The Holocene 16,4 (2006) pp. 551–560

Holocene climate changes in the monsoon/arid transition reflected by carbon concentration in Daihai Lake of Inner Mongolia

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Received 26 July 2005; revised manuscript accepted 24 November 2005

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Abstract: Two sediment cores recovered in the central part of Daihai Lake in north-central China were analysed at 2- to 4-cm intervals for total inorganic and organic carbon (TIC and TOC) concentrations. The TIC concentration is inferred to reflect temperatures over the lake region and an increase in the TIC concentration implies an increase in the temperature. TOC concentration is considered to reflect the precipitation in the lake basin and higher TOC concentrations denote more precipitations. Thus AMS ^{14}C time series of the TIC and TOC records of Daihai Lake sediments uncovers a detailed history of changes in temperature and precipitation in north-central China during the last *c.* 12 000 yr. The Holocene, an epoch of postglacial warmth, started *c.* 11 500 cal. yr BP, and can be subdivided into three stages: the early (*c.* 11 500–8100 cal. yr BP), middle (*c.* 8100–3300 cal. yr BP) and the late Holocene (*c.* 3300–0 cal. yr BP). The climate was warm and dry during the early Holocene, warm and wet during the middle Holocene, and in the late Holocene became cooler and drier but displayed a relatively warmer and wetter interval between *c.* 1700 and 1300 cal. yr BP. The Holocene Climatic Optimum, defined as a postglacial episode of both megathermal and megahumid climate, might have occurred in north-central China between *c.* 8100 and 3300 cal. yr BP, and the climate during this period was variable and punctuated by cool and/or dry events. We infer that changes in the temperature were directly controlled by changes in summer solar radiation in the Northern Hemisphere resulting from progressive changes in the Earth's orbital parameters. Whereas an increase in the monsoonal precipitation could be closely related to an increase in the sea surface temperature of the low-latitude Pacific Ocean, an increase in the temperature and size of the Western Pacific Warm Pool and a westward shifted and strengthened Kuroshio Current in the western Pacific.

Key words: Monsoon/arid transition, Daihai Lake, sediment cores, carbon concentrations, temperature, precipitation, Holocene, Inner Mongolia.

Introduction

More than 30 years ago, Zhu (1973) made a novel suggestion about climate changes in China over the last 5000 years. Having investigated historical documents, mammal fossils and plant remains from archaeological relics, he concluded that (1) during the period from 3000 to 1100 BC, the mean annual temperature and winter temperature in the area of the middle and lower reaches of the Yellow River were 2°C and 3–5°C higher than today, respectively; (2) since 1100 BC, the mean annual temperature displayed 2–3°C of fluctuations with cold intervals around 1000 BC and AD 400, 1200 and 1700, and relatively warm episodes in the Han (206 BC–AD 220) and Tang (AD 618–907) Dynasties; and (3) such climate changes are global in extent with cooling starting from eastern Asia and gradually spreading to western Europe and warming from the

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10.1191/0959683606hl950rp

west to the east. Encouraged by Zhu's findings, extensive investigations into Holocene climates of China were launched in the latter half of the 1970s, and a large body of data had been yielded up to the beginning of 1990s (eg, Zhang *et al.*, 1981; Kong *et al.*, 1982; Li, 1983; Wang, 1983; Zhou *et al.*, 1984; Li and Liang, 1985; Wang and Fan, 1987; Geng and Zhang, 1988; Xia, 1988; Xu *et al.*, 1988; Liu, 1989; Du *et al.*, 1989; Kelts *et al.*, 1989; Thompson *et al.*, 1989; Zhang *et al.*, 1989; Sun and Yuan, 1990; An *et al.*, 1990; Chen *et al.*, 1991; Gasse *et al.*, 1991; Lister *et al.*, 1991; Sun *et al.*, 1991; Cui and Song, 1992; Shi and Kong, 1992; Li *et al.*, 1992; An *et al.*, 1993; Feng *et al.*, 1993; Fontes *et al.*, 1993; Gu *et al.*, 1993). Based on some of these data including pollen assemblages, mammal fossils, palaeosols, lake levels, ice caps, coastlines and archaeological relics, Shi and Kong (1992) pointed out that the so-called Holocene Megathermal Period (HMP) occurred in China from *c.* 8500 to 3000 cal. yr ago. Changes in the climate of the HMP were characterized by four stages, ie, an unstable stage of warm and cold fluctuations with an increase in precipitation from *c.* 8500 to 7200 cal. yr ago, a stable warm and wet stage with markedly increased precipitation from *c.* 7200 to 6000 cal. yr ago viewed as the megathermal maximum, a stage of drastic climatic oscillations with episodes of rapidly falling temperatures from *c.* 6000 to 5000 cal. yr ago, and a fairly warm and wet stage from *c.* 5000 to 3000 cal. yr ago with an ameliorated climate relative to the preceding stage but intercalated with great floods around *c.* 4000 cal. yr ago (Shi and Kong, 1992; Shi *et al.*, 1992, 1993).

Recently An *et al.* (2000) synthesized the existing data of lake levels, pollen profiles and eolian deposits from different regions of China and reconstructed a spatial and temporal distribution of East Asian summer monsoon precipitation during the Holocene. By defining the peak monsoonal precipitation as the Holocene Climatic Optimum (HCO), An *et al.* (2000) developed a conceptual model that the HCO reached a maximum at different times in different regions of China; eg, *c.* 9000 (10 000–8000) cal. yr ago in northeastern China, *c.* 9000 (10 000–7000) cal. yr ago in north-central and northern east-central China, *c.* 6000 (7000–5000) cal. yr ago in the middle and lower reaches of the Yangtze River, and *c.* 3000 cal. yr ago in South China. This regional shift in the maximum precipitation belt from northwest to southeast over the last 10 000 years was thought to be linked with the progressive weakening and southeastward retreat of the East Asian summer monsoon through the Holocene (An *et al.*, 2000).

Despite the attempts made over the past decades to understand the process of Holocene climate change, fundamental questions still exist concerning the nature and timing of the HCO and the similarities and differences between changes in temperature and in precipitation during the Holocene. This may be due to (1) the low resolution and/or the poor continuity of sedimentary sequences; (2) insufficient reliability of radiocarbon datings; and (3) uncertainties in the interpretation of proxy indices. The Holocene climate history is essential background for understanding the present climatic conditions and to constrain predictions of future climatic trends.

Daihai Lake, a closed lake in Inner Mongolia, north-central China, sits at a critical juncture at the confluence of warm, moist monsoonal circulations and cold, dry polar airflows (Figure 1). In the present study, we provide data of inorganic and organic carbon concentrations of two 11-m-long sediment cores recovered in the central part of Daihai Lake. Data from these high-quality cores will be used to provide a reliable radiocarbon chronology and reveal a detailed history of changes in temperature and precipitation during the Holocene over the monsoonal/arid transition of north-central China. These would be useful to improve our understanding of the

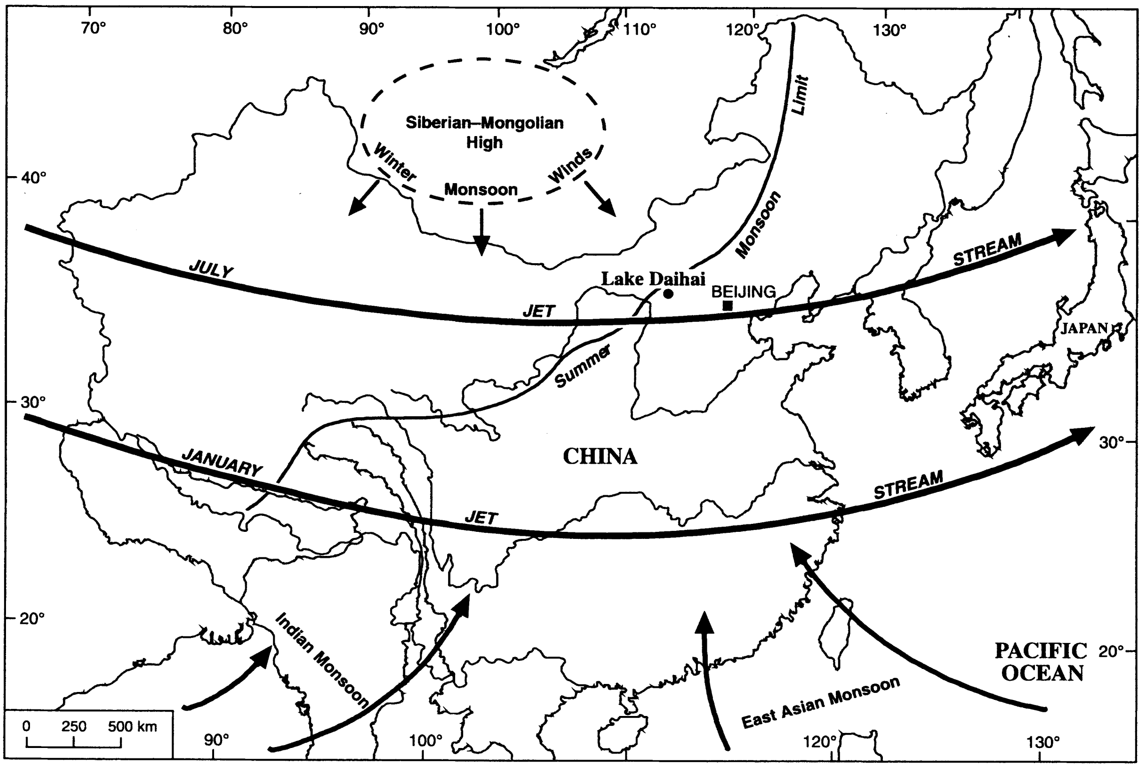

Figure 1 Map showing the climatic system of China including the East Asian and Indian summer monsoons, the winter monsoon winds associated with the Siberian–Mongolian High, and the Westerly winds generalized as the mean locations of the jet stream. The summer monsoon is a steady flow of warm, moist air from the tropical oceans, and the winter monsoon is a flow of cold, dry air out of north-central Asia. Compiled from Gao (1962), Chinese Academy of Sciences (1984) and Zhang and Lin (1992)

nature of Holocene climatic processes and the dynamic linkage between regional and global climate changes.

Geology, tectonics and physiography of the Daihai Lake region

Daihai Lake (40°29′ to 40°37′N, 112°33′ to 112°46′E) lies 10 km east of Liangcheng County of the Inner Mongolia Autonomous Region in north-central China (Figures 1 and 2). It has an area of 133.5 km^2, a maximum water depth of 16.1 m, a mean water depth of 7.4 m and an elevation of 1221 m a.s.l. (measurements in July 1986 by Wang *et al.*, 1990).

Daihai Lake occurs in an inland graben basin and is part of the Inner Mongolian platform, which is built up of Archaeozoic gneissose rocks (Zhang, 1937; Li, 1979). The Proterozoic and Palaeozoic Erathems were lacunar in this area (Li, 1979; Wang *et al.*, 1990). The Mesozoic Erathem consists of Late Jurassic tuff and tuffaceous breccia scattered in the north mountain areas (Wang *et al.*, 1990), and Late Cretaceous mudstone, sandy mudstone, sandstone and conglomerate dispersed in the south mountain areas (Song *et al.*, 1986). The Tertiary System includes palaeo-weathering crusts and fluvio-lacustrine deposits of the Neogene Period and basaltic rocks (Li, 1979). Palaeo-weathering crusts are distributed in the south mountain areas, overlying Archaeozoic metamorphic rocks (Li, 1979) or intervening between basaltic rocks (Song *et al.*, 1986). Fluvio-lacustrine deposits outcrop in the south mountain areas, mainly covering the Archaeozoic gneiss (Li, 1979). Basaltic rocks are widespread in the south mountain areas (Li, 1979; Song *et al.*, 1986). Quaternary unconsolidated deposits are distributed in the lake basin and river valleys (Zhang, 1937; Li, 1979).

Tectonics of the Daihai Lake area can be divided into two main episodes: the Yanshan movement during the Late Mesozoic and the Himalayan movement from the Miocene to Early Pleistocene (Li, 1979; Song *et al.*, 1986). The Yanshan movement resulted in major normal faults striking in NEE–SWW with high dip angles in this area (Li, 1979; Wang *et al.*, 1990). Intense activity of the Himalayan movement reactivated palaeofaults, gave rise to neofaults and created the Daihai Lake basin in the Late Pliocene to Early Pleistocene (Li, 1979; Song *et al.*, 1986). During the latter episode, differential movements of the north and south blocks led to an asymmetrical basin with a steep northwest side and a gentle southeast side (Li, 1979; Wang *et al.*, 1990) (cf. Figure 2).

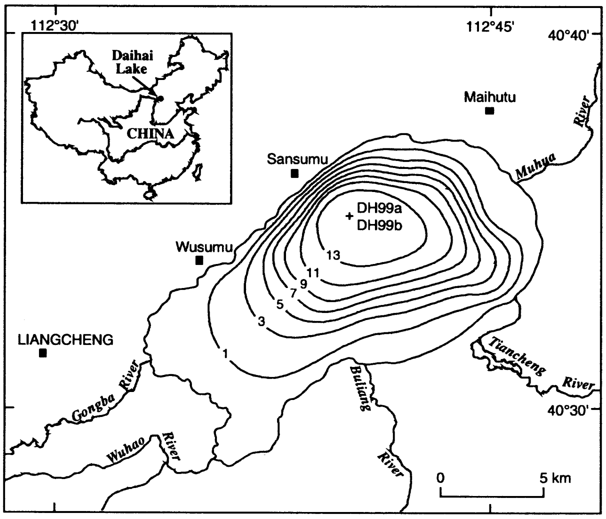

Figure 2 Map of Daihai Lake showing locations of DH99a and DH99b sediment cores. Mountains border the lake on the north and south; undulating hills occur on the east; and plains are present along the western shore. Five major rivers enter the lake, but no rivers drain the lake. The bathymetric survey of the lake was implemented in June 2000 with a FURUNO echo sounder (Model FE–606) (contour in metres)

The Daihai Lake basin is bordered by the Manhan Mountains on the north and Matou Mountains on the south. Hills are distributed on the east and plains are present along the western shore. The Manhan and Matou Mountains have highest peaks of 2305 and 2035 m a.s.l., respectively. The lake has a catchment of 2289 km^2 (Figure 2).

Daihai Lake is located at the transition from semi-humid to semi-arid areas in the middle temperate zone of China (Figure 1). Mean annual temperature is 5.1°C with a July average of 20.5°C and a January average of −13.0°C (Figure 3). Mean annual precipitation is 423 mm, and about 80% of the annual precipitation falls in June–September with a peak mean rainfall of 122 mm in August (Figure 3). Mean annual evaporation reaches 1162 mm, which is 2.8 times the annual precipitation (Figure 3). The lake is covered with *c.* 60 cm of ice from November to March. In the lake region, the winter climate is controlled by the dry, cold northwesterly winter monsoon that brings cold waves and generates dust storms from late autumn to spring; whereas the summer climate is dominated by the warm, moist southeasterly summer monsoon that is responsible for most of the annual precipitation and for rainstorm activities (Gao, 1962; Chinese Academy of Sciences, 1984; Zhang and Lin, 1992).

Coring and sampling of Daihai Lake sediments

In the summer of 1999, two sediment cores, designated DH99a and DH99b, were extracted in the central part of Daihai Lake, using a Japanese-made TOHO drilling system (Model D1–B) (Figure 2; Table 1). DH99a was recovered at a water depth of 13.1 m to a sediment depth of 11.96 m; DH99b, *c.* 60 m southeast of DH99a, was recovered at a water depth of 13.1 m to a sediment depth of 24.10 m. Sediment cores of DH99a and the upper 12.87 m of DH99b were taken in half-split polyethylene tubes by a piston corer, and the lower part below 12.87 m of DH99b taken in vinyl liners by a dual-tube (inner and outer tubes) core barrel. Sediment recovery reached 98.5% for DH99a core and 84.5% for DH99b core (Table 1). Core sections were split, photographed and described on site. Cores

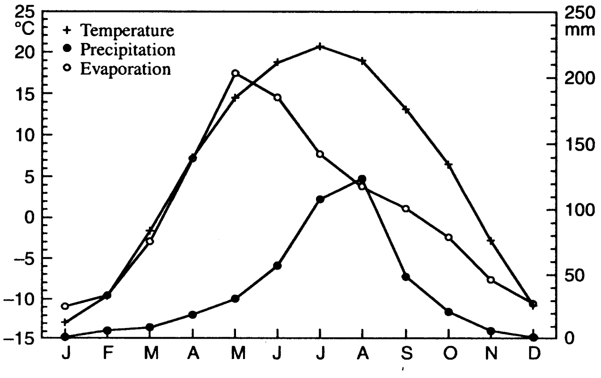

Figure 3 Monthly changes of mean annual temperature, mean annual precipitation and mean annual evaporation in the Daihai Lake region. Data are averaged by observations of the years 1959–1988

Table 1 General information of DH99a and DH99b sediment cores recovered in the central part of Daihai Lake

Core	Location	Water depth (m)	Core depth (m blf)	Samples	Recovery (%)
DH99a	40°35.165′N, 112°40.057′E	13.10	11.96	590	98.5
DH99b	40°35.134′N, 112°40.061′E	13.10	24.10	1013	84.5

were cut continuously into 2-cm segments for laboratory analyses.

DH99a core sediments are composed of homogeneous silt and silty clay and can be divided into two parts: a greenish-grey to greyish-black upper part with burrows and a light to dark gray, laminated lower part (Figure 4). DH99b core sediments generally consist of homogeneous silt and silty clay but contain several intercalations of sand and granules in the lower part. The upper 12 m of DH99b core exhibits a close correlation in lithology, lamination and colour with DH99a core.

The upper 11 m of both DH99a and DH99b cores was used for the present study. DH99a was sampled at 2- or 4-cm intervals; and DH99b sampled at 2-cm intervals for the determination of carbon concentrations. Both DH99a and DH99b cores were sampled at 20-cm intervals for C/N measurements. Eight bulk samples were collected for AMS radiocarbon dating from the organic-rich horizons of DH99a core sediments.

Chronology of Daihai Lake sediment cores

Radiocarbon samples from DH99a core were dated with a HVEE Tandetron AMS-II system at the Center for Chronological Research, Nagoya University, Japan. Organic carbon was extracted from each sample and dated following the method described by Kitagawa *et al.* (1993) and Nakamura *et al.* (2000). Each sample was pretreated with 1.2 M HCl at 80°C for 2 h, twice, to remove carbonates, and then rinsed and dried at 90°C. After the pretreatment, the residue, containing *c.* 2 mg of carbon, was put into a vycor tube together with *c.* 200 mg of CuO and a few pieces of Ag wire. The tube was flame-sealed and heated to 900°C for 2 h after evacuating. The resulting CO_2 was purified in a glass vacuum line using liquid N_2, C_2H_5OH–liquid N_2 mixture (−100°C) and *N*-pentane (−130°C). The pure CO_2 was then converted to graphite by catalytic reduction on Fe powder.

The $^{14}C/^{12}C$ and $^{13}C/^{12}C$ ratios of each sample, with an oxalic acid standard (SRM-4990C, commonly designated HOxII), were measured with a HVEE AMS system. Each sample was measured three times, and each measurement lasted 30 min. The typical uncertainty resulting from counting statistics was 0.3%. In order to correct the $^{14}C/^{12}C$ ratios for isotopic fractionation, the $\delta^{13}C$ value of each sample was analysed with a conventional multicollector mass spectrometer. The background level of the AMS system measured using pure graphite powder is between 50 and 55 ka BP.

The ^{14}C ages of eight bulk samples from DH99a core were determined with a half-life of 5568 yr (Figure 4; Table 2). The conventional ages were converted to calibrated ages using CALIB 4 of the INTCAL98 radiocarbon age calibration program (Stuiver *et al.*, 1998) (Figure 4; Table 2). The ages of sampled horizons of DH99a core were derived by linear interpolation between radiocarbon-dated horizons.

The chronology of DH99b core was developed by using five age control points (Figure 5). As stated above, the upper 12 m of DH99b core can be closely correlated in lithology, lamination and colour with DH99a core. Based on these correlations, five horizons with the most evident features of the sediment cores were selected, and the ages of these horizons of DH99a

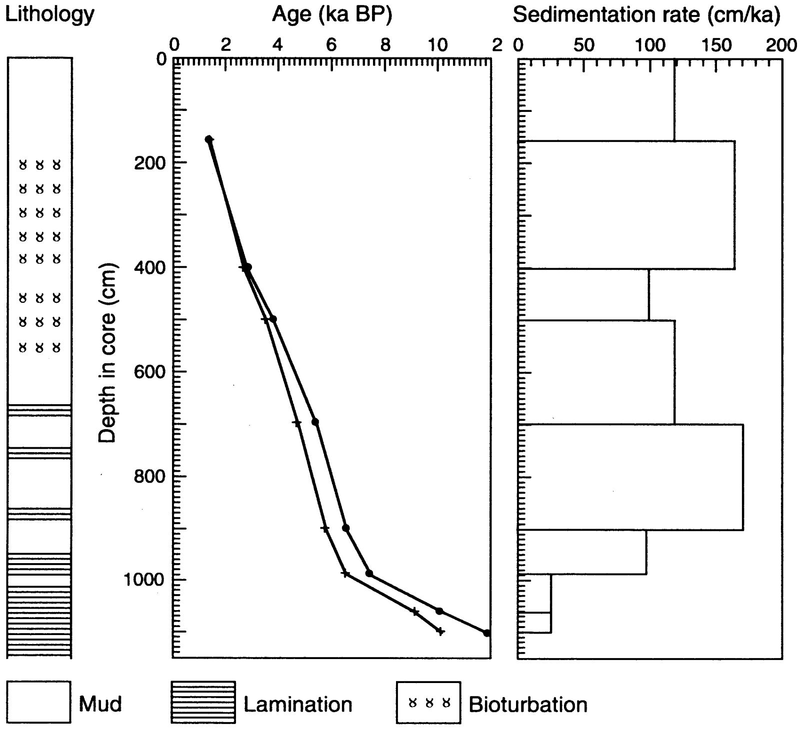

Figure 4 Lithology, age–depth curve and sedimentation-rate histogram of the upper 11 m of DH99a sediment core recovered in the central part of Daihai Lake. Crosses represent AMS radiocarbon datings, and solid circles represent calibrated radiocarbon ages. Sedimentation rates (cm/ka) were calculated between calibrated radiocarbon ages

Table 2 AMS radiocarbon dates of samples from the upper 11 m of DH99a sediment core recovered in the central part of Daihai Lake

Laboratory number	Depth in core (cm)	Dating material	$\delta^{13}C$ (‰)	AMS ^{14}C age (^{14}C yr BP)	Calibrated ^{14}C age (2σ) (cal. yr BP)
NUTA2-2954	160	Organic matter	−25.1	1434±28	1385–1290
NUTA2-2864	402	Organic matter	−26.8	2688±27	2845–2750
NUTA2-2868	501	Organic matter	−25.2	3531±28	3885–3700
NUTA2-2719	701	Organic matter	−24.8	4729±32	5585–5325
NUTA2-2721	901	Organic matter	−24.3	5809±33	6720–6500
NUTA2-2724	989	Organic matter	−25.1	6593±34	7565–7430
NUTA2-2877	1063	Organic matter	−25.5	9175±34	10 470–10 235
NUTA2-2725	1103	Organic matter	−24.7	10 171±39	12 300–11 570

core were applied to those of DH99b core (Figure 5). The ages of sampled horizons of DH99b core were derived by interpolating between the five age control points.

AMS ^{14}C datings indicate that Daihai Lake sediments reach a thickness of *c.* 11 m for the Holocene Epoch (Figures 4 and 5). As shown in Figure 4, the age–depth curve of the upper 11 m of DH99a sediment core displays a prominent inflection at *c.* 7500 cal. yr BP, yielding average sedimentation rates of *c.* 132 cm/ka for the segment since *c.* 7500 cal. yr ago and *c.* 26 cm/ka for that before. The average sedimentation rates and a sampling interval of 2 cm provide potential temporal resolutions of *c.* 15 yr for the last *c.* 7500 yr and *c.* 77 yr for the period before *c.* 7500 cal. yr BP.

TIC and TOC of Daihai Lake core sediments

Total carbon (TC %) and total inorganic carbon (TIC %) concentrations were measured with an Elementar High TOC II analyser that employs two cuvette multichannel infrared detectors to detect respectively the quantities of CO_2 resulting from total carbon and from total inorganic carbon. Samples were ground into powder finer than 180 mesh and dried at 110°C for 24 h. Each sample was separately weighed to *c.* 300 mg and *c.* 30 mg for analyses of TC and TIC, respectively. In order to completely convert carbon to CO_2, samples for TC analysis were fully combusted at 1150°C; whereas samples for TIC analysis were reacted in excess 9% HCl. A reference soil sample, GBW07402, was separated into four weighed portions with two portions for TC and another two for TIC and analysed in parallel with the samples each day. All of the TC and TIC values were normalized to the reference soil sample, the certified TC and TIC values of which are 0.75% and 0.26%, respectively. The High TOC II automatically yields the TC and TIC concentrations of a sample with a relative analytical error of $\leq 1\%$. The TOC value is the difference between the TC and TIC concentrations.

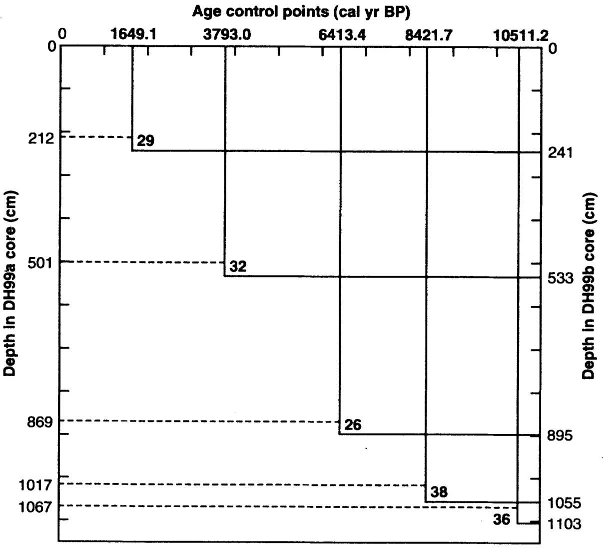

Figure 5 Age control points of the upper 11 m of DH99b sediment core recovered in the central part of Daihai Lake at a water depth of 13.1 m, derived by correlating lithology, laminae and colour with DH99a sediment core. Bold numerals inside the diagram indicate the differences between DH99b and DH99a core depths at the same age control point

Data of the TC, TIC and TOC concentrations and C/N ratios of DH99a and DH99b core sediments spanning the last *c.* 12 000 yr were plotted against calibrated radiocarbon ages (Figure 6a and b). As shown in Figure 6a and b, the TIC record of the Holocene Epoch is characterized overall by two stages, the period from *c.* 11 500 to 2900 cal. yr BP and the subsequent interval after *c.* 2900 cal. yr BP. TIC began to increase gradually *c.* 11 500 cal. yr ago and reached the highest values of the Holocene around *c.* 11 000 cal. yr BP. From *c.* 11 000 to 2900 cal. yr BP, TIC generally displayed a decreasing trend with three low-value peaks occurring *c.* 9400–8600, 7100–6500 and *c.* 4400–4100 cal. yr ago, respectively, and two in-between intervals of relatively higher values. Since *c.* 2900 cal. yr ago, the TIC has assumed the lowest values of the whole Holocene but exhibited relatively higher values at the interval between *c.* 1700 and 1300 cal. yr BP which subdivides a subsequent episode of the last *c.* 1300 yr from a preceding episode of *c.* 2900 to 1700 cal. yr BP.

The TOC record of the Holocene Epoch is characterized by three stages, ie, the early Holocene before *c.* 8100 cal. yr BP, middle Holocene between *c.* 8100 and 3300 cal. yr BP and the late Holocene after *c.* 3300 cal. yr BP. Before *c.* 8100 cal. yr BP, TOC was generally low and fluctuated twice within a narrow range. From *c.* 8100 to 3300 cal. yr BP, the TOC maintained high values and displayed high-frequency, high-amplitude fluctuations. During this period, TOC increased gradually from *c.* 8100 to 7000 cal. yr BP, reached greatest values and fluctuated with a higher frequency and a higher amplitude between *c.* 7000 and 4500 cal. yr BP, and assumed relatively lower values with fluctuations from *c.* 4500 to 3300 cal. yr BP. After *c.* 3300 cal. yr BP, an abrupt and large decrease of TOC values occurred. During this period, the TOC decreased to the lowest values of the whole Holocene but demonstrated relatively higher values at the interval from *c.* 1700 to 1300 cal. yr BP, which subdivides a subsequent episode of the last *c.* 1300 yr from a preceding episode of *c.* 3300 to 1700 cal. yr BP.

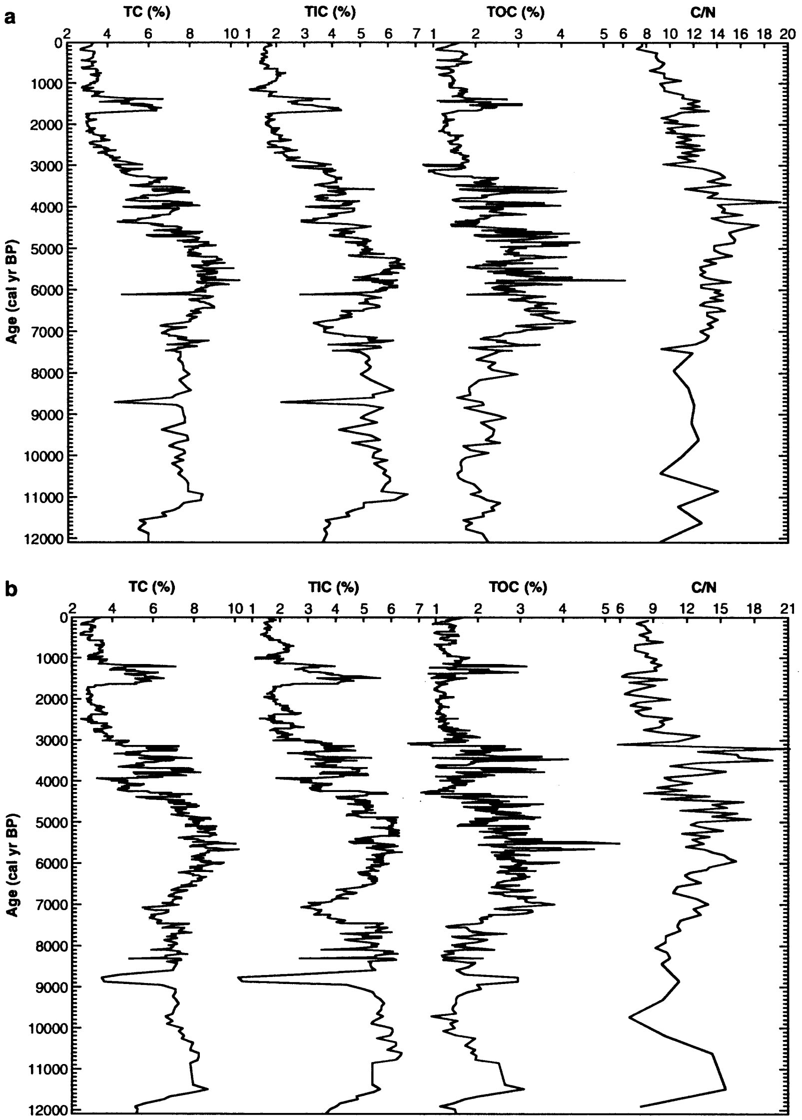

Figure 6 (a) Concentrations of total carbon (TC, %), total inorganic carbon (TIC, %), total organic carbon (TOC, %) and ratios of total organic carbon to total nitrogen (C/N) of DH99a core sediments spanning the last *c*. 12 000 yr plotted against calibrated radiocarbon ages. (b) Concentrations of total carbon (TC, %), total inorganic carbon (TIC %), total organic carbon (TOC, %) and ratios of total organic carbon to total nitrogen (C/N) of DH99b core sediments spanning the last *c*. 12 000 yr plotted against calibrated radiocarbon ages. The chronology was derived by interpolating between age control points

Discussion

Interpretation of TIC and TOC

Carbonates in lake sediments mainly comprise terrigenous clastic carbonates derived from the drainage basin and lacustrine authigenic carbonates formed in the lake waterbody (Lerman, 1979; Håkanson and Jansson, 1983). Mineralogical analysis of samples taken from surface sediments of Daihai Lake indicated that the deep water midlake zone is dominated by microcrystalline calcite yielded by inorganic precipitation in lake water and calcareous shells produced by the living organisms (Wang *et al.*, 1990). These results suggest that carbonates in Daihai Lake sediment cores recovered in the central part of the lake are predominately authigenous in origin and were formed by chemical or biochemical processes. Daihai Lake, a closed-basin lake, lies in the semi-arid region (Figure 1). Most of the lake water is derived from precipitation (*c*. 50%) and drainage (*c*. 40%) entering the lake (Wang *et al.*, 1990). About 80% of the annual precipitation falls in June–September, and the annual evaporation is 2.8 times the annual precipitation (Figure 3). Consequently authigenic carbonates formed in Daihai Lake by chemical and biochemical processes are closely associated with the evaporation of the lake water which primarily controls the chemical composition and salinity of the lake water (Lerman, 1979; Wang *et al.*, 1990). Given that the evaporation of lake water is mainly controlled by temperature and atmospheric relative humidity, and humidity is determined by temperature and atmospheric precipitation, we infer that the formation of authigenic carbonates in Daihai Lake can be linked predominantly with temperature. When temperature rises, evaporation is enhanced, leading to supersaturation of Ca^{2+} and Mg^{2+} in lake waters and thus promoting precipitation of carbonates in the lake. Therefore we interpret the TIC concentration of Daihai Lake sediments as a proxy index for temperature changes in the lake region, and an increase in the TIC concentration is related to an increase in the temperature over the lake region.

The organic matter in lake sediments has two principal sources, ie, autochthonous, aquatic plants living in the lake water, and allochthonous, terrestrial plants growing in the lake catchment (Lerman, 1979; Talbot and Johannessen, 1992; Meyers, 1994). C/N ratios of lacustrine organic matter can be used to distinguish between autochthonous and allochthonous origins of the organic matter (Talbot and Johannessen, 1992; Meyers, 1994). Aquatic phytoplankton predominantly has atomic C/N ratios between 4 and 10, whereas terrestrial vegetation has C/N ratios of 20 and greater (Meyers, 1994). Commonly, lacustrine organic matter can be considered as a mixture of aquatic and higher terrestrial plants, providing that the C/N ratios range from 10 to 20 (Meyers, 1994). Elemental analyses of a 80-m sediment core recovered from the western shore of Daihai Lake suggested that the C/N ratios of the lacustrine organic matter were greater than ten at times during the last interglaciation and the Holocene and lower than seven during the last glaciation (Wang *et al.*, 1990). Figure 6a and b shows the C/N ratios of the organic matter in Daihai Lake core sediments from the early to middle Holocene where they reach values > 10. Based on these results, we infer that changes in the content of the organic matter in Daihai Lake sediments can be linked with changes in the amount of terrestrial organic input to the lake. The area of the Daihai Lake catchment is 17 times that of the lake water. Fluvial transport can be an effective means of supplying organic matter to the lake. In general, when the precipitation over the lake region intensifies, the soil erosion in the lake catchment would be enhanced and the transport capacity of streams and rivers entering the lake would be increased, leading to relatively more land-derived organic matter carried to the lake (Lerman, 1979; Håkanson and Jansson, 1983). Therefore we interpret the TOC concentration of Daihai Lake sediments as a proxy index for precipitation changes in the lake region, ie, an increase in the TOC concentration is related to an increase in the precipitation intensity over the lake region.

Holocene temperature and precipitation changes

Figure 7 shows the five-point running means of TIC and TOC concentration data from DH99a core sediments spanning the last *c.* 12 000 yr. It was drawn against calibrated radiocarbon ages at a 100-yr resolution. The TIC record indicates that temperature changes over the Daihai Lake region during the Holocene are characterized by two stages: a warm period from *c.* 11 500 to 2900 cal. yr BP and a cool interval after *c.* 2900 cal. yr BP. During the warm period, the temperature displayed a general decreasing trend with three declines occurring *c.* 9400–8600, 7100–6500 and *c.* 4400–4100 cal. yr ago, respectively. Since *c.* 2900 cal. yr ago, the climate has been characterized by cool conditions but became relatively warmer at the interval between *c.* 1700 and 1300 cal. yr BP. The TOC record suggests that precipitation change over the Daihai Lake region during the Holocene is characterized by three stages: a dry episode before *c.* 8100 cal. yr BP then a wet period between *c.* 8100 and 3300 cal. yr BP and a dry episode after *c.* 3300 cal. yr BP. Before *c.* 8100 cal. yr BP, the precipitation was lower overall, but slightly intensified at two intervals of *c.* 11 300–11 000 cal. yr BP and *c.* 9700–8900 cal. yr BP. During the period of *c.* 8100–3300 cal. yr BP, the climate was generally wet but displayed high-frequency, high-amplitude fluctuations. The episode after *c.* 3300 cal. yr BP was dominated by a dry climate but intercalated by a short interval of enhanced precipitation rates from *c.* 1700 to 1300 cal. yr BP.

Pollen data from the DH99a sediment core suggested that the lake basin was dominated by mixed coniferous and broadleaved forests from *c.* 7900 to 2900 cal. yr BP, reflecting warm and humid climatic conditions in the lake area during this period (Xiao *et al.*, 2004). Before *c.* 7900 cal. yr BP, the climate was dry, as indicated by arid herbs and shrubs covering the lake region. Since *c.* 2900 cal. yr ago, the forests disappeared, reflecting a cool and dry climate. However, a recovery of the woody plants that occurred from *c.* 1700 to 1350 cal. yr BP implies an amelioration in climate of the lake area during this episode. The TIC and TOC data are in good agreement with the pollen-based inference of temperature and precipitation changes over the lake region during the Holocene.

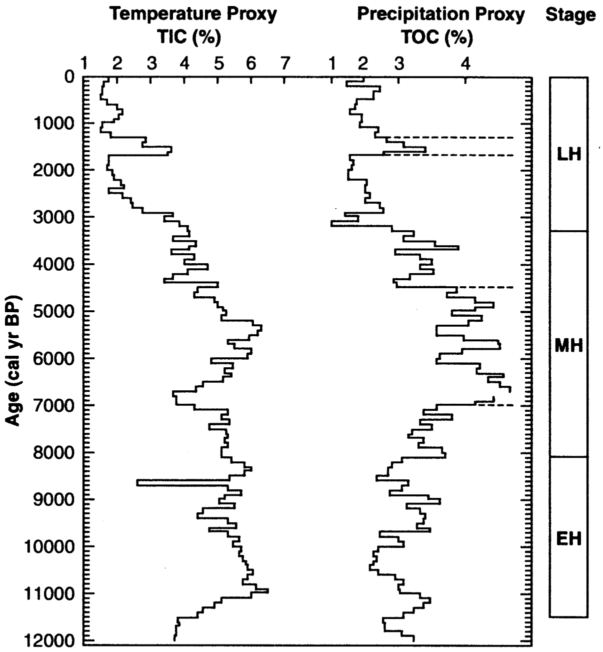

Figure 7 Five-point running means of TIC and TOC concentration data from DH99a core sediments spanning the last *c.* 12 000 yr, drawn against calibrated radiocarbon ages at a 100-yr resolution. TIC and TOC concentrations are used to indicate, respectively, temperature and precipitation changes in the monsoonal/arid transition of north-central China. EH, MH and LH shown to the right of the diagram are abbreviated from early, middle and late Holocene, respectively, and indicate the stages characterizing temperature and precipitation variations. Horizontal solid and dashed lines mark the boundaries between stages and between substages, respectively

As shown in Figure 4, the age–depth curve of the upper 11 m of DH99a sediment core displays an apparent inflection at core depth of 9.89 m, reflecting a great increase in the sedimentation rate of Daihai Lake sediments *c.* 7500 cal. yr BP. This accelerated accumulation of clastic materials in the lake basin might be associated with an increase in the precipitation intensity over the lake region *c.* 8000 cal. yr ago.

Zhu (1973) investigated historical documents, mammal fossils and plant remains from archaeological relics and pointed out that the mean annual temperature in north-central China began to decrease 1100 BC after having maintained a value about 2°C higher than today's for about 2000 years. Based on pollen assemblages, mammal fossils, palaeosols, lake levels, ice caps, coastlines and archaeological relics data, Shi and Kong (1992) and Shi *et al.* (1992) suggested that the so-called Holocene Megathermal terminated in China around 3000 cal. yr ago. Our TIC data concur with the previous inferences about the end of the maximum Holocene warmth.

Initiation and division of the Holocene Epoch

Over the past several decades, most of the research on Holocene climates have been directed toward the Holocene Megathermal (also designated the Holocene Optimum) (Hafsten, 1970; Bates and Jackson, 1987; Shi *et al.*, 1992; Winkler and Wang, 1993; An *et al.*, 1993). However, little attention has been paid to the initiation of the Holocene warm climate. This is also one of the reasons why the onset of the Holocene Climatic

Optimum was placed at various times (eg, 10 000–7500 ^{14}C yr BP by Shi *et al.*, 1992). Consequently it is necessary to distinguish the onset of the Holocene Epoch from that of the Holocene Climatic Optimum. The Holocene was originally defined as an epoch of postglacial warmth following the Pleistocene (Hafsten, 1970). Only the temperature (not including the precipitation) can therefore be used as an index to distinguish the Holocene from the Pleistocene. In other words, the initiation of the Holocene Epoch should be assigned to the time when temperature started to rise. Our TIC-derived inference of temperature changes in north-central China over the last *c.* 12 000 yr indicates that the Holocene Epoch started *c.* 11 500 cal. yr BP (Figure 7).

Taking precipitation into consideration, we infer that the Holocene Epoch can be subdivided into three stages: the early Holocene from *c.* 11 500 to 8100 cal. yr BP, middle Holocene between *c.* 8100 and 3300 cal. yr BP and the late Holocene after *c.* 3300 cal. yr BP. During the early Holocene, the climate was warm and dry with two relatively humid intervals of *c.* 11 300–11 000 and 9700–8900 cal. yr BP. The climate of the middle Holocene was warm and wet but variable with cool and/or dry events. In the late Holocene, the climate became cool and dry but displayed a relatively warmer and wetter interval between *c.* 1700 and 1300 cal. yr BP.

Nature and delimitation of the Holocene Climatic Optimum

The Holocene Climatic Optimum has attracted wide and close attention over the past 30 years (Hafsten, 1970), not only because it is an important recent climatic episode but also because it may serve as an important analogue for future climatic change (Shi *et al.*, 1992). The optimum was originally regarded as the period of the Holocene Megathermal (Hafsten, 1970) or as the time of maximum postglacial warmth (Winkler and Wang, 1993).

As one of the two major climatic parameters, precipitation can have more effective influences on the vegetation and environment, especially in the region of the East Asian monsoon, than temperature (Chinese Academy of Sciences, 1984). Bates and Jackson (1987) defined the Holocene Climatic Optimum as a postglacial interval of the most equable climate with warm temperatures and abundant rainfall. We concur with Bates and Jackson (1987) that the Holocene Climatic Optimum is not only related to temperature but also to precipitation and should be defined as a postglacial period of both megathermal and megahumid climate. Our TIC and TOC data suggest that the Holocene Climatic Optimum occurred in north-central China between *c.* 8100 and 3300 cal. yr BP when the climate was not only warm but also wet, compared with either the early (*c.* 11 500–8100 cal. yr BP) or the late (*c.* 3300–0 cal. yr BP) Holocene.

In addition, the concept of the Holocene optimum was originally derived from the middle Holocene Atlantic interval of the northern European pollen climatostratigraphy (Hafsten, 1970). Because this pollen-based optimum was characterized by a warm and moist climate (Hafsten, 1970), the original concept did not imply a megathermal but also megahumid climatic condition, although it was only regarded as the megathermal. A similarly ambiguous interpretation applies to the Holocene Megathermal, spanning from *c.* 8500 to 3000 ^{14}C yr BP, proposed by Shi and Kong (1992) and Shi *et al.* (1992) on the basis of pollen assemblages, mammal fossils and palaeosols in China. In our view, the Holocene Megathermal may have started *c.* 11 500 cal. yr ago, as indicated by our TIC data, if it is considered solely as the time of maximum postglacial warmth.

Possible causes of Holocene temperature and precipitation changes

For more than 2 Ma, the Earth's climatic history has been characterized by global glacial/interglacial cycles that are controlled by the changing seasonality of solar radiation resulting from progressive changes in the Earth's orbital parameters (Hays *et al.*, 1976; Imbrie *et al.*, 1984). Numerical simulations suggested that summer solar radiation in the Northern Hemisphere began to increase 12 000 cal. yr BP and reached a maximum (7% more than the present value) 11 000 to 10 000 cal. yr BP, and decreased toward modern values after 9000 cal. yr BP (Kutzbach and Street-Perrott, 1985; COHMAP Members, 1988; Kutzbach *et al.*, 1998). As shown in Figure 7, the temperature over the Daihai Lake region in north-central China started to increase *c.* 11 500 cal. yr ago, culminated at the interval of *c.* 11 100 to 10 800 cal. yr BP, and then displayed a general trend of decrease, displaying a close correlation with orbitally induced variations in insolation. This leads us to infer that the pattern of changes in the temperature in north-central China during the Holocene was controlled by changes in summer solar radiation in the Northern Hemisphere.

Most of the annual precipitation in north-central China is associated with the East Asian summer monsoon, which is driven by the atmospheric pressure gradient between the Pacific Ocean and the Asian continent (Gao, 1962; Chinese Academy of Sciences, 1984; Zhang and Lin, 1992). Because the pressure gradient is controlled by the thermal contrast between the ocean and the continent, it would be enhanced when the low-latitude Pacific Ocean warms up, resulting in an increase in the thermal contrast. Under this condition, the summer monsoon circulation would be intensified and bring more moisture/rainfall from low latitudes of the Pacific Ocean to the land. Therefore the sea surface temperature of the low-latitude Pacific can be a forcing factor on the East Asian monsoonal precipitation. Moreover, the Western Pacific Warm Pool (WPWP) and the Kuroshio Current originating from the North Equatorial Current in the western Pacific may also be considered as possible driving forces. An increase in the WPWP temperature and size and a westward shifted and strengthened Kuroshio Current all could favour the thermodynamic contrast between the low-latitude Pacific and the Asian continent, thereby strengthening the East Asian monsoon circulation. Analyses on the abundance of the planktonic foraminifer *Pulleniatina obliquiloculata* (the main Kuroshio Current indicator species) of core sediments from the southern and northern Okinawa Trough suggested that the Kuroshio Current shifted westward and strengthened *c.* 7500 to 6000 cal. yr ago, leading to an increase in the sea surface temperature (Shieh and Chen, 1995; Jian *et al.*, 1998, 2000). Between *c.* 4000 and 3000 cal. yr BP, the abundance of *Pulleniatina obliquiloculata* decreased sharply, implying that the Kuroshio Current weakened or shifted to the Pacific at that time (Shieh and Chen, 1995; Jian *et al.*, 1998, 2000). These data provide support for our TOC-based inference of the possible mechanisms responsible for precipitation changes over the Daihai Lake region during the Holocene.

Conclusions

The TIC and TOC concentrations of Daihai Lake sediments can serve as reliable proxies for past changes in temperature and precipitation. An increase in the TIC concentration implies an increase in the temperature over the lake region, whereas higher TOC concentrations reflect greater precipitation rates in the lake basin. The TIC record of Daihai Lake sediments, spanning the last *c.* 12 000 yr, suggests that the Holocene Epoch, an epoch of postglacial warmth, started *c.* 11 500 cal. yr BP. Changes both in the TIC and in the TOC indicate that the Holocene Epoch can be subdivided into three stages: the early Holocene (*c.* 11 500–8100 cal. yr BP), middle Holocene (*c.* 8100–3300 cal. yr BP) and the late Holocene (*c.* 3300–0 cal. yr BP). The climate was warm and dry during the early Holocene, warm and wet during the middle Holocene and in the late Holocene became cool and dry but displayed a relatively warmer and wetter interval between *c.* 1700 and 1300 cal. yr BP. The Holocene Climatic Optimum, defined as a postglacial episode of both megathermal and megahumid climate, might have occurred in north-central China between *c.* 8100 and 3300 cal. yr BP, as marked by high TIC and TOC values. However, during the Holocene Climatic Optimum the climate was variable and punctuated by cool and/or dry events. The pattern of changes in the temperature in north-central China during the Holocene was directly controlled by changes in summer solar radiation in the Northern Hemisphere resulting from progressive changes in the Earth's orbital parameters. Whereas an increase in the monsoonal precipitation over the semi-arid/semi-humid transition could be closely related to an increase in the sea surface temperature of the low-latitude Pacific Ocean, an increase in the temperature and size of the Western Pacific Warm Pool and a westward shifted and strengthened Kuroshio Current in the western Pacific.

Acknowledgements

This study was supported by the Grants NSFC 49925205, KZCX2-SW-133, KZCX2-SW-118, NSFC 40021202 and 2004CB720202. We thank John Dodson, Arlene M. Rosen and Xiaoqiang Li for helpful comments and suggestions resulting from their review of the manuscript.

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