light scattering (De Boer et al., 1987). Organic matter and carbonates were removed with H_2O_2 (30%) and HCl (10%), respectively, and sodium pyrophosphate solution ($Na_4P_2O_7 \cdot 10 H_2O$; 0.1 M) was used as a dispersion medium. The measurements were carried out in several runs until a reproducible signal was obtained. The first reproducible run was taken for further statistical treatment. The grain size fractions were calculated according to Ad-hoc AG Boden (2005). The skewness (ϕ -scale) was determined by the logarithmic method of moments by means of a modified version of Gradistat 4.2 (Blott and Pye, 2001).

Element concentrations of Al, Ca, Fe, K, Mg, Mn, P, S and Ti were measured at intervals of 2 cm ($N=77$) using ICP-OES (Varian 725-ES). For this purpose, oven-dried (50°C) aliquots were pestled (<40 μm) and homogenized. The samples were digested with a microwave-based procedure using modified aqua regia, which consists of 1 mL deionized water, 2 mL HCl (30%) and 4 mL HNO_3 (30%).

With the use of syringes, sediment samples were obtained at ~4 cm intervals ($N=41$) from the core and freeze-dried. Aliquots were ground and analysed for total organic carbon (TOC) and total nitrogen (TN) contents with a CNS elemental analyser (Euro EA 3000). TOC was determined after the destruction of carbonates with 2 M H_3PO_4 . Subsequently, the molar TOC/TN ratio was calculated.

Additionally, mineralogical investigations on the pestled samples ($N=10$) were carried out using an x-ray diffractometer (D8-Discover, Bruker AXS) equipped with a $CuK\alpha$ x-ray tube and a gas proportional counter (HI-STAR area detector, Bruker AXS). The evaluation of the data was performed by means of the software Match! 2.0.9 and MacDiff 4.2.6.

Macro-charcoal particles (>150 μm) were counted for samples evenly spaced at 1 cm intervals along the upper part of the sediment core (first 145 cm). The samples (1 cm³ each) were prepared following the method of Stevenson and Haberle (2005), which is a modification of a method developed by Rhodes (1998). Weak hydrogen peroxide (6% H_2O_2) was used to partially digest and bleach organic material in the sediment samples when counted under a binocular dissecting microscope. The sample preparation procedure aims to ensure that little particle fragmentation occurs during preparation. Results are expressed as number of charred particles per cubic centimetre.

Charcoal raw data were interpolated to constant 5 years, corresponding approximately to the median temporal resolution.

Interpolated charcoal concentrations (number of particles per cubic centimetre) were multiplied by estimated sedimentation rate (cm²/yr) to obtain the charcoal accumulation rate (CHAR, particles/cm²/5 yr) of each sample. Low-frequency variations in a charcoal record ($C_{background}$) represent changes in charcoal production, sedimentation, mixing and sampling. $C_{background}$ was estimated with a locally weighted regression using a 100-year window in order to maximize the signal-to-noise index and the goodness-of-fit between the empirical and the modelled C_{noise} distributions (Higuera et al., 2009). $C_{background}$ was subtracted to obtain a residual series, C_{peak} . It is assumed that C_{peak} is composed of two subpopulations (Higuera et al., 2008, 2009): C_{noise} , representing variability in sediment mixing, sampling and analytical and naturally occurring noise, and C_{fire} , representing charcoal input from local fires. A Gaussian mixture model was used for each sample to identify the C_{noise} distribution. The 99th percentiles of the C_{noise} distributions were considered as thresholds separating samples into 'fire' and 'non-fire' events. The peaks which passed the threshold criterion were subjected to a 'Poisson minimum-count' screening in order to eliminate the peaks that result from statistically insignificant variations in charcoal counts. Peak fire episodes refer to one or more fires occurring within the time span of the charcoal peak. Past fire regime characteristics were inferred based on the temporal pattern of identified charcoal peaks via calculation of fire frequencies smoothed with a 200-year window. All statistical treatments were done using the program CharAnalysis (Higuera et al., 2009).

Proxy determination for palaeoenvironmental processes

Palaeorainfall proxies

Grain size can be used as a proxy for variations in transport energy or lake levels and, hence, climate variability (Conroy et al., 2008). In detail, high rainfall intensities and/or amounts possibly result in enhanced erosion in the catchment as well as an increased transport capacity and competence of the tributary which might lead to the deposition of coarser clastic material in the lake (Håkanson and Jansson, 1983). According to Nichols (2009), grain size can yield information on the flow velocity and hence the runoff during the time of sediment deposition.

In the Lake Kalimpaa catchment, sediment erosion and transport are likely driven by runoff. Channel erosion and denudation of soil material are probably the major causes for the transport of sediments, although dense vegetation cover accompanied by high interception protects the soil surface.

It is assumed that the deposition of coarse grain sizes reflects periods or events characterized by high runoff and, hence, higher rainfall intensities. In contrast, the deposition of fine grain sizes is linked to periods of lower average rainfall and, thus, lower transport energy of the inflow. In such a small system, probably lower runoff facilitates the deposition of finer particles due to the absence of turbulences in the lake water which are caused by the inflow during periods of greater rainfall and runoff.

The skewness (Sk) of grain size distributions of deposited sediments is a result of the composition of the source material as well as the energy level of the transport process. If transport processes exhibit a high energy level, the deposited sediments become coarser, and their grain size distributions are more positively skewed (on ϕ -scale). If the energy level is low, the deposited sediments become finer and more negatively skewed (McLaren and Bowles, 1985).

It is supposed that the main source of Al, Ca, K, Mg and Ti are the minerals of the Kambuno Granite and its weathering products. K is mainly associated with K-feldspars, biotite and muscovite as well as, to a lower extent, with illite. Mg is related to biotite and

clay minerals, such as montmorillonite; Ca occurs, for instance, in plagioclase and illite. Ti is chemically immobile and occurs mainly in heavy accessory minerals like rutile and ilmenite, which are extremely resistant against weathering (Goldich, 1938; Li et al., 2003; Shotyk et al., 2001). Therefore, Ti was used in many other studies on lake sediments as an indicator for the input of clastic, terrigenous material (e.g. Haberzettl et al., 2005; Kasper et al., 2012; Whitlock et al., 2007) – a process that is often driven by precipitation and runoff in the lake catchment.

During the chemical weathering of feldspars and micas to clay minerals, K, Ca and Mg get dissolved. In contrast, Al, which is part of feldspars and micas as well as clay minerals, is nearly insoluble and less mobile than the alkali and alkaline earth elements (Middelburg et al., 1988; Nesbitt et al., 1980). Kaolinite and gibbsite, which are common weathering products of granites under tropical conditions (West and Dumbleton, 1970), contain Al but no K, Ca and Mg. Therefore, Al is used as denominator in various element/Al ratios in the following to compensate variable depletion effects which are primarily caused by concentrations of the redox sensitive element Fe.

In many other studies, element/Al ratios like K/Al and Ti/Al are related to weathering intensities in the source area, input pathways or the strength of transport processes (Boyle, 1983; Lückge et al., 2001; Müller et al., 2001; Zabel et al., 2001). Engstrom and Wright (1984) and Mackereth (1966) found that alkali and alkaline earth elements (e.g. Ca, K and Mg) accumulate in lake sediments during periods of intense erosion, when mineral matter is transported into the lake. In contrast, low values of alkali and alkaline earth elements in lake sediments occur when erosion is low, and leaching of the catchment soils is dominant. Granite is usually deeply weathered in tropical climates, and thus, unweathered minerals like feldspars are more prominent in areas with higher slope angles (Ruxton, 1959). Therefore, the source area of feldspars and micas is possibly the steeper slopes around the lake, and their transport into the sediment occurs via terrigenous runoff during periods of high erosion. Accordingly, K/Al, Ca/Al and Mg/Al reflect the variability of the proportion of chemically less weathered feldspars and micas to clay minerals, especially kaolinite. The Ti/Al ratio mainly reflects changes in grain size (Boyle, 1983; Zabel et al., 2001). Ti is associated with coarser material, while Al rather represents the fine-grained fraction, so that the Ti/Al ratio is linked to the strength of fluvial transport which reflects hydrological variability. Therefore, Ti/Al, K/Al, Mg/Al and Ca/Al ratios may be used as proxies for palaeorainfall similar to other studies on tropical lake sediments (Felton et al., 2007; Warrior and Shankar, 2009). High ratios are interpreted as periods and/or events of high erosion and, accordingly, high rainfall intensities in the lake catchment.

Proxies for catchment disturbances and changes in redox conditions

Fire frequency data derived from macro-charcoal analysis are used to reconstruct the fire history around Lake Kalimpa. Such forest fires may cause substantial disturbances within the lake catchment regarding changes in vegetation and sedimentological processes. Enhanced erosion as well as an increased supply of organic matter entering the lake can be the consequences of these disturbances.

Fe, Mn, P, S, TOC and TN are typically part of a common reaction and transport cycle in sediments (Van Cappellen and Wang, 1996). The significantly higher presence of allochthonous Fe and Mn is characteristic of tropical lakes (Crowe et al., 2008). In soil samples from the upper horizons of nine sites in the catchment area of Lake Kalimpa, average contents of ~2.5% of Fe and ~340 ppm of Mn were measured (Markussen, 2000). As it will be demonstrated later, Fe and Mn concentrations are significantly

higher in certain sections of the sediment core than those in the topsoil. This cannot be explained solely by an increased input rather by the accumulation of these elements due to another process(es), such as redox reactions in the sediment and/or the water column. Since this is accompanied by relatively high TOC/TN ratios, which can indicate a shift to a more terrestrial origin of the organic matter (Haberzettl et al., 2008; Mayr et al., 2005; Meyers, 1994), it is hypothesized that sharp increases in TOC, TN, S, Fe and Mn concentrations result from the supply of organic material from the catchment. This promotes reducing conditions in the sediment due to microbial decomposition. In contrast, low molar TOC/TN ratios likely arise from a comparatively low input of terrestrial organic matter or a higher occurrence of phytoplankton, which is typically characterized by TOC/TN ratios ranging from 4 to 10 (Kasper et al., 2013; Meyers, 1994).

The microbiological decomposition of organic material in lake water and sediment is an oxygen-consuming process that produces anoxic environments (Davison, 1993). In lakes, Fe and Mn occur in various oxidation states (Fe^{II} and Fe^{III} ; Mn^{II} , Mn^{III} and Mn^{IV}) depending on the given redox conditions. Under oxidizing conditions, both elements exhibit low solubility, where Mn is soluble at higher redox potentials than Fe (Sigg and Stumm, 1996). Fe that enters lakes via rivers occurs mainly in particulate form (>99%; Salomons and Forstner, 1984) as ferric (oxyhydr)oxide or bound in the lattice of micas and clay minerals. Mn is also predominantly supplied by solids, such as MnO_2 , and to lower amounts as dissolved Mn^{2+} (Davison, 1993; Engstrom and Wright, 1984). There seems to be a succession of redox processes in the sediment record from Lake Kalimpa, during which particulate $\text{Fe}(\text{III})$ -(oxyhydr)oxides are dissolved to Fe^{2+} which precipitates as amorphous $\text{Fe}(\text{II})$ -sulphide or, for instance, mackinawite, or it becomes mobile and reprecipitates as $\text{Fe}(\text{III})$ -(oxyhydr)oxide at the oxic/anoxic boundary. The identification of $\text{Fe}(\text{II})$ -sulphides is inferred from the black sediment colour and its association with high Fe and S bulk concentrations (Emerson, 1976; Engstrom and Wright, 1984). The affinity of P to be adsorbed on the surfaces of Fe -(oxyhydr)oxides is known from the literature (e.g. Buffle et al., 1989; Lijklema, 1980). According to Lopez et al. (2006), high Fe and P values are indicative for the precipitation and accumulation of authigenic Fe. Moreover, P is also associated with organic matter.

Results

Core lithology and mineralogy

The core sections KAL 1-1 and 1-2 consist mainly of finely laminated silts with a few homogeneous sections and distinct sand layers. Based on obvious changes in sediment structure, colour and macroscopic grain size, six lithological units can be distinguished (Figure 3). Unit I (153–128 cm; ~AD 560–1090) exhibits finely laminated blackish grey and light grey silts. Unit II (128–118 cm; ~AD 1090–1190) is characterized by homogeneous black sediments composed of fine silts to fine sandy coarse silts. Finely laminated, light greyish to grey layers consisting of medium to fine sandy coarse silts occur in unit III (118–93 cm; ~AD 1190–1450; Figure 3). Mica particles, probably muscovite, are conspicuous between ~110 and 40 cm (~AD 1275–1965). Partially laminated, dark brown to black fine sandy coarse silts occur in unit IV (93–77 cm; ~AD 1450–1620). Unit V (77–48 cm; ~AD 1620–1910) exhibits a greyish colour and contains partially laminated, fine sandy coarse silts with an intercalated sand layer. The uppermost unit VI (48–0 cm; ~AD 1910–2006; Figure 3) consists of brownish medium to fine sandy silts. It is assumed that human impact in the catchment area (e.g. by road construction, camp site) superimposes any effects of climatically induced changes during the 20th century (Haberzettl et al., 2013). Nevertheless, it cannot be ignored that

Figure 3. (a and b) Geochemical and (c) granulometric (Cl: Clay, FSi: fine silt, MSi: medium silt, CSi: coarse silt, FSa: fine sand, MSa: medium sand, CSa: coarse sand) parameters of the Kalimpaa sediment core plotted versus sediment depth (age scale is also depicted on the right). A schematic illustration of the lithology is given on each plot on the left. The grey and white bars represent the lithological units.

climate could have also caused the marked increase in sedimentation rate for the most recent sediments. Since the distinction between climatic and human-driven impacts seems not possible with certainty, no palaeoclimatic interpretation has been done for unit VI in the following.

X-ray diffractograms of all measured samples show comparable spectra. The most common sediment minerals are quartz, alkali feldspars, plagioclase, muscovite, biotite (chemically unweathered minerals from the Kambuno Granite), kaolinite and, to a lesser extent, illite (weathering products of the Kambuno

Table 1. Correlation matrix including the Pearson product–moment correlation coefficient and the related *p*-value of the grain size fractions from all measured samples of the Lake Kalimpa record.

	Cl	FSi	MSi	CSi	FSa	MSa	CSa
Pearson's <i>r</i>							
	<2 µm	2–6.3 µm	6.3–20 µm	20–63 µm	63–200 µm	200–630 µm	630–2000 µm
<i>p</i>							
Cl	–	0.92	0.74	–0.81	–0.79	–0.10	–0.07
FSi	<0.001	–	0.77	–0.88	–0.80	0.01	0.03
MSi	<0.001	<0.001	–	–0.57	–0.94	–0.19	–0.11
CSi	<0.001	<0.001	<0.001	–	0.50	–0.18	–0.14
FSa	<0.001	<0.001	<0.001	<0.001	–	0.14	0.04
MSa	0.23	0.93	0.02	0.02	0.09	–	0.95
CSa	0.37	0.76	0.18	0.10	0.65	<0.001	–

The limits of grain size fractions are according to Ad-hoc AG Boden (2005) as follows: clay (Cl), fine silt (FSi), medium silt (MSi), coarse silt (CSi), fine sand (FSa), medium sand (MSa) and coarse sand (CSa). Highly significant correlations ($p < 0.001$) are highlighted (bold: highly positively correlated, bold italic: highly negatively correlated).

Granite). In some samples, goethite and gibbsite were detected, which are typical for weathered granites in tropical regions as well as clay minerals (West and Dumbleton, 1970). Furthermore, x-ray diffraction spectra indicate that carbonates are of minor importance in this record which was confirmed by multiple negative tests with hydrochloric acid.

Grain size analysis

The core sections KAL 1-1 and 1-2 are dominated by medium to coarse silt and accessorially contain some fine sand layers. With a mean of ~78.3% in all samples, silt is the most common fraction followed by sand (~13.5%) and clay (~8.2%). A correlation matrix of the calculated grain size fractions (Table 1) exhibits positive correlations between clay (Cl), fine silt (FSi) and medium silt (MSi). Coarse silt (CSi) and fine sand (FSa) are also positively correlated but negatively correlated to the aforementioned. Moreover, there is a positive correlation between medium sand (MSa) and coarse sand (CSa) which are only sporadically present in the record (Table 1). On this basis, the grain size fractions can be grouped into classes, namely, one of Cl+FSi+MSi and one of CSi+FSa. They show an opposing trend (Figure 3c) but depend on each other and, thus, probably represent the same palaeoenvironmental signal. In contrast, the third class consisting of MSa+CSa is interpreted as an additional signal.

Units I and II (153–118 cm; ~AD 560–1190) are characterized by low but slightly increasing CSi+FSa and Sk values as well as high but slightly decreasing Cl+FSi+MSi values (Figure 3c). The most prominent peak in MSa+CSa occurs at the base of unit II (at 128 cm; ~AD 1090). The lowermost section of unit III (118–112 cm; ~AD 1190–1250) exhibits low values for CSi+FSa and Sk as well as high values for Cl+FSi+MSi again. For the remaining part of units III, IV and V (112–48 cm; ~AD 1250–1910), CSi+FSa and Sk values first show a decreasing trend and then an increasing trend reaching their maxima within unit V (at 53 cm; ~AD 1860; Cl+FSi+MSi, vice versa). Over the entire record (units I–V), an increasing trend of CSi+FSa and Sk values as well as a decreasing trend of Cl+FSi+MSi values can be identified.

Geochemistry

With an average concentration of 9.3%, Al is the most abundant of the measured elements. It shows a decreasing trend from unit I to unit V (153–48 cm; ~AD 560–1910; Figure 3a). Concentrations

of K, Mg and Ti show an increasing trend and compared to Al opposite trend. Mg and Ti reach their maximum at 53 cm (~AD 1860) together with maximum values in CSi+FSa and Sk. Ca values are low in units I and II (153–118 cm; ~AD 560–1190) and on a higher level in the units III–V (118–48 cm; ~AD 1190–1910; Figure 3a).

All graphs of the element/Al ratios exhibit a similar pattern (Figure 4). They are characterized by low values in unit I (153–128 cm; ~AD 560–1090) and exhibit an increasing trend starting from units II to V (128–48 cm; ~AD 1090–1910) with maximum values at 53 cm (~AD 1860). Increased element/Al ratios coincide for large parts of the record with the macroscopic conspicuously presence of mica particles. A similar pattern in Ti/Al, K/Al, Mg/Al and grain size data is especially notable for the sections comprising the highest peaks within unit V (at 53 cm, ~AD 1860 and 49 cm, ~AD 1910).

TOC and TN are highly correlated ($r = 0.97$; $p < 0.001$). TOC values range from 0.24% up to 5.85%, TN from 0.02% up to 0.31% (Figure 3b). Both are low in unit I (153–128 cm; ~AD 560–1090) and increase markedly in unit II (128–118 cm; ~AD 1090–1190), with lower levels in unit III (118–93 cm; ~AD 1190–1450) and subsequently higher again in unit IV (93–77 cm; ~AD 1450–1620). TOC and TN values remain on high levels in unit V (77–48 cm; ~AD 1620–1910), where they reach their maximum of 5.85% for TOC and 0.31% for TN. The molar TOC/TN ratio shows two levels (Figure 5). The lower level in unit I (153–128 cm; ~AD 560–1090) exhibits values of around 14.3, and the higher level within units II–V (128–48 cm; ~AD 1090–1910) is characterized by mean values around 22.0.

Fe concentrations average 5.7% in the Kalimpa record (Figure 3b) and reach a maximum of 25.7% within unit II (128–118 cm, ~AD 1090–1190). Fe and S concentrations are strongly correlated ($r = 0.96$; $p < 0.001$) and exhibit distinctive peaks in the units II and IV (128–118 cm, ~AD 1090–1190 and 93–76 cm, ~AD 1450–1620; Figure 3b). Mn and P values also show peaks in these two sections but are characterized by higher values in the sediments above and below the peaks of Fe and S. Especially in unit V (77–48 cm; ~AD 1620–1910), Mn and P values are above average and show a similar pattern to TOC and TN (Figure 3b).

Macro-charcoal and fire frequency

A total of 11 fire episodes occurred locally during the past 1300 years, and 7 additional fire episodes failed to pass the screen

Figure 4. Granulometric data (CSi + FSa: coarse silt + fine sand; skewness) as well as selected element/Al ratios of the Kalimpa record plotted versus age. All graphs are interpreted to exhibit a rising trend to wetter conditions (higher rainfall intensities and/or mean rainfall) on centennial to millennial time scale from AD 560 to 1910. Note that the uppermost unit VI (grey bar) is not included in the palaeoclimatic interpretation.

Figure 5. Macro-charcoal concentrations (number of particles per cubic centimetre), fire frequency, Fe, TOC and TOC/TN (molar) as well as the medium and coarse sand content (MSa + CSa) of the Kalimpa record plotted versus age. Fire frequency calculated on the fire peaks detected with the software CharAnalysis, smoothed with a 200-year window. Fire peaks which passed the 'Poisson minimum-count' screening are indicated with black crosses, and the insignificant peaks are indicated as grey circles. Additionally shown are the *Weinmannia* pollen data (Biagioni et al., unpublished data) which probably act as secondary forest species in the Lake Kalimpa catchment. The grey bars represent the lithological units II and IV (AD 1090–1190 and AD 1450–1620) which are interpreted as periods of disturbance events in the Kalimpa catchment.

test (Figure 5). Fire frequencies were higher in unit II (up to 2 fires per 200 years at 128–118 cm; ~AD 1090–1190) and unit IV (up to 4 fires per 200 years at 93–76 cm; ~AD 1450–1620). In unit VI (48–0 cm; ~AD 1910–2006), fire frequencies gradually increased until today.

Discussion

Palaeorainfall in Central Sulawesi

Based on variations in the established palaeorainfall proxies (K/Al, Ca/Al, Mg/Al, Ti/Al, CSi + FSa, Sk), the Lake Kalimpa

Figure 6. Comparison of (a) coarse silt and fine sand data (CSi+FSa) representing terrigenous input to Lake Kalimppaa with other studies; (b) modelled number of El Niño events using input data from the eastern Pacific region. Shown is the number of events in 500-year overlapping windows (overlapping every 10 years; digitized from Clement et al., 2000); (c₁) red colour intensity of sediments from Laguna Pallcacocha, Ecuador, representing the layers deposited during El Niño events (grey) and (c₂) the resulting modelled number of El Niño events per 100 years (black; Moy et al., 2002); (d) reconstructed sea surface temperatures of Makassar Strait derived from Mg/Ca ratios (Newton et al., 2006); and (e) leaf wax δD from Lake Lading (East Java) as palaeorainfall proxy (Konecky et al., 2013). The periods of the ‘Little Ice Age’ (LIA; AD 1550 to 1850) and the ‘Medieval Warm Period’ (MWP; AD 900–1300) according to Oppo et al. (2009) are shown on the right.

record likely reveals a centennial to millennial-scaled trend towards wetter conditions characterized by higher rainfall intensities and possibly higher mean rainfall from ~AD 560 to the 20th century. The period from ~AD 560–1090 was characterized by drier conditions, while an increasingly wetter climate can be inferred from ~AD 1090 to 1910 (Figure 4).

A long-term trend towards wetter conditions is also observed in sediments from two other lakes in East Java (Konecky et al., 2013; Rodysill et al., 2012; Figure 6e). Rodysill et al. (2012) explain the trend as a consequence of migration of the Intertropical Convergence Zone (ITCZ) with increased precipitation during its southward displacement. In comparison, Konecky et al. (2013) conclude that the migration of the ITCZ influences the climate variability on multidecadal to centennial time scales, while it is the strengthening of the Walker circulation and its associated changes in ENSO variability that produces the increasingly wetter climate during the last millennium. Yan et al. (2011) arrive at similar conclusions, namely, precipitation changes in response to the combined influence of the migration of the ITCZ and the position and strength of the Pacific Walker circulation in the western tropical Pacific.

The palaeorainfall proxies obtained from the Lake Kalimppaa record show long-term similarities with ENSO variability from the eastern Pacific region as well as the South American continent (Figure 6a–c). An ENSO record derived from the sediments of Laguna Pallcacocha, southern Ecuador, reveals that the number of El Niño events per 100 years decreased since ~AD 1150 until today (Moy et al., 2002) consistent with increasing terrigenous input to Lake Kalimppaa (Figure 6a–c). Another lacustrine archive from Galápagos exhibits a decreased ENSO frequency between AD 1300

and 1850 (Conroy et al., 2008). From Kau Bay (Halmahera; Figure 1a), a region where rainfall is strongly dependent on ENSO, it is known that the El Niño activity decreased steadily from ~AD 1300 (Langton et al., 2008). A long-term trend starting from ~AD 560 onwards is visible in both the established palaeorainfall proxies for the Kalimppaa record and the output of the coupled ocean atmosphere model from Clement et al. (2000; Figure 6a and b) which reflects the number of El Niño events occurring over a 500-year interval. These similarities of the ENSO and CSi+FSa data (Figure 6a–c) indicate that palaeorainfall in Central Sulawesi is related to the variability of ENSO on centennial to millennial time scale and, thus, changes in the Pacific Walker circulation.

Two studies carried out at Makassar Strait (Newton et al., 2006; Oppo et al., 2009; Figures 1 and 5d) revealed that the SST in this region was ~0.5–1.5°C lower during the LIA (~AD 1550–1850) compared with modern SST and those during the ‘Medieval Warm Period’ (MWP; ~AD 900–1300; Oppo et al., 2009). The authors infer that a cooling of the North Pacific surface water, which is transported by ocean currents through the Makassar Strait, is responsible for lower SST during this period. These cooler SST phases are associated with the southward displacement of the ITCZ during the LIA, which led to wetter conditions at Makassar Strait (Newton et al., 2006), similar to the region around Lake Kalimppaa in Central Sulawesi (Figure 6a–d). Sachs et al. (2009) note that the ITCZ reached its southernmost position between AD 1400 and 1850 with the result that drier conditions occurred north of the equator and wetter conditions in the southern tropics (Newton et al., 2006). Tierney et al. (2010), who examined marine sediments off the coast of Southwest Sulawesi (Figure 1a), inferred

that the hydrological variability and the monsoon strength in the IPWP are dependent on migrations of the ITCZ. These authors suggest teleconnections between ENSO and the monsoon with a weak Indian monsoon and a more El Niño-like mean state during the MWP and a strong Indian monsoon and a more La Niña-like mean state during the LIA (Tierney et al., 2010). It seems therefore that the southward displacement of the ITCZ may have caused higher rainfall intensities and possibly higher mean rainfall around Lake Kalimpa during the LIA.

Both the monsoon and ENSO climate systems are interacting through teleconnections (Ju and Slingo, 1995; Soman and Slingo, 1997; Torrence and Webster, 1999). Variations in the Pacific Walker circulation and/or SST anomalies during El Niño events could influence the global scale divergence, which can result in a shift of the ITCZ and, thus, changes of the monsoon dynamics (Ju and Slingo, 1995; Soman and Slingo, 1997; Torrence and Webster, 1999). The position of the ITCZ as well as the mean state of ENSO/Pacific Walker circulation, therefore, may be considered interactive and co-responsible for the long-term rainfall variability in Central Sulawesi on centennial to millennial time scale. The interpretation of the Kalimpa record suggests a general weakening of the Pacific Walker circulation and a more El Niño-like mean state from ~AD 560 to 1090. In contrast, the strengthened Pacific Walker circulation and the southward displacement of the ITCZ probably are the causes for the wetter climate in Central Sulawesi during the LIA, which is consistent with the interpretation of Yan et al. (2011).

Palaeoenvironmental disturbance events in the catchment of Lake Kalimpa

In the Lake Kalimpa record, peaks in Fe, Mn, P, S, TOC and TN occur almost simultaneously with increased fire frequency in unit II (128–118 cm; ~AD 1090–1190) and unit IV (93–76 cm; ~AD 1450–1620; Figure 5). The most prominent peaks of these elements coincide in unit II with macro-charcoal and MSa+CSa (Figure 5). Increased fire frequency data indicate periods during which forest fires occurred more frequently in the drainage basin of Lake Kalimpa. Hence, it is assumed that these disturbance events are a potential cause for the increased supply of organic material into the lake, which in turn may lead to enhanced TOC, TN and TOC/TN values. A similar pattern showing increased TOC and charcoal values was found in the sediments from Lago dell'Accesa (Tuscany, Italy; Vannièr et al., 2008). As a result of microbial decomposition of the organic matter, anoxic conditions prevailed at Lake Kalimpa and, thus, enhanced the formation of black sediment layers which contain high Fe, Mn, P and S amounts.

As noted, the deposition of MSa+CSa seems to reflect a different process compared with the other grain size fractions (Table 1). Due to the simultaneous occurrence of the most prominent peaks in MSa+CSa and macro-charcoal (Figure 5), the deposition of these coarse materials is interpreted as an input signal after catchment disturbance (Cerdà and Lasanta, 2005) which is likely associated with a forest fire around ~AD 1090 (Figure 5). Thus, the fire likely facilitated the erosion and deposition of MSa+CSa.

Following the first period of inferred increasing fire frequency (~AD 1090–1210), changes in the vegetational composition occurred within the catchment. These alterations are reflected within the units II and III (123–95 cm; ~AD 1140–1430) and were characterized by an expansion of *Weinmannia* which probably acts as secondary forest species in the Kalimpa drainage basin (Biagioni et al., unpublished data). In contrast, *Weinmannia* pollen concentrations remained low after the second period of disturbance (~AD 1460–1620). However, pollen data of fast-growing pioneer species like *Macaranga* and *Mallotus* increased during this period indicating disturbance in the forest (Biagioni et al., unpublished

data). *Weinmannia* increased again in unit VI (47–35 cm; ~AD 1930–1975), when the vegetation cover in the catchment area was likely disturbed due to the road construction (Figure 5).

Considering the macro-charcoal and sedimentological findings from KAL 1-1 and 1-2, at least two disturbance events occurred in the catchment area that are reflected in units II and IV (~AD 1090–1190; ~AD 1450–1620). The changes in fire frequencies between ~AD 1090–1190 and ~AD 1450–1620 have affected the geochemical composition of the lacustrine sediments. The alterations within the catchment during the 20th century are possibly caused by human impact (Haberzettl et al., 2013).

From archaeological and palynological investigations in Central Sulawesi, it has been concluded that anthropogenic impact in the Besoa Valley, ~25 km south of Lake Kalimpa, started ~2000 years ago (Kirleis et al., 2011, 2012) when the montane rainforest was replaced by grassland. However, considerable human modifications of the landscape in the catchment of Lake Kalimpa are not assumed before the 20th century.

Natural fires occurring during drought periods seem to be the most likely triggers of the assumed disturbances in the Kalimpa drainage basin. Probably, drought stress accompanied by increased plant mortality (McDowell et al., 2008; Zach et al., 2010) fostered the forest fires as it is known from eastern Borneo during the strong El Niño event from 1997/1998 (Siebert and Hoffmann, 2000; Van Nieuwstadt and Sheil, 2005), when fires also occurred on Sulawesi (Rowell and Moore, 2000; Sastry, 2002). Droughts in Indonesia result from the failure of the monsoon, which often coincides with ENSO warm events (D'Arrigo et al., 2006). According to Quinn et al. (1978), over 90% of droughts in Indonesia during the period from AD 1861 to 1976 are associated with a warm phase of ENSO.

The ~800 year-record obtained from Lake Lamongan (Crausbay et al., 2006; Figure 1a) reveals two periods of multidecadal drought from ~AD 1275–1325 and ~AD 1450–1650 (Figure 7), probably as a result of ENSO variations. More recent investigations on the timing of droughts in East Java have been carried out by Rodysill et al. (2013) who use U-series dating and suggest that the onset of the latter drought at Lake Lamongan was more than 300 years later around ~AD 1790. In sediments from Lake Logung (also East Java; Figure 1a) spanning the past ~1400 years, the long-term trend towards wetter conditions was superimposed by four decadal to centennial-scale droughts between ~AD 930–1130, ~AD 1460–1640, ~AD 1790–1860 and ~AD 1985–2008 (Rodysill et al., 2012; Figure 7). The authors discuss these drought occurrences in relation to both migration of the ITCZ and variability in ENSO. Two of the four droughts (~AD 1460–1640 and ~AD 1790–1860) took place when the ITCZ was displaced to the south, a period that is actually characterized by a wetter mean climate on centennial to millennial time scale. These droughts hence represent unusual events on an interannual to multidecadal time scale.

Comparisons of the data from Lake Kalimpa with the drought occurrences observed by Crausbay et al. (2006) and Rodysill et al. (2012, 2013) show that disturbance events at Lake Kalimpa partly coincide with drought periods in East Java. The older two of four drought periods observed in the Lake Logung record match temporally with disturbance events at Lake Kalimpa (Figure 7; Rodysill et al., 2012). Therefore, it is suggested that they are regional in spatial extent since age differences are within the range of dating uncertainties. The second drought period (~AD 1450–1620) at Lake Kalimpa coincides well with findings from Lake Logung (~AD 1460–1640) and the radiocarbon dated drought at Lake Lamongan (~AD 1450–1650; Crausbay et al., 2006) but not with the same drought period applying U-series dating (Rodysill et al., 2013; Figure 7).

These similarities indicate the occurrence of two drought periods that found their expression at least in Central Sulawesi and East Java during this time. Thus, it seems likely that the long-term

Figure 7. Comparison of the Fe data from Lake Kalimpa indicative for disturbance events with total inorganic carbon (TIC) data representing periods of drought at Lake Logung, East Java (Rodysill et al., 2012). The black bars on the right represent periods of drought (based on radiocarbon dating) observed from Lake Lamongan, also East Java (Crausbay et al., 2006). The grey bar on the right represents the time period of the more recent drought at Lake Lamongan on the basis of U-series dating (Rodysill et al., 2013). The greyish bars (representing the core units II and IV of the Kalimpa record which were deposited when disturbance events occurred in the catchment) are linked to periods of drought obtained from the Lake Logung record.

trend towards higher rainfall intensities and possibly higher mean rainfall was superimposed by individual, interannual to multi-decadal-scaled drought periods which were likely associated with intense ENSO warm events. The drought indicated from ~AD 1450 to 1620 occurred during a period when the ITCZ was displaced to the south (Sachs et al., 2009), and wetter conditions were prevailing at Lake Kalimpa on the centennial to millennial time scale. This may indicate that the movement of the ITCZ is not the main trigger for interannual to multidecadal drought occurrences in Central Sulawesi rather the variability of the Pacific Walker circulation and, hence, ENSO.

Conclusion

The Lake Kalimpa record is one of only a few terrestrial archives from Sulawesi providing information on palaeoenvironmental and palaeorainfall changes as well as fire history throughout the past ~1500 years. The two main conclusions of this study are the following: (a) in Central Sulawesi, a long-term trend towards wetter conditions (higher rainfall intensities and/or mean rainfall) probably occurred on the centennial to millennial time scale starting from ~AD 560 to the 20th century with highest rainfall intensities during the LIA and (b) two disturbance events (~AD 1090–1190

and ~AD 1450–1620) caused by forest fires occurred in the catchment area of Lake Kalimpa. A comparison with other records exhibits that the long-term trend towards wetter conditions is associated with migrations of the ITCZ and the millennial-scale variability of ENSO/Pacific Walker circulation. The disturbance events around Lake Kalimpa are probably related to regional droughts affecting at least East Java and Sulawesi. The occurrence of droughts in Indonesia, which can be accompanied by forest fires, is mostly caused by the failure of the monsoon during ENSO warm events (El Niño years). While a major human impact in the Kalimpa catchment cannot be excluded completely before the 20th century, this seems rather unlikely considering the regional correlation of drought periods at these times.

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References

- Ad-hoc AG Boden (Ad-hoc-Arbeitsgruppe der Staatlichen Geologischen Dienste und der Bundesanstalt für Geowissenschaften und Rohstoffe) (2005) *Bodenkundliche Kartieranleitung*. Stuttgart: Schweizerbart.
- Aldrian E and Susanto RD (2003) Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology* 23(12): 1435–1452.
- Aldrian E, Dümenil-Gates L, Jacob D et al. (2004) Long-term simulation of Indonesian rainfall with the MPI regional model. *Climate Dynamics* 22(8): 795–814.
- Blott SJ and Pye K (2001) GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26(11): 1237–1248.
- Boyle EA (1983) Chemical accumulation variations under the Peru Current during the past 130,000 years. *Journal of Geophysical Research* 88(C12): 7667–7680.
- Buffle J, De Vitre RR, Perret D et al. (1989) Physico-chemical characteristics of a colloidal iron phosphate species formed at the oxic-anoxic interface of a eutrophic lake. *Geochimica et Cosmochimica Acta* 53(2): 399–408.
- Cerdà A and Lasanta T (2005) Long-term erosional responses after fire in the Central Spanish Pyrenees. 1. Water and sediment yield. *Catena* 60(1): 59–80.
- Clement AC, Seager R and Cane MA (2000) Suppression of El Niño during the mid-Holocene by changes in the Earth's orbit. *Paleoceanography* 15(6): 731–737.
- Conroy JL, Overpeck JT, Cole JE et al. (2008) Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews* 27(11–12): 1166–1180.
- Crausbay SD, Russell JM and Schnurrenberger DW (2006) A c. 800-year lithologic record of drought from sub-annually laminated lake sediment, East Java. *Journal of Paleolimnology* 35(3): 641–659.
- Crowe SA, O'Neill AH, Katsev S et al. (2008) The biogeochemistry of tropical lakes: A case study from Lake Matano, Indonesia. *Limnology and Oceanography* 53(1): 319–331.
- Culmsee H, Leuschner C, Moser G et al. (2010) Forest aboveground biomass along an elevational transect in Sulawesi, Indonesia, and the role of Fagaceae in tropical montane rain forests. *Journal of Biogeography* 37(5): 960–974.
- Dam RAC, Fluin J, Suparan P et al. (2001) Palaeoenvironmental developments in the Lake Tondano area (N. Sulawesi, Indonesia) since 33,000 yr B.P. *Palaeogeography, Palaeoclimatology, Palaeoecology* 171(3–4): 147–183.
- D'Arrigo R, Wilson R, Palmer J et al. (2006) Monsoon drought over Java, Indonesia, during the past two centuries. *Geophysical Research Letters* 33(4): L04709.
- Davison W (1993) Iron and manganese in lakes. *Earth-Science Reviews* 34(2): 119–163.
- De Boer GBJ, De Weerd C, Thoenes D et al. (1987) Laser diffraction spectrometry: Fraunhofer diffraction versus Mie scattering. *Particle & Particle Systems Characterization* 4(1–4): 14–19.
- Diaz HF and Kiladis GN (1992) Atmospheric teleconnections associated with the extreme phases of the Southern Oscillation. In: Diaz HF and Markgraf V (eds) *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge: Cambridge University Press, pp. 7–28.
- Emerson S (1976) Early diagenesis in anaerobic lake sediments: Chemical equilibria in interstitial waters. *Geochimica et Cosmochimica Acta* 40(8): 925–934.
- Engstrom DR and Wright HE Jr (1984) Chemical stratigraphy of lake sediments as a record of environmental change. In: Haworth EY and Lund JWG (eds) *Lake Sediments and Environmental History*. Minneapolis, MN: University of Minnesota Press, pp. 11–67.
- Felton AA, Russell JM, Cohen AS et al. (2007) Paleolimnological evidence for the onset and termination of glacial aridity from Lake Tanganyika, Tropical East Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252(3–4): 405–423.
- Gagan MK, Hendy EJ, Haberle SG et al. (2004) Post-glacial evolution of the Indo-Pacific Warm Pool and El Niño-Southern Oscillation. *Quaternary International* 118–119: 127–143.
- Godfrey JS (1996) The effect of the Indonesian throughflow on ocean circulation and heat exchange with the atmosphere: A review. *Journal of Geophysical Research* 101(C5): 12217–12237.
- Goldich SS (1938) A study in rock-weathering. *Journal of Geology* 46(1): 17–58.
- Gordon AL, Susanto RD and Field A (1999) Throughflow within Makassar Strait. *Geophysical Research Letters* 26(21): 3325–3328.
- Griffiths ML, Drysdale RN, Gagan MK et al. (2010) Evidence for Holocene changes in Australian-Indonesian monsoon rainfall from stalagmite trace element and stable isotope ratios. *Earth and Planetary Science Letters* 292(1–2): 27–38.
- Gunawan D (2006) *Atmospheric variability in Sulawesi, Indonesia – Regional atmospheric model results and observations*. PhD Thesis, University of Göttingen.
- Haberzettl T, Fey M, Lücke A et al. (2005) Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). *Journal of Paleolimnology* 33(3): 283–302.
- Haberzettl T, Kück B, Wulf S et al. (2008) Hydrological variability in southeastern Patagonia and explosive volcanic activity in the southern Andean Cordillera during Oxygen Isotope Stage 3 and the Holocene inferred from lake sediments of Laguna Potrok Aike, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* 259(2–3): 213–229.
- Haberzettl T, St-Onge G, Behling H et al. (2013) Improving late Holocene radiocarbon-based chronologies by matching paleomagnetic secular variations to geomagnetic field models – An example from Lake Kalimpa (Sulawesi, Indonesia). In: Jovane L, Herrero-Bervera E, Hinnov LA et al. (eds) *Magnetic Methods and the Timing of Geological Processes*. London: Geological Society of London (special publications no. 373), pp. 245–259.
- Håkanson L and Jansson M (1983) *Principles of Lake Sedimentology*. Berlin, Heidelberg: Springer.
- Higuera PE, Brubaker LB, Anderson PM et al. (2008) Frequent fires in ancient shrub tundra: Implications of paleorecords for arctic environmental change. *PLoS One* 3(3): e0001744.
- Higuera PE, Brubaker LB, Anderson PM et al. (2009) Vegetation mediated the impacts of postglacial climatic change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs* 79: 201–219.

- Hope G (2001) Environmental change in the Late Pleistocene and later Holocene at Wanda site, Soroako, South Sulawesi, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 171(3–4): 129–145.
- Ju J and Slingo J (1995) The Asian summer monsoon and ENSO. *Quarterly Journal of the Royal Meteorological Society* 121(525): 1133–1168.
- Kasper T, Frenzel P, Haberzettl T et al. (2013) Interplay between redox conditions and hydrological changes in sediments from Lake Nam Co (Tibetan Plateau) during the past 4000 cal BP inferred from geochemical and micropalaeontological analyses. *Palaeogeography, Palaeoclimatology, Palaeoecology* 392: 261–271.
- Kasper T, Haberzettl T, Doberschütz S et al. (2012) Indian Ocean Summer Monsoon (IOSM)- dynamics within the past 4 kyr recorded in the sediments of Lake Nam Co, central Tibetan Plateau (China). *Quaternary Science Reviews* 39: 73–85.
- Keil A, Zeller M, Wida A et al. (2008) What determines farmers' resilience towards ENSO-related drought? An empirical assessment in Central Sulawesi, Indonesia. *Climatic Change* 86(3–4): 291–307.
- Kirleis W, Müller J, Kortemeier C et al. (2012) The megalithic landscape of central Sulawesi, Indonesia. Combining archaeological and palynological investigations. In: Bonatz D, Reinecke A and Tjoa-Bonatz ML (eds) *Crossing Borders: Selected Papers from the 13th International Conference of the European Association of Southeast Asian Archaeologists, Berlin, 2010*. Singapore: NUS Press, pp. 199–220.
- Kirleis W, Pillar VD and Behling H (2011) Human-environment interactions in mountain rainforests: Archaeobotanical evidence from central Sulawesi, Indonesia. *Vegetation History and Archaeobotany* 20(3): 165–179.
- Konecky BL, Russell JM, Rodysill JR et al. (2013) Intensification of southwestern Indonesian rainfall over the past millennium. *Geophysical Research Letters* 40(2): 386–391.
- Korte M and Constable C (2011) Improving geomagnetic field reconstructions for 0–3 kyr. *Physics of the Earth and Planetary Interiors* 188(3–4): 247–259.
- Langton SJ, Linsley BK, Robinson RS et al. (2008) 3500 yr record of centennial-scale climate variability from the Western Pacific Warm Pool. *Geology* 36(10): 795–798.
- Leemhuis C (2005) *The impact of El Niño Southern Oscillation events on water resource availability in Central Sulawesi, Indonesia. A hydrological modelling approach*. PhD Thesis, University of Göttingen.
- Lijklema L (1980) Interaction of orthophosphate with iron(III) and aluminum hydroxides. *Environmental Science and Technology* 14(5): 537–541.
- Livingstone DA (1955) A lightweight piston sampler for lake deposits. *Ecology* 36(1): 137–139.
- Li X, Wei G, Shao L et al. (2003) Geochemical and Nd isotopic variations in sediments of the South China Sea: A response to Cenozoic tectonism in SE Asia. *Earth and Planetary Science Letters* 211(3–4): 207–220.
- Lopez P, Navarro E, Marce R et al. (2006) Elemental ratios in sediments as indicators of ecological processes in Spanish reservoirs. *Limnetica* 25(1–2): 499–512.
- Lückge A, Doose-Rolinski H, Khan AA et al. (2001) Monsoonal variability in the northeastern Arabian Sea during the past 5000 years: Geochemical evidence from laminated sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology* 167(3–4): 273–286.
- McDowell N, Pockman WT, Allen CD et al. (2008) Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? *New Phytologist* 178(4): 719–739.
- Mackereth FJH (1966) Some chemical observations on post-glacial lake sediments. *Philosophical Transactions of the Royal Society: Biological Sciences* 250(765): 165–213.
- McLaren P and Bowles D (1985) The effects of sediment transport on grain-size distributions. *Journal of Sedimentary Petrology* 55(4): 457–470.
- Markussen M (2000) *Zusammenfassender Endbericht des Aufenthaltes in Palu/Indonesien vom 20. Mai bis 10. August 2000 mit den Ergebnissen der bodenkundlichen Untersuchungen*. Report, University of Göttingen, Göttingen.
- Mayr C, Fey M, Haberzettl T et al. (2005) Palaeoenvironmental changes in southern Patagonia during the last millennium recorded in lake sediments from Laguna Azul (Argentina). *Palaeogeography, Palaeoclimatology, Palaeoecology* 228(3–4): 203–227.
- Meyers PA (1994) Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chemical Geology* 114(3–4): 289–302.
- Middelburg JJ, Van der Weiden CH and Woittiez JRW (1988) Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks. *Chemical Geology* 68(3–4): 253–273.
- Morey SL, Shriver JF and O'Brien JJ (1999) The effects of Halmahera on the Indonesian throughflow. *Journal of Geophysical Research* 104(C10): 23281–23296.
- Moy CM, Seltzer GO, Rodbell DT et al. (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420(6912): 162–165.
- Müller J, Oberhänsli H, Melles M et al. (2001) Late Pliocene sedimentation in Lake Baikal: Implications for climatic and tectonic change in SE Siberia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 174(4): 305–326.
- Nesbitt HW, Markovics G and Price RC (1980) Chemical processes affecting alkalis and alkaline earths during continental weathering. *Geochimica et Cosmochimica Acta* 44(11): 1659–1666.
- Newton A, Thunell R and Stott L (2006) Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysical Research Letters* 33(19). Epub ahead of print 12 October. DOI: 10.1029/2006GL027234.
- Nichols G (2009) *Sedimentology and Stratigraphy*. Chichester: Wiley-Blackwell.
- Oppo DW, Rosenthal Y and Linsley BK (2009) 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. *Nature* 460(7259): 1113–1116.
- Priadi B, Polve M, Maury RC et al. (1994) Tertiary and quaternary magmatism in Central-Sulawesi: Chronological and petrological constraints. *Journal of Southeast Asian Earth Sciences* 9(1–2): 81–93.
- Quinn WH, Zopf DO, Short KS et al. (1978) Historical trends and statistics of the Southern Oscillation, El Niño, and Indonesian droughts. *Fishery Bulletin* 76(3): 663–678.
- Rhodes AN (1998) A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* 8: 113–117.
- Rodysill JR, Russell JM, Bijaksana S et al. (2012) A paleolimnological record of rainfall and drought from East Java, Indonesia during the last 1,400 years. *Journal of Paleolimnology* 47(1): 125–139.
- Rodysill JR, Russell JM, Crausbay SD et al. (2013) A severe drought during the last millennium in East Java, Indonesia. *Quaternary Science Reviews* 80: 102–111.
- Rowell A and Moore PF (2000) *Global Review of Forest Fires*. Gland: WWF/IUCN.
- Ruxton BP (1959) Notes on weathering zones and soils on granitic rocks in two tropical regions. *Journal of Soil Science* 10(1): 54–63.
- Sachs JP, Sachse D, Smittenberg RH et al. (2009) Southward movement of the Pacific intertropical convergence zone AD 1400–1850. *Nature Geoscience* 2: 519–525.

- Salafsky N (1994) Drought in the rain forest: Effects of the 1991 El Niño-Southern Oscillation event on a rural economy in West Kalimantan, Indonesia. *Climatic Change* 27(4): 373–396.
- Salomons W and Forstner U (1984) *Metals in the Hydrocycle*. Berlin, Heidelberg: Springer.
- Sastry N (2002) Forest fires, air pollution and mortality in south-east Asia. *Demography* 39(1): 1–23.
- Shotyk W, Weiss D, Kramers JD et al. (2001) Geochemistry of the peat bog at Etang de la Gruère, Jura Mountains, Switzerland, and its record of atmospheric Pb and lithogenic trace metals (Sc, Ti, Y, Zr, and REE) since 12,370 ¹⁴C yr BP. *Geochimica et Cosmochimica Acta* 65(14): 2337–2360.
- Siebert F and Hoffmann AA (2000) The 1998 forest fires in East Kalimantan (Indonesia): A quantitative evaluation using high resolution, multitemporal ERS-2 SAR images and NOAA-AVHRR hotspot data. *Remote Sensing of Environment* 72(1): 64–77.
- Sigg L and Stumm W (1996) *Aquatische Chemie: Eine Einführung in die Chemie wässriger Lösungen und natürlicher Gewässer*. Zürich: VDF Hochschulverlag.
- Simandjuntak TO, Rusmana E, Surono et al. (1991) *Geologic Map and Report of the Poso Quadrangle, South Sulawesi. Scale 1:250,000*. Bandung: Geological Research and Development Centre.
- Soman MK and Slingo J (1997) Sensitivity of the Asian summer monsoon to aspects of sea-surface-temperature anomalies in the tropical Pacific Ocean. *Quarterly Journal of the Royal Meteorological Society* 123(538): 309–336.
- Stevenson J and Haberle SG (2005) *Macro Charcoal Analysis: A modified technique used by the Department of Archaeology and Natural History*. PalaeoWorks Technical Report 5, April. Available at: <http://palaeoworks.anu.edu.au/paltr05.pdf>.
- Tierney JE, Oppo DW, Rosenthal Y et al. (2010) Coordinated hydrological regimes in the Indo-Pacific region during the past two millennia. *Paleoceanography* 25(1). Epub ahead of print 5 March. DOI: 10.1029/2009PA001871.
- Torrence C and Webster PJ (1999) Interdecadal changes in the ENSO-monsoon system. *Journal of Climate* 12(8): 2679–2690.
- Van Cappellen P and Wang Y (1996) Cycling of iron and manganese in surface sediments: A general theory for the coupled transport and reaction of carbon, oxygen, nitrogen, sulfur, iron, and manganese. *American Journal of Science* 296(3): 197–243.
- Vanniëre B, Colombaroli D, Chapron E et al. (2008) Climate versus human-driven fire regimes in Mediterranean landscapes: The Holocene record of Lago dell'Accesa (Tuscany, Italy). *Quaternary Science Reviews* 27(11–12): 1181–1196.
- Van Nieuwstadt MGL and Sheil D (2005) Drought, fire and tree survival in a Borneo rain forest, East Kalimantan, Indonesia. *Journal of Ecology* 93(1): 191–201.
- Warrier AK and Shankar R (2009) Geochemical evidence for the use of magnetic susceptibility as a paleorainfall proxy in the tropics. *Chemical Geology* 265(3–4): 553–562.
- Weber R (2006) *Kulturlandschaftswandel in Zentralsulawesi. Historisch geographische Analyse einer indonesischen Bergregenwaldregion* (Pazifik Forum, Band 12). Göttingen: Universitätsverlag.
- West G and Dumbleton MJ (1970) The mineralogy of tropical weathering illustrated by some west Malaysian soils. *Quarterly Journal of Engineering Geology and Hydrogeology* 3(1): 25–40.
- Whitlock C, Dean W, Rosenbaum J et al. (2007) A 2650-year-long record of environmental change from northern Yellowstone National Park based on a comparison of multiple proxy data. *Quaternary International* 188(1): 126–138.
- Yan H, Sun L, Oppo DW et al. (2011) South China Sea hydrological changes and Pacific Walker Circulation variations over the last millennium. *Nature Communications* 2(293). DOI: 10.1038/ncomms1297.
- Zabel M, Schneider RR, Wagner T et al. (2001) Late quaternary climate changes in Central Africa as inferred from terrigenous input to the Niger Fan. *Quaternary Research* 56(2): 207–217.
- Zach A, Schuldt B, Horna V et al. (2010) The hydraulic performance of tropical rainforest trees in their perhumid environment – Is there evidence for drought vulnerability? In: Tschardt T, Leuschner C, Veldkamp E et al. (eds) *Tropical Rainforests and Agroforests under Global Change* (Environmental Science and Engineering). Berlin, Heidelberg: Springer, pp. 391–410.