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# Transient coupling relationships of the Holocene Australian monsoon

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ABSTRACT

The northwest Australian summer monsoon owes a notable degree of its interannual variability to interactions with other regional monsoon systems. Therefore, changes in the nature of these relationships may contribute to variability in monsoon strength over longer time scales. Previous attempts to evaluate how proxy records from the Indonesian–Australian monsoon region correspond to other records from the Indian and East Asian monsoon regions, as well as to El Niño-related proxy records, have been qualitative, relying on 'curve-fitting' methods. Here, we seek a quantitative approach for identifying coupling relationships between paleoclimate proxy records, employing statistical techniques to compute the interdependence of two paleoclimate time series. We verify the use of complex networks to identify coupling relationships between modern climate indices. This method is then extended to a set of paleoclimate proxy records from the Asian, Australasian and South American regions spanning the past 9000 years. The resulting networks demonstrate the existence of coupling relationships between regional monsoon systems on millennial time scales, but also highlight the transient nature of teleconnections during this period. In the context of the northwest Australian summer monsoon, we recognise a shift in coupling relationships from strong interhemispheric links with East Asian and ITCZ-related proxy records in the mid-Holocene to significantly weaker coupling in the later Holocene. Although the identified links cannot explain the underlying physical processes leading to coupling between regional monsoon systems, this method provides a step towards understanding the role that changes in teleconnections play in millennial-to orbital-scale climate variability.



## 1. Introduction

The northwest Australian summer monsoon, and the related circulation over the Maritime Continent (i.e. the Indonesian–Australian summer monsoon – IASM), is a critical feature of the global low latitude circulation. It provides a global heat source, and is the primary region of latent heat release associated with both the Southern Oscillation and the Madden–Julien Oscillation (MJO; McBride, 1998; Hung and Yanai, 2004). Despite its importance, the Australian summer monsoon, occurring over the northwest Kimberley region of Australia, is relatively shallow, with sensible heating only observed below 750 hPa (Hung and Yanai, 2004). Monsoon precipitation is relatively low, with annual November to April precipitation over northwestern Australia ranging from a mean of 1200 mm (Kimberley Coastal Camp; Bureau of Meteorology (2014b)) in the northwest, to 500 mm at the south (Jubilee Downs, Broome; Bureau of Meteorology (2014b)), over a distance of some 500 km. Such a relatively weak monsoon system, located at the southern margins of the more general IASM regime, should be sensitive to changes in forcing mechanisms acting at both the global and regional scale, and over short and long time scales.

While a range of considerations come into play (e.g. Chang et al., 1979; Hung and Yanai, 2004; Wheeler et al., 2009), the dominant control on the Australian summer monsoon relates to the controlling role of the thermal land–sea contrast that manifests itself in the heat lows that develop during the summer months. IASM strength is also tied to the latitudinal position of the Intertropical Convergence Zone (ITCZ), separating equator-ward easterlies from poleward westerlies. The monsoon regime is characterised by summer rainfall associated with low-level westerlies that extend from the equator to around 15° S. The position of these westerlies is associated with the monsoon trough, representing a broad zone of strong convective activity with generally westerly inflow and characterised by the occurrence of monsoon depressions and tropical cyclones, defining the southern edge of the IASM region. With the progression of the seasons there is a northward displacement of the

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ITCZ, such that by the boreal summer it is located well to the north of the Maritime Continent, and is now associated with the East Asian summer monsoon (Chen et al., 2004).

It is the onset of westerly flow which defines the Australian summer monsoon circulation, and ‘active’ monsoon phases are linked to the MJO, resulting in strong convective activity and precipitation over the monsoon region (Hung and Yanai, 2004; Wheeler et al., 2009). Interhemispheric interactions between the IASM and the Northern Hemisphere are provided by cold surges emanating directly out of the East Asian winter monsoon, and leading to strong convective activity in the South China Sea and over the wider IASM region (Chang et al., 1979). It has also been suggested that these cold surges may also be directed into the Arabian Sea, enhancing MJO activity (Wang et al., 2012a), which provides a link with the Northern Hemisphere. These relationships make it clear that the present IASM is driven by an ensemble of regional and global scale climate controls (e.g. Chang et al., 1979; Meehl, 1987; Hung et al., 2004; Wang et al., 2012a).

When considered over longer time scales, additional drivers at both the global and regional scale need to be introduced. Milankovich insolation forcing of global monsoon systems has been long recognised (e.g. Clemens et al., 1991; Bowler et al., 2001; Wang et al., 2008). Coupled ocean-atmospheric modelling studies have sought to explain the response of the northwest Australian monsoon to direct insolation forcing (Liu et al., 2003; Wyrwoll et al., 2007, 2012). These results suggest that although precession dominates changes in Northern Hemisphere monsoon strength, the Australian monsoon response is also significantly impacted by ocean temperature feedbacks (Liu et al., 2003) and tilt forcing (Wyrwoll et al., 2007). Liu et al. (2003) suggest that the enhanced Australian monsoon at 11,000 years BP, contrary to reduced summer insolation, is due to a combination of sea surface temperature feedbacks and inflows from a strong East Asian winter monsoon.

The interconnected nature of these coupling relationships provides evidence for the ‘global monsoon’ model as advocated in recent literature (Trenberth et al., 2000; Wang et al., 2009, 2012b, 2014). This concept has been advanced to portray monsoon activity as a single body of tropical convection migrating about the equator according to seasonal heating, and tied closely to the positioning of the ITCZ (Wang et al., 2009, 2014). Over longer time scales, a coherent response of regional monsoons to Milankovich insolation forcing is noted by Kutzbach et al. (2008). Using an accelerated transient simulation spanning 284,000 years, the authors display a positive response in regional monsoon systems to orbital forcing, with lead/lag relationships driven by local land and sea surface temperature feedbacks. As such, the global monsoon model has been extended to the paleoclimate context to describe this somewhat synchronous response to orbital forcing (Ziegler et al., 2010) as well as abrupt events such as the Heinrich Stadials (Cheng et al., 2012).

Here, we use complex network theory to analyse relationships between the northwest Australian summer monsoon, related monsoon systems and likely forcing climate states. We explore these relationships within the context of the ‘global monsoon’, and through this we seek to separate global, interconnected relationships and drivers from more local controls. Using this approach, we attempt to establish the changing nature of the dynamical coupling relationships of the Australian summer monsoon over Holocene time scales.

## 2. Methods

Complex network theory offers a method for identifying coupling relationships and long-range teleconnections by connecting ‘similar’ data sets. As such, it provides a suitable approach to assess interactions between monsoon systems within the context of the global monsoon (Donges et al., 2009). By defining a measure of similarity between climate time series, climate networks have been shown to provide insight into dynamical interactions beyond the scope of traditional statistical analysis (e.g. Donges et al., 2009, 2013; van der Mheen et al., 2013; Peron et al., 2014). Measures of similarity include linear cross-correlation, mutual information, and event synchronisation between extremes (Donges et al., 2009; Rehfeld and Kurths, 2014). Applying complex network methods to modern climate data is relatively straightforward, due to the availability of gridded datasets and high-density observation networks, but they also provide a powerful technique for analysing paleoclimate time series. This is demonstrated by Rehfeld et al. (2013) who developed a paleoclimate network of the Indian and East Asian summer monsoons covering the past 1100 years, demonstrating distinct changes in network structure between the Medieval Warm Period, Little Ice Age and present day. The application of these techniques is facilitated by the development of a Matlab toolbox (Rehfeld and Kurths, 2014; http://tocsy.pik-potsdam.de/nest.php). Here, we first construct a climate network using modern convective indices to demonstrate the veracity of complex network theory to identify dynamically-based coupling relationships between climate systems. We then develop a method for creating paleoclimate networks using a range of proxy records. The resulting paleoclimate networks identify linkages at the global and regional scale, and demonstrate the transient nature of coupling relationships of the northwest Australian monsoon region throughout the Holocene.

### 2.1. Data

Our main aim is to capture coupling relationships of the Holocene Australian summer monsoon, but we first test the suitability of complex networks to identify dynamically-based coupling relationships using modern climate data. Seasonal convective indices are constructed using monthly values for 1948–2013 of mid-tropospheric (500 mb) vertical velocity ($\omega$), a surrogate for convection (NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/; Kalnay et al., 1996). In order to capture only coupling between deep convection, such as that associated with the monsoon circulation, we extract only three months of data from each year: December to February (DJF) or June to August (JJA), setting the values for the other nine months to zero (Table 1). This data is averaged over the regions covering northwest Australia ($NWAus_{DJF}$), northeast Australia ($NEAus_{DJF}$), the Maritime Continent ($MC_{DJF}$), the western Indian Ocean ($IO_{DJF}$), the Indian summer monsoon region ($ISM_{JJA}$), the East Asian summer monsoon region ($EASM_{JJA}$), and the Eastern Equatorial Pacific ($EEP_{DJF}$). Note that the use of convective indices prevents the incorporation of the East Asian winter monsoon in our analysis. The East Asian winter monsoon is characterised by northerly winds driven by the Siberian High, causing cold surges outflowing over the South China Sea. There is some related convective activity in southern China, but insufficient to be captured by a convective-based index.

Following this, paleoclimate networks are produced for rolling 3000 year windows at millennial intervals over the period 9000 years BP to Present. We select proxy records (Table 2) within the broad Indian Ocean–Pacific region according to high temporal resolution and low age uncertainty, as per Rehfeld and Kurths (2014). Although one prefers a database comprised of a single proxy for reasons of comparability, one is often constrained by the number of proxy records available. We therefore combine speleothem (Dykoski et al., 2005; Fleitmann et al., 2007; Hu et al., 2008; van Breukelen et al., 2008; Griffiths et al., 2009; Dong et al., 2010;