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Progress in Natural Science 18 (2008) 1459–1464

Progress in Natural Science

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Review

Progress in studies of the climate of humid period and the impacts of changing precession in early-mid Holocene

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Received 9 December 2007; received in revised form 27 May 2008; accepted 28 May 2008

Abstract

Studies on the climate of humid period and the impacts of changing precession in the early-mid Holocene are reviewed in this paper. High-resolution proxy data indicated that the African Humid Period, strong summer monsoon from the Arabian Sea to South Asia, northward migration of ITCZ (Intertropical Convergence Zone) over the northern South America, and the humid period of China appeared in 10.5–5.5 kaBP, 10.0–6.0 kaBP, 10.5–5.4 kaBP, and 11.0–8.0 kaBP, respectively. Modeling studies proved that summer insolation over the Northern Hemisphere increased following the changes of precession in the early Holocene, which increased the land–sea temperature contrasts, intensified the summer monsoon circulation in the Northern Hemisphere, and finally induced a humid climate over the area under the influence of summer monsoon. However, modeling results underestimated the increase of precipitation and the degree of northward extension of monsoon rain belt compared with palaeo-environmental data. These discrepancies between the modeling results and the palaeo-environmental data may be associated with the changes of North Atlantic circulation, sea ice and vegetation covers. Moreover, climate of the humid period was not stable, in which several droughts were inlaid on centennial scale. In this review, perspectives for further studies of the climate change of the humid period in the early-mid Holocene are also proposed.

Keywords: Holocene; Humid period; Precession; Summer monsoon

1. Introduction

As the earth's climate entered into the Holocene (11.5 kaBP, calendar year, where kaBP means thousand years before 1950 A.D.) from last glacier, the temperatures in the high latitudes became warmer than that in the glacial time. In tropics, the precipitation increased prominently. The African Humid Period is an excellent example [1,2]. Studies also indicated that the humid period occurred over the area from the Arabian Peninsula to the Bay of Bengal and the coastal area of Venezuela over the northern South America in the early-mid Holocene [3–5]. In addition, the existence of Holocene humid period in China was also confirmed [6]. The climate model simulations of Holocene suggested that the humid period over the above-mentioned areas may have been controlled by a primary factor, the changes of precession [7–10]. The changing precession caused an increase in the amplitude of the seasonal cycle of insolation over the Northern Hemisphere, and enhanced the summertime land–sea temperature contrasts, and thereby strengthened the northern summer monsoons and increased the precipitation in the early Holocene. Today, with more high temporal resolution palaeo-environmental data (locations of the representative proxy data are shown in Fig. 1) and an improved climate model, details of the humid climate in the early-mid Holocene have been further

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doi:10.1016/j.pnsc.2008.05.011

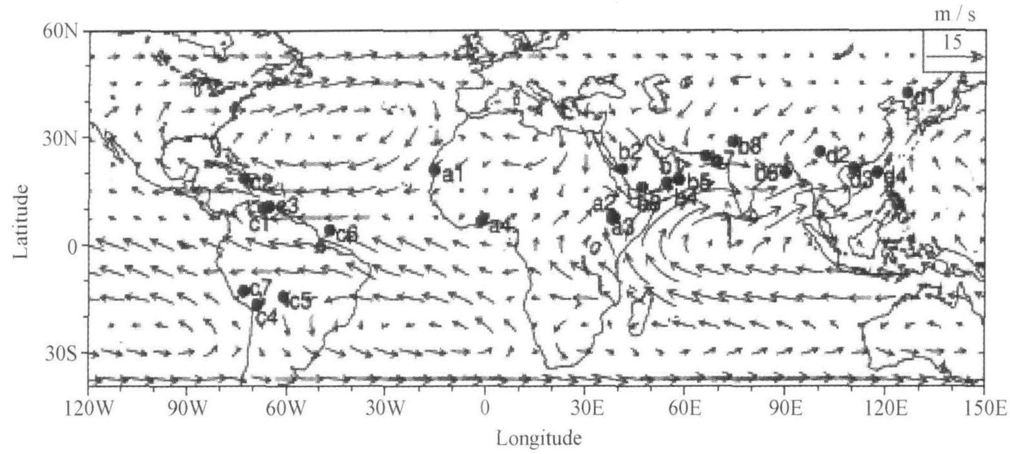

Fig. 1. Schematic map of the representative proxy data sites reviewed in this paper and the 850 hPa summer (June–August) wind field obtained from NCEP Reanalysis-2 (1979–2007), which reflects the summer monsoon circulation (units: m/s). a1–a4 indicate the African Humid Period and the details can be seen in Table 1; b1–b8 indicate the Asian southwest monsoon and the details can be seen in Table 2; c1–c7 indicate humid period in South America; d1–d4 indicate the humid period in China and details can be seen in Table 3. The NCEP Reanalysis-2 was downloaded from the website http://www.cdc.noaa.gov/PublicData/tables/monthly.html.

understood. In this paper, studies on the climate of the humid period in the early-mid Holocene during the past 10 years are reviewed.

2. Evidence for humid period

2.1. Green Sahara

Sahara was not an extremely arid desert as it is today until the Pyramid Period (about 4.5 kaBP). Palaeo-environmental data and magnificent petrogram verified that Sahara was wet in the early-mid Holocene known as "Green Sahara" [1,2]. The first assessment of the humid period, based on the widespread palaeo-environment data, was provided by Street and Grove [11], in which globally 141 closed lake records during the past 30 ka were analyzed. The lake-level status is classified as follows: high status: ⩾70% of the highest level; intermediate status: 20–70% of the highest level; and low status: ⩽20% of the highest level. The results demonstrated that the frequency of high lake level in tropical Africa was higher during the period of 10–5 kaBP (^{14}C year) than that before 10 kaBP and after 5 kaBP. Recently, further studies also supported the occurrence of the African Humid Period in the early-mid Holocene using high temporal resolution palaeo-environmental data. For example, the reduced terrigenous (eolian) concentrations in the marine sediment records in the coastal area of Mauritania of Northwest Africa suggested a great increase in rainfall and vegetation cover during 14.8–5.5 kaBP in the now hyperarid Sahara desert [12]. In addition, the diatoms-inferred electric conductivity in the Lake Abiyata of the East African Rift stayed at a relatively low level from 10.8 to 6.0 kaBP, which implied a wet climate during this period [13]. In 2004, Hoelzmann [2] pointed out that the African Humid Period occurred in the period of 10.5–5.5 kaBP through the analysis of 23 palaeolake series, 14 palaeo-vegetation series from North Africa to the Arabian Sea and 5 sediment series adjacent to the Arabian Sea (10°N–23°N, 20°W–70°E).

As shown in Table 1, there are four representative sequences of the African Humid Period. The sites of these sequences are under the influence of the summer monsoon (Fig. 1). The 1st and 4th sequences began earlier because the influence of the starting time of the strengthening summer insolation over the Northern Hemisphere was considered. The 3rd one is separated into two episodes due to the interruption caused by the 8.2 kaBP, a cold event. Generally, these sequences supported that the African Humid Period occurred in 10.5–5.5 kaBP. Therefore, in this review the African Humid Period is assumed to be from 10.5 kaBP to 5.5 kaBP.

2.2. Evidence from the Arabian Peninsula to the Bay of Bengal

Gupta [16] investigated the variations in Asian southwest monsoon intensity by exploring the sediment records from the Gulf of Oman, and found that the peak

Table 1
Representative sequences of the African Humid Period

No.	Location	Proxy	Humid period (kaBP)	References
1	Coast of West Africa	Terrigenous concentrations	14.8–5.5	[12]
2	East African Rift	Diatoms-inferred conductivity	10.8–6.0	[13]
3	The Horn of Africa	Lake level	10.7–9.5, 6.3–5.1	[14]
4	Tropical Africa	Lake level	14–5.5	[15]

of southwest summer monsoon intensity was at 10 kaBP and 9 kaBP, then weakened till to 1.4 kaBP. Overpeck [3] also pointed out that the southwest monsoon was strong during 10.8–6.1 kaBP by comparing 3 planktic foraminifer records of the marine sediment 150 km adjacent to the Oman margin (RC27) and the pollen records with 25 palaeo-environmental series from North Africa, the Arabian Peninsula, North India, and the Qinghai-Tibet Plateau. Other studies also supported that the Asian southwest monsoon was strong in the early-mid Holocene. For example, the $\delta^{18}O$ records in stalagmite indicated that the southwest summer monsoon had strengthened significantly since 10.3 kaBP, and then weakened gradually from 7.0 kaBP [17]. The lake sediments [18] suggested that there are four lakes that expanded during 11.0–7.5 kaBP in Yemen. Recently, Staubwasser [4] also obtained a similar conclusion, which showed that the South Asian monsoon rainfall enhanced during 9–6 kaBP.

The sequences given in Table 2 are located in the South Asian monsoon region (b1–b8 in Fig. 1). Although these sequences that are derived from different proxy data are not exactly consistent, they supported that there was an interval in the early-mid Holocene, in which the South Asian monsoon was strong and the climate was wet. Among these sequences, the 2nd and 5th sequences are the typical representatives due to the integration of many proxy data [2,3]. Therefore, in this review, the Holocene humid period from the Arabian Peninsula to India is considered to be 10–6 kaBP.

2.3. Evidence in South America

The influences of the changing precession on the climate of South America are also examined in this review. If the changing precession is the basic driver of the Holocene humid period, there should have been an evidence for opposite responses in precipitation on both the sides of the equator in South America. The continental shelf of the North Venezuela, which is located at about 10°N, sits at the present northern limit of the summer migration of ITCZ (Intertropical Convergence Zone) and the associated rainfall belt. In summer, the rainfalls flow directly into the Cariaco Basin from the land with terrigenous material (c1 in Fig. 1). Therefore, the variations in the content of Fe and Ti in the marine sediments can reflect the changes of terrigenous material and rainfalls on land [5]. The variations in the concentrations of Fe and Ti suggested that there was plentiful precipitation during 10.5–5.4 kaBP. Other proxies also proved that the changing precession dominates climate humidity variations of South America in Holocene, such as lake records in Haiti [22] (c2 in Fig. 1) and pollen records in the Lake Valencia of North Venezuela [23] (c3 in Fig. 1).

Table 2
Period of the strong Asian southwest monsoon

No.	Location	Proxy	Strong monsoon period (kaBP)	References
1	Oman	$\delta^{18}O$ in stalagmite	9.6–5.5	[17]
2	Arabian Peninsula	Palaeo lake Palaeo vegetation	9.9–6.1	[2]
3	Yemen	Lake sediments	11.0–7.5	[18]
4	Gulf of Oman	Foraminifer (%)	10.2–6.5	[16]
5	Gulf of Oman	Pollen	10.8–6.1	[3]
6	Bay of Bengal	$\delta^{18}O$ in foraminifer	7.9–5.2	[19]
7	Indus	$\delta^{18}O$ in foraminifer	9.4–5.0	[20]
8	Thar Desert	Lake sediments	7.3–4.9	[21]

The variation of humidity in the south-central South America is another strong evidence for the impacts of the changing precession on the climate of South America. In contrast to the situations in the northern South America, droughts occurred in south-central South America in the early-mid Holocene while it was moist in the late Holocene. Sediments in the Lake Titicaca of southern Peru indicated that there were plentiful rainfall in 4.0–2.4 kaBP [24] (c4 in Fig. 1). Pollen records from the southern Amazon suggested that the humid evergreen forest expanded farther southward in the late Holocene [25] (c5 in Fig. 1). The runoff of the Amazon decreased in the early Holocene [26] (c6 in Fig. 1), which is similar to the situations of $\delta^{18}O$ in the Lake Junin of the central Peru [27] (c7 in Fig. 1). Núñez [28] analyzed the archaeological evidence from the Atacama Desert of northern Chile to the Plateau (20°S–25°S) in South America and pointed out that there was a significant decline, even a hiatus in human occupation during 9.0–4.5 kaBP (calendar year) due to aridity stress, known as Silencio Arqueológico. Furthermore, much more palaeo-environmental evidence, such as palaeolake sediments and pollen and alga records, also indicated that droughts expanded from North Chile to Peru and lakes shrank, even disappeared during 8.0–3.6 kaBP (^{14}C year).

2.4. Climate of the humid period in China

Based on the data from ice core, inland palaeolakes, palaeosols in loess and eolian sands, sea level fluctuations, palaeozoological and archeological evidence, Shi [29] pointed out that Holocene Megathermal appeared mainly in China during 8.5–3 kaBP and lasted till 5.5 ka. During this period, the climate was warm and wet, the summer monsoon strengthened and the vegetation belt shifted northward 2–5° over the plain of the eastern China, especially in Megathermal Maximum ca. 7.2–6.0 kaBP [30,31]. In addition, An et al. [32] examined the Holocene optimum in different parts of China with precipitation or effective moisture and pointed out that the humid period existed in Northeast China and North China in 12.0–10.0 kaBP and 10.0–7.0 kaBP (^{14}C year), respectively. They also indicated that the humid period reflects the enhancement of the Asian summer monsoon and may result from the changes of precession.

In the past 10 years, more and more high-resolution palaeo-environmental sequences have been exploited to study the changes of the climate humidity in Holocene. Based on these high-resolution data, the Holocene climate in China can be examined on centennial, multi-decadal, even on annual time-scale. Four palaeo-environmental sequences, which are situated in South and Northeast China (d1–d4 in Fig. 1), are summarized in Table 3. The humid period is defined as the anomaly exceeding 1σ. It can be found that ca. 11.0–8.0 kaBP is the common interval in these sequences. Additionally, the 1st and 2nd series seem to be interrupted by a cold event. Therefore, in this review, 11.0–8.0 kaBP is considered as the Holocene humid period in China.

3. Modeling studies

The impacts of the changing precession on the climate have been extensively studied using the atmosphere circulation model (AGCM) since the 1980s [37–39]. deMenocal [12] examined the relationship between the African Humid Period and the changing insolation, and pointed out that the African Humid Period corresponds to the interval in which the insolation increases by 4% than that of today. Prell and Kutzbach [40] through sensitive experiments also indicated that the rainfalls increase by 25–50% in the tropics of the Northern Hemisphere when the insolation increases 10%.

Since the 1990s, PMIP (Palaeoclimate Modelling Intercomparison Project) began to focus on the climate change research of two slices including the 21 kaBP, which represents the Last Glacier Maximum (LGM), and 6 kaBP. The IPCC AR4 indicated that the development of glacier is associated primarily with the temperature in the summer [41]. Due to the existence of the Laurentide ice sheet, the boundary condition is too complex in early Holocene. Consequently, the 6 kaBP is still used to represent the warm period of the Holocene in the modeling study, although it is not the warmest episode in the Holocene. The PMIP has integrated 18 model results to evaluate the paleoclimate changes. There are two palaeo-environmental datasets which are provided to test the modeling results. The GLSDB (Global Lake Status Data Base) [42], which collected lake level, area and capacity records spanning the past 30 kaBP, indicated that it was wetter in North Africa, the Arabian Peninsula, Southwest China and the Central America at 6 kaBP than it is today. BIOME6000 [43], which is a widespread vegetation distribution dataset derived from the pollen and plant fossils records, showed that the forest advanced to the inland of China and vegetation of Sahel expanded to Sahara when monsoon activities enhanced. Consequently, there are two ways to examine the palaeoclimate by comparing the model results with the observations using forward modeling techniques or inverse techniques. The former firstly requires the environmental indexes, such as vegetation and hydrographic indexes from environmental model, and then compares them with BIOME. The latter firstly obtains the temperature and precipitation information from palaeo-environmental data using inverse techniques, and then compares them with the modeling results. The results showed that AGCM can generally capture the major features of the impacts of the changing precession on climate: the increased seasonal cycle of insolation in Northern Hemisphere, the rising summer temperature over Eurasia, the increased evaporation transport from ocean to continents, the strengthening summer monsoon, the advancement of rain belt from Sahel to Sahara and increased rainfalls in the inland of Asia. However, the model results usually underestimated the increase of rainfall and the degree of northward extension of the rain belt [44]. For example, BIOM suggested that grassland can reach 23°N at 6 kaBP; however, in the model result rainfall is 100 mm less than that needed, and Chad Lake in the model result was 30% smaller than the observations of GLSDB.

The seasonal temperature cycle on the land in AOGCM (Atmosphere-Ocean Coupled Model) is more prominent than that in AGCM [8]. The warming associated with the changing precession is postponed to July–October in AOGCM when compared with that in June–September in AGCM. Ocean favors the enhancement of summer monsoon and induces the migration of rain belt farther northward over Africa in the model. The maximum rain belt reaches 10°–15°N in AGCM and farther northward to 15°–18°N in AOGCM. However, this is still not enough to properly explain the grassland distribution of North Africa in the early Holocene.

Studies also indicated that the feedbacks involving oceans, vegetation cover and sea ice play very important roles in climate changes [45–49]. Therefore, it is urgent to develop an advanced coupled ocean-atmosphere-vegetation model to improve the model simulation. In addition, the African Humid Period began and terminated abruptly [50], which may be associated with multi-equilibrium states [51]. Long-term climate simulation should be carried out to examine the abrupt climate change in Holocene using advanced earth system models of intermediate complexity (EMIC) [52].

Table 3
Holocene climate of the humid period in China

No.	Location	Proxies	Climate of humid period (kaBP)	References
1	Hani	$\delta^{13}C$ in peat (‰)	10.8–9.5, 8.8–8.3	[33]
2	Erhai Lake	TOC (%)	11.0–10.0, 8.5–6.0	[34]
3	Lake Huguang Maar	TOC (%)	11.0–8.2	[35]
4	South China Sea	Climate humidity (relative value)	11.0–8.2	[36]

4. Conclusions and perspectives

A great number of high-resolution proxy data indicated that the humid period appeared in Africa, from the Arabian Sea to South Asia, the northern South America and China in the early-mid Holocene. Due to the predominance of monsoon precipitation in these regions, the monsoon activities determine the occurrence of humid period. The humid period over the above-mentioned areas seems to not have begun at the same time in Holocene. This difference may be associated with boundary conditions and proxy data [32]. Although the intervals of humid period are not exactly consistent in these regions, they are in agreement during the period of 10–8 kaBP. These study results suggested that the Holocene humid period of these regions which cover a vast tropical monsoon area, should be mainly controlled by a planetary scale factor. In boreal tropics, the Holocene climate was featured with large humidity changes in contrast to large temperature changes in boreal extratropics. The climate simulation of Holocene forced with the changing precession obtained similar results. Therefore, the general agreement in the Holocene humid period among palaeo-environmental data, and the insolation variations driven by the changing precession and Holocene climate simulations, indicated that the precession is the most important driver of the variations in Holocene summer monsoon precipitation in boreal tropics.

Comparison of paleoclimate records with the Holocene climate model simulation indicated that there are some discrepancies, for example, the model results underestimated the amplitude of the summer monsoon precipitation variations and the degree of northward extension of monsoon rain belt. These discrepancies may come from the following two aspects: The climate model is not perfect and needs to improve further; these may suggest that the Holocene humid period in monsoon regions may be influenced by other factors, which are not included in the model. The orbital (precession) forcing and the associated strengthening monsoon circulation may have combined to produce the changes in ocean surface temperature, e.g. in Tropical Atlantic, and that in turn caused further enhancement of monsoon circulation and precipitation in the early to mid-Holocene [45]. In addition, the changes in vegetation cover could modify and amplify the climate system response to orbital (precession) forcing over the Northern Hemisphere in Holocene both directly (primarily through the changes in surface albedo) and indirectly (through the changes in oceanic temperature, sea ice cover and ocean circulation) [49]. Thereby, the Holocene humid period is not only primarily controlled by the changes of precession, but also influenced by the synergistic effects of the changes in vegetation cover, ocean temperature, and sea ice at boreal latitudes, and in subtropics, the atmosphere-vegetation feedback is the most important. In order to understand the occurrence and changes of the Holocene humid period further it is urgently needed to develop an advanced coupled atmosphere-ocean-vegetation climate model in the future.

Palaeo-environmental data indicated that there are some millennial oscillations signals superimposed on the decreased trend of precipitation in Holocene, such as droughts occurred at 8.2 kaBP, 4.2–4.0 kaBP and lasted several hundred years. These droughts or millennial climate oscillations may be associated with the changes of THC (thermohaline circulation) or ocean circulation. Therefore, the observations also show that precession changes are not the only factor influencing the precipitation variations over tropical monsoon area in Holocene [53]. Additionally, the relationship between precipitation and summer monsoon intensity depends on the geographical location. In terms of summer precipitation in China, when the summer monsoon enhances, the rainfall increases in North China, in contrast to decreasing in the middle and lower reaches of the Yangtze River. Thereby, more caution is required to examine the variations of monsoon circulation using precipitation in China. However, situation in Indian Peninsula is not like that in China, in which the precipitation changes are consistent except for the northern parts of India.

Acknowledgement

This work was supported by the Ministry of Science and Technology of China (Grant No. 2006BAC03B03).

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