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Key Points:
- Continental margin sediments off northwestern Australia record large continental aridity shifts at 5.3, 3.8, 2.8, and 1.4 Ma
- Grain size and chemistry of the terrigenous fraction of seafloor sediments and source areas on land allow a characterization of river mud
- Monsoonal activity responds to changes in Indian-Ocean SSTs and drives river runoff in northwestern Australia

Supporting Information:
- Supporting Information S1
- Figure S1
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A 5.3-Million-Year History of Monsoonal Precipitation in Northwestern Australia

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Abstract New proxy records from deep-sea sediment cores from the northwestern continental margin of Western Australian reveal a 5.3 million year (Ma) history of aridity and tropical monsoon activity in northwestern Australia. Following the warm and dry early Pliocene (~5.3 Ma), the northwestern Australian continent experienced a gradual increase in humidity peaking at about 3.8 Ma with higher than present-day rainfall. Between 3.8 and about 2.8 Ma, climate became progressively more arid with more rainfall variability. Coinciding with the onset of the Northern Hemisphere glaciations and the intensification of the Northern Hemisphere monsoon, aridity continued to increase overall from 2.8 Ma until today, with greater variance in precipitation and an increased frequency of large rainfall events. We associate the observed large-scale fluctuations in Australian aridity with variations in Indian Ocean sea surface temperatures, which largely control the monsoonal precipitation in northwestern Australia.

Plain Language Summary Australia is the driest inhabited continent on the planet, with its moisture mostly sourced from the tropical monsoon in the north and the southern westerlies in the south. The continent has experienced large climate fluctuations in the geologic past, but long continuous records of paleoenvironmental changes are lacking, particularly prior to ~0.55 Ma. Here, we address this paucity by presenting a continuous and fluctuating record of continental aridity and monsoonal activity in northwestern Australia since the Pliocene (5.3 Ma). These records are based on bulk-chemical X-Ray Fluorescence scans and particle-size distributions of the terrigenous fraction in two marine sediment cores from the NW Western Australian continental margin. A comparison with present-day sources of windblown and fluvial sediments taken near the NW Western Australian coast corroborates our interpretation of the terrigenous fraction in the marine sediment cores. We show how the northwestern part of the Australian continent has experienced large climate fluctuations since 5.3 Ma, expressed by large aridity contrasts and great changes in monsoonal precipitation that are driven by Indian Ocean sea-surface temperatures.

1. Introduction

Present-day climate in NW Western Australia is characterized by dry winters and hot wet summers, typified by cyclones and cyclonic depressions of the Australian summer monsoon (Australian Bureau of Meteorology, 2017). Tropical cyclones develop during periods of high (higher than 26.5 °C; De Deckker, 2016; De Deckker et al., 2002; Tory & Dare, 2015) sea-surface temperatures (SSTs) in the Indian Ocean and Indo-Pacific Warm Pool (IPWP). Next to tropical cyclones, monsoonal precipitation is also brought about by so-called cyclonic depressions, which also deliver extensive amounts of rainfall. The strong seasonal contrast in precipitation causes major rivers to remain dry for most of the year and only discharge large floods, full of sediments, during the rainy season and mostly coinciding with cyclones and cyclonic depressions. The strong seasonality also results in large wind-driven dust outbreaks, which mostly occur in late spring-early summer prior to the rainy season when river/lake beds, and soils are driest (DustWatch Australia: Community-based wind erosion monitoring, 2017). Reflecting these seasonally contrasting

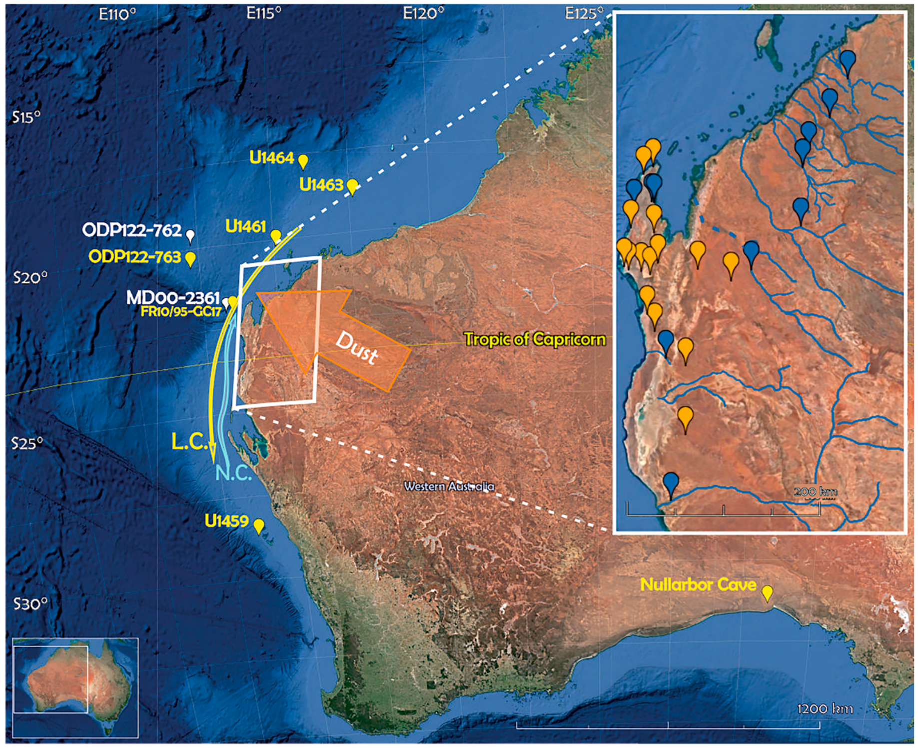

Figure 1. Google Earth map of northwestern Western Australia and its continental margin showing the positions of the two studied sites (ODP122-762B and MD00-2361 white pins), as well as—right insert—the land samples of river beds (blue pins) and dune systems (orange pins), for which the bulk chemical compositions are compared to those measured in the sediment cores (see supporting information). The large rivers draining into the eastern Indian Ocean are also shown. L.C. = Leeuwin Current; N.C. = Ningaloo (counter) Current. Cores of comparable studies are indicated with yellow pins: FR10/95-GC17 (van der Kaars & De Deckker, 2002; just east of MD00-2361), ODP122-763 (O'Brien et al., 2014); IODP356-U1464 (Groeneveld et al., 2017), IODP356-U1463 (Christensen et al., 2017), IODP356-U1461 (Ishiwa et al., 2019), IODP356-U1459 (Groeneveld et al., 2017) and Nullarbor Caves (Sniderman et al., 2016).

processes, the terrigenous sediment fraction that ends up on the northwestern Western Australian continental shelf and slope is a mixture of airborne dust emitted during the dry season and river-transported mud during the rainy season and in particular during monsoonal activity, some of which caused by cyclones (Stuut et al., 2014). There are many studies showing that fine-grained sediments supplied by rivers can travel long distances in the ocean before settling on the seafloor (Hopkins et al., 2013; Palma & Matano, 2017; Prins et al., 2000; Shanmugam, 2018; see supporting information).

Changes in environmental conditions in northwestern Western Australia are now well documented for the late Quaternary (last ~550 ka), notably indicating dryer (arid) conditions during glacials. Fossil pollen and charcoal in marine sediments from an adjacent core [van der Kaars & De Deckker, 2002; FR10/95-GC17; see Figure 1] located on the fringe of the IPWP reveal a much drier Last Glacial Maximum (LGM), characterized by a shrubland vegetation type as opposed to open *Eucalyptus* woodlands, which prevailed during the wetter period before the LGM (van der Kaars & De Deckker, 2002). Similarly, van der Kaars et al. (2006) demonstrated—based on pollen transfer functions applied to core top sediments—that the LGM was much drier than present, and several authors also found that the Australian-Indonesian monsoon did not operate at that time (Brown et al., 2009; Marshall & Lynch, 2008; Tripati et al., 2014; van der Kaars et al., 2006). These observations were mechanistically corroborated by a study offshore northwestern Western Australia of SSTs covering the past 550 ka, showing a 6–9 °C temperature drop during glacials (Spooner et al., 2011). Nevertheless, such a large SST reduction only occurred at the edge of the IPWP (where the studied core was obtained), whereas inside the IPWP, in the Timor Sea, SST dropped at the LGM by 4.2 ± 0.34 °C (Levi et al., 2007) and by 3.5 ± 0.48 °C in an adjacent core (Xu et al., 2008). Such a temperature drop from the modern value of 28.6 °C (De Deckker, 2016) would explain the drastic decline of monsoonal activity during glacial periods as a result of the reduction of convective cloud formation as seen today for the tropical Pacific Ocean when temperature is below 26 °C (Waliser & Graham, 1993), thereby decreasing heavy rainfall and monsoonal activity. In addition, there is evidence also that the intertropical convergence zone shifted northward from Australia during the LGM as demonstrated by Spooner et al. (2005) from a core in the Banda Sea. We can assume that this phenomenon was a repetition of previous glacial periods.

Based on particle-size distributions and major element geochemistry of marine sediments, Stuut et al. (2014) reconstructed paleoenvironmental conditions in northwestern Western Australia for the last 550 ka. Generally, this record describes a glacial-interglacial variability between colder and drier glacials characterized by coarse-grained dust input versus warm and humid interglacials characterized by increased river runoff. In particular, the fluvially transported sediments, principally engendered by monsoonal rains, dominate the sedimentary record with thick sequences of brown muds mixed with pelagic sediments. During dry phases, the sediment is beige in color and contains ample quartz grains and other minerals that are blown offshore (Stuut et al., 2014). Ishiwa et al. (2019), based on X-Ray Fluorescence (XRF) records of nearby site U1461, derive a drying trend throughout the last 14,000 years. Further continuous records of Australia's hydroclimate are scarce, particularly in the northwestern part of the continent [see Christensen et al., 2017, for a compilation of Neogene climate records]. Christensen et al. (2017) present a record of downhole measurements at IODP site U1463 (see Figure 1 for location) in which they interpret the natural gamma radiation in the sediments as a measure for the concentration of the elements K, Th, and U, which are interpreted as reflecting windblown or riverine flux of detrital material in the marine system. Both U(%) and Th/K are interpreted as proxies for aridity, whereas K(%) is interpreted as a proxy for humidity and continental runoff and terrigenous input. Subsequently, they speculate that the observed variations in windblown or riverine fluxes are driven by the Indonesian Throughflow, with a large shift from dry to wet conditions during the Miocene-Pliocene transition and a general drying trend between 3.4 and 1 Ma. The upper 72 m of the U1463 core record, spanning the upper 1 Ma, has not been measured in this core. During the same IODP leg, site U1459 was drilled at 28°4′S/113°3E (see Figure 1 for location) and also measured with the same gamma ray scanner, resulting in paleoclimate records for most of the Miocene [18–6 Ma; Groeneveld et al., 2017]. Groeneveld et al. (2017) interpret their derived K(%) as showing variations in riverine input and, thus, the amount of rainfall over southwest Western Australia. As opposed to the northern Australian record, they derive a very dry Early and Middle Miocene and a gradual wetting trend toward the Pliocene, which they ascribe to an equatorward migration of the southern westerlies. In contrast, and although being related to the same moisture source, on the basis of fossil pollen in cave deposits in southern Australia (see Figure 1 for location), Sniderman et al. (2016) derive a Southern Hemisphere hydroclimate record from the latest Miocene to the middle Pliocene, showing an abrupt onset of warm and wet climates early within the Pliocene.

Here, we present new XRF data from the lower part of core (MD00-2361), extending the record down to 1 Ma (Figure 2). We additionally present new data from a neighboring sediment core ODP122-762 (260 km away and some ~350 km away from the nearest present-day Australian coastline; see Figure 1) which provides a nearly identical climate record to MD00-2361 for the last 1 Ma and extends the environmental reconstructions down to the Miocene-Pliocene boundary (5.3 Ma). To study the aeolian and fluvial end members, we also conducted a field study in the source areas of the sediment cores (viz. northwestern Western Australia bordering the coastline; Figure 1). We sampled both river beds and sand dunes, for which we then analyzed the bulk chemical composition in the same way as we did for the marine sediment cores (see supporting information).

On the basis of their combined particle-size and chemical analyses of the upper 500 ka of core MD00-2361, Stuut et al. (2014) argued that the Fe/Ca ratio reflects the relative contributions of terrigenous and marine fractions in the core. Interglacial stages are characterized by huge amounts of river runoff, resulting in thick brown mud deposits (see Stuut et al., 2014, their Figure 2), as opposed to layers of carbonate-rich hemipelagic sediments deposited during glacial stages. In addition, these glacial stages are also characterized by coarse-grained windblown quartz particles and other robust mineral grains that only rarely occur during interglacial stages, which is reflected in the Zr/Fe ratio.

2. Material and Methods

Site ODP122-762 hole B (19°53.24′S, 112°15.24′E, 1,360-m water depth; Figure 1) was drilled on the top of the Montebello Saddle, which forms a large plateau on the northwestern Australian continental slope

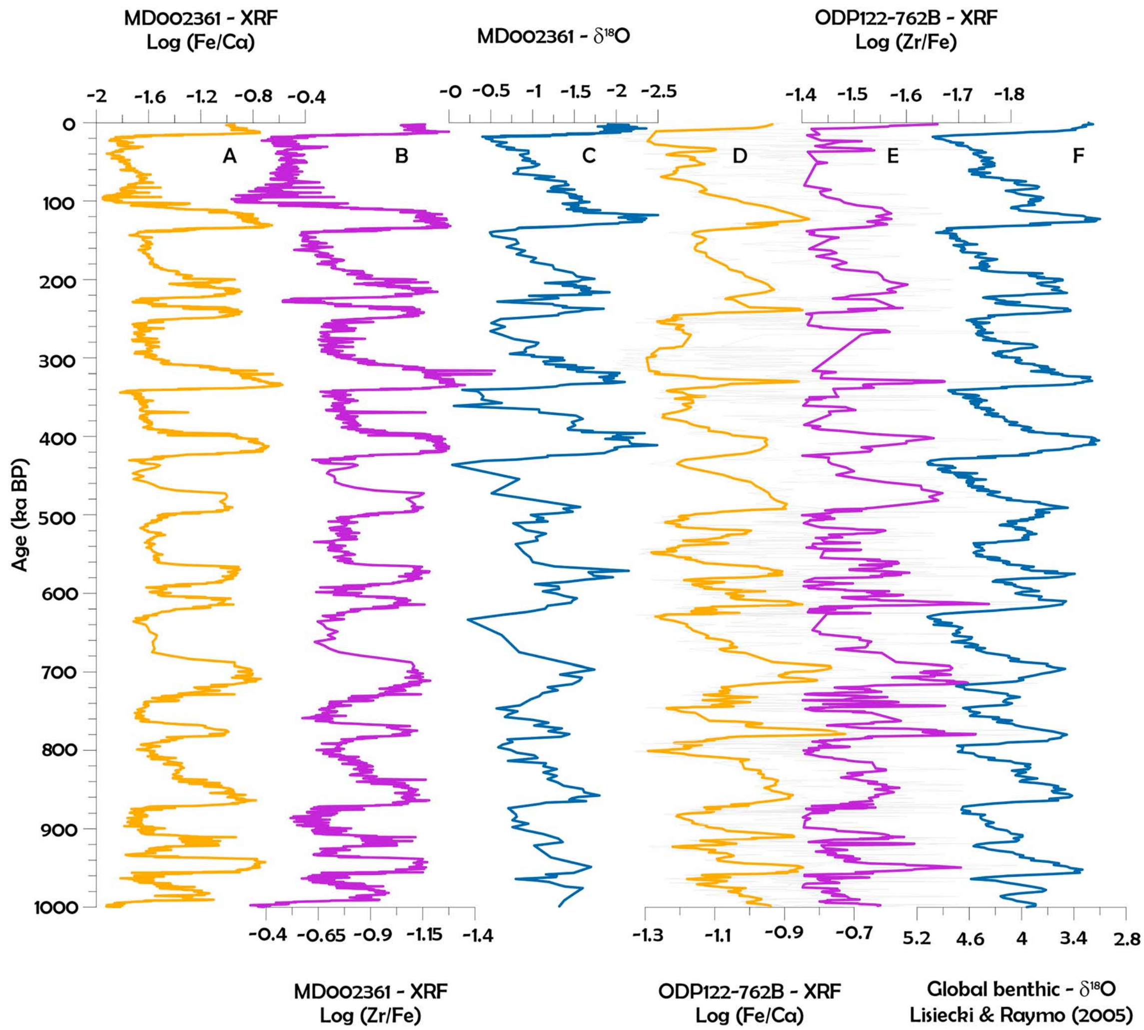

Figure 2. Proxy records for northwestern Western Australian climate of the last 1 Ma. (A) MD00-2361 Log Fe/Ca, a proxy for the amount terrigenous sediments (both aeolian dust and fluvial mud). (B) MD00-2361 Log Zr/Fe (note reversed axis), a proxy for the proportion river mud versus aeolian-dust input. (C) MD00-2361 $\delta^{18}O$, measured on *Globigerinoides ruber*, following Spooner et al. (2011), reflecting the convolved influences of global sea level and local temperature/salinity fluctuations. The lower 450 ka of the MD00-2361 records are new data, complementary to Stuut et al. (2014). (D) ODP122-762B Log Fe/Ca raw data in gray, 5-point running average in orange. (E) ODP122-762B Log Zr/Fe (note reversed axis), raw data in gray, five-point running average in purple. (F) Published $\delta^{18}O$ record of the global oxygen-isotope stack (Lisiecki & Raymo, 2005).

(Haq et al., 1990). The age model was constructed using initially the existing preliminary shipboard magnetostratigraphy (Tang, 1992), which was slightly revised and complemented by new calcareous nannofossil datum events based on Anthonissen and Ogg (2012), which resulted in 16 additional tie points (Table S1). Subsequently, a visual correlation of the Log (Fe/Ca) XRF record and the Lisiecki and Raymo (2005) $\delta^{18}O$ stack curve was made, which resulted in 175 additional tie points (Figure S7, available at the www.pangaea.de data archive web site).

Core MD00-2361 (22°04.92′S, 113°28.63′E, 1,805-m water depth; Figure 1) was retrieved from a saddle in between the Cape Range Canyon and the Cloates Canyon, to avoid mass deposits that may have travelled through these canyons (Spooner et al., 2011). The age model of the upper 550 ka of the core was published by Spooner et al. (2011) based on the $\delta^{18}O$ of *Globigerinoides ruber*. Following their method, for this study, we increased the resolution below ~250 ka and additionally extended it to 1 Ma.

Bulk chemical (XRF) data were obtained at 2-cm resolution for core ODP122-762B at the Kochi Core Center, Japan, using an ITRAX core scanner and for core MD00-2361 at NIOZ, the Netherlands (see supporting information for details). Following Stuut et al. (2014), the Log (Fe/Ca) is used as a proxy for land-derived material and Log (Zr/Fe) as a proxy for the contribution of fluvial mud versus aeolian dust. Bulk chemical

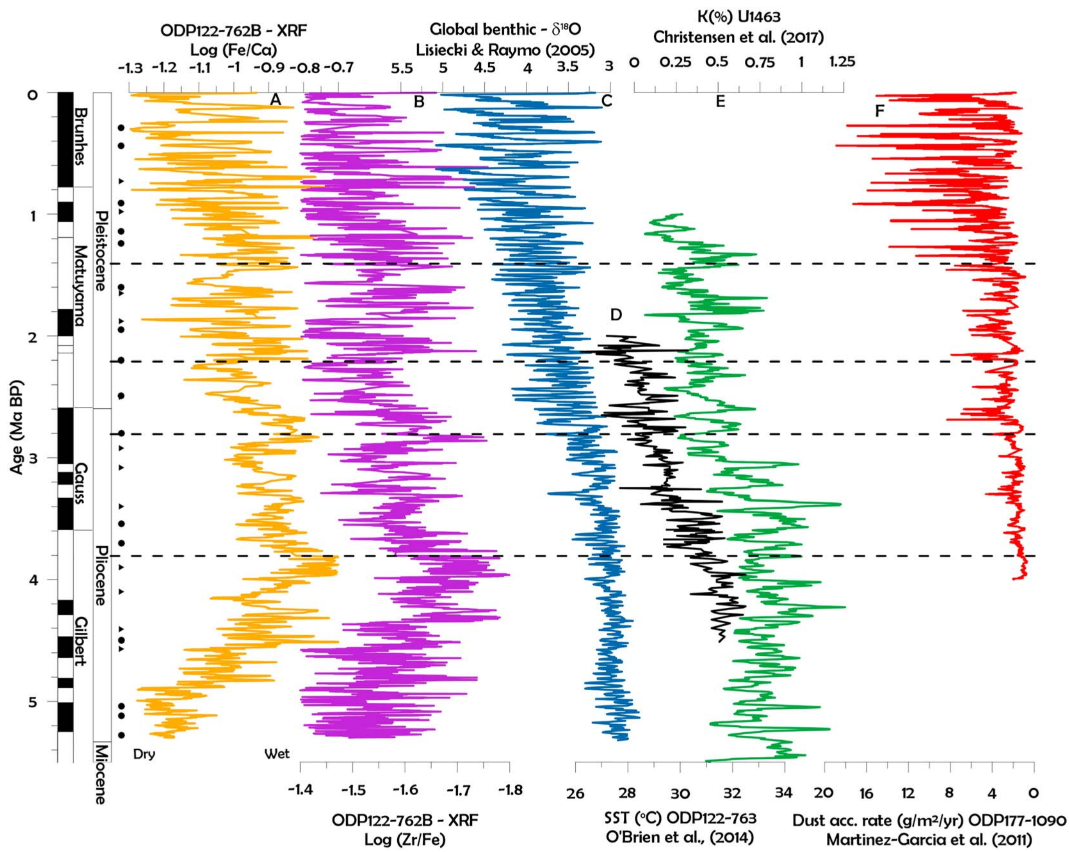

Figure 3. Proxy records for northwestern Australian climate of the last 5.3 Ma. Black dots (N = 16) on the left show new tie points provided by calcareous nannofossil-based biostratigraphy (black triangles, N = 13; see Table S1), which served as initial age model, together with the published shipboard magnetostratigraphic tie points (Tang, 1992). This initial age model was then refined by additional tie points (N = 175) after visual correlation with the L&R2005 stack (Lisiecki & Raymo, 2005). (A) Log (Fe/Ca, five-point running average in orange), (B) Log (Zr/Fe, five-point running average in purple; note the reversed axis to facilitate visibility/correlation) are used as proxies for terrigenous-sediment input and proportion river mud versus aeolian-dust deposition, respectively. (C) The oxygen isotope record (Lisiecki & Raymo, 2005; blue) represents global sea level combined with other factors such as oceanic temperatures as evidenced by the difference in amplitude between the start and end of the Pliocene. (D) SST in ODP122-763A [O'Brien et al., 2014; black; see Figure 1 for location], (E) K (%) in U1463 [Christensen et al., 2017; green; see Figure 1 for location], and (F) Dust in ODP-177-190 (Martinez-Garcia et al., 2011; red) and are shown for comparison. SST = sea surface temperature.

(XRF, Avaatech at NIOZ) data were also obtained on discrete samples from river beds and dunes in the source area of the sediments that are blown and flown to the core sites (Figures 1 and S6).

3. Results

The bulk chemical records of the two analyzed cores show nearly identical patterns for the last 1 Ma, characterized by large-amplitude changes in both Zr/Fe and Fe/Ca (Figure 2). Cycles in Zr/Fe and Fe/Ca also line up with the planktonic δ^{18}O record of Spooner et al. (2011) indicating a consistent relationship between glacial/interglacial conditions and northwestern Western Australian climate over the last 1 Ma. Core ODP122-762 contains a detailed and continuous Pliocene-Pleistocene paleoclimate archive of continental northwestern Australia (Figure 3). It shows a gradual increase in precipitation from 5.3 to 3.8 Ma and a more rapid return to drier conditions from 3.8 Ma to the present on which two types of variations are superimposed: (1) long-term oscillations (>500 ka) and (2) orbital-scale (41 and 100 ka) glacial cyclicity. From 2.8 to 2.2 Ma, the marine sediments show a decreasing trend in the terrigenous sediment component. A transitional period with dramatic high-amplitude variability in discharges occurred between 2.2 and 1.4 Ma. Between 1.4 Ma and the present, the sediments gradually became dominated by marine pelagic carbonates once more and the amplitude of changes between dry and wet intervals increased dramatically.

From the observation that the glacial-interglacial succession continues throughout the last 1 Ma in both cores as well as during the past 5.3 Ma in the ODP core, we conclude that our proxy records from

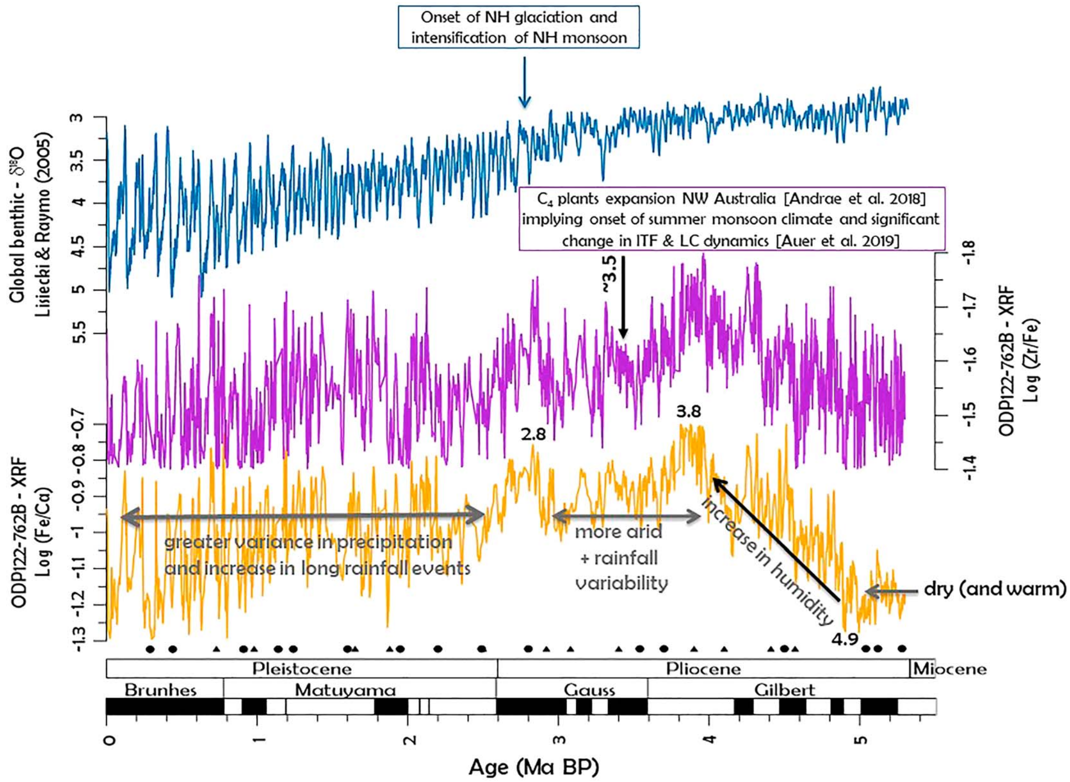

Figure 4. Proxy records for northwestern Australian climate of the past 5.3 Ma (refer to Figure 3 for more details) obtained from ODP122-762B. The main trends interpreted from our records are shown, in comparison with the global benthic $\delta^{18}O$ stack (Lisiecki & Raymo, 2005). The major shift in C_4 plants implying onset of summer monsoon climate in Australia at ~3.5 Ma, as described by Andrae et al. (2018), and the reorganization of the ITF and LC north of Australia by Auer et al. (2019) due to tectonic changes are also shown. See text for further discussion on the chronology of such change.

northwestern Western Australia provide a regional signal of precipitation through river-sediment discharge and deposition at sea.

4. Discussion

Modern precipitation around the IPWP and adjacent regions, including northwestern Australia, is dictated by the summer monsoon of which about 70% of the rainfall is caused by the occurrence of tropical cyclones (Dare et al., 2012). We therefore interpret the chemical records of our sediment cores in terms of runoff related to monsoonal rains in northwestern Australia as it is predominantly when cyclonic depressions transgress over northern Australia that huge fluvial discharges occur at sea (Figure S2).

Since the beginning of the Pliocene at 5.3 Ma, global temperatures were substantially higher than they are today (Fedorov et al., 2006) with likely significantly higher occurrence of monsoonal rains and even possibly tropical cyclones (Fedorov et al., 2010), which helped maintain enduring El Niño conditions and which is also reflected in our records (Figure 4). See also Wara et al. (2005), who refer to it as "a permanent El Niño." This contrasts with the present day, when monsoonal precipitation is most intense during neutral and La Niña years (Dare, 2013), related to the increased zonal SST and SSS gradients in the tropical Pacific Ocean (see supporting information). We hypothesize that this was also the case during the mid-Pliocene as our records show a decrease in runoff at 3.8 Ma.

In addition, Andrae et al. (2018) in their pollen studies on core ODP 763A reveal the onset of Australian C_4-plant expansion at ~3.5 Ma (Figure 4). This timing coincides almost exactly with inferred changes in the Indonesian Throughflow and Leeuwin-Current dynamics recognized in core U1463 by Auer et al. (2019). Our records show a much earlier shift in the elemental ratio records after 3.8 Ma. We note that Auer et al.'s (2019) record does not extend that far back in time. In addition, Andrae et al.'s (2018) record for the percentage of C_4 plants has only one analysis between ~3.5 and ~4.2 Ma. It may be therefore that the humid phase in Andrea et al.'s (2018) Figure 3d could have ended earlier than 3.5 Ma.

From about 3 Ma onward, due to global cooling and the increasing latitudinal temperature gradients since the Pliocene, there was an amplification of obliquity cycles in equatorial SSTs (Fedorov et al., 2006) and a gradual drying up of the northwestern Australian continent. A suite of additional processes has been suggested as possible drivers of the ongoing global cooling during the Pliocene, including lower global sea level (Gallagher et al., 2001), closing of the Panama Seaway (Karas et al., 2017), uplift of the Tibetan Plateau (An et al., 2001), and northward movement of the Australian continent, possibly partially blocking the Indonesian Throughflow (Cane & Molnar, 2001) and tectonic readjustment, as discussed by Auer et al. (2019). Eventually, all these changes led to glaciation of the Northern Hemisphere. Soon after, our records show a greater variance in precipitation and an increase in long rainfall events (Figure 4).

Modeling experiments have suggested that reducing the warm water exchange between the Pacific and Indian Oceans via the Indonesian Throughflow may have led to a precipitation dipole, with increased rainfall over eastern Australia and up to 30% reduction of rainfall over northwestern Australia (Krebs et al., 2011). The gradual drying trend is clearly reflected in our records, as well as increasing amplitude changes between wet and dry phases since about 2.4 Ma, similar to increased amplitudes in the global benthic $\delta^{18}O$ stack (Lisiecki & Raymo, 2005; Figure 3C) as well as the Southern Hemisphere dust fluxes reconstructed from a sediment core from the South Atlantic (Martinez-Garcia et al., 2011; Figure 3F). At the same time, our Log (Fe/Ca) record shows a general decrease since 1.4 Ma, which we interpret as a gradual decrease in river runoff, which is paralleled by an increase in dust fluxes in the Atlantic Ocean.

Our records do not show a clear relation with the recently published K(%) record, interpreted as proxy for continental aridity, measured in IODP core U1463 [Christensen et al., 2017; see Figure 1 for location and Figure 3E for the K(%) record], which could be related to the large smoothing that occurs during downhole natural gamma ray measurements. However, both records show a similar high-amplitude signal during both the Late Miocene and the Pliocene, which is not apparent in the benthic $\delta^{18}O$ stack and which we interpret as a sensitive response to changes in the driving mechanism. Comparison of our records to the SST record of nearby core ODP122-763A [Karas et al., 2011; revised by O'Brien et al., 2014] does not show an obvious correlation, apart from a decreasing temperature trend throughout the Pliocene. However, particularly for the earlier part of the record (4.4–3.6 Ma), when our records indicate wettest conditions on the northwestern Australian continent, the SSTs are above 30.5 °C, therefore implying that high rainfall can be generated despite the fact that convective clouds are absent above that threshold today (Waliser & Graham, 1993).

Finally, the Late Pleistocene part of our record shows a strong resemblance to the global $\delta^{18}O$ stack (Lisiecki & Raymo, 2005), including a shift from obliquity (41 ka)-dominated cyclicity to eccentricity (100 Ka)-dominated climate swings since about the mid-Pleistocene transition at about 800 ka (Lisiecki, 2010; see supporting information for time series analysis).

5. Conclusions

Our study suggests that the Australian continent has experienced a vivid environmental history with large fluctuations in monsoonal activity and very likely caused by monsoonal rainfall. This has important implications for the evolution of the fauna and flora as well as the development of the fire-adapted vegetation (Martin, 2006; Miller et al., 2005). Although northwestern Australia has become increasingly arid since the mid-Pliocene (~3.8 Ma), our records suggest the Holocene exists in the wettest phase of the high-frequency, large-amplitude swings in discharge states that have characterized regional climate variability since the early Pleistocene (~2.2 Ma) with rainfall rates among the highest of the past 5.3 Ma.

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