Black soot and the survival of Tibetan glaciers

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We find evidence that black soot aerosols deposited on Tibetan glaciers have been a significant contributing factor to observed rapid glacier retreat. Reduced black soot emissions, in addition to reduced greenhouse gases, may be required to avoid demise of Himalayan glaciers and retain the benefits of glaciers for seasonal fresh water supplies.

aerosols | climate change | fresh water | glacier retreat | Tibetan Plateau

Glaciers on the Tibetan Plateau, sometimes called Earth's "third pole," hold the largest ice mass outside the Polar Regions. These glaciers act as a water storage tower for South and East Asia, releasing melt water to the Indus, Ganges, Brahmaputra, and other river systems, providing fresh water to more than 1 billion people (1, 2). Glacial melt provides up to two-thirds of the summer flow in the Ganges and half or more of the flow in other major rivers (3). One-quarter of the population of China is in western regions where glacial melt provides the main dry season water source (4).

Tibetan glaciers have been melting at an accelerating, alarming rate over the past decade, raising the threat that many of the glaciers could be gone by midcentury (5, 6). As glaciers recede and release stored water, flow temporarily increases, but the future fresh water supply is threatened (5–8). Once headwater glaciers are gone, however, a dramatic decline in dry season water availability may ensue. Total precipitation may increase with global warming (1, 9), but a likely result of glacier loss will be heavier spring floods and much reduced fresh water availability during subsequent dry seasons.

Climate on the Tibetan Plateau is changing rapidly; over the past three decades, the large area at altitude above 4,000 m has warmed 0.3 °C per decade (Fig. S1), which is twice the rate of observed global warming. Climate change on the plateau may have large regional effects, for example, on the Asian monsoon, and even global repercussions (3). Glacier retreat in the Tibetan Plateau presumably is driven by warming due to increasing greenhouse gases (1), but the rapidity of glacier retreat and the up to 0.3 °C warming of per decade during the past 30 years suggest additional mechanisms may be involved.

Black soot in aerosol pollution can warm the troposphere, perhaps contributing to surface melt (10–12). Absorption is caused primarily by the black carbon (BC), whereas organic carbon (OC) absorbs mainly in the UV and slightly in the visible region (13–15). Black soot incorporated in snowflakes darkens snow and ice surfaces, increasing surface melt (16–18). Simulations show that the added absorption by snow exceeds the "dimming" effect (reduced solar irradiance at the ground due to atmospheric aerosols) and becomes significant when BC reaches amounts on the order of 10 ng g^{-1} or more (15, 19).

The Tibetan Plateau is located close to regions in South and East Asia that have been (20) and are predicted to continue to be (21) the largest sources of black soot in the world. The extensive black soot aerosols could be lofted to the high Tibetan Plateau and incorporated in snowflakes that when falling on the glaciers darken their surface, which has led to initial studies of the amount of BC and OC in the snow and ice of Himalayan glaciers (22, 23). Yet, black soot-induced reduction of snow albedo and its contribution to glacier retreat have only begun to receive attention, so there is a need for more extensive field data. Here, we report measurements of the BC and OC content in ice cores that sample snow deposited during the past half century on five widely spaced glaciers on the Tibetan Plateau.

Results

We extracted ice cores from five locations on the Tibetan Plateau (Fig. 1) to investigate temporal changes of black soot amount. The period covered, based on annual layering of the ice, extends back to the 1950s. We show (Fig. 2) BC and OC concentrations (ng g^{-1}) and the annual deposition flux (i.e., the annual mass of BC or OC per unit area). At the third site, Rongbuk Glacier on Mt. Everest, we compare our BC concentration with a prior result (23), finding close agreement.

Interpretation of the temporal changes of black soot amount depends on knowledge of the meteorology and major black soot emission sources. The largest snowfall source on the plateau is the Indian monsoon, which reaches about 30–32 °N during summer (Fig. 1). Snowfall on the northern and northwestern parts of the plateau is associated mainly with the westerly jet stream, which moves southward toward the Himalayas in winter. Thus, black soot deposited on Himalayan glaciers derives primarily from two directions: west and south. The northern and northwestern plateau is under control of the westerly jet stream all year, so its upwind sources are principally Europe and the Middle East. Glaciers in the southern part of the plateau receive deposits from the west in winter and from the south in summer.

We find relatively high black soot concentrations in the 1950s-1960s at all Tibetan locations except the Zuoqiupu, likely because of the large European source at that time (15), despite the long transport distance (24). Lack of a notable 1950s-1960s peak at the Zuoqiupu may be due to the circuitous path required for European air to reach that location on the eastern plateau, and thus the greater proportion of Asian aerosols there. Decreased BC and OC concentrations on the northwestern and central plateau in the 1970s-1980s, relative to 1950s-1960s, are consistent with the fact that European sources decreased because of environmental regulations (19).

Glaciers on the southern plateau should receive black soot both from the south via the Indian monsoon during summer and from the west via winter westerlies. Overall, there is evidence of increasing BC and OC concentrations on southern Tibetan glaciers (Zuoqiupu, Noijin Kangsang, and East Rongbuk, in Fig. 2) since 1990. This post-1990 difference between southern and

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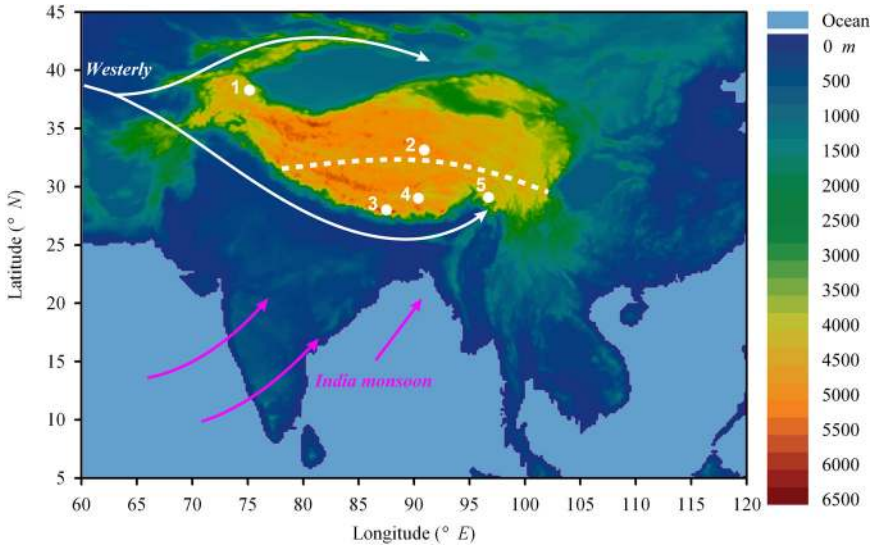

Fig. 1. Five ice cores were extracted at the indicated locations, altitude, and ice core length: 1, Mt. Muztagh Ata (75.10 °E, 38.28 °N, 6,300 m, 40.0 m); 2, Tanggula glacier (92.09 °E, 33.11 °N, 5,800 m, 32.5 m); 3, East Rongbuk glacier, Mt. Everest (86.96 °E 28.02 °N, 6,500 m, 22.3 m); 4, Noijin Kangsang glacier (90.20 °E, 29.04 °N, 5,950 m, 23.5 m); and 5, Zuoqiupu glacier (96.92 °E, 29.21 °N, 5,600 m, 97.0 m). White dashed line is the northern boundary of the India monsoon based on $\delta^{18}O$ seasonal changes from our precipitation isotope observation network on the Tibetan Plateau.

northern glaciers reflects regional differences in source strength and transport pathways for atmospheric black soot between Europe and Asia, including regional differences in the degree of environmental regulation.

In addition to contributions from the monsoon, the brown haze found during winter and spring to lie against the Himalayas (12) contains black soot blown onto the southeastern Tibetan Plateau by the southern branch of the westerlies that sweep over the south side of the Himalaya–Hindu Kush range (Fig. 1). This makes the Zuoqiupu site the most representative of Asian sources among the five glaciers. Fig. 3 shows the Zuoqiupu data broken down by monsoonal and nonmonsoonal periods. The monsoonal period has lower BC and OC concentrations because of the high precipitation rate, but the source is unambiguously Asian, primarily the Indian subcontinent. The Zuoqiupu data indicate an increasing Asian source since the 1990s, especially during the present decade of rapid industrial growth. An increase of BC and OC emissions by about 30% between 1990 and 2003 has been estimated (20). Our Zuoqiupu data suggest that Asian emissions continued to increase after 2003.

Discussion

We show that the black soot content is sufficient to affect the surface reflectivity of the glaciers and that the black soot amount has increased rapidly since the 1990s, coincidentally with the accelerating glacier retreat and increasing industrial activity in South and East Asia. We suggest that a successful strategy for humanity to retain the fresh water benefits of Himalayan glaciers will need to reduce black soot emissions so as to restore more pristine high-reflectivity snow and ice surfaces, as well as stabilize and possibly reduce greenhouse gas amount.

BC concentrations of 10 ng g^{-1} significantly alter the albedo (reflectivity) of a thick snow layer. The visible albedo of deep fresh snow, about 0.9–0.97, is decreased by 0.01–0.04 by a BC amount of 10 ng g^{-1} (16, 18), thus increasing absorption (1 minus albedo) of visible radiation by 10–100%, depending on the size and shape of snow crystals and on whether the soot is incorporated within snow crystals or externally mixed (16, 18). The impact of albedo change is magnified in the spring, at the start of the melt season, because it allows melt to begin earlier. Then, as melting snow tends to retain some aerosols, the surface concentration of black soot increases, and BC becomes even more effective at increasing melt of snow and ice.

Seasonal variation of BC probably maximizes its impact on snowmelt. Lowest BC concentration is during the monsoon season, whereas the highest concentration is associated with the South Asian Haze (12), which peaks during November–March, spreading northeastward along the south side of the Himalayas. Thus, highest black soot concentration in unmelted snow occurs at the time of maximum snow extent, accelerating spring melt and lengthening the melt season. In addition, the ice cores used to measure black soot concentration are obtained in the accumulation zone of the glaciers; i.e., in regions where snow melt is negligible. In the ablation zone on the glaciers, the melting process tends to increase the concentration of black soot on the glacier surface, thus increasing the impact of black soot on glacier melt.

Quantitative modeling of the effect of black soot on glacier dynamics is a current challenge, but some indication of the outcome may be provided by results of initial analyses of the closely related problem of black soot's effect on regional climate in areas with extensive snow and sea ice. These studies (14, 18, 19, 25) suggest that black soot is responsible for a substantial fraction of the regional warming of the past century, comparable to the fraction attributable to carbon dioxide. Assessment of black soot's impact on glaciers will need to include the contribution that black soot makes to regional climate change, as well as direct effects on the glacier.

Although northern hemisphere temperature change should be the primary factor influencing Tibetan glacial variations, we now recognize the role of black soot as an important secondary factor that can reinforce temperature-driven glacier responses. Tibetan glaciers retreated rapidly in the 1950s and 1960s, but in the 1970s many glaciers advanced, and the snowline dropped (8). Given the enhanced black soot levels in the 1950s and 1960s and the near-zero trend of Himalayan temperature between 1955 and 1980 (Fig. S1), we regard black soot as a potential factor that may have contributed to the observed glacial changes. The spatial variability of glacier retreat is also consistent with a role for black soot, because the most rapid glacier retreat and the highest black soot concentrations are located around the margin of the plateau (8, 13).

A principal obstacle to quantitative analysis of the albedo change due to black soot deposition on glaciers is the degree to which the

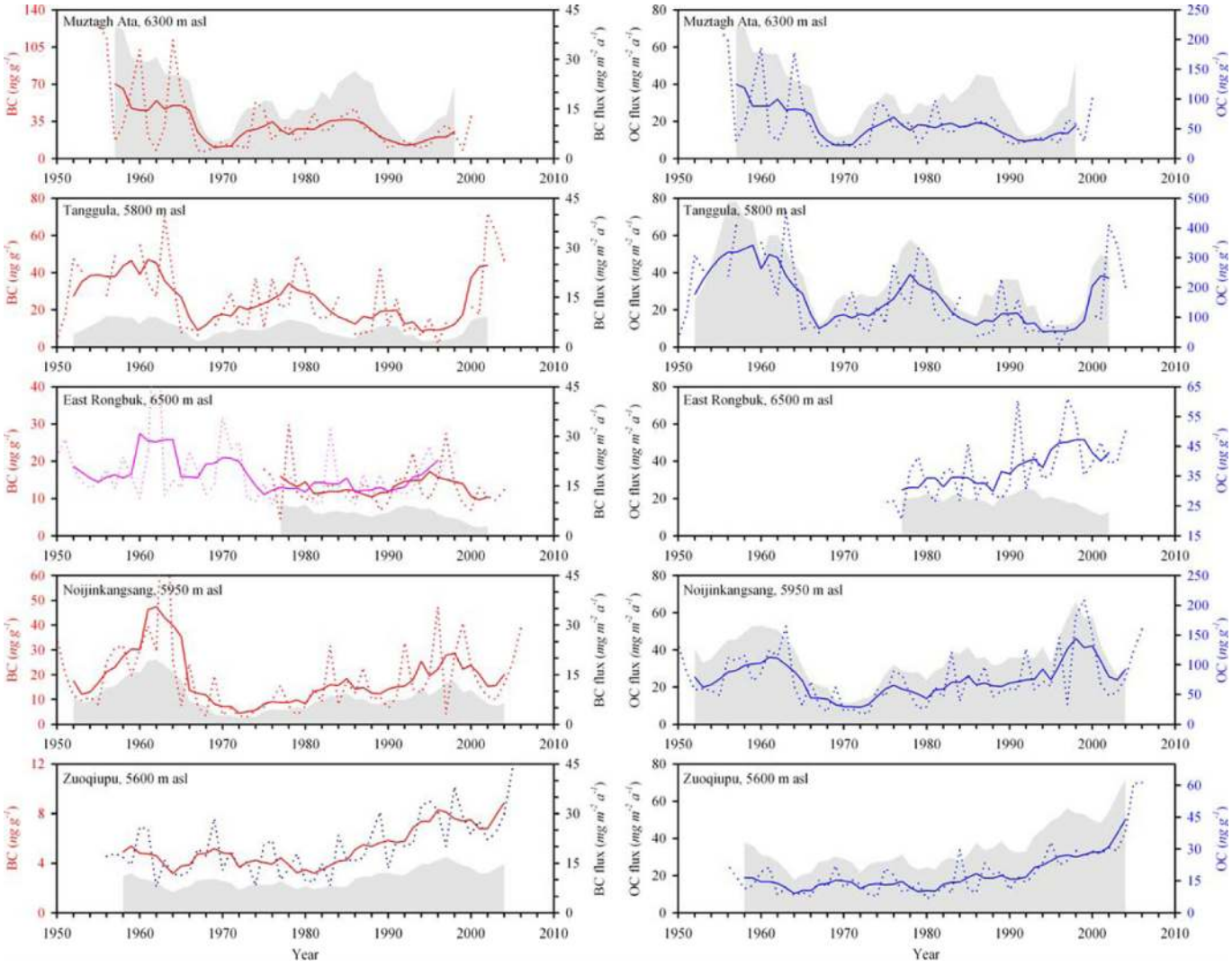

Fig. 2. BC and OC in the five ice cores. Dotted line is annual concentration (ng g^{-1}), solid line is 5-year running mean, and gray shaded region is the integrated annual deposition. Results of Ming et al. (23) for the East Rongbuk glacier on Mount Everest are shown for comparison.

surface black carbon concentration increases as the snow melts. We made an estimate of the potential increase of black soot concentration due to snowmelt in the region of the Zuoqiupu glacier, as summarized in Fig. 4. We staked a glacier area adjacent to the Zuoqiupu glacier (22 stakes at altitudes between 5,000 and 5,500 m) and measured the change of snow depth through the 2007

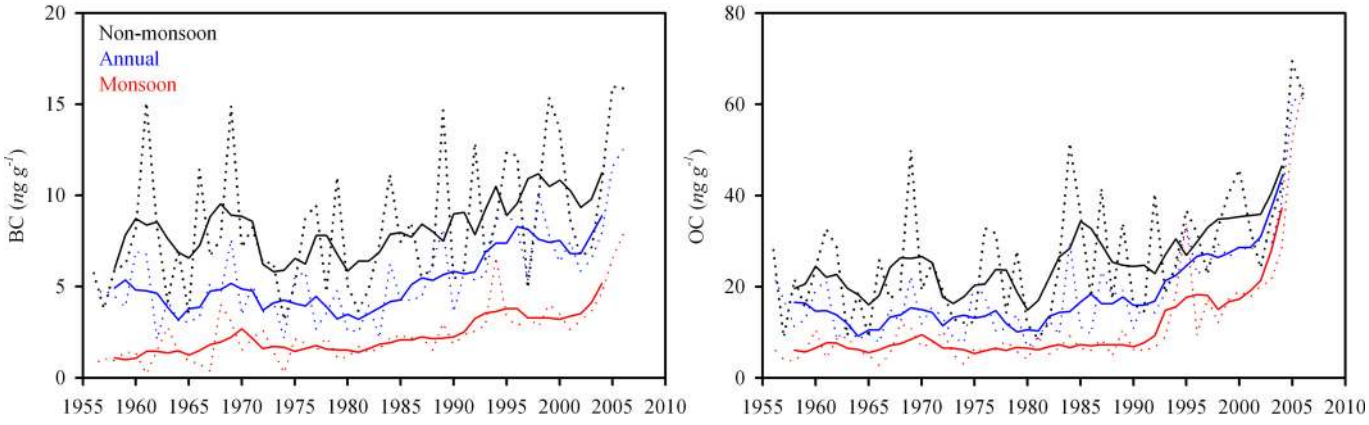

Fig. 3. BC and OC concentrations in the Zuoqiupu ice core for the monsoon (June–September) and nonmonsoon (October–May) seasons, and for the annual mean.

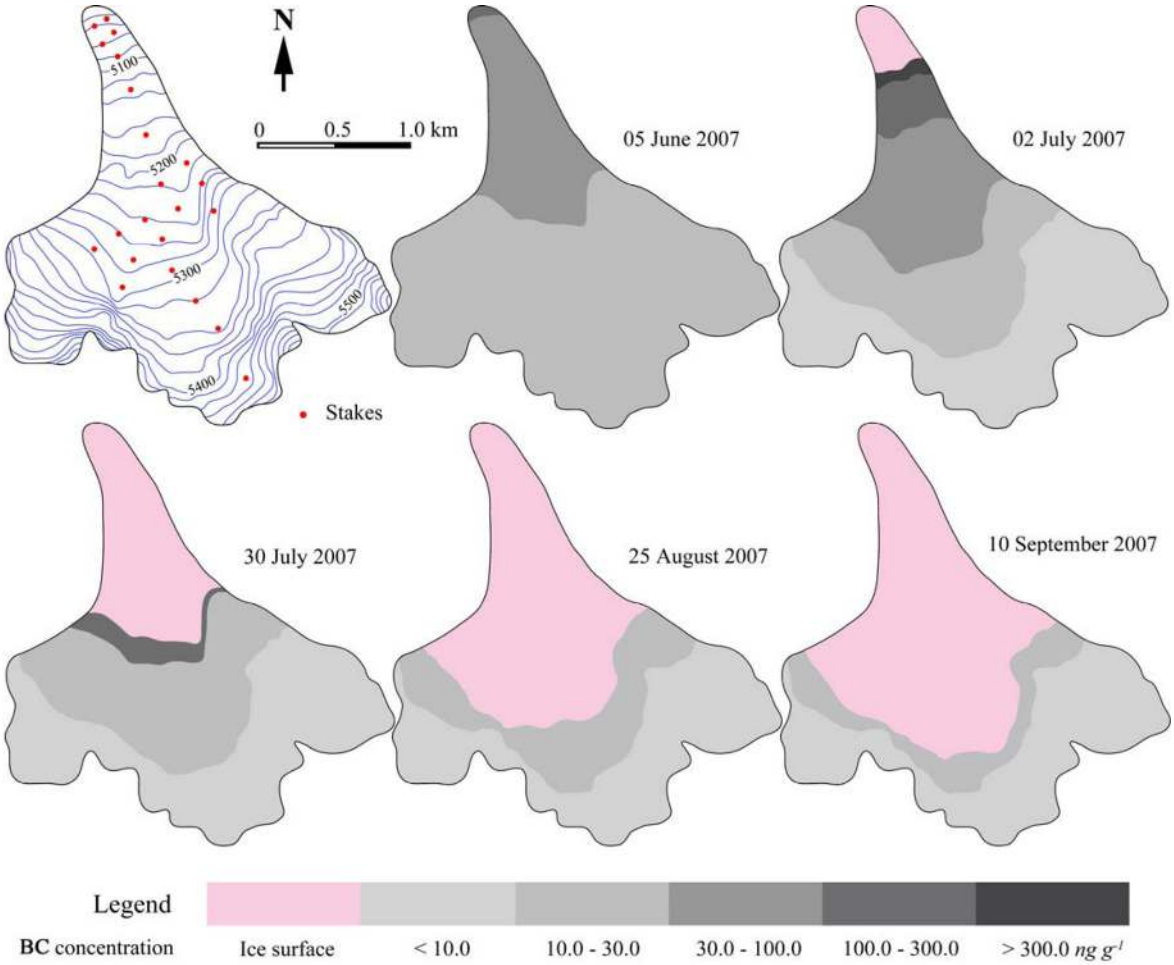

Fig. 4. Topography and calculated BC concentration on a glacier adjacent to the Zuoqiupu that was staked at the indicated locations to measure snow depth throughout the 2007 melt season. Calculated concentrations assume that the annual BC amount measured at the summit is distributed uniformly through the remaining snow depth; i.e., the BC is not carried away by melt water.

melting season. The highest stake was well into the accumulation zone, with no detectable snowmelt. EC concentration in 2006 on the Zuoqiupu was 15.9 and 7.9 ng g^{-1} in the nonmonsoon and monsoon periods, respectively. We assume that the BC deposition and snowfall were uniform over the staked region. We assume that as snow melted, all BC remained, uniformly mixed, in the unmelted snow. Resulting BC concentrations under these assumptions are shown in Fig. 4. Surely, the assumption that no BC runs way in the melt water exaggerates mean BC concentration but, on the other hand, remaining BC tends to be more concentrated toward the surface, rather than uniformly mixed, thus increasing its effectiveness in absorbing sunlight. Fig. 4 suggests that great enhancements in surface BC concentration, an order of magnitude or more, are possible. Snow sampling at high temporal resolution on a Qilian Shan glacier revealed that the fresh snow cover melted within 2 days, exposing dirtier underlying snow with BC concentration seven times greater than the fresh snow (22). Future studies should include sampling of BC concentration during the melt season, a task that was beyond the scope of the present investigation.

Scenarios for future climate usually assume that most fossil fuels will be burned, causing additional global warming of at least several degrees Celsius. In that event, most glaciers, worldwide, will be lost this century, with severe consequences for fresh water supplies (1, 7, 26), as well as many other climate effects (7).

Scenarios with dramatic climate change are not inevitable. An alternative scenario, which stabilizes global temperature at a level near the range of the Holocene, requires reduction of the major human-made climate-forcing agents that have a warming effect, including black soot as well as the greenhouse gases (10). If coal emissions were phased out over the next two decades, and if unconventional fossil fuels, such as tar sands and oil shale, were not developed, atmospheric CO_2 could peak at 400–425 ppm and conceivably return to a level of 350 ppm or less via improved forestry and agricultural practices (27). Such a scenario for CO_2, along with reduction of other greenhouse gas and black soot emissions, might avoid demise of Tibetan glaciers and the deleterious effect of glacier loss on fresh water supplies, while having other benefits for global climate and human health.

Materials and Methods

We sampled ice cores at intervals of 10–25 cm of core length. After the outer 1.0 cm of the ice core was pared away, residual inner ice of mass 150–300 g was melted and immediately filtered through prefired quartz fiber filters. BC and OC on the filters were measured by using the Interagency Monitoring of Protected Visual Environments (IMPROVE) thermal/optical reflectance protocol (28). Analytical uncertainties for the possible carbon artifacts were evaluated via four parallel ice samples cut lengthways in an ice core with high dust loading, which were assessed to be ≈15% for BC and ≈16% for OC. Detailed procedures on the ice preparation and analytical method are summarized in the *SI Text*.

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