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The transitional climate of the late Miocene Arctic: Winter-dominated precipitation with high seasonal variability

Brian A. Schubert[1], A. Hope Jahren[2], Sergei P. Davydov[3], and Sophie Warny[4]
[1]School of Geosciences, University of Louisiana at Lafayette, Lafayette, Louisiana 70504, USA
[2]Centre for Earth Evolution and Dynamics, University of Oslo, N-0315 Oslo, Norway
[3]North-East Science Station, Far East Branch of Russian Academy of Sciences, Cherskiy, Russia
[4]Department of Geology and Geophysics and Museum of Natural Science, Louisiana State University, Baton Rouge, Louisiana 70803, USA

ABSTRACT

The late Miocene (11.6–5.3 Ma) was an important transitional period following the greenhouse conditions of the Eocene. In order to gain insight into the Arctic paleoclimate of the time, we performed high-resolution intraring $\delta^{13}C$ analyses on fossil wood collected from the late Miocene Khapchansky sediments of northeastern Siberia (~69°N). From these data we quantified the ratio of summer to winter precipitation (P_s/P_w) and compared it to current values for the region determined from modern wood samples and instrumental records. We observed much greater frequency of winter-dominated precipitation ($P_s/P_w < 1$) and much greater variability in P_s/P_w during the Miocene than today. Specifically, years with $P_s/P_w < 1$ occurred three times more often, and years with at least three times as much precipitation in summer or winter ($0.33 < P_s/P_w < 3.0$) occurred approximately twice as often during the Miocene than today. We attribute the high interannual variability in precipitation to an inconsistent moisture source associated with the relatively unstable and incomplete ice cover in the Arctic Ocean during the late Miocene. Our result highlights the potential for enhanced variability in Arctic precipitation in response to Arctic sea ice decline caused by anthropogenic, CO_2-induced warming.

INTRODUCTION

Eastern Siberia (a 7.3 × 10^6 km^2 area, similar to Australia in size) features numerous plant fossil localities (e.g., Baekovo and Nekkeiveem, Khapchan-Timmerdekh, Mamontova Gora), many with exceptionally preserved Neogene fossils (e.g., Baranova and Grinenko, 1989; Baranova et al., 1970; Dorofeev, 1969; Grinenko et al., 1989; Nikitin, 2007). The Miocene (23–5.3 Ma) is particularly well represented within the sediments of eastern Siberia (Gnibidenko et al., 2011; Nikitin, 2007; Volkova and Kul'kova, 1996; Volkova et al., 1986). This period represents a notable time characterized by global cooling (with the exception of the Middle Miocene Climatic Optimum) following the greenhouse conditions of the Paleogene (Zachos et al., 2008); however, the Arctic hydrology is poorly constrained. We hypothesize year-to-year variability in seasonal precipitation increased in the Arctic during the late Miocene as a result of unstable and intermittent sea ice cover (Darby, 2014; Stein et al., 2016). To test this, we present a reconstruction of seasonal precipitation at annual resolution for the late Miocene using high-resolution $\delta^{13}C$ measurements across fossil growth rings, thus producing the first interannual paleoclimate record for the Siberian Arctic. Resolution of year-to-year changes in seasonal precipitation represents a critical advance beyond the reconstruction of mean annual conditions, particularly in assessing the influence of climate on vegetation. Within modern environments, the timing and amount of seasonal precipitation have been shown to exert a strong influence on net primary productivity (Robertson et al., 2009), ecosystem respiration (Chimner and Welker, 2005), and species diversity and abundances (Robertson et al., 2010). Within Arctic environments specifically, winter precipitation (including snowfall and snowmelt) has been shown to affect the distribution of plant species (Beck et al., 2005), net ecosystem production (Uchida et al., 2010), and the length of growing seasons (Ernakovich et al., 2014). For these reasons, we sought to quantify the seasonal variability of precipitation during the late Miocene, and discuss the effect of ice cover in the Arctic Ocean on precipitation and Arctic vegetation, as characterized by the fossil record.

MATERIALS AND METHODS

We collected mummified fossil wood from the Finish Stream site (68.724°N, 161.587°E) located near the Cherskiy Field Station in eastern Siberia (Sakha Republic, Russia; Fig. 1A). Wood samples as much as 10 cm in length and 3 cm in diameter were excavated from the late Miocene Khapchansky horizon (Fig. DR1 in the GSA Data Repository[1]). In order to refine the age context of the Finish Stream site, a palynology analysis was performed (see the Data Repository). Six mummified wood pieces were sampled using a razor blade parallel to the growth rings for intraring $\delta^{13}C$ analysis (for methods, see our previous studies on modern and fossil wood: Jahren and Sternberg, 2008; Schubert and Jahren, 2011, 2015; Schubert et al., 2012; Schubert and Timmermann, 2015; see the Data Repository).

In order to contrast the results of our paleoclimate analysis using fossil wood against an analysis of modern wood collected from the same site, we sampled wood from two living *Pinus pumila* (dwarf Siberian pine; PINE01 and PINE02) growing at the Cherskiy site (Fig. DR2), using the same methods (see the Data Repository). These plants were chosen due to their similarity to the *Pinus* wood fragments identified within the late Miocene Khapchansky horizon (Grinenko et al., 1997). The modern wood samples ranged from ~3 to 4 cm in diameter and showed clear annual growth rings (Fig. DR2).

RESULTS

When we examined the isotope data gained from the analysis of modern *Pinus* wood growing at the Cherskiy site, we found that both samples showed similar intraring $\delta^{13}C$ patterns (Fig. 2A), but that sample PINE01 had a significantly ($p < 0.0001$) higher $\delta^{13}C$ value ($\delta^{13}C = -27.4‰ \pm 0.6‰$, $n = 107$) than PINE02 ($\delta^{13}C = -28.1‰ \pm 0.5‰$, $n = 148$). The total range of $\delta^{13}C$ values in the modern wood, however, was small (−29.4‰ to −26.3‰). In contrast, we observed a wide range in $\delta^{13}C$ values for the fossil wood (−27.2‰ to −20.8‰), resulting from the larger number of samples analyzed; however, each showed a similar intra-annual $\delta^{13}C$

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[1] GSA Data Repository item 2017133, supplementary information on the stratigraphic context and palynology analysis, stable isotope methods, and photographs of the field site and collected specimens, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

GEOLOGY Data Repository item 2017133 | doi:10.1130/G38746.1

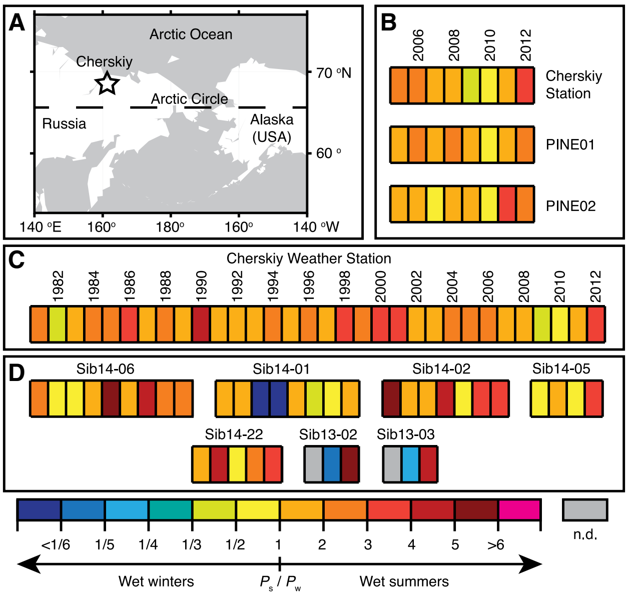

Figure 1. Seasonal precipitation, measured as the ratio of summer (P_s: May through October) to winter (P_w: November through April) precipitation. Each colored rectangle represents one year. A: Location of modern and fossil wood samples collected near Cherskiy, Russia (star). B: Comparison of year-to-year changes in P_s/P_w measured at the Cherskiy weather station to those determined from high-resolution $\delta^{13}C$ measurements across two modern *Pinus pumila* plants (PINE01, PINE02). C: Long-term record of P_s/P_w measured at the Cherskiy weather station. D: Late Miocene P_s/P_w determined from high-resolution $\delta^{13}C$ measurements across six pieces of fossil wood. Interannual changes in P_s/P_w determined from modern growth rings are consistent with the local weather station (B), but show much less variability than values determined for the late Miocene using fossil wood (D). This contrasts with the low variability in P_s/P_w determined for the Arctic Eocene (Schubert et al., 2012). The gray box (labeled n.d.) indicates that P_s/P_w could not be determined ($\delta^{13}C_{max}$ occurred at the start of the profile and therefore $\delta^{13}C_{min}$ was not present).

pattern (Fig. 2B) consistent with modern and fossil evergreen wood, as observed in wood from around the world (Schubert and Jahren, 2011; Schubert et al., 2012). The fossil wood sample Sib13, measured across two different radii, showed excellent intrasample reproducibility in the $\delta^{13}C$ pattern (Fig. 2A), suggesting that the radius sampled does not affect the $\delta^{13}C$ pattern, consistent with previous studies on other species (e.g., Verheyden et al., 2004).

The intra-annual $\delta^{13}C$ pattern within the mummified fossil wood has previously been used to reconstruct the ratio of summer (P_s) to winter (P_w) precipitation for the site at which the plant grew (Schubert et al., 2012; Schubert and Timmermann, 2015), using the following equation derived from patterns seen in 33 modern angiosperms and gymnosperms growing across a wide range of environments (including high latitude), totaling 15 sites (Schubert and Jahren, 2011):

$$P_s/P_w = e\hat{}\left\{\left[\Delta\left(\delta^{13}C\right) - (0.01L + 0.13) - 0.73\right]\big/ -0.82\right\}, \quad (1)$$

where L is latitude, e is a mathematical constant (~2.718), and $\Delta(\delta^{13}C)$ is calculated as the difference between the maximum $\delta^{13}C$ value of a given year ($\delta^{13}C_{max}$) and the preceding minimum $\delta^{13}C$ value of the annual cycle ($\delta^{13}C_{min}$) [$\Delta(\delta^{13}C) = \delta^{13}C_{max} - \delta^{13}C_{min}$].

We compared values of P_s/P_w calculated, according to Equation 1, from high-resolution $\delta^{13}C$ analysis across modern wood of *P. pumila* growing at the Cherskiy site with the actual climate conditions, as recorded in terms

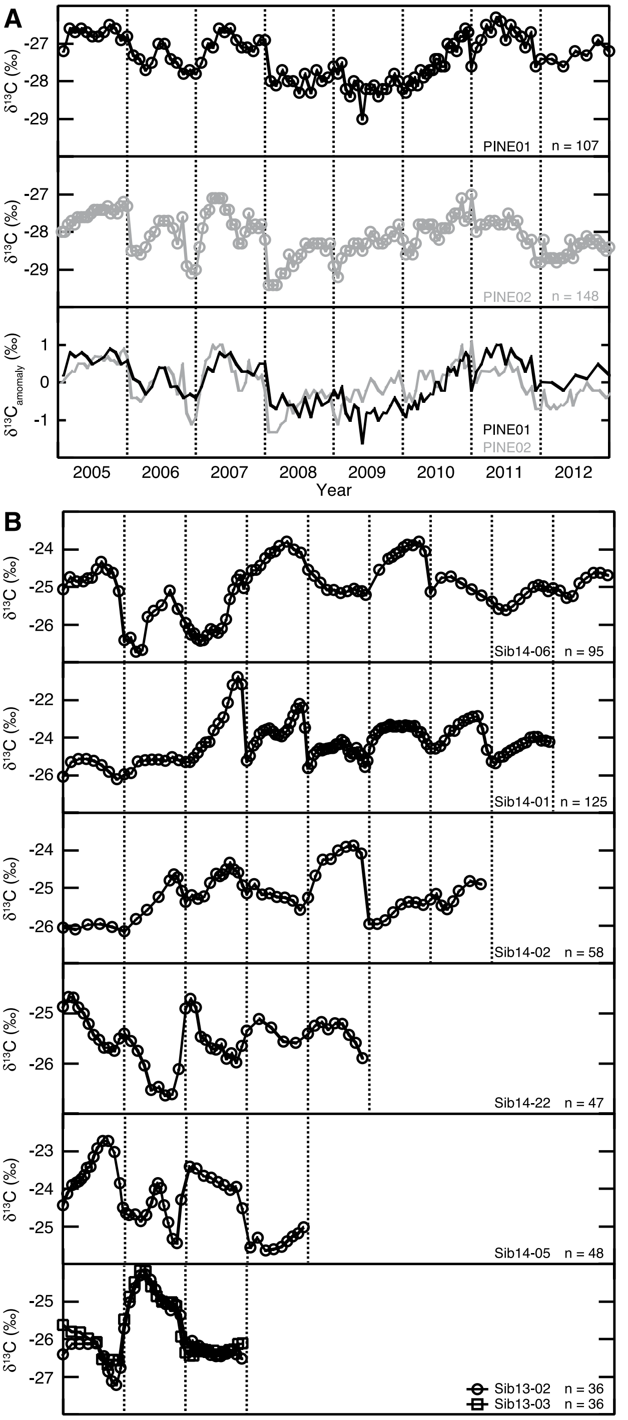

Figure 2. High-resolution $\delta^{13}C$ measurements across annual growth rings. Vertical dashed lines mark ring boundaries; growth is from left to right. A: Modern *Pinus pumila* wood. Although $\delta^{13}C$ values measured within PINE01 were significantly higher than in PINE02, the relative changes in $\delta^{13}C$ ($\delta^{13}C_{anomaly}$) were consistent between both samples. B: Late Miocene wood. The $\delta^{13}C$ pattern of each fossil suggests that the plants represent evergreen (rather than deciduous) species (Helle and Schleser, 2004; Schubert and Jahren, 2011), and are therefore consistent with the *Pinus* wood fragments previously identified within this horizon (Grinenko et al., 1997).

of seasonal precipitation. Across eight consecutive years (2005–2012), our calculated P_s/P_w values agreed well with P_s/P_w values determined from a local weather station (Fig. 1B); specifically, the average P_s/P_w determined from the intra-annual $\delta^{13}C$ data ($P_s/P_w = 1.75 \pm 0.53$, n = 8) was not significantly different ($p = 0.85$) from data collected at the local weather station ($P_s/P_w = 1.67 \pm 0.84$, n = 8). When expanding our examination of the climate at this site across the entirety of its record (n = 32 yr; 1981–2012), we saw that the site consistently had a summer-dominated precipitation regime, with more than 90% of the years between 1981 and 2012 exhibiting greater precipitation during summer than during winter (Fig. 1C).

In order to test whether this summer-dominated precipitation regime also existed in the Arctic during the time when our fossil plants were growing (i.e., the late Miocene), we performed high-resolution $\delta^{13}C$ analyses across 36 fossil growth rings taken from 6 different mummified wood fossils (Fig. 2B). From these data we reconstructed P_s/P_w values for each year of growth using Equation 1 (Fig. 1D).

The year-to-year variability in P_s/P_w calculated for the late Miocene using Equation 1 (Fig. 1D) is striking compared with the lack of year-to-year variability evidenced within the modern climate record at the site (Fig. 1C), and as reflected by modern wood growing at the site (Fig. 1B). Nearly one-third of the late Miocene $\delta^{13}C$ profiles within rings (11 out of 36 yr) indicated a winter-dominated precipitation regime, compared to only 3 of 32 yr within the modern extended record. In addition, according to the reconstructed late Miocene data set, extreme seasonal variability (defined as years with at least 3× more precipitation during summer, or during winter; i.e., $0.33 < P_s/P_w < 3.0$) was approximately twice as common compared to today.

DISCUSSION

The P_s/P_w values reconstructed for northeastern Siberia during the late Miocene indicate that the summer-dominated precipitation regime characteristic of the modern Arctic (New et al., 2002) was not a stable feature throughout the Neogene. At present, the very low temperatures found across the continental regions of the Arctic preclude the presence of significant water vapor within the atmosphere during winter, resulting in a consistently summer-dominated pattern in annual precipitation (Fig. 1C).

Using the Yanran flora, Popova et al. (2012) reconstructed both cold month mean temperature (CMMT) and mean annual precipitation (MAP) for a site in northeastern Siberia, located <100 km from the Cherskiy site and dated to be late Miocene. Popova et al. (2012) determined the CMMT to have been −3 °C, much higher than today's CMMT at Cherskiy (−35 °C). This higher temperature during the late Miocene could have allowed for substantially more atmospheric water vapor relative to today (e.g., Higgins and Cassano 2009); Popova et al. (2012) reconstructed the MAP to 581–1206 mm, similar to London, UK (602 mm) or New York City, USA (1200 mm), and much higher than today's MAP at Cherskiy (233 mm).

The extreme seasonal variability in precipitation patterns reconstructed here for the late Miocene (Fig. 1D) was contemporaneous with the onset of Arctic sea ice (Lavrushin and Alekseev, 2005). The first formation of ice within the Arctic Ocean represented the culmination of long-term and global-scale cooling driven by a decline in atmospheric CO_2 levels that began during the Eocene (Zachos et al., 2008) and extended into the late Miocene (Herbert et al., 2016). The perennial ice cover in the central Arctic Ocean observed today was lacking, at least intermittently (Darby, 2014), during the late Miocene (Stein et al., 2016).

This relatively unstable and incomplete ice cover during the late Miocene likely resulted in high interannual variations in evaporation of water from the Arctic Ocean that we observed in the high interannual precipitation variability signal of our data (Fig. 1D). This climate configuration likely persisted until the Pliocene, by which time this region began forming permafrost sediments (Sher et al., 1979) and the entire Eurasian sector of the Arctic Ocean was fully ice-covered (Knies et al., 2014). Thus, the late Miocene represented a transitional period for Arctic climate, i.e., much cooler and more seasonally variable than the consistently summer-precipitation greenhouse conditions of the Eocene (Jahren and Sternberg, 2003; Schubert et al., 2012), but not yet ice-locked into the colder winters of the Pliocene (Popova et al., 2012). We attribute the greater precipitation seasonality in the Arctic during the late Miocene to the onset of intermittent Arctic sea ice.

The unique transitional climate conditions of the late Miocene were also associated with a shift from forest cover to more open landscapes in the Siberian Arctic (Popova et al., 2013). Pollen extracted from sediments at the Cherskiy site corroborated these claims, and indicated an environment dominated by shrubs and microplants, rather than trees, during the late Miocene; the lack of any report of large wood fragments within the Khapchansky horizon was also consistent with more limited biomass in this region during the late Miocene, and with the aridification of both western and eastern Siberia (Miao et al., 2012). The wood pieces we collected from the Finish Stream site were small (<10 cm in length, <3 cm in diameter) (Fig. DR1), in contrast to the very large wood pieces and stumps identified in the Arctic during the Eocene (e.g., Jahren, 2007) and middle Miocene (Williams et al., 2008).

CONCLUSIONS

The high variability in $\Delta(\delta^{13}C)$ determined for fossil wood of late Miocene age from northeastern Siberia is in stark contrast to that measured within growth rings sampled from modern wood collected at the site. Our data suggest that the Arctic site had a mix of summer- and winter-dominated precipitation regimes during the late Miocene, and that high year-to-year variability in the timing of maximum precipitation was common. This seasonal variability, combined with the unique light regime of the Arctic, likely had a governing influence in limiting the plant biomass found represented in the fossil record of the region. Taken together, our results highlight the important role of winter temperatures and the presence of sea ice in regulating precipitation delivery and the resulting plant biomass in the Arctic during the late Miocene.

High variability in seasonal precipitation could therefore return to Arctic regions as a result of high-latitude warming driven by increasing atmospheric CO_2. Models and observational data suggest that increased heavy precipitation events occur in response to higher temperatures (Fischer and Knutti, 2015). Sea ice affects the Arctic hydrologic cycle by altering large-scale atmospheric circulation patterns and the amount of evaporation and precipitation (Kopec et al., 2016). As sea ice declines, models predict that precipitation will increase, especially in winter months, as a result of enhanced warming, water vapor, and evaporation; decreases in sea-level pressure; and an increase in convective and low cloud cover (Deser et al., 2010; Singarayer et al., 2006). It therefore follows that more intermittent sea ice as a result of global warming may lead to more variability in the source and timing of precipitation in the coming decades. Our work illustrates how seasonally variable precipitation regimes have significant ramifications for primary productivity within Arctic regions.

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