

A global-scale test for monsoon indices used in palaeoclimatic reconstruction

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Received 19 October 2012; received in revised form 23 January 2013; accepted 1 February 2013

Available online 14 March 2013

Abstract

The monsoon has received broad attention because of its economic and ecological importance. Many studies based on isotopic, palaeomagnetic, sedimentological, palaeobotanical or palaeontological proxy data have addressed the Neogene evolution of the Asian monsoon. Quantitative estimations of monsoon intensity in geological history are needed to study its evolution. Good tools are also needed to discriminate between past monsoonal or non-monsoonal climates. Several indices have been proposed to describe the seasonality in precipitation or monsoon strength based mainly on precipitation parameters. However, these indices have never been tested nor validated on a global scale. Herein, we look at four indices used in recent studies. The values of these indices are calculated for the present condition on a global scale using a geographical information system. We found that all four indices reconstruct false positive scenarios, i.e., non-monsoonal regions (either high latitudes or equatorial regions) with high index values. And some indices fail to give high values for some monsoonal regions like India. These indices cannot be used to discriminate between monsoonal and non-monsoonal climates through geological time. However, they can be used when the presence of the monsoon is confirmed by other means, and in such cases they are useful for measuring monsoon intensity. The monsoonal precipitation is characterized by its amount, annual range, and seasonal distribution but these three aspects of the monsoon are not sufficiently summarized in one index value. Parameters useful for palaeomonsoon description, such as the ratio of summer precipitation and the daily rate of summer precipitation, should be directly included in methods of palaeoclimatic reconstruction.

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Keywords: Monsoon; Index; Climate; Geographical information system; Palaeoclimatic reconstruction

1. Introduction

The monsoon is an important feature of the modern climate: more than two-thirds of the world population is affected by monsoonal rainfalls (Wang and Ding, 2006). The monsoon corresponds to a seasonal reversal of atmospheric circulation, and thus brings rainfalls (Trenberth et al., 2000, 2006; Zhang and Wang, 2008). This reversal is due to a reversal in the heating and temperature gradients between a continent and adjacent oceans (Trenberth et al., 2006; Zhang and Wang, 2008). With the development of the technology, the monsoon has been recently described on a global perspective (Trenberth et al., 2006; Wang, 2009; Wang and Ding, 2006). The global

monsoon is now understood as a manifestation of the seasonal migration of the intertropical convergence zone (Wang, 2009). Six monsoon domains are generally described: the Asian monsoon, the Indonesian and Australian monsoon, the North African monsoon, the South African monsoon, the North American monsoon, and the South American monsoon (Zhang and Wang, 2008).

Some other summer monsoon domains have been described from the geological past, such as the Eocene summer monsoon in Antarctica (Jacques et al., *in press*). Palaeoclimatologists need good criteria or indices to describe past monsoons.

Among these monsoon domains, the Asian monsoon is the most studied. In recent years, the evolution of the Neogene Asian monsoon has attracted broad attention because it influenced the whole atmospheric circulation on earth (Sun and Wang, 2005). Such reconstructions are based on various proxies: isotopic data (Dettman et al., 2003; Jia et al., 2003; Kaakinen et al., 2006; Passey et al., 2009; Quade et al., 1989; Steinke et al., 2010), sedimentological data (Clift et al., 2002; Rea et al., 1998; Sun,

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2004; Vandenberghe et al., 2004; Wan et al., 2007), palaeomagnetic data (An et al., 2001; Guo et al., 2002), palaeobotanical data (Hoorn et al., 2000; Jacques et al., 2011a; Jiang and Ding, 2008, 2009; Kou et al., 2006; Liu et al., 2011; Srivastava et al., 2012; Sun and Wang, 2005; Xia et al., 2009; Xie et al., 2012; Xing et al., 2012), and palaeontological data (Chen et al., 2003; Li et al., 2008; Liu et al., 2009; Wang et al., 2008). Several climatic models also look at changes in the monsoon system during the Neogene (Boos and Kuang, 2010; Liu and Yin, 2002; Micheels et al., 2007, 2011; Prell and Kutzbach, 1992; Ramstein et al., 1997; Tang et al., 2011; Tong et al., 2009; Zhang et al., 2007). These studies focus on the evolution of the monsoon by looking at the variation of the proxies; however, most of them do not quantify the intensity of the monsoon.

Modern climatologists have defined several indices to describe monsoon intensity. Because the monsoon is characterized primarily by the annual reversal of surface winds (Zhang and Wang, 2008), most of these indices have been defined based on winds and atmospheric circulation. For example, Jhun and Lee (2004) proposed an index for the Asian winter monsoon based on wind speed at the 300-hPa level. Wang et al. (2001) suggested two monsoon indices for the Asian summer monsoon based on wind at 850-hPa level. Such indices are difficult to reconstruct for the geological past, even if granulometry studies (Sun, 2004; Vandenberghe et al., 2004) can be used to reconstruct past wind speeds. However, the monsoon mainly influences ecosystems through rainfalls. This influence is due to both the water brought to the ecosystem and the release of latent heat (Zhang and Wang, 2008). Therefore, the monsoon can be described by its rainfalls. The definition of a monsoon summer rainy season generally considers three aspects of the precipitation: the annual range of precipitation, an intense rainfall rate, and the seasonal distribution of the precipitation over the local summer (Wang and Ho, 2002). Two definitions of the monsoon have been proposed based on the precipitation parameters: a monocriterion definition (Lau and Yang, 1997) or a multicriteria definition (Zhang and Wang, 2008). Wang and Ding (2006) studied the evolution of the monsoon based on several precipitation parameters.

Several monsoon/seasonality indices have already been described based on precipitation parameters that either are or are not associated with temperature parameters (Liu and Yin, 2002; Liu et al., 2011; van Dam, 2006; Xing et al., 2012). These studies are based on model results (Liu and Yin, 2002), small

mammals (van Dam, 2006) or palaeobotanical (Liu et al., 2011; Xing et al., 2012) palaeoclimatic reconstructions. However, the indices have never been tested on a broad scale.

The aim of this study is (1) to look at how monsoon indices behave on a global scale using modern climate data and a geographical information system, and (2) to propose a method to describe palaeomonsoons.

2. Materials and methods

2.1. Climatic data

We used basic worldwide climatic data for this study. The primary climatic data used are: mean monthly temperatures and monthly precipitation over 12 months. These parameters are available on a gridded dataset (Hijmans et al., 2005) and can be downloaded from the Internet, <http://www.worldclim.org/>. These data are based on at least 30 year records (Hijmans et al., 2005). We do not consider Antarctica as it is absent from the meteorological data we use.

We used a 2.5' grid. This resolution is high enough to avoid averaging the climatic parameters on areas that are too large. A higher resolution map would not result in a better image because we are limited by the definition of the image.

2.2. Monsoon indices

We used Zhang and Wang (2008) to define the monsoonal regions based on precipitation parameters. This definition is based on two criteria: amount of rain in the summer and seasonality. Therefore, it is more efficient than mono-criterion definitions (e.g., Lau and Yang, 1997), because it better reflects the complexity of the monsoon (Zhang and Wang, 2008). A region is described as having a summer monsoon if the summer daily rate of precipitation (SDR) is over 3 mm and the rate of summer precipitation (RSP) over the whole year is more than 55% (Zhang and Wang, 2008). We chose this definition of monsoonal regions because it is based primarily on the same set of parameters as the monsoon indices we study, i.e., precipitation parameters. It prevents artifacts resulting from the use of different datasets in the reference and in the studied indices. This definition results in monsoon domains that coincide primarily with the domains defined by previous literature (Zhang and Wang, 2008). One should keep in mind

Table 1
Definitions of the parameters used in this study. For RSP and SDR, summer is defined as MJJAS in the Northern Hemisphere and NDJFM in the Southern Hemisphere (Zhang and Wang, 2008). For Ts and Rs, summer is defined as JJA (DJF) in the Northern (Southern) hemisphere (Liu and Yin, 2002). For Tw and Rw, the summer is defined as DJF (JJA) in the Northern (Southern) hemisphere (Liu and Yin, 2002). The growing season corresponds to these months for which mean monthly temperature is over 10 °C (Wolfe, 1993).

Parameter	Definition	Reference
RSP	Ps/MAP	Zhang and Wang (2008)
SDR	Ps/Ds	Zhang and Wang (2008)
Liu and Yin index	$(Ts - Tw) \times (Rs - Rw)$	Liu and Yin (2002)
van Dam index	MPWET – MPDRY	van Dam (2006)
Liu et al. index	$(WMT - CMT) \times (MPWARM - MPDRY)$	Liu et al. (2011)
Xing et al. index	$(MP3WET - MP3DRY) \times 100/GSP$	Xing et al. (2012)

that, even if this definition eases the comparisons made in this paper, it can have some bias and is, therefore, not perfect. These parameters have also already been used to define past monsoon domains (Jacques et al., *in press*). We also looked at the worldwide repartition of these two parameters, SDR and RSP (Table 1).

We selected four monsoon indices that are defined only by precipitation and temperature parameters (Table 1) because these parameters are available in palaeoclimatic reconstructions. The Liu and Yin index was defined to study the sensitivity of the East Asian monsoon to different forcing factors using a climatic model (Liu and Yin, 2002). The van Dam index was defined to reconstruct monsoon strength based on palaeoprecipitation results derived from small mammal proxies (van Dam, 2006). The Liu et al. index was defined to study monsoon evolution based on fossil pollen data (Liu et al., 2011) and palaeoclimatic reconstructions using the coexistence approach (Mosbrugger and Utescher, 1997). The Xing et al. index was defined to study monsoon strength based on a fossil leaf physiognomy proxy (Xing et al., 2012) and palaeoclimatic reconstruction using CLAMP (climate leaf multivariate program; Jacques et al., 2011b; Wolfe, 1993).

2.3. Index computation

The values for the different parameters and indices were calculated with the spatial analyst of the geographical information software ArcGis 9.3 (Esri Company, Redlands, CA). The spatial analyst allows calculations for all cells of the gridded dataset at the same time. When a calculation required division by zero for some cells, the results of these cells are shown as blank/missing. The color gradient of the resulting raster was calibrated according to the mean and standard deviation of the parameter.

For the Xing et al. index, we had to exclude some regions. In cold areas, there is no growing season, and the calculation makes no sense. In regions with high winter precipitation, GSP might be much lower than MP3WET, sometimes estimating values over 100. We, therefore, excluded regions with

(MP3WET-MP3DRY) higher than GSP from the analysis. In our study, the Xing et al. index is always below 100.

3. Results

3.1. Monsoonal regions

Regions with a summer monsoon according to the definition of Zhang and Wang (2008) are indicated in Fig. 1. Tropical regions are represented largely by a monsoonal climate, but the equatorial regions are not. Central North America and some mountain regions of Europe are also indicated to be monsoonal, even if these regions are not considered to have a monsoon. A part of the Yangtze Basin in China is reconstructed as having no monsoon.

3.2. Rate of summer precipitation

The world distribution of the rate of summer precipitation (RSP) over the annual precipitation (Fig. 2) shows that the rate of summer precipitation is important in most regions of the globe except in regions with Mediterranean climates: the Mediterranean basin, Middle East, Western coast of North America, a part of Chile, southern South Africa, and southern Australia. This rate is also low near the Equator.

3.3. Summer daily rate of precipitation

The summer daily rate (SDR) of precipitation is high in the intertropical regions (Fig. 3). It is also high in a few temperate regions: southern Chile, Japan and Korea, and New Zealand.

3.4. Liu and Yin index

The Liu and Yin index is very high for India and eastern Asia, as expected for monsoon regions (Fig. 4). However, it is also high for high latitudes of the Northern Hemisphere, where there is no monsoon, and low for the monsoon regions of America and Africa.

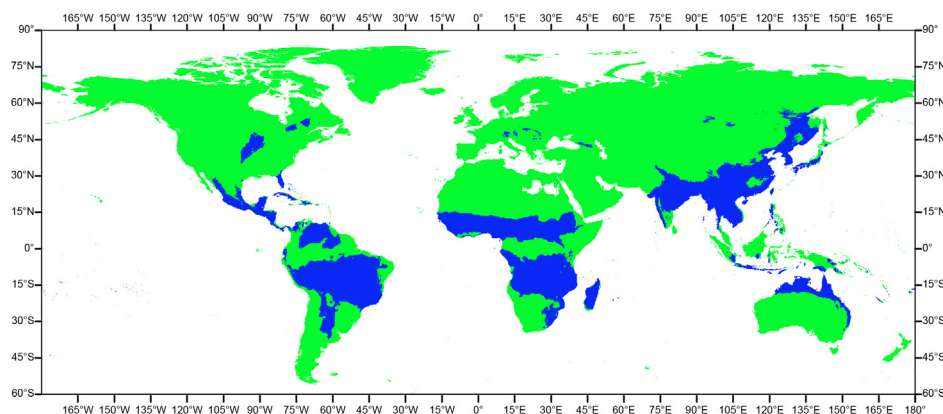


Fig. 1. World map of monsoonal regions. Regions with a summer monsoon according to Zhang and Wang (2008), i.e., summer daily rate precipitation over 3 mm and summer precipitation representing more than 55% of annual precipitation (dark gray), and regions without a summer monsoon (light gray). Note that some regions, e.g., some parts of North Africa, are white because the annual precipitation is considered zero, and the rate of summer precipitation, thus, cannot be calculated.

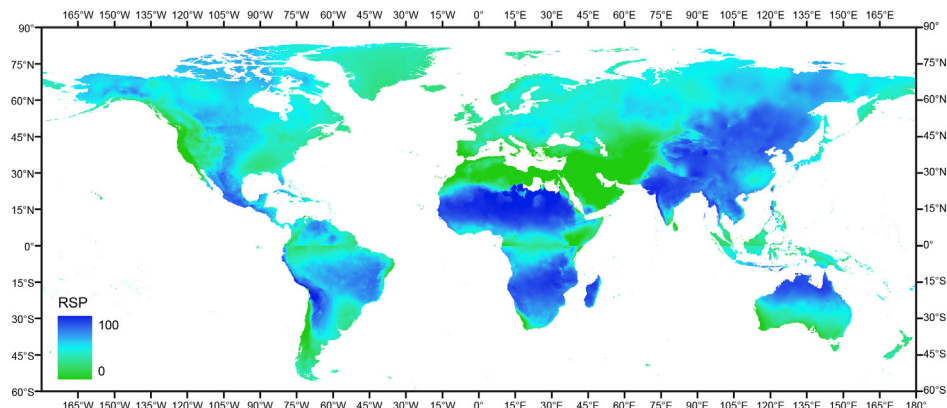


Fig. 2. World map of the rate of summer precipitation (RSP). Note that some regions, e.g., some parts of North Africa, are white because the annual precipitation is considered as zero, and the rate of summer precipitation, thus, cannot be calculated.

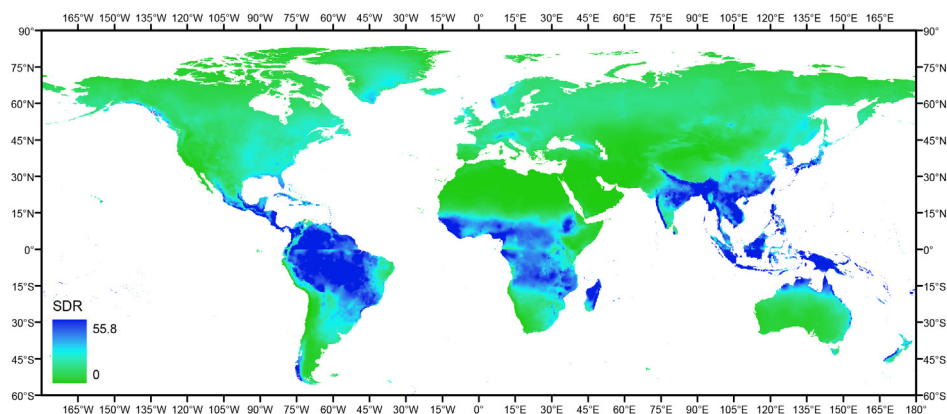


Fig. 3. World map of the summer daily rate (SDR) of precipitation.

3.5. van Dam index

The van Dam index values are high for the intertropical regions (Fig. 5). It also indicates high values for the north western coast of North America, and central Chile.

3.6. Liu et al. index

The Liu et al. index values are high for eastern Asia, and high latitudes of the Northern Hemisphere (Fig. 6). However, values for all other regions, including India, are low.

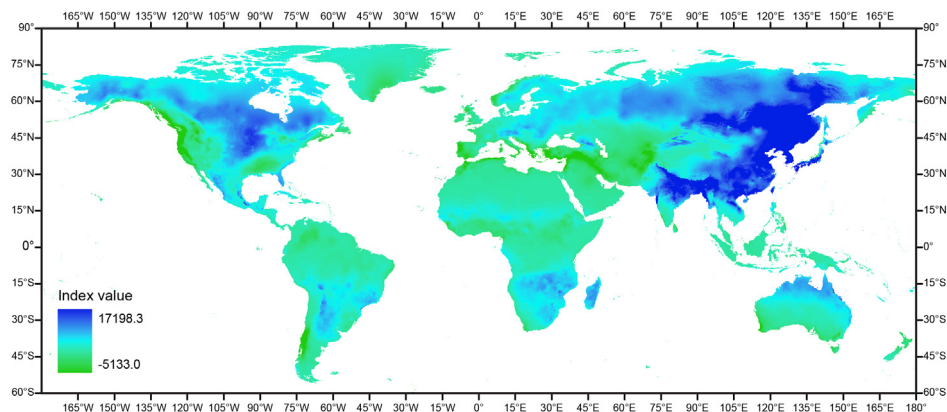


Fig. 4. World map of Liu and Yin (2002) index.

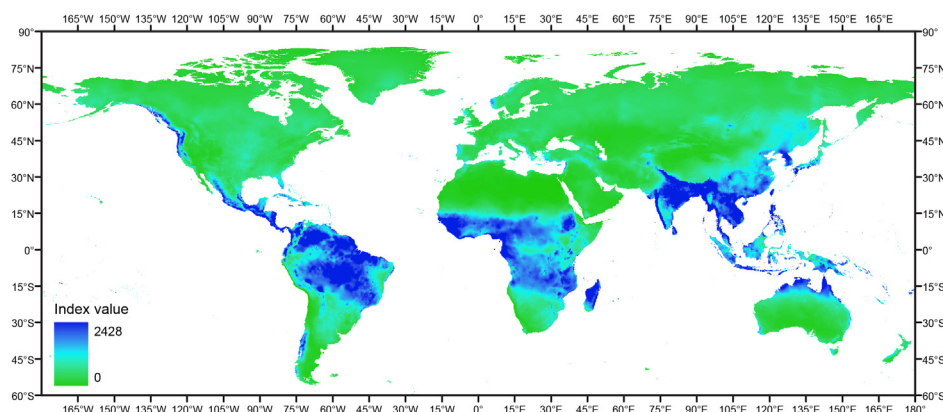


Fig. 5. World map of van Dam (2006) index.

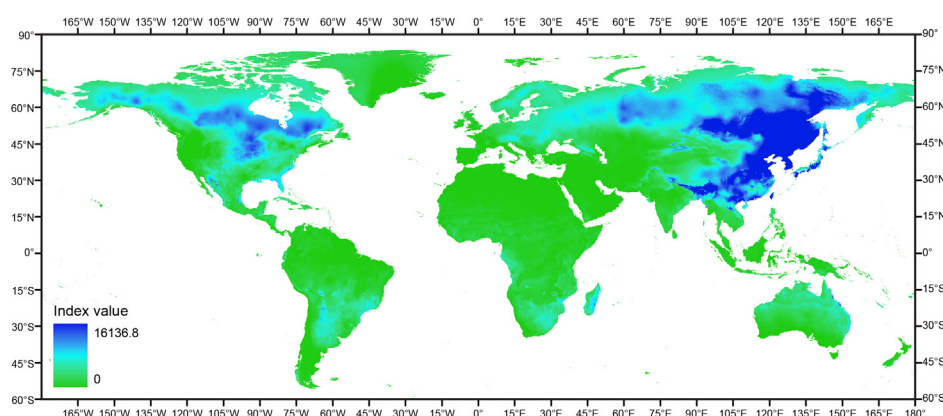


Fig. 6. World map of Liu et al. (2011) index.

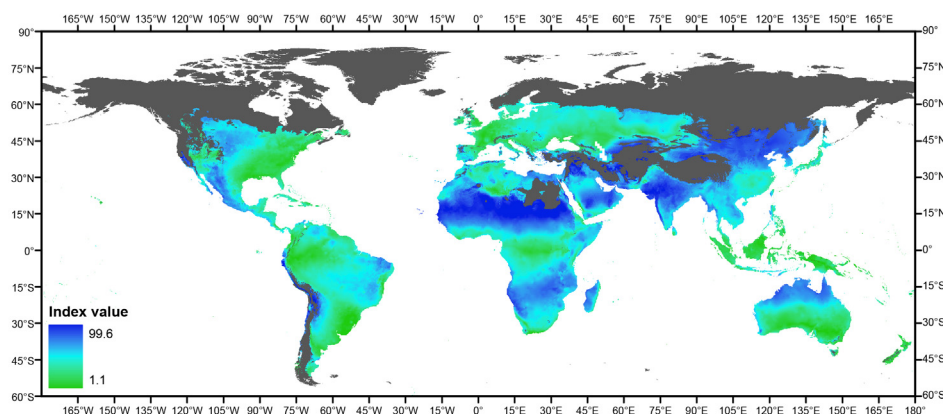


Fig. 7. World map of Xing et al. (2012) index. Note that this index cannot be calculated for all regions (black areas).

3.7. Xing et al. index

The Xing et al. index could not be calculated for some regions, especially at high latitudes, where GSP is null (Fig. 7). The index is high for India, northern Africa, the Middle East, and northern Australia but not very high for eastern China.

4. Discussion

4.1. Bias in indices

The monsoon indices studied here were mostly designed to look at monsoon strength in monsoonal regions. Some authors

warned that their indices are only applicable in some regions; for example, the Liu and Yin index and Liu et al. index are defined for the mid-latitudes (Liu and Yin, 2002; Liu et al., 2011). In this paper, we look at these indices at a global scale in order to test their applicability for estimating monsoon conditions in the geological past.

Both the Liu and Yin and Liu et al. indices use the difference between temperatures in winter and summer and indicate high values for high latitudes (Figs. 4 and 6). At high latitudes, seasonality in temperature is very important. Therefore, these indices are flawed when regions with high temperature seasonality are considered. In contrast, these index values will be low in regions with more equable temperatures (Africa and South America).

The van Dam index values are high for the north-western coast of North America, and central Chile (Fig. 5). This index only looks at the seasonality in precipitation, but not at the distribution of the precipitation throughout the year. Therefore, a high index value will also be retrieved for regions with high winter precipitation but low summer precipitation, even if the climate is not monsoonal.

The Liu et al. index values are low for intertropical regions (Fig. 6). This index uses the differences in the precipitations between the driest and warmest months. However, in tropical regions, the warmest month does not usually occur at the same time as the monsoon rainfalls, but is usually dry. Therefore, this index overlooks the seasonality in precipitation in intertropical regions.

The Xing et al. index (Fig. 7) works well in Yunnan, the region for which it was first designed (Xing et al., 2012). However, values are high for some desert regions such as parts of the Sahara and Arabic peninsula. This index considers the proportion between seasonality in precipitation and annual precipitation. In very dry regions, non-significant seasonality can give very high values.

4.2. Comparison between indices

The Liu et al. index is clearly a derivation of the Liu and Yin index for application as a palaeobotanical proxy (Liu et al., 2011). Therefore, it suffers from the same bias at high latitudes. However, it adds a strong bias at low latitudes where it is unable to reconstruct a monsoon signal.

In contrast to other indices, the van Dam index mainly discriminates temperate regions from monsoon regions. However, it fails to clearly separate equatorial regions from monsoon regions.

The Xing et al. index successfully reconstructed the differences between the Indian monsoon and the South-East Asian monsoon (Molnar et al., 2010). However, it indicates a monsoon signal in desert regions.

The different indices do well in reconstructing some aspects of the monsoon but fail to reconstruct others.

4.3. Looking for a global index

When dealing with palaeoclimate reconstruction, we would like to be able to retrieve information on palaeomonsoons. The

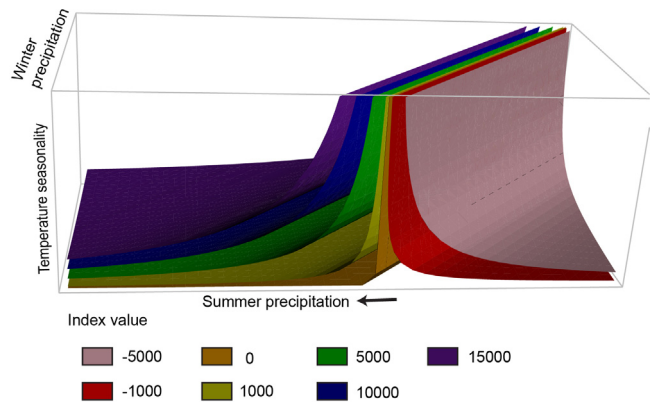


Fig. 8. Isosurfaces of the Liu and Yin index according to temperature seasonality, summer precipitation, and winter precipitation. Note that the isosurfaces are hyperbolic. Note that if summer precipitation is replaced by MPWARM and winter precipitation is replaced by MPDRY, the isosurfaces will then correspond to the Liu et al. index.

use of some monsoon indices might be tempting: if the index indicates a high value, a monsoon climate might be reconstructed. However, our work on a global scale indicates that the four studied indices all retrieve high values for non-monsoonal regions. In other words, all indices can retrieve a false positive. Therefore, we do not think these indices are appropriate for discriminating between monsoonal and non monsoonal climates in the past. However, they can provide useful information on monsoon strength when the presence of a monsoon is confirmed. We now aim to precisely determine the conditions in which these indices can be used.

When looking at the behavior of the Liu et al. index (Fig. 8), isosurfaces correspond to a hyperbole. For high temperature seasonality, the index is only dependent on the precipitation seasonality; for high precipitation seasonality, the index is only dependent on the temperature seasonality. Therefore, in regions with a strong monsoon, the difference in index values only represents differences in temperature seasonality, not in precipitation seasonality. At higher latitudes, where temperature seasonality is high, small differences in precipitation induce strong differences in the index value. Therefore, the interpretation of this index should be context specific (e.g., high temperature seasonality or high precipitation seasonality). Since the Liu et al. index is built on the same mathematical model, it suffers from the same bias.

When looking at the behavior of the Xing et al. index (Fig. 9), it is obvious that for low precipitation regimes, only a slight difference in seasonality can result in important variation in the index value. For example, if GSP is 20 mm, a difference of 1 mm in precipitation seasonality induces a change of 5 in the index value. Therefore, we suggest the use of this index only for GSP over 500 mm. In such cases, a 1 mm change in precipitation seasonality corresponds to a change less than 0.2 in the index value.

The modern monsoonal regions are better reconstructed using several criteria, such as levels of SDR and RSP. In fact, these criteria have been directly designed to describe a monsoon climate (Zhang and Wang, 2008). It is easier to define the monsoon when looking at modern monsoons

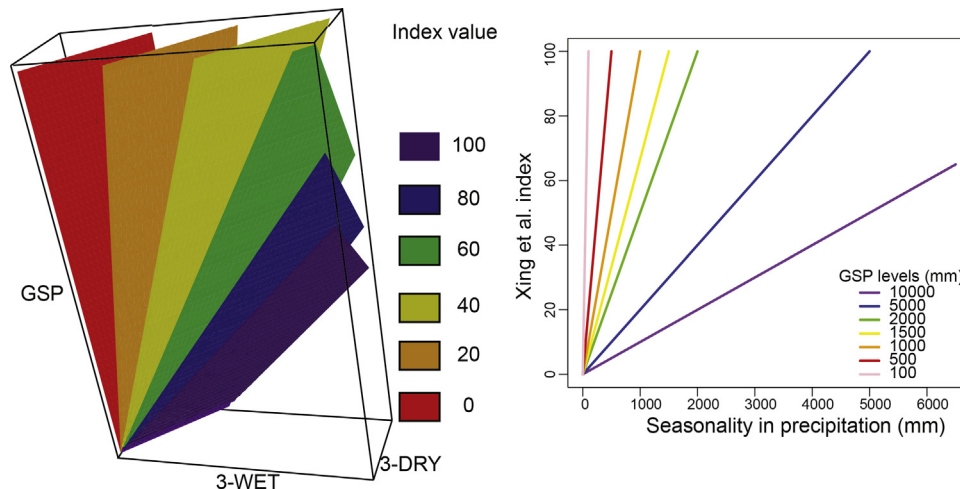


Fig. 9. On the right, isosurfaces of the Xing et al. index according to GSP, 3-WET and 3-DRY. On the left, variation of Xing et al. on seasonality in precipitation according to different levels of GSP. Note that for low levels of GSP, the index values vary strongly even for small changes in seasonality.

than by building indices based on parameters available from palaeoclimatic reconstructions. The monsoonal precipitation is characterized by its amount, annual range, and seasonal distribution (Wang and Ho, 2002). A unique index cannot summarize these three aspects in only one value.

In recent work, an Eocene Antarctic monsoon was defined (Jacques et al., in press). The authors did not use a monsoon index derived from the palaeoclimatic reconstruction parameters to define the monsoon but built a new calibration for palaeoclimatic reconstruction that directly gives estimations of parameters significant for the monsoon, i.e., SDR and RSP. Two palaeoclimatic reconstruction methods are widely used in palaeobotany: CLAMP (Wolfe, 1993) and the coexistence approach (Mosbrugger and Utescher, 1997). These methods were defined primarily in North America and Europe, respectively. These regions are mostly without present-day monsoon conditions. As a consequence, these methods were not designed to use parameters most useful to define a monsoon. In this paper, we show that the best method is to estimate the monsoon-sensitive parameters directly in the palaeoclimatic reconstruction process. When the monsoon palaeoclimate is characterized, the monsoon indices discussed above can be used to reconstruct its intensity.

Acknowledgments

We thank Angela Bruch and Cheng Quan for kindly reviewing the manuscript. This work was supported by a 973 Programme of MoST of China (20120CB821900), the National Natural Science Foundation of China (Grants 41272007, 31100166, 41030212), the Key Laboratory of Biodiversity and Biogeography, Kunming Institute of Botany, Chinese Academy of Sciences (KLBB 201201), and the State Key Laboratory of Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, CAS) (Nos. 123106, 123107, 123108).

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