Evidence for cooler European summers during periods of changing meltwater flux to the North Atlantic

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We analyzed fossil chironomids (nonbiting midges) and pollen in two lake-sediment records to reconstruct and quantify Holocene summer-temperature fluctuations in the European Alps. Chironomid and pollen records indicate five centennial-scale cooling episodes during the early- and mid-Holocene. The strongest temperature declines of ≈1°C are inferred at ≈10,700–10,500 and 8,200–7,600 calibrated ^{14}C years B.P., whereas other temperature fluctuations are of smaller amplitude. Two forcing mechanisms have been presented recently to explain centennial-scale climate variability in Europe during the early- and mid-Holocene, both involving changes in Atlantic thermohaline circulation. In the first mechanism, changes in meltwater flux from the North American continent to the North Atlantic are responsible for changes in the Atlantic thermohaline circulation, thereby affecting circum-Atlantic climate. In the second mechanism, solar variability is the cause of Holocene climatic fluctuations, possibly triggering changes in Atlantic thermohaline overturning. Within their dating uncertainty, the two major cooling periods in the European Alps are coeval with substantial changes in the routing of North American freshwater runoff to the North Atlantic, whereas quantitatively, our climatic reconstructions show a poor agreement with available records of past solar activity. Thus, our results suggest that, during the early- and mid-Holocene, freshwater-induced Atlantic circulation changes had stronger influence on Alpine summer temperatures than solar variability and that Holocene thermohaline circulation reductions have led to summer-temperature declines of up to 1°C in central Europe.

Holocene paleotemperature reconstructions for central Europe indicate centennial-scale cooling episodes during the Holocene (the present interglacial; the past ≈11,500 years) (1). However, the amplitude and forcing mechanisms of these temperature fluctuations are uncertain. Two climate-forcing hypotheses for early- and mid-Holocene temperature fluctuations in Europe have been presented recently. The first hypothesis proposes that changes in freshwater runoff from North America associated with the melting of the remnant North American ice sheet triggered centennial-scale changes in the North Atlantic thermohaline circulation (THC), leading to a cooler climate around the North Atlantic (2–4). The second hypothesis suggests that changes in solar irradiance were responsible for Holocene climatic changes. By affecting North Atlantic surface-ocean circulation, these insolation changes may have influenced the THC, leading to an amplified effect on the North Atlantic climate system (5).

We used biological temperature proxies in lake sediments to produce a regional early- and mid-Holocene summer-temperature reconstruction for the Swiss Alps (Fig. 1), which we compared with available records of North American meltwater runoff to the North Atlantic (3) and past solar irradiance (5). Both terrestrial vegetation and lacustrine ecosystems in the Alps are strongly influenced by summer climate (6, 7). Furthermore, modern meteorological data from this region indicate that temperature variations are more pronounced at higher altitudes than in the lowlands (8). Thus, if Holocene THC changes affected central European summer climate, we would expect to find a distinct biological response at sensitive altitudes in the Alps.

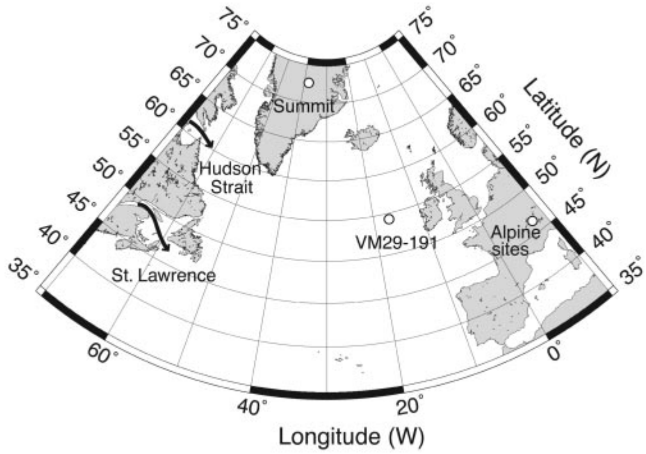

Fig. 1. Locations of the study sites in the Swiss Alps, the North Atlantic sediment core VM29-191, the Greenland Summit ice cores, and the two discussed early- and mid-Holocene discharge routes of North American freshwater runoff to the North Atlantic.

GEOLOGY

Methods

Chironomid assemblages in lakes are related closely to the ambient summer air temperature, and therefore, fossil chironomids can be used for quantitative reconstruction of past summer temperatures (6). We analyzed fossil chironomid assemblages in the Holocene sediments of Hinterburgsee (8°4′03′′E, 46°43′ 06′′ N), which is a lake situated at 1,515 m above sea level (asl) in the northern Swiss Alps (9, 10). A chironomid July air-temperature transfer function, based on weighted-averaging partial least-squares regression and calibrated on surface-sediment chironomid assemblages from 81 lakes in northern and central Switzerland (9), was used to reconstruct July air temperatures from the fossil record. A locally weighted regression smoother (11) was used to summarize centennial-scale temperature variations in the relatively noisy record. This smoothing method has the advantage that it is relatively insensitive to single outlying values. In temperate climates, the position of the alpine tree line is closely related to growing-season temperatures (7). Therefore, past changes in tree-line altitude provide information about past summer-temperature variability. We analyzed pollen in the sediments of Gouillé Rion (2,343 m asl, 7°21′50′′E, 46°09′3′′N), a small lake at present-day tree-line level in the central Swiss Alps, to produce a semiquantitative record of past tree-line fluctuations (12). In this region, *Pinus cembra* (Swiss stone pine)

Abbreviations: THC, North Atlantic thermohaline circulation; cal. B.P., calibrated ^{14}C years B.P.; IRD, ice-rafted debris.

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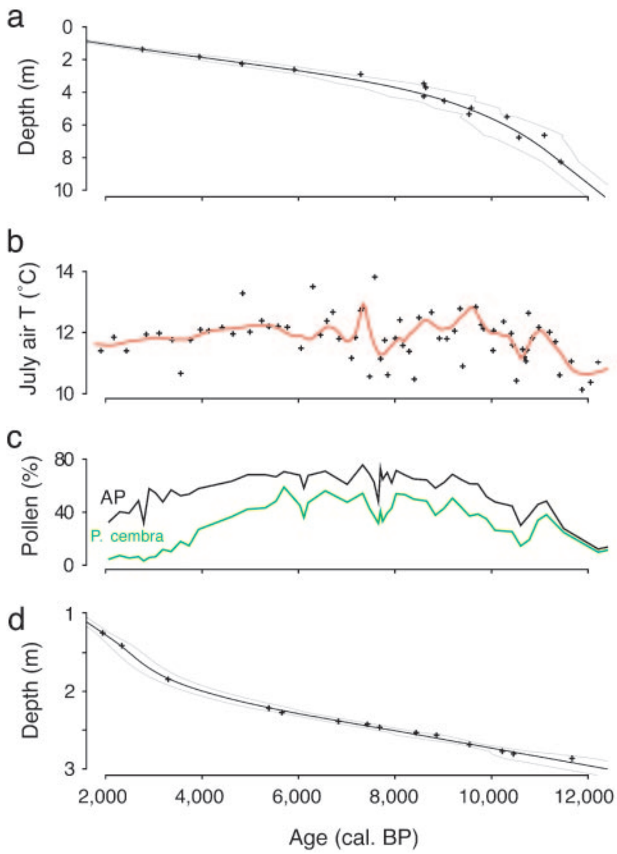

Fig. 2. Holocene summer-temperature reconstructions from the Alps. (*a*) Age–depth relationship calculated for the Hinterburgsee sediments (black line). Crosses indicate calibrated radiocarbon ages, and gray lines indicate the 95% age confidence intervals. (*b*) Chironomid-inferred July air temperatures from the Hinterburgsee sediments (crosses) smoothed with a locally weighted regression smoother (span 0.1). (*c*) Arboreal pollen (AP) and *P. cembra* pollen in the Gouillé Rion sediments. (*d*) Age–depth relationship for the Gouillé Rion sediments (black line). Crosses and gray lines are as described for *a*.

was one of the dominant tree-line species and was restricted to a narrow altitudinal band (≈1,900–2,400 m asl) in the early and mid-Holocene. Before the onset of human forest clearance and pasturing at ≈5,500 years B.P. (12), reduced percentages of *P. cembra* pollen in the lake sediments reflect either lower pollen productivity in the vegetation belt just below the alpine tree line or a regional decline in tree-line elevation, both of which are possible consequences of decreased summer temperatures. The two sediment records are dated by 16 and 14 accelerator mass spectrometry ^{14}C measurements on identified terrestrial plant remains, respectively (see supporting information, which is published on the PNAS web site). To compare these archives with each other and with proxy records of potential climate forcings, we calculated age–depth relationships by using nonlinear weighted regression within the framework of generalized additive models. The approach has the advantage of providing 95% age confidence intervals that take into account the errors of radiocarbon measurement, radiocarbon calibration, and the developed age–depth regression (13) (Fig. 2).

Results and Discussion

In both the smoothed chironomid-based July air-temperature reconstruction from Hinterburgsee and the tree-line reconstruction from Gouillé Rion, the initial rise in summer temperatures at the end of the Younger Dryas at ≈11,500 calibrated ^{14}C years B.P. (cal. B.P.) is followed by five centennial-scale coolings during the early- and mid-Holocene (Figs. 2 and 3). Previous organism-based temperature reconstructions from the Alps inferred a similar pacing of Holocene cold events, with estimated summer-temperature decreases of 0.7–0.8°C during the cold intervals (1). Our data indicate that the two strongest decreases in Alpine summer temperatures took place at ≈10,700–10,500 and 8,200–7,600 cal. B.P. (events A and C, Fig. 3 *b* and *c*), whereas other coolings were of smaller amplitude. The first of these major cold events (event A) has an age that is similar to that of a Holocene cold episode reported from the Faroe Islands, Germany, and western Norway (14, 15). The beginning of the second major cold event (event C) shows a close temporal agreement with the 8,200 years B.P. event in the Greenland ice-core records (16) and with cold oscillations described in other European paleoclimatic archives (16–18). In our Alpine temperature reconstructions, cooling event C is of longer duration than the 8,200 years B.P. event in the Greenland ice cores, suggesting that cooling in the Alps may have been protracted by several centuries.

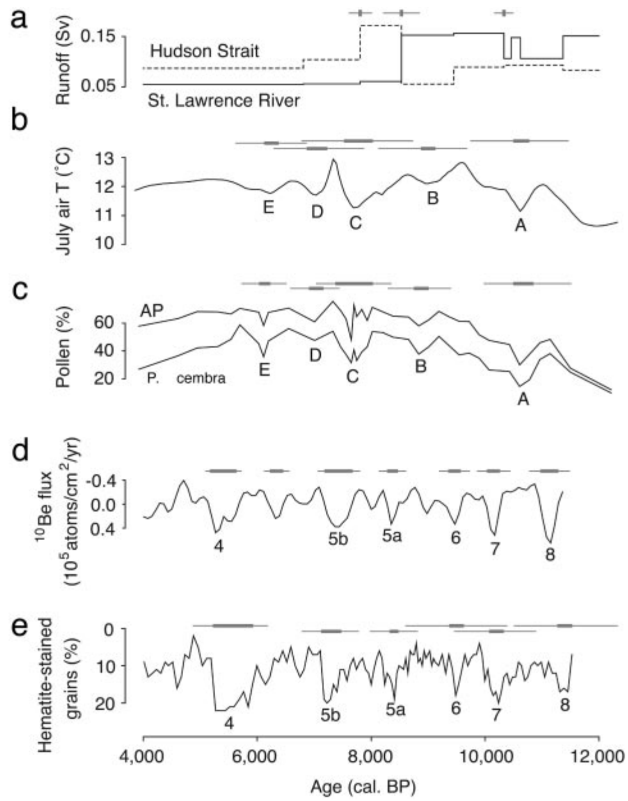

Fig. 3. Alpine temperature reconstructions and proxy records of climate-forcing factors. (*a*) Reconstruction of Hudson Strait (dashed line) and St. Lawrence River (solid line) runoff (3). Horizontal bars indicate 95% age confidence intervals of the major rerouting events (3). (*b*) Smoothed chironomid-inferred July air temperatures from Hinterburgsee in the Swiss Alps. Horizontal bars indicate minima (thick bars) and the corresponding 95% age confidence intervals (thin bars) based on the age–depth relationship shown in Fig. 2. (*c*) Arboreal pollen (AP) and *P. cembra* pollen from Gouillé Rion, Swiss Alps. Horizontal bars are as described for *b*. (*d*) Smoothed and detrended ^{10}Be flux in the Greenland Summit ice cores (Fig. 1) (5). Horizontal bars indicate maxima (thick bars) and corresponding 95% age confidence intervals (thin bars) assuming a 1% dating error (standard deviation) in the Greenland ice cores (16). (*e*) Ice-rafted hematite-stained grains in the North Atlantic sediment core VM29-191 (Fig. 1) (5). An age–depth relationship for this record has been calculated based on the original ^{14}C dates and by using the same methods as used for the Alpine sediment sequences to ensure the comparability of the age assessment and age error estimates between the different ^{14}C dated records (see supporting information). Horizontal bars indicate maxima (thick bars) with the corresponding 95% age confidence intervals (thin bars).

Reconstructions of the direction of runoff from the remnant Laurentide Ice Sheet indicate two major early- and mid-Holocene reorganizations of the routing of meltwater from North America to the North Atlantic (3, 4). These runoff changes and associated meltwater outbursts provide a mechanism that may have decreased the salinity of North Atlantic surface waters and led to a THC slowdown (2–4). A major increase in the baseline runoff down the St. Lawrence River took place between ≈10,700 and 10,300 cal. B.P., when runoff previously flowing down the Mississippi River was diverted eastward (3). This rerouting event was accompanied by abrupt meltwater pulses down the St. Lawrence valley (4). A second major reorganization of runoff routes to the North Atlantic occurred at ≈8,400 cal. B.P. with the collapse of the Laurentide Ice Sheet (2). This event abruptly released up to 163,000 km^3 freshwater into the Labrador Sea and was followed by several centuries of increased freshwater flux through the Hudson Strait (3, 4).

For both of these rerouting events, unambiguous evidence for a coeval reduction in the THC is lacking (19, 20). However, individual North Atlantic sediment cores indicate a reduction in benthic $\delta^{13}C$ centered on ≈10,300 (3, 21) and ≈8,200 cal. B.P. (20), suggesting that North Atlantic deep-water formation may have been reduced. Coupled atmosphere–ocean climate model runs indicate that, at least for the second rerouting event, the released volume of freshwater may have been sufficient to reduce North Atlantic deep-water formation considerably (4, 22). In North Atlantic sediments, distinct shifts to planktonic Foraminifera assemblages indicative of cooler surface waters (dated to 10,400–10,300 and 8,200–8,000 cal. B.P.) support the occurrence of a major shift in ocean circulation during both meltwater reroutings (21). Within their dating uncertainty, the two major temperature decreases in our Alpine records are in agreement with changes in the routing of North American runoff to the North Atlantic (Fig. 3 *a–c*). Cooling A coincides with the redirection of meltwater runoff at ≈10,700–10,300 cal. B.P. Cooling C lags the final collapse of the Laurentide Ice Sheet and the increased freshwater flux through the Hudson Strait at ≈8,400 cal. B.P. However, within the dating uncertainty of the records, this cooling episode and the redirection of meltwater runoff can be brought into agreement at ≈8,300–8,200 cal. B.P. (Fig. 3 *a–c*). Coupled atmosphere–ocean climate models predict a decrease in mean annual temperature of 0.5–2°C in central Europe as a consequence of a Holocene reduction of the THC (22–25). In the smoothed chironomid-based paleotemperature record, mean July air temperature decreased by ≈1°C during cooling episodes A and C, which agrees well with ≈2°C cooler July air temperatures due to a THC reduction predicted by a general circulation model for central England (25), given that most climate models indicate a stronger temperature decrease in northwestern than in central Europe.

Solar-induced latitudinal shifts in the extent of North Atlantic drift-ice have been put forward as an alternative mechanism that may have influenced North Atlantic surface-water salinity and, thereby, the THC (5). Drift-ice proxies in North Atlantic sediments and reconstructions of production rates of cosmogenic isotopes feature a number of synchronous Holocene maxima (5). The production of ^{10}Be and ^{14}C is influenced by solar activity, and, hence, the close agreement between the cosmogenic isotope and drift-ice records suggests that at least North Atlantic surface currents have been influenced by past solar variability (5). A similar pacing of cold events as in the North Atlantic records of ice-rafted debris (IRD) is apparent in our temperature reconstructions (Fig. 3 *b–e*). Within the dating uncertainty of our chronologies, cooling episodes in the Alpine records can be brought into agreement with IRD maxima in the North Atlantic. However, the absolute dating of cold phases in the two records shows a poor agreement. Furthermore, distinct differences in the amplitude of individual cold events exist. In the North Atlantic record, most early- and mid-Holocene IRD events are of a similar magnitude (events 4–8, Fig. 3 *d* and *e*), with event 4 indicating by far the longest and most pronounced increase in ice-rafting. However, the two strongest coolings in the Alpine records are found earlier, and changes in solar activity are clearly not sufficient to explain the different amplitude of cold episodes in the Alps. Therefore, it seems that even though past solar variability may have had some effect on summer temperatures in the Alps, meltwater-associated changes in the THC provide the more plausible explanation for the two most prominent centennial-scale summer-temperature decreases in our reconstructions.

Northern Hemisphere proxy records are now available that suggest climatic changes at similar times and periodicity as the Holocene IRD events in the North Atlantic, including records of past lake productivity from Alaska (26), windblown dust from Greenland ice cores (27), and lake-level changes from central Europe (28). All of these records are potentially influenced by winter precipitation (lake levels and lake productivity) or winter atmospheric-circulation patterns (Greenland dust). In contrast, our Alpine reconstructions, which represent temperatures during the growing season, suggest that, at least in central Europe, summer temperature showed a Holocene pattern that was significantly different from that in the North Atlantic IRD records. Within the limits of our ^{14}C chronology, major summer-temperature decreases were coeval with variations in meltwater flux to the North Atlantic, and the amplitude of the summer-temperature decrease is consistent with model predictions of the effects of a Holocene THC reduction on European climate. Thus, our results suggest that meltwater-induced THC changes were the more dominant forcing of Holocene summer temperatures in central Europe than past solar variability leading to cool summers at ≈10,700–10,500 and 8,200–7,600 cal. B.P.

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