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. Paleoecological 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.

Warming over the past century has caused widespread and rapid changes in the Arctic cryosphere, hydrosphere, and biosphere (1, 2). Many of these changes are incompletely documented due to the sparse coverage and short history of high-latitude monitoring networks. Paleoclimate proxy records provide opportunities both to document recent changes at remote sites and to assess their significance relative to natural variability (3, 4). Paleoclimate data from past interglacial periods in particular provide windows into naturally warmer climates and attendant changes in greenhouse gases, ice sheets, sea level, and ecosystems (5–9).

Terrestrial paleoclimate archives that record multiple interglacials are rare in the Arctic due to widespread glacial erosion, but recent research has revealed the preservation of ancient sediments in some glaciated terrains where ice sheets were minimally erosive (10). We have recovered intact lacustrine sediments predating the Last Glacial Maximum from Lake CF8 on Baffin Island, yielding a 200,000-year record of natural rainfall and attendant changes in greenhouse gases, ice sheets, sea level, and ecosystems (5–9).

Cores recovered from Lake CF8 (Fig. 1; 70° 33.42′ N, 68° 57.12′ W, 195 m asl) contain four organic lake sediment units, which are separated by inorganic sands and record portions of the past three interglacial periods and one stadial. Radiocarbon (14C) ages from the uppermost organic unit span the Holocene, i.e., the past 11,000 years (12). Based upon 14C and optically-stimulated luminescence (OSL) dating reported by


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covered by an ice sheet. Each glacial period is represented in the 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 $^{210}$Pb (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 alkalinizing 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 CO\(_2\) and trapped respired CO\(_2\) 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, chironomids 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, *Oliveridium/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, SO\(_4\) concentrations in Lake CF8 (< 25 \(\mu\)eq 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 reincarnation 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 (\(Z_{\max} = 10\) m; surface area ~ 0.3 km\(^2\)), 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 theses (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-GLS elemental analyzer. C/N is reported as weight ratios. Downcore data are plotted versus cumulative dry mass (cumulative sediment thickness multiplied by dry density) to account for compaction.

DCA was conducted using R v 2.5.1 on the data matrix shown in Fig. S1. Raw data were averaged over 10-cm intervals of the long record and 0.5- to 1.0-cm intervals of the surface core to reduce all proxies to a common resolution. Data were normalized (divided by the maximum value for each proxy) and not 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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Observations of warming in the high northern latitudes provide a variety of scientific datasets to better understand the forcings and feedbacks at work in the global climate system. Instrumental data and satellites show that most of the current Arctic warming is the result of large changes in winter temperatures and that, by comparison, changes in summer temperatures have been relatively modest (1). Yet changes in seasonal temperatures are having a profound influence on glaciers, sea ice cover, snow cover, nutrient flux, and vegetation assemblages, causing shifts in both terrestrial and marine ecosystems (2, 3). Profoundly provocative is the suggestion that rapid melt rates now observed at the margins of the Greenland Ice Sheet (GIS) still lag significantly behind recent Northern Hemisphere warming (4).

How out of the ordinary are these changes? Although changes of the last few decades can be assessed in the short term against instrumental and historical data and observations, it is only paleoclimate records that provide the necessary perspective to inform these questions. Kaufman et al. (5) documented that the past decade was the warmest for the last 2,000 years by using high-resolution lake sediment, ice core, and tree ring records from multiple sites across the Arctic. The report by Axford et al. in this issue of PNAS (6) builds on this necessary paleo-perspective by comparing a lake sediment record of the last century to interglacial episodes preserved at depth in the same lake on the Clyde Forelands, Baffin Island, in the eastern Canadian Arctic.

Records of past interglacials (warm intervals) are somewhat rare in the terrestrial arctic, and finding well-preserved, organic-rich interglacial lake sediments stacked in sequence within the limits of the Laurentide Ice Sheet are even rarer. Yet Axford and colleagues (7) have previously reported discovering three interglacials [marine isotope stage (MIS) 1, substages 5a and 5e, and MIS 7] preserved between interceding glaciogenic sands.

This new study (6) of Lake CF8 on eastern Baffin Island (Fig. 1) describes a variety of proxies (including chironomids, diatoms, chlorophyll-a, organic carbon, etc.) that collectively provide a measure of past lake temperature, productivity, and pH. Axford et al. (6) use these data to evaluate the lake system’s response to changes in insolation driven by Earth’s orbital forcing (8) for each interglacial episode over the past 200,000 years. The overall trends in most of the proxies follow a similar pattern for interglacial MIS 1 and 5, with MIS 7 interpreted to be the tail end of the interglacial preceding glacial onset into MIS 6. Their argument concerning the biological response for each interglacial is aimed squarely at the Holocene, the best-dated part of the record characterized by a marked peak in insolation until ~8,000 years ago [the so-called Holocene Thermal Maximum (9)]. They then infer insolation forcing for MIS 5e and 7 notably because the dating of these intervals in their long sediment core is not so well constrained. Nevertheless, using detrended correspondence analysis (DCA), a type of ordination analysis popular in ecosystem studies, on the measured proxies averaged to achieve a common sampling resolution, they show that for both of the earlier warm interglacial sequences the proxies all fall within a relatively well-defined window described by the first and second DCA axes. In contrast, these same proxies measured on sediments representing the past century show an “ecological trajectory” away from this interglacial window, suggesting that factors causing this change are unprecedented for the past 200,000 years. Lakes throughout the Arctic document remarkable 20th-century change (10) but few can make the direct comparison to earlier interglacials. So to answer our earlier questions: yes, this has happened before but not quite like this. Having said that, some readers will agree that the comparison needs to be viewed with some caution given that the raw sampling interval of the record over the past century is better than that for earlier interglacials.

Several points highlight the significance of this work in the context of what is known about the Arctic past and present. First, although Lake CF8 shows remarkable ongoing change in summer-based proxies over the later half of this century, it is located where maps of recent (2003–2007) National Centers for Environmental Prediction surface air temperature data show little or no change in summer; in contrast, large positive anomalies of 2–3 °C occur over the region in autumn (September–November; ref. 1). In other words, it could be that later onset of winter is driving ecological change. Second, the interglacial records from Lake CF8 join a number of long lacustrine records from around the Arctic that extend to the last interglacial and beyond (11), yet very few extend to MIS 7. Lake El’gygytgyn in central Chukotka was recently drilled in spring 2009 with the expectation that it will extend continuously to 3.6 million years (12). Published records demonstrate continuous deposition to nearly 350,000 years B.P., including MIS 9 (refs. 13 and 14 and Fig. 2). Long paleolimnologic records from other Arctic lakes include those from Imuruk, Squirrel, and Ahaliorak lakes in the western Arctic (11).

What do the interglacials in this and other Arctic lake records inform us about the future? In short, if it happened before, it could happen again, and it’s happening now. A growing number of observations show that summer Arctic sea ice was much reduced during MIS 5e and may have been almost seasonal because of Milankovitch-driven summer insolation as much as 11–13% above present (11). Emerging records from the central Arctic Ocean [Arctic Coring Expedition (ACEX) and Greenland Arctic Shelf Ice and Climate Project (GreenICE); Figs. 1 and 2] also point to seasonally open water during MIS...
Greenland ice core (North Greenland Ice Core Project) carbon (25). (relative % herb pollen (24). In Lake E in northern Russia. The age model for Lake E cores is same as in ref. 14. In 18432/H20841 durations of interglacial MIS are indicated by yellow bars. (Fig. 2. stretched so that the MIS correlate with those in ref. 15. (Fig. 2. Smol JP, Douglas MSV (2007) From controversy to consensus: Making the case for recent climate change in the Arctic. (5). Therefore, we need only look to Arctic records of the mid-Pliocene to capture our geologic moment of déjà vu when CO2 is estimated to have been in the range of 350 to 400 ppm like it is now (19). Intermittently throughout this time period sea level may have been + 5 to +40 m above present (ref. 19 and references therein), driven in part by massive reductions in Antarctic ice sheets (20). Syntheses of this Pliocene interval and later interglacials (ref. 21 and www.globalchange.gov/publications/reports/scientificassessments/saps/sap1-2) leave little doubt that renewed studies in the high latitude are well justified to test and improve the chronological coherence of Arctic records. With a seasonally ice-free Arctic now projected to be only a few decades from now, perhaps Yogi Berra was right: “it’s déjà vu all over again.”

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