

1000 years of climatic change in China: ice-core $\delta^{18}\text{O}$ evidence

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ABSTRACT. Since 1987, ice cores have been drilled from the Dunde and Guliya ice caps on the Tibetan Plateau, western China. Here, the oxygen isotopic ($\delta^{18}\text{O}$) records for the last 1000 years from both these cores are compiled and compared. Using surface temperature observations since the mid-1960s from meteorological stations on the plateau and $\delta^{18}\text{O}$ measured on precipitation collected contemporaneously, the empirical relationship: $\delta^{18}\text{O} = 0.6 T_s - 12$ is established. $\delta^{18}\text{O}$ appears to serve as a reasonable proxy for regional surface temperatures and a reasonable basis for reconstructing 1000 a proxy temperature records from Dunde and Guliya. The reconstructed temperature histories for Dunde (on the eastern Tibetan Plateau) and Guliya (on the western Tibetan Plateau) show some centennial-scale similarities, but reveal quite different histories for higher-frequency variability over the last millennium. The ice-core $\delta^{18}\text{O}$ histories from Dunde and Guliya are compared with a tree-ring index from western China and the dust-fall record from eastern China, but show no consistent relationship. The most prominent similarity between the reconstructed temperature histories for Dunde and Guliya is the marked warming of the last few decades. From the 1000 a perspective provided by these ice-core records, the recent warming on Dunde is unique in its strength and persistence; however, the warming on Guliya (inferred from ^{18}O enrichment) is more recent (since 1985) and not unprecedented. This recent warming over the Tibetan Plateau is evident in the limited meteorological records.

INTRODUCTION

In the last decade, ice cores have provided a variety of unique paleoclimatic histories. For an overview see Langway and Oeschger (1989) and White and others (1989). Most of these have centered on high-latitude ice cores such as those from Greenland (e.g. Dansgaard and others, 1969, 1982; Grootes and others, 1993), the Canadian Arctic (Koerner and Fisher, 1990) and Antarctica (Epstein and others, 1970; Lorius and others, 1979, 1985). To complement these polar histories and provide further constraints upon models of global climatic variations, ice-core histories from high-elevation ice caps in the subtropics and tropics have begun to emerge. The first such history was from the Quelccaya ice cap ($13^{\circ}56'\text{S}$, $70^{\circ}50'\text{W}$; 5670 m a.s.l.) in Peru (Thompson and others, 1985, 1986, 1988). More recently a record was obtained from the Dunde ice cap ($38^{\circ}06'\text{N}$, $96^{\circ}24'\text{E}$; 5325 m a.s.l.; Fig. 1) in China (Thompson and others, 1989; Thompson, 1992).

Eastern China is rich in historical and documentary sources of climate information for the last millennium. Most of the Chinese paleoclimatic reconstructions are from regions east of 110°E and focus upon conditions during winter, although limited summer histories are emerging (Bradley and others, 1987). In western China, proxy histories (tree rings, ice cores) are severely limited, and their verification is hampered by the short and sparse

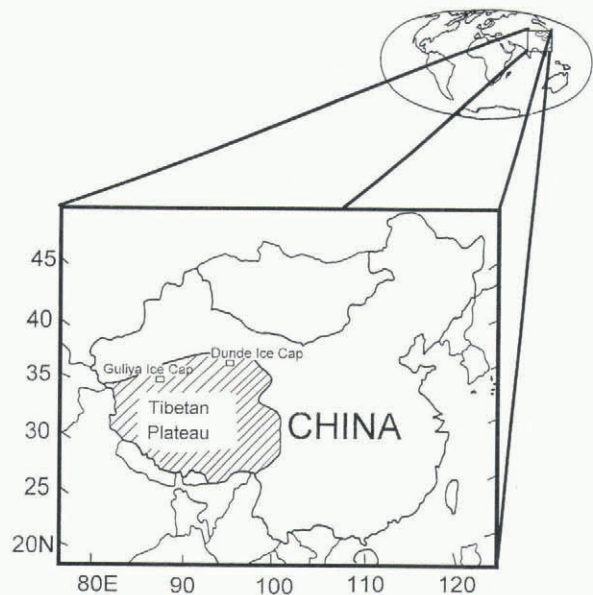


Fig. 1. Map showing the location of Dunde and Guliya ice caps, China.

meteorological records (Bradley and Jones, 1993).

Nevertheless, the climate history of western China, particularly on the Tibetan Plateau, is an important component for reconstructing and understanding the

Earth's climate history. The Tibetan Plateau, with an average elevation of ≈ 4500 m, is one of the Earth's most imposing geomorphic features and affects the large-scale atmospheric circulation in the Northern Hemisphere (Reiter and Ding, 1980, 1981). The extensive summer heating of the plateau establishes and maintains the Asian summer monsoon circulation (Reiter and Gao, 1982). Thus, studies of the climate regime of the Tibetan Plateau have flourished and the potential for histories from western China has sparked the interest of the paleoclimatic community.

Since 1987, ice-core paleoclimate records have been emerging from two ice caps on the plateau: the Dundee ice cap on the northeastern side, and more recently the Guliya ice cap ($35^{\circ}17'N$, $81^{\circ}29'E$; 6710 m a.s.l.) on the northwestern side (Fig. 1) where a glaciological program was conducted from 1990 to 1992. In 1990 one pit was sampled and two cores were drilled: an 8 m core (C-1) and a 12 m core (C-2). In 1991 one pit was sampled and two cores were drilled: a 30 m core (C-1) and a 16 m core at the summit core (SC-1). In 1992 two deeper ice cores were recovered: a shorter core (C-1; 92.3 m) at site 1 extended to an unconformity (see Thompson and others, 1995); the longer core (C-2; 308.6 m) reached bedrock at site 2. These cores are being analyzed for insoluble particulate concentrations and size distributions, anion (SO_4^{2-} , NO_3^- , Cl^-) concentrations, and $\delta^{18}O$. This paper focuses upon the similarities and differences of the Dundee and Guliya $\delta^{18}O$ records for the last 1000 a and compares these proxy histories with the limited data from western China and the more abundant climate histories from eastern and southern China.

DISCUSSION

Figure 2 demonstrates the reproducibility of the $\delta^{18}O$ records in cores drilled at the same location on Guliya in three consecutive years (1990–92). The 1991 core was returned frozen while the 1990 and 1992 cores were cut, melted and bottled for return shipment. The first constraint upon the paleoclimatic utility of $\delta^{18}O$ is the degree to which it reflects near-surface air temperature. To explore this, $\delta^{18}O$ was measured on precipitation samples collected at the Delingha meteorological station south of the Dundee ice cap, and these were compared with contemporaneous air temperatures also measured at Delingha (Yao and Thompson, 1992). The empirical relationship between $\delta^{18}O$ and air temperature (Fig. 3a) derived from these data is given by

$$\delta^{18}O = 0.6T_s - 12$$

where T_s is air temperature. The $\delta^{18}O$ –temperature coefficient of 0.6 is identical to that established for the longer records from other mid- and high-latitude regions (e.g. Rozanski and others (1992) report a value of 0.6). To test further how well $\delta^{18}O$ reflects air temperatures, the annual averages of $\delta^{18}O$ for the three cores from site 1 on Guliya (Fig. 2) are compared (Fig. 3b) with mean annual air temperatures from Mangnai meteorological station ($38.2^{\circ}N$, $90.1^{\circ}E$; 3139 m a.s.l.). The agreement between mean annual $\delta^{18}O$ and air temperatures is quite

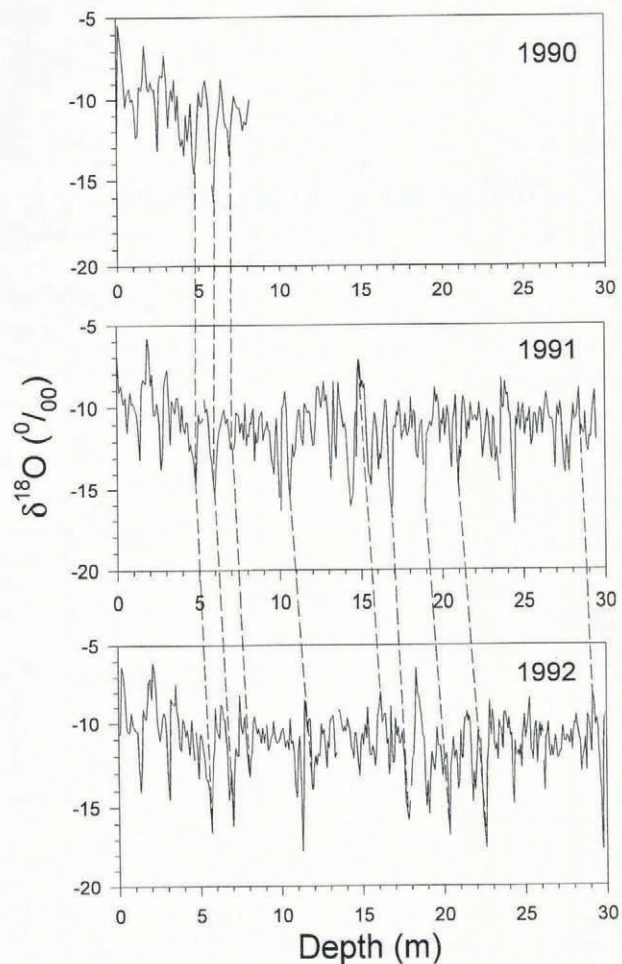


Fig. 2. The continuous isotopic profiles for three cores drilled in successive years (1990–92) at the same site on the Guliya ice cap. The dashed lines indicate correlative features.

good considering the distance and elevation differences and other environmental factors which may affect $\delta^{18}O$. A marked warming trend since 1985 is evident in both the ice-core records and the station observations. It is clear that $\delta^{18}O$ of the snow falling on Guliya provides a reasonable proxy for the near-surface air temperature.

The time-scales for the upper 380 a of the Guliya and Dundee cores were established by counting the visible dust layers deposited annually. This allows the annual averages of dust content and $\delta^{18}O$ to be calculated. For the older part of the Dundee cores the time-scale is a model-based time–depth relationship for the combination of cores 1 and 3 in which similar features were considered coeval. Since it was impossible to count annual dust layers down to the bottom of both Dundee cores, the final time-scale is based on the flow-model approach. In contrast, the dating for the last 1000 years from the Guliya core-2 is based on counting visible dust layers (see Thompson and others (1995) for Guliya time-scale discussion).

Figure 4a and b illustrate the 1000 a $\delta^{18}O$ record from Guliya core-2 and the combined histories from the Dundee deep cores (1 and 3). A surprising result is the marked difference in the $\delta^{18}O$ histories from these two ice caps. The difference in mean values (Dundee: -10.88% ; Guliya: -14.77%) is expected and consistent with the different elevations of the drill sites (Dundee: 5325 m a.s.l.; Guliya:

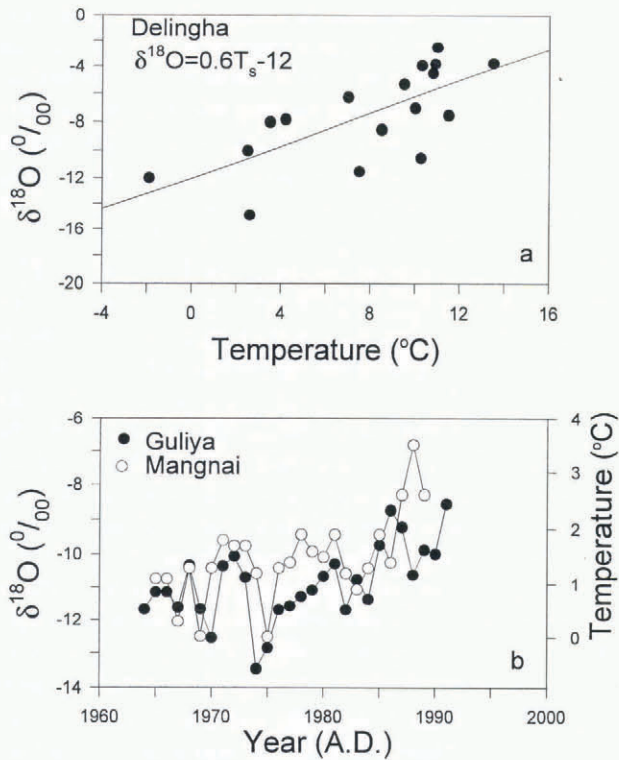


Fig. 3. *a.* Mean annual air temperatures from the Delingha meteorological station (Yao and Thompson, 1992) are plotted against the mean annual $\delta^{18}\text{O}$ data from contemporaneous precipitation samples. *b.* Mean annual temperatures from Mangnai meteorological station are plotted against the mean annual $\delta^{18}\text{O}$ data from the Guliya ice cap.

6200 m a.s.l.). However, the major warm and cool periods (isotopically inferred) are highlighted using a 50 a running mean (Fig. 4; dark curves) and clearly reveal a period from 1250 to 1500 when warming on Guliya was contemporaneous with cooling on Dundee. In fact, comparison of the 50 a running means suggests that the temperature regimes (inferred from $\delta^{18}\text{O}$) on these two ice caps are dissimilar at times and often in anti-phase. Although some modest time-scale inaccuracies are possible, these are unlikely to account for the differences in the $\delta^{18}\text{O}$ patterns in the Dundee and Guliya ice cores.

The two ice caps are situated 1400 km apart on opposite sides of the Tibetan Plateau under the influence of somewhat different climatic regimes. Dundee lies on the northeastern margin of the plateau while Guliya is on the northwestern side. Thus, it is not surprising that their $\delta^{18}\text{O}$ histories appear different, particularly since moisture sources vary over the plateau (Luo and Yanai, 1983, 1984). Observations of contemporary climate regimes on the plateau (Qian and others, 1988) reveal such spatial differences. Most of the moisture for the eastern side of the plateau, where Dundee is located, is associated with the highly convective Indian monsoonal rains from south-western China (Luo and Yanai, 1983). Here the release of latent heat associated with cumulus-convective precipitation contributes to atmospheric heating (Tao and Ding, 1981; Yeh, 1981; Luo and Yanai, 1984). On the western side of the plateau, heating is largely from vertical convection driven by surface heating. The prevailing

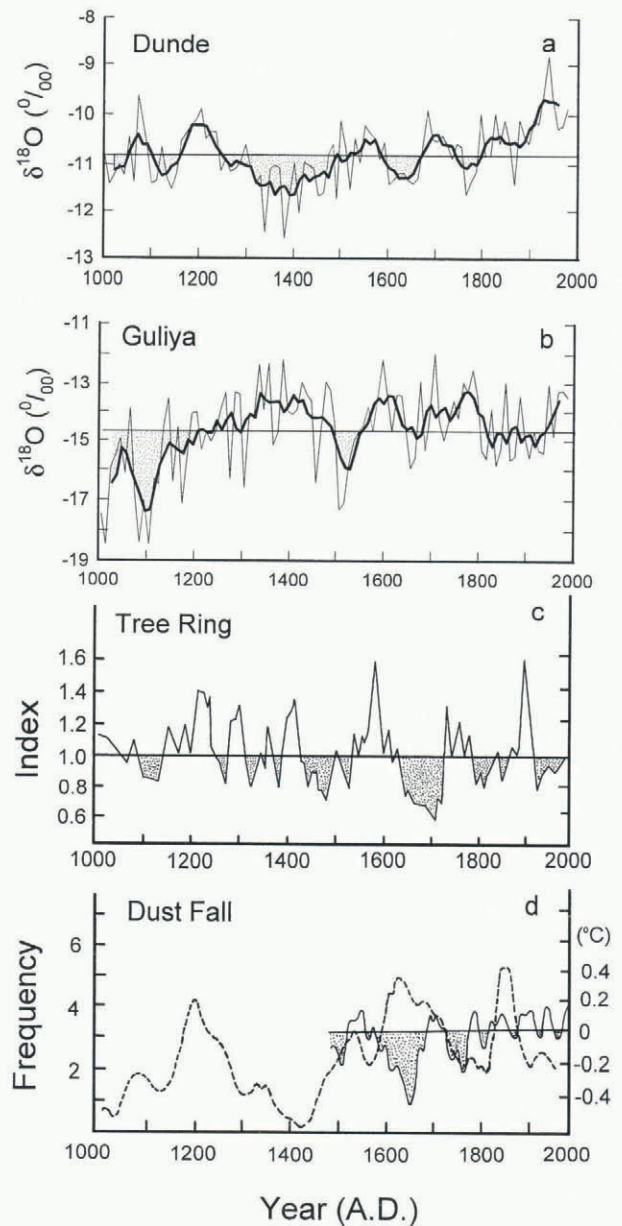


Fig. 4. The decadal average $\delta^{18}\text{O}$ from *a.* the Dundee ice cap and *b.* the Guliya ice cap are shown for the last 1000 a. The darker solid line indicates the 50 a running mean. *c.* Tree-ring widths from four juniper trees provide a proxy for climate in the Qilian Shan of north-central China (after Wang and others, 1983). *d.* Dust-fall frequency has been recorded in central and eastern China. The dashed line represents the 50 a running mean (after Zhang, 1984), and the solid line indicates temperature fluctuations (Chu, 1973).

moisture source for the Guliya ice cap, on the western side of the plateau, is the Arabian Sea (Ohata and others, 1989). On Guliya the annual precipitation is lower, averaging ≈ 180 mm w.e. (Thompson and others, 1995), compared to 400 mm w.e. on Dundee (Thompson and others, 1990; Thompson, 1992).

Other factors affecting the preserved $\delta^{18}\text{O}$ history include: localized snow drifting; the addition of locally derived moisture from nearby convective activity due to intense radiational heating of the surrounding area; loss of mass by ablation; and differing accumulation rates.

Figure 2 illustrates that the three ice cores from Guliya show consistent isotopic patterns, suggesting that, at the same site at least, the effect of these localized factors is minor. The potential contribution of these factors to differences on Guliya and Dundee is difficult to assess.

COMPARISON WITH OTHER DATA

Proxy histories are necessarily imperfect representations of their surroundings because they are limited by the robustness of their time-scale, their spatial representativeness and the physical interpretation of the proxy itself. One of the few proxy records available from western China is a 935 a record of tree-ring widths in four juniper trees covering the upper and lower limits of the forest zone in the Qilian Shan region (Wang and others, 1983). Thinner rings are interpreted as reflecting sub-optimal growing conditions which could be cooler temperatures, reduced precipitation or some combination. Wang and others (1983) interpreted thin ring widths as reflective of cooler temperatures, and noted three prominent and/or prolonged cool periods and one less extensive event (Fig. 4c). Cooler conditions lasting about 70 a are centered on 1480, 1690 and 1810 while a shorter cool phase appears much earlier in the record, around 1120. Wang and others (1983) suggested that the three cold periods of the Ming–Qing dynasty (1428–1865) correspond to the so-called “Little Ice Age” in Europe, with the main cold period at 1725.

The major occurrences of thinner tree rings appear to be associated qualitatively with more negative (cooler) $\delta^{18}\text{O}$ intervals on Guliya, but show little correspondence to the Dundee $\delta^{18}\text{O}$ record. This is interesting as the junipers are from ≈ 3000 m in the Qilian Shan where the Dundee ice cap is located. Also note from the earlier discussion that the $\delta^{18}\text{O}$ histories from Dundee and Guliya are dissimilar at times, with some longer-term cooler and warmer intervals out of phase.

Two of the three “Ming–Qing-dynasty” cool phases (inferred from limited tree-ring data) appear in the $\delta^{18}\text{O}$ history from Guliya which also suggests a persistence of cooler conditions from 1800 to the mid-1900s. Interestingly, the most prolonged cooling in the Guliya $\delta^{18}\text{O}$ history is from about 1050 to 1200, contemporaneous with the marked yet brief decline in ring widths. It should be noted that this early part of the tree-ring record is based upon two trees, which highlights the spatial limitation of the data. In fact, the tree-ring thicknesses appear to be more reflective of the net accumulation histories on the two ice caps (see Thompson and others, 1995, figs 7 and 8), but still with a stronger resemblance to the Guliya history. Previous investigations of tree-ring records from lower-elevation (<3500 m) sites in Tibet (Wu, 1992) have indicated that ring widths in this dry region are more reflective of precipitation variations than of temperature variations. The ice-core data would tend to support this idea.

Figure 4d presents a history of the frequency of dust fall (dashed line) for an area from Xinjiang to the east coast of China and from Nei Mongol to the south of the Yangtze River (Zhang, 1984), an area consistent with the loess distribution in China (Liu and others, 1981).

Inferred (proxy) temperatures since 1500 (solid line: after Chu, 1973) led Zhang to suggest that cooler periods were associated with more dusty atmospheric conditions, while dust flux appears diminished when conditions are warmer. The transportation of dust from northwest to southeast China is related mainly to variations in atmospheric circulation over mainland China. In winter, the strong Siberian high moves southward, leading the polar frontal zone south as well. This enhances the stronger winter monsoon and favors the entrainment and transport of dust during cold periods (Zhang, 1984). The dust is entrained within the Mongolian cyclone, is transported eastward by the upper-level westerlies and slowly settles out over the eastern half of China. In addition, most of the periods of high dust deposition appear to be associated with conditions of lower humidity, indicating that dust storms are associated with the dry season (Zhang, 1984).

The dust history (Fig. 4d) from eastern China shows no consistent relationship with the Dundee and Guliya $\delta^{18}\text{O}$ records over the last 1000 a. The low frequency of dust storms from 1300 to 1450 AD is correlative with isotopically warmer conditions on Guliya and cooler conditions on Dundee. As with the temperature comparisons discussed above, the eastern China dust history appears more consistent with the net accumulation histories from Guliya and Dundee (Thompson and others, 1995, figs 7 and 8). The period of elevated dust (eastern China) from 1150 to 1300 AD is associated with reduced accumulation on Guliya after which the frequency of dust storms in the east drops as accumulation on Guliya increases. In the more recent (better documented and dated) part of these records the peak in dust flux in about 1850 AD is correlative with a period of substantially lower net accumulation on both Guliya and Dundee. Likewise, the reduction in dust-storm frequency since the turn of the 19th century is associated with well above average net accumulation on both ice caps.

These records suggest a very complex relationship between the temperature and precipitation over the plateau and the temperature and atmospheric dustiness over the eastern half of China. This preliminary investigation suggests that net accumulation on the ice caps, rather than temperature, appears more closely related to atmospheric conditions (temperature and dustiness) in the eastern half of China where proxy and historical climate observations are more abundant. Also, for the earlier part of the record (prior to 1500 AD) the lack of observations (e.g. tree rings, dust fall) and their imprecise time-scales make comparison with the ice-core histories tentative at best. It is necessary to stress as well that 70–80% of precipitation on the ice caps falls during the summer monsoon season so that the $\delta^{18}\text{O}$ history probably reflects summer conditions more strongly than annually averaged conditions, and that at these high elevations there is a potential for sublimation (^{18}O enrichment) during the dry part of the year. Thus, $\delta^{18}\text{O}$ measurements are predestined to be imperfect representations of near-surface air temperatures. Much of the dust deposition on the ice caps (and over eastern China as well) is associated with the dry winter monsoon season so that dust flux is likely to be more representative of atmospheric conditions in winter than of annually averaged conditions.

The more recent part of the ice-core $\delta^{18}\text{O}$ records is compared with surface temperature observations in Figure 5. The 5 a running mean of the annual $\delta^{18}\text{O}$ values from 1850 to 1992 from Guliya and Dundee (both dated to 1850 by layer counting) is shown in Figure 5a and b. As noted earlier, isotopically warm and cold periods are not synchronous for Dundee and Guliya, and this is particularly true for annual and decadal-scale data. However, both records reveal a persistence of higher $\delta^{18}\text{O}$ values (warmer temperatures) since the 1940s, similar to the warming in the Northern Hemisphere land-surface temperatures since the 1920s (Fig. 5c) and the Indian Ocean surface temperatures (Fig. 5d). The $\delta^{18}\text{O}$ data from Guliya and Dundee also correspond reasonably well with the temperature record from the Indian Ocean (Briffa and Jones, 1993), which is encouraging as the precipitation reaching the western part of the Tibetan Plateau originates primarily over the Indian Ocean during the summer monsoon season (Luo and Yanai, 1983, 1984).

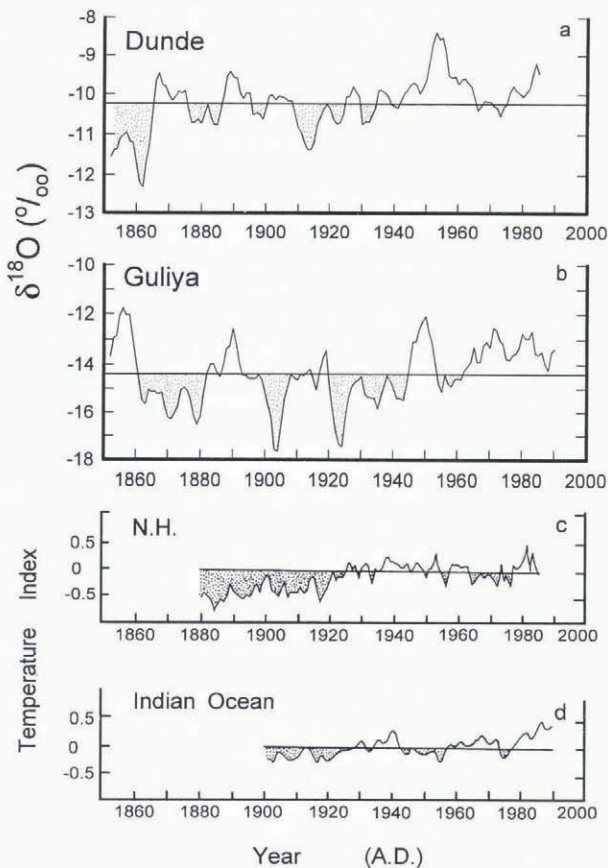


Fig. 5. The 5 a running mean of $\delta^{18}\text{O}$ from 1850 to 1992 from a. Dundee and b. Guliya ice caps is compared with two other temperature histories: c. Northern Hemisphere temperature variations (Hansen and Lebedeff, 1987) and d. Indian Ocean surface temperature data (Briffa and Jones, 1993).

Longer temperature histories are available from southern and eastern China. Here ‘Mei Yu’ or plum rains are a main source of precipitation, dominant in spring and summer, over most of China south of the

Yangtze River. Summer air temperatures from southeastern China (Fig. 6b) and from the lower Yangtze River (Fig. 6c) have been reconstructed for the last five centuries. The coldest period, the mid-17th century (around 1650 AD), is prominent in all records. The normalized mean summer temperatures (Fig. 6d) and the normalized mean winter temperatures (Fig. 6e) also indicate cooler conditions around 1850 AD. Note that the $\delta^{18}\text{O}$ records in Figure 6 are shown with respect to their (1860–1959) means for consistency with the other data (Fig. 6b–e). The Dundee $\delta^{18}\text{O}$ history is much more similar to the temperature history in southeastern China than is the Guliya $\delta^{18}\text{O}$ history. The most prominent climate event in all the records ($\delta^{18}\text{O}$, tree ring, dust fall) is the cool period around 1650 AD which appears to have affected both eastern and western China. Another

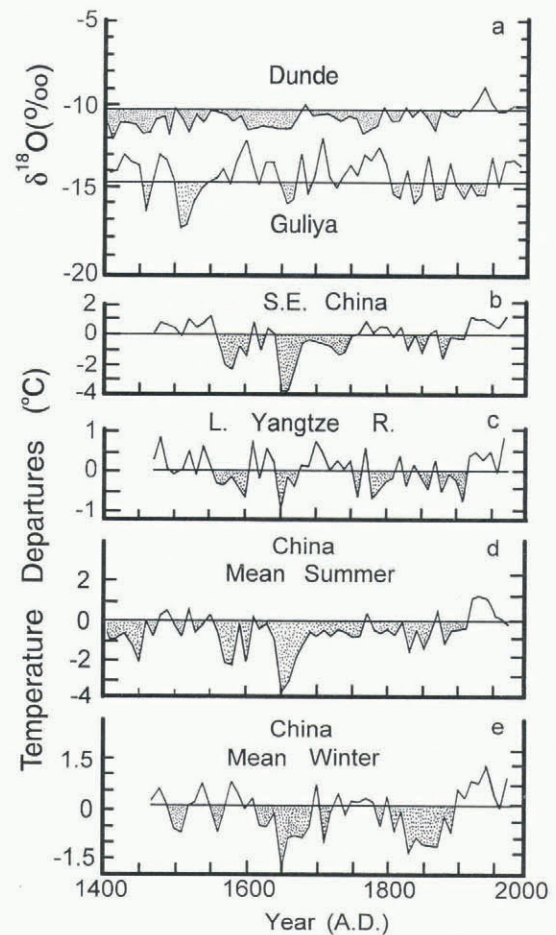


Fig. 6. Decadal averages of $\delta^{18}\text{O}$ from a. Dundee and Guliya are compared with available temperature records from other areas of China. All data are shown relative to their respective 1860–1959 means. b. Summer temperature variations in southeast China are from Wang and others (1991). c. Summer temperature anomalies for the Lower Yangtze River are from Wang and Wang (unpublished information, 1992) and Bradley and Jones (1993). d. Mean normalized summer temperatures for eastern China are from Wang and Wang (1990); Wang (1991); and Wang and others (1991). e. Mean normalized winter temperatures for eastern China are from Zhang and Gong (1979); Zhang (1980); Wang and Wang (1990); Wang (1991); and Wang and others (1991).

important feature in 1000 a $\delta^{18}\text{O}$ records from Dundee and Guliya is a warming trend in the 20th century. Although not as prominent in the decadal averaged data from Guliya, since 1985 it is unambiguously an "isotopically" warm feature in both summer and winter (i.e. the highest and lowest $\delta^{18}\text{O}$ values) for all three cores (Fig. 2).

CONCLUSIONS

The 1000 a $\delta^{18}\text{O}$ records from the Dundee and Guliya ice caps on the Tibetan Plateau, western China, display different climatic variations which may reflect their different moisture sources. Altitude differences only affect $\delta^{18}\text{O}$ mean values, and dating errors are unlikely to contribute strongly to the observed differences. The $\delta^{18}\text{O}$ measurements of snow collected on Guliya reflect air-temperature trends at Mangnai meteorological station, suggesting that $\delta^{18}\text{O}$ of the snow falling on Guliya provides a reasonable proxy for the near-surface air temperature.

The ice-core $\delta^{18}\text{O}$ histories from Dundee and Guliya are compared with a tree-ring index from western China and the dust-fall record from eastern China, but show no consistent relationship. Interestingly, the net accumulation histories from Dundee and Guliya appear to be more consistently related to each other and with dust fall in eastern China. Large-scale trends in the $\delta^{18}\text{O}$ history from Dundee are more similar to those in eastern China than are the trends from the Guliya ice cap far to the west. Both ice-core histories and the other limited proxy records suggest a widespread cool period around 1650 AD. The Guliya history contains a major cool phase around 1500 AD, but this does not appear to have extended to the east. Finally, a most important observation is the recent warming reflected in the records from both ice caps. The warming appears to have begun several decades earlier on the lower-elevation Dundee ice cap and more recently, since 1985, on the higher Guliya ice cap to the west. The older parts of the Guliya core are currently being analyzed and along with the contemporaneous history from Dundee should provide a proxy record, particularly as transfer functions between $\delta^{18}\text{O}$ and temperature and the relationship between temperature and precipitation are better established.

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