A pollen record of Holocene climatic changes from the Dunde ice cap, Qinghai-Tibetan Plateau

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ABSTRACT

Pollen preserved in ice cores from the Dunde ice cap provides a sensitive record of Holocene climatic changes and vegetational response in the northern Qinghai-Tibetan Plateau at time scales ranging from millennia to centuries and decades. Pollen analysis of the annually resolvable ice layers for a 30 yr period (1957–1986) suggests that total pollen concentration is correlated positively with summer precipitation and negatively with summer temperature; thus it is a sensitive indicator of moisture availability and vegetation density in the steppe and desert regions around Dunde. High pollen concentrations between 10 000 and 4800 yr B.P. suggest that the summer monsoon probably extended beyond its present limit to reach Dunde and westernmost Tibet in response to orbital forcing. The summer monsoon retreated time-transgressively across the Qinghai-Tibetan Plateau during the middle Holocene. Relatively humid periods occurred at 2700–2200, 1500–800, and 600–80 yr B.P., probably as a result of neoglacial cooling. Prominent pollen changes during the Medieval Warm Period (790–620 yr B.P.) and the Little Ice Age (330–80 yr B.P.) suggest that the vegetation in the Qinghai-Tibetan Plateau region is sensitive to abrupt, century-scale climatic changes, such as those anticipated in scenarios of greenhouse warming.

INTRODUCTION

Few high-resolution paleoclimatic data are available in the Qinghai-Tibetan Plateau to evaluate the sensitivity of the plateau to orbitally forced and century-scale climatic changes during the Holocene (Thompson et al., 1989, 1997; Yao and Thompson, 1992; Gasse et al., 1991, 1996; Lister et al., 1991). Existing records (e.g., Thompson et al., 1989; Gasse et al., 1991, 1996; Du et al., 1989) are equivocal with regard to the existence and timing of an early Holocene summer monsoon maximum, as predicted by climate-modeling results. Most of these records, except for those from ice cores (Thompson et al., 1989, 1997), also lack sufficient temporal resolution to reveal abrupt or century-scale climatic events during the late Holocene such as the Little Ice Age (LIA) and the Medieval Warm Period (MWP). Here we present the results of pollen analysis of ice cores from the Dunde ice cap that provide a high-resolution record of Holocene climatic changes and vegetational response in the northern part of the Qinghai-Tibetan Plateau.

Even though pollen is a major source of paleoclimatic proxy data for terrestrial environments, it has not been a parameter routinely incorporated in ice-core studies. Previous pollen studies were mainly conducted on polar ice cores (Fredskild and Wagner, 1974; Lichti-Federovich, 1975; McAndrews, 1984; Short and Holdsworth, 1985; Bourgeois, 1986), where pollen concentrations are typically very low and the pollen was mostly derived from long-distance transport from vegetation sources hundreds to thousands of kilometers away. Recently, pioneer studies have demonstrated the potential for obtaining sensitive pollen records of climatic changes from tropical ice cores (Thompson et al., 1988, 1995). Compared with polar ice cores or lake sediments, the high accumulation rates in nonpolar ice cores permit paleoclimatic reconstruction at decadal, annual, or even seasonal resolutions. Nonpolar ice cores are close to vegetation sources; thus they typically have higher pollen concentrations and therefore higher sensitivity to vegetational and climatic changes than that offered by polar ice cores. Our pollen study of the Dunde ice cap is the first systematic pollen analysis of an ice core from a nonpolar region.

STUDY REGION

The Dunde ice cap (38°06′N, 96°24′E) is situated on a southern branch of the Qilian Mountains which forms the northern margin of the Qinghai-Tibetan Plateau (Thompson et al., 1989). It is 140 m thick and has a summit elevation of 5325 m. It is bordered by deserts of the Qaidam Basin to the south and west and the Gobi Desert to the north (Fig. 1). Shrubs and herbs of Chenopodiaceae, *Ephedra*, and *Nitraria* are characteristic dominants in the deserts. Steppes and alpine meadows, dominated by *Artemisia* and Cyperaceae, respectively, occur around the ice cap and also to the east and southeast. Trees are absent in the Dunde region. The mean annual temperature at the Dunde ice cap is –7.3 °C. Annual accumulation measured from the annual ice layers at the top of Dunde is approximately 400 mm (water equivalent), but the precipitation of the surrounding region is much lower, about 100–200 mm per year. Over 80% of the snow at Dunde falls in the summer wet season (Thompson et al., 1989).

METHODS

Ice cores retrieved from the Dunde ice cap have already produced a wealth of high-temporal-resolution paleoclimatic data for the northern part of the Qinghai-Tibetan Plateau (Thompson et al., 1989, 1990; Yao and Thompson, 1992). For our pollen study, we used meltwater samples from two long cores D-1 and D-3, supplemented by samples from shallow cores 1 and 2. Meltwater samples ranged in volume from 175 to 850 mL (mean = 419 mL). Samples were evaporated on a hot plate and centrifuged to reduce the water volume, and then treated with acetolysis solution to remove organic matter. One tablet of *Lycopodium* marker spores was added to each sample before processing for estimating pollen concentration; at least 1000 marker grains were counted per sample. For most samples, the pollen sum ranged from 20 to 100.

We used the previously published age model for the Dunde ice cores to provide chronological control for the pollen samples (Thompson et al., 1989, 1990). All ages reported in this paper are in calendar years before 1986 (cal. yr B.P.; 1986 is the year when the core was taken), unless otherwise speci-

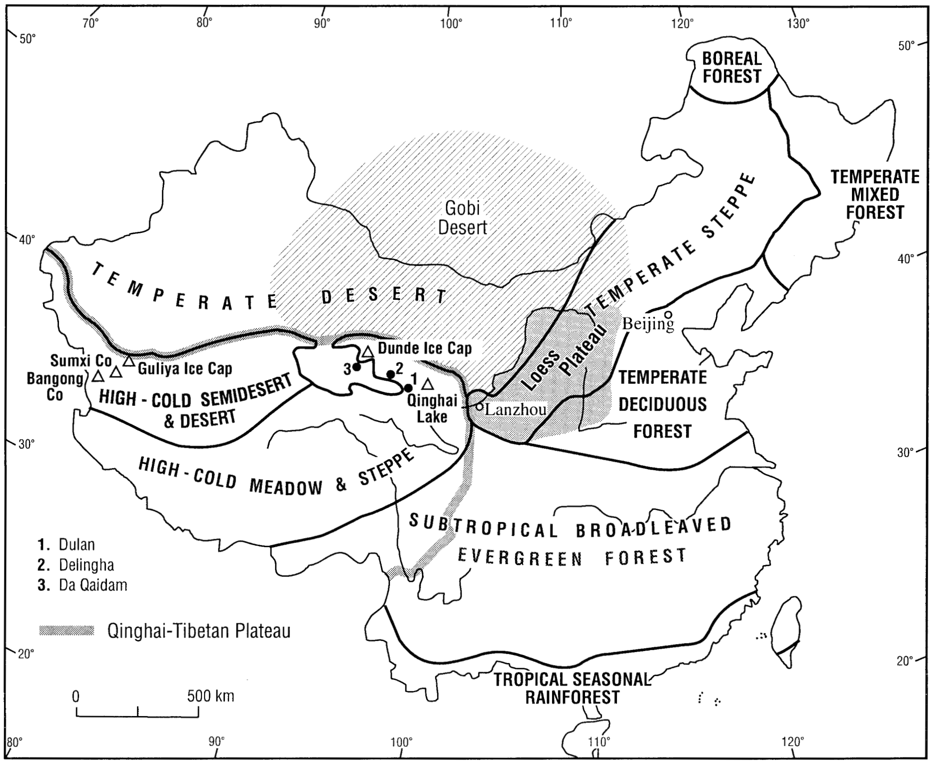

Figure 1. Map of vegetation regions of China (Hou, 1983; Liu, 1988) showing location of Dunde ice cap and other paleoclimatic data sites (triangles) and three climate stations (black dots) discussed in text.

fied. Because of the exponential thinning of the annual layers downcore, time resolution decreases from 1 yr per pollen sample (i.e., annual) for the past 160 yr, to 10 yr per sample (i.e., decadal) at about 230 yr B.P., 100 yr (i.e., centennial) at about 2300 yr B.P., and about 1000 yr (millennial) at the Holocene–late Pleistocene transition at about 11 000 yr B.P. Altogether, more than 560 samples were analyzed for pollen.

Because of the relatively large volume of meltwater needed for the pollen analysis and the depletion of samples for other analytical purposes, samples for the present study had to be derived from different ice cores: core D-3 (11 000–336 yr B.P.; A.D. 1947–1976), core D-1 (335–60 yr B.P.), shallow core 1 (A.D. 1927–1946), and shallow core 2 (A.D. 1977–1986). These cores were all taken at the Dunde summit within 100 m of each other (Thompson et al., 1989). The use of different cores does not seem to affect the results of the pollen analysis. None of the pollen or climatic boundaries identified here coincides with any core boundary; there is generally good continuity in pollen data across core boundaries. We also confirmed our results by performing comparative pollen studies between overlapping time segments of different cores.

CLIMATE SENSITIVITY OF THE DUNDE POLLEN RECORD

To establish the climate sensitivity of the Dunde pollen record, we examined the pollen deposited in the annual ice layers of core D-3 and shallow core 2 for the 30 yr period from 1957 to 1986 (Fig. 2). Total pollen concentrations increased distinctly after 1965, from ~290 grains per liter during 1957–1964 to an average of 1140 grains per liter during 1965–1986. This distinct shift after 1965 was accompanied by a notable increase in the percentages of meadow components (Cyperaceae, *Polygonum*) and tree pollen (*Quercus*, Cupressaceae), and a decrease in *Ephedra*, a desert shrub. We correlated the pollen data with the climate records for the corresponding period from three stations closest to the Dunde area—Delingha, Dulan, and Da Qaidam (Fig. 2). At all three climate stations, there was a remarkable increase in summer (June-July-August) precipitation after 1965, coincident with the post-1965 increase in pollen concentrations. Summer temperature showed a decreasing trend after 1965, whereas winter temperature seemed to be increasing. These effects may be part of a continent-scale summer climatic "jump" that occurred in the subtropical to mid-latitude regions across the African and Eurasian continents during the mid-1960s (Yan et al., 1990). For the whole 30 yr period, total pollen concentrations in the Dunde ice cores were positively correlated with the mean summer precipitation (correlation coefficient $r = 0.76$) and mean winter temperature ($r = 0.68$), and negatively correlated with the mean summer temperature ($r = -0.52$), of these three climate stations in the northern part of the Qinghai-Tibetan Plateau.

Most of the pollen grains (especially those of *Artemisia*, Chenopodiaceae, *Ephedra*) deposited in the ice cores were derived from xerophytic vegetation growing in the steppe and desert regions adjacent to the Dunde ice cap. In these regions, precipitation is about 50–200 mm per year, whereas the annual potential evapotranspiration is typically >2000 mm (Zhang and Lin, 1985). It is

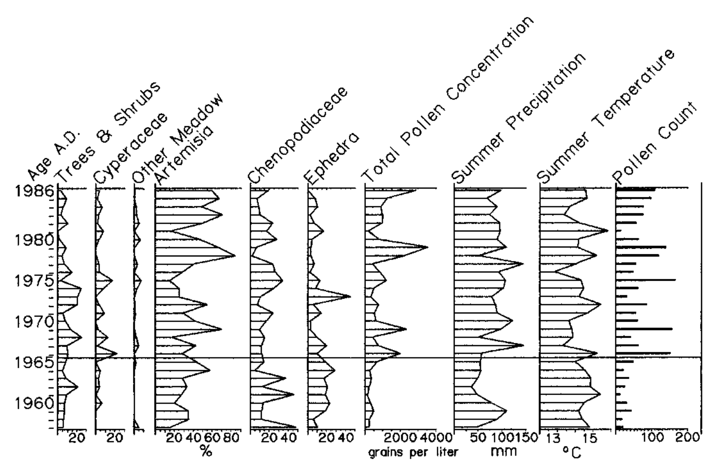

Figure 2. Pollen data and climatic trends for 30 yr period, A.D. 1957–1986, from northern Qinghai-Tibetan Plateau. Pollen data are from core D-3 (1957–1976) and shallow core 2 (1977–1986). Pollen percentages, calculated by using sum of all pollen and spores, are shown here for selected major taxa or ecological groups. "Trees and shrubs" include *Pinus*, Cupressaceae, *Quercus, Alnus, Carpinus, Ulmus*, Rosaceae, and *Salix*. "Other meadow" group includes *Humulus*, Caryophyllaceae, *Ranunculus*, and *Polygonum*. Total pollen concentration is sum of all pollen taxa, expressed as number of pollen grains per liter of meltwater. Curves for summer (June-July-August) precipitation and temperature are average values from three stations closest to Dunde (Delingha, Dulan, and Da Qaidam) for same period. Solid line marks increase in summer precipitation and decrease in summer temperature after 1965 and corresponding increase in pollen concentrations.

reasonable to interpret that in such moisture-stressed environments, vegetation density and productivity (which affect pollen concentrations in the ice cores) are limited by the effective moisture available to the plants. Effective moisture will increase if precipitation during the growing season (summer) increases or if the summer temperature decreases (i.e., reduced evapotranspiration). Warmer winters are also favorable to plant growth by permitting earlier snow melt and increased soil moisture in the spring. Therefore, total pollen concentrations in the Dunde ice cores can be used as a proxy for moisture availability in the region.

HOLOCENE POLLEN RECORD

In the pollen diagram for the entire Holocene (Fig. 3), the low pollen concentration (200 grains per liter) in the 11 ka sample implies dry conditions during the Late Glacial Stage. Vegetation density and productivity increased during the early to middle Holocene, as suggested by relatively high (330–550 grains per liter) pollen concentrations during ca. 10–4.8 ka. At the same time, the pollen percentages of *Artemisia* (typical of steppes) were consistently high (>40%), and those of Chenopodiaceae (typical of deserts) were relatively low (<20%), resulting in a relatively high *Artemisia*/Chenopodiaceae (A/C) pollen ratio. The A/C ratio has been commonly used by palynologists as a humidity index in arid and semiarid regions (El-Moslimany, 1990; Van Campo and Gasse, 1993; Van Campo et al., 1996). The rationale is that an increase in atmospheric or soil moisture in ecotonal areas will favor the populations of the steppe components over those of the desert plants, perhaps causing the steppe region to expand at the expense of the desert. Thus the increased vegetation density and the expansion of steppe over desert during the early to middle Holocene were likely due to higher summer precipitation caused by an intensified summer monsoon, as predicted by the results of climate modeling experiments (COHMAP Members, 1988).

The pollen-derived reconstruction of a wetter climate, or summer monsoon maximum, at Dunde during the early to middle Holocene (10–4.8 ka) is consistent with the oxygen isotope record showing a gradual ^{18}O enrichment throughout the Holocene with a warm period centered at ca. 8–6 ka followed by the maximum warmth in the past 100 yr (Thompson et al., 1989). The pollen record, particularly the increasing abundance of Chenopodiaceae pollen and the declining *Artemisia*/Chenopodiaceae pollen ratio, indicates a general drying trend after the middle Holocene. Recent work linking monthly $\delta^{18}O$ in snow and/or rain fall and temperature measured at the Delingha meteorological station 150 km from the Dunde ice cap yields a coefficient of determination R^2 of 0.86 for the period since April 1991 (Yao et al., 1996). However, it is possible that $\delta^{18}O$ in this part of the Qinghai-Tibetan Plateau can be significantly depressed by an increase in the proportion of summer monsoonal precipitation, which is more depleted in ^{18}O than the continental, convective type of precipitation (Yao et al., 1992, 1996; Gasse et al., 1996). Thus, the more negative $\delta^{18}O$ values in the early Holocene samples could have been caused by an increase in summer precipitation due to an intensified summer monsoon, as the pollen record indicates. In this way, the pollen record is a useful supplement to the oxygen isotope data and a sensitive paleoclimatic proxy in ice-core research, because it integrates the biotic response to climatic changes at the regional scale.

The notion of wetter summers at Dunde during 10–4.8 ka can be compared with the paleoclimatic records from Sumxi Co (Gasse et al., 1991; Van Campo and Gasse, 1993) and Bangong Co (Gasse et al., 1996; Van Campo et al., 1996) in westernmost Tibet (Fig. 1). Pollen, diatom, and isotopic data from these two lakes suggest that the summer monsoon maximum occurred during the early to middle Holocene (10–6.0 ^{14}C ka), only interrupted by an abrupt return to dry conditions during 8.0–7.7 ^{14}C ka. On the other hand, pollen data from Qinghai Lake in the northeastern part of the Qinghai-Tibetan Plateau show forest expansion during 8.0–3.5 ^{14}C ka (Du et al., 1989), implying a summer monsoon maximum during the middle Holocene instead. It is notable that the Dunde ice cap and the two western Tibetan lakes are situated near or outside the extreme limits of the summer monsoon influence today, whereas the climate of Qinghai Lake is more humid (annual precipitation 300 mm) and more monsoonal. The time-transgressive nature of the monsoon maximum at these three sites along a modern precipitation gradient probably reveals the retreat of the summer monsoon front during the Holocene. The summer monsoon was greatly intensified around 10 ka and extended beyond its present limit to reach westernmost Tibet during the early to middle Holocene. It retreated eastward from Bangong Co and Sumxi Co after 6.8 ka (6.0 ^{14}C ka) and from the Dunde region after 4.8 ka. It was further weakened over the Qinghai Lake region after 3.8 ka (3.5 ^{14}C ka), where the climate is marginally influenced by the summer monsoon today.

Pollen concentrations declined to a Holocene minimum of 50–400 grains per liter during 4.8–2.7 ka, indicating a period of lower effective moisture. Tree pollen grains are also absent or rare, suggesting a reduction in the frequency or intensity of southeasterly winds and, hence, a weakening of the summer monsoon. This episode coincides with a relatively warm period (4.9–2.9 ka) identified from the oxygen isotope data of Dunde (Yao et al., 1992). Paleoclimatic data from Sumxi Co and Bangong Co (Gasse et al., 1996; Van Campo et al., 1996) also record a progressive drying of the climate after 6.0 ^{14}C ka, culminating in a period of maximum aridity at ca. 4.0–3.0 ^{14}C ka.

The intervals 2.7–2.2 ka, 1.5–0.8 ka, and 0.6–0 ka were comparatively humid periods with higher vegetation density and productivity, as suggested by relatively high pollen concentrations (400–1300 grains per liter) and fluctuating but generally low A/C pollen ratios. Tree pollen grains are well represented in these intervals, as well as pollen taxa characteristic of alpine meadow of higher elevations (e.g., Cyperaceae, *Polygonum*). Lower summer temperatures may have played a more important role than increased summer precipitation in enhancing the effective moisture during these late Holocene humid episodes. Oxygen isotope data from the Dunde ice cores also indicate a general cooling trend since ca. 3000 yr B.P., with remarkably cold periods at 1400–800 yr B.P. and 550–60 yr B.P. (Thompson et al., 1989; Yao and Thompson, 1992).

Samples from ca. 790–620 yr B.P. (A.D. 1200–1370) contain abundant dust particles but very

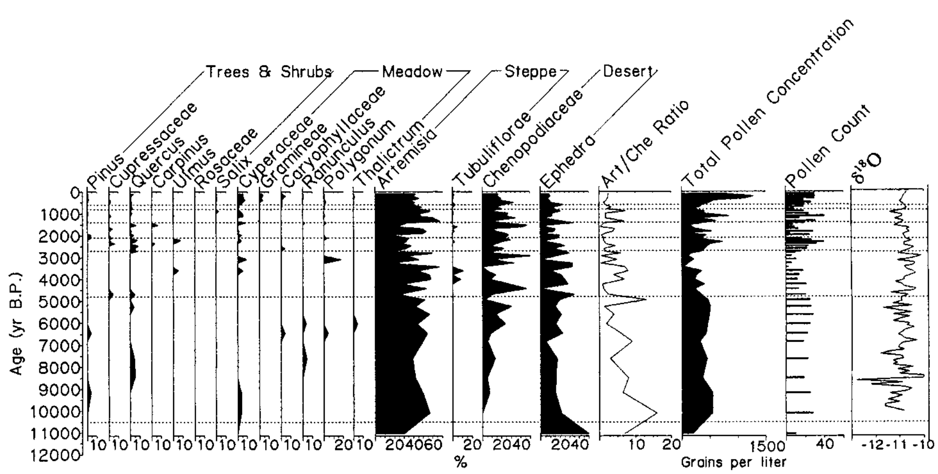

Figure 3. Pollen percentage diagram for past 11 000 yr from Dunde ice cores. Time resolution for samples >2000 yr old is >100 yr per sample. For past 2000 yr, the 355 samples are grouped into 100 yr averages, and pollen count is average count per sample. Pollen zone boundaries are drawn according to climatic episodes discussed in text. Oxygen isotope curve is from Yao et al. (1992).

low pollen concentrations (180–340 grains per liter, calculated on 100 yr averages). These data suggest an interval with warm, dry summers and very windy conditions coincident with part of the Medieval Warm Period (MWP) (Hughes, 1994). Oxygen isotope data from Dunde also suggest a warm period at ca. 700 yr B.P. (Yao and Thompson, 1992). During this warm, dry period, vegetation density was reduced, and strong wind probably swept across the expanded desert surfaces and deposited more dust on the Dunde ice cap.

After 620 yr B.P., pollen concentrations rose sharply back to pre-MWP levels, reaching a Holocene maximum of 1150–1300 grains per liter during 330–80 yr B.P. (A.D. 1660–1910). The data imply the prevalence of cool, humid conditions during the Little Ice Age. The Little Ice Age has been identified from the oxygen isotope data at Dunde and other paleoclimatic data from China (Yao et al., 1991).

CONCLUSIONS

Pollen in nonpolar ice cores is an important source of paleoclimatic information; thus pollen analysis should be included in any paleoclimatic studies of nonpolar ice cores. The Dunde pollen record documents an early to middle Holocene summer monsoon maximum, followed by a time-transgressive retreat of the summer monsoon front eastward across the northern Qinghai-Tibetan Plateau. Moreover, the distinct pollen changes recorded in the Dunde ice cores associated with the mid-1960s climatic "jump," the Medieval Warm Period, and the Little Ice Age suggest that the vegetation in the Qinghai-Tibetan Plateau is sensitive to century-scale or short-term climatic changes. Climate modeling results predict that greenhouse warming will strongly affect the climate of the Qinghai-Tibetan Plateau and adjacent areas of Central Asia (Hansen et al., 1988). Ice-core evidence from Central Asia suggests that unprecedented levels of warming might have already occurred during the last several decades (Thompson et al., 1993). High-resolution pollen data from ice cores provide a means by which the ecosystem response to such past and future climatic changes can be monitored.

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