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Climate of the Past Discussions

Detailed insight into Arctic climatic variability during MIS 11 at Lake El'gygytgyn, NE Russia

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Abstract

Here we present a detailed multiproxy record of the climate and environmental evolution at Lake El'gygytgyn/Far East Russian Arctic during the period 430–395 ka covering the Marine Isotope Stage (MIS) 12/11 transition and the thermal maximum of super interglacial MIS 11. The MIS 12/11 transition at Lake El'gygytgyn is characterized by initial warming followed by a cold reversal implying similarities to the Bølling/Allerød (B/A) to Younger Dryas (YD) pattern of the last deglaciation. Full and remarkably stable interglacial conditions with mean temperatures of warmest month (MTWM) ranging between ca. 10–15 °C, annual precipitation (PANN) ranging between ca. 300–600 mm, strong in-lake productivity, coincide with dark coniferous forests in the catchment, annual disintegration of the lake ice cover and full mixis of the water column. Such conditions persisted for ca. 27 kyrs between ca. 425–398 ka. The Lake El'gygytgyn record closely resembles the climate pattern recorded in Lake Baikal (SE Siberia) sediments and Antarctic ice cores implying strong teleconnections between northern and southern hemispheres during MIS 11. A peak warm period between ca. 418–415.5 ka and a precipitation anomaly at ca. 401 ka at Lake El'gygytgyn, in contrast, appear to be an expression of more regionally confined climate variations.

1 Introduction

An understanding of past environmental changes is of particular importance to facilitate the prediction of both the magnitude and regional repercussions of future environmental changes, especially in a warming world. Future changes are expected to be especially pronounced in the polar regions, which are now experiencing observable environmental warming and change (IPCC, 2007; ACIA, 2004). The Arctic plays a major role in the global climate system by triggering complex feedback processes involving the ocean, atmosphere, cryosphere and continental land masses. It is necessary to understand the function of the Arctic in the past and in particular during past interglacials when orbital geometries were similar to today in order to more accurately predict the magnitude of future environmental changes. Marine records covering these time spans are available from the Arctic and sub-Arctic oceans (cf. McManus et al., 1999). In contrast, long continuous terrestrial records of the Arctic are scarce, with ice cores from the Greenland ice sheet only extending back to the last interglacial period (NGRIP Members, 2004).

Lake El'gygytgyn, situated in a ca. 3.6 Ma old meteorite impact crater (Layer, 2000) in north-eastern Russia contains the longest terrestrial Arctic climate record (Melles et al., 2012) because the lake and its catchment were never covered by large scale Quaternary ice sheets (Glushkova and Smirnov, 2007; Melles et al., 2012). In spring 2009, the ICDP (International Continental Scientific Drilling Program) El'gygytgyn Drilling Project drilled three holes in the center of the lake (ICDP Site 5011-1A, B, and C; Fig. 1; Melles et al., 2011), following a comprehensive geophysical site survey and pilot coring (Gebhardt et al., 2006; Melles et al., 2007; Schwamborn et al., 2008; Juschus et al., 2009). A 318 m long composite profile of the lacustrine sediments in ICDP Site 5011-1 was constructed by splicing the best-preserved sediment intervals in overlapping core sequences from the deep drilling and from the pre-site survey (Melles et al., 2012).

Numerous so-called "super interglacials" have been identified in the Quaternary sediment record from Lake El'gygytgyn. Among these "super interglacials", the marine isotope stage (MIS) 11 appears to be the most outstanding in terms of its temperature, vegetation cover, in-lake productivity, and duration (Melles et al., 2012). Because of the similarity of the Earth's orbital parameters during both the Holocene and MIS 11, MIS 11 is considered a close analogue for the present interglacial (e.g. McManus et al., 1999; Loutre and Berger, 2003; EPICA community members, 2004; Prokopenko et al., 2010). A detailed analysis of climate variability during MIS 11 in the Arctic will contribute to narrowing uncertainties for future climate change and its impact in this vulnerable environment.

The aims of this study are (1) to provide detailed insight into the climatic and environmental variability at Lake El'gygytgyn during MIS 11 using temporarily highly resolved

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datasets along with previously published low-resolution datasets (Melles et al., 2012) in order to provide a better understanding of the climatic evolution during MIS 11 in the Arctic. Moreover, (2) we aim to compare the Lake El'gygytgyn MIS 11 record with other Arctic and global climate records in order to identify common patterns and discuss possible causes of climate variability and stability during this super interglacial.

2 Site information

Lake El'gygytgyn (67°30° N, 172°05° E) is a meteorite impact crater-lake situated in the Far East Russian Arctic, approximately 100 km north of the Arctic Circle (Fig. 1). The impact occurred 3.58 ± 0.04 Ma ago (Layer, 2000) and formed a crater of 18 km in diameter (Fig. 1) into ignimbrites, tuffs, and andesite-basalts (Belyi and Raikevich, 1994; Nowaczyk et al., 2002). The lake itself is roughly circular with a diameter of 12 km (Fig. 1), covers an area of 110 km^2, and has a subsurface bowl-shaped morphology with a maximum water depth of 175 m. The permafrost-dominated catchment with an area of 293 km^2 is bordered by the outer rim of the impact crater structure, and is drained by 50 ephemeral streams that enter the lake at 492 m a.s.l. (Nolan and Brigham-Grette, 2007). The lake is drained to the Bering Sea by the Enmyvaam River at its south-eastern termination.

The climate at Lake El'gygytgyn is cold and dry with mean winter and summer temperatures ranging between −32 and −36 °C (January) and +4 and +8 °C (July, August), respectively (Treshnikov, 1985), and a mean annual precipitation of 250 mm (Glotov and Zuev, 1995). The cold conditions are reflected in the depth of permafrost, which is modelled to be 330–360 m thick (Mottaghy et al., 2012). Although the study area belongs to the southern shrub and typical tundra zone, the local vegetation is rather sparse. The area is dominated by hummock and moss tundra with some prostrate willows and dwarf birch (for detailed vegetation description see Andreev et al. 2012 and references therein). The small catchment to lake surface area ratio (< 3 : 1), in combination with cold and dry climate conditions and a thin soil and vegetation cover make

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Lake El'gygytgyn an oligotrophic to ultra-oligotrophic lake (Cremer and Wagner, 2003). With a yearly ice-cover lasting from mid-October until early to mid-July, the lake is cold-monomictic and thermally stratified during the ice-covered season (Nolan et al., 2003).

3 Methods

The analytical work conducted for this study focused on the interval 19.63–17.94 m below lake floor (blf) in the composite ICDP 5011-1 core from Lake El'gygytgyn, encompassing the thermal optimum of MIS 11 and the transition from MIS 12.

Fourier transform infrared spectroscopy (FTIRS) has been used for high-resolution (2.5 mm intervals) reconstruction of biogenic silica (BSi) and total organic carbon (TOC). The principles of the method and analytical procedures are described in detail by Vogel et al. (2008), Rosén et al. (2011), and Meyer-Jacob et al. (2012). Concentrations of BSi and TOC in this study are based on internal calibration models in accordance with Vogel et al. (2008) and specifically developed for sediments of ICDP site 5011-1 (Meyer-Jacob et al., 2012). Sediment samples were freeze-dried and ground to a particle size $< 63\,\mu m$ prior to the FTIR measurement. Sample material weighing 0.011 g was then mixed with 0.5 g of oven-dried spectroscopic grade potassium bromide (KBr) (Uvasol, Merck Corp.) and subsequently homogenized using a mortar and pestle. A Bruker IFS 66v/S FTIR spectrometer (Bruker Optics Inc.) equipped with a diffuse reflectance accessory (Harrick Inc.) was used for the analysis under vacuum (4 mbar) conditions. Each sample was scanned 64 times at a resolution of $4\,cm^{-1}$ (reciprocal centimeters) for the wavenumber range from 3750 to $400\,cm^{-1}$ or from 2666 to 25 000 nm. The FTIR analysis was performed in a temperature-controlled laboratory ($25 \pm 0.2\,^{\circ}C$), in which the samples were stored at least 5 h prior to the measurement to achieve constant measuring conditions. Baseline correction and multiplicative scatter correction (MSC) were applied to normalize the recorded FTIR spectra and to remove spectral variations caused by noise (Geladi et al., 1985; Martens and Næs, 1989). Partial least squares (PLS) regression was used to develop calibration models between

FTIR spectral information and the corresponding conventionally measured concentrations of BSi and TOC.

The content of total organic carbon (TOC) in the 5011-1 core composite was determined in steps of 2 cm with a DimaTOC carbon analyzer (Dimatec Corp.) in aqueous suspension based upon the difference between total carbon and total inorganic carbon. Total nitrogen (TN) concentrations were measured with a Vario Micro Cube combustion CNS elemental analyzer (VARIO Co.).

Titanium (Ti), manganese (Mn), and iron (Fe) count rates were determined on core halves using an X-ray fluorescence (XRF) core scanner (ITRAX, Cox Ltd., Sweden), equipped with a Mo-tube, which was set to 30 kV and 30 mA. XRF scanning was performed at 2 mm resolution using an integration time of 10 s per measurement. Details of the scanning and data correction are given in Melles et al. (2012) and Wennrich et al. (2012). For a better comprehensibility, in the following, the Mn/Fe ratio is presented as the ratio of Mn to Fe integrals multiplied by a factor of 1000.

The development of the age model for the composite core ICDP 5011-1 followed a 3-step approach based on magnetostratigraphy and tuning of proxy records to the LR04 stack (Lisiecki and Raymo, 2005) and the summer insolation at 65° N (Laskar et al., 2004) and is outlined in detail in Melles et al. (2012) and Nowaczyk et al. (2012). The temporal resolutions in the interval 19.63–17.94 m, covering the period between 393.5–431.3 ka, are 0.025–0.122 kyrs for high-resolution (2.5 mm) FTIRS-BSi and FTIRS-TOC, 0.20–0.96 for low resolution (2 cm) TOC and TN, 0.0198–0.0974 kyrs for Ti and Mn/Fe, and 0.6–2.9 kyrs for palynological data and biome-derived climate variables.

4 Results and discussion

4.1 Proxy interpretation

4.1.1 In-lake productivity indicators (BSi, TOC, TOC/TN)

BSi in lakes is formed by silicious microfossils, mostly diatom frustules, and hence, is often used as a proxy for primary production. In Lake El'gygytgyn, diatoms are the main primary producers and well preserved in the sediment record (Snyder et al., 2012; Cherepanova et al., 2007; Cremer and Wagner, 2003). Aquatic production is primarily controlled by the availability of light, and thus, the duration of ice cover at Lake El'gygytgyn, but also the amount of nutrients delivered from the catchment and through recycling from the sediment-water interface. Nutrient supply from the catchment is dependent on the rate of chemical weathering in the active layer of the permafrost, on the formation of soils, and vegetation cover. Nutrient recycling from the sediment-water interface and its transport into the photic zone is promoted by full mixis of the water column during periods when the lake ice cover disintegrates. In summary, all major factors controlling primary productivity, and thus, BSi flux to the sediment at Lake El'gygytgyn are strongly tied to temperature variability.

The amount of TOC in Lake El'gygytgyn sediments also depends on lacustrine primary production, but is additionally controlled by organic matter (OM) supply from the catchment and decomposition in the lake (Melles et al., 2007, 2012). To distinguish between autochthonous versus allochthonous sources of OM we make use of the TOC/TN ratio with values < 10 typically indicative of in situ produced OM and values > 20 typically indicative for terrestrial OM (Meyers and Ishiwatari, 1993).

4.1.2 Clastic input and stratification indicators (Ti, Mn/Fe)

Ti is a relatively immobile lithogenic element that occurs in a variety of mineral phases, widely independent on grain size. Therefore, it is commonly used as an indicator for allochthonous clastic sediment supply. The amounts of Fe and Mn are also related to clastic input, but both elements are also sensitive to redox changes in aquatic environments (cf. Davison, 1993). Mn is more soluble under reducing conditions than Fe, making it possible to use the Mn/Fe ratio as a paleo-redox indicator with low values typically implying more reducing conditions (cf. Davison, 1993).

4.2 Lithology

In close correspondence with Melles et al. (2012), the core interval between 19.63–17.94 m can be subdivided into three lithofacies with distinct differences in sediment structure, composition, and color.

4.2.1 Lithofacies A

Lithofacies A occurs in 18.02–17.94 and 19.63–19.16 mblf (Fig. 2) and is defined by the presence of fine clastic laminations on millimeter to sub-millimeter scale and by colors ranging from dark gray to black. Because the core interval investigated here comprises transitions to lithofacies B, clastic laminations are rather weakly expressed and are intercalated with more homogenous light gray to brown intervals (17.97–17.94, 19.34–19.32, 19.56–19.45 m blf), which we assigned for this paper to lithofacies A. Laminae, when present, are characterized by upward grading from silt to clay. The grain size distribution is dominated by silt (68–70 vol %) and clay (25–31 vol %) with minor concentrations of sand-sized particles (0.5–5 vol %; Francke et al., 2012). TOC concentrations < 1 %, BSi concentrations < 15 %, a TOC/TN ratio of 5–10, Ti count rates between 1000–2100, and a Mn/Fe ratio of < 10 are further characteristics of lithofacies A (Fig. 2).

Based on its lithological and compositional characteristics, lithofacies A has previously been assigned to reflect pronounced glacials/stadials and perennial lake-ice cover (Melles et al., 2007, 2012; Frank et al., 2012). These settings exclude mixing of the water column, which, in turn, reduces oxygen availability in the water column. The

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low oxygen availability and reducing conditions in the water column are expressed in overall low Mn/Fe values and the preservation of primary laminations due to the absence of any bioturbation. Low TOC and BSi concentrations and high Ti count rates (Fig. 2) point to an overall low-productivity environment. Likewise the low TOC/TN ratios indicate that OM predominantly originates from aquatic sources. Millimeter-scale laminations with upward grading are likely a result of pulsed fluvial sediment input derived from a sparsely vegetated catchment and/or exposed shelf areas during lake-level lowstands. Sediment suspension plumes entering the lake basin through small moats around the margins of the ice-covered lake would explain the silt deposition, followed by clay when the inflow diminishes and the remaining suspension load settles (Melles et al., 2012).

4.2.2 Lithofacies B

Lithofacies B, occuring in 18.20–18.02 and 19.14–19.01 mblf, appears relatively homogenous with finely dispersed vivianite crystals and lack of distinct sedimentary structures (Fig. 2). Colors gradually change through this facies between gray and light brown. Probably as a result of its transitional character between lithofacies A and C, commonly occurring greenish bands described as a distinct feature of lithofacies B by Melles et al. (2012) are lacking. The grain size distribution is dominated by silt (68–71 vol %) and clay (25–28 vol %) with minor concentrations of sand-sized particles (2–5 vol %; Francke et al., 2012). TOC concentrations of 0.5–1 %, BSi concentrations of 15–30 %, a TOC/TN ratio of 5–10, Ti count rates between 700–1300, and a Mn/Fe ratio of 10–15 are further characteristics of lithofacies B (Fig. 2)

Lithofacies B is the most abundant facies in the ICDP Site 5011-1 record from Lake El'gygytgn and is interpreted as representing varying interglacial/interstadial climate and environmental conditions (Melles et al., 2012). Gradual color changes suggest alternating sedimentary sources and/or depositional processes. The overall massive nature of the sediments along with a slightly elevated Mn/Fe ratio indicate mixing during summer ice break-up and regularly occurring oxygen replenishment of the water

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column, thus allowing for bioturbation (Melles et al., 2007). Elevated but variable TOC and BSi concentrations along with a TOC/TN ratio < 10 suggests significant productivity and a predominantly autochthonous origin of OM.

4.2.3 Lithofacies C

Lithofacies C, occurring in 18.98–18.20 mblf, is defined by its distinctly reddish-brown color and the presence of faint pale, millimeter to centimeter-scale laminations (Fig. 2). Vivianite crystals occur finely dispersed and in form of discrete layered agglomerations. Laminae and bandings in lithofacies C are distinctly different from those observed in lithofacies A. SEM images indicate that the 1–2 mm thick pale bands delineating the laminations in lithofacies C reflect a transition from poorly sorted silty sediment to a nearly homogenous band of finer particles with only a few scattered silt-sized clasts. The basal contact of the pale bands is typically sharp, although not planar when viewed at the grain scale. The pale bands gradually transit into the background style of sediments, which persist until the next band occurs (Melles et al., 2012). Another feature distinct for the investigated core section is the occurrence of discrete millimeter-scale dark bands rich in OM in 18.83–18.69 mblf. The grain size distribution is dominated by silt (68–71 vol %) and clay (23.5–27 vol %). The concentrations of sand-sized particles is slightly higher (3–6 vol %) compared to lithofacies A and B (Francke et al., 2012). TOC concentrations range between 0.5 and 3.4 % with maximum values centered at 18.34 and in 18.80–18.72 mblf (Fig. 2). BSi concentrations range between 20 and 55 % with maximum values (> 35 %) occurring in 18.79–18.34 mblf and peak values centered at 18.49 mblf. The TOC/TN ratio shows values between 7–25 with a distinct peak at 18.34 m. Ti count rates are generally < 1000 with lowest values < 500 between 18.79–18.31 mblf (Fig. 2). The Mn/Fe ratio shows values well above 10 with peak values exceeding 20 between 18.76 and 18.36 mblf (Fig. 2).

The reddish-brown color indicative of lithofacies C in combination with a high Mn/Fe ratio suggests oxidation of bottom sediments by a well-ventilated water column. As for lithofacies B, this coincides with elevated summer temperatures and seasonal

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ice break-up leading to full mixis of the water column. The origin of the banding in lithofacies C, reflecting the lack of bioturbation, is not yet fully understood. One possibility is variable fluvial sediment supply and the absence of endobenthic fauna due to seasonal oxygen depletion of the bottom water. This could take place in wintertime, when degradation of OM takes place in a stratified water column beneath the lake ice (Melles et al., 2012). Highest TOC and BSi concentrations in combination with lowest Ti count rates imply strongest productivity, inhibited flux and/or dilution of clastic matter by biogenic components during deposition of lithofacies C. Higher TOC/TN values compared to lithofacies A and B point to an increased contribution of terrestrial sources of OM. However, with the exception of the maximum centered at 18.34 mblf, it can be assumed that OM in lithofacies C is primarily of aquatic origin.

4.2.4 Mass movement deposits

Mass movement deposits occurring at ca. 19.01–18.98 and 19.16–19.14 mblf are indicated by an apparent sharp base and an upward grading from fine sand to silt. These deposits, according to the classification of Kukkonen et al. (2012), originate from turbidity currents. Nevertheless, erosion of previously deposited sediments is thought to be minimal (Melles et al., 2007, 2012). In difference to all mass movement deposits thicker then 5 cm, these two thin layers were not omitted from the core composite of ICDP Site 5011-1 (Melles et al., 2012).

5 Interpretation

5.1 Climate and environmental evolution at Lake El'gygytgyn during MIS 11

This Section aims at documenting climate and environmental change at Lake El'gygytgyn during the period 430–395 ka covering the thermal optimum of MIS 11 (424–374 ka) in light of available high-resolution datasets as well as previously

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published palynological data and a biome-based climate reconstruction (Melles et al., 2012).

Overall low BSi and TOC concentrations along with a lithology characterized by lithofacies A sediment types, high Ti count rates, and a low Mn/Fe ratio point to a low productivity environment and perennial ice coverage on the lake for the period ca. 430–425 ka (Fig. 3a, b, d, e). Pollen assemblages imply a gradual replacement of herb-dominated Arctic tundra and establishment of forest-tundra and northern larch taiga environments with alder and birch shrubs. Correspondingly, mean temperatures of the warmest month (MTWM; Fig. 3i) and annual precipitation (PANN; Fig. 3k) gradually increase from ca. 4–12 °C and ca. 200–400 mm, respectively, between ca. 430–425 ka (Melles et al., 2012). Emplacement of forest-tundra probably started in sheltered south-exposed areas of the crater and its surroundings and did not cover the whole catchment area. A patch like vegetation pattern and soil stabilization only in confined areas is supported by relatively high Ti count rates indicating high fluxes of allochthonous clastic matter. The lagged response of in-lake productivity in comparison to the gradual establishment of forest-tundra in the vicinity of the lake may be explained by a delay in nutrient delivery from the catchment. We assume that soil formation, and thus, formation of nutrient-delivering substrates only took place in areas with a denser vegetation cover. These areas were probably sparse within the confined crater catchment during this initial warming phase, and thus, nutrient fluxes did not increase significantly. A suppressed flux of terrestrial-derived nutrients during this phase is supported by low TOC/TN values (Fig. 3c) and low concentrations of terrestrial biomarkers (D'Anjou et al., 2012). In addition, nutrient replenishment through remobilization from the sediment-water interface may have been restricted to years with full disintegration of the lake-ice cover. This is confirmed by a low Mn/Fe ratio (Fig. 3e). However, the occurrence of light brown homogenous sediments intercalated with darker layered and laminated sediments in lithofacies A and the transition to lithofacies B sediment types in this time interval (Figs. 2 and 3) imply that full mixis of the water column may have occurred during restricted periods allowing for bioturbation and oxidation of the sediments.

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BSi and TOC concentrations show a significant increase between 425–424 ka marking the beginning of enhanced in-lake productivity at Lake El'gygytgyn at the beginning of MIS 11 (Fig. 3a and b). Deposition of the light brown, homogeneous lithofacies B (Figs. 2 and 3) along with a slight increase in the Mn/Fe ratio (Fig. 3e) imply annual mixis and a well-oxygenated water column. The increase in in-lake productivity is matched by a concomitant increase in spruce pollen percentages and a decrease in grass and other herb pollen percentages (Fig. 3; Melles et al., 2012). A somewhat stronger flux of OM and a suppressed flux of allochthonous clastic matter resulting from a denser vegetation cover in the confined crater catchment is expressed by a slight increase of the TOC/TN ratio and a decrease in Ti count rates, respectively (Fig. 3c and d). Biomarkers indicative of terrestrial OM do, however, not show an observable contemporaneous increase (D'Anjou et al., 2012). In close correspondence to the observed changes in in-lake productivity and vegetation, MTWM increases to ca. 15 °C and PANN to > 600 mm (Melles et al., 2012; Fig. 3i and k), thus, completing a coherent picture of a significant climate amelioration in a time span of only ca. 1 kyr at Lake El'gygytgyn. Following the climate amelioration between ca. 425–424 ka, a setback to a slightly less productive environment and a somewhat colder and drier climate between ca. 424–420 ka is indicated by a decrease in in-lake productivity indicators, spruce pollen contents, fluxes of terrestrial OM, MTWM, PANN, and an increase in the flux of allochthonous clastic matter (Fig. 3).

A significant increase in in-lake productivity indicators, tree and shrub pollen contents, MTWM, and PANN at ca. 420–418.5 ka marks the beginning of relatively stable, long-lasting optimum climate conditions of MIS 11 at Lake El'gygytgyn, which lasted from ca. 418.5 to ca. 402 ka (Fig. 3). BSi shows only minor fluctuations and reaches maximum concentrations of more than 50 % at ca. 418.5–402 ka (Fig. 3a). These values are unmatched in the remaining record from ICDP site 5011-1 (Meyer-Jacob et al., 2012) making diatom frustules the main sediment component (Figs. 2 and 3a). This in combination with a high diatom diversity (Snyder et al., 2012), high TOC concentrations, a high Mn/Fe ratio, low Ti count rates, and a lithology characterized by brown oxidized sediments (Figs. 2 and 3) indicates a very productive lake environment with annual ice break up and full mixis of the water column. High in-lake productivity during this period is a result of mild and moist climate conditions, as indicated by MTWM ranging between ca. 12–15 °C and PANN ranging between ca. 450–700 mm (Melles at al., 2012; Fig. 3i and k). Nutrient fluxes from the catchment were likely promoted by the development of soils as a result of the emplacement of dark coniferous forests with high amounts of spruce and interspersed patches of *Sphagnum* bogs (Melles et al., 2012; Fig. 3g). Higher fluxes of catchment-derived nutrients are also indicated by a slightly higher TOC/TN ratio (Fig. 3c) and a significant increase in terrestrial biomarker concentrations (D'Anjou et al., 2012).

Despite the coherent picture of stable optimum climate and environmental conditions between ca. 418.5–402 ka, subtle variability in the proxy and lithological record point to subtle environmental variability. Coinciding peaks in MTWM, PANN, spruce pollen, and TOC (Fig. 3b, g, i, k), together with the occurrence of OM-rich lenses in the sediment record between 418–415.5 ka (Fig. 2), indicate the warmest and wettest phase at Lake El'gygytgyn during MIS 11. Interestingly, the occurrence of OM-rich lenses and high TOC concentrations cannot be explained by a significant increase in in-lake productivity or fluxes of terrestrially derived OM alone. BSi concentrations (Fig. 3a) and the concentration of individual diatom taxa (Snyder et al., 2012) as well as the TOC/TN ratio (Fig. 3c) do not show significant fluctuations coinciding with increased TOC concentrations (Fig. 3) and lithological peculiarities (Fig. 2) between ca. 418–415.5 ka. Thus it seems likely that elevated TOC concentrations and occurrences of OM rich lenses are an effect of enhanced preservation of OM due to oxygen depletion in the water column, which is thought to mainly occur during the ice-covered season. The particularly pronounced effect of OM preservation seen during this period might have in addition been promoted by the mild and moist climate conditions (Melles et al., 2012; Fig. 3). A higher lake level and flooded shelf areas would have led to a more effective warming of surface waters. One could thus further assume that the lake might have, following full mixis of the water column that under recent conditions occurs shortly after

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ice break-up, developed a more sustained temperature stratification of the water column. This in combination with an overall denser vegetation cover, that is characterized by a high amount of tall growing spruce stands between ca. 418–415.5 ka (Fig. 3g), along the shoreline might have reduced wind drag on the water surface and further supported temperature stratification after ice break up.

A gradual decrease in in-lake productivity indicators, tree and shrub pollen, MTWM, and PANN, and a gradual increase of allochthonous clastic matter commencing between ca. 402–398 ka points to a gradual climate deterioration at Lake El'gygytgyn over a period of ca. 4 kyr (Fig. 3). A remarkable feature during this phase is the concomitant occurrence of peak TOC and TOC/TN values centered at ca. 401 ka, reaching up to 3.4 % and 25, respectively (Fig. 3b, c). These peak values point to a significant input of terrestrial OM, which can be interpreted as a result of enhanced soil erosion. Highest diatom diversity during this period supports a high availability of nutrients (Snyder et al., 2012) potentially as a result of a stronger flux from the erosion of catchment soils. Interestingly, terrestrial plant macrofossils or other lithological peculiarities are not observable in thin sections and terrestrial biomarker concentrations show no significant increase (D'Anjou et al., 2012) in the respective interval. Enhanced soil erosion around 401 ka could be a result of (1) stronger precipitation during summer months, (2) forest clearance and soil destabilization as a result of climate deterioration or (3) a combination of both. In light of the available low-resolution pollen data with high percentages of spruce, high MTWM, and high PANN around 401 ka (Fig. 3f, g, i, k) it seems that an increase in precipitation during summer months is the most likely cause for enhanced soil erosion. From 398 ka all proxies and pollen spectra indicative for open grass-sedge habitats (Melles et al., 2012; Fig. 3) suggest a return to glacial/stadial conditions at Lake El'gygytgyn comparable to those at the MIS 12/11 transition (Fig. 3).

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5.2 The MIS 11 climate record from Lake El'gygytgyn viewed in a global context

Comparison of the Lake El'gygytgyn climate record with other globally distributed climate records and the Northern (65° N) and Southern (65° S) Hemisphere summer insolation (Laskar, 2004) suggests intriguing similarities but also differences with respect to the duration, overall stability, and short-term climate fluctuations during MIS 11 (Fig. 4).

Between ca. 425–398 ka the investigated proxies and lithological peculiarities indicate high productivity, annual ice break up and full mixis of the water column, and a vegetation characterized by dark coniferous forests. This suggests that full interglacial conditions appeared for 27 kyrs at Lake El'gygytgyn during MIS 11 (Figs. 3 and 4). The beginning and duration of these conditions compares well with the terrestrial records from Lake Baikal (ca. 424–396 ka; Prokopenko et al., 2010) and the EPICA Dome C (EDC) ice core record (ca. 424–394 ka; EPICA community members, 2004). The slightly shorter duration inferred for Lake El'gygytgyn may be a result of age-model discrepancies between the records, which can easily be in the order of several kyrs (EPICA community members, 2004; Prokopenko et al., 2010; Pol et al., 2011; Nowaczyk et al., 2012). The long duration of full interglacial conditions during MIS 11 is commonly explained as being a result of low-amplitude insolation variations and long-lasting high CO_2 concentrations (Loutre and Berger, 2003; Raynaud et al., 2005; Fig. 4). These conditions prevented Northern Hemisphere ice sheets from growing and are thought to have led to a partial or even complete disintegration of the Greenland (GIS) and West Antarctic Ice Sheets (WAIS; Willerslev et al., 2007; Raymo and Mitrovica, 2012), further promoting interglacial conditions through positive albedo feedbacks.

The indicated long-term stability of climate and environmental conditions during MIS 11 at Lake El'gygytgyn is another striking feature, which is also apparent at Lake Baikal (Karabanov et al., 2003; Prokopenko et al., 2010) and in the EDC ice core record

(EPICA community members, 2004; Pol et al., 2011). In contrast, marine sea surface temperature (SST) records from the Atlantic and Pacific oceans show a somewhat stronger variability (Fig. 4e, f, g, h; Martrat et al., 2007; Schaefer et al., 2005; Kandiano and Bauch, 2007; Li et al., 2011). The contrasting patterns between the high latitude terrestrial and mid-latitude marine sites might be related to atmospheric and ocean circulation patterns specific for this type of interglacial conditions (Melles et al., 2012). Based on the coincidence of super interglacial conditions documented in the Lake El'gygytgyn record with a diminished WAIS, and open water conditions in the Ross embayment, Melles et al. (2012) suggest a reduction of Antarctic Bottom Water (AABW) formation and upwelling in the northern North Pacific during MIS 11. In consequence, surface-water stratification in the northern North Pacific during MIS 11 may have resulted in higher SSTs, raising air temperatures and precipitation rates over adjacent land masses via effects on the dominant pressure patterns (Siberian High and Aleutian Low; Melles et al., 2012). Interestingly, a steep SST gradient from north to south as a result of continued melting of ice sheets, surface-water freshening, and concomitant effects on ocean and atmospheric circulation has also been suggested for the North Atlantic during MIS 11 (Kandiano et al., 2012 and references therein). However, in order to detangle the underlying mechanisms behind the observed differences at marine and terrestrial sites more detailed studies incorporating terrestrial and marine records from additional globally distributed sites are required.

Subtle deviations from the overall stable climate and environmental conditions at Lake El'gygytgyn are centered between 425–424, 424–420, 418–415.5, and at 401 ka. Of these, the periods between 425–424, 418–415.5, and at 401 ka are characterized by deviations towards warmer and the one between 424–420 ka towards colder climate conditions (Figs. 3 and 4). The initial warming between 425–424 ka followed by a cold reversal between 424–420 ka appears to be matched by a similar contemporaneous pattern in the Lake Baikal BSi record (Fig. 4d; Karabanov et al., 2003) and the EDC ΔT record (Fig. 4i; EPICA community members, 2004). An early warming phase followed by a period of colder climate conditions in the Northern Hemisphere could be the

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expression of a MIS 11 analogue for the Bølling/Allerød (B/A) – Younger Dryas (YD) climate repercussion. Similarly, early warming followed by a cold reversal in the EPICA Dome C ΔT record (Fig. 4i) has been proposed to be a possible MIS 11 analogue for the Antarctic cold reversal (ACR; EPICA community members, 2004). The indicated coeval timing of the B/A-like event at lakes El'gygytgyn and Baikal with the ACR-like event (Fig. 4) makes it tempting to propose a similar underlying mechanism for climate evolution during the MIS 11/12 transition as has been proposed for the last deglaciation (Blunier et al., 1997). However, the error of the respective age models makes a direct correlation of the observed events rather speculative.

The warm period between 418–415.5 ka, suggested as being the warmest period during MIS 11 at Lake El'gygytgyn, appears to be unmatched in the other climate records (Fig. 4). At Lake Baikal this period is characterized by somewhat colder conditions (Fig. 4d; Karabanov et al., 2003; Prokopenko et al., 2010). Also marine SST records (Fig. 4e, f, g, h; Schaefer et al., 2005; Martrat et al., 2007; Kandiano and Bauch, 2007; Li et al., 2011) and the EDC ΔT record (Fig. 4i; EPICA community members, 2004) do not show deviations towards warmer than average MIS 11 conditions (Fig. 4). The lacking evidence of peak warm periods in the other climate records along with a lower Northern Hemisphere summer insolation (Fig. 4m; Laskar, 2004) and no significant increase in greenhouse gas concentrations (Fig. 4l; Siegenthaler et al., 2005; Loulergue et al., 2008) suggest the peak warm period at Lake El'gygytgyn between 418–415.5 ka to be a regional phenomenon. Possible explanations for this peak warm period could be the combined effects of the establishment of stratification in the northern North Pacific and intrusions of warmer water into the Arctic Ocean as suggested by Melles et al. (2012). The establishment of stratification in the northern North Pacific would require a reduction in AABW formation through ice-free conditions in the Ross embayment and at least a partial disintergration of the WAIS (Melles et al., 2012). Enhancement of water intrusions into the Arctic Ocean would require a substantial rise of the relative sea level as result of the disintegration of the WAIS and the GIS (Melles et al., 2012). Interestingly, the period between 418–415.5 ka is characterized by a 0.34

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per mill decrease (3.75 per mill/418 ka−3.41 per mill/415 ka) in the stacked LR04 benthic $\delta^{18}O$ record (Fig. 4k; Lisiecki and Raymo, 2005) equivalent to a ca. 30 m rise in relative sea level, when using a conversion factor of 0.11 per mill/10 m (Fairbanks and Matthews, 1978). However, minimum $\delta^{18}O$ values of 3.11 per mill at ca. 405 ka in the LR04 record (Fig. 4k; Lisiecki and Raymo, 2005) and radiometrically dated evidence for a MIS 11 sea-level highstand 21 m higher than present from Bermuda at ca. 400 ka (Olson and Hearty, 2009) suggest that sea level rose by another ca. 30 m between 415−400 ka. Therefore, it can be assumed that the GIS and WAIS had a comparable or even larger volume as today between 418−415.5 ka, thus making stratification of the northern North Pacific and intrusions of warmer waters into the Arctic Ocean unlikely as an explanation for peak warm conditions at Lake El'gygytgyn during this period, albeit without excluding these processes to have caused the exceptional climate at Lake El'gygytgyn during the entire MIS 11. Hence, the reason for peak warm conditions at Lake El'gygytgyn between 418−415.5 ka remains elusive.

The increase in MTWM and PANN associated with a significant increase in soil erosion centered at 401 ka (Figs. 3 and 4) and interpreted as being a result of enhanced summer precipitation at Lake El'gygytgyn can probably be regarded as a very restricted regional anomaly. Evidence for a similar climate anomaly is lacking from marine and ice core records (Fig. 4). On the other hand, a similar rainfall anomaly and enhanced soil erosion event centered at ca. 400 ka has also been identified at Lake Baikal (Prokopenko et al., 2010). Events with a similar geochemical signature during the MIS 4–2 interval at Lake Baikal have previously been linked to Heinrich events/Bond cycles (Prokopenko et al., 2001, 2010). The rainfall anomaly recorded at lakes El'gygytgyn and Baikal around ca. 400–401 ka is associated with rather mild climate conditions and a minimum in iceberg discharge into the North Atlantic (McManus et al., 1999; Kandiano et al., 2010), as would be the case during Heinrich-events, thus ruling a cooling of North Atlantic surface waters and associated changes in atmospheric circulation patterns out as possible explanation. The short-lived character of the anomaly

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in combination with its implied extraregional character, however, point to a change of internal factors of the climate system as reason for the anomaly.

A gradual climate deterioration commencing at ca. 400 ka associated with a subtle decrease in summer insolation (Laskar, 2004) and slow ice build up on the Northern Hemisphere landmasses (Imbrie et al., 1984, 1993; Lisiecki and Raymo, 2005) is a coherent feature visible in nearly all marine and terrestrial records during MIS 11 (Fig. 4). In contrast, other interglacials, for example MIS 5e, show a more rapid climate deterioration towards their end, at Lake El'gygytgyn (Cunningham et al., 2012) as well as at other globally distributed sites (cf. Sirocko et al., 2005).

6 Conclusions

Detailed evaluation of lithological, geochemical, and palynological data provide further evidence for the exceptional character of the MIS 11 "super interglacial" at Lake El'gygytgyn and in the Arctic. Its climate stability, duration, and a gradual climate deterioration towards the end in combination with its outstanding appearance as one of the warmest interglacials in the Lake El'gygytgyn record during the entire Quaternary (Melles et al., 2012) make MIS 11 unique. The close correspondence of the climate signal recorded at Lake El'gygytgyn with other globally distributed sites emphasize the value of the Lake El'gygytgyn record as the most promising archive for the long-term climate history in the terrestrial Arctic.

Despite the overall stability of climate and environmental conditions at Lake El'gygytgyn, subtle deviations from the average have been identified for the periods 425–424 (warming), 424–420 (cooling), 418–415.5 (peak warm), and around 401 ka (precipitation anomaly). Correlation of these climate swings at Lake El'gygytgyn to other globally distributed sites is hampered because of the apparent large errors of individual age-models. It can, however, be noted that the warm event at 425–424 ka followed by a cooling at 424–420 ka may be the expression of a B/A-YD- like climate repercussion that occurred during the MIS 12/11 transition similar to the last MIS 2/1 deglaciation. The precipitation anomaly identified at 401 ka at Lake El'gygytgyn may be correlated to a similar contemporaneous anomaly at Lake Baikal implying a possible extraregional character of this event. In contrary, peak warm conditions recorded between 418–415.5 ka at Lake El'gygytgyn seem to be a regional phenomena. In order to better define the nature of these relatively short-termed climate variations it would be valuable to conduct more detailed highly-resolved palynological investigations on the MIS 11 sediment succession from Lake El'gygytgyn.

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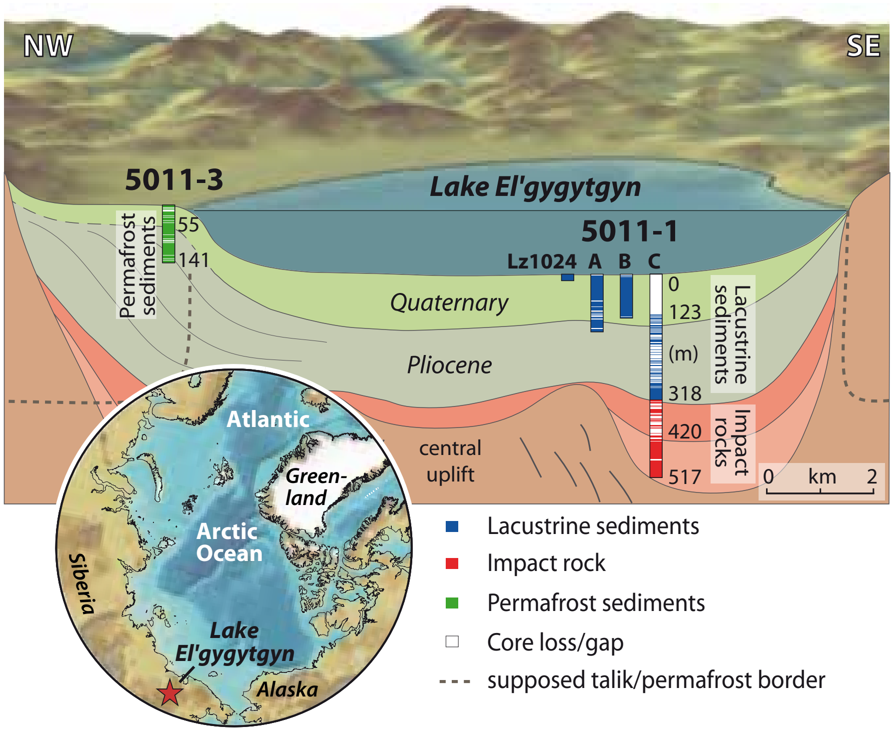

Fig. 1. Location of Lake El'gygytgyn in North-Eastern Russia (inserted map) and schematic cross-section of the El'gygytgyn basin stratigraphy showing the locations and recoveries of ICDP Sites 5011-1 and -3 (modified after Melles et al., 2012).

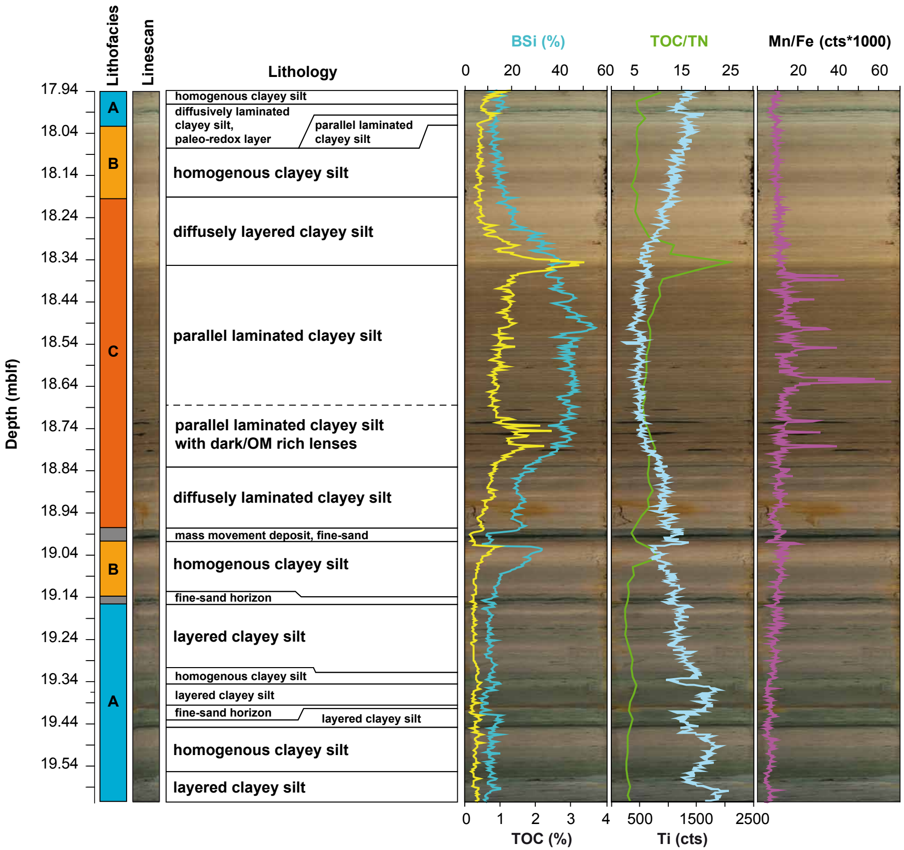

Fig. 2. Lithofacies classification, color linescan, lithological description and geochemical indicators (BSi = biogenic silica; TOC = total organic carbon; TN = total nitrogen; cts = counts) underlain by stretched line scan images for the interval 17.94–19.63 m from the core composite of ICDP Site 5011-1 comprising the MIS 12/11 transition and MIS 11.

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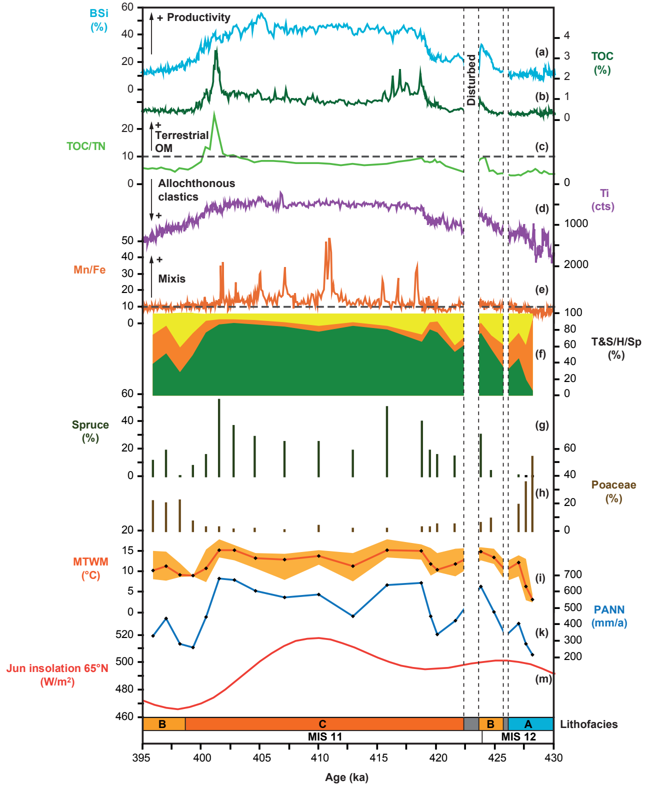

Fig. 3. Indicators for climate and environmental change at Lake El'gygytyn during for the period 430–395 ka covering the MIS 12/11 transition and full interglacial conditions of MIS 11. **(a)** biogenic silica (BSi) concentrations, **(b)** total organic carbon (TOC) concentrations, **(c)** total organic carbon/total nitrogen (TOC/TN) ratio, **(d)** Ti counts (cts), **(e)** Mn/Fe ratio (Melles et al., 2012), **(f)** percentages of trees (T) and shrubs (S; green shading), herbs (H; orange shading), and spores (Sp; yellow shading; Melles et al., 2012), **(g)** spruce (*Picea*) pollen percentages (Melles et al., 2012), **(h)** grass (*Poaceae*) pollen percentages (Melles et al., 2012), **(i)** mean temperature of the warmest month with orange shaded error range (MTWM; Melles et al., 2012), **(k)** annual precipitation (PANN; Melles et al., 2012), **(m)** summer (june) insolation at 65° N (Laskar, 2004), lithofacies, and MIS 12/11 boundary according to Lisiecki and Raymo, 2005. Vertical dashed lines mark the boundaries of disturbed sections.

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Detailed insight into Arctic climatic variability during MIS 11

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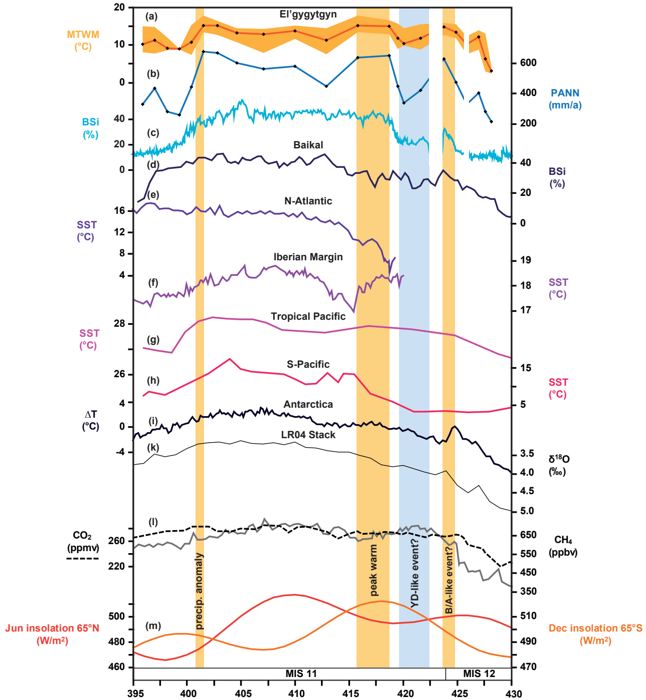

Fig. 4. Comparison of Lake El'gygytgyn climate indicators with other globally distributed climate records between 430–395 ka. **(a)** Mean temperature of the warmest month (MTWM) from Lake El'gygytgyn (Melles et al., 2012), **(b)** annual precipitation (PANN) from Lake El'gygytgyn (Melles et al., 2012), **(c)** biogenic silica (BSi) concentrations from Lake El'gygytgyn, **(d)** biogenic silica (BSi) concentrations from Lake Baikal (Prokopenko et al., 2006), **(e)** sea surface temperatures (SST) from the N-Atlantic (Kandiano and Bauch, 2007), **(f)** SST's from the Iberian Margin/N-Atlantic (Martrat et al., 2007), **(g)** SST's from the tropical Pacific (Li et al., 2011), **(h)** SST's from the S-Pacific (Schaefer et al., 2005), **(i)** temperature anomaly relative to the mean of the last 1000 yr (ΔT) from the EPICA Dome C ice core record (Jouzel et al., 2007), **(k)** LR04 benthic oxygen isotope stack (Lisiecki and Raymo, 2005), **(l)** CO_2 (Siegenthaler et al., 2005) and CH_4 (Loulergue et al., 2008) concentrations from the EPICA Dome C ice core record, **(m)** summer insolation at 65° N (June) and 65° S (December; Laskar, 2004). Orange shading highlights warm and blue shading cold events in the Lake El'gygytgyn record. B/A = Bølling/Allerød, YD = Younger Dryas.