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Leaf physiognomy and climate: Are monsoon systems different?

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ABSTRACT

Our understanding of past climatic changes depends on our ability to obtain reliable palaeoclimate reconstructions. Climate Leaf Analysis Multivariate Program (CLAMP) uses the physiognomy of woody dicot leaf assemblages to quantitatively reconstruct terrestrial palaeoclimates. However, the present calibrations do not always allow us to reconstruct correctly the climate of some regions due to differing palaeofloristic histories. Present calibrations are also inappropriate for regions experiencing strong monsoon regimes. To help solve this problem, we have established a new calibration that can accommodate monsoonal climates in Asia. Our new calibration is based on the Physg3brcAZ dataset with 45 new Chinese sites added. These Chinese sites are taken from humid to mesic vegetations across China, and all are influenced by monsoonal conditions to some extent. They plot in a distinct part of physiognomic space, whether they are analysed as passive or active samples. The standard deviations for the new monsoonal calibration (1.25 °C for MAT and 217.7 mm for GSP) are in the same range as those observed for previous calibrations. The new monsoonal calibration was tested using a cross validation procedure. The estimates derived from the new monsoonal calibration (PhysgAsia1) for the Chinese sites are more accurate than those obtained from the Physg3brcAZ calibration, especially for the moisture related parameters. The mean absolute error for GSP of the Chinese sites is 294.6 mm in the new monsoonal calibration, whereas it was 1609.6 mm in the Physg3brcAZ calibration. Results for the three wettest months and three driest months are also more accurate and precise, which allows us to study the seasonality of the precipitation, and hence the monsoon. The new monsoonal calibration also gives accurate results for enthalpy reconstruction. Enthalpy is a parameter that is used for palaeoaltimetry, the new calibration is therefore useful for studies of land surface height changes in China, height changes which in turn can affect the strength of the monsoon.
The new monsoonal calibration was tested on two fossil sites from the Late Miocene of southwestern China, namely the Lincang and Xiaolongtan palaeofloras. A comparison of results from the new monsoonal calibration and the Physg3brcAZ calibration shows that there is no strong difference in temperature estimates for the two calibrations, but there is a strong difference in the moisture related parameters. The use of this new monsoonal calibration is recommended for palaeoclimate reconstructions in China.

1. Introduction

The monsoon is a climatic system that has a strong impact in Asia, and large populations of almost the whole of East and southeastern Asia depend upon the water it delivers. In terms of rainfall there are two seasons with markedly different characteristics. The summer is warm and wet, whereas the winter is cool and dry. As a result, the most pronounced seasonal variations in precipitation, and to a lesser extent temperature, on Earth are found over the Asian monsoon regions (Lau and Chan, 1983; Murkani et al., 1986). The elevation and surface area extent of the Tibetan Plateau is primarily responsible for amplifying the monsoon (Raymo and Ruddiman, 1992; An et al., 2001). Other factors can also influence the monsoon characteristics,

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Abbreviations: 3-DRY, precipitation of the three consecutive driest months; 3-WET, precipitation of the three consecutive wettest months; CCA, canonical correspondence analysis; CLAMP, climate leaf analysis multivariate program; CMMT, mean temperature of the coldest month; LGS, length of the growing season; GSP, growing season precipitation; MAT, mean annual temperature; MMGSP, mean monthly growing season precipitation; RH, relative humidity; SH, specific humidity; WMMT, mean temperature of the warmest month.

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for example: orbital forcing, polar ice-cap surface, the altitude of the Himalayas, carbon dioxide concentration (Prell and Kutzbach, 1992), and the position of the Tibetan Plateau (Molnar et al., 2010).

To study the evolution of the monsoon through geological time, several proxies can be used: carbon isotopic data (Quade et al., 1989; Passey et al., 2009), oxygen isotopic data (Dettman et al., 2001), Nd isotopic data (Garzione et al., 2005), marine sediments (An et al., 2001), palaeomagnetic data (Guo et al., 2002), and the palaeobotanical record (Sun and Wang, 2005). Palaeobotanical studies allow a detailed reconstruction of palaeoclimates and infer the monsoon strength (Xia et al., 2009; Jacques et al., in press). These palaeobotanical records are valuable because they give quantitative estimates of a range of climate variables including precipitation differences between dry and wet seasons, and hence a quantitative estimate of monsoon strength.

Several methods of palaeoclimate reconstruction using palaeobotanical data are based on leaf physiognomy. There is a strong climate-driven selection on leaf architecture (e.g., Spicer et al., 2004, 2009); therefore, leaf physiognomy is largely independent of taxonomy (Spicer, 2000, 2007, 2008; Spicer et al., 2009). The percentage of dicotyledonous leaves with entire margins in a flora has long been recognized to correlate with the mean annual temperature (e.g., Bailey and Sinnott, 1915, 1916). CLAMP (Climate–Leaf Analysis Multivariate Program) links 31 physiognomic features to eleven climatic parameters (Wolfe and Spicer, 1999). CLAMP is based on a direct ordination method: CCA (Canonical Correspondence Analysis, ter Braak, 1986). In the ordination space, known as "physiognomic space", sample sites are represented by points and climate parameters by vectors. The position of collection sites along the vectors and their meteorological data allow for the calibration of the vectors for palaeoclimatic reconstruction. Recent mathematical improvements have been proposed for CLAMP (Teodoridis et al., 2011), including transformations of the physiognomic characters to better fit the theoretical conditions required for Canonical Correspondence Analysis. However, these improvements do not bring new sampling sites to the training dataset, i.e. new possible physiognomic–climate relationships.

The precision that can be obtained from quantitative methods such as CLAMP is dependent on the training dataset (Spicer et al., 2009). Different climate regimes show different physiognomy: for example the so-called alpine nest (Wolfe, 1993), New Zealand (Stranks and England, 1997), and Siberia (Spicer et al., 2004). Kowalski (2002) also noted that there is a geographic variation in the relationship between climate and leaf morphology based on South American samples. At present the calibration data mostly lack subtropical and tropical sites (Spicer et al., 2009), and performance of CLAMP has yet to be extensively tested in subtropical and tropical regions (Spicer et al., 2005). The reconstruction of the Lincang palaeoclimate using the existing Physg3b CLAMP calibration results in astonishing estimates of precipitation (Jacques et al., in press). A closer look at the physiognomic space showed that the Lincang fossil assemblage plotted away from all sites in the calibration dataset (Jacques et al., in press).

Another palaeoclimate reconstruction method (the Coexistence Approach) indicated that Lincang palaeoclimate was a monsoonal regime (Jacques et al., in press), in congruence with other data showing that the monsoon was already established by the beginning of the Neogene (Clift et al., 2008). This suggests that CLAMP is not well calibrated for monsoonal climate regions. The aim of this paper is to expand the CLAMP calibration with new data from monsoon regions, therefore developing a CLAMP calibration dataset that is more appropriate for Asian monsoonal climates.

2. Materials and methods

2.1. The new Chinese sites

For this study, we used 45 Chinese sites that have never been included in any CLAMP dataset as active samples before (Table 1). Su et al. (2010) used these sites to establish a new leaf margin analysis regression linking the percentage of leaves possessing entire margins with MAT. The five coldest sites of Su et al. (2010) were removed because they had less than the 20 woody dicotyledonous species (dicots) required for the CLAMP procedure. The remaining sites are dispersed throughout humid to mesic vegetation in China, from tropical Hainan Island to the north-eastern province of Liaoning; therefore, they represent tropical to cold temperate climates (Su et al., 2010). As the monsoon widely affects the Chinese climate, all these sites experience some monsoonal influence. For each site, all woody dicots were sampled for sun and shade mature leaves (Su et al., 2010). Sites with low human disturbance were chosen for sampling. All samples were scored according to the standard CLAMP scoring procedure (Su et al., 2010). Su et al. (2010) included the monocot *Smilax* in their scoring, but we excluded it here to follow CLAMP protocols that only consider dicots.

Table 1
Geographic coordinates, elevation and number of taxa sampled of the Chinese sites (data from Su et al., 2010).

No	Sample site	Province	Taxa number	Latitude (°N)	Longitude (°E)	Altitude (m)
1	Taibai	Shaanxi	21	34.05	107.60	1044
2	Huanren	Liaoning	22	41.62	125.93	371
3	Anshan	Liaoning	23	41.00	123.13	116
4	Guiyang	Hunan	23	25.62	112.73	386
5	Yantai	Shandong	23	37.27	121.37	420
6	Lingchuan	Guangxi	25	25.17	110.55	235
7	Jingdong	Yunnan	26	24.45	100.90	1441
8	Jiangkou	Guizhou	27	27.90	108.72	1080
9	Jiaohe	Jilin	27	43.75	127.05	425
10	Weishan	Yunnan	27	25.18	100.35	2320
11	Chuzhou	Anhui	28	32.30	118.28	55
12	Baisha	Hainan	29	18.83	109.22	309
13	Lichuan	Hubei	29	30.43	108.68	1377
14	Xichou	Yunnan	29	23.43	104.67	1495
15	Lüchun	Yunnan	30	22.98	102.45	1870
16	Pingbian	Yunnan	30	22.90	103.70	2033
17	Chengkou	Chongqing	31	31.97	108.65	753
18	Xinyang	Henan	31	31.82	114.07	187
19	Lushan	Jiangxi	31	29.55	115.98	1032
20	Zhenyuan	Yunnan	32	23.98	101.12	1095
21	Zaoqing	Guangdong	33	23.12	112.48	130
22	Shiyan	Hubei	33	32.53	110.75	373
23	Pingwu	Sichuan	34	32.55	104.57	1127
24	Pu'er	Yunnan	35	22.62	101.05	1255
25	Kunming	Yunnan	35	24.98	102.63	2274
26	Longsheng	Guangxi	35	25.82	110.03	335
27	Baoxing	Sichuan	36	30.38	102.82	1069
28	Napo	Guangxi	38	23.30	105.80	1168
29	Liuyang	Hunan	39	28.43	114.10	1175
30	Dong'an	Hunan	39	26.40	111.03	551
31	Wuyishan	Fujian	39	27.77	117.68	725
32	Yongxiu	Jiangxi	39	29.10	115.58	694
33	Shimen	Hunan	40	30.03	110.62	439
34	Jinyunshan	Chongqing	41	29.83	106.38	819
35	Gongshan	Yunnan	43	27.73	98.65	1650
36	Wuming	Guangxi	43	23.43	108.42	222
37	Wuzhishan	Hainan	43	18.87	109.68	619
38	Xinhua	Hunan	44	28.15	111.30	398
39	Mengla	Yunnan	44	21.63	101.58	847
40	Liupanshui	Guizhou	44	26.47	104.82	2064
41	Tongshan	Hubei	45	29.42	114.65	505
42	Chongyi	Jiangxi	45	25.65	114.32	416
43	Yushan	Jiangxi	47	28.88	118.07	776
44	Jinfoshan	Chongqing	55	29.05	107.18	1651
45	Weng'an	Guizhou	58	26.97	107.63	878

For the calibration, meteorological data associated with the sampled sites are required. The meteorological stations should be close to the sites and have at least 30 yr of continuous record (Wolfe, 1993). As Su et al. (2010) noted however, many sample sites in China are not close to climate stations, which limits the direct use of climate station records. Spicer et al. (2009) developed a new way to produce meteorological data for CLAMP calibration using global gridded climate data. Spicer et al. (2009) interpolated a 0.5°×0.5° grid of meteorological data based on the global climate dataset of New et al. (1999). The temperature estimates using gridded and ungridded data are similar, but gridded meteorological data tend to give lower values for precipitation variables (Spicer et al., 2009). Such differences can be explained: the results given by a gridded dataset reflect regional observations averaged over the grid cell, while those given by an ungridded dataset reflect more local conditions (Spicer et al., 2009). Gridded data for specific sites can be generated online at http://www.paleo.bris.ac.uk/ummodel/scripts/html_bridge/clamp_UEA.html. This site returns meteorological data for any site based on its longitude, latitude and altitude.

2.2. Comparison with previous datasets

Two calibration datasets are currently available for CLAMP analyses on the CLAMP website: Physg3arcAZ and Physg3brcAZ. Physg3brcAZ includes 144 sites, primarily from North America and Japan, with a few sites from Puerto-Rico, Fiji and New Caledonia (Wolfe, 1993). Physg3arcAZ includes 173 sites, among them the 144 Physg3brcAZ sites plus 29 sites corresponding to the alpine nest (Wolfe, 1993). The alpine are the coldest sites known to have a different physiognomic behavior (Wolfe, 1993); they are characterized by a WMMT lower than 16 °C and a CMMT lower than 3 °C (Wolfe, 1993). Existing datasets are clearly biased towards temperate climates of the Northern Hemisphere. Therefore, we need to look at the behavior of monsoonal sites compared to those sites present in existing CLAMP datasets.

CLAMP analysis is based on an ordination method, Canonical Correspondence Analysis (CCA; ter Braak, 1986). CCA allows for the inclusion of sites either as active or passive samples, i.e. with or without associated meteorological data. We analysed the Chinese sites as passive samples with the Physg3brcAZ dataset, and as active samples with both the Physg3arcAZ and Physg3brcAZ datasets. All these analyses were made with the software CANOCO v.4.5 (ter Braak and Smilauer, 1997–2002). To be consistent, gridded meteorological data were used for all datasets.

2.3. Establishing a new calibration

To develop a new model appropriate for monsoonal climates, we assembled a new dataset that combines the Physg3brcAZ sites with the new Chinese sites. This new dataset is called PhysgAsia1. Here PhysgAsia1 is analysed with gridded meteorological data, GridMetAsia1. The new dataset includes 189 sites. The correlation between physiognomic characters and climate parameters was explored using CCA (ter Braak, 1986), as implemented in CANOCO v.4.5 (ter Braak and Smilauer, 1997–2002). All the procedures follow the protocols given on the CLAMP website (http://clamp.ibcas.ac.cn).

In physiognomic space, climate parameters are represented by vectors, sites by points. The orthogonal projection of a site to a climatic vector in the first four axes of variation defines its vector score. The relationships between the climatic parameters and vectors can then be investigated. In CLAMP, for each climatic parameter a 2nd order polynomial regression is fitted between the vector scores and the observed climatic values (Spicer, 2008). Because there are 11 climatic parameters studied, a CLAMP calibration consists of 11 regressions. For this study, the software SPSS v.17.0 was used to fit the regressions. The standard deviation of the residuals about the regression line is used as a measure of the uncertainty of the climate estimates. This method of estimating uncertainty incorporates uncertainty across all physiognomic space (i.e. all leaf character states across all taxa), rather than attempting to isolate individual leaf character/climate variable relationships. Such isolation would negate the multivariate nature of foliar physiognomic adaptations to climate.

2.4. Cross-validation test of the new calibration

The new PhysgAsia1 calibration dataset needs to be tested to see how well it estimates monsoonal climate characteristics. The problem is that all available monsoonal sites are included in the calibration dataset; therefore, they cannot be used to test the model. To overcome this problem, we used a cross-validation procedure (Stone, 1974; Geisser, 1975). Five sites were randomly removed from the dataset, a new calibration was established without them, and then their climate was predicted using this slightly modified calibration. This process was repeated until all sites were excluded once. As the whole new dataset includes 189 sites, of which 45 sites are in the monsoonal region, the removal of only five sites should only have a small effect on the model. Because our focus is the estimation of monsoon climates, this procedure was applied only to monsoonal sites. To ensure the randomness of site selection, we logged on to the www.random.org website and used the sequence generator from 1 to 45 (made on 25.10.2010).

The mean absolute error between the estimated and observed values for all Chinese sites was then calculated for each climate parameter. To serve as a reference, we calculated the same mean errors when all Chinese sites were included as passive samples, i.e. when the climate values were estimated only based on a Physg3brcAZ calibration.

2.5. Application to fossil sites

The new calibration (PhysgAsia1) was used to recalculate the climatic values of two Late Miocene fossil sites from Yunnan in southwest China: Lincang (Jacques et al., in press) and Xiaolongtan (Xia et al., 2009). The Lincang site is situated near Zhongzhai village (23°54′ N, 100°01′ E) and the fossil assemblage lies within the Bangmai Formation. Fossils belonging to 73 species, 51 genera and 35 families were recovered from this assemblage (Guo and Zhou, in press; Jacques et al., in press). The Xiaolongtan site is situated within the top layer of lignite in the eponymous coalmine (23°49′ N, 103°12′ E) and belongs to the Xiaolongtan Formation; fossils belonging to 54 species, 45 genera and 21 families were collected from there (Zhou, 1985; Xia et al., 2009). A monsoonal palaeoclimate has been suggested for both these floras. Therefore, they offer a good opportunity to test the reconstruction of past monsoon climates. Because the leaf physiognomic scores of the calibration datasets recently underwent minor revision, we also slightly revised the leaf physiognomic scores of the two fossil floras. The classic CLAMP procedure was applied using the PhysgAsia1 calibration dataset. The two cited studies (Xia et al., 2009; Jacques et al., in press) used the ungridded Met3br dataset. In order to standardize the comparison, we also recalculated the palaeoclimatic estimates for these two floras using the gridded GRIDMet3brAZ dataset.

3. Results

3.1. The Chinese sites and the existing CLAMP datasets

When the 45 new Chinese sites were included as passive samples and analysed with the Physg3brcAZ dataset and the GRIDMet3brAZ climate data, they form a cluster in physiognomic space that is distinct from the positions of other sites previously in the dataset (Fig. 1). This cluster lies close to the GSP vector, which indicates that the Chinese sites display physiognomy typical of a strong precipitation signal. It is clear from this distinctive positioning that leaf physiognomy of monsoonal vegetation in China is different from leaf physiognomy of all previous sites included in this dataset.

When the 45 new Chinese sites were included as active and analysed together with the Physg3arcAZ dataset, they again formed a

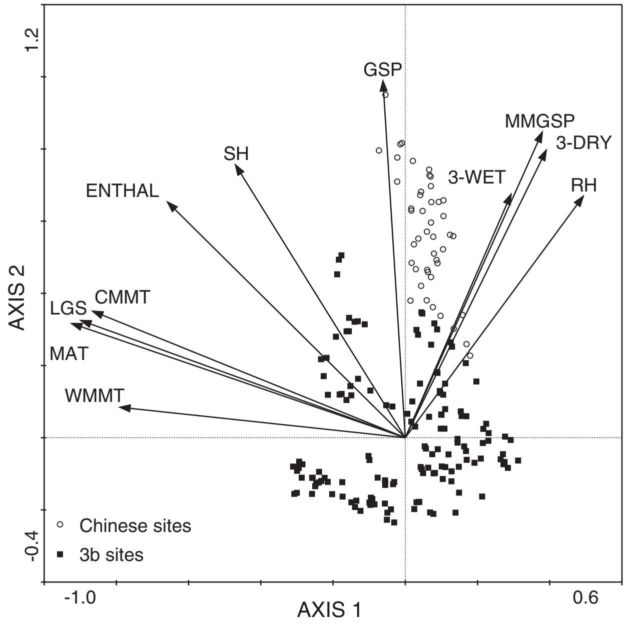

Fig. 1. Physiognomic space of the Physg3brcAZ calibration with Chinese sites included as passive samples. Chinese sites (circles) group in the upper left quadrant, away from most 3b sites (squares).

cluster distinct from other sites (Fig. 2). Moreover, no Chinese sites showed affinities with the alpine nest (triangles).

3.2. The new CLAMP calibration

We used the PhysgAsia1 dataset to establish the new calibration. The positions of these sites in physiognomic space are given both in a three-dimensional view (Fig. 3) and in a two-dimensional view (Fig. 4). The Chinese sites clearly fill a new part of physiognomic space, and bring new information to the CLAMP calibration dataset. The trend in GSP is indicated as a color gradient from red (dry) to blue (wet): the positions of the monsoonal sites show no strong correlation with non-monsoonal sites with a similar GSP (Fig. 4).

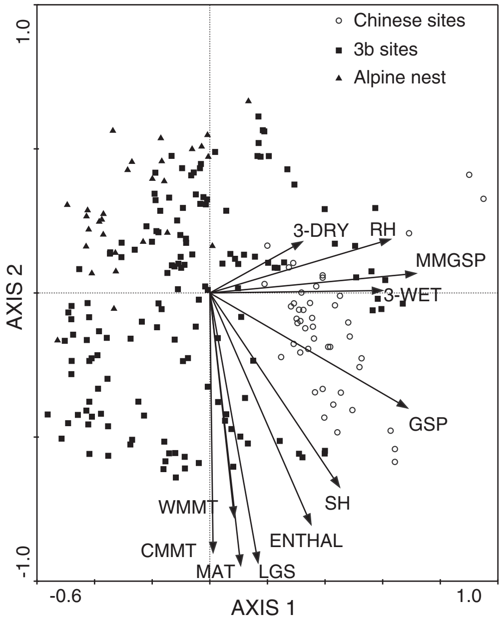

Fig. 2. Physiognomic space of the Physg3arcAZ calibration with Chinese sites included as active. No Chinese site (circles) plots within the existing CLAMP alpine nest (triangles).

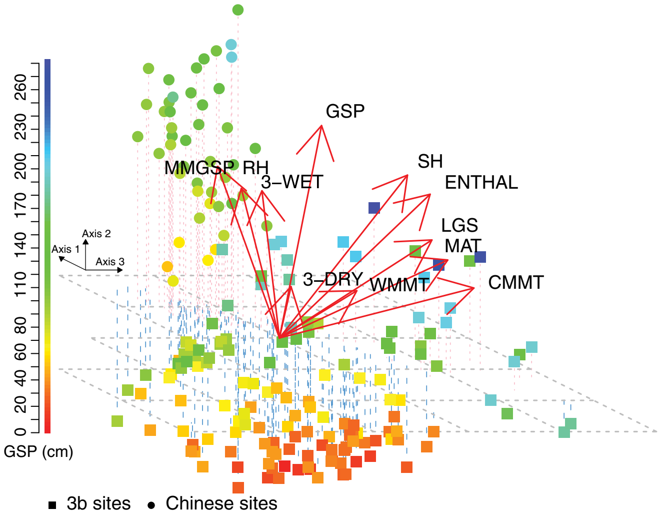

Fig. 3. Three-dimensional view of physiognomic space using the PhysgAsia1 dataset for calibration. The color gradient refers to GSP. Chinese sites (circles) group away from the 3b sites (squares), even those with high GSP scores (in blue).

Regressions of observed climatic parameters on vector scores were established for all eleven climatic parameters (available from the CLAMP website). Regressions of observed MAT and GSP on vector scores are shown in Figs. 5 and 6 respectively. The standard deviation of the residuals was evaluated for each climatic parameter (Table 2). Compared to the Physg3brcAZ calibration, our new calibration which includes the monsoonal sites, shows similar uncertainty, except for CMMT and 3-DRY where the uncertainty is higher.

3.3. Cross-validation of the new model

Results of the cross-validation test are expressed as the mean absolute errors between observed and estimated values for each climatic parameter (Table 3). The disparity is very large for precipitation parameters when the Chinese sites are included as passive samples in the Physg3brcAZ dataset: the mean absolute error for GSP is over 1600 mm. The new calibration yields dramatically reduced errors for precipitation values (e.g. less than 300 mm for GSP). All other climatic parameters also show a better precision (Table 3).

3.4. Application to fossil sites

Climatic values for the Lincang and Xiaolongtan fossil sites using the ungridded, and gridded Physg3brcAZ, and PhysgAsia1 datasets are given in Table 4. There is little difference between all models for temperatures, but the values for precipitation are markedly different. For Lincang, GSP decreases from 4587.4 mm using the ungridded Physg3brcAZ calibration to 2269.7 mm using the new calibration.

4. Discussion

4.1. Leaf physiognomy is different in monsoon climates

Analysis of Chinese sites either as passive (Fig. 1) or active (Figs. 3, 4) with the Physg3brcAZ dataset always results in them occupying a region of physiognomic space that is distinct from that occupied by sites comprising the original Physg3brcAZ dataset. Because this difference also exists when sites are passive, it is not an artifact due to some structure in the meteorological data. An initial interpretation might be that the monsoon brings high precipitation

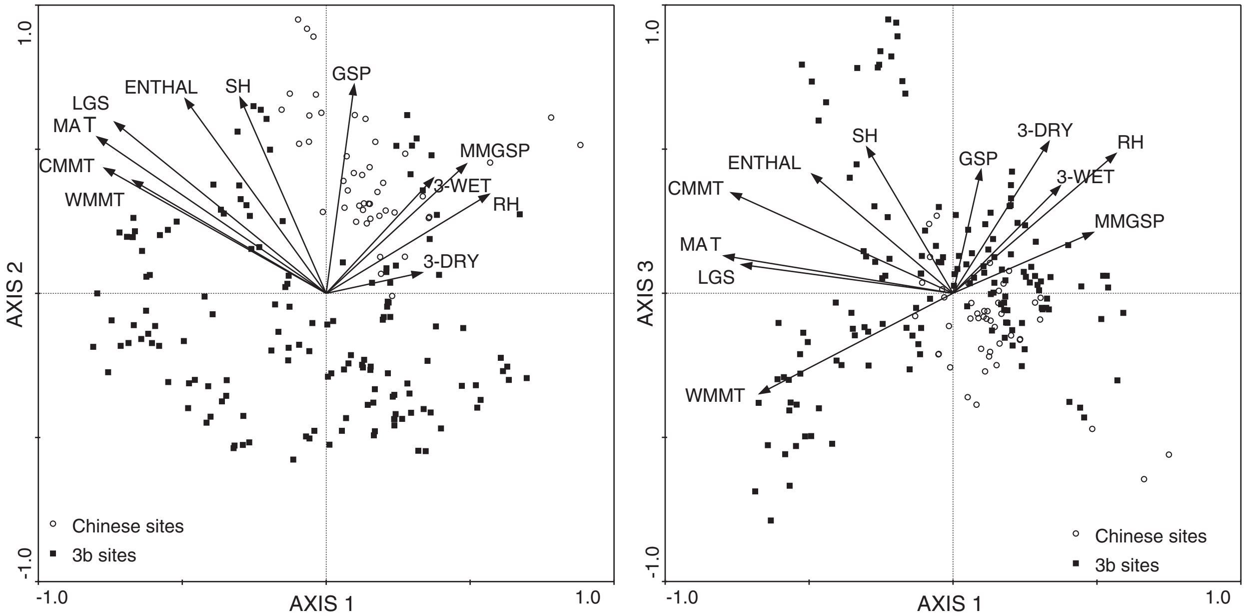

Fig. 4. Two-dimensional views of the physiognomic space of the PhysgAsia1 calibration in Axis 1/2 space and Axis 1/3 space. On the Axis 1 vs. Axis 3 diagram, points grouped in the upper left corner are high GSP sites from Puerto Rico and Fiji.

and that this position is due to differences in GSP. However, the Physg3brcAZ dataset already includes some high-GSP sites, from Puerto Rico and the Fiji Islands. Looking at the 3-dimensional representation of physiognomic space (Fig. 3) it is clear that the positions of the monsoon sites are not only a function of a GSP gradient. On the axis 3 versus axis 1 projection (Fig. 4), high GSP sites of Puerto Rico and Fiji Islands are totally separate from the Chinese sites. On the other hand, 3-DRY and 3-WET vectors point towards the high precipitation values in the Chinese dataset (Figs. 3 and 4); thus, the trend in the Chinese data is aligned with the vectors of seasonality in rainfall. We suggest that this association could be used to recognize a monsoon signal. We are aware that our new dataset is biased towards Chinese sites, and that the Asian monsoon influences many other countries. Clearly, therefore, our hypothesis of a monsoonal signal has to be validated using additional data from other regions under monsoonal influence, such as India.

The Asian monsoon climate, compared to other climates, is characterized by a wet summer and a dry winter, with a rather high GSP (Lau and Chan, 1983). Air masses are generally saturated with moisture during the warm season, but plants experience drier conditions during the winter. In South China, the growing season extends almost throughout the year with many evergreen taxa present in the vegetation (Wu, 1980). Leaves must be adapted to the entire growing season (Spicer et al., 2004). Therefore, through natural selection, only leaves that can resist seasonal drought grow under monsoonal conditions. This might have selected features that are not encountered in high-precipitation regimes without strong seasonality in precipitation. Characters relating to the size of the leaf, acute teeth and attenuate apex seem to have a strong influence on the position of the Chinese sites. However, more studies are needed to understand how site positions in the CLAMP physiognomic space are driven by specific physiognomic characters.

Because leaf physiognomies are different under monsoon climates from those in wet climates without strong seasonality in precipitation, we expect to be able to distinguish such climates based on fossil leaf assemblages. To do so, we first need a good calibration based on a modern training set.

4.2. The new calibration

Some of the Chinese sites come from north-east China where the climatic conditions are very cold, especially in winter. Before establishing a new calibration, we tested whether or not some Chinese sites belong to the alpine nest, as sites from the alpine nest are

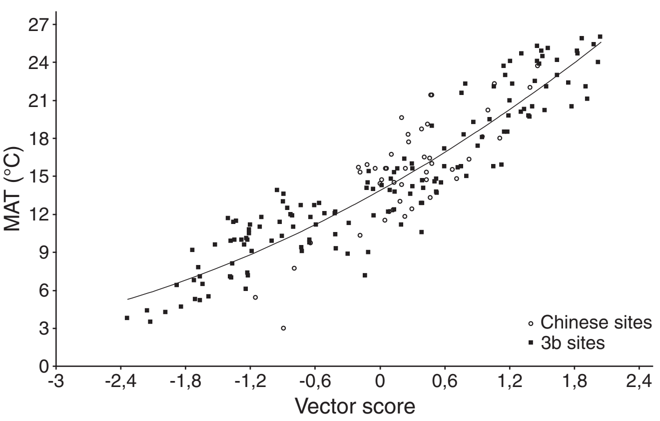

Fig. 5. Regressions of observed gridded MAT on vector score, PhysgAsia1 calibration.

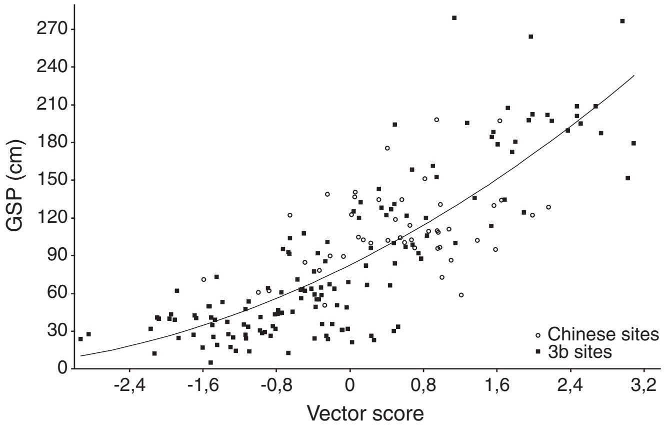

Fig. 6. Regressions of observed gridded GSP on vector score, PhysgAsia1 calibration.

Table 2
Standard errors of CLAMP calibrations.

Climate parameter	Gridded Physg3brcAZ	PhysgAsia1
MAT (°C)	1.17	1.25
WMMT(°C)	1.39	1.51
CMMT (°C)	1.88	2.57
LGS (month)	0.69	0.74
GSP (mm)	201.8	217.7
MMGSP (mm)	26.1	25.3
3-WET (mm)	146.3	139.0
3-DRY (mm)	32.0	41.2
RH (%)	5.08	6.04
SH (g/kg)	1.00	1.09
ENTHAL (kJ/kg)	4.5	5.4

Table 3
Mean absolute errors between estimated and observed values for the 45 Chinese sites analysed with the Physg3brcAZ dataset. Chinese sites are included either as passive or active samples; when included as passive, we used a cross-validation process.

Climate parameter	Chinese sites as passive	Chinese sites as active
MAT (°C)	3.18	2.21
WMMT(°C)	3.53	2.56
CMMT (°C)	4.30	3.84
LGS (month)	1.48	1.19
GSP (mm)	1609.6	294.6
MMGSP (mm)	216.2	33.3
3-WET (mm)	416.7	123.8
3-DRY (mm)	269.6	50.9
RH (%)	9.90	5.57
SH (g/kg)	4.02	1.72
ENTHAL (kJ/kg)	18.8	7.6

known to lower the accuracy and precision of temperature reconstructions (Wolfe, 1993). When the Chinese sites were analysed with the Physg3arcAZ dataset that included the alpine nest, none of the Chinese sites plotted within this nest (Fig. 2). Therefore, we kept all the Chinese sites for the new calibration and excluded alpine nest sites that are part of the Physg3arcAZ dataset (i.e. we used the Physg3brcAZ dataset).

It is possible to include any sites in a CLAMP calibration dataset. However, all calibrations are not of the same value: a good calibration should be able to predict climatic parameters confidently and with small standard deviations. The new calibration (PhysgAsia1) shows similar standard deviations compared to the gridded Physg3brcAZ calibration (Table 2). There is a significant loss of accuracy only for CMMT and 3-DRY. The ability to predict Chinese climatic parameters using the gridded Physg3brcAZ calibration is poor for moisture related variables (Table 3): whereas all Chinese sites have a 3-DRY value below 200 mm, the mean absolute error for this parameter is 269.6 mm when Chinese sites are passive. The cross-validation test indicates a real increase in predictive capability for moisture related variables of the Chinese sites (Table 3): the mean absolute error for 3-DRY decreases to 50.9 mm. Previous CLAMP calibrations were known to have a poor correlation between physiognomy and precipitation parameters under wet climates; the new calibration proposed here overcomes this problem, at least for Chinese monsoonal sites. The ability of the new calibration to predict more accurately (as indicated by cross-validation) precipitation variables is very important: it allows for a good evaluation of past monsoon strength and evolution. Use of correction coefficients as proposed by Teodoridis et al. (2011) may improve further the accuracy of the calibration.

CLAMP can also be used to reconstruct enthalpy, a property of the atmosphere useful in determining palaeoaltitudes (Forest et al., 1995; Wolfe et al., 1998; Spicer et al., 2003). For the new calibration, the standard deviation is estimated at 5.4 kJ/kg and the cross-validation test gives a mean absolute error of 7.6 kJ/kg, compared to 4.5 and 18.8 kJ/kg, respectively, for the Physg3brcAZ calibration alone. Thus the new model can also give improved precision for enthalpy estimates, and therefore palaeoaltitude estimates, for regions with a complicated geological history linked with the uplift of the Tibetan Plateau, i.e. southwestern China.

Gridded data usually give lower precipitation values than ungridded data for the Phys3brcAZ dataset (Spicer et al., 2009). The difference between gridded and ungridded was not tested for the Chinese sites. However, as the new calibration is based on the GRIDMet3brAZ dataset, we also expect lower precipitation values for gridded data than for ungridded data. Spicer et al. (2009) noted that "3-WET and 3-DRY values should be regarded as indicative of the degree of seasonal variations in rainfall". As the seasonal variations between the wet and dry seasons is a major interest in monsoonal reconstruction, gridded data should be accurate enough, and in any case it is the gridded form of climate data that is used extensively in climate model evaluation studies.

4.3. Estimation of palaeoclimates

The new calibration was used to reconstruct the palaeoclimate of two Late Miocene leaf assemblages from Lincang and Xiaolongtan. The values obtained for temperature variables are similar to those observed with the gridded and ungridded Physg3brcAZ dataset (Table 4). This suggests that CLAMP is robust in estimating temperatures.

The new calibration gives significantly lower values for precipitation parameters (Table 4). The gridded Physg3brcAZ estimates of precipitation parameters for the Yunnan fossil sites are lower than

Table 4
Palaeoclimatic reconstruction of two Late Miocene fossil sites, Lincang and Xiaolongtan, using three different CLAMP calibration datasets (Ungridded Physg3brcAz, Gridded Physg3brcAZ, PhysgAsia1), the Chinese Leaf Margin Analysis (LMA) and Coexistence Approach (CA).

Climate parameter	Lincang					Xiaolongtan				
	LMA	CA	Ungridded Physg3brcAZ	Gridded Physg3brcAZ	PhysgAsia1	LMA	CA	Ungridded Physg3brcAZ	Gridded Physg3brcAZ	PhysgAsia1
MAT (°C)	22.0 ± 1.9[a]	18.5–19.0	23.2	20.9	19.8	20.1 ± 2.3	16.7–19.2	21.7	19.6	19.9
WMMT(°C)		27.3–27.8	29.0	28.9	27.3		25.4–26.0	29.0	27.5	26.7
CMMT (°C)		9.6–12.5	13.5	11.9	11.2		7.7–8.7	13.5	11.8	12.5
LGS (month)			12.9	11.1	10.2			11.9	10.5	10.1
GSP (mm)		1213–1394[b]	4587.4	2934.2	2269.7		1215–1639[b]	3199.3	2230.6	1970.3
MMGSP (mm)			494.8	346.9	231.4			332.7	253.2	201.4
3-WET (mm)			1948.8	1060.0	924.4			1377.1	921.9	827.8
3-DRY (mm)			1324.2	350.8	220.6			749.4	261.5	210.3
RH (%)			78.1	82.28	84.98			73.00	76.87	80.72
SH (g/kg)			12.10	13.71	13.15			10.61	11.44	12.58
ENTHAL (kJ/kg)			326.1	347.8	344.1			321.5	337.5	342.3

[a] Data from Jacques et al. (in press).

[b] Mean annual precipitation.

those from the ungridded Physg3brcAZ (Table 4), as is generally the case between these two calibrations (Spicer et al., 2009). However, the values obtained by the new calibration are significantly lower than those obtained by the gridded Physg3brcAZ calibration. Therefore, we can conclude that the lowering of precipitation estimates is only partly due to the use of gridded data; the inclusion of monsoonal calibration sites is responsible for some of this decrease. Because the new calibration corresponds to a real improvement in estimating precipitation parameters, we recommend its use for all Chinese and East Asian fossil sites when a monsoonal climate is suspected. To facilitate wider use of our new calibration, all necessary files, i.e. physiognomic data, meteorological data, and the scoring spreadsheets, are available as supplementary data and on the CLAMP website.

Several geographic regions have already proven to have different physiognomic signatures (Stranks and England, 1997; Kowalski, 2002; Spicer et al., 2004). As a result, several CLAMP calibrations are available. Does the use of the new monsoonal calibration for reconstructing palaeoclimates bias the results towards a monsoonal regime? In other words, can one confidently demonstrate a monsoonal type of palaeoclimate using the new calibration? To see if a monsoonal signal is likely we suggest an initial exploration of physiognomic space with all available calibration sites: if the fossil assemblage plots inside or near the monsoonal cluster, then the monsoonal calibration can be used with confidence. A way to avoid these multiple calibrations is to use a nearest neighbor approach, like that proposed by Stranks and England (1997). But this method has still to be implemented in a user friendly way.

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