Recent changes in a remote Arctic lake are unique within the past 200,000 years

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The Arctic is currently undergoing dramatic environmental transformations, but it remains largely unknown how these changes compare with long-term natural variability. Here we present a lake sediment sequence from the Canadian Arctic that records warm periods of the past 200,000 years, including the 20th century. This record provides a perspective on recent changes in the Arctic and predates by approximately 80,000 years the oldest stratigraphically intact ice core recovered from the Greenland Ice Sheet. The early Holocene and the warmest part of the Last Interglacial (Marine Isotope Stage or MIS 5e) were the only periods of the past 200,000 years with summer temperatures comparable to or exceeding today’s at this site. Paleoclimatic and geochemical data indicate that the past three interglacial periods were characterized by similar trajectories in temperature, lake biology, and lakewater pH, all of which tracked orbitally-driven solar insolation. In recent decades, however, the study site has deviated from this recurring natural pattern and has entered an environmental regime that is unique within the past 200 millennia.

Fig. 1. Study site location and sediment stratigraphy. (A) Black dot shows location of Lake CF8 on Baffin Island in the Eastern Canadian Arctic. Bold line indicates approximate extent of ice sheets during the Last Glacial Maximum. (B) Stratigraphy and magnetic susceptibility of Lake CF8 sediments. Sediment units are represented as roman numerals I-VII [after (10)]. Org. — organic-rich lake sediments; Min. — minerogenic sediments. Organic units are correlated with ice volume minima (interglacials/interstadials) in the global ice volume record of (13) based on the geochronology of (10).

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stratigraphy by an unconformity (recording a hiatus in deposition) overlain by sands deposited by ice-marginal meltwater streams that flowed into the lake during deglaciation. This paper presents high-resolution multiproxy data from the four organic units, including the uppermost (20th century) sediments. The soft uppermost sediments were recovered and subsampled separately with a specialized coring device, and dated using excess ^210Pb (14).

Our study employs aquatic invertebrate and algal assemblages, augmented by sediment biogeochemistry, as proxies for climate and limnological change. The larvae of chironomids, or nonbiting midges (Chironomidae), have chitinous head capsules that are preserved in lake sediments. Chironomid species distributions are often temperature dependent, and subfossil assemblages are increasingly used for quantitative temperature inferences (15). Diatoms (Bacillariophyceae), unicellular algae with siliceous valves, are sensitive to water chemistry and regional climate (16). Chironomid and diatom assemblages have both shown sensitivity to recent Arctic warming (4). To assess aquatic conditions more generally, we inferred chlorophyll-a [a proxy for primary production (17, 18)] spectroscopically, measured percent organic carbon, and calculated the ratio of carbon to nitrogen [an indicator of organic material source (19)] in bulk sediments.

Results and Discussion

All proxies at Lake CF8 express considerable variability within each of the three interglacial periods (Fig. 2), which underscores the amplitude of natural variability experienced in the Arctic during warm-climate intervals. In general, the high-amplitude trends in lake-sediment proxies and of reconstructed temperature changes at this site are consistent with evidence for the strong sensitivity of Arctic climate and ecosystems to radiative forcing (1). Orbitally-driven summer solar insolation has been the primary forcing of interglacial climate evolution here, as evidenced by the similarity between trends in June insolation (20) and chironomid-inferred temperature and diatom-inferred pH at Lake CF8 over the well-dated Holocene (Fig. 2). Biological assemblages (and thus biologically-derived temperature and pH inferences) show similar trends through the Holocene and Last Interglacial, and trends within MIS 7 (presumably we have captured only its waning stages) are similar to those of the late Holocene. The lake biology followed a similar trajectory in response to changing climate through each of the past three interglacial periods, despite intervening continent-scale glaciation, species extirpations, and subsequent recolonizations.

Trends in diatom assemblages illustrate the points above: the dominant diatom taxa (e.g., the genera Fragilaria sensu lato and Aulacoseira) follow the same general trajectory within each interglacial period. At the onset of both the Last Interglacial and the Holocene the assemblage is dominated by small, benthic Fragilaria (Fig. 2). These alkaphilous taxa are common initial colonizers following deglaciation, because they benefit from alkalining base cations released from fresh sediments deposited by glaciers. These cations would have been quickly depleted around Lake CF8, where minimally-erosive ice-sheet advances...
deposited relatively little sediment (10), such that the continuing regulation of acid-base equilibria was governed by climate. As climate cooled with declining insolation in the latter part of each interglacial period, acidophilous *Aulacoseira* taxa increased (Fig. 2). Declining pH was likely a response to increasingly prolonged seasonal lake-ice cover, which simultaneously limited photosynthetic drawdown of limnetic CO₂ and trapped respired CO₂ within the lake (21, 22). Similar patterns of chemical and biological lake ontogeny have been recorded elsewhere over the Holocene on Baffin Island (21, 22).

Through the mid to late Holocene, declining summer insolation has caused progressive cooling in the Northern Hemisphere (23) and under natural forcing, climate would on average be expected to cool over coming centuries. Indeed, chironomids record cooling through the late Holocene at Lake CF8, as cold-tolerant taxa became increasingly dominant. But after approximately AD 1950, chironomid taxa with cold temperature optima abruptly declined (Fig. 2), matching the lowest abundances of the past 200,000 years. The two most extreme cold stenotherms, *Oliveriadiria/Hydrobaenus* and *Pseudodiamesa*, disappeared entirely (14). At the same time, aquatic primary production (inferred from chlorophyll-a and C:N) increased, as has been documented at other lakes in the region (16). Such evidence for 20th-century warming at Lake CF8 adds to mounting evidence from high-latitude northern sites suggesting that the natural late-Holocene cooling trajectory has been preempted in the Arctic (2, 24).

Although 20th-century warming is clearly recorded in the proxy data, Lake CF8 is not simply returning to the environmental regime seen during past warm periods (i.e., the early Holocene and MIS 5e). Rather, recent warm decades are ecologically unique. For example, there has been an unprecedented increase in the diatom species *Eunotia exigua*, which was present only intermittently through the preindustrial record (Fig. 2). This epiphytic species, commonly associated with aquatic mosses (25), may currently be responding to expanded habitat availability due to declining lake ice cover through the 20th century (26). Although *E. exigua* is relatively acidophilic, its increase does not imply recent acidification, as it has replaced other diatom taxa with similar pH optima (27); accordingly, there is no corresponding change in diatom-inferred pH (Fig. 2). Moreover, postindustrial acidification from long-range emissions is not a likely explanation for recent changes at Lake CF8 because acidic deposition is extremely low in this region (28). In fact, SO₄ concentrations in Lake CF8 (< 25 μeq L⁻¹) are a fraction of those recorded in lakes affected by acidic deposition (29), and lower than other Baffin Island lakes, which have recorded increases in alkaliphilic taxa over the same period (22).

To place the complex 20th-century environmental changes objectively within the context of three interglacial periods, we used detrended correspondence analysis [DCA, an indirect ordination technique (30)] to summarize major trends across the range of biological and geochemical proxies. DCA axes can be viewed as latent variables that capture the major gradients within multivariate ecological data sets. DCA results from samples predating the 20th century fall within three distinct clusters reflecting the range of natural interglacial conditions experienced by the lake in the past 200,000 years (Fig. 3A): lake reineckey following deglaciation, relatively warm full interglacial conditions, and descent into glacial conditions. DCA scores for 20th-century samples fall outside this broad range of natural variability, reflecting recent increases in lake productivity (inferred from chlorophyll-a and C:N), loss of cold-tolerant chironomid taxa, and changes in the diatom assemblage (Figs. 2 and 3). The lake has followed a trajectory through the 20th century toward increasingly exceptional environmental conditions with no natural analogues in the past 200,000 years. The 20th century is the only period for which all proxies show trends consistent with warming despite declining orbital forcing, which, under natural conditions, would cause climatic cooling. The timing of this shift coincides with widespread Arctic change, including warming attributed to a combination of anthropogenic forcings that are unprecedented in the Arctic system (1, 31). Thus, it appears that the human footprint is beginning to overpower long-standing natural processes even at this remote site.

The recent environmental changes at Lake CF8 are echoed across the Arctic, in dramatic 20th-century biological shifts documented in numerous Arctic lakes and ponds (4, 26, 32). The sediment record from Lake CF8 places these widespread changes in the context of multiple interglacial periods, and it suggests that ecosystems and environmental conditions in many lakes and ponds in the Arctic may now be outside the range of natural Quaternary variability. Lake ecosystems, which respond rapidly to climate and other environmental change, may be harbingers of similarly dramatic future changes in other parts of the Arctic system.

**Materials and Methods**

Lake CF8 (Zmax = 10 m; surface area ~ 0.3 km²), on the coastal Clyde Foreland of northeastern Baffin Island, is a small through-flowing lake fed primarily by
snowmelt. Mean annual temperature at nearby Clyde River is ~12.8 °C and mean July temperature is ~4.4 °C (33). Repeated field observations reveal that the lake is ice-covered for at least 9 months/year. The local bedrock is Precambrian granite and gneiss.

Chironomids were analyzed according to standard protocol (39), with a minimum of 50 whole head capsules enumerated per sample and following the taxonomy used by (34). Twenty-two different chironomid taxa were identified at this site. Temperature inferences used the weighted averaging model of (34), which incorporates data from (35) and has a root mean square error of prediction (RMSEP) of 2.2 °C. As with any transfer function, chironomid-inferred temperatures contain some statistical uncertainty (14, 34). Although absolute temperature values have a statistical uncertainty of ± 2.2 °C, reconstructed trends in past temperature at this site are likely robust because the amplitude of these trends exceeds the statistical uncertainty of the model; furthermore, these trends are supported by many other proxies from the region (36).

Diatom preparation followed standard protocol (38), with a minimum of 200 diatom valves enumerated per sample; taxonomy and pH inferences followed (16). A total of 123 diatom species from 36 genera were enumerated. Detailed results of paleoecological analyses are presented in text supplemental reports (27, 37). Chlorophyll-a was inferred from reflectance spectra (650–700 nm) of freeze-dried bulk sediment samples using a FieldSpec Pro spectroradiometer (17). This spectral method captures both chlorophyll-a and the byproducts of its degradation, so diagenetic effects are not problematic (17, 18). C and N were measured on bulk sediment using a PDZ Europa ANCA-GSL elemental analyzer (17, 18). C and N were downweighted. To compare 20th century samples with only preindustrial samples, the uppermost interval in the long record (which has not been dated with 210Pb) was omitted from this analysis. Axes 1 and 2 had gradient lengths 1.74 and 1.46 and explained 34.3 and 24.8% of the variance, respectively.

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