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Rapid Communication

Early rice farming and anomalous methane trends

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ABSTRACT

The anthropogenic explanation for the increase in atmospheric methane concentration during the last 5000 years requires large CH_4 emissions from human activities beginning early in the Bronze Age. This paper presents a compilation of 311 archeological sites in rice-growing regions of China. The number of new sites between 6000 and 4000 years ago increased almost ten-fold compared with those during previous millennia. This early spread of rice production across most of the area in China where irrigated rice is grown today supports the hypothesis that early farming caused the anomalous methane reversal.

1. Introduction

Atmospheric methane concentrations decreased during the first half of the Holocene, but then reversed direction and began to increase 5000 years ago (Fig. 1). This reversal and subsequent increase have been variously attributed to natural and anthropogenic factors.

Schmidt et al. (2004) proposed that the trend resulted mainly from an increase in natural CH_4 emissions from expanding circum-Arctic wetlands. Previously, however, Chappellaz et al. (1997) and Brook et al. (2000) had ruled out a boreal source based on a late-Holocene decrease in the interhemispheric CH_4 gradient (recently confirmed by Brook and Mitchell, 2007). This gradient is an index of the difference between CH_4 concentrations recorded in Greenland and Antarctic ice. Greater releases from boreal sources boost CH_4 concentrations more in nearby Greenland ice than in distant Antarctic ice, thereby increasing the gradient, and conversely. Between ~3750 and ~750 years ago, the gradient decreased, and box modeling of this change indicates reduced emissions from circum-Arctic sources (Chappellaz et al., 1997). Despite the fact that wetlands were still slowly expanding in north-polar regions during the late Holocene (Smith et al., 2004), the decrease in boreal emissions appears to have been caused by the onset of cooler summers (COHMAP Members, 1988; Koerner and Fisher, 1990) and by a change toward drier bog types (MacDonald et al., 2006).

The reduced interhemispheric CH_4 gradient indicates that the increased methane emissions must have come from the subtropics and tropics (Chappellaz, et al., 1997). Although low-latitude wetlands are the world's largest natural methane source, however, they were not the cause of the late-Holocene CH_4 increase. During the last 9000 years, a progressive weakening of the orbitally driven summer monsoon has caused methane-emitting wetlands and lakes in the tropics and subtropics to shrink or disappear (Kutzbach, 1981; COHMAP Members, 1988). Large-amplitude $\delta^{18}O$ trends in speleothem calcite show a progressive weakening of summer monsoons during the middle and late Holocene in both Asia (Yuan et al., 2004) and in the Indian monsoon sector (Fleitmann et al., 2003).

The only natural source remaining in the tropics is wetlands in river deltas. Schmidt et al. (2004) hypothesized that the growth of tropical river deltas played a role in the late-Holocene methane increase. Much of this delta growth, however, was not natural in origin. By the time of the Bronze Age, extensive forest clearing for agriculture was causing widespread erosion that led to increased sediment loads in rivers and to enlargement of deltas (Roberts, 1998; Stefani and Vincenz, 2005; Vella et al., 2005). Anthropogenic influences thus account for a substantial and possibly dominant fraction of any late-Holocene increase in CH_4 fluxes from deltaic areas.

The rising methane trend of the last 5000 years is anomalous compared to the downward CH_4 trends during previous early interglacial intervals (Ruddiman and Thomson, 2001; Ruddiman, 2003, 2007). Because these earlier downward trends were unquestionably of natural origin, the upward trend in the late Holocene is anomalous by comparison.

With CH_4 emissions from natural sources decreasing rather than rising during the last 5000 years, the only plausible low-latitude source of methane to explain the rising concentrations in the atmosphere is early agricultural activity (Ruddiman and

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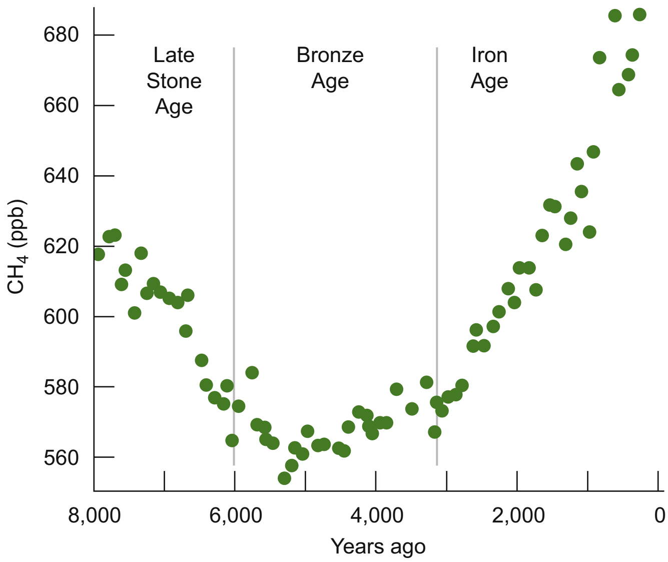

Fig. 1. Holocene methane trend: Methane trends during the last 8000 years of the Holocene from Antarctic Dome C (EPICA Community members, 2004). The reversal of the downward trend near 5000 years ago and subsequent increase coincide with increased human agricultural activities during the Bronze and Iron Ages. In China, the Bronze Age began ~4500 years ago.

Thomson, 2001; Ruddiman, 2003). Early farming activities that caused increased methane emissions include: irrigating rice paddies (which in effect creates anthropogenic wetlands), tending methane-emitting livestock, burning seasonal (grass) biomass, and generating human waste. An obvious question is whether or not human activities could have become sufficiently extensive by 5000 years ago to reverse the downward trend in atmospheric methane concentrations (Fig. 1). This paper addresses that issue by examining the extent of early rice irrigation in China based on archeological evidence.

2. The spread of rice irrigation in China

The broad outlines of the history of early rice farming and the associated 'rice cultures' of China are known (Yan, 1982; You, 1995; Wu, 1998; An, 1999). Evidence of rice use prior to 9000 years ago has been found in warm, summer-wet regions of south-central China (Fig. 2) (Peng, 1998; Xiang, 2005; Sheng et al., 2006). The time of first planting of rice is somewhat uncertain, but was unambiguously underway by 6500–6000 years ago (Fuller et al., 2007). Irrigation of wet-adapted rice strains in river valleys had begun by 6500 years ago and had spread across much of Southeast Asia by 3000 years ago (Glover and Higham, 1996; Zou et al., 2000; Li et al., 2007). Rice cultivation appears to have originated independently in the Ganges River regions of eastern India and then spread across India and eastward into Southeast Asia mostly after 3000 years ago (Fuller, 2006). Small terraced hillside plots appeared by 2000–1000 years ago (Jia, 2003). This progressive spread of rice across southern Asia occurred during a time of steadily rising CH_4 concentrations (Fig. 1).

This paper presents a synthesis of 311 archeological sites where rice remains from ancient cultures have been found in China (Appendix A in supplementary materials). The sites contain rice remains such as husks, kernels, phytoliths, with occasional stalks and leaves. Radiocarbon dates on materials found in association with the rice remains are available for 98 of the sites. The dated materials include charcoal, wood, bones, rice husks, other plant remains, and peat.

The other 213 sites occur within the context of specific rice cultures for which bounding ^{14}C dates are available from other locations in China (Table 1). Ages for these sites are placed midway between the bounding ages for the cultural intervals in which they occur. All ^{14}C dates and age estimates have been converted to calendar years using the INTCAL04 program (Reimer et al., 2004). For a similar analysis, see Gong et al. (2007).

The ages of site occupation are divided into 1000-year intervals (Figs. 2b–h, 3). Two dozen sites pre-date 7000 years ago, with a marked increase in subsequent millennia. The largest number of new sites in any millennium—99—appears between 5000 and 4000 years ago, followed by a decrease since that time. This trend persists regardless of how the ^{14}C-dated cultural intervals are characterized—whether by the oldest, youngest, or midpoint age.

Two biases are likely to have affected the trends shown in Figs. 2 and 3. Many archeological studies look for the earliest evidence of an ancient culture or a new agricultural technique. This bias toward older sites works in a direction opposite to that needed to explain the rapid increase in documented sites prior to 4000 years ago, but it probably accounts for the abrupt decrease in new sites after that time. Increasingly detailed historical records kept since the start of the Shang dynasty 3600 years ago (Xia-Shang-Zhou Chronology Project Expert Group, 2000) may have led to reduced archeological interest. A second bias arises from the likelihood that younger occupations may have disturbed older ones. By overprinting older sites, this preservation bias could have contributed to the rapid increase in new sites prior to 4000 years ago (Fig. 3).

Archeologists interpret most of the rice grown at these sites as having been irrigated (Ling et al., 2005). The presence of aquatic pollen assemblages at some locations supports this interpretation (Yan, 1982). More definitively, wells and irrigation canals first appeared between 7000 and 6000 years ago (Tetsuro et al., 1998; Hunan Provincial Institute of Cultural Relics and Archaeology, 1999). In addition, information on the type of rice remains at 91 sites shows only three with rice strains typical of dry land farming. Finally, almost all the sites in this compilation lie adjacent to fields that are irrigated today.

Irrespective of the two biases noted above, these archeological data show that irrigated rice farming spread across much of China millennia ago. The 221 sites that predate 4000 years ago cover most of the region where irrigated rice is grown today, with the exception of the upper valley of the Yangtze River and scattered areas of southern China (Fig. 3). Irrigation continued to spread into these areas during the millennia prior to the industrial era (Fig. 2h).

This early expansion of irrigated rice agriculture occurred during a time of major regional climatic change. Most of the earliest rice-growing sites (those dating to between 10,000 and 7000 years ago) were situated near lakes to take advantage of readily available water. Lake-level, pollen, and speleothem $\delta^{18}O$ trends show, however, that summer monsoons progressively weakened across the northern tropics (including China) after the early Holocene (COHMAP Members, 1988; Yuan et al., 2004). During this drying trend, near 7000 years ago, farmers began using irrigation to overcome the diminishing monsoonal rainfall and grow rice in areas lying beyond the immediate confines of lakes, streams and rivers. In effect, humans began to create their own wetlands (rice fields) to replace natural ones that were drying out.

3. Link to Holocene changes in atmospheric methane

Today, the ~0.3 million km^2 of irrigated land in China account for ~20% of the global total (IRRI, 2007). Because irrigation started

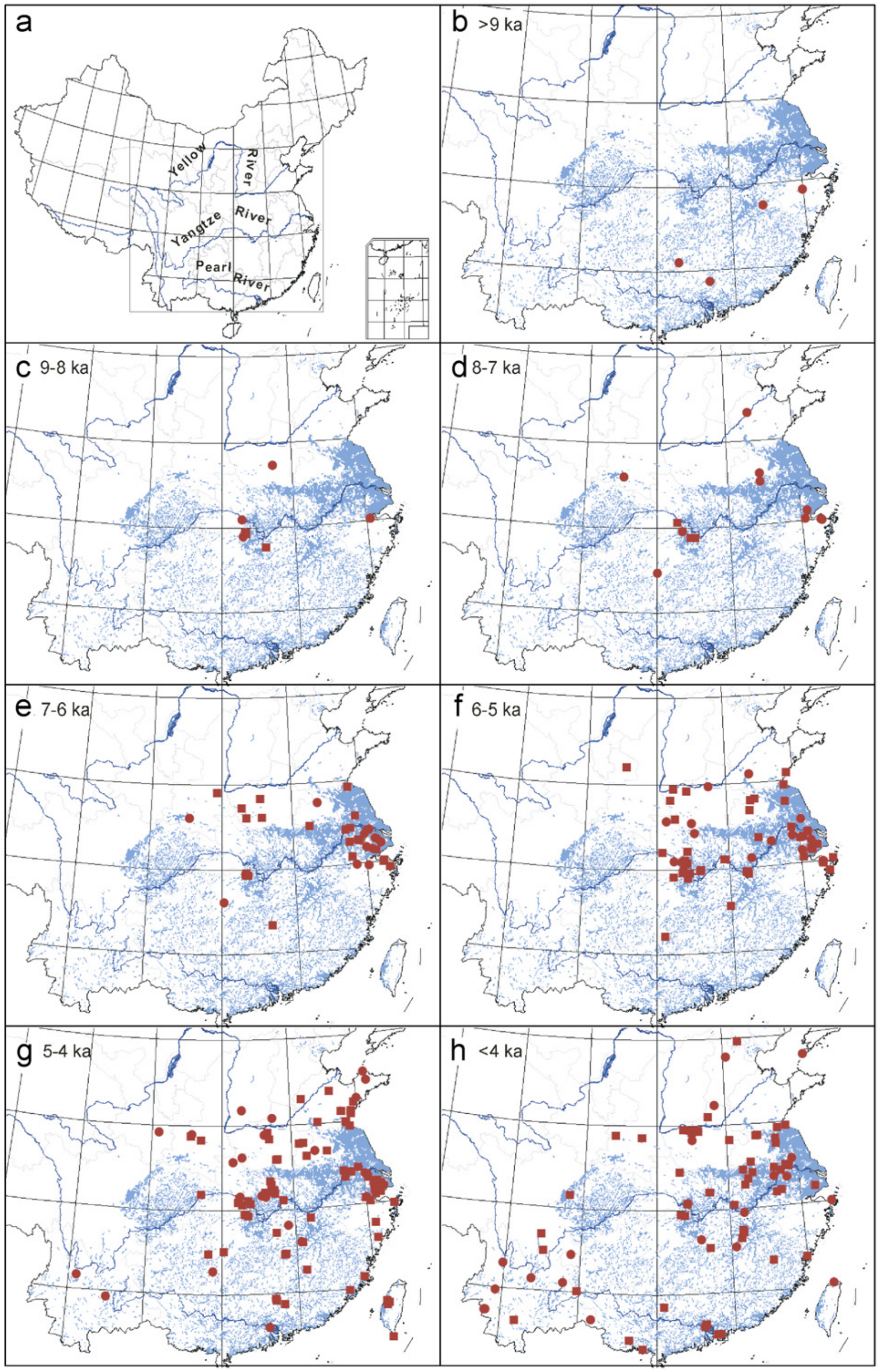

Fig. 2. Holocene spread of rice growing in China: (a) Map of China and area (in box) of ancient rice-growing sites. (b)–(h) Appearance of new archeological sites during millennia indicated. Red circles show sites with ^{14}C dates; red squares show sites with ages constrained by limits of ^{14}C-dated cultural intervals (Table 1). Modern areas of rice irrigation are shown in blue.

early in China, it could have accounted for a larger percentage of global irrigation and methane emissions during these earlier millennia. The rice-irrigation trends in Figs. 2 and 3 must have figured prominently in the anomalous reversal and subsequent rise of atmospheric CH_4 concentrations shown in Fig. 1.

Unfortunately, this compilation of archeological sites cannot be used to estimate either the total extent of irrigated land or the amount of methane emissions during past millennia. Today, rice is grown in enormous numbers of very small plots (Fig. 2), and far more than three hundred sites would be required to estimate the total area irrigated, now or for any time in the past. Nevertheless, the evidence that irrigation techniques had already penetrated into most regions of present-day irrigation by 4000 years ago (Fig. 4) points to a substantial early impact on methane emissions.

By 2000 years ago, census counts in China indicate a population of 50 million people, which represented roughly the same 25% of worldwide population as today (McEvedy and Jones, 1978). Consequently, the initial growth toward large populations

Table 1
Bounding ages of rice cultures in China and source references

Culture	Age	Source reference
Pengtoushan	9000–8000	Zhang, J., Wang, X., 1998. Agricultural Archaeology (1), 108–117
Zaoshixiaceng	8000–7000	Archaeological Team of Yueyang and Luo, R., 1994. Archaeological collections of Hunan Province 6, 142–153
Beixing	7300–6000	Institute of Archaeology of Shandong. The 20th Century Archaeological Discovery and Analysis in Shandong (Science Press, Beijing, 2005)
Majibang	7000–6000	Zheng, J., Chen, C., 2005. Southeast Culture (4), 16–25
Hemudu	7000–5200	Lin, H., 1992. Primary Study on Hemudu Culture. Zhejiang People's Press, Hangzhou
Yangshao	7000–5000	Shi, X., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, pp. 595–602. Encyclopedia of China Publishing House, Beijing
Daxi	6400–5300	Ren, S., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, pp. 83–84. Encyclopedia of China Publishing House, Beijing
Dawenkou	6300–4600	Institute of Archaeology of Shandong, 2005. The 20th Century Archaeological Discovery and Analysis in Shandong. Science Press, Beijing
Liangzhu	5300–4200	Wu, R., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, pp. 271–272. Encyclopedia of China Publishing House, Beijing
Zhuweicheng	5100–3800	Tang, S., 1996. Discussion on Zhuweicheng culture. Relics from South (2), 56–66
Qujialing	5000–4600	Ren, S., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, pp. 404–405. Encyclopedia of China Publishing House, Beijing
Shanbei	5000–4500	Peng, S., 1982. Archaeology (1), 40–47
Tanshishan	5000–4000	Lin, Q., 2004. Relics from South (3), 16–27
Longshan (central China)	4900–4000	Tong, Z., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, p. 290. Encyclopedia of China Publishing House, Beijing
Longshan	4600–4000	Tong, Z., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, p. 290. Encyclopedia of China Publishing House, Beijing
Shixia	4900–4700	Li, Y., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology, p. 475. Encyclopedia of China Publishing House, Beijing
Shijiahe	4600–4000	He, J., 2004. Neolithic Culture in Middle Yangtze River Region. Hubei Education Press, Wuhan
Niuchouzii	4500–3500	Zang, Z., 1990. Zhejiang Academic Journal (6), 46–47
Zhishanyan	4000–3000	You, X., 1986. Cultural Relics (2), 31–36, 43
Shang	3715–3072	Xia-Shang-Zhou Chronology Project Expert Group, 2000. Report on the Xia-Shang-Zhou Chronology Project, 1996–2000, simplified ed. World Publishing Co., Ltd., Beijing
Western Zhou	3071–2721	Xia-Shang-Zhou Chronology Project Expert Group. Report on the Xia-Shang-Zhou Chronology Project, 1996–2000 (simplified edition). (World Publishing Co., Ltd., Beijing, 2000)
Warring period	2422–2171	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Western Han	2156–1927	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Eastern Han	1925–1730	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Three Kingdoms	1750–1670	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Tang	1332–1043	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Song	990–671	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Yuan	679–582	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing.
Ming	582–306	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing
Qing	306–39	Zhang, R., 2006. Ancient Chinese History. Peking University Press, Beijing

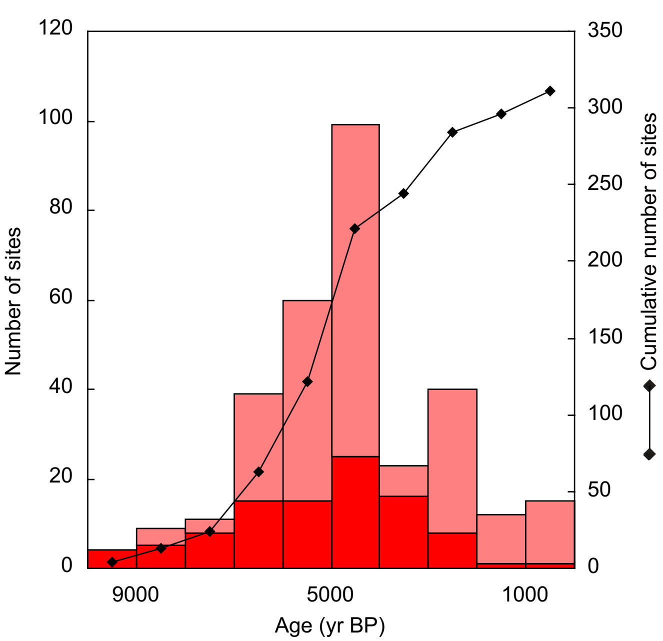

Fig. 3. Appearance of rice sites since 10,000 years ago: Histogram of appearance of new rice-cultivation sites per 1000-year interval. Dark red bars are sites with ^{14}C dates; light red bars are sites from dated cultural intervals. Black line shows the cumulative number of rice sites.

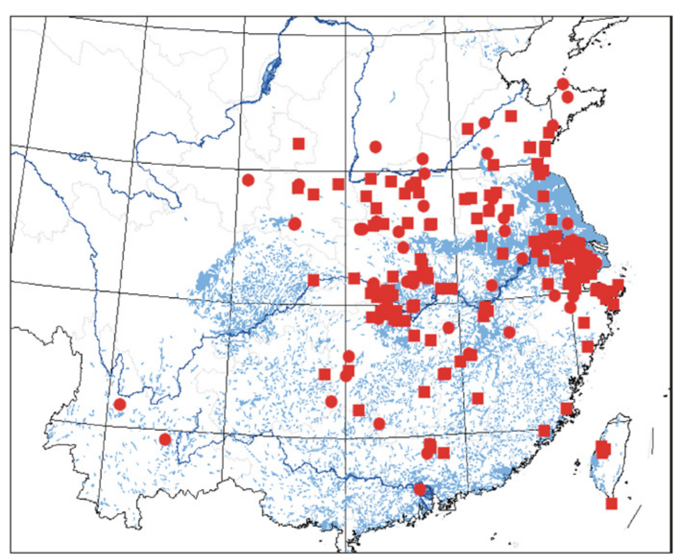

Fig. 4. Rice agriculture by 4000 years ago: By 4000 years ago, archeological sites (red) show that rice irrigation was present across most of China where rice is grown today (blue). Red circles show sites with ^{14}C dates; red squares show sites with ages constrained by limits of ^{14}C-dated cultural intervals (Table 1).

in China must have occurred prior to 2000 years ago. Today, rice supplies a large part of total human nutritional needs in highly populated regions of southern Asia, with yields per unit area as much as 3–4 times larger than those from dry-land crops such as wheat, millet, and barley. The onset of rice irrigation in China and southern Asia prior to 2000 years ago is likely to have played a major role in the early population expansions (Li et al., in press).

Early population growth would have led to other kinds of methane emissions (Ruddiman and Thomson, 2001; Ruddiman, 2003). Growing human populations needed to tend increasing numbers of methane-emitting livestock both as a source of food and as a means to plow larger plots of rice and other crops. Cold-season burning of crop cover and weeds to clear rice paddies for the next growing season would have emitted additional methane as an indirect byproduct. Waste from growing human populations would have added to the total. These factors would have further boosted the rice-paddy methane emissions triggered by early irrigation. Methane releases only stay in the atmosphere for an average of 10 years, but the ongoing rise in methane concentrations over the last 5000 years would have been sustained by the progressive expansion of irrigation from China (and apparently from the independent cultivation center in India) and the resulting growth of large populations (Gong et al., 2007).

Early methane emissions were one part of early agricultural intervention in greenhouse-gas emissions. In addition, deforestation (and consequent release of CO_2) was underway across Europe, much of southern and eastern Asia, and in the Americas (Ruddiman, 2007), and CO_2 remains in the atmosphere much longer than methane. The combined methane and CO_2 emissions from early human activities drove atmospheric greenhouse-gas concentrations toward the upper limit of the natural range that had prevailed during previous orbital cycles (Petit et al., 1999). These increased gas concentrations offset most of a natural cooling that would have occurred in recent millennia and may have prevented the onset of the early stages of a new glaciation (Ruddiman, 2003; Vavrus et al., in press).

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Appendix A. Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2008.03.007.

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