Transient coupling relationships of the Holocene Australian monsoon

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Abstract

The modern-day northwest Australian summer monsoon is dynamically coupled to other regional monsoon systems and inflows from the Indian Ocean, however, the nature of these relationships over longer time scales is uncertain. 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, has 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 which correspond to physically-based mechanisms. This method is then extended to a set of paleoclimate proxy records from the Asian, Australasian and South American regions spanning the past 9,000 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 monsoon proxy records, as well as those possibly related to ITCZ positioning, 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.

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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]). But 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 November to April precipitation over northwestern Australia ranging from a mean annual of 1200mm (Kimberley Coastal Camp; Bureau of Meteorology [2014b]) in the northwest, to 500mm at the south (Jubilee Downs, Broome; Bureau of Meteorology [2014b]), over a distance of some 500km. 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. A primary control of IASM strength is the latitudinal position of the Intertropical Convergence Zone (ITCZ), separating equatorward westerlies from poleward easterlies. 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 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]. It seems likely that MJOs are ‘excited’ by cold surges from the East Asian winter monsoon directed into the Arabian Sea Wang et al. [2012a], which provides a link with the Northern Hemisphere. Additional inter-hemispheric 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]. 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], Mechl 1987, Hung et al. 2004, Wang et al. 2012).

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 inter-connected nature of some 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, 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 Kuzbacz 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 relationship and long-range teleconnections by connecting ‘similar’ data sets, and as such 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 theory 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 1,100 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

Table 1: Geographical regions used to create the modern convective indices

| Code      | Location                        | Lat/Lon Bounds       | Season |
|-----------|---------------------------------|----------------------|--------|
| NWAusDJF  | Northwest Australia             | 10-20°S; 115-140°W   | DJF    |
| NEAusDJF  | Northeast Australia             | 10-20°S; 140-150°W   | DJF    |
| MC_DJF    | Maritime Continent              | 5°N-10°S; 90-150°W   | DJF    |
| IO_DJF    | Western Indian Ocean            | 0-15°S; 45-60°W      | DJF    |
| ISM_JJA   | Indian summer monsoon region    | 5-25°N; 70-100°W     | JJA    |
| EASM_JJA  | East Asian summer monsoon region| 10-20°N; 100-120°W   | JJA    |
| EEP_DJF   | Eastern equatorial Pacific      | 0-10°N; 230-250°W    | DJF    |

While our main aim is to capture coupling relationships of the Holocene Australian summer monsoon, we first test the suitability of complex networks to identify dynamically-based coupling relationships using modern climate data. To achieve this, seasonal convective indices are constructed from monthly values for 1948-2013 of mid-tropospheric (500mb) vertical velocity ($\omega$) as 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 cou-
Figure 1: a) DJF 1981–2010 850mb winds and 500mb omega (NCEP Reanalysis). Also shown are the location of the boxes over which 500mb omega is averaged to produce modern convective indices, and the location of proxies. b) As above, for JJA.
Table 2: Proxy records in the paleoclimate network analysis

| Code | Location                        | Lat/Lon       | Proxy Type                | Reference                        | Average Time Step (years) |
|------|---------------------------------|---------------|---------------------------|----------------------------------|---------------------------|
| F07  | Qunf Cave, Oman                 | 17.17°N, 54.30°E | Speleotherm δ18O         | Fleitmann et al., 2007           | 7.7                       |
| M14  | Lonar Lake, India               | 19.98°N, 76.51°E | Multi-proxy               | Menzel et al., 2014              | 18.8                      |
| H08  | Heshang Cave, China             | 30.45°N, 100.42°E | Speleotherm δ18O         | Hu et al., 2008                  | 7.8                       |
| D05  | Dongge Cave, China              | 25.28°N, 108.08°E | Speleotherm δ18O         | Dykoski et al., 2005             | 14.7                      |
| Y07  | Lake Huguang Maar, China        | 21.15°N, 110.28°E | Ti concentration         | Yancheva et al., 2007            | 0.8                       |
| D10  | Sanbao Cave, China              | 31.67°N, 110.43°E | Speleotherm δ18O         | Dong et al., 2010                | 10.2                      |
| G09  | Liang Luar Cave, Indonesia      | 8.52°S, 120.43°E | Speleotherm δ18O         | Griffiths et al., 2009           | 10.1                      |
| D13  | Cave KNI-51, Australia          | 15.30°S, 128.62°E | Speleotherm δ18O         | Denniston et al., 2013           | 6.2                       |
| M02  | Laguna Pallacocha, Ecuador      | 2.77°S, 79.23°W  | Red colour intensity     | Moy et al., 2002                 | 0.8                       |
| vB08 | Cueva del Tigre Perdido, Peru   | 5.94°S, 77.31°W  | Speleotherm δ18O         | van Breukelen et al., 2008       | 19.4                      |
| H01  | Caricao Basin                   | 10.70°N, 65.17°W  | Ti concentration         | Haug et al., 2001                | 5.6                       |

Plugging 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 (NWAusDJF), northeast Australia (NEAusDJF), 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 3,000 year windows at millennial intervals over the period 9,000 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, and so we use a combination of speleothem [Fleitmann et al., 2007, Hu et al., Dykoski et al., 2005, Dong et al., 2010, Griffiths et al., 2009, Denniston et al., 2013, van Breukelen et al., 2008], titanium [Yancheva et al., 2007, Haug et al., 2001], sediment [Moy et al., 2002] and multi-proxy [Menzel et al., 2014] data sets. The IASM region is represented in the proxy record database by two speleothem records, G09 (Liang Luar, Flores; Griffiths et al. 2009) and D13 (Cave KNI-51, northwest Australia; Denniston et al. 2013), both of which are interpreted as capturing monsoon precipitation trends and variation. The Chinese speleothem δ18O records (D05, H08, D10)
have each been interpreted as a proxy for precipitation changes driven by the East Asian summer monsoon, while the Lake Huguang Maar record Yancheva et al. [2007] has been discussed in the context of the East Asian winter monsoon, which in turn is coupled to the IASM region in the modern climate through cold surges. We also include two widely used proxy records: the titanium concentration seties from the Cariaco basin (H01; Haug et al. [2001]) has been cited in studies in the context of Holocene ITCZ positioning, and the Laguna Pallacocha sediment record from Peru (M02; Moy et al. [2002]) is a very widely used proxy for changes in El Niño intensity and frequency over the last 12,000 years.

2.2 Constructing complex networks

Estimating correlations between paleoclimate records is fraught with difficulty, and therefore an intuitive qualitative curve-fitting approach is typically employed. We apply methods widely accepted by statistical physicists which have been successfully applied in the context of financial markets [Zhuang et al., 2014], solar activity [Zou et al., 2014], disease dynamics [Zhang et al., 2010; Wu et al., 2015; Li et al., 2015], and pigeon interactions in flight [Dieck Kattas et al., 2012; Xu et al., 2012]. In a climate or paleoclimate context, one may envisage such a network as a number of nodes, each corresponding to the site of a climate or paleoclimate data set. If a statistically significant ‘similarity’ between two data sets is found, then an edge is drawn between the two nodes. More formally, for a database of \( n \) time series, denoted \( X_i \), we may describe the set of nodes as

\[ V \subset \{ v_i : i \in [n] \} \]

and the set of edges is given by \( E \subset \{ e_{i,j} \} \) where \( e_{i,j} = 1 \) is \( X_i \) and \( X_j \) are found to be ‘similar’, and \( e_{i,j} = 0 \) otherwise. We define similarity between two time series, \( X_i \) and \( X_j \), by mutual information, a nonlinear, symmetric (and thus non-directional) measure of how much information is shared between the two time series. Mutual information, \( I(X_i, X_j) \) is given by:

\[
I(X_i, X_j) = \sum_{x_i \in X_i} \sum_{x_j \in X_j} p(x_i, x_j) \log \left( \frac{p(x_i, x_j)}{p(x_i)p(x_j)} \right)
\]

where \( p(x_i) \) is the probability mass function of random variable \( X_i \), and \( p(x_i, x_j) \) is the joint probability mass function of \( X_i \) and \( X_j \). Note that, if \( X_i \) and \( X_j \) are independent, \( p(x_i, x_j) = p(x_i)p(x_j) \), and hence mutual information is zero. If they are not independent, then the amount to which \( p(x_i, x_j) \) differs from the product \( p(x_i)p(x_j) \) provides a measure of the similarity of the two time series. We interpret this as a measure of coupling strength, with the information transfer between climate indices occurring through physical atmospheric flows and pressure-driven teleconnections. This measure is preferred over linear cross-correlation for its ability to capture nonlinear relationships; cross-correlation can produce spurious results for nonlinear time series [Kantz and Schreiber, 2003]. Similarly, the event synchronisation function has been used to quantify coupling between extreme events (e.g. Rehfeld and Kurths [2014]). However, this requires the use of only the data
beyond, say, the 90% percentile, which for these convective indices would provide only around 20 data points in each time series. Prior to estimation, the raw time series data is detrended using a Gaussian high-pass filter. For the modern climate indices, only the non-zero data points are detrended.

Paleoclimate time series are often distributed along irregular time intervals due to sampling constraints. To account for this, a Gaussian kernel is used to ‘match’ data in paired paleoclimate time series. [Rehfeld et al. 2011] demonstrate that this reduces bias in the resulting mutual information estimate compared to linear interpolation. We use the Matlab toolbox of [Rehfeld and Kurths 2014] to produce estimates of Gaussian kernel weighted mutual information, $I_G(X_i, X_j)$. This method does not produce symmetric estimates of $I_G$, so we define:

$$I_G(X_i, X_j) = \max(I_G(X_i, X_j), I_G(X_j, X_i))$$

The asymmetric estimates of $I_G$ do not imply directionality in the network, but are simply due to the unequal sampling rates of the two paleoclimate time series [Rehfeld et al., 2011].

Statistically significant coupling relationships are defined using a Monte Carlo simulation of 2000 networks. The simulated networks are based on the same original vertex set, $V$, but with each vertex now corresponding to a set of uncoupled random time series. The parameters (linear drift and constant diffusion) for these time series are estimated from the corresponding original (modern or paleoclimate) time series, $X_i$. We estimate these parameters through linear regression of the underlying time series. We then define a coupling relationship between two time series as being statistically significant based on the 95th percentile of mutual information estimates from the set of simulated networks. Only connections which are defined as statistically significant are displayed in the network. The Laguna Pallacocha record from Ecuador (M02, Moy et al. 2002), however, is not well suited to be modelled by Brownian motion. Instead, this time series is comprised of a number of large events which are registered well above a baseline level of near zero. We therefore introduce a Poisson process, to model the event time series defined by the 90% quantile in the Laguna Pallacocha record. This event time series is well approximated by a Poisson process ($\chi^2 = 1.85$, $p = 10.12$, at a 95% significance level).

Having constructed networks for the paleoclimate database (Table 2) at 3,000 year windows throughout the Holocene, we seek to evaluate changes in network density and structure. This may be attempted through a number of measures provided by graph theory [Newman 2010]. The degree, $d_i$, of a vertex, $v_i$, describes the number of edges incident to the vertex, providing a description of how coupled the time series at $v_i$ is to other records.
in the network. Similarly, the network average degree, \( d_n \), is given by:

\[
d_n = \frac{1}{n} \sum_{i=1}^{n} d_i
\]

This quantifies the total amount of coupling within the network. In addition to total network connectivity, we consider the degree distribution, the probability distribution of \( d_i \) across the network. This allows us to determine whether the modern climate or paleoclimate records are all coupled to a similar degree, or whether a few records in particular are more dominant, potentially driving the broader monsoon network. In addition, we compare the observed degree distribution with the one from a random network where any two nodes are connected with probability \( p = \frac{|E|}{|E_T|} \), where \( E_T \) gives the total number of possible edges. Note that this produces a binomial degree distribution, against which our observed degree distributions may be compared.

### 3 Testing complex networks using modern climate data

As the coupling relationships between modern regional climate systems are relatively well known, they provide a suitable control against which we evaluate the use of complex networks. Figure 2a displays the known dynamical mechanisms by which the Indian, East Asian and Indonesian-Australian monsoons interact. Note that, with the Indian and East Asian summer monsoons active in boreal summer (JJA), and the East Asian winter monsoon and Indonesia-Australian summer monsoon occurring in austral summer (DJF), some of these interactions occur with a seasonal lag.

In providing an explanation for the coupling relationships recognised in the ‘modern’ date, we initially appeal to Chiang’s [2009] framework for understanding the climate of the tropics. Chiang [2009] outlines two models of tropical circulation. At its most general, the climate of the topics is explained by the Hadley circulation and its response to seasonal heating. In this model, the migration of the ITCZ is primarily responsible for the distribution and timing of precipitation across the tropics. However, he notes that this simple explanation is only sufficient in an aquaplanet setting, and that the existence and location of land masses introduces regionality. It is within this second model that the regional monsoons are explained, asymmetries recognised, and the role of ENSO incorporated.

Figure 2a depicts the ITCZ positioning in boreal and austral summer, with convergence-driven convective activity located over India, southern China and northern South America in JJA, while in DJF the ITCZ sits south of the equator, bringing convective activity to the Indonesian-Australian region and the Indian Ocean stretching from Indonesia to the north tip of Madagascar. Interactions between different regional features are also depicted.
Figure 2: a) Recognised interactions within the Asian-Australasian monsoon systems. We note the northward (JJA) and southward (DJF) positioning of the ITCZ, as well as i) convective centre of the Bay of Bengal associated with the Indian summer monsoon, ii) northerly cold surges associated with the East Asian winter monsoon, iii) the Indo-Pacific Warm Pool, iv) the Niño 3.4 region, and v) the Madden-Julian Oscillation. b) Modern climate network. Nodes are located in the centre of the zonal averaging region given in Table 1. Linked nodes are considered to be coupled at the 95% significance level.
Outflows from the Bay of Bengal, associated with the Indian summer monsoon, are a key moisture source in the East Asian summer monsoon [Yihui and Chan, 2005]. The Bay of Bengal is also the point of origin of convective centres which are displaced southwards over a number of months towards the Indonesian-Australian monsoon region [Meehl, 1987]. [Hung et al., 2004] demonstrate a correlation between the Indian and Australian monsoon regions, but describe a “communication gap” between the two systems, with heavy (weak) Indian summer monsoon precipitation followed by heavy (weak) Australian monsoon precipitation. It is worth noting that this analysis combined the northwest and northeast of Australia into a single region, creating correlations with the El Niño-Southern Oscillation (ENSO) which are likely due to the impact of ENSO on tropical northeast Australia. The relationship between ENSO and the Indian [Krishnamurthy and Goswami, 2000] and East Asian [Wang et al., 2000] summer monsoons is well established. Shifts in both the Walker and Hadley cells caused by warm (cool) sea surface temperature anomalies in the eastern equatorial Pacific act to dampen (strengthen) the Indian summer monsoon, while El Niño events establish Rossby waves traveling towards China, setting up a region of anticyclonic circulation over the Philippine Sea and suppressing East Asian summer monsoon convection. Finally, the East Asian winter monsoon establishes northerly winds over China, producing irregular low-level surges of cool air which travel southwards across the South China Sea and into the Indonesian sector [Chang et al., 1979]. These surges are able to enhance convective activity, uplifting the already warm, moist air. A second outflow of cold air has been observed to travel westward, flowing to the north of the Tibetan Plateau before being deflected southwards and across the Arabian Sea. [Wang et al., 2012a] demonstrate that this influx of cool air excites the Madden-Julien Oscillation, thus acting as a secondary forcing mechanism on the Indonesian-Australian monsoon regime.

The mutual-information based climate network (Figure 2b) captures many of the interactions outlined above. Due to the fact that the convective indices incorporate only boreal summer East Asian region, we cannot capture any of the interactions involving the East Asian winter monsoon region. As noted in the methods section, this is intentional, as our ω-based indices cannot capture East Asian winter monsoon strength. The climate network, however, does miss two accepted coupling relationships. We expect a link to be observed between the east equatorial Pacific (EEP_{DJF}) and northeast Australia (NEAus_{DJF}). There are two possible reasons for not capturing this in our analysis; either the link is missing because the signal cannot be distinguished through the noise of the climate time series, or the box size of the northeast Australian region (cf Figure 1) might be unable to accurately capture regional precipitation using the NCEP/NCAR reanalysis. This is an issue which translates into the paleoclimate context directly, as many proxy records will not provide a ‘pure’ signal of monsoon-related precipitation, but rather capture a number of other climate and environmental changes.

The second link missing in the modern climate network is between the Maritime
Continent (MC$_{DJF}$) and northwest Australia (NWAus$_{DJF}$). Given that the Indonesian-Australian summer monsoon extends across both regions, a coupling relationship between the two time series would be expected. However, Haylock and McBride [2001] examine DJF rainfall measured at 63 stations across Indonesia, demonstrating limited spatial coherence across the region, with no single forcing mechanism or predictor of wet season precipitation. As such, averaging DJF convective activity across the region is unlikely to produce an index which can be interpreted easily in the context of coupling relationships with other convective indices.

Despite the two network links we do not observe, we have confidence in the ability of complex networks to capture coupling relationships between climate signals. The fact that no coupling relationships were identified by the climate network which do not correspond to any understood dynamical relationship further supports this, and validates the decision to produce networks based on mutual information. The spurious values which can arise when estimating cross-correlation between non-linear time series could lead to coupling relationships being identified which have no physical basis.

4 Coupling relationships of the Australian summer monsoon over the last 9,000 years

The Holocene combines, among other things, a period of changing solar insolation forcing, sea surface temperature feedbacks, and changes in land extent following the last deglaciation (cf. Lambeck and Nakada [1990], Liu et al. [2003], Jansen et al. [2008]). From these conditions alone, we can expect changes in coupling relationships and teleconnections between regional monsoon systems. This can be formally demonstrated using complex network analysis, the validity of which we have demonstrated in the context of the modern climate. We produce paleoclimate networks at 3,000 year windows from 9,000 yrs BP to Present. Each edge in the paleoclimate networks (Figure 3) identifies a statistically significant amount of information shared between two paleoclimate proxy records, and we interpret this as a dynamic coupling relationship between the two regional climate regimes. As such, the degree of connectivity within the network may be considered in the context of the collective behaviour of regional monsoon systems during the Holocene. Clearly, our focus is on the Australian summer monsoon, consequently we emphasise nodes G09 and D13 (corresponding to Liang Luar, Flores, Indonesia: Griffiths et al. [2009], and Cave KNI-51, northwest Australia: Denniston et al. [2013]), to enable us to draw inferences regarding the coupling relationships of the Indonesian-Australian monsoon regime.
4.1 Overall trends in network relationships

The paleoclimate networks are observed to grow increasingly connected from 9,000-6,000 yrs BP to 6,000-3,000 yrs BP, and then decline steadily into the latest Holocene (Figure 3). In particular, the nodes corresponding to proxies from the vertices H01 (Cariaco Basin; Haug et al. [2001]), M02 (Laguna Pallacocha, Ecuador; Moy et al. [2002]), vB08 (Cueva del Tigre Perdido, Peru; van Breukelen et al. [2008]), and Y07 (Lake Huguang Maar, China; Yancheva et al. [2007]) display high degree throughout the mid-Holocene, while only M02 is seen to be highly coupled in the later Holocene. We quantify total network connectivity through the average network degree. This highlights a shift towards vertices of higher degree until 6,000 to 3,000 yrs BP, followed by a return to vertices of lower degree (Figure 4). To determine if the coupling relationships are evenly distributed across the network we compare the observed degree distribution for each 3,000 year window with the one of a random graph. This random graph has the same number of nodes and edges as the observed network. For the periods 8,000-5,000 yrs BP through to 6,000-3,000 yrs BP, the paleoclimate networks are skewed, with some nodes having significantly higher degree than might be expected (Figure 4). In the early (9,000-6,000 yrs BP) and later (5,000-2,000 yrs BP to 3,000-0 yrs BP) Holocene the networks more closely resemble the degree distributions for a random graph (Figure 4). The only outlier in the later Holocene is the Laguna Pallacocha record (M02; Moy et al. [2002]), which maintains a degree of 9 or 10 despite an average network degree of less than 5.

4.2 Coupling relationships of the IASM region

The proxy records within the Indonesian-Australian monsoon region are G09 and D13, speleothem δ¹⁸O records located in Indonesia and northwest Australia respectively [Griffiths et al., 2009, Denniston et al., 2013]. Both records have been interpreted as indicators of monsoon-dependent precipitation, yet no connection between the two time series is identified in the paleoclimate networks (Figure 3). Other paleoclimate proxy records from the region include speleothem δ¹⁸O data from Gundung Buda, Borneo [Partin et al., 2007] and a sediment core from offshore Sumba island, Indonesia [Steinke et al., 2014]. Neither dataset fits the criteria for inclusion in the paleoclimate network analysis, but plotting the time series (Figure 5) indicates significant internal heterogeneity within the Indonesian-Australian monsoon region, particularly from 6,000 years BP onwards. Given the lack of spatial coherence observed in the modern day IASM region [Haylock and McBride, 2001], the lack of coupling between the Liang Luar (G09; Griffiths et al. [2009]) and Cave KNI-51 (D13; Denniston et al. [2013]) records is not surprising.

Despite the differences between the Liang Luar (G09; Griffiths et al. [2009]) and Cave KNI-51 (D13; Denniston et al. [2013]) records, they display similar coupling relationships
Figure 3: Paleoclimate networks for a) 9,000-6,000 yrs BP, b) 8,000-5,000 yrs BP, c) 7,000-4,000 yrs BP, d) 6,000-3,000 yrs BP, e) 5,000-2,000 yrs BP, f) 4,000-1,000 yrs BP, g) 3,000-0 yrs BP.
Figure 4: a) Network average degree; b-h) Degree distributions for observed paleoclimate network (grey) and those of a random graph with the same number of edges (black).
Figure 5: Holocene proxy records from the Indonesian-Australian monsoon region. a) speleothem $\delta^{18}$O record from Cave KNI-51, northwest Australia (D13; Denniston et al. [2013]), b) speleothem $\delta^{18}$O record from Flores, Indonesia (G09; Griffiths et al. [2009]), c) speleothem $\delta^{18}$O record from Gundung Buda, Borneo (Partin et al. 2007), d) sediment record from offshore Sumba Island, Indonesia (Steinke et al. 2014).
with other, non-IASM proxies (Figure 3). From 9,000-6,000 yrs BP to 4,000-1,000 yrs BP, these two records are coupled (with some inconsistency over time) to number of records forming a belt from the Arabian Peninsula to South America: Qunf Cave, Oman (F09; Fleitmann et al. [2007]), Lonar Lake, India (M14; Menzel et al. [2014]), Lake Huguang Maar, southern China (Y07; Yancheva et al. [2007]), Cueva del Perdido, Peru (vB08; van Breukelen et al. [2008]), and Cariaco Basin (H01; Haug et al. [2001]). There is, additionally, some coupling between records in the Indonesian-Australian and East Asian summer monsoon regions from 6,000-3,000 yrs BP to 5,000-2,000 yrs BP. However, in the latest Holocene (3,000-0 yrs BP), the only record which both Liang Luar (G09; Griffiths et al. [2009]) and Cave KNI-51 (D13; Denniston et al. [2013]) are connected to is the Laguna Pallacocha record from Ecuador (M02; Moy et al. [2002]).

4.3 Interpretation of IASM coupling relationships of the last 9,000 years

The paleoclimate proxy records from Oman, India, southern China, Peru and Cariaco Basin have each been interpreted in the context of ITCZ positioning. The titanium concentration time series from Cariaco basin (H01; Haug et al. [2001]) and the speleothem oxygen isotope composition in Cueva del Tigre Perdido, Peru (vB08; van Breukelen et al. [2008]) are dependent on the position of the ITCZ during boreal winter [Haug et al., 2001]. The Lake Huguang Maar sediment record in southern China (Y07) is interpreted as a proxy for the East Asian winter monsoon strength, determined over millennial scales by the position of the ITCZ [Yancheva et al., 2007]. Menzel et al. [2014] developed a bioclastic climate index for Lonar Lake in central India. While the Lonar Lake record is not explicitly interpreted as an indicator of ITCZ positioning, the early Holocene Indian summer monsoon strength is tied to ITCZ migration [Menzel et al., 2014]. Finally, Qunf cave in southern Oman (F09; Fleitmann et al. [2007]) is situated at the southern edge of the modern position of the ITCZ in boreal summer. A northwards shift of the ITCZ causes southwesterly flow associated with the Indian summer monsoon to extend over the lower tip of the Arabian Peninsula, lifting the local temperature inversion and triggering deep convective precipitation. The coupling relationships identified between F09 and M14 from 9,000 to 4,000 years BP (Figure 3a-c) therefore support a northerly positioning of the ITCZ, as expected under a Northern Hemisphere precessional bias. At the same time, the monsoon region of Indonesia and northwest Australia experiences a weak but strengthening monsoon, and the density of coupling relationships with ‘ITCZ-proxies’ and the East Asian summer monsoon proxies indicates an Indonesian-Australian monsoon modulated by global-scale forcing.

The northwest Australian proxy from Cave KNI-51 (D13; Denniston et al. [2013]) displays the most connections with other proxy records during the period 6,000-3,000 yrs BP. This coincides with a period of dense coupling across the full network. Inspection of the
raw data (Figure 5) shows this period to be transitional, as expected with a shift to Southern Hemisphere precessional-bias, and thus the paleoclimate network seems to capture this global-scale response to changes in Milankovich forcing.

From 5,000-2,000 years BP onwards, the number of coupling relationships between the IASM proxies and the ITCZ-related and Chinese proxy records begins to decline. Widespread network connectivity has also declined, and the absence of coupling between F09 (Qunf Cave, Oman; Fleitmann et al. [2007]) and M14 (Lonar Lake, India; Menzel et al. [2014]) may indicate that the networks have captured the southward progression of the ITCZ driven by a Southern Hemisphere precessional bias. These two coincident trends suggest that global-scale synchronicity declines in the later Holocene as direct insolation forcing decreases in the Northern Hemisphere, dampening the strength of the Indian and East Asian monsoon, and thus weakening interhemispheric coupling relationships with the IASM region. As such, a model emerges whereby Milankovich insolation forcing acts as a control on regional monsoon strength not only through direct radiative forcing, but also indirectly, by modulating the strength of coupling relationships between regional monsoon systems.

This model correlates with proxy records from the Indonesian-Australian monsoon region. Denniston et al. [2013] note that although precession and tilt favour the Southern Hemisphere following 6,000 years BP, precipitation over northwest Australia is observed to decline. Liu et al. [2003] present sea surface temperature feedbacks as an explanatory mechanism for the counterintuitive response to precessional forcing over northwest Australia, while Wyrmoll et al. [2007] demonstrate that tilt as well as precession plays a critical role in determining monsoon precipitation over northwest Australia, with enhanced precipitation observed in simulation studies with high tilt, even under a Northern Hemisphere precession bias. In fact, the simulation results display changes in interhemispheric outflows to the Southern Hemisphere between different precession and tilt scenarios [Wyrmoll et al. 2007]. The observed weakening in coupling relationships between the IASM region and the Northern Hemisphere into the later Holocene suggests that the transient nature of teleconnections between regional climate systems may have played a critical role in determining the response of the Indonesian-Australian monsoon to Milankovich insolation forcing.

By the latest Holocene (3,000-0 years BP) the Laguna Pallacocha record in Peru (M02; Moy et al. 2002) is the only record coupled to both the IASM proxy time series. Mutual information, as a nonlinear measure of similarity between time series, should be able to quantify the coupling relationships of the Laguna Pallacocha red intensity index (M02; Moy et al. 2002). Because this time series is not suitably represented by Brownian motion (unlike, say, the δ18O speleothem time series), we have defined statistical significance based on simulations of a surrogate Poisson process. This Poisson process is derived from an ‘event’ time series created from 90th percentile events within the M02 record, and is well
approximated by a Poisson process. However, the mutual information estimates calculated from these surrogate Poisson time series will not correspond directly with estimates calculated using the original M02 record. As a result, caution must be exercised when drawing conclusions regarding coupling relationships with the M02, Laguna Pallacocha record. In the latest Holocene, dense coupling with the M02 record is observed, including both the IASM records. Moy et al. [2002] interpret the events recorded in the red intensity index as indicative of moderate-to-strong El Niño events and argue that the record demonstrates an increase in these events from around 3,000 years BP until 1,200 years BP. Similar claims have been drawn from lake sediment records from Galapagos (Conroy et al., 2008), and proxy records of upwelling on the Peruvian margin [Rein et al. 2005] and Panama basin [Cabarcos et al., 2014]. Recent, sub-annual resolution coral $\delta^{18}O$ records capturing changes in sea surface temperature from within the Niño 3.4 region (5°S to 5°N, 120° to 170°W) sit contrary to this, and argue that changes in ENSO variability since 7,000 years ago are hard to distinguish beyond internal variability, however these records do not provide a continuous record across the period [Cobb et al., 2013]. In the Australian summer monsoon context, a number of authors have suggested that enhanced ENSO activity in the latest Holocene may have contributed to a period of aridity evidenced in speleothem and paleoenvironmental records from northwest Australia [Shulmeister and Lees, 1995, McGowan et al. 2012, Denniston et al. 2013]. It has been recognised for a long time that there is no apparent impact of ENSO on monsoon precipitation over northwest Australia [McBride and Nicholls, 1983]. This is also evident in the BoM precipitation records [Bureau of Meteorology, 2014a], with the exception of the 1982–1983 El Niño event, during which the Southern Oscillation Index reached a record low of -33. During this event, there was a clear reduction in Australian summer monsoon rainfall. As such, there is the possibility of an ENSO-northwest Australian teleconnection, although only under an anomalously large shift in the Walker circulation. The paleoclimate networks provided here suggest, albeit tentatively, that a teleconnection between ENSO events and IASM precipitation may well have been present during the latest Holocene. However, given that the Laguna Pallacocha record is, itself, dependent on teleconnections with the central Niño 3.4 region, we make no firmer claims, as the degree to which the Peruvian precipitation captured in the M02 Moy et al. [2002] sediment record is dependent on ENSO may also be transient during the later Holocene.

In summary, by using the verified complex networks method to identify significant coupling relationships between paleoclimate proxy records, we are able to make the following comments:

1. The observed coupling relationships between proxy records from the Indian, East Asian and Indonesian Australian monsoon regions highlight the validity of the ‘global monsoon’ model.
2. However, these coupling relationships are observed to change over the last 9,000 years. In particular, a global-scale transition is observed, whereby the paleoclimate network decreases in connectivity towards the later Holocene. This may indicate reduced global-scale coupling as precession favours the Southern Hemisphere, causing a southward shift in the ITCZ.

3. In the Australian summer monsoon context, connections are first observed with a number of Northern Hemispheric proxy records. This corresponds with an understanding of interhemispheric flows modulating monsoon strength over northwest Australia (e.g. [Liu et al. 2003]). In the latest Holocene, these coupling relationships are lost and the Laguna Pallacocha record (M02; [Moy et al. 2002]) is connected instead. This raises the possibility of an ENSO teleconnection to northwest Australia during this period. This shows some alignment with the dual-model of tropical climate set out by [Chiang 2009], with global scale controls (i.e. ITCZ) and those derived from regional differences (i.e. ENSO) both playing a role in determining regional monsoon strength throughout the last 9,000 years.

5 Conclusions

Identifying potential coupling relationships between climate systems using paleoclimate proxy records is a broadly qualitative process. Here, we demonstrate the efficacy of complex networks to identify coupling relationships and teleconnections which correspond to known dynamical mechanisms. Extending this method to a multi-proxy database of paleoclimatic time series, we are able to draw conclusions regarding the nature of coupling across the Asian-Australasian monsoon region. Our results recognise an element of the global monsoon concept, with regional monsoons displaying some degree of coupling over the period. The global paleomonsoon model, however, does not adequately represent the transient nature of coupling relationships, while our findings demonstrate a strengthening of coupling relationships across the broad Asian-Australasian monsoon regions during the mid-Holocene, followed by a tendency to reduced coupling in the later Holocene. Our findings at this stage are preliminary, and dependent on the availability of suitable proxy datasets, but we envisage that once more datasets become available, a stronger case can be made. In the context of the Australian summer monsoon, we observe coupling relationships to other low latitude regions throughout the Holocene. While we offer tentative explanations for these, we stress that the observed links are unable to tell us about the underlying mechanism. We can, however, state with confidence that the networks demonstrate effectively that the strength of coupling relationships between the northwest Australian monsoon region and other regional climate systems were transient over the past 9,000 years. Given the coupling relationships observed, the next step is to ask why they exist. We recommend further research in the context of available model simulations, and in developing methods to assess the direction of information flow, in an effort to identify
the underlying mechanisms determining and driving the coupling relationships.

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