Continuous 150 k.y. monsoon record from Lake Eyre, Australia: Insolation-forcing implications and unexpected Holocene failure

John W. Magee Department of Earth and Marine Sciences, Australian National University, Canberra, ACT 0200, Australia
Gifford H. Miller Institute of Arctic and Alpine Research and Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309-0450, USA
Nigel A. Spooner Daniele Questiaux - Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

ABSTRACT

Our reconstructed history of Lake Eyre provides the first continuous continental proxy record of Australian monsoon intensity over the past 150 k.y. This continental record’s broad correspondence to the marine isotope record demonstrates that this very large catchment, with its hydrology dependent on a planetary-scale climate element, responds to Milankovitch-scale climate forcing. Abrupt transitions from dry phases to wet phases (ca. 125 and 12 ka) coincide with Northern Hemisphere winter insolation minima rather than Southern Hemisphere summer insolation maxima, indicating that Northern Hemisphere insolation exerts a dominant control over the intensity of the Australian monsoon. Stratigraphic and dating uncertainties of other wet phases preclude conclusive correlation to specific insolation signals but, within the uncertainties, are consistent with Northern Hemisphere forcing. Regardless of the hemispheric forcing, the low intensity of the early Holocene Australian monsoon—by comparison with the last interglacial and particularly the last high-level lacustrine event at 65–60 ka when all forcing elements were modest—is an enigma that can be explained by a change in boundary conditions within Australia.

Keywords: Australia, paleomonsoon, paleoclimate, lake sediment, playa, Milankovitch.

INTRODUCTION

There is a paucity of long continental records, apart from the loess sequences of China and central Europe, that can be compared to the marine oxygen isotope and ice-core records. This absence is particularly glaring for the Southern Hemisphere. However, at a global scale, detailed correlation of marine and continental records at glacial-interglacial time scales is essential if we are to unravel the complexities of cause and process in Quaternary climatic variation. Large lakes, with catchments of >10^6 km^-2, provide the best opportunity to capture global rather than regional climate signals (Carmouze et al., 1983; Colman et al., 1995). The Lake Eyre lake-level curve presented here allows comparison of a detailed, large-scale, continental paleoclimate record with insolation changes (Berger and Loutre, 1991), sea-level variation (Lambeck and Chappell, 2001), and the marine isotopic record (Martinson et al., 1987) over the past 150 k.y.

The Australian monsoon, at the periphery of the planetary monsoon, is erratic in both time and space, varying significantly with components of the ocean-atmosphere system such as the Walker Circulation and the El Niño–Southern Oscillation (ENSO). The northern Australian heat-driven low-pressure zone anchors the equatorial trough, drawing summer monsoon flow into northern Australia (Allan, 1985). However, debate exists as to whether the modern summer monsoon is driven by southward displacement of the Intertropical Convergence Zone due to outflow from the Northern Hemisphere Siberian high-pressure cell and is merely anchored by the Australian heat low or whether the latter plays a more active forcing role (Allan, 1985; Suppiah, 1992). This debate mirrors uncertainty over the cause(s) of Quaternary changes in the monsoon: the proposed causes are changes in winter insolation over Asia (Miller et al., 1999) vs. changes in summer insolation over northern Australia (Chappell and Syktus, 1996; Wyrwoll and Valdes, 2003). Resolution of this debate will be enhanced by a continuous late Quaternary record from monsoonal Australia.

LAKE EYRE RECORD

Lake Eyre, in the area with Australia’s lowest, least reliable rainfall, far exceeded by evaporation, is currently an ephemeral playa at the southwest margin of an extremely large internal drainage network (1.2 × 10^6 km^-2) fed dominantly by a summer monsoon rainfall catchment to the northeast (Fig. 1). A smaller local catchment west of the lake is too small to maintain a water body, even with significantly enhanced runoff, when the lake area, catchment area, and climate relationship is assessed (Bowler, 1981). In the modern climatic regime, even though this local catchment is in the zone of uniform seasonal rainfall, significant runoff is only associated with the incursion of discrete monsoon-derived rain depres-
sions characterized by intense convection. Thus, although Lake Eyre is well south of the monsoon rainfall zone, its sedimentary history and paleohydrology constitute a record of monsoon runoff and allow investigation of the Australian monsoon through the Quaternary. Lake-floor, shoreline, fluvial, and downwind transverse dune sediments provide evidence of both wetter and drier periods in Lake Eyre. High beaches, deep-water sediments, and fluvial aggradation in inflowing streams indicate perennial lacustrine conditions wetter than today. Under drier conditions, playa deepening occurs as evaporation lowers the saline water table and salt-disrupted sediment is deflated to downwind transverse dunes or lunettes. Inflowing streams incise to the lowered base level. Stratigraphic analysis of the various types of sediments throughout the basin provides a nearly continuous record of lake-level changes over the past 150 k.y., chronologically constrained by using multiple dating techniques. The chronology in Figure 2 is based on 30 previously unpublished optically stimulated luminescence (OSL) dates with additional control from 8 thermoluminescence (TL), 25 accelerator mass spectrometry (AMS) $^{14}$C (calibrated), and 8 thermal-ionization mass spectrometry (TIMS) U-Th determinations. Further helping to constrain this chronology, though not plotted, are an additional 8 OSL dates, $>100$ AMS $^{14}$C dates, and $>1400$ amino acid racemization determinations (on bird eggshell and mollusks). Effective wetness is indicated by the absolute height of shorelines, and effective aridity is established from the depth of playa deflation during arid phases.

Greatest effective aridity in the past 150 k.y. occurred in marine oxygen isotope stage (MIS) 6, when basin deflation was 4.3 m lower than today (Magee et al., 1995; Magee and Miller, 1998). This arid event was followed abruptly by formation of the deepest perennial lake (phase V at +10 m relative to the Australian height datum [AHD—mean sea level]), nearly 25 m above the modern playa. At least 6 m of finely laminated gysiferous and calcareous clay were deposited with salinity stratification and strongly reducing bottom conditions. Actively meandering inflowing streams deposited thick, lateral-accretion sediments and fluvioeluvial sediment at river mouths. The sedimentary record for the onset of this phase at a number of sites (Magee et al., 1995) demonstrates an abrupt transition from deep playa deflation to continuous regular flooding due to a marked enhancement of the Australian monsoon leading to no dry episodes. Coeval fossil assemblages indicate diverse and abundant aquatic and terrestrial ecosystems and include now-extinct megafauna (Telford and Wells, 1990). Records signifying an enhanced Australian monsoon during the last interglacial come from other Lake Eyre catchment fluvial sites (Croke et al., 1996; Nanson et al., 1988) and other monsoon-fed lakes of northern Australia (Bowler et al., 1998, 2001).

The lake shallowed and briefly dried at least once, but no evidence is seen of deflation or pedogenesis; then the lake refilled to +5 m relative to AHD between 100 and 75 ka (phase IV), when lacustrine deep-water clays, calcareous nearshore and beach sands, and clastic gysiferous evaporites were deposited coevally with renewed fluvial aggradation. Fluctuations in lake level and salinity suggest decreasing regularity of inflow and gradual diminution of the monsoon toward the end of phase IV. Sediments of phase IV were pedogenically modified and eventually truncated by deflation when the lake dried at 75–70 ka and disrupted gysiferous playa sediments were transported downwind. Incision of tributary rivers into previous fluvial and lacustrine sediments, extending almost to the modern level, documents a transition to significant aridity.

Lacustrine conditions returned at 65–60 ka (phase III), depositing lake sediment and a prominent beach sand, rich in the brackish-water gastropod Coxiellada gilesii, at ~3 m relative to AHD; coeval fluvial aggradation and vertical accretion of overbank muds occurred. Though having shallower water and shorter duration than phases V and IV, phase III had significantly deeper water and longer duration than the modern ephemeral events and represents the last deep-water perennial lake in the basin and moderately effective monsoon precipitation. Following phase III, eolian redistribution of regressive shoreline sediments, later mixed with gypsum and pelletal clay derived from playa deflation, formed the Williams Point eolian unit (Magee and Miller, 1998). The consequence of this deflation event was the excavation of the modern Lake Eyre playa, and it represents a major change in hydrological conditions from high to low water tables, rather than extreme aridity.

A minor low-level perennial lake ca. 40 ka reached ~10 m relative to AHD (phase II) and deposited a broad low beach and laminated shallow-water eolian gypsum evaporites and clay. Coeval local landscape stability resulted in pedogenesis on the Williams Point eolian unit, as shown by gypsum-filled polygonal cracks and abundant large gypsum tree bole and root casts. The presence of trees significantly larger than at equivalent sites today and the enhanced gypsum mobility compared to that in modern soils suggest local precipitation more effective than today’s. The low-level perennial lake at this time may have received some local inflow but must still have required modest monsoon precipitation.

Drier conditions after 40 ka truncated the Williams Point eolian unit soil to the horizon cemented by secondary gypsum. Prolonged irregular minor playa deflation due to episodic depression of the water table held sway from 35 ka to 14 ka and deposited a thin unit of playa-marginal lunette sediments, the Shelly Island unit (Magee and Miller, 1998). The onset of low-level perennial lacustrine conditions (phase I) ca. 12 ka is well constrained by precise AMS $^{14}$C dates on rigorously pretreated samples (Gillespie et al., 1991) from shallow-water laminated gysiferous clays. Preserva-
tion of a salt crust of Last Glacial Maximum (LGM) age below the phase I sediments demonstrates that it was protected from dissolution by a dense, highly saline bottom layer and accumulating sediment pile, indicating an abrupt transition to continuously wetter conditions similar to that that occurred at the onset of phase V. Although there is no stratigraphic certainty that the onset of the event is necessarily constrained by the earliest (12 ka) date from the single sediment core, the event must postdate the termination of Shelly Island unit deposition, which is well constrained to 14 ka (Magee and Miller, 1998). Termination of Shelly Island unit deposition, the first sign of increasing moisture in the basin, was coeval with monsoon reinitiation at 14 ka in the Kimberley region of northwestern Australia (Wyrwoll and Miller, 2001). The size, complexity, and location of the Lake Eyre catchment probably combine to delay the onset of true lacustrine conditions in the basin compared to the more rapid response in the Kimberley sites. Reduced inflow after 4 ka established the modern ephemeral flooded playa regime. The absence of early Holocene beaches suggests that the lake was below the highest floods of the modern ephemeral regime (−6.7 to −8.8 m relative to AHD) (Dulhunty, 1975), suggesting a mode change to less frequent but more extreme events, perhaps reflecting a change in the character of ENSO, as suggested by previous studies (Rodbell et al., 1999).

**DISCUSSION AND CONCLUSIONS**

Comparison of the timing and magnitude of Lake Eyre lake-level, area, and volume fluctuations with insolation variations and sea level (Fig. 3) allows assessment of possible Australian summer monsoon controls on the Milankovitch time scale, but precise correlation of most events is precluded by the relatively low precision of the luminescence dating. The lake-level and lake-volume curves are similar: phase III is intermediate between the MIS 5 high-lake-level events (phases IV and V) and the later low-lake-level events (phases I and II), but lake area—the best proxy for evaporation—indicates a similarity of phase III to phases I and II. The onsets of the well-constrained modest early Holocene event (phase I) and the less precisely dated, the well-constrained modest early Holocene phase I lake level was strikingly lower than the levels achieved early in the last interglacial, when sea level and insolation forcing were similar. This contrast is further enhanced by comparison with the last significant lacustrine event, which was related to more effective penetration of monsoon moisture into the continental interior at 65–60 ka (phase III, at −3.5 m relative to AHD), when sea level was much lower and astronomic forcing less favorable than in the Holocene in both hemispheres (Fig. 3). The similarity of lake area in the phase III event compared with the lake area during phases II and I suggests the possibility that the enhanced lake at 65 ka might have been due to reduced evaporation caused by lower temperatures rather than to enhanced monsoon inflow. However, the absence of a water body in the basin during late MIS 3 and 2 (Magee and Miller, 1998), despite a more significant temperature reduction of 9 °C (Miller et al., 1997), indicates a water balance that requires enhanced inflow to maintain a significant lake.

There is abundant evidence of substantial reinvigoration of the planetary monsoon in the early Holocene from outside Australia (Carmouze and Lemoalle, 1983; Hoelzmann et al., 2000; Liu and Ding, 1998; Rousseau et al., 2000; Wasson, 1995; Williams et al., 2000) and coeval reactivation of the monsoon along between MIS 4 and MIS 3, where uncertainty of the marine chronology is high (Martinson et al., 1987), and the exact correlation of the phase III deposits to the marine record is equivocal. Dry conditions and Lake Eyre deflation are associated with the cold arid conditions and sea-level minima of the LGM and the penultimate glacial maximum; more moderate drying and deflation at 75–70 ka mark the transition to colder, more arid conditions at the end of MIS 5.

Increased atmospheric methane in the ice cores dominantly reflects expansion of tropical wetlands when the Asian monsoon is enhanced (Brook et al., 2000; Chappellaz et al., 1997), and should therefore parallel the Lake Eyre lake-level curve if the Australian monsoon is driven by Northern Hemisphere insolation. Phases V and I correlate well with the Vostok ice-core methane record (Petit et al., 1999), but correlation of phases IV, III, and II is less certain, perhaps reflecting uncertainty in both chronologies. Phase III correlates well with the early MIS 3 methane peak in the revised Vostok methane chronology (Ruddiman and Raymo, 2003), which is tuned to Northern Hemisphere insolation but tied to the Greenland Ice Core Project ice-core layer-counting chronology for the most recent methane peak.

Regardless of which hemisphere’s insolation exerts the strongest control, the early Holocene phase I lake level was strikingly lower than the levels achieved early in the last interglacial, when sea level and insolation forcing were similar. This contrast is further enhanced by comparison with the last significant lacustrine event, which was related to more effective penetration of monsoon moisture into the continental interior at 65–60 ka (phase III, at −3.5 m relative to AHD), when sea level was much lower and astronomic forcing less favorable than in the Holocene in both hemispheres (Fig. 3). The similarity of lake area in the phase III event compared with the lake area during phases II and I suggests the possibility that the enhanced lake at 65 ka might have been due to reduced evaporation caused by lower temperatures rather than to enhanced monsoon inflow. However, the absence of a water body in the basin during late MIS 3 and 2 (Magee and Miller, 1998), despite a more significant temperature reduction of 9 °C (Miller et al., 1997), indicates a water balance that requires enhanced inflow to maintain a significant lake.

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the northern Australian fringe (Nanson et al., 1991; Nott and Price, 1994). We attribute the failure of the Holocene monsoon to penetrate into the Australian interior, as it had done as recently as 65–60 ka, to be related to a change in boundary conditions over the Australian landmass. Decreasing the transfer of moisture from the biosphere to the atmosphere during the monsoon season would inhibit the penetration of monsoon rainfall into the Lake Eyre catchment. A plausible boundary-condition change that could affect the efficiency of landward transfer of monsoon moisture is the large-scale alteration of the biota—by human burning—across the northern half of the continent, as suggested by Johnson et al. (1999) from vegetation changes recorded in the carbon isotopic signature of emu eggshells. However, Kershaw et al. (2003) argued that MIS 3 continent-wide vegetation changes, seen in marine core pollen records, occurred slightly later than reported by Johnson et al. (1999), and may have a more complex cause.

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REFERENCES CITED