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Orbital time-scale circulation controls of the Australian summer monsoon: a possible role for mid-latitude Southern Hemisphere forcing?

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ABSTRACT

Discussions of the Quaternary paleoclimatology of the northwestern Australian summer monsoon have emphasized inter-hemispheric forcing of the northern Australian summer monsoon by the East Asian winter monsoon. Here we draw on the results of general circulation model experiments to examine Southern Hemisphere circulation characteristics that controlled the Australian summer monsoon in response to Milankovitch insolation forcing. The experiments suggest that during tilt- and precession-driven Southern Hemisphere low-latitude insolation highs, the monsoon regime has the potential to be forced by inflow from the mid-latitudes of the Southern Hemisphere. To lend credence to the general circulation model results, we employ a simple force balance model to demonstrate the dynamics controlling Southern Hemisphere inflow into the monsoon region of northwestern Australia, and draw attention to work that suggests this mechanism may explain recent precipitation trends in the region. Our findings caution against drawing correlations of stratigraphic events in the East Asian – Australian monsoon records, without first having a full appreciation of the dynamics that controlled paleoclimate states.

1. Introduction

Quaternary paleoclimate evaluations of the controls of the Australian summer monsoon have emphasized forcing relationships between the East Asian and Australian monsoon regimes (Chappell and Syktus, 1996; Liu and Ding, 1998; An, 2000; Wyrwoll and Miller, 2001; Liu et al., 2003; Miller et al., 2005; Wyrwoll et al., 2007). In this scheme, the controlling influence of the East Asian winter monsoon on the Australian summer monsoon is achieved through outflow from the East Asian winter anticyclone (Siberian high pressure). The potential for such outflow is made apparent by the present-day Northern Hemisphere winter circulation over the East Asian – northern Australian region (Fig. 1). More specific support for a direct forcing relationship is offered by the role that Northern Hemisphere sourced 'cold-surges' (e.g. Lau and Chang, 1987; Ding and Sikka, 2006) play in triggering monsoon activity in northern Australia over synoptic time-scales (Suppiah and Wu, 1998). It is well known that such surges can lead to the flare-up of deep convection over the South China Sea and the maritime continent of the Indonesian sector (Compo et al., 1999; Carrera and Gyakum, 2007), and that this can be related to active periods of the Australian summer monsoon, especially during the onset phases (Suppiah, 1992; Suppiah and Wu, 1998).

Given these clear indications of the relationship between the East Asian winter monsoon and the Australian summer monsoon it should not be surprising that this relationship has found strong resonance in explanations of Quaternary paleomonsoon events (An, 2000; Magee et al., 2004; Miller et al., 2005), and could invite attempts to correlate stratigraphic events between the two monsoon regimes (An, 2000). What should not be overlooked, in using this mechanism to explain long-term trends, is that East Asian outflow ('cold-surges') is only one mechanism of a multi-faceted monsoon system which possesses a range of controls operating at both short and long time-scales (Gentilli, 1971; Davidson et al., 1983; McBride, 1987, 1998; Suppiah and Wu, 1998; Bowler et al., 2001; Liu et al., 2003; Chang et al., 2004; Hung and Yanai, 2004; Wheeler and McBride, 2005; Kim et al., 2006; Wyrwoll et al., 2007; Marshall and Lynch, 2008). Among these is the potential that the northern Australian summer monsoon may be forced by in-flow, not from the Northern Hemisphere, but from the mid-latitudes of the Southern Hemisphere (Davidson et al.,

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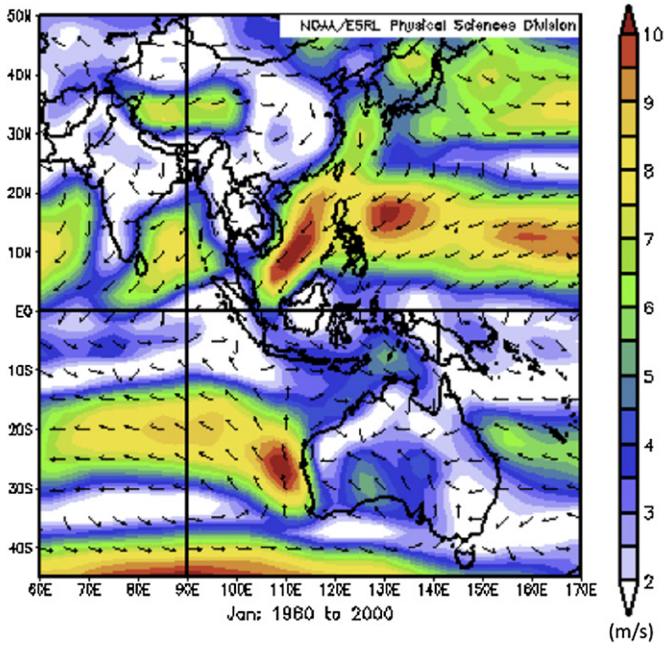

Fig. 1. Outflow from East Asia and from the mid-latitudes of the eastern Indian Ocean giving inflow into the monsoon region of northwestern Australia – composite mean January 1000 hPa vector winds (m/s) (NCEP/NCAR Reanalysis).

1983; Hung and Yanai, 2004) – see Fig. 1. In this paper we develop these claims, applicable to seasonal times scales, to advocate a possible role for mid-latitude Southern Hemisphere controls of the northern Australian summer monsoon over orbital time-scale precession-tilt forcing events.

2. The Australian summer monsoon and the 'model' monsoon circulation during perihelion and tilt events

The Australian summer monsoon is part of the wider monsoon regime extending over much of the Indonesian – Papua New Guinea region north of the Australian continent. It is recognized as a major tropical heat source, being a primary region of latent heat release associated with the Southern Oscillation and the Madden–Julian Oscillation (McBride, 1998). The importance of the Madden–Julian Oscillation as a driver of the northwest Australian monsoon has not received much attention in the paleoclimate literature. This, despite the fact that it is a global-scale feature of the tropical atmosphere, taking the form of an enhanced convective system, that propagates eastwards over the Indian and western Pacific oceans, providing a major source of intra-seasonal rainfall for the monsoon regime of northwestern Australia (e.g. Wheeler et al., 2009). The seasonal cycle of monsoon events is characterized by the reversal in winds, with the summer monsoon onset of northern Australia related to the beginning of a sustained period of westerly winds, and the defined onset of the monsoon generally taking place during late December (Drosdowsky, 1996). The onset coincides with the Intertropical Convergence Zone (ITCZ) located south of the Equator and strong convective activity over northern Australia. It is customary to describe the northern Australian monsoon season as being characterized by "burst" (active) and "break" (inactive) events with some burst events clearly related to the outflow of cold surges from East Asia (Suppiah and Wu, 1998). More limited attention is given to the likely significance of inflow associated with intrusion of mid-latitude troughs (but see: McBride, 1987 and Hung and Yanai, 2004).

In the Quaternary paleoclimate literature there have traditionally been questions about the sensitivity of the Australian monsoon regime to Milankovitch insolation controls (COHMAP, 1988). This is not surprising given the relatively small size of the continent and the absence of an elevated heat source, with sensible heating only observed below 750 hPa (e.g. Hung and Yanai, 2004). But with the results of more recent Atmosphere Ocean General Circulation Model (AOGCM) sensitivity experiments, it is clear that the Australian monsoon regime is forced by insolation changes incident on precession and tilt events (Wyrwoll et al., 2007; Marshall and Lynch, 2008).

For our present objectives we initially use the results of an experiment using NCAR Community Climate Model (CCSM3), a global fully coupled climate model with no flux adjustments, to establish likely Southern Hemisphere mid-latitude forcing of the northern Australian summer monsoon over orbital time-scales. The atmospheric model is the NCAR Community Atmosphere Model Version 3 (CAM3), which is a three-dimensional primitive equation model solved with the spectral method in the horizontal (Collins et al., 2006). The Ocean model is the NCAR implementation of the Parallel Ocean Program (POP) and is a three-dimensional primitive equation model in spherical polar coordinates with dipole grid and vertical Z coordinate (Gent et al., 2006). The sea ice model is a dynamic-thermodynamic model, which includes a sub-grid-scale ice thickness parameterization (Briegleb et al., 2004). The land model includes a river routing scheme and specified land cover and plant functional type (Dickinson et al., 2006). The coupled CCSM3 simulations discussed in this paper are at T31 atmosphere-land grid (and equivalent grid spacing of approximately 3.75° in latitude and longitude, 26 levels in vertical) coupled with the X3 ocean-sea ice grid (100×116 points and 25 levels to 5-km depth).

In determining the model Australian summer monsoon response to Milankovitch insolation variations, changes in tilt and precession were specified. The changes used in the simulation experiments are provided in Table 1. The January–March precipitation and associated surface wind field changes are shown in Fig. 2. In this figure we have separated the effect of precession and tilt. In the experiments, Southern Hemisphere precession (PS) with tilt either high (PS–PN)TH or low (PS–PN)TL, results in a significant increase in the daily rate of precipitation over the monsoon region of northern Australia. In the case of Northern Hemisphere precession (PN), with tilt high (TH–TL)PN, an increase in precipitation over the monsoon region of northwestern Australia remains evident. The case of the three simulation results (Fig. 2a–c) all show a strong Southern Hemisphere sourced mid-latitude flow – emanating from south of Australia and flowing along the western margin of the continent, and then trending into the monsoon region of the northwest of Australia. These strong flows coincide with: (i) Southern Hemisphere perihelion and (ii) high tilt – with both these orbital configurations corresponding with increased precipitation over the monsoon region of northwestern Australia. It is noteworthy that, in these model domains, the Southern Hemisphere inflow is noticeably stronger than that sourced from East Asia.

These results parallel the outcome of a previous AGCM experiment, using the HadAM3 version of the U.K. Meteorological Office's

Table 1
Experimental design – orbital configurations for model experiments.

Experiment		Perihelion	Tilt (°)
Precession North	Tilt High	June 15	24.45
Precession South	Tilt High	December 15	24.45
Precession North	Tilt Low	June 15	22.45
Precession South	Tilt Low	December 15	22.40

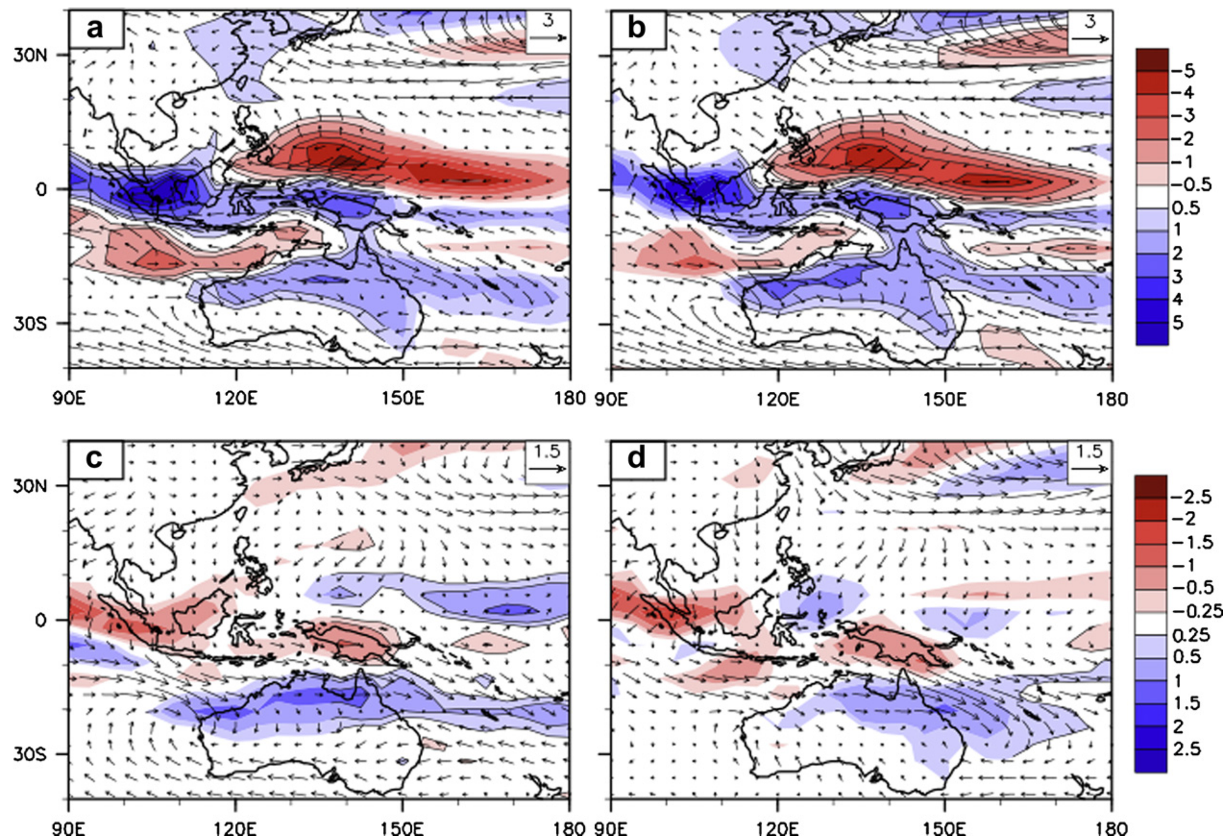

Fig. 2. January–February–March precipitation (mm/day) and surface winds: (a) (PS–PN)TH; (b) (PS–PN)TL; (c) (TH–TL)PN; (d) (TH–TL)PS.

Unified Model (for details, see Wyrwoll and Valdes, 2003). The sensitivity experiment used present-day boundary conditions (sea-surface temperatures, sea-level, CO_2, ice volumes) with insolation values set at 115 Ka, during which the low latitudes of the Southern Hemisphere saw elevated insolation levels associated with a Southern Hemisphere perihelion (see Wyrwoll and Valdes, 2003 for details). The simulation, while clearly limited in its veracity, by amounting to no more than an insolation sensitivity experiment, also shows that significant March precipitation increase is matched by strong Southern Hemisphere sourced inflow over northwestern Australia.

3. Analytical model of the dynamics of Southern Hemisphere inflow into the summer monsoon region of northwestern Australia

The model mean-flow fields, with the south-north flow paralleling the western margins of the continent being very prominent, draw attention to the claims of Davidson et al. (1983) of a triggering of monsoon "blow-up" through surges of low-level southerly winds that parallel the western margin of the continent. While the circulation envisaged by this mechanism resembles simulation results, the stumbling block in this analogy is that Davidson et al. (1983) are concerned with intra-seasonal "break" and "burst" time-scales, while our simulation results capture a 'mean' seasonal monsoon state. Furthermore, it should be remembered that Davidson et al. (1983) note, and reinforced by McBride (1987), that the surge associated with anticyclonicity provides the function of a trigger that acts only once more planetary-scale factors have built up a "stage where the troposphere is in a state of readiness for the monsoon onset" (McBride, 1987 p. 217). For our purposes, this translates into a claim that the Australian summer monsoon over orbital-time scales is forced by a combination of controls, of which inflow from the mid-latitudes of the Southern Hemisphere was an important element controlling the strength of the Australian summer monsoon.

It is fairly straightforward to demonstrate that the southerly sourced inflow into the monsoon region of northwestern Australia is a reflection of the relative importance of the pressure gradients and the Coriolis force. Consider the trajectory of an air parcel in a two-dimensional flow in a constant (in time and space) pressure gradient field. Let the velocity of the parcel at time t be $U(x,y,t) = (u(X,Y), v(X,Y))$ where $X(t)$ and $Y(t)$ are the eastward and northward displacements of the parcel at time t. Let the pressure gradient be (P_x, P_y), then the equations of motion are:

$$\begin{aligned} \frac{Du}{Dt} + vf &= -P_x \\ \frac{Dv}{Dt} - uf &= -P_y \end{aligned} \tag{1}$$

with the Coriolis parameter $f = f_0 - \beta Y(t)$, using a β plane approximation. We expect the flow to be largely determined by the pressure gradient and f_0, with relatively small variations due to the beta effect, so we look for solutions of the form:

$$\begin{aligned} u &= u_0 + \beta u_1 \\ v &= v_0 + \beta v_1 \end{aligned}$$

with initial conditions $X(0) = Y(0) = 0$; $u(0,0) = U, v(0,0) = V$. Substitution in Equation (1) and collection of the zero-order terms in Equation (1) yields the following system of equations, written in matrix form as:

$$\begin{pmatrix} u_0 \\ v_0 \end{pmatrix}' = f_0 \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} + \begin{pmatrix} f_0 u_g \\ -f_0 v_g \end{pmatrix}$$

where (u_g, v_g) is the geostrophic wind corresponding to the pressure gradient at the initial position (i.e. $f = f_0$). Solution of this system for (u_0, v_0) followed by an integration with respect to time, and application of the initial condition, provides the following expression for the zero-order displacements:

$$\begin{pmatrix} X_0(t) \\ Y_0(t) \end{pmatrix} = \begin{pmatrix} u_g t \\ v_g t \end{pmatrix} + \frac{1}{f} \begin{pmatrix} (U - u_g)\sin ft + (V - v_g)(\cos ft - 1) \\ (V - v_g)\sin ft + (U - u_g)(1 - \cos ft) \end{pmatrix} \tag{2}$$

As might be expected, this represents geostrophic motion plus inertial oscillations with amplitude proportional to the initial departure from geostrophic balance. For simplicity in illustrating the mechanism, we now assume that $U = u, V = v$, so that the inertial oscillations vanish. Collection of first-order terms produces the system:

$$\begin{pmatrix} u_1 \\ v_1 \end{pmatrix}' = f_0 \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} u_1 \\ v_1 \end{pmatrix} + Y \begin{pmatrix} v_0 \\ -u_g \end{pmatrix} \tag{3}$$

Solutions of Equation (3) and integration as before show that the first-order correction to the displacements are:

$$\begin{pmatrix} X_1(t) \\ Y_1(t) \end{pmatrix} = \begin{pmatrix} \dfrac{v_g^2 t}{f_0^2} + \dfrac{u_g v_g t^2}{2f_0} - \dfrac{u_g v_g}{f_0^3} - \dfrac{v_g^2}{f_0}\sin ft + \dfrac{u_g v_g \cos ft}{f_0^3} \\ \dfrac{-u_g v_g t}{f_0^2} + \dfrac{v_g^2 t^2}{2f_0} - \dfrac{v_g^2}{f_0^3} + \dfrac{v_g^2}{f_0^3}\cos ft + \dfrac{u_g v_g \sin ft}{f_0^3} \end{pmatrix}$$

The significant feature of this solution is the quadratic dependence on ug and vg, and hence the pressure gradient. This implies that an increased pressure gradient will have a relatively larger effect on the first-order components of the flow than on the main zero-order component. We illustrate this effect with a numerical example, comparing the displacements of two parcels initially at latitude 10°S and 25°S respectively, under two pressure gradient fields. For purposes of illustrating the effect we again ignore purely oscillatory terms. Table 2 summarizes the results of the calculation.

The same results are shown in Fig. 3, from which it is evident that although an increase in the forcing pressure gradient, such as might be produced by increased land heating during a time of increased insolation, produces longer trajectories in a given time period for air parcels both to the north and the south of the low centre, the Coriolis effect deflects the flow in both cases equatorwards, so that inflow is increased from the south but decreased from the north. In short, an increase in the intensity of the heated region in a latitude band where the Coriolis effect is not insignificant may be expected to result in an increased inflow from poleward but not from equatorwards. We qualify these claims by drawing attention to the idealized nature of the discussion, and are fully cognizant of the fact that a wide range of other factors need to be introduced in a more realistic and complete discussion of the controls of the inflow into the monsoon region of northwestern Australia.

Table 2
Summary results of a comparison of the displacements of two parcels of air after 12 h, located initially at 10°S and 25°S respectively, under two pressure gradient fields. Note that (u_g, v_g) is taken as a proxy for pressure.

	(u_g, v_g)	X_0 (12) km(h)	βX_1 (12) km(h)	Y_0 (12) km(h)	βY_1 (12) km(h)	X (12) km(h)	Y (12) km(h)
10°S							
$f = 0.0909$	(19,19)	222	56	−222	19	278	−204
$\beta = 0.0015$	(37,37)	444	228	−444	102	704	−343
25°S							
$f = 0.2212$	(19,19)	−222	30	222	24	−193	246
$\beta = 0.0014$	(37,37)	−444	117	−444	93	−328	537

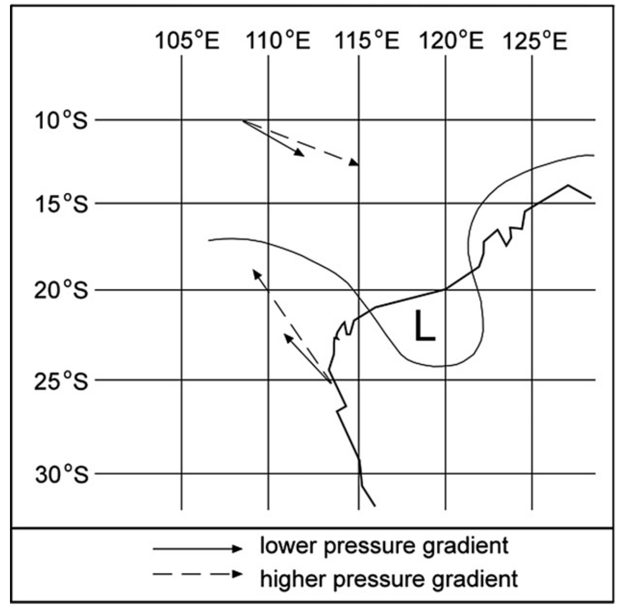

Fig. 3. Displacements of two parcels of air after 12 h, located initially at 10°S and 25°S respectively, under two pressure gradient fields (see Table 2 for summary of the calculation results).

4. Discussion

In light of the emphasis that is generally placed on the relationship between the Australian and East Asian monsoon regimes over Quaternary time scales, the prominence that Southern Hemisphere sourced inflow plays is noteworthy. From the results of the AOGCM experiment and the analytical model presented in this study, it would seem likely that mid-latitude Southern Hemisphere inflow into the monsoon region of northwestern Australia can, with the right conditions, be an important mechanism determining the strength of the monsoon over Quaternary time scales. The mechanism we propose finds resonance in the work of Hung and Yanai (2004) who demonstrate that a strong Southern Hemisphere inflow is a prominent feature of the present-day circulation of the Australian summer monsoon, with the pattern taking a form very similar to that evident in our AOGCM results. In their analysis they recognize that prior to the onset of the monsoon over northwestern Australia, a mid-latitude trough extends along the western coast of Australia. With the trough moving inland, a cyclone develops in the western part of Australia. This leads to the general flow structure of the Australian monsoon, with a monsoon low over northern Australia, and anticyclones located over the western and eastern sides of the Australian continent, giving rise to the characteristic westerly inflow and with it, the onset of the monsoon. The Madden–Julian Oscillation can also play an important role in providing a westerly inflow into the monsoon region of northwestern Australia and with it, deep convection over the monsoon region (Hung and Yanai, 2004; Wheeler and McBride, 2005).

In the overall scheme of monsoon controls, sensible heating over the Australian continent has to be seen as **the** 'priming'

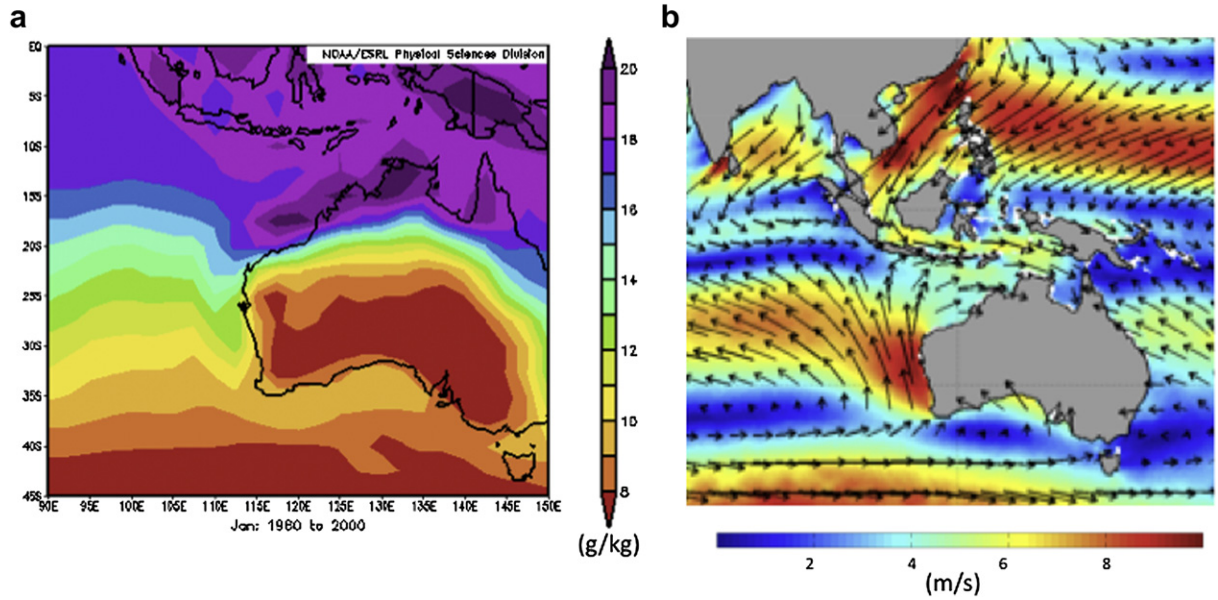

Fig. 4. (a) Present day 1000 hPa composite mean specific humidity (g/kg) – NCEP/NCAR Reanalysis; and (b) Scatterometer Climatology of Ocean Winds (SCOW) vector averaged wind speed (m/s) and direction (http://cioss.coas.oregonstate.edu/scow/).

mechanism of monsoon activity (Hung and Yanai, 2004; Kullgren and Kim, 2006). Despite sensible heating over the Australian continental monsoon region being restricted to levels below 750 hPa (Hung and Yanai, 2004), the Australian continent clearly does provide a significant sensible heat source, which has the potential to be strengthened by increases in Milankovitch driven insolation changes – providing a forcing component of the paleomonsoon regime (Wyrwoll and Valdes, 2003; Wyrwoll et al., 2007; Marshall and Lynch, 2008). The increased heating of the Australian continent would lead to an enhanced ocean-land contrast, which when coupled to the increased south-north pressure gradient, results in a south-north circulation that transports low-level moist air inland to intensify the monsoon circulation over northwestern Australia.

There are clearly questions that can be raised as to the appropriateness of relating a precession-driven Milankovitch climate-state to an intra-seasonal mechanism that triggers summer monsoon events. However, the argument can be firmed because present-day seasonal climate states also draw attention to the likely importance of south-north flow to the northwest Australian monsoon. Fig. 4a shows specific humidity over the northeastern Indian Ocean during January, with elevated moisture levels extending southwards from the northwest monsoon region. Linking this to the present-day surface wind field (Fig. 4b) makes it evident that the southerly flow advects moisture into the monsoon region of northwestern Australia. A further consideration results from the fact that a significant part of the southerly flow follows a Coriolis driven path into the subtropical Indian Ocean. From the work of Shi et al. (2008), in which observational precipitation trends were linked to coupled climate modeling studies, it is clear that such a flow is conducive to stronger westerly inflow into the summer monsoon region of northwestern Australia and increased precipitation rates. This mechanism is thought to account for a large part of the circa 50% increase in precipitation that has occurred over northwestern Australia in the last 50 years. Similarly, with precession-tilt changes driving stronger southerly inflow from the mid-latitudes of the Southern Hemisphere, a stronger northwest Australian summer monsoon should have occurred.

5. Conclusions

The general circulation model experiments and the related analytical results, linked to the explanations of the observational precipitation trends, make it clear that a stronger Southern Hemisphere low latitude–mid latitude pressure gradient, may have been a control of the strength of the summer monsoon in northwestern Australia. With a strong south–north circulation pattern in the eastern Indian Ocean, enhancing moisture inflow into the northwest Australian monsoon region, increased monsoon precipitation should be expected. The arguments based on the model results should be taken to act as a prompt to further examine these issues, but also provide an awareness of the multi-faceted nature of the paleoclimatology of the Australian summer monsoon regime. With this recognition comes the appreciation of the possibility of equifinality of forcing mechanisms, in which monsoon events may result from a suite of controls of the Australian summer monsoon – stressing the importance of giving due consideration to the dynamics that controlled paleomonsoon events before correlating events from apparently linked stratigraphic records.

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