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Finding Dry Spells in Ocean Sediments

By Stephen J. Gallagher and Peter B. deMenocal

ABSTRACT. Ocean basins are the ultimate repositories of sediment. Their slow, continuous accumulation over geologic history provides valuable archives that document major climate events and transitions in Earth history. Mineral dust plumes borne by prevailing winds are dominant sources of terrigenous sedimentation off regions such as the Saharan, Arabian, Kalahari, Patagonian, and Australian deserts. Scientific ocean drilling off Africa and Arabia has recorded consistent glacial-stage increases in eolian dust fluxes throughout the Pliocene-Pleistocene, where elevated dust flux values during glacial periods and stadia have been interpreted as reflecting real hydroclimate progression toward greater glacial aridity. International Ocean Discovery Program Expeditions 356, 363, and 369 (conducted in 2015, 2016, and 2017, respectively) recovered extensive sedimentary climate archives off Australia. Ongoing analyses of these strata reveal a marine record of the onset of continental aridity as Australia migrated northward by 25° over the last 50 million years. These Southern Hemisphere oceanic records will continue to yield key information on global climate evolution, allowing us to understand how deserts and monsoonal systems have evolved through time.

INTRODUCTION

Terrestrially derived sediment and dust are ultimately stored in oceanic basins. Gradual, yet continuous, accumulation of these sediments through geological time has created superb archives of global climate variability, transitions, and events in Earth history. Plumes of mineral dust carried by prevailing winds are the main terrigenous sediment source off subtropical hyperarid areas such as the Arabian, Australian, Saharan, Kalahari, and Patagonian deserts. Charles Darwin commented on these African dust storms in 1846 during the first leg of his *Beagle* voyage: “During our stay of three weeks at St. Jago [Cape Verde], the wind was N.E. as is always the case this time of

year; the atmosphere was often hazy, and very fine dust was almost constantly falling, so that the astronomical instruments were roughened and a little injured.” This paper reviews the dust and aridification archives accumulated off the African continent and finishes with a look to future revelations to be obtained from recent scientific ocean drilling records off western Australia.

OUT OF AFRICA AND ARABIA: OCEANIC DUST ARCHIVES REVEAL ARIDIFICATION AND DESERT HISTORY

Downcore changes in eolian sediment abundance are used to chart the (geo)historical variability of northwest African

aridity. Nearly 180 million tons of African dust are transported by the winds to the ocean each year from Saharan source areas (Yu et al., 2015). The potential utility of mineral dust fluxes for recording hydroclimate is supported by strong historical correlations between Sahelian rainfall anomalies and eolian dust flux measurements recorded in Barbados (Prospero and Lamb, 2003) and in a marine core just offshore from the Senegal River near the Mauritania canyon (16°50'N, 16°44'W, Mulitza et al., 2010).

Noting a close correspondence between glacial cycles and elevated dust concentrations, Parkin and Shackleton (1973) influenced decades of researchers by proposing links between high-latitude ice cover and low-latitude aridity. Scientific ocean drilling off Africa and Arabia has recorded consistent glacial-stage increases in eolian dust fluxes throughout the Pliocene-Pleistocene (Figure 1a,b; Clemens and Prell, 1991; Tiedemann et al., 1994; deMenocal, 1995). Elevated dust flux values during glacial periods and stadia (relatively cold periods within a glacial period) have been interpreted as reflecting real hydroclimate changes toward greater glacial aridity.

Recent advances in grain size data analysis document that the glacial sediments not only have higher dust concentrations and burial fluxes but also have

much coarser grain size distributions. By “unmixing” grain size spectra into finer-grained fluvial and coarser eolian end-members, Tjallingii et al. (2008) noted that glacial stages and shorter stadial (Heinrich) events were characterized by much coarser and more abundant eolian grain sizes, consistent with stronger, more competent transporting wind speeds during cooler periods. Current views suggest that the observed two- to fourfold increases in glacial-age dust fluxes observed across the global tropics and subtropics (Clemens and Prell, 1991; Tiedemann et al., 1994; deMenocal, 1995; Winckler et al., 2008) reflect glacial increases in dust transport due to stronger, more gusty winds associated with increased glacial pole-equator temperature gradients (McGee et al., 2010).

A fundamental challenge to interpreting sedimentary dust fluxes solely in terms of changes in aridity has emerged from hydrogen isotopic measurements of plant leaf waxes preserved in the same sediment cores where dust fluxes are measured. This organic geochemical paleohydrological proxy tracks regional rainfall gradients today and in the past (Tierney et al., 2017b). Analysis of northwest African sediment cores documents paleohydrological cycles paced principally by orbital precession, with only weak expression of glacial-interglacial 100,000-year and 41,000-year cycles observed in dust flux records (Figure 1c; Tierney et al., 2017a; Kuechler et al., 2018). These precessional plant wax wet-dry cycles match similar pacing observed in Mediterranean sapropel (organic sediment rich) cycles that extend back to the late Miocene.

Together, the eolian dust and plant wax isotopic data clarify interpretations of the deep-sea sedimentary record of continental climate change. Consistent with orbital theory, subtropical continental wet-dry cycles were mainly paced by orbital precession, whereas the glacial dust flux increases are mainly reflective of more effective dust transport due to stronger, gustier subtropical wind fields, not greater aridity (McGee et al., 2013).

Hence, there is an opportunity to use these differential proxy responses to simultaneously explore monsoonal hydroclimate responses to orbital precession forcing within the Pliocene-Pleistocene context of increasing glacial climate variability after 2.8 million years ago. To date, studies indicate that the amplitude of monsoonal hydroclimate response to orbital forcing appears to have been large and persistent with no secular change over the last 5 million years (Rose et al., 2016; Kuechler et al., 2018).

A PORTRAIT OF AN ARID LAND: OCEAN DRILLING TO UNCOVER 50 MILLION YEARS OF AUSTRALIAN CLIMATE EXTREMES

International Ocean Discovery Program (IODP) Expeditions 356, 363, and 369 conducted from 2015 to 2017 cored up to 1 km into the seabed from 14°S to 34°S off western Australia (Figure 2). These expeditions recovered excellent records of climate and ocean conditions as Australia drifted northward by 25° latitude over the last 50 million years. Fossil and sediment information trapped in these

layers contain a marine record of continental aridity, Australian monsoons, and westerly winds, permitting investigation of how the present climate extremes of Australia evolved (Figure 2).

The Australian Monsoon

North Australia is influenced by strong summer westerly and southwesterly winds that source warm, moist equatorial air, resulting in the monsoonal rains and cyclonic activity north of the monsoon shear line. Monsoonal seasonal runoff delivers large amounts of river sediment to the Australian continental shelf via the Fitzroy, De Grey, Ashburton, and Fortescue Rivers (Figure 2). In contrast, the trade winds off northwest Australia transport continental wind-blown dust when the trade winds dominate during the winter dry season (Figure 2; see also Stuut et al., 2014).

The Westerlies Regime

Strong westerly winds dominate the mid-latitude regions south of 26°S on the western margin of Australia. The north-to-south movement of the westerlies results in significant seasonal precipitation

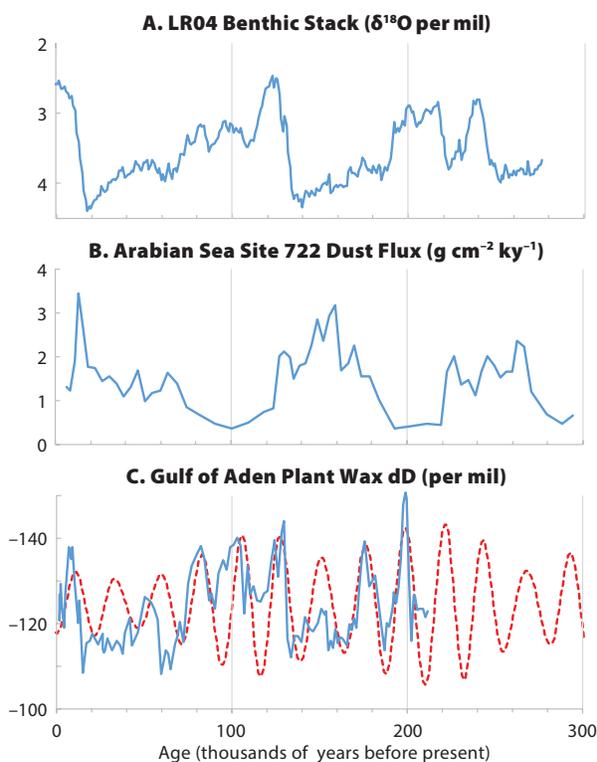


FIGURE 1. (A) Benthic oxygen isotope stack (Lisiecki and Raymo, 2005). (B) Mineral dust flux record from ODP Site 722, Arabian Sea (Clemens and Prell, 1991). (C) Stable hydrogen isotopic composition of plant waxes at core site RC9-166 in the Gulf of Aden (Tierney et al., 2017a), with orbital precession (red dashed line, negative values upward).

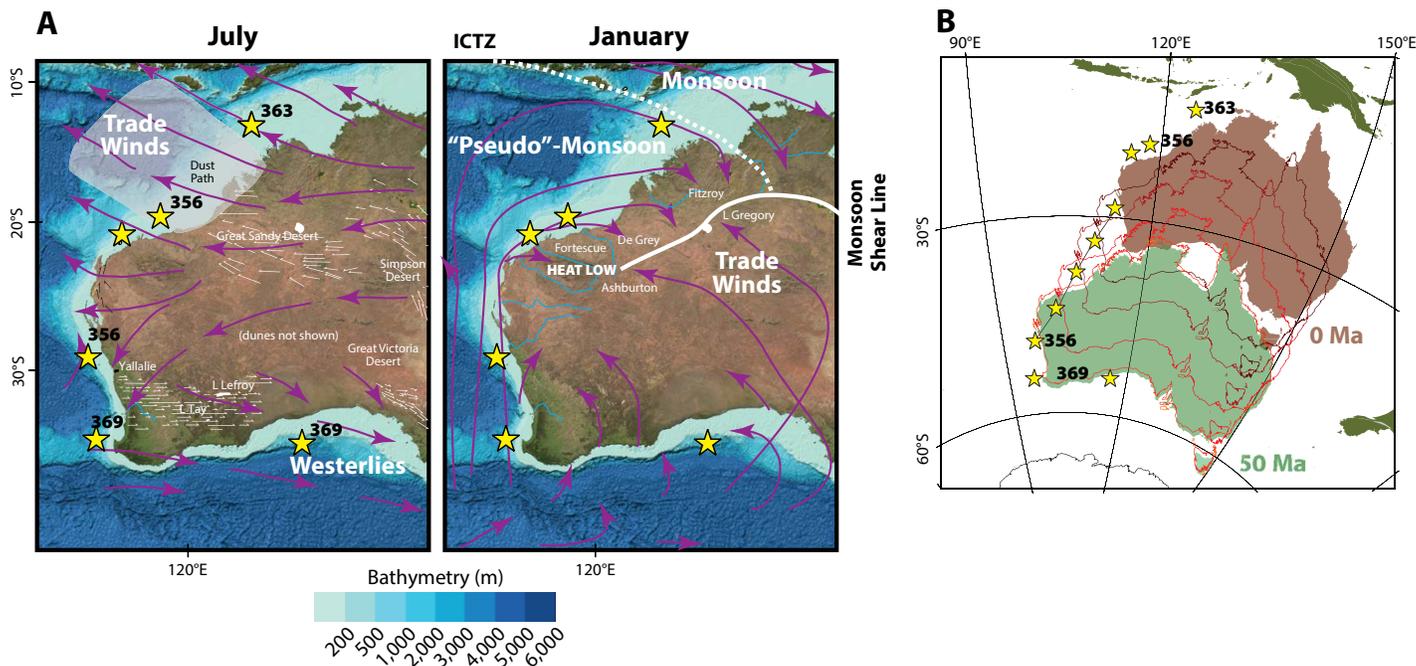


FIGURE 2. (A) Atmospheric circulation (purple arrows) for July and January (Gentili, 1972), with the mean monsoon shear line (solid white line; McBride, 1986) and Inter Tropical Convergence Zone (ICTZ; dotted white line) noted. During austral summer (January), precipitation dominates, as the region is influenced by strong westerly and southwesterly winds that bring in moist equatorial air. Base map adapted from General Bathymetric Chart of the Oceans (GEBCO; <https://www.gebco.net/>). Dunefield map and dust path (white arrows) from Hesse et al. (2004). Stars indicate recent IODP expeditions. (B) Plate tectonic motion of Australia since 50 million years ago in 10 million year intervals, with the path line for Site U1459 (Exp. 356) adapted from Gallagher et al. (2017).

changes (winter wet, summer dry) in the southern half of Australia (McLaren et al., 2014; Groeneveld et al., 2017).

The Paleomonsoon and Northwest Australian Climate

Northern and interior Australia had seasonally wetter monsoonal precipitation 23 to 14 million years ago when the monsoonal front was in a similar position to today's (Herold et al., 2011). Arid conditions that persisted from 16 to 6 million years ago in northwest Australia (IODP Expedition 356; Groeneveld et al., 2017) transitioned to a wetter period, with year-round rainfall, at ~5.5 million years ago (IODP Expedition 356; Christensen et al., 2017; De Vleeschouwer et al., 2018), and then to seasonal (monsoonal) rainfall at ~3.3 million years ago. Indonesian Throughflow restriction and falling continental humidity culminated in arid conditions at ~2.4 million years ago, resulting in a seasonal (monsoonal) regime. Over the last 2 million years, interglacial wetter (strong monsoon) and arid

glacial (weak monsoon) conditions persisted in Australia's northwest (Gallagher et al., 2014). Arid conditions intensified in a stepwise manner, with drying after ~1.5 million years ago and 0.6 million years ago coinciding with the contraction of megalakes in southeast Australia at ~1.5 million years ago (McLaren et al., 2014) and the expansion of the Simpson Desert at ~1 million years ago (Fujioka and Chappell, 2010).

Southwest Australian Climate and the History of the Westerlies

Compared to the northwest Australian region, little is known of the long-term history of the southwest Australian climate. Fossil and modern sand dunes and dust pathways reflect past wind strength and the relative strength of the westerly winds (Hesse et al., 2004). During the Last Glacial Maximum (18,000 years ago), the westerlies shifted ~3° northward, then returned to their present position after 8,000 years (Hesse et al., 2004), with a pattern similar to that of today.

Forty to 25 million years ago, wetter conditions created extensive river systems (Martin, 2006). After 15 million years ago, these river systems dried up, suggesting more arid conditions. Floral fossils in lake sediment suggest a wetter climate compared to today in southwest Australia ~4 million years ago and a transition to arid conditions after 3 million years ago that ultimately led to the drying out of most lakes at around 600,000 years ago (Martin, 2006).

CONCLUSIONS

Analyses of oceanic dust archives off Africa and Arabia show the extremes of climate in these regions over the last several million years. These scientific ocean drilling cores record in great detail the variation in extent of the Sahara Desert and the African monsoon over glacial and interglacial periods. Analyses of recently obtained IODP drilling records off western Australia reveal over 50 million years of monsoonal and oceanic history and ultimately provide an account of

Australian aridification. These offshore ocean archives yield well-constrained histories that are rarely preserved in harsh arid terrestrial environments of continental regions and that will continue to bring key information on global climate evolution, allowing us to understand how deserts and monsoonal systems have evolved. 

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