PAPER

# Evidence for cold events in the early Holocene from the Guliya ice core, Tibetan Plateau, China

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**Abstract** **Evidence for the "8.2 ka cold event" has been provided mostly from the circum-North Atlantic area. However, whether this cold event occurred in other places is a key to understanding its cause. Here, we provide the evidence for the "8.2 ka cold event" from the Guliya ice core in the northwest Tibetan Plateau, and it was found that the peak cooling (~8.3—8.2 ka) in this ice core was about 7.8—10℃, which was larger than the cooling in the North Atlantic region. The primary causes for this episode were diminished solar activity and weakened thermohaline circulation. Moreover, another weak cold event, centered about 9.4 ka, was also recorded in the Guliya ice core record. These two cold events were concurrent with the ice-rafting episodes in the North Atlantic during the early Holocene, which implies that the millennial-scale climatic cyclicity might exist in the Tibetan Plateau as well as in the North Atlantic.**

**Keywords: Guliya ice core, early Holocene, abrupt climate change, solar activity, thermohaline circulation.**

Hitherto the warm Holocene has been viewed as climatically stable[1], however, recently developed paleoclimate records from ice cores[2] and high latitude marine sediments[3,4] show that Holocene climate was instead rather unstable. Cooling events of relatively short duration have recurred during this interstadial period, especially in the early Holocene, but were less well studied owing to the low resolution of sediments in most areas. Nevertheless, the reliability of our prediction for future climate variations can be improved by investigating the patterns, causes and mechanisms of the occurrences of these events.

A cold event occurring at about 8.4—8.0 ka (hereafter called the "8.2 ka cold event") is a focal issue in the study of past global changes. This is not only because this event is the most significant one in the post-glacial climatic change as reflected by the Greenland ice core record[5], but also abrupt environmental changes occurred in other areas[6]. So far most evidence for this event has been provided from the records of ice cores[1,5], deep sea sediments[3,7—9], lacustrine deposits[10—12] and tree-rings[9] around the North Atlantic areas. The analyses for the spatial and temporal characteristics and spatial coupling of this event have been limited by the paucity of records from other areas. With these restrictions in mind, we discuss here the possible extent and cause of the "8.2 ka cold event" based on the records from the Guliya ice core, the Tibetan Plateau, in addition to the paleoclimatic and paleoenvironmental data from different regions in the world.

## 1 Changes in $\delta^{18}O$ in Guliya ice core during the early Holocene

A 309-m-long ice core was drilled at 6200 m a.s.l. on the Guliya Ice Cap (35° 17′N, 81° 29′E) by a Chinese-American Scientific Expedition Team in 1992. The dating of its upper part was dependent mainly on the seasonal characteristics of dust and $\delta^{18}O$[13,14]. These dating methods could not be applied below the depth of about 120 m (~1700 aBP), owing to the thinning of annual layers below the limits of visual detection. The lower part of this core was dated by means of ice modeling, special stratigraphical layers (such as small ice crystal size in ice ages), methane matching and cosmogenic isotopes[15,16]. The estimated age for the bottom ice of this core is about 760 ka based on the data of $^{36}Cl$ concentration[16], which is consistent with the age of the Qinghai-Tibetan Plateau stepping into cryosphere[17]. Until now, lots of research results about this deep ice core have been published[15,16, 18].

Fig. 1 shows the changes in $\delta^{18}O$ recorded in the Guliya ice core during the early Holocene. If the 3-point running mean line of $\delta^{18}O$ (thin curve) is lower than the average value (dotted line), the climate is considered to be cold. Therefore, there were two cold periods during the early Holocene, about 9.6—9.2 ka and 8.4—8.0 ka, and the latter was very significant. The mean value of $\delta^{18}O$ in

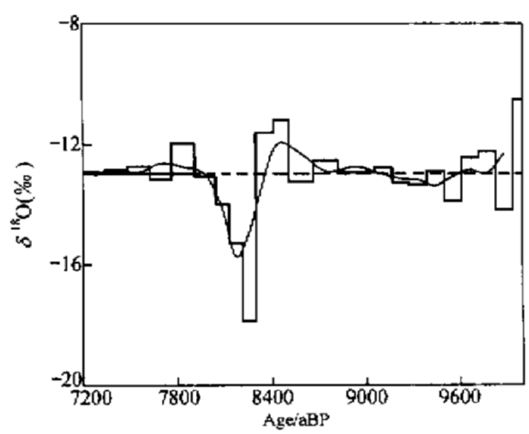


Fig. 1. Changes in $\delta^{18}O$ recorded in the Guliya ice core from 10 ka through 7.2 ka. The solid curve depicts $\delta^{18}O$, the thin curve is its 3-point running mean, and the mean for the entire period is shown by the dotted line.

the period 8.4—8.0 ka (about −15.2‰) was lower than the mean $\delta^{18}O$ before and after that period by 2.7‰ and 2.3‰, respectively. This provides the evidence that the "8.2 ka cold event" existed beyond the circum-North Atlantic area. Moreover, a distinctive characteristic was illustrated in the $\delta^{18}O$ signal in the Guliya ice core that its value decreased abruptly from −11.6‰ at about 8.4 ka to −17.9‰ at about 8.3 ka, and then increased gradually to −13.0‰ at about 8.0 ka. This indicates that the $\delta^{18}O$ drop during this event is larger in the Guliya ice core (about 4.9‰—6.3‰) than in the GISP2 ice core (about 2‰[5]), and that the progression of this cold event was different in these two far-flung climate records. Fig. 2(b) shows that the pattern of $\delta^{18}O$ decrease and increase in the GISP2 ice core during this cold event was nearly symmetric.

## 2 Magnitude of temperature decrease during the "8.2 ka cold event"

In recent years, the climatological significance of $\delta^{18}O$ in precipitation on the Tibetan Plateau was studied[23—25], and it was found that the changes of $\delta^{18}O$ were mainly influenced by air temperature over the northern part of the Plateau. An obvious positive correlation also existed between $\delta^{18}O$ in precipitation and air temperature in the catchment area of the Urumqi River in Central Asia[26]. All these observations indicate that $\delta^{18}O$ is a good proxy for temperature in the northern Tibetan Plateau, moreover a change in $\delta^{18}O$ by 1‰ is equivalent to a temperature change of about 1.6℃ in this area[25]. This quantitative relationship, close to that in modern precipitation in Europe (1.7℃/1‰ [27]) and in Greenland (1.8℃/1‰ [28]), suggests that the peak cooling during the "8.2 ka cold event" in the Guliya ice core record was ~7.8—10℃, which was larger than the ~6±2℃[5] cooling in the GISP2 record. Also, the 10℃ cooling in the Tibetan Plateau record was a climatic feature that was distinct in its magnitude and abruptness.

Considering variations in resolution in different stratigraphic media in different areas, we should compare the magnitudes of temperature decreases in these areas on the same time scale ($10^2$ a) around the "8.2 ka cold event" (table 1). The concept that the Tibetan Plateau is a sensitive region to the global climate change has been proposed[29] based on the comparisons of the differences in $\delta^{18}O$ between the Last Glacial Maximum and the present in ice cores from the Tibetan Plateau and the polar regions, the consistency of abrupt climatic changes during the Last Glacial Age recorded in ice cores from the Tibetan Plateau and the Greenland, and the fact that magnitudes of variations in air temperature increased with altitude around the Tibetan Plateau in recent years. From table 1, it can be seen clearly that the magnitude of temperature decrease at the "8.2 ka cold event" was the largest one on the Tibetan Plateau. This also supports the concept that the Tibetan Plateau is a region sensitive to the global climate change. The feedback between snow cover and climate change might be a basic cause for the large magnitude of temperature variations over the Tibetan Plateau. When the climate becomes cold, snow cover on the Tibetan Plateau increases in area and duration throughout the year, thus increasing the albedo of the surface, and reflecting solar radiation away from the land and decreasing surface and lower atmospheric temperatures. However, when the climate becomes warm, snow cover on the Plateau will be reduced in area and duration, and the decreasing albedo causes energy absorption that melts snow, frozen soil and glaciers and causes gradual climate warming.

Table 1 Comparisons of the magnitudes of temperature decreases on the time scale of $10^2$ a in different areas at the "8.2 ka cold event"

| Region | Temperature decrease/℃ | Data source |
|---|---|---|
| Greenland | ~ 2.8 | [10] |
| North Sea | >2 | [9] |
| North Atlantic | ~ 2 | [3] |
| Central Europe | ~ 1.7 | [10] |
| North Tibetan Plateau | ~ 3.7—4.3 | this paper |

## 3 Discussion

In the earlier study on the Dunde ice core record, it was pointed out that there was a strong cold event in the early Holocene that lasted about 3—4 centuries[30]. Considering the uncertainty of the Dunde time scale[31], it might be concluded that the strong cold event from 8.9 ka to 8.7 ka might have corresponded to the "8.2 ka cold event". Some terminal moraines formed around 8.0 ka along the perimeters of the existing Guliya and Dunde Ice Caps in the northern Tibetan Plateau[32—33], and in the area of an ancient Daocheng Ice Cap in the eastern Tibetan Plateau[34]. Periglacial involutions were also well developed in the Gonghe Basin in the northeast Tibetan Plateau at about 8.35 ka[35]. Because 7.65—7.2 $^{14}C$ ka corresponds with 8.4—8.0 calendar ka[36], the low water temperature event of Qinghai Lake at about 7.5 $^{14}C$ ka[37], the coniferous forest expansion from mountain to plain in the region of Beijing at about 7.7 $^{14}C$ ka[38], and 1—2℃ cooling in eastern China at about 7.7—7.5 $^{14}C$ ka[39], should be coincident with the "8.2 ka cold event". A small dip centered near 8.2 ka in the otherwise steady rise in the Ters sea-level curve[40] reflects the global chill that proceeded the movement of oceanic water to land where it then froze. This is confirmed by the glacier advances around 8.0 ka in the Scandinavian Peninsulas[41—43], the Alps[41], the Tibetan Plateau[32—34] and the Southern Andes[44]. Desiccation of most lakes in the Asia and North Africa around 7—8 $^{14}C$ ka[45] suggest weakening of the monsoon circulation. All these examples cited above imply that the occurrence and/or impact of the "8.2 ka cold event" were global, which suggests that this cold event might be caused by external and/or internal factors that can influence the global climate change[46].

We have found a positive correlation between the concentration of nitrate ($NO_3^-$) in the Guliya ice core record and the solar activity in the most recent 1000 years[47,48]. If this correlation is a modern analog for what existed in the past, the lower $NO_3^-$ concentrations around 8.5—8.1 ka (fig. 2(g)) suggest that solar activity was diminished. Based on the $\Delta^{14}C$ in tree-ring records, Stuiver et al. [22] found that the solar activity exhibited a multitude of oscillations with the Maunder and Sporer types in the Holocene, while an unusual "triple event" (a rapid sequence of the Maunder-and-Sporer-type disturbances) occurred from 8.4 ka to 7.8 ka (see fig. 2(f), denoted by $T_1$). Most recently, Perry et al. [49] calculated the solar output over the last 90 ka, pointing out that it was relatively small around 8.2 ka. Thus the weak solar activity or the weak solar radiation is a logical candidate for an external forcing of the "8.2 ka cold event".

Most studies[50—53] have shown that changes in the Atlantic Ocean circulation can influence abrupt climate fluctuations on a global scale. The formation of North Atlantic Deep Water (NADW) drives the global thermohaline 'conveyor belt', so an input of excess freshwater (from melting snow and ice, high precipitation, and/or runoff of rivers) to this region, where water moving from lower latitudes has higher sea surface temperatures and salinities than the surrounding water at the same latitudes, can result in changes in production rates of NADW, which results in changes in global thermohaline circulation and climate. Some models[54,55] project that the production rate of NADW slows when excess freshwater discharge of 0.06—0.1Sv（$1Sv = 10^6 m^3 s^{-1}$） is achieved over at least 500 years. In this case, the global thermohaline circulation will be affected strongly, and less heat gained by atmosphere through the process of formation of NADW will cause climate cooling around the North Atlantic Ocean, which could result in reorganization of the global atmospheric circulation. The glacial lakes Agassiz and Ojibway (originally dammed by a remnant of the Laurentide ice sheet) drained catastrophically at about 8.47 ka calendar; this would have released about $2\times10^{14} m^3$ of fresh water into the Labrador Sea[56], one of the three major areas of NADW formation, which reduced sea surface salinity and altered ocean circulation, and thereby initiated the "8.2 ka cold event". The estimated magnitude of atmospheric cooling over that oceanic region was one-third of that during the Younger Dryas[56]. Cold air over the North Atlantic Ocean could be spread to Europe by atmospheric circulation, and westerly, in this case, could be intensified and shifted southward, therefore much polar cold air could be transmitted to large areas in the Northern Hemisphere including the Tibetan Plateau. Those processes might be the linkages between the abrupt climatic events in the North Atlantic Ocean and other regions in the Northern Hemisphere. Therefore, the reduced production rate of NADW was a relatively independent internal factor causing the "8.2 ka cold event". Moreover, a weak North Atlantic thermohaline might cause an accumulation of heat in some regions of the South Oceans, which could mitigate climate cooling in the Southern Hemisphere at this cold event, just like 'bipolar seesaw effect'[57]. Maybe that was why there was no notable evidence for the "8.2 ka cold event" in the Southern Hemisphere.

The "8.2 ka cold event" could result in a decrease in thermal gradient between the landmass and ocean, which might have weakened the African-Asian monsoon. The area of the wetlands in the region might have diminished resulting in a reduction in $CH_4$ emission. A small decrease in $CH_4$ concentration in the Greenland ice core record[19] around this time (see fig. 2(c)) was probably related to those processes. The ocean circulation changes were the essential cause of atmospheric $CO_2$ variations, and the Antarctic Ocean was the most critical region[58]. Recently, it was pointed out that the terrestrial net primary production (i.e. formation or diminution of forests on a large scale) could regulate atmospheric $CO_2$ concentration[59]. Therefore, it could be assumed that the general decline in atmospheric $CO_2$ concentration in the early Holocene revealed by Antarctic ice core record (see fig. 2(d))[20] might be related to the formation and expansion of the northern forests just after several ice sheets melted, and its minimum value at about 8.2 ka might be related either to an increase in absorption of the ocean in this cold event or to changes in biological productivity in oceans affected by the weak thermohaline circulation. Those analyses show that changes in atmospheric $CH_4$ and $CO_2$ concentrations were attributed to the self-organization, self-regulation, and feedback mechanisms in the Earth's climate system, but were not the causes of the "8.2 ka cold event". Moreover, decreases in atmospheric $CH_4$ and $CO_2$ concentrations were so small that they could not have been a contributing factor. Relatively strong volcanic eruptions occurred at the beginning of this climatic disruption, but at its peak volcanic activity was rather calm (fig. 2(e)) [21], therefore this was probably not a basic cause of the "8.2 ka cold event", although it might have intensified the cooling to some extent at the beginning.

A relatively weak cold event from about 9.6 ka to 9.2 ka was recorded in the Guliya ice core record (see fig. 1), and it had a corresponding signal in the Dunde ice core[30]. The North Atlantic deep-sea cores revealed that an ice-rafting episode similar to the 8.1 ka event[3] occurred around 9.4 ka. Dramatic climatic variations occurred in the North Atlantic area and on the Tibetan Plateau at nearly the same time, and this implies that a millennial-scale cycle might also be embedded in the climate

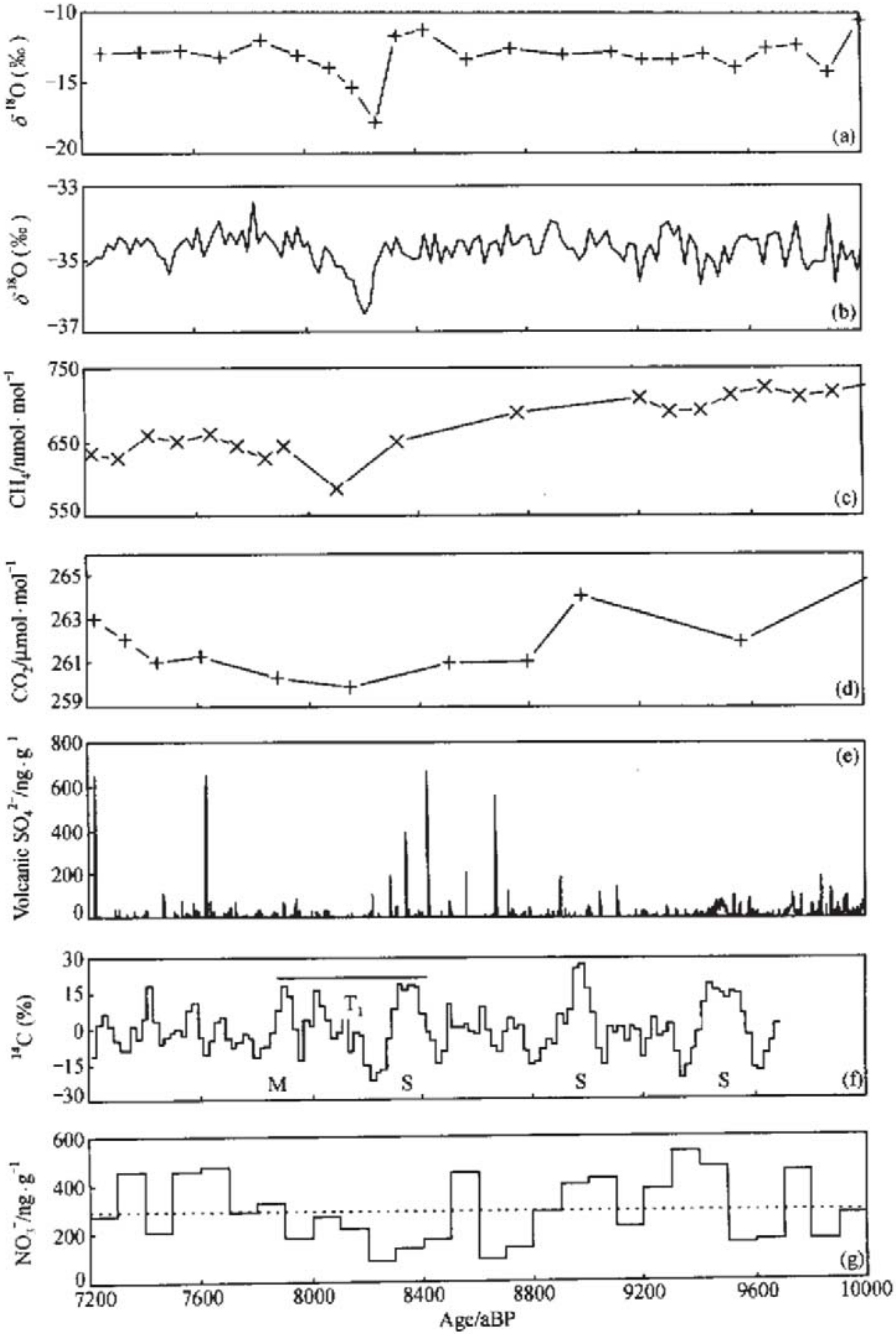


Fig. 2. Comparisons of the changes in temperature, atmospheric greenhouse gas concentrations, volcanic activity and solar activity from 10 ka to 7.2 ka. Changes in $\delta^{18}O$ in (a) the Guliya ice core and (b) in the GISP2 ice core[5]. (c) $CH_4$ concentration variations in the GRIP ice core[19]. (d) $CO_2$ variations in the Taylor Dome ice core, Antarctica[20]. (e) Changes in volcanic $SO_4^{2-}$ concentration in GISP2 ice core[21]. (f) Relative changes in $^{14}C$ production rate ($\Delta Q/Q_t$, %), M and S nomenclature identify Maunder- and Sporer-type perturbations, triple event is denoted by $T_1$[22]. (g) The $NO_3^-$ concentration record from the Guliya ice core.

records from the Tibetan Plateau as well as in the North Atlantic records. The simultaneous climate variations on these time scales in these distant regions might have common causes, however such issues require further investigation. In fig. 2(c), (d), it can be seen that small decreases in atmospheric $CH_4$ and $CO_2$ concentrations occur simultaneously with the weak cold event at about 9.4 ka, which implies that there was a small self-reorganization in the Earth's climate system. Fig. 2(g) shows that this weak cold event might also have been related to weak solar activity.

## 4 Conclusions

Two early Holocene cold events recorded in the Guliya ice core were investigated above. They are dated at around 9.2—9.6 ka and 8.0—8.4 ka, occurring nearly simultaneously with two ice-rafted episodes in the North Atlantic Ocean. The later cooling, which was very distinct, was characterized by the abrupt onset of lower temperatures followed by slow warming. The occurrence of this in an Asian climate record is evidence that "the 8.2 ka cold event" extended beyond the circum-North Atlantic region. The prevailing westerlies might have been the major link between abrupt climatic changes in the North Atlantic area and on the northern Tibetan Plateau. Confirmation of this 8.2 ka cold event occurs in glacial and lacustrine deposits from different areas, which suggests that the influence of this cold event may have been global. Comprehensive analyses indicate that the weakening solar insolation might have been the external cause of the "8.2 ka cold event", and the reduced production rate of NADW[60] was a relatively independent internal cause. Moreover, the cause of the weak cold event around 9.6—9.2 ka was also possibly related to the weaker solar activity.

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