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A High-Resolution Millennial Record of the South Asian Monsoon from Himalayan Ice Cores

L. G. Thompson,[1,2*] T. Yao,[3] E. Mosley-Thompson,[1,4] M. E. Davis,[1,2] K. A Henderson,[1,2] P.-N. Lin[1]

A high-resolution ice core record from Dasuopu, Tibet, reveals that this site is sensitive to fluctuations in the intensity of the South Asian Monsoon. Reductions in monsoonal intensity are recorded by dust and chloride concentrations. The deeper, older sections of the Dasuopu cores suggest many other periods of drought in this region, but none have been of greater intensity than the greatest recorded drought, during 1790 to 1796 A.D. of the last millennium. The 20th century increase in anthropogenic activity in India and Nepal, upwind from this site, is recorded by a doubling of chloride concentrations and a fourfold increase in dust. Like other ice cores from the Tibetan Plateau, Dasuopu suggests a large-scale, plateau-wide 20th-century warming trend that appears to be amplified at higher elevations.

The Holocene climate of the southern Tibetan Plateau has been dominated by the South Asian Monsoon in the summer and by westerly cyclonic activity in the winter. The strength of the monsoon is determined by a number of forcing mechanisms operating over a variety of time scales. Northern Hemisphere (NH) insolation has been relatively high over the past 10,000 years with correspondingly greater monsoonal activity than during the last glacial stage, when NH insolation was lower. At that time, reduced differential heating between the Indian Ocean and the Asian continent weakened the summer circulation, producing cooler, drier conditions over Asia and across the southern plateau (*1*). On shorter time scales, variations in the strength of the South Asian Monsoon have been explained by changes in internal boundary conditions, such as increasing tropical sea surface temperatures (*2*, *3*), variations in Eurasian snow cover (*4–7*), and linkages with the El Niño–Southern Oscillation (ENSO) (*8–10*). The Himalayas contain the largest volume of ice outside the polar regions, and the meltwater from its glaciers form the headwaters of such important rivers as the Indus and the Ganges. Here, we examine the variability of the South Asian Monsoon as recovered from Himalayan ice cores.

In 1997, three ice cores were recovered from the Dasuopu glacier (28°23′N, 85°43′E) with the use of an electromechanical drill in dry holes (Fig. 1). The first core (C1) was 159.9 m long and was drilled at 7000 m above sea level (a.s.l.) down the flow line from the top of the col, and two cores (C2 and C3), 149.2 and 167.7 m long, respectively, were drilled to bedrock 100 m apart on the col at 7200 m a.s.l. Visible stratigraphy showed no hiatus features in any of the cores. C2 was brought (in a frozen state) to the Lanzhou Institute of Glaciology and Geocryology (LIGG), C3 was brought (also frozen) to the Byrd Polar Research Center, and C1 was split between the two institutes. All cores were analyzed over their entire lengths for oxygen isotopic ratio ($\delta^{18}O$), chemical composition, and dust concentration. Most of the results presented here are from C3, which was cut into 6903 samples for both $\delta^{18}O$ and hydrogen isotopes (δD) and into 6419 samples each for insoluble dust, chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-) analyses. Borehole temperatures were −16.0°C at 10 m depth and −13.8°C at the ice-bedrock contact, demonstrating that the Dasuopu glacier is frozen to its bed.

In general, the bulk of the annual precipitation received in the Himalayas arrives during the summer monsoon season. At the col of Dasuopu, the average annual net balance is ~1000 mm water equivalent (w.e.) as determined by snow pit and shallow core studies and by the measurement of a 12-stake accumulation network established during a reconnaissance survey in July 1996. The high annual accumulation allows preservation of distinct seasonal cycles, particularly in $\delta^{18}O$, dust, and NO_3^-, which make it possible to reconstruct an annual record for the last 560 years from the upper 87% of C3. As in tropical cores from the Andes (*11–15*), $\delta^{18}O$ enrichment and high aerosol concentrations occur in the winter dry season, and $\delta^{18}O$ depletion and lower aerosol concentrations occur during the wet summer season. The annual layer counting was verified at 42.2 m by the location of a 1963 beta radioactivity horizon produced by the 1962 atmospheric thermonuclear tests in the Arctic. Surprisingly, despite the proximity of the Himalayas to the volcanically active Indonesian archipelago, no obvious traces of historically known eruptions (e.g., Krakatau and Tambora) were found. Based on the dust and $\delta^{18}O$ stratigraphy, C3 was annually dated to 1440 A.D. ± 3 years at a depth of 145.4 m. Below this horizon, layer thinning made annual resolution of the records impossible. Therefore from 1439 to 1000 A.D. (145.4 to 154.6 m), the time scale was determined by extrapolating the depth-age relation established for the upper 145 m and by assuming a constant annual accumulation rate. Thus, for the lower section only decadal averages were calculated with

[1]Byrd Polar Research Center, The Ohio State University, Columbus, OH 43210, USA. [2]Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences, Lanzhou China. [3]Department of Geological Sciences, [4]Department of Geography, The Ohio State University, Columbus, OH 43210, USA.

*To whom correspondence should be addressed. E-mail: thompson.3@osu.edu

an estimated uncertainty of ±5 years at 1000 years before the present.

Most of the annual precipitation on Dasuopu falls during the summer monsoon season (June through August) and the moisture originates in the Indian Ocean. During the winter, snowfall is carried by the westerly winds, with the moisture most likely originating in the northern Atlantic Ocean and augmented by evaporation from the Mediterranean Sea. The desert regions of Asia and northern Africa are major sources for windblown aerosols in the NH (*16–18*), with the greatest aerosol entrainment occurring from mid-February through late May (*19*). Aerosol concentrations in the Dasuopu cores are generally highest in the spring before the onset of the summer monsoons, in response to reduced precipitation and more productive (drier) source regions (such as the southern Tibetan Plateau, northwestern India, and the Near East). The negative relation between decreased regional precipitation and atmospheric dustiness as recorded in the Dasuopu core is illustrated in Fig. 2. The summer (June through September) precipitation for Indian regions 3, 7, and 8 [see fig. 1 in (*20*)], located directly south and west of the Himalayas, is negatively correlated ($R = -0.351$; $R^2 = 0.123$; sig. = 99.9%) with annual dust concentrations from Dasuopu from 1871 to 1994. On Dasuopu, the dust arrives primarily in winter and early spring and most of the precipitation (snow) falls in summer. The Dasuopu record represents conditions at a single location, and a dating error of just 1 year may affect the statistical correlation; therefore, a 3-year unweighted running mean was applied to both records, giving $R = -0.472$ ($R^2 = 0.222$; sig. = 99.9%). Thus, contemporary records demonstrate that dry conditions south of the Himalayas produce enhanced dust deposition on the high ice fields downwind.

The ~560-year records of annually averaged $\delta^{18}O$, dust, and chloride concentrations from C3 are illustrated in Fig. 3. Several spikes are apparent in the concentrations of dust and chloride, suggesting that these periods have conditions of low precipitation in the source areas. Historical records document numerous incidents of monsoon failures and drought in India and Asia. There is evidence (Fig. 3) for two major monsoon failures that resulted in devastating Indian droughts (1790 to 1796 and 1876 to 1877). The 1790 to 1796 drought is strongly recorded by high dust and Cl^- concentrations and enriched $\delta^{18}O$. It is the largest such feature in the annually resolved part of the core record (e.g., the last ~560 years). To examine this event more closely, the individual sample data are illustrated (Fig. 4) for the 30-year period from 1780 to 1810. Drought conditions, recorded by elevated spring dust and chloride levels, started abruptly in 1790 and persisted through 1796. Interestingly, the reduction of rainfall in southern India began in 1789, more than a year before similar droughts in Australia, Mexico, the Atlantic Islands, and

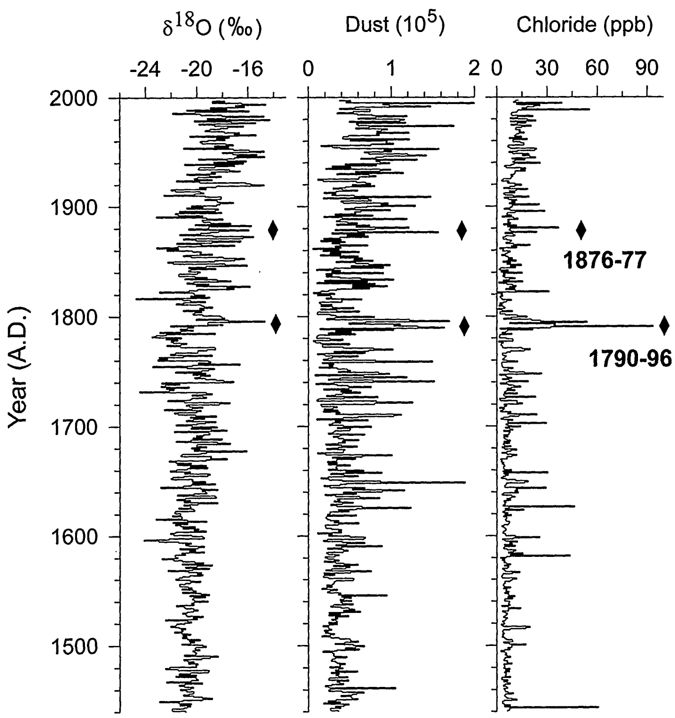
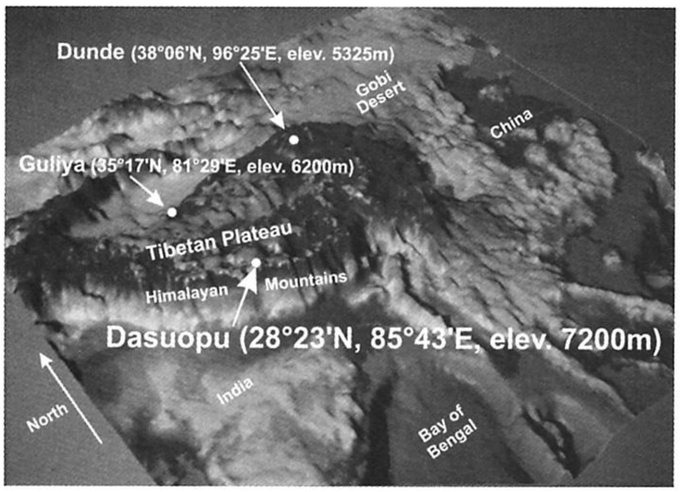


Fig. 3. Annual averages of $\delta^{18}O$, dust, and chloride are shown from 1440 A.D. to present. Dust concentrations are per milliliter sample for particles with diameters >0.63 μm. Diamonds indicate the two largest historically documented monsoon failures.



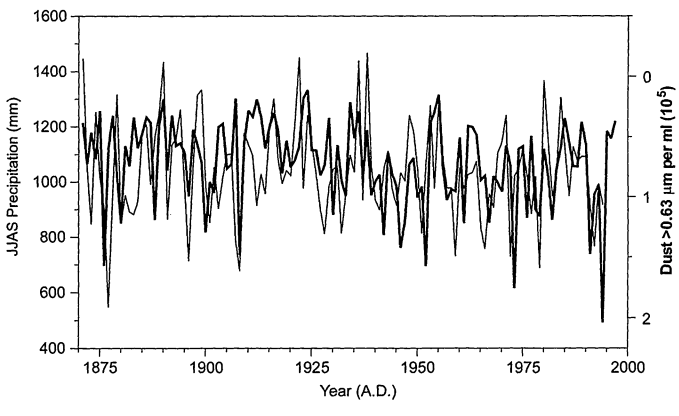


Fig. 1 (left). Locations of Dasuopu glacier relative to the Guliya and Dunde sites where previous ice cores were recovered. **Fig. 2 (right).** Annual dust concentration (darker line) on Dasuopu is negatively correlated with summer precipitation (June through September) to the south and west, demonstrating the strong control of dust by rainfall in the nearest source region. Precipitation (reverse axis) is calculated using the area weighted average from regions 3, 7, and 8, as defined by Gregory and Parthasarathy (*20*), updated by Sontakke *et al.* (*33*), and available at http://grads.iges.org/india/partha.subdiv.html.

southern Africa (*21*). According to these historical records, in 1792 at least 600,000 people died in just one region of northern India from the epic droughts associated with this event. The onset of this event in the Dasuopu cores is concurrent with the very strong ENSO of 1790 to 1793 that was followed by a moderate ENSO event from 1794 to 1797 as historically documented (*22*, *23*). The Nile River experienced below normal flood levels from 1790 to 1797 (*22*). These data, along with other evidence, suggest an association between ENSO and failure of the Asian monsoon (*8*, *10*).

Figure 5 (A through G) presents the decadal values of deuterium excess (*d*), $\delta^{18}O$, dust, and anion concentrations for the last 1000 years. The monsoon failure of the 1790s (and to a lesser extent the 1876 to 1877 drought) appears exceptionally large from the perspective of the last 1000 years. The ice core record suggests earlier, more modest monsoon failures in the 1640s, 1590s, 1530s, 1330s, 1280s, and 1230s; however, none of these approach the magnitude of the catastrophic 1790 to 1796 event.

Figure 5E illustrates decadally averaged snow accumulation (A_n) variations since 1450 A.D. as recorded in C2 and C3. Both accumulation records are shown to demonstrate the degree of spatial variability in A_n, even among sites in close proximity. From 1600 to 1817, A_n ranged between 0.5 and 1.2 m of w.e. and was followed by a significant increase ranging between 1.0 and 1.7 m, which persisted until 1880. Since 1880, A_n has decreased gradually to its present levels. This observation raises an obvious question: Are these temporal variations in A_n due to climate changes or to ice flow dynamics? The answer is revealed by the comparison of decadal averages of *d* (Fig. 5F) with the A_n profiles. Inspection of the high-resolution upper sections of the core (*24*) indicates that *d*, like $\delta^{18}O$ and δD, decreases during the summer monsoon season. Likewise, *d* also decreases on longer time scales in association with increases in A_n, such as that from 1800 to 1880 (Fig. 5, E and F). This suggests that increased A_n primarily reflects enhanced monsoon intensity, not ice flow. Thus, decreases in *d*, along with A_n increases in the Dasuopu ice core record, suggest an intensification of the summer monsoon circulation throughout most of the 19th century. In addition, the lack of similar variations in $\delta^{18}O$ over this period (Fig. 5G) suggests that $\delta^{18}O$ is controlled by processes other than precipitation (*15*).

Since 1860 A.D., concentrations of Cl^-, NO_3^-, and SO_4^{2-} have doubled, insoluble dust concentrations have quadrupled, and $\delta^{18}O$ has been enriched by 2‰; and this is evident in both the annual (Fig. 3) and decadally averaged (Fig. 5) data. Between 1440 and 1997, the annual averages of dust and $\delta^{18}O$ in Dasuopu are positively correlated (R^2 = 0.25, sig. = 99.9%). If, as we purport here, $\delta^{18}O$ is a proxy for temperature in the Himalayas, then its strong correlation with dust levels implies a direct link between warming and increased atmospheric dustiness. The latter could result from a reduction in snow cover, increased aridity, and/or increased agricultural activity in the source regions. The enhanced anion concentrations may also be attributed to increased land use and widespread biomass burning for domestic energy, as well as the increased industrialization in Nepal and India during the 20th century.

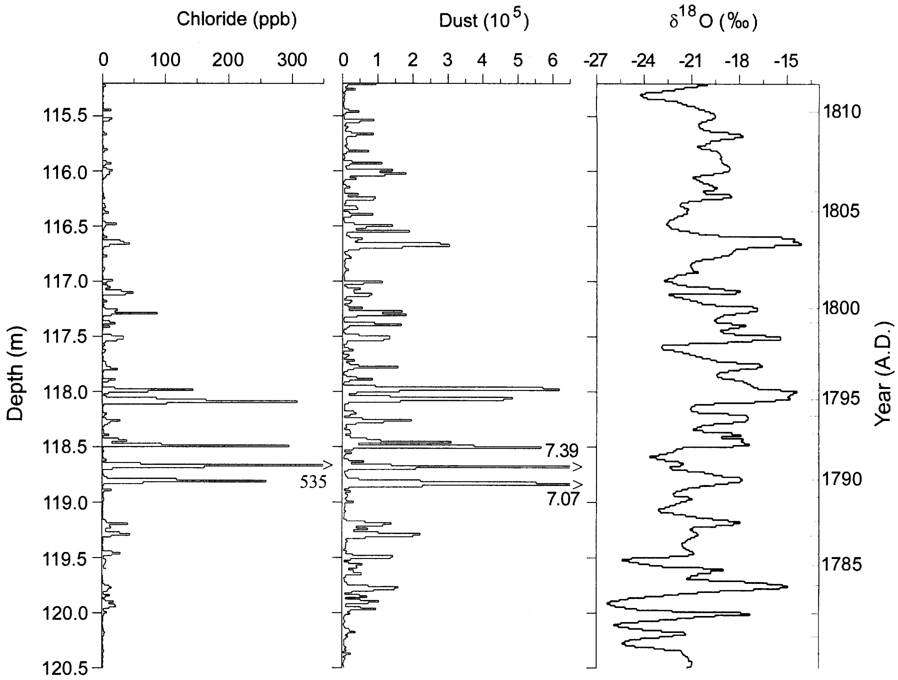
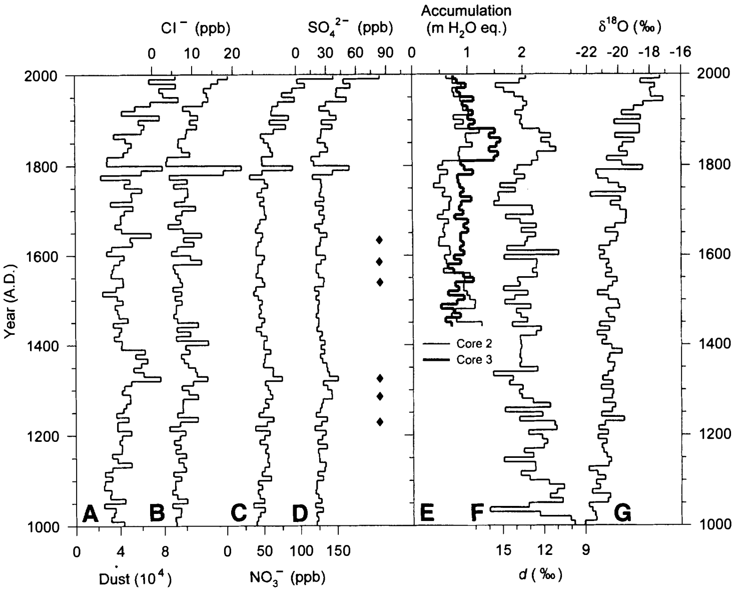


Fig. 4. This section of core illustrates $\delta^{18}O$ and the unusually high concentrations of dust and chloride associated with the 1790 to 1796 monsoon failure. Throughout the event, increased concentrations of dust and Cl^- are deposited during the dry season of each annual cycle. The scales are expanded to accommodate the magnitude of the drought event, and thus, the much lower background concentrations used for annual dating are not seen clearly.

Long ice core records are available from three different sites on the Tibetan Plateau. The Dunde ice cap (5325 m a.s.l.), the Guliya ice cap (6200 m a.s.l.) and Dasuopu (7200 m a.s.l.) form a regional triangular pattern with summit elevations decreasing from south to north (Fig. 1). Dasuopu, the highest site, has the "coldest" isotopic average (–20.32‰ for the last millennium) whereas the lowest elevation site, Dunde, has the least isotopically depleted average (–10.81‰, for the last millennium) (*24*). Because the precipitation at both these sites is dominated by the advection of moisture from the Indian Ocean with possible contributions from the Arabian Sea during the summer monsoon, these data provide qualitative support for the hypothesis that temperature, not the amount effect, is the dominant process controlling $\delta^{18}O$ over the Tibetan Plateau. First, a fresh snow sampling program has demonstrated that over much of the northern half of the Tibetan Plateau $\delta^{18}O$ of snowfall is highly correlated with air temperatures (*25*). Secondly, a linear correlation of the 5-year running means of annual NH temperature anomalies (*26–28*) with the 5-year running means of the Dasuopu $\delta^{18}O$ data (Fig. 6B) gives an R^2 of 0.37 (sig. 99.9%), whereas a much weaker relation exists between Dasuopu $\delta^{18}O$ and accumulation (R^2 = 0.19) (Fig. 6C). Also a similarly strong correlation (R^2 = 0.30, sig. 99.9%) is found for NH temperatures and $\delta^{18}O$ from the Dunde ice cap on the northeastern edge of the Plateau (*29*, *30*).

The Dasuopu $\delta^{18}O$ record, like that of Dunde, suggests evidence of a significant 20th-century warming. This isotopic warming is the most regionally consistent climate signal of the last 1000 years. Over most of the millennium, the $\delta^{18}O$-inferred temperature variations recorded on Guliya (*31*) have been generally out of phase with those on Dunde (*29*, *30*), suggesting different large-scale climate regimes on the northeastern and northwestern sides of the Tibetan Plateau. The millennial $\delta^{18}O$ histories from Dasuopu and Dunde contain broadly similar trends, although the recent



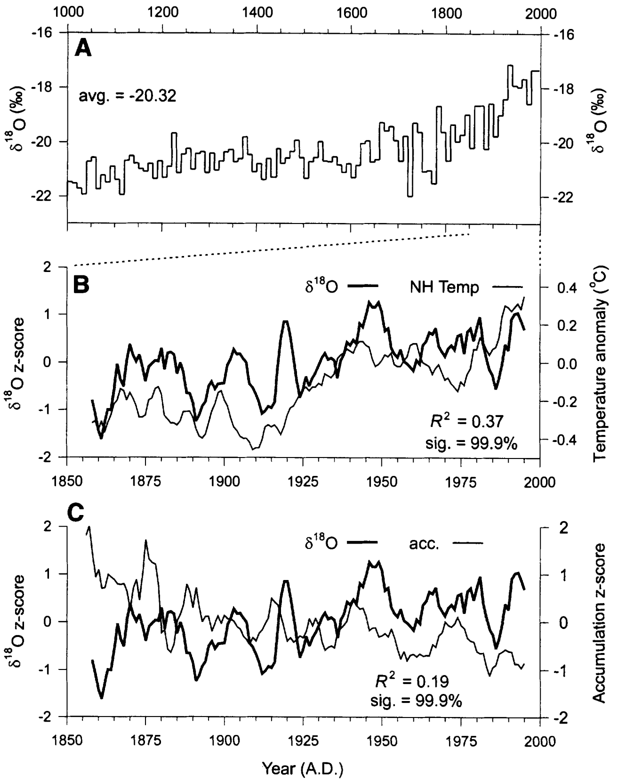


Fig. 5 (left). Decadal values of (**A**) dust, (**B**) Cl⁻, (**C**) NO_3^-, (**D**) SO_4^{2-}, (**E**) net accumulation (for cores 2 and 3), (**F**) deuterium-excess (*d*), and (**G**) $\delta^{18}O$ are shown for the last 1000 years. Accumulation rates are reconstructed after Bolzan (*34*) and Reeh (*35*). Diamonds indicate correlative increases in these parameters that may reflect six monsoon failures that were much less dramatic than that of 1790 to 1796. **Fig. 6 (right).** (**A**) Decadal averages of $\delta^{18}O$ for the last 1000 years on Dasuopu reveal the isotopic enrichment beginning in the 19th century and intensifying in the 20th century. (**B**) Five-year running means of $\delta^{18}O$ from Dasuopu are significantly correlated with NH temperature anomalies since 1860. (**C**) Five-year running means of $\delta^{18}O$ and accumulation from Dasuopu are weakly correlated. *Z* scores for the Dasuopu $\delta^{18}O$ and accumulation data were calculated using respective means of −18.63‰ and 1104.4 mm and respective σ of 1.92‰ and 423.7 mm.

isotopic enrichment is more pronounced on Dasuopu. However, since 1800, $\delta^{18}O$ has increased at all three sites, suggesting that a large spatial-scale warming has affected the Tibetan Plateau region.

Meteorological observations on the Plateau are relatively few and of short duration. A recent study (*32*) uses monthly surface air temperature data from most meteorological stations on the Tibetan Plateau since their installation in the 1950s. Not only do Liu and Chen (*32*) report a linearly increasing annual temperature trend of ~0.16°C per decade from 1955 to 1996 and an increasing winter trend of ~0.32°C per decade, they also report evidence that the rate of warming has increased with elevation. Their 1960 to 1990 records from 178 stations across the Tibetan Plateau reveal that the greatest rate of warming (~0.35°C per decade) occurred at the highest elevation sites. Consistent with these recent meteorological data, the $\delta^{18}O$ records from the three Plateau ice cores reveal the same trend, that is, increased isotopic enrichment (e.g., warming) with increasing elevation. Specifically, on Dunde the average $\delta^{18}O$ during the last two centuries is 1‰ higher than the millennial mean, while on Guliya it is 2‰, and on Dasuopu the enrichment is 3‰. For the 20th century, the isotopically inferred temperatures on both Dunde and Dasuopu are the warmest of the millennium, and the recent warming is most pronounced at Dasuopu, the highest elevation site.

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