Early to Middle Miocene monsoon climate in Australia

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ABSTRACT

The present-day Australian monsoon delivers substantial moisture to the northern regions of a predominantly arid continent. However, the pre-Quaternary history of the Australian monsoon is poorly constrained due to sparse and often poorly dated paleoclimate proxy evidence. Sedimentological and paleontological data suggest that warm, humid, and seasonal environments prevailed in central and north Australia during the Miocene, though it is unclear whether these were products of the Australian monsoon. We perform a series of sensitivity experiments using an atmospheric general circulation model, combined with an offline equilibrium vegetation model, to quantitatively constrain the areal extent of the Miocene monsoon. Our results suggest a weaker than modern monsoon climate during the Miocene. This result is insensitive to atmospheric CO_2, although somewhat sensitive to vegetation interactions and the presumed distribution of inland water bodies. None of our Miocene experiments exhibit precipitation rates greater than modern over north Australia, in disagreement with paleoclimate record interpretations. Vegetation modeling indicates that inferred precipitation values from fossil flora and fauna could only support Miocene vegetation patterns if atmospheric CO_2 was twice the modern concentration. This suggests that elevated CO_2 was critical for sustaining Miocene vegetation.

INTRODUCTION

The arid climate of present-day Australia is ameliorated by the summer monsoon, which delivers substantial moisture to the northern regions of the continent. Due to limitations in the temporal and spatial resolution of paleoclimate records, studies of the paleo-Australian monsoon have focused on the late Quaternary (e.g., Miller et al., 2005; Wyrwoll and Valdes, 2003). Therefore, while it is believed that the Australian monsoon existed by the Neogene, little is known of its pre-Quaternary dimensions or intensity (Bowman et al., 2010).

During the Early to Middle Miocene, a period of well-documented global warmth (e.g., Wan et al., 2009; You et al., 2009), Australia was ~8° south of its current position. Nevertheless, sedimentological and paleontological data suggest that warm, humid, and perhaps seasonal environments existed in central and north Australia (e.g., Macphail, 2007; Martin, 2006), though it is unclear whether these were the result of a monsoon-dominated landscape. Significant drainage in central Australia last occurred during the Middle Miocene (Quilty, 1994), with fossil flora and fauna indicating permanent water bodies and riparian rainforests (Alley, 1998; Benbow et al., 1995; Martin, 2006; Quilty, 1994). Fossil flora from central Australia suggest that conditions were seasonally too dry to support rainforests away from watercourses (Alley, 1998; Benbow et al., 1995; Greenwood, 1996; Guerin and Hill, 2006; Macphail, 2007). However, in northern and northeastern Australia, an abundant tropical forest biota has been interpreted to represent widespread rainforest (Archer et al., 1994; Travouillon et al., 2009). Despite the evidence for increased effective moisture, quantitative climate proxies from central and north Australia are sparse (Table 1), and much of the existing qualitative evidence is poorly constrained. The Miocene therefore provides an appropriate period to investigate the pre-Quaternary monsoon with numerical models.

Previous studies utilizing general circulation models (GCMs) have demonstrated sensitivity of the Australian monsoon to atmospheric CO_2 (Suppiah, 1995) and vegetation (Miller et al., 2005), parameters that are poorly constrained for the Miocene (e.g., Pagani et al., 1999; You et al., 2009; Wolfe, 1985). Inland water bodies (Benbow et al., 1995; Martin, 2006) may have also provided sources of atmospheric moisture during the Miocene. Understanding the climatic impact of these uncertainties is critical in constraining the antiquity of the Australian monsoon and in developing a fuller characterization of the history of Australian hydroclimatology. In this study we perform a series of sensitivity experiments using an atmospheric GCM and offline vegetation distribution model to (1) determine the extent of Miocene monsoonal conditions in Australia, and (2) explore possible causes of the reconstructed paleoclimate patterns.

EXPERIMENT DESIGN

The Community Atmosphere Model 3.1 (CAM; Collins et al., 2006) and Community Land Model 3 (CLM; Vertenstein et al., 2004) are used to examine the extent of monsoon climate in Miocene Australia. Both models are configured with a horizontal resolution of ~3.75° × 3.75° in latitude and longitude. Our control simulation (MIO) is forced with topography from Herold et al. (2008) with minor alterations, the most significant of which is the opening of the Tethys seaway. Vegetation distributions in these experiments are fixed based on those in Herold et al. (2010), including broadleaf vegetation in north Australia, shrubland in west Australia, and mixed vegetation in Central and southeastern Australia. Atmospheric CO_2 is set to 355 ppmv, midway between the majority of Miocene estimates and

TABLE 1. QUANTITATIVE CLIMATE PROXIES COMPARED WITH CONTROL SIMULATION MIO

Proxy location	Paleo-latitude (°S)	Variable*	Proxy	MIO
Bullock Creek (Markwick, 2007)	25	CMMT	≥5 °C	12 °C
Dunsinane[†]	26	MAP	500–800 mm	595 mm
Kangaroo Well (Megirian et al., 2004)	29.7	MAT	14–20 °C	19.5 °C
Kangaroo Well (Megirian et al., 2004)	29.7	MAP	<600 mm	395 mm
Moranbah[§]	30	MAP	950–1950 mm	820 mm
Northeast Australia (Feary et al., 1991)	17–31	SST	~18–21 °C	19.5–25 °C
Lake Palankarinna (Markwick, 2007)	36	CMMT	≥5 °C	6 °C
Kiandra (Greenwood et al., 2004)	42	MAT	17.3 °C	13.5 °C
Kiandra[§]	42	MAP	585–1198 mm	540 mm
Bacchus Marsh[§]	45	MAT	10.7 °C	8.6 °C
Gippsland basin (Sluiter et al., 1995)	45	MAT	19 °C	11.5 °C
Gippsland basin (Greenwood et al., 2004)	45	MAT	17.1 °C	11.5 °C
Gippsland basin (Sluiter et al., 1995)	45	MAP	1500–2200 mm	530 mm

*CMMT—Coldest month mean temperature; MAP—mean annual precipitation; MAT—mean annual temperature; SST—sea-surface temperature.

[†]The presence of a species-poor deciduous vine thicket at Dunsinane (Guerin and Hill, 2006) implies MAP in the range 500–800 mm at that site in the Late Oligocene to Early Miocene (Greenwood, 1996).

[§]Based on leaf area analysis (Greenwood et al., 2010) using data from Greenwood and Christophel (2005).

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equivalent to values used in modern CAM and CLM simulations.

To simulate Miocene oceanic conditions we employ a thermodynamic, mixed-layer ocean model forced with mixed-layer depths and heat fluxes from a Community Climate System Model 3 (CCSM3; http://www.cesm.ucar.edu/models/ccsm3.0/) simulation applying the Miocene boundary conditions described here and run to equilibrium. Each CAM-CLM experiment is run for 75 yr with the mean of the past 30 yr used for analysis. We utilize a Student's T-test to establish statistical significance of the changes and focus our discussion on features that are significant to >95%.

Apparent increases in global chemical weathering and erosion indicate a correlation between warm Miocene climate and CO_2 (Wan et al., 2009). Leaf stomata indices also suggest that CO_2 was significantly higher than present during the Miocene (Kürschner et al., 2008). However, alkenone-based proxies indicate that CO_2 was lower than present (Pagani et al., 1999). Given the equivocal evidence for Miocene CO_2, we compare MIO to a second experiment with doubled CO_2 (710 ppmv, called 2xCO2). To constrain the upper and lower error introduced by inaccuracies in our vegetation, we compare MIO with two additional experiments applying altered Australian vegetation. In one experiment, C_3 grassland is prescribed to the entire continent (GRASS). In the other, broadleaf evergreen vegetation is prescribed (TROPICAL). Finally, we test the effect of an inland moisture source on monsoon climate by prescribing four grid cells in central Australia as wetland (WETLAND; Fig. 1F). A modern-day experiment, with a CO_2 of 355 ppmv, is conducted for comparison (MODERN).

To define regions of monsoon climate we use the criteria of Zhang and Wang (2008), who classified a region monsoonal when (1) precipitation rate during summer, defined as November to March (NDJFM) in the Southern Hemisphere, exceeds 3 mm/day, and (2) the ratio of summer to annual precipitation is 55% or greater. Based on modern observations, this method compares well with previous definitions of the regional monsoons (Zhang and Wang, 2008).

As vegetation in CLM is fixed, to determine which CAM-CLM experiment supports a vegetation distribution most characteristic of the fossil flora we apply temperature, precipitation, and insolation data from each Miocene experiment to BIOME4 (using the anomaly procedure of Kaplan et al., 2003). BIOME4 is a biogeographical and biogeochemical vegetation model capable of predicting the distribution of 27 vegetation types for modern and paleoclimates (Kaplan et al., 2003). BIOME4 experiments are run at a 0.5° resolution.

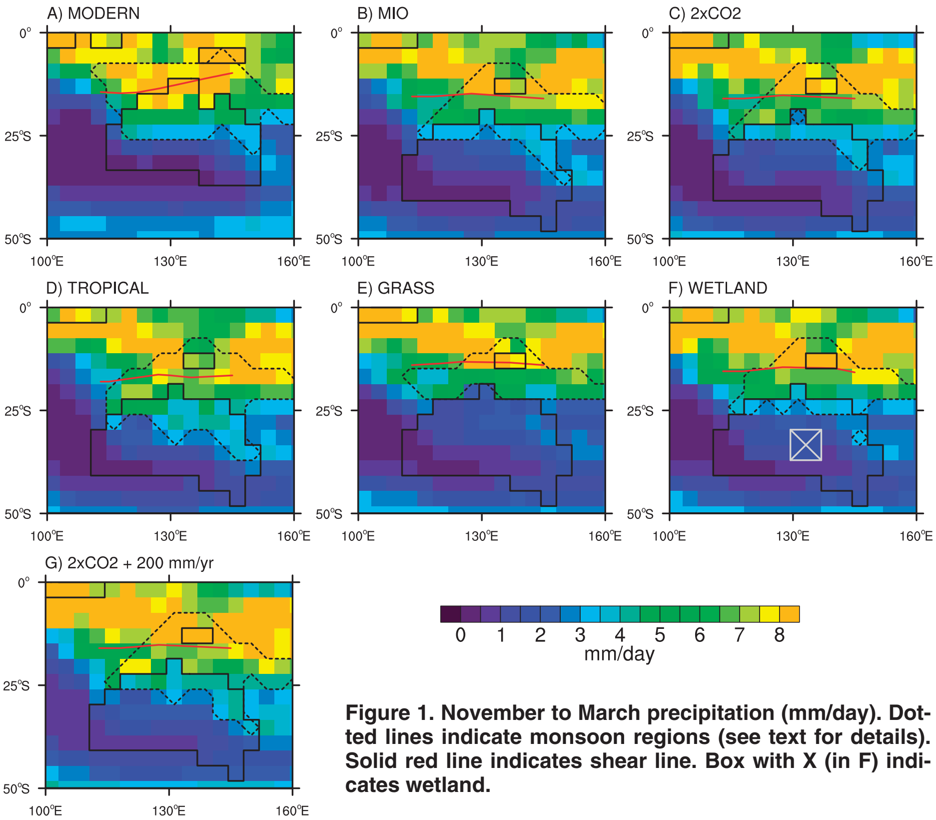

Figure 1. November to March precipitation (mm/day). Dotted lines indicate monsoon regions (see text for details). Solid red line indicates shear line. Box with X (in F) indicates wetland.

RESULTS

We first compare our control Miocene experiment (MIO) with Early to Middle Miocene proxy data (Table 1). MIO is drier and cooler than proxy values in southeastern Australia, though shows closer agreement with proxy values in central and north Australia. This suggests that the meridional temperature gradient in our model is too steep, a result ameliorated by an increase in CO_2.

The monsoon domain in MIO is limited to the northern fringe of Australia with an incursion down the east coast (Fig. 1B). This incursion extends farther south than present due in part to lower albedo vegetation in northeastern Australia in the Miocene compared to the present. Lower continental precipitation in MIO compared to MODERN is partly explained by the location of the shear line (defined by the zero contour of zonal wind; Fig. 1B). The shear line delineates the boundary between dry southerly winds and moisture-laden northerly winds. While Australia is 7.5° farther south in MIO compared to MODERN, the shear line is not offset as far, thus reducing continental precipitation.

The 2xCO2 experiment shows little change in shear line position and continental precipitation, and thus the monsoon domain is similar to MIO (Fig. 1C). The insensitivity of the shear line is consistent with simulations of the present-day monsoon (Suppiah, 1995).

Summer precipitation and monsoon domain increase considerably in TROPICAL compared with MIO (Fig. 1D). In GRASS, precipitation is reduced to <3 mm/day over the entire continent, resulting in a complete absence of monsoon conditions (Fig. 1E). WETLAND exhibits an increase in precipitation over southern Australia, though still remains below 3 mm/day. Conversely, precipitation decreases in northeastern Australia, reducing the monsoon domain compared with MIO (Fig. 1F).

Applying output from each Miocene experiment to BIOME4 produces vegetation distributions substantially drier than suggested by fossil flora (Figs. 2B–2F). Each distribution except that forced by output from 2xCO2 and TROPICAL sees tropical and warm-temperate forest contract toward the north and east coasts compared to the modern, replaced mostly with grassland and dry shrubland. Experiment 2xCO2 accommodates the warmest vegetation.

DISCUSSION

The monsoon domain exhibits a greater sensitivity to vegetation than to a doubling of CO_2 (Fig. 1). Comparing each Miocene experiment, summer precipitation and monsoon domain are greatest in TROPICAL. However, maximum summer precipitation in TROPICAL is still two-thirds that of MODERN. Mean annual precipitation (MAP) over central and north Australia is also lower in TROPICAL than MODERN. Thus

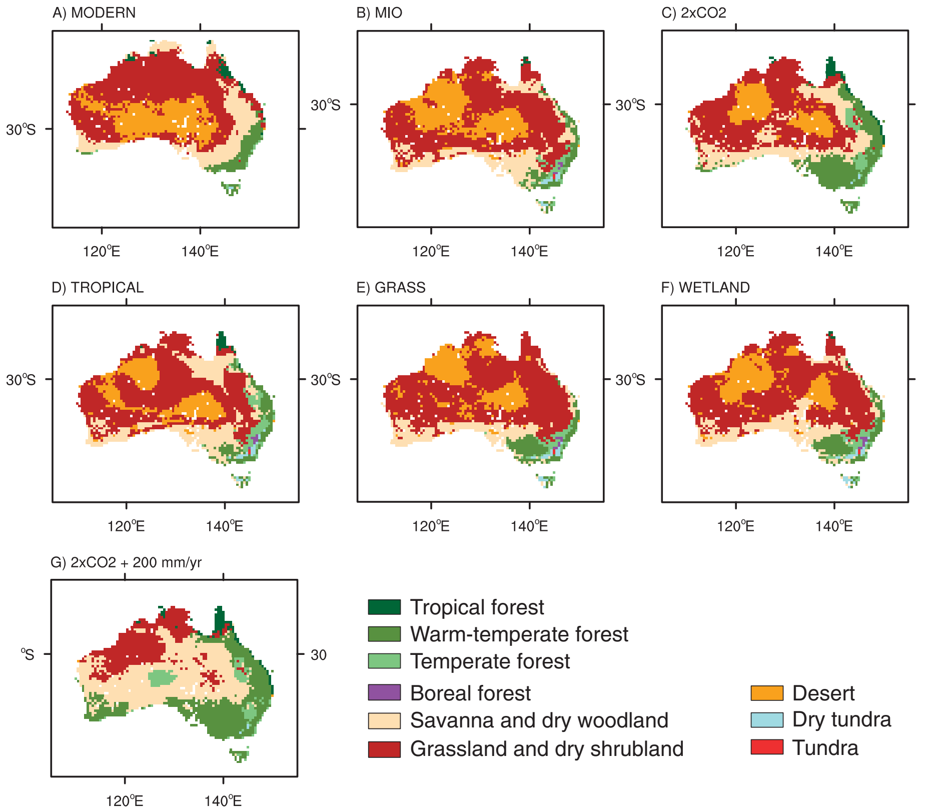

Figure 2. BIOME4 (see text) experiments forced with temperature, precipitation, and insolation data from each Community Atmosphere Model–Community Land Model experiment. MODERN is calculated using baseline climatology provided for BIOME4. To facilitate comparison, predicted biomes are reduced to nine simplified biomes (according to Harrison and Prentice, 2003).

none of our Miocene experiments are as wet as the modern day, making the vegetation mosaic interpreted from fossil flora difficult to explain.

The absence of a river and lake model in CAM-CLM may partly explain deficient precipitation in our Miocene experiments, as well as the vegetation mosaic interpreted from fossil flora and fauna. Several lines of evidence suggest that one or more inland water bodies of considerable size existed in central Australia (Benbow et al., 1995; Markwick, 2007; Martin, 2006; Quilty, 1994). More efficient drainage (Quilty, 1994) may have permitted precipitation in north Australia to sustain inland water bodies as well as riparian forests throughout the Lake Eyre catchment, removing the requirement for high local precipitation (Megirian et al., 2004). Wyrwoll and Valdes (2003) demonstrated that insolation-driven amplifications of the monsoon were associated with the formation of Pleistocene mega lakes in north Australia. However, the persistence of inland water bodies throughout the Early to Middle Miocene requires a longer period change. Features distinguishing Miocene geography from the present, mainly marine transgressions across the Murray and Eucla Basins (Langford et al., 1995), are not resolved in our model, and might have some impact. Nonetheless, our results show that the effect of inland moisture sources would have been local and insufficient to constitute a monsoon climate (Fig. 1F) or MAP greater than present. The assignment of broadleaf evergreen vegetation in TROPICAL can also be interpreted as an end-member result of infinitely efficient and widespread drainage, under which the monsoon domain expands significantly but still does not produce precipitation rates exceeding modern day rates. However, if forest was sustained mostly in riparian and lacustrine settings due to favorable drainage and geography (e.g., Alley, 1998; Megirian et al., 2004), then high precipitation may not have been necessary. Testing this hypothesis should be the subject of future work.

Experiment 2xCO2 accommodates vegetation distributions most consistent with fossil flora, supporting the view that extremely low CO_2 (Pagani et al., 1999) was not biologically conducive to Miocene vegetation (Cowling, 1999). Kaplan et al. (2003) observed a bias toward broadleaf vegetation at high latitudes in BIOME4; however, the overall dryness of the simulated vegetation (Fig. 2), as well as proxy records (Table 1), indicates that our CAM-CLM experiments underestimate precipitation. There is a 200 mm margin between the maximum 600 mm MAP reconstructed from fossil fauna at Kangaroo Well (Megirian et al., 2004) and the 400 mm simulated in 2xCO2. Similar margins of 100–200 mm/yr exist between our 2xCO2 experiment and proxy data at Dunsinane and Moranbah. These three locations offer the only quantitative estimates of MAP in central and north Australia. Additional modeling with BIOME4 shows that a continent-wide MAP increase of 200 mm to the 2xCO2 experiment, distributed evenly across each month, removes desert from central Australia. This allows savanna and dry woodland to dominate, though tropical forest remains absent from north Australia (Figs. 1G and 2G). This pattern is compatible with data suggesting that rainforest was restricted to lacustrine and riverine environments and that open forest or woodland dominated the interfluves (Alley, 1998; Guerin and Hill, 2006; Macphail, 2007; Megirian et al., 2004). An increase in MAP of 200 mm to each other Miocene experiment sees the continental interior dominated by grassland and dry shrubland (not shown), suggesting that elevated CO_2 was important for sustaining Miocene vegetation. Interestingly, we find that growth of tropical forest across north Australia comparable to previous interpretations (Archer et al., 1994; Wolfe, 1985) requires an increase in MAP of 700 mm in the 2xCO2 case; this is larger than available quantitative estimates and almost double the simulated precipitation. Interpretation of extensive rainforest in north Australia during the Miocene from fossil fauna may therefore be the result of preferential fossilization in riparian and lacustrine settings, as well as a broad definition of rainforest (Greenwood, 1996), and may not be representative of the wider environment.

CONCLUSIONS

While parts of far north Australia were likely monsoonal during the Miocene, our experiments suggest it is unlikely that the monsoon extended farther south than present. The model results in most cases seem to systematically produce precipitation values lower than required by paleoclimate proxies, matching recent results for the Eocene Arctic (Greenwood et al., 2010). Although the proxy records have their own uncertainties, if we assume that the error is primarily within the modeling we can estimate the magnitude of the modeling biases. Vegetation modeling indicates a dry bias in our simulations of ~200 mm/yr and requires doubled CO_2 concentrations to support reconstructed flora distributions including extensive savanna and woodland in central Australia. Conversely, widespread rainforest in north Australia is not supported without an arguably unrealistic increase in precipitation. This suggests that Miocene paleoflora was only viable under higher than modern CO_2 concentrations, consistent with leaf stomata indices (Kürschner et al., 2008), global climate modeling (You et al., 2009), and weathering and erosion rates (Wan et al., 2009). These results stress a need for high-resolution regional climate modeling explicitly incorporating paleodrainage and dynamic vegetation. Investigation into Miocene orbital dynamics, greater distribution of quantitative paleoclimate data, and an improved ability to distinguish fossil presence from dominance will also better constrain geological interpretations and future models.

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