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Hydrological and temperature change in Arctic Siberia during the intensification of Northern Hemisphere Glaciation

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A B S T R A C T

The Pliocene epoch represents an analog for future climate, with atmospheric carbon dioxide concentrations and continental configurations similar to present. Although the presence of multiple positive feedbacks in polar regions leads to amplified climatic changes, conditions in the Pliocene terrestrial Arctic are poorly characterized. High latitude sedimentary records indicate that dramatic glacial advance and decay occurred in the Pliocene Arctic, with attendant effects on global sea-level. Understanding these deposits and their implications for Earth's future requires developing a sense of climatic evolution across the Pliocene–Pleistocene transition and during the intensification of Northern Hemisphere Glaciation (iNHG) ∼2.7 million yr ago (Ma). Here we reconstruct Arctic terrestrial environmental change from 2.82–2.41 Ma (Marine Isotope Stages (MIS) G10–95) using the distribution of branched glycerol dialkyl glycerol tetraethers (brGDGTs) and the isotopic composition of plant leaf waxes (δD_{wax}) in a sedimentary archive from Lake El'gygytgyn, Northeast Russia. Our records reveal changes in proxy behavior across this interval that we attribute to changing boundary conditions, including sea level, sea ice, vegetation and pCO_2 during different MISs. We find that brGDGT temperatures and δD_{wax} are decoupled for most of the record, although both show an increasing range of glacial–interglacial variability following iNHG. δD_{wax} is stable from MIS G10–G4 despite changes in vegetation and temperature, suggesting different sources or pathways for moisture to Lake El'gygytgyn during the Late Pliocene.

1. Introduction

The Pliocene was a global warm period 5.332–2.588 million yr ago (Ma) (Gibbard et al., 2010) when atmospheric carbon dioxide (pCO_2) was 350–450 ppm (Zhang et al., 2013; Martínez-Botí et al., 2015), and it has been proposed as an analog for future warming (Thompson and Fleming, 1996). Of particular interest is the intensification of Northern Hemisphere glaciation (iNHG) ∼2.73 Ma, during Marine Isotope Stage (MIS) G6, which has been studied in many high-latitude marine records (Fig. 1) (e.g. Haug et al., 2005; Naafs et al., 2012; Hennissen et al., 2015; Bailey et al., 2013; Kleiven et al., 2002; Martínez-Garcia et al., 2010). Northern landmasses were permanently altered by the growth of large ice sheets after iNHG, yet few terrestrial records from this period have been studied. Unfortunately, high-resolution, continuous terrestrial sections of Pliocene age are rare in the high latitudes. Pleistocene glaciations repeatedly scoured the continents, precluding the uninterrupted deposition of sediment necessary to develop a continuous view of terrestrial Arctic climate change since the Pliocene (Miller et al., 2010).

In 2009, a sediment core from Lake El'gygytgyn, Russia, spanning the last ∼3.6 Ma was recovered. This record provides a unique view of environmental change preceding, during, and following iNHG. Although pollen-based temperature estimates have been published for Lake El'gygytgyn (Melles et al., 2012; Brigham-Grette et al., 2013), these are regional in nature and potentially subject to large errors based on the modern analogue approach (Andreev et al., 2014). Organic geochemical proxies provide an independent means of examining terrestrial temperature and hydrological change (e.g. Weijers et al., 2007a; Pautler et al., 2014) and may provide a more local signal in a lacustrine environment (Buckles et al., 2014). Here we apply two such proxies that have previously been used to reconstruct past Arctic temperature from marine and lacustrine sediments (e.g. de Wet et al., 2016; Pautler et al., 2014). Firstly, we use the methylation/cyclization (MBT/CBT) ratio based on branched glycerol dialkyl glycerol tetraethers (brGDGTs) (Weijers et al., 2007b; Peterse et al., 2012). Secondly, we measure the deuterium to hydrogen ratio on terrestrial higher plant leaf waxes (n-alkane δ^2H, δD, or δD_{wax}) (e.g. Sachse et al., 2012).

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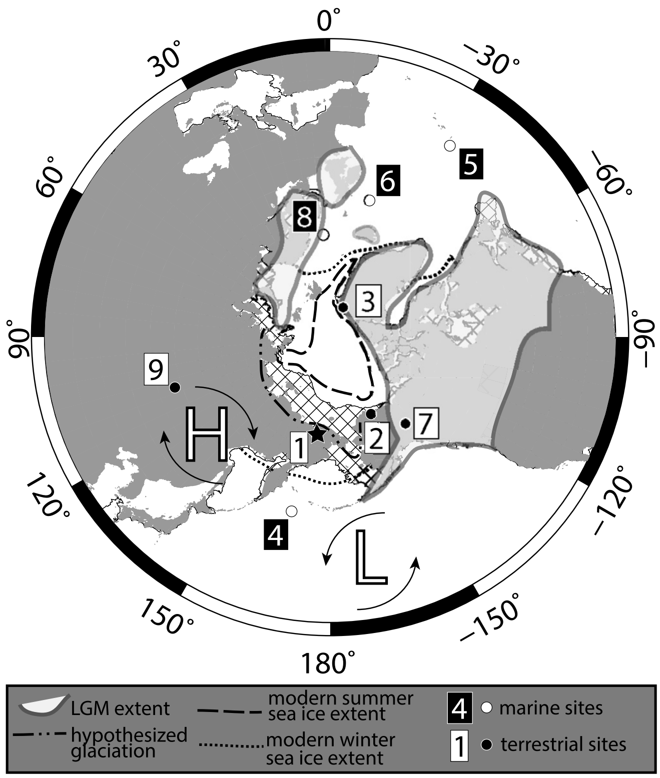

Fig. 1. Lake El'gygytgyn and surrounding records. The dashed black line indicates approximate September sea-ice extent; dotted black line indicates March sea-ice extent (http://neo.sci.gsfc.nasa.gov). The hatched area marks modern seafloor that becomes subaerial during Last Glacial Maximum (LGM) style glaciations (the −120 m bathymetric contour). The transparent gray areas mark the approximate extent of LGM ice sheets; a dotted black line in Siberia from 90–180° longitude marks the hypothesized extent of the East Siberian Ice Sheet, which existed during some Plio-Pleistocene glacial stages (Niessen et al., 2013). Records and localities discussed in the text are marked: (1) Lake El'gygytgyn (this study), (2) Fish Creek (Brigham-Grette and Carter, 1992), (3) Kap København (Funder et al., 2004), (4) ODP 882 (Haug et al., 2005), (5) U1313 (Naafs et al., 2012; Hennissen et al., 2015), (6) ODP 611 (Bailey et al., 2013), (7) Yukon (Duk-Rodkin and Hughes, 1994), (8) Vøring Sea (Kleiven et al., 2002), (9) Lake Baikal. Arrows indicate prevailing winds around the approximate mean position of the Aleutian Low (L) and Siberian High (H).

2. Study area and regional setting

Lake El'gygytgyn is located in northeastern Arctic Russia (67.5°N, 172°E, Fig. 1). A bolide impact created the lake, resulting in a small catchment with a high degree of topographic relief (Layer, 2000; Nolan and Brigham-Grette, 2007). The lake and its catchment are roughly circular, with diameters of ∼12 km and ∼18 km, respectively. The 175-meter deep lake is ice-covered for ∼10 months of the year, with most inflow during the early June freshet, delivered by 50 small creeks around the perimeter (Nolan and Brigham-Grette, 2007).

Lake El'gygytgyn was unscathed by the periodic glaciations of the Plio-Pleistocene, perhaps due to the arid climate of northeast Chukotka (Barr and Clark, 2011). As such, it has accumulated a continuous sedimentary record since its formation (Brigham-Grette et al., 2013). In 2009, the International Continental Scientific Drilling Program recovered 318 m of composite core from the lake (Brigham-Grette et al., 2013; Melles et al., 2012). Three separate drives comprise the composite core, which were correlated based on their lithological properties (Gebhardt et al., 2013). The age model is based on a three-tiered system of tie points: primarily, on twelve magnetic reversals dated by the geomagnetic polarity timescale; secondarily, by tuning the elemental ratio of silica/titanium and hue angle to the benthic oxygen isotope ($\delta^{18}O$) stack of Lisiecki and Raymo (2005); and lastly, by tuning of magnetic susceptibility and percent total organic carbon (%TOC) to Northern Hemisphere summer insolation (Nowaczyk et al., 2013). The uncertainty in absolute age is 3–15 thousand years (kyr), with higher uncertainties during the Pliocene portion of the record (Nowaczyk et al., 2013). Differences in spatial and temporal averaging in sediments of the three proxies used (*n*-alkanes, brGDGTs, and pollen) may account for some of the differences discussed here, and is further explored in the supplementary materials. However, we anticipate these to be minimal as the mean sedimentation rate during our study interval results in each 1-cm thick sample representing ∼300 yr. In addition, measuring proxies (MBT/CBT and δD_{wax}) on the same samples permits observations that are unaffected by changes to the age model.

Lake El'gygytgyn sits between two prominent atmospheric pressure centers in the Northern Hemisphere, the Siberian High and the Aleutian Low (Fig. 1). Although their position and strength show significant interannual variability, their mean position causes extreme windiness at the lake (Fig. 1) (Mock et al., 1998). Aloft, the persistent East Asian Trough in the jet stream brings southerly flow to the lake (Mock et al., 1998). In summer, the Pacific subtropical high sits over the northeastern Pacific, bringing predominately southerly surface flow (Mock et al., 1998). Historical observations of atmospheric circulation patterns are consistent with weather station data spanning 2002, which showed winds were predominantly south-easterly and north-westerly (Nolan et al., 2013). The lake is extremely arid (<200 mm a^{-1}), with precipitation occurring in approximately equal amounts in summer and winter (Nolan and Brigham-Grette, 2007). Although the Siberian High and Aleutian Low are persistent features of the climatology, they are subject to change as the jet stream kinks and migrates, and the mean climatology at the lake may have shifted over time, especially over the long duration of this study. In addition, the imposition of large ice masses in the Northern Hemisphere has dramatic consequences for the atmospheric pressure centers mentioned here. Studies of the Last Glacial Maximum indicate an intensified Aleutian Low, and a potential splitting of the jet stream aloft advecting more southerly-sourced air over Lake El'gygytgyn (Bromwich et al., 2004). In sum, the position of Lake El'gygytgyn makes it sensitive to changes both in the Chukchi Sea and terrestrial Siberia (Fig. 1).

3. Sampling and methods

3.1. Sample preparation

Sediment samples were collected at one-centimeter intervals from the working half of each core section where possible, and the archive half where necessary. For this study, we analyzed samples every ∼10 cm throughout the composite core, resulting in a climate reconstruction with ∼2 kyr resolution from 2.82–2.41 Ma (mean sample spacing = 2.3 kyr, median = 1.3 kyr). Freeze-dried, homogenized samples were extracted using a Dionex accelerated solvent extraction (ASE 200) system with a mixture of dichloromethane (DCM):methanol (9:1, v:v). Total lipid extracts (TLEs) were dried under a stream of N_2 and separated into apolar, ketone, and polar fractions by sequential elution over activated Al_2O_3 using DCM:hexane (9:1, v:v) (apolar), DCM:hexane (1:1, v:v) (ketone), and DCM:methanol (1:1, v:v) (polar).

3.2. brGDGT analysis

One half of each polar fraction was filtered through a 0.45 µm PTFE filter in hexane:isopropanol (99:1, v:v), then dried under a stream of N_2 and dissolved in 100 µl hexane:isopropanol containing 0.1 µg of a C_{46} GDGT internal standard. BrGDGTs were