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The paleoclimatology of Lake Baikal: A diatom synthesis and prospectus

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Abstract

The paleoclimatic archive held in Lake Baikal sediments is of significant importance, given the lake's position in one of the world's most continental regions where there are few continuous, high quality records spanning the Quaternary. Here I review diatom and associated biogenic silica records from Lake Baikal sediments and provide a paleoclimatic synthesis of changes at various timescales over the Quaternary. I initially highlight major climatic and hydrological aspects of Lake Baikal, as understanding the contemporary system (both regionally and within the lake) are fundamental to understanding past change interpreted from the sedimentary archive. In this respect, special attention is given to factors that can affect the integrity of the diatom record, most notably dissolution processes. These mechanisms are likely to have had a relatively greater impact on the preservation of diatom valves during glacial periods because of overall lower diatom productivity. Lower diatom numbers and relative increased dissolution during cold periods explains the lack of diatoms and low biogenic silica concentrations found in the lake sediments during glacial periods. The biogenic record highlights the nature of the 100 ka cycle especially during the last 800 ka, although there is also a strong precessional component. Further work is needed to reassess biological responses in Lake Baikal with respect to different orbital forcing mechanisms, together with their impacts on evolution and speciation of diatoms. The biological record from Lake Baikal confirms that the last interglacial in central Asia lasted approximately 10.5 ka. Productivity in the lake (as inferred from diatom biovolume accumulation rates) exhibits millennial-scale variability with the occurrence of centennial-scale reductions in diatom biomass throughout the last interglacial period. The most severe reduction in diatom biomass (at c. 120 ka BP) is concurrent with millennial-scale cooling in the North Atlantic region. Links to changes in North Atlantic ocean thermohaline circulation via teleconnections are also evident in the nature of the abrupt ecological changes in the lake throughout the last 60 ka, linked to ice-rafting into the North Atlantic, otherwise known as Heinrich events. New robust radiocarbon chronologies for sediments deposited during the late glacial and Holocene in Lake Baikal allow detailed, multi-decadal records to be constructed for the last 14,000 years. Cooling events associated with millennial-scale cycles are also apparent in the Lake Baikal record, and both the diatom record and oxygen isotope record of the diatom silica highlight that biological responses to these abrupt events are almost simultaneous. Comparisons made between Lake Baikal records with others worldwide highlights that many of the Holocene cooling events are associated with melt-water outburst from the Laurentide ice sheet, and changes in solar insolation. During the last 1000 years, snow cover on Lake Baikal has been inferred from past diatom assemblages, and is closely linked to weakening of the North Atlantic Oscillation, allowing increasing intensity of the Siberian High to develop and during the 17th and 18th centuries. In the last 150 years, diatom species have been shown to be sensitive indicators of recent warming. However, impacts from future global

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warming will be complex, and are likely to impact not only on the balance between endemic and cosmopolitan diatoms throughout the lake, but on the balance between siliceous and non-siliceous algae, and sources of primary productivity.

Keywords: paleoclimate; Quaternary; diatoms; biogenic silica; dissolution; oxygen isotope analysis of diatom silica; central Asia; Lake Baikal; last interglacial; millennial-scale variability; MIS 3; Holocene; last 1000 years

1. Introduction and scope

Approximately 2.75 million years ago, major changes in the Earth's climate were occurring, with significant intensification of Northern Hemisphere Glaciation (NHG) dramatically influencing ecosystems across the globe (Ravelo et al., 2004). Long-term climatic changes over the Quaternary period are dominated by Glacial–Interglacial (G–IG) cycles linked to changes in orbital parameters and to non-linear responses, such as changes in global ice volume and thermohaline circulation, which are variable through time. Fundamental to any change is the amount of total summer insolation received at temperate latitudes, e.g. 65 °N, controlling the persistence of NH ice sheets (Imbrie et al., 1992). More recently, Kukla et al. (2002) and Kukla and Gavin (2005) have suggested that the difference between March and September insolation at the equator is a better index for correlation with paleoclimatic data.

A key challenge for paleoclimate research has been to accurately reconstruct the impacts of e.g. changes in thermohaline circulation at high resolution on remote, continental ecosystems far from oceanic influences. As highlighted by Colman et al. (1995), prior to Lake Baikal research in the 1990s, there were few, long, continuous sequences from continental regions. Notable exceptions included Devils Hole in Nevada, USA (which is influenced by moisture regimes from the Pacific (e.g. Winograd et al., 1992)) and the Chinese loess sequences in central Asia (which contains a detailed East Asian monsoon climate record) (Porter, 2001)). Despite loess records being extremely important archives, their resolution is usually not as high as that potentially obtained from other archives such as lake sediments, at the sub-millennial and sub-centennial scales (although there are recent, notable exceptions e.g. Chen et al., 2003). The sedimentary archive of Lake Baikal is essentially uninterrupted for many millions of years, and climate inferences can be reconstructed at millennial (e.g. Williams et al., 1997; Edlund and Stoermer, 2000), centennial (Karabanov et al., 2000a; Rioual and Mackay, 2005), decadal (e.g. Mackay et al., 2005) and pluriannual (Boës et al., 2005) scales. The potential therefore for detailed studies that can reconstruct even the most rapid or abrupt changes (comparable with the marine sediment and ice core records) is enormous.

There is little doubt that Lake Baikal is one of the most interesting and scientifically challenging freshwater ecosystems on our planet. Scientific endeavors have been on-going since early last century, including the pioneering investigations on the lake's physical limnology and hydrodynamics by Vereschagin (1936, 1937). Since the break-up of the former Soviet Union, extensive collaborative programs have been established between Russian and foreign research centers, such as the Baikal Drilling Program (BDP) (see Williams et al., 2001 for an excellent review) and the Baikal International Centre for Ecological Research (BICER) (Grachev, 1994).

This paper provides a synthesis of Lake Baikal paleoclimate studies which exploit the sedimentary diatom record and associated diatom/biogenic silica (BioSi). I focus on diatoms and biogenic silica because they are the most extensively utilized paleoclimatic proxies found in Lake Baikal sediments, and arguably the most important. Other sources of biogenic silica do exist (e.g. from chrysophytes and sponge spicules) but they form a relatively minor component (less than c. 2%; Granina et al., 1992). Although other biological proxies have been exploited, e.g. pollen (Bezrukova et al., 2005; Tarasov et al., 2005), most others are not preserved in sufficient numbers in the sedimentary record, in the main due to intense carbon recycling that occurs at the sediment surface–water interface (implications of which I discuss in more detail below). Recently, studies investigating photosynthetic pigment analysis have been published which greatly contribute to the diatom and biogenic silica work in terms of providing a more complete picture of past productivity and other algal groups in the lake (e.g. Tani et al., 2002; Fietz et al., 2007). Therefore, where appropriate, proxy-based evidence of other biological indicators is used to confirm interpretations made in this synthesis.

Increasingly sophisticated questions are being asked with respect to the magnitude and impacts of climate variability over different timescales and across different regions of the world. This paper is timely because it is only by synthesizing reconstructions from one of the most of important sites for paleoclimate reconstructions in central Asia, can we comprehensively assess the regional impacts of climate variability via teleconnections, such as those initiated by changes in thermohaline circulation in the North Atlantic. In this paper, I outline in Section 1 the major hydrological and climatic features of the Lake Baikal region, while Section 2 discusses the properties of diatoms in Lake Baikal, relevant to their use as paleoclimatic proxies. The third section provides a synthesis of studies that have utilized either diatoms or aspects of diatom silica to reconstruct central Asian paleoclimate at various timescales throughout the Quaternary (here taken as beginning c. 2.75 Ma). For each timescale, I initially outline current issues, followed by a critical examination of how the Lake Baikal records have added to the scientific body of knowledge. Central to these findings are the causes of climate change over the Quaternary, and there have been several accounts published recently on possible climate forcing mechanisms throughout this epoch (e.g. Maslin et al., 2001; Bradley, 2003; Nesje et al., 2005). I therefore take the opportunity to provide an assessment of potential forcing mechanisms in central Asia during each of the relevant timeframes below, which are likely to be contributing to change in the region of Lake Baikal.

1.1. Regional setting, lake morphology and hydrology

Lake Baikal is situated in a rift zone in southeastern Siberia between 51° 28′–55° 47′ N and 103° 43′–109° 58′ E (Fig. 1). The rift zone began to form during the Tertiary over 30 million years ago and occupies the world's deepest continental depression, at over 1160 m below sea-level (Kozhova and Izmest'eva, 1998). Quaternary glaciations have had major impacts on the lake's hydrology, sedimentology, ecosystem and shoreline. However, the bottom sediments of the lake itself have never been directly been glaciated (Grosswald and Kuhle, 1994). Lake Baikal therefore, contains a potential uninterrupted paleoclimate archive consisting of over 7500 m of sedimentary deposits, extending back more than 20 million years (Williams et al., 2001). The lake's three deep basins are separated by two underwater highs: the Selenga Delta separates the south and central basins, while an underwater mountain range, the Academician Ridge, separates the central basin from the north (Fig. 1). To the east and west of Lake Baikal itself are large, steeply sloping mountain ranges (e.g. Khamar–Daban and the Primorsky mountain ranges), broken only occasionally by valleys and deltas belonging to some of the larger rivers.

More than 300 rivers flow into Lake Baikal, with the largest and most significant being the Selenga, Upper Angara, and Barguzin Rivers, contributing c. 47%, 13%, and 6% of the total annual river inflow respectively (Granina, 1997) (Fig. 1). The Angara River in the south basin is the lake's current outflow. Chemical constituents of fluvial input into the lake, and of the lake itself, are summarized by Falkner et al. (1991), Granina (1997) and Mackay et al. (2002). Relevant to this synthesis is the distribution of Si in the lake, which is less than one third of that in source rivers (primarily due to intensive uptake by diatoms that dominate the phytoplankton community) (Votintsev, 1961). The depth-weighted average of Si concentration differs between each of the three basins. Concentrations are lowest in the south basin (0.85 mg/l), highest in the central basin (1.06 mg/l), while in the north basin they are c. 0.95 mg/l (Domysheva et al., 1998). These differences partly explain the relative concentrations of sedimentary biogenic silica found in the lake, which are higher in the north basin than the south. However, also important in this respect is the greater input of terrigenous matter into the south and central basins via rivers, especially the Selenga River, which has a dilution effect on sedimentary silica concentrations (Granina et al., 1993; Stoermer et al., 1995; Heim et al., 2005).

Lake Baikal is the world's deepest lake (c. 1642 m, INTAS project 99-1699 Team, 2002) and contains the world's largest volume of surface freshwater (c. 23,000 km^3; Kozhov, 1963) accounting for some 20% of global resources. The water volume of the lake is replaced every 377–400 years (Afanasyev, 1976; Gronskaya and Litova, 1991). However, what sets Lake Baikal apart from other deep lakes is that its entire water column is oxygenated, due to spring and autumn overturn and to deep-water renewal (Weiss et al., 1991; Shimaraev et al., 1994; Wüest et al., 2005). These oxygenated waters result in the oxidation of even the deepest sediment surfaces (Leibovich, 1983; Martin et al., 1998), which support an extensive, and almost wholly, endemic deep-water fauna (Fryer, 1991). Given its great age, depth, and fully oxygenated water column Lake Baikal is perhaps best well known for its high degree of biodiversity; over 2500 plant and animal species have been documented in Baikal, most of which are believed to be endemic (Timoshkin, 1997). However, a fully oxygenated water column has important implications for the paleoclimate record, due to continual grazing on remains of plants and animals that are transported to the bottom of the lake (Kozhova and Izmest'eva, 1998; Martin et al., 2005). Unlike many other large, deep lakes therefore, few potential biological proxies are incorporated into the sediment record. For those that do preserve in substantial quantities, such

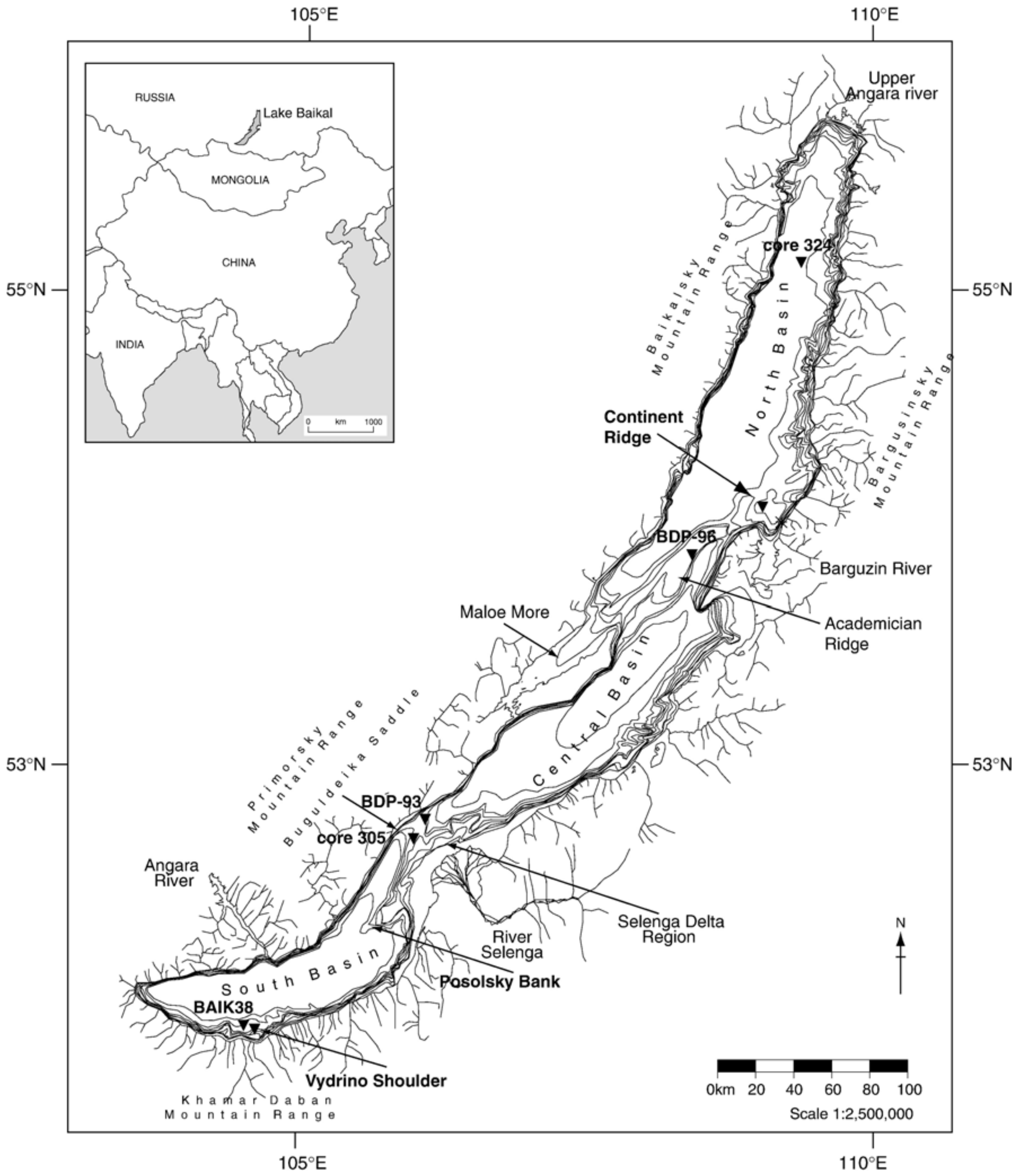

Fig. 1. Geographical location and physical geography of Lake Baikal. Main locations mentioned in text are highlighted on the map, including core locations from previous studies.

as diatoms, their importance as paleoclimatic proxies is raised.

1.2. Climate

The region of central Asia that includes Lake Baikal (Fig. 1) is characterized by the world's highest degree of continentality (Lydolph, 1977). Mean daily air temperatures in July are c.+19 °C, while January air temperatures fall to an average of c.−25 °C (Kozhova and Izmest'eva, 1998). Summers, although short, are relatively warm and wet, and winters are long, cold and dry. The lake itself is an important location for paleoclimate studies because it sits at a juncture between major climate systems. During spring, there is a strong westerly progression of cyclones moving through west Siberia to the Lake Baikal region because of the intensification of zonal circulation (Lydolph, 1977). In summer, low-pressure systems form along the Asiatic polar front and as the strength of the westerly transport weakens cyclonic activity and rainfall increases (Fig. 2). In autumn, deep intrusions of cold arctic air from the Kara Sea to the Lake Baikal region bring widespread cooling throughout eastern Siberia, which marks the beginning of the growth of the Siberian High (pressure at sea-level can exceed 1050, hPa), which dominates this region of central Asia in winter (Gong and Ho, 2002; Panagiotopoulos et al., 2005) (Fig. 2b).

In recent decades, wintertime warming in central Asia has been greater than any other region of the world, and this trend is expected to continue; winter temperatures are predicted to increase by between 2 and 5 °C over the next 50 years (IPCC, 2001). These changes are linked to declining intensity of the Siberian High, and general circulation model (GCM) predictions of future

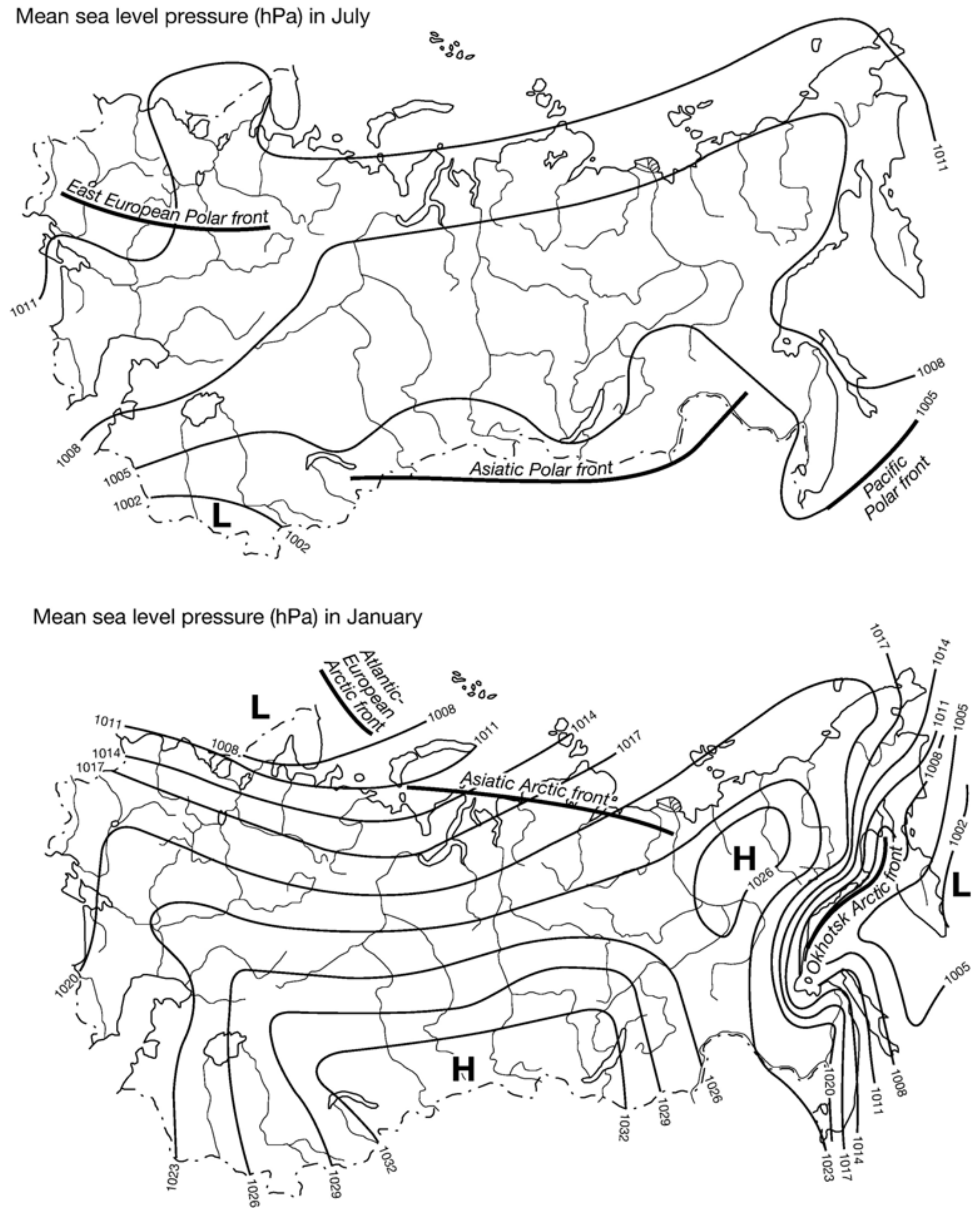

Fig. 2. Mean sea-level pressure (hPa) across central Asia in (a) July and (b) January. Redrawn and modified from Shahgedanova (2002).

climate change suggest as greenhouse gas (GHG) concentrations increase, the intensity of the SH will continue to decrease until at least 2100 AD (e.g. Gillett et al., 2003). The global significance of this warming is important both in terms of accelerating permafrost reduction (resulting in increased methane release from thaw lakes (Walter et al., 2006)) and declining snow cover extent, which have wide-reaching implications for albedo feedback mechanisms and monsoon intensity and for concentrations of methane in the atmosphere.

Across the Lake Baikal region, almost 50% of annual rainfall falls in July and August, influencing fluvial and nutrient input into the lake and associated sedimentation processes. However, there is marked spatial variation: rainfall is highest over the Khamar Daban mountain ranges to the south of Lake Baikal (up to 1400 mm/yr) while over the lake surface, precipitation is only c. 200–500 mm/yr. The lowest amounts of rain are deposited over the central basin (c. 200 mm/yr) (Shimaraev et al., 1994), and the catchment in this region is classed as semi-arid. Winds are also important across Lake Baikal, as they influence ice break-up in spring, mixing of open water during spring and autumn overturn, and timing of ice formation in winter (Shimaraev et al., 1994; Todd and Mackay, 2003). For example, strong winds (over 20 m/s) from the northwest and northeast dominate across the lake during late autumn–winter.

One of the most important controls on the physical, chemical and biological processes within Lake Baikal is the formation of ice (together with associated snow cover) across the lake during winter and spring. Ice formation is complex (Verbolov et al., 1965; Kouraev et al., in press) and the spatial variability in the duration of ice cover, type of ice formation, and snow cover extent all have significant impacts on diatom communities within the lake (e.g. Morley, 2005; Mackay et al., 2006). Ice formation begins in the north basin in late October, and although ice starts to break-up around late May, the north basin does not become completely ice-free until mid-June. In the south basin on the other hand, ice begins to form in January, starts to break-up around late March and the south basin is usually ice-free by mid-May (Shimaraev et al., 1994). These patterns of ice formation and break-up are linked to large-scale atmospheric circulation patterns, including the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO), and the position and intensity of the Siberian High (Livingstone, 1999; Todd and Mackay, 2003). Snow cover in this region of central Asia is also influenced by a complex set of interactions. For example, declining SSTs in the mid- to high-latitudes of the North Atlantic appear to be associated with increasing snow depths across eastern Siberia (Ye, 2000, 2001). The amount of snow produced is also dependent on the inverse relationship between temperature and relative humidity (Peixoto and Oort, 1992), accounting for increased modeled snow extent during colder periods in the Holocene in the Lake Baikal region (Bush, 2005).

2. Lake Baikal diatoms and their representation in the sediment record

Diatoms are important primary producers and crucial to the ecosystem functioning of Lake Baikal — phytoplankton biomass in spring (which consists mainly of planktonic diatoms) usually determines productivity of the whole year in the pelagic lake (Popovskaya, 2000). The most common planktonic diatoms in Lake Baikal are dominated by both endemic taxa (e.g. *Aulacoseira baicalensis* (Meyer) (Simonsen), *Cyclotella minuta* (Skv.) Antipova and *Stephanodiscus meyerii* Genkal and Popovskaya) and cosmopolitan taxa (e.g. *Synedra acus* (Kütz.) Hustedt and its varieties and *Nitzschia acicularis* W. Smith). Currently, about 30 modern species of diatom phytoplankton are known, and a list of over 400 benthic taxa was published in 1993 (Pomazkina and Votyakova, 1993). As is common to other large lakes, the littoral regions contribute a relatively minor component of overall productivity (Tilzer and Serruya, 1990). Furthermore, during summer stratification there is a shift from diatom-dominated phytoplankton to dominance by autotrophic picoplankton, especially the cyanobacteria *Synechocystis limnetica* Popovskaya (Popovskaya, 2000; Fietz et al., 2005).

Nevertheless, the distribution of Lake Baikal diatoms exhibits significant spatial variability across the lake, dependant on a number of factors including climate (e.g. ice and snow cover) and hydrological factors such as water depth and fluvial input (Bonderenko et al., 1996; Popovskaya, 2000; Mackay et al., 2003, 2006; Heim et al., 2005). As much as 40% of the lake's diatoms may be endemic (Skvortzow, 1937), although this figure is being revised upwards as more comprehensive studies in deeper, littoral zones (>20 m) are carried out and centers of hyper-endemicity recognized around the lake (Flower et al., 2002; Flower, 2005). The diatom assemblages in Lake Baikal contain several examples of species flocks, and relict distributions of previously more widespread taxa (e.g. Edlund and Jahn, 2001; Williams and Reid, 2004; Flower, 2005).

Due to the intense seasonality of the region, and to the sheer size of the lake, which covers 4° latitude, across which a distinct climatic gradient exists (Shimaraev et al., 1994), Lake Baikal diatoms and BioSi have been shown to be extremely useful paleoclimate proxies. It is therefore important to assess factors that may impact on diatom integrity before their final incorporation into the sedimentary record. The first comprehensive diatom-based paleoclimate record for Lake Baikal was from a site off the Selenga Delta in the south basin (core 305), spanning the Late Glacial and Holocene periods (Bradbury et al., 1994) (Fig. 1). Although it is of low resolution (c. 500 yrs), this investigation is nonetheless important because it addressed for the first time many of the issues that subsequent studies have tackled, with varying degrees of success. These include: (i) spatial variability of diatoms around the lake; (ii) problems of constructing accurate and precise chronologies; (iii) the correlation of multiple cores from different sites; (iv) the influence of sediment inhomogeneities such as turbidites; (v) the very low occurrence or even apparent absence of diatom valves from sediments deposited during glacial stages. One of the earliest studies on spatial variability sought to describe differences in diatom communities between the open pelagic water and several bays and sors (Meyer, 1930). Subsequent studies have used surface sediments taken from around the lake to investigate spatial variability of diatoms (e.g. Stoermer et al., 1995; Mackay et al., 1998; Likhoshway et al., 2005) and have tried to relate these to prevailing climatic and hydrological conditions (Mackay et al., 2003, 2006). Constructing robust and accurate chronologies is a challenge faced by all paleoclimatic researchers, and aspects relevant to this synthesis are discussed below in Sections 3 and 4. The occurrences of turbidites in Lake Baikal are well known (e.g. Karabanov and Fialkov, 1987; Nelson et al., 1995; Vologina et al., 2003) and can cause hiati in otherwise diatom-dominated profiles (e.g. Mackay et al., 1998; Colman et al., 1999). However, steps can be taken to only investigate cores which have minimal turbidite influence through the careful selection of sedimentary environments (Charlet et al., 2005).

Of importance to this synthesis is the decline, or apparent absence, of diatoms during glacially deposited sediments. All studies which analyze diatoms or BioSi as proxies to investigate long-term records of past climate variability, do so on the basis that peak diatom or BioSi values correspond to interglacials, and core sections where diatoms are almost completely absent correspond to glacial stages. Initially, Karabanov et al. (1992) suggested that the decline during glacial stages was due to a combination of prevailing cold temperatures, increased turbidity of the lake water, decreased nutrient supply and changes to the thermodynamics of the water column (Bezrukova et al., 1991; Shimaraev et al., 1992). Subsequent studies however, have moulded these factors into two alternative scenarios.

First, glacier meltwater in the headwaters of rivers flowing into the lake will have transported fine clays and other terrigenous material into the pelagic regions of Lake Baikal, creating sufficiently turbid conditions to significantly reduce photosynthetic activity and repress diatom populations (Bradbury et al., 1994). Karabanov et al. (2004) expand on this hypothesis, suggesting that low nutrients, low surface water temperatures and increased turbidity was responsible for the repeated destruction of the pelagic and benthic food webs in Lake Baikal during glacial periods throughout much of the Quaternary.

The second scenario proposes that major changes in thermodynamic conditions of the water column in Lake Baikal during glacial periods will have ensured that diatoms were transported out of the photic zone for longer periods (Shimaraev et al., 1992). This will have occurred due to generally colder conditions and increased winds resulting in deeper and extended periods of water column mixing, increasing the depth of the epilimnion. Both these processes will have resulted in significantly reduced diatom productivity in the lake, which together with an overall shortened growing season will have resulted in lower diatom numbers. Furthermore, increased aridity during colder climates will have weakened chemical weathering, reducing the release of phosphorus and silica from minerals in the catchment (Shimaraev and Mizandrontsev, 2003) that again will have had a significant negative effect on phytoplankton growth.

Perhaps the major implication between these two scenarios is the impact on evolutionary processes in Lake Baikal. Molecular phylogenetic studies have demonstrated that faunal flocks of several species are very ancient (e.g. gammarids) (Sherbakov, 1999), while the paleo diatom record shows that many species have persisted through successive G–IG cycles over hundreds of thousands of years (including *A. baicalensis* and *C. minuta*; Khursevich et al., 2001). The scenario put forward by Karabanov et al. (2004) therefore has species adapted to very deep waters existing in shallow, warmer waters during glacials, on the basis of very low diatom numbers in the sedimentary record. It is difficult to conceive of a scenario whereby prolonged cold periods resulted in either the total decline of the pelagic foodweb, or the restriction/migration of pelagic adapted diatoms and other organisms into restricted shallow water niches. Moreover, some of the shallow water environments suggested by Karabanov et al. (ibid.) to be refuges are themselves likely to have been more turbid due to increased terrigenous input, e.g. the shallow waters of the Selenga Delta region.

It is likely therefore, that the combination of factors originally proposed by Karabanov et al. (1992), will all have contributed to fewer diatoms growing in Lake Baikal during periods of glaciation. Further explanation is however needed to account for the apparent near absence of diatom valves from glacial sediments. I contend that rather than invoking the concept of shallow water refugia for diatom species otherwise adapted to survive the deep waters of Lake Baikal, it is more likely that secondary processes are operating. These will include relative increases in grazing pressure and dissolution in the water column and at the surface sediment–water interface, operating to cause the absence of diatoms in the sedimentary record (Carter and Colman, 1994; Ryves et al., 2003; Swann and Mackay, 2006).

2.1. Diatom dissolution

Common to the marine environment, the entire water column of Lake Baikal is under-saturated with respect to silica (Falkner et al., 1991), and therefore diatom valve dissolution will always be an important process through glacial and interglacial cycles. In a study comparing recent diatom fluxes through the water column with fluxes being incorporated into the sediments, Ryves et al. (2003) demonstrated that in the south basin of Lake Baikal, only c. 1% of valves are preserved in the sedimentary record. This figure is similar to diatom preservation into marine sediments (e.g. Tréguer et al., 1995; Treppke et al., 1996), and accounts for an enrichment of Si of c 1.5 mg/l in the bottom waters of Lake Baikal (Votintsev, 1961; Votintsev et al., 1965; Falkner et al., 1997). Once incorporated into the sediments, dissolution of diatom silica continues into the pore-waters, until saturation is reached, thereby buffering against further dissolution (Conley and Schelske, 1989; Carter and Colman, 1994). This occurs within the silica asymptotic concentration zone, which generally lies within the uppermost (c. 30 cm) sections of the sediment. However, during glacial periods, Si release from e.g. silicates and aluminosilicates is reduced (Shimaraev and Mizandrontsev, 2003), resulting in relative increased clastic input into the lake. In marine systems when this occurs, low Si concentrations in sediment pore-waters results in a decline in the buffering capacity against Si dissolution, leading to the increased loss of BioSi from the sedimentary record (e.g. Conley and Schelske, 1989; Carter and Colman, 1994).

The problem of dissolution affecting Lake Baikal records of glacial and interglacial paleoclimate has been recognized since some of the earliest studies (e.g. Colman et al., 1995). Although the impact of dissolution on weakly silicified diatom species has been acknowledged for some time now (Bradbury et al., 1994; Likhoshway et al., 1996) it is only recently that quantitative impacts of dissolution on diatom populations have been investigated (Ryves et al., 2003; Battarbee et al., 2005; Mackay et al., 2005). Dissolution during interglacials is problematic from a paleoenvironmental perspective because dissolved valves are often difficult to taxonomically identify. Furthermore, assemblages may be biased towards more robust, heavily silicified species (Battarbee et al., 2005) influencing paleoclimatological reconstructions (Mackay et al., 2005) or more seriously, taxa may be removed from the record altogether (Likhoshway et al., 1996; Ryves et al., 2003).

During glacial periods, a number of other factors may result in the dissolution of diatom frustules having a relatively greater impact than during interglacials. First, as diatoms are a major primary producer in Lake Baikal, it is probable that relative grazing pressures increased both in the water column and surface sediments during colder periods, resulting in greater valve fragmentation and increased susceptibility to dissolution. Second, biogenic silica records observed in faster accumulating sediments such as those at the Buguldieka Saddle more faithfully reflect diatom concentrations than records observed from slowly accumulating sediments on the Academician Ridge or Continent Ridge (Swann and Mackay, 2006). Third, Francus and Karabanov (2000) present evidence that microbioturbation was stronger within glacially deposited sediments, promoting dissolution through irrigation and physical breakage of diatom valves (Ryves et al., 2003). Fourth, the role of bacterial assemblages is increasingly recognized in having a significant impact on aiding dissolution through the removal of the protective organic layer which surrounds diatom valves (Bidle and Azam, 1999; Bidle et al., 2003). Although microbial activity in Lake Baikal has been known for many decades (Kuznetsov, 1951), the role of saprophytic bacteria in the deepest waters of the lake may further promote attack on diatoms throughout the entire water column (Straskrábová et al., 2005). Again, fewer valves due to lower productivity will have resulted in relative increases in decomposition.

It is reasonable to conclude, therefore, that the apparent absence of diatom valves from glacially deposited sediments is not necessary a reflection of the absence of diatoms from the pelagic regions of the lake, but is more simply a function of overall lower productivity and relative increase in factors that promote breakage and dissolution. As Carter and Colman (1994) previously pointed out, very low BioSi values found in glacial sediments need not represent periods of zero productivity. Indeed, such analyses take no account of productivity from other algal types, especially picoplankton within the lake. For example, a different approach to reconstructing algal paleoproductivity was taken by Tani et al.

(2002) and Soma et al. (2007) using photosynthetic pigments such as carotenoids and chlorophyll *a* derivatives (e.g. steryl chlorin esters (SCEs), which form when zooplankton predate on phytoplankton. They found that during the late glacial, approximately 30% of organic carbon in the lake was still autochthonous, although this was mainly derived from algae other than diatoms. Moreover, they provide convincing evidence (from increasing ratio between SCEs to total chl*a* with sediment depth) that grazing of phytoplankton by zooplankton occurred during the late glacial period. A more comprehensive assessment of the potential limitations of BioSi as a paleoclimate proxy in glacially deposited sediments in Lake Baikal is given by Swann and Mackay (2006) and in Section 3.4 below.

In all, despite dissolution of diatom silica impacting aspects of the paleoclimatic record, the paleoclimatic interpretations are nevertheless robust, especially when comparisons are made with records from regions elsewhere in the northern hemisphere. I merely contend here that the potential impact of dissolution processes needs to be at best considered, or at least acknowledged, during interpretation of the sedimentary record.

3. Paleoclimate synthesis

At a primary level, insolation received is modified by orbital parameters, with a frequency of every c. 100 ka (eccentricity), 41 ka (obliquity) and 23 & 19 ka (precession). Between 2.75 Ma and 0.8 Ma BP, cycles are predominantly controlled by obliquity, occurring every 41 ka. After 0.8 Ma, 100 ka cycles appear to dominate, i.e. approximating to eccentricity, and this change in emphasis between the orbital parameters is commonly referred to as the Mid-Pleistocene Revolution (MPR). Although over the last 800 ka, the cyclicity and amplitude of these cycles do not change, G–IG cycles themselves intensify, which has been attributed to internal feedback mechanisms undergoing extensive reorganization, leading to recorded variability in climate. These non-linear responses are reviewed in Maslin et al. (2001).

There are a number of problems associated with eccentricity forcing G–IG cycles, most notably that insolation change is too small at 100 ka to account for the climatic effects experienced (e.g. Imbrie et al., 1993). Shackleton (2000) proposed that changes in atmospheric CO_2 drives the eccentricity signal seen in marine core proxies rather than changes in ice volume, although no causal mechanism has been found between eccentricity and the response of the global carbon cycle. Other researchers have looked for alternative drivers for the 100 ka cyclicity, including changes in orbital inclination and the role of interplanetary dust (IDP) (e.g. Muller and MacDonald, 1997), although Winckler et al. (2004) suggest that the IDP records in marine sediments exhibit a periodicity of 41 ka, and as such IDP is not the driving factor for G–IG cycles. Other researchers have questioned the role of the 100 ka cycle altogether, and suggest that the 100 ka cycle is simply an artifact of spectral analysis on quasi-periodic deglaciations occurring over a relatively short time-span (e.g. Maslin and Ridgwell, 2006). Instead, it is suggested that deglaciation events over the last 800 ka are triggered every 4th or 5th precessional cycle (Raymo, 1997), although why subsequent glaciation periods intensify is still uncertain.

The sedimentary archive of BioSi from Lake Baikal has been shown by the BDP group to be highly sensitive to G–IG cycles (Colman et al., 1995; Williams et al., 1997). This is perhaps not surprising given the lake's extreme continental setting and received insolation close to 65 °N, resulting in the impacts of obliquity and precession on summer temperatures. However, while peaks in BioSi are correlated to peaks in $\delta^{18}O$ in marine sediments (e.g. Colman et al., 1995), global ice volume minima occur often many thousands of years after each solar insolation maximum. Goldberg et al. (2000) tried, to a limited extent, to compensate for this bias by absolute dating (using U-series analysis) of two peaks of BioSi corresponding to interglacials MIS 5 and MIS 7. From these dates, they estimated that global changes in ice volume lagged warming by approximately 8–9 ka. In all the BDP records therefore, the tuning of the BioSi record to $\delta^{18}O$ potentially loses important information in the form of leads and lags in the Lake Baikal record, as may occur due to its remoteness from changes in ice volume. Recently, a new astronomically tuned age model has been proposed by Prokopenko et al. (2006), based on correlating timing of September perihelia with peak biogenic silica concentrations. This new chronology offers some substantial improvement on the established age model, as it is no longer tied to e.g. ODP-correlated timescales. It is therefore able to provide an independent chronological framework with which to compare long Quaternary records from Lake Baikal with other continental and marine sequences (Prokopenko et al., 2006). Where appropriate I have tried to incorporate new insights from this new age model, although existing paleoclimate studies are reviewed on the basis of their original chronologies.

I have structured this synthesis to account for a range of timescales across the Quaternary, from reconstructing impacts due to changes in orbital forcing and received insolation (e.g. G–IG cycles), to the finely resolved changes that are concurrent with small shifts in received solar insolation from changes in sun spot activity in the last 1000 years. Although the extent of glaciation throughout the NH is still under debate, this is especially true of the Siberian region, where there is apparently little consensus (see Ehlers and Gibbard, 2003). In many regions, including central Asia, records and evidence of past glaciations are rarely preserved. It is also in this context therefore that the long Lake Baikal paleoclimatic record will be of particular value.

3.1. Glacial–interglacial impacts on the Lake Baikal sedimentary record

Evidence for ecosystem responses in Lake Baikal to changes in NH insolation and orbital parameters were established over 20 years ago (e.g. Goldyrev, 1982; Bezrukova et al., 1991, highlighted in Karabanov et al., 1992), with the finding that Lake Baikal sediments consisted of alternating layers (or 'rhythms') of organic, diatom-rich, and inorganic (clayey) diatom-poor sediments. It was soon recognized that these changes in BioSi were indicative of changing diatom productivity linked to climate (Granina et al., 1992). Records were comparatively short however, spanning only the previous glacial and last interglacial. The impetus of the BDP sought to explore these alternating rhythms at much longer timescales (BDP-96 Members 1997; Williams et al., 2001). In determining first order linkages between BioSi as a proxy for diatom production in the lake, BDP-93 (see Fig. 1 for location) studies relied heavily on comparisons with two other proxies of past climate variability. The first of these was the SPECMAP record (which details non-linear responses to global ice volume) from ODP 677 (extracted from the Panama Basin; Shackleton et al., 1990), and the second was summer temperature reconstructions from energy balance models (EBMs) (driven by insolation) constructed for central Asia (Short et al., 1991).

Colman et al. (1995) detailed relationships between BioSi and orbital forcing, and was the first seminal paper by the BDP team to demonstrate that continental interiors are "…well integrated in the global climate system". By comparing BioSi records with SPECMAP and Short et al.'s (1991) EBM of summer temperatures, Colman et al. (1995) showed, using spectral analysis, that while the 100 ka cycle was dominant, insolation patterns at 23, 19 and 41 ka were also apparent. These cycles largely concur with periodicities also witnessed in Chinese loess sequences, especially the strength of the 100 ka cycle for the last 800 ka years (An, 2000). What Colman et al. (1995) found surprising was the dominance of precession over obliquity in the Lake Baikal record, suggesting that aspects of the climate system driven by low latitude insolation are impacting ecosystems, including Lake Baikal, at more northerly latitudes.

Colman et al. (1995) acknowledged that because their record spanned less than three eccentricity cycles (c. 250 ka), this was seen as a potential weakness for making claims on the influence of 100 ka cycle in these remote continental regions. They further highlighted possible second order effects of dissolution on the BioSi record and associated spectral analysis. Therefore a new BDP program was funded to extract cores (up to c. 300 m depth) from slower accumulating sediments on the Academician Ridge (BDP-96; Fig. 1), which significantly extended the paleoclimatic record back 5 Ma BP (Williams et al., 1997). In relation to the focus of this synthesis, although ecosystem responses to warm climate were established between 5 Ma–c. 3 Ma, here I focus only on the timeframe since the onset of major NHG at c. 2.75 Ma. At this time, major changes in diatom species assemblages were recorded and linked to changes in global climate with the extinction of two endemic genera to the lake, *Stephanopsis* and *Tertiarus* (Khursevich et al., 2000).

Williams et al. (1997) provided further evidence of the links between diatom productivity and insolation parameters driven by orbital forcing through spectral analysis and comparisons between the BioSi record with SPECMAP and EBM temperature models described above. Influences of orbital forcing on patterns in BioSi levels can best be summarized to exhibit three phases during the Quaternary. First, between the start of the Quaternary to c. 1.6 Ma, both eccentricity and obliquity are weak, although spectral analysis suggests that cycles exist with frequencies between 166 and 333 ka. Second, after the Pliocene–Pleistocene boundary, between c. 1.8 Ma and 0.8 Ma, obliquity strengthened. Third, from 0.8 Ma up to the present, eccentricity forcing was strongest, but precession only became apparent over the last c. 0.4 Ma, perhaps due to its modulation by eccentricity. Especially notable was that all isotope stages identified in the marine record (MIS) were apparent in the Lake Baikal profile during the Brunhes chron (0.8 Ma to present) (Fig. 3). The team also determined that diatom productivity responses in Lake Baikal were not as non-linear as the marine proxy responses to changing global ice volume, which they attributed to the influence of precession acting to modify the eccentricity pattern in such continental regions (Williams et al., 1997). However, the comparisons made with EBM temperatures were different, perhaps because of a number of factors, including (i) basic model limitations, which were unable to take account of unquantified feedback mechanisms

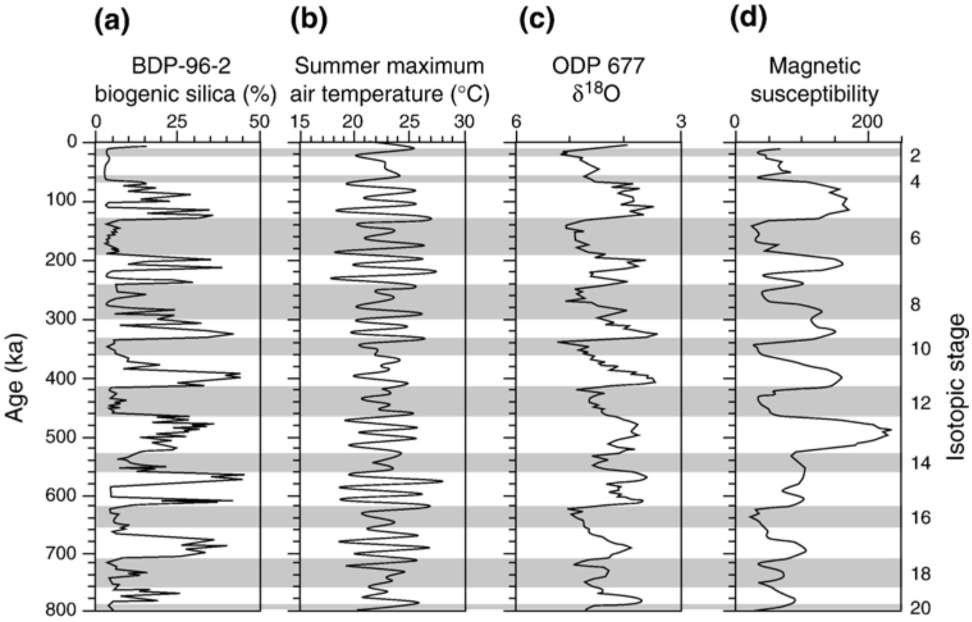

Fig. 3. Comparison of (a) the Baikal paleoclimate record for the past 800 kyr (correlation of BDP-96-2, BioSi) with (b) the predicted summer maximum air temperature record for Siberia (65 °N) from energy balance modelling, (c) the $\delta^{18}O$ record of ODP site 677 as a global ice volume proxy, and (d) a composite magnetic susceptibility record from Chinese loess sequences. Adapted and redrawn from Williams et al. (1997).

between the ocean, atmosphere and the cryosphere; and (ii) the truncation, or 'clipping' of the BioSi record due to dissolution processes having a relatively greater impact on biogenic silica profiles during colder periods, including glacial inception (Swann and Mackay, 2006). This was a direct result of the many 'zero' values in the BioSi typically recorded during glacial periods, which had an effect of shifting predicted 41 ka and 23 ka cycles into the 100 ka cycle frame (Williams et al., 1997).

Given the robust interpretations possible from the BioSi record, researchers soon became interested in examining the source diatoms to find out how individual species responses were impacted by climate changes over the Quaternary. Outside of the many mainly taxonomic papers, one of the first studies to relate changes in Lake Baikal diatom composition to changes in orbital forcing was by Grachev et al. (1998) who worked on BDP cores extracted form the Academician Ridge. Their data reinforce the observations that relatively few planktonic taxa tended to dominate the sedimentary assemblages during interglacials (Julius et al., 1997). But they also noted the successionary nature of the changing flora, especially during the last c. 1 Ma, as diatom abundances suggested progressively longer, more severe glaciations, with different species often dominating the record at different stages for less than 1000 years. Notably, although many of these taxa are now extinct (Khursevich et al., 2001) several included those commonly found in the lake today, such as *C. minuta*, *A. baicalensis*, and *Aulacoseira skvortzowii* Edlund, Stoermer and Taylor.

However, the most detailed study on diatom species responses to orbital forcing (and associated non-linear responses) indicates that over the last 0.8 Ma (since the onset of the MPR) 31 local diatom assemblage zones can be characterized, corresponding to MIS 1–19 (Khursevich et al., 2001) (Fig. 4). This paper is important because Khursevich et al. make the link between diatom evolution and insolation changes, thereby adding to the debate on evolutionary pressures on relatively short, and often abrupt, timescales. [Other evolutionary drivers may include factors such as competitive exclusion (Stoermer et al., 1995), since Lake Baikal is one of the few freshwater ecosystems that is old enough for the process to drive planktonic diversity within the lake (Julius et al., 1997)]. More specifically, species responses varied depending on whether insolation amplitude was small (e.g. as occurred between MIS 15a–11, corresponding to the almost continuous presence of *Stephanodiscus distinctus* Khursevich and its varieties) (Prokopenko et al., 2002b) or large (e.g. as occurred between MIS 19–15e, during which time each precessional cycle is dominated by a different species that

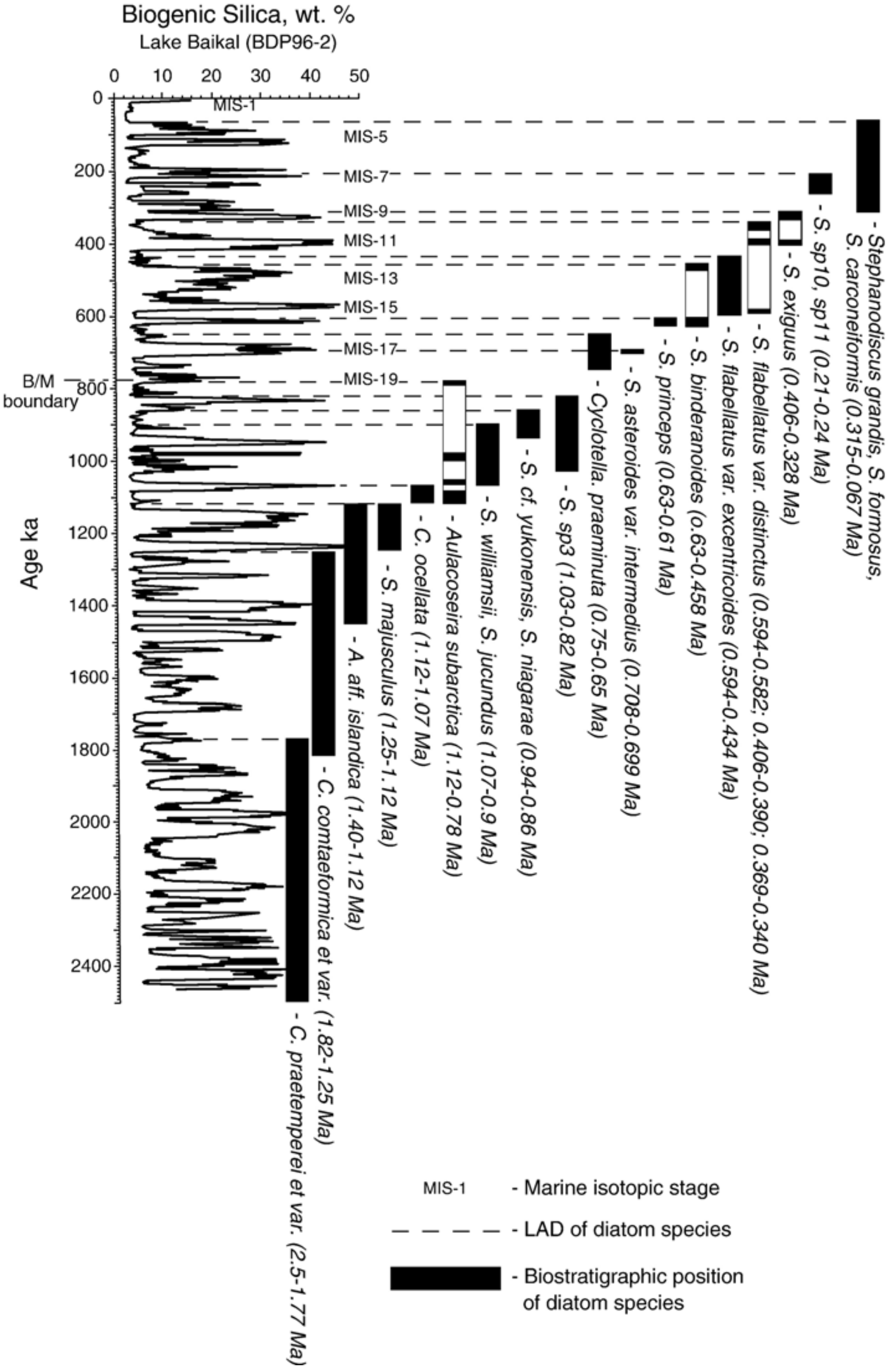

Fig. 4. Biostratigraphic position of diatom species plotted against BioSi analysis (after correlation to ODP site 677; see text for details) through the Quaternary in Lake Baikal from core BDP-96-2. The dotted lines represent last appearance datum (LAD) of diatom species. Redrawn from Khursevich et al. (2000).

subsequently became extinct). Furthermore, during the Brunhes chron, there are also apparent differential speciation rates between the genera, with 16 new species of *Stephanodiscus* being recorded in comparison to only four for *Cyclotella* (Khursevich et al., 2000, 2001). Importantly, as ice volume increased during each subsequent glaciation, indicative of prolonged glacial periods (e.g. Berger and Jansen, 1994), it has not resulted in the decimation of species within the lake, as suggested by Karabanov et al. (2004) for reasons outlined in Section 2 above. Such diatom responses to climate during the Pleistocene have not been witnessed in any other freshwater or marine environment (Khursevich et al., 2001). Detailed records also exist for changes in diatom assemblage composition prior to the Brunhes chron, with the onset of NHG influencing extinctions in at least two genera in the lake towards the beginning of the Quaternary. Following this time, endemic *Cyclotella* species developed and dominated the diatom flora, including *C. praetemperei* Khursevich til c. 1.7 Ma, followed by *C. comtaeformic*a Khursevich up to c. 1.25 Ma (Khursevich et al., 2000, 2005). Khursevich et al. (2000) notes that at the beginning of the Quaternary, two genera become extinct, whereas at the Plio-pleistocene boundary, only two varieties become extinct, highlighting that in this region at least, the most dramatic climatic effects were experienced during the earlier epoch. Complementary observations by Edlund (2006) highlight that over the last 500 ka, despite the high degree of endemicity, phytoplankton species diversity remains poor during interglacials (although no account was taken of the possible impacts of dissolution on the more finely silicified cosmopolitan taxa, including *Synedra* spp. (Ryves et al., 2003; Battarbee et al., 2005). Nevertheless, this low species diversity is in contrast to other biological groups in Lake Baikal (e.g. Baikalian amphipods; Kozhova and Izmest'eva, 1998), which may be a result of interactions between phytoplankton growing in open water with little niche diversification and few resource gradients, over glacial–interglacial cycles (Edlund, 2006).

3.2. Climate instability during the last interglacial

Recent work undertaken on interglacial climate change has been done within the context of assessing past variability with a view to understanding Holocene climate change and predicting trends in future global warming (e.g. Howard, 1997; Loutre and Berger, 2003; Van Kolfschoten et al., 2003; CAPE-Last Interglacial Project Members, 2006). There is much work still to be published on Lake Baikal interglacial sediments, as research to date has tended to focus on reconstructing past change over long timescales with relatively low (millennial) resolution (e.g. Edlund and Stoermer, 2000). However, a growing number of studies in the literature specifically investigate diatom proxy evidence for climate variability during, e.g. MIS 11 (Karabanov et al., 2003), MIS 5e (Karabanov et al., 2000b; Rioual and Mackay, 2005), and MIS 1 (Bradbury et al., 1994; Mackay et al., 1998, 2005; Karabanov et al., 2000a, 2005; Morley, 2005).

The last interglacial in central and eastern Siberia is poorly characterized, mainly because there are few sites with continuous records spanning this period (CAPE-Last Interglacial Project Members, 2006). Lake Baikal sediments offer great potential therefore in providing information on climate variability, in a region remote from oceanic influences. The last interglacial in this region is known as the Kazantsevo, and is equivalent to the Eemian in northwest Europe and the Mikulino in western Siberia. There has been a tendency in the literature to equate the Kazantsevo/Eemian with MIS 5e, but pollen-derived evidence suggests that these are not directly synchronous (e.g. Shackleton et al., 2003), and hereon I only refer to the Kazantsevo interglacial *sensu stricto*. In this section, I will use the last interglacial records from Lake Baikal to assess how knowledge from this region of central Asia furthers our understanding of the duration of the last interglacial, and whether the proxy evidence suggests that the last interglacial was characterized by climate instability or not. The principal proxies used to reconstruct last interglacial climates from Lake Baikal are BioSi (Karabanov et al., 2000b; Prokopenko et al., 2002a), diatom species composition and derived productivity from biovolume accumulation rates (BVAR) (Rioual and Mackay, 2005), pollen (Granoszewski et al., 2005; Tarasov et al., 2005) and most recently pigments (Fietz et al., 2007). Measurements of biovolume are useful in sediments where there is a substantial range in relative sizes between species, as is the case in the last interglacial sequence of Lake Baikal. This is because although small diatom species may dominate counts, their contribution to biomass may actually be rather minor (Hillebrand et al., 1999), in comparison to less common, large-celled species, which contain more carbon than small cells (Reynolds, 1984) and therefore can dominate algal biomass. In the diatom record, biovolume changes are mainly controlled by the very large endemic (and now extinct) species *Stephanodiscus grandis* Khursevich and Loginova — see Plate 1 Fig. 1 in Rioual and Mackay (2005). Ryves et al. (2003) show that diatom phytoplankton biovolumes are at a minimum when the lake is frozen, highlighting the fact that diatom biomass is low under ice. As overall diatom biovolume is determined by larger-celled species, the relative impact of dissolution on the last interglacial BVAR record is not likely to be great, as these larger, heavily silicified valves are most resistant to dissolution.

The first detailed treatment of the Kazantsevo interglacial stemmed from the tuning of the peak in the BioSi

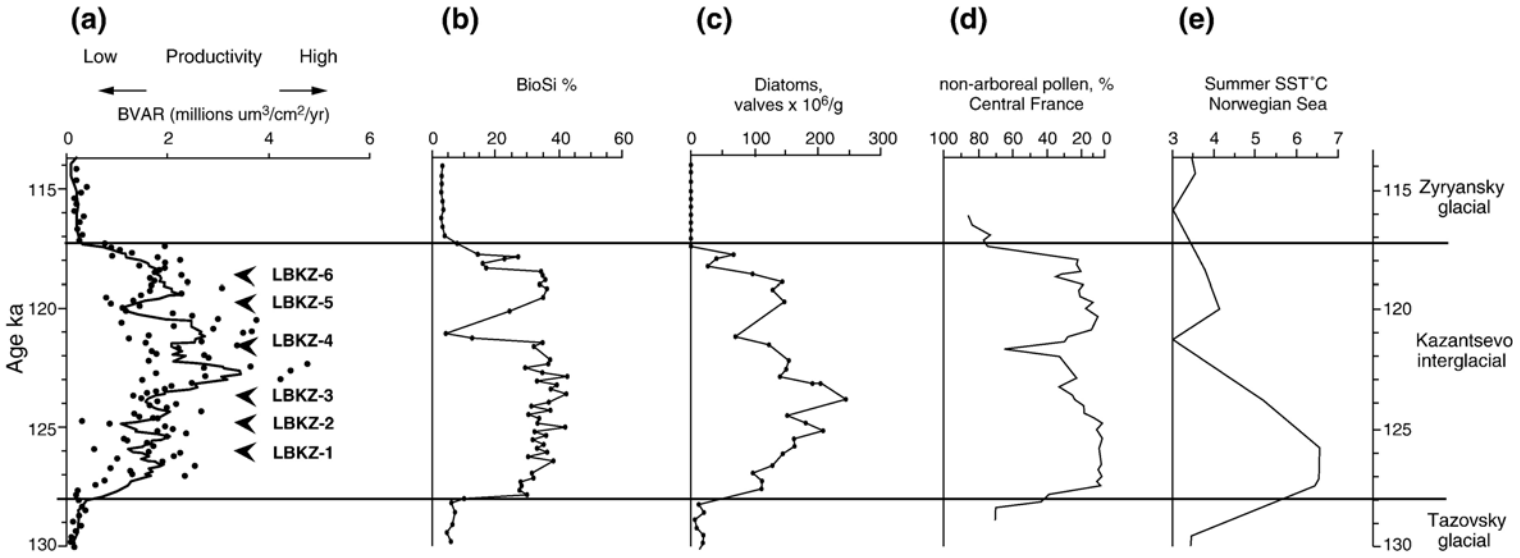

Fig. 5. (a) diatom biovolume accumulation rates (BVAR), (b) BioSi, and (c) diatom abundance records of last interglacial (Kazantsevo) productivity in Lake Baikal. Profile (a) is from the Continent Ridge core CON01-603-5 in the northern basin (Rioual and Mackay, 2005), and profiles (b) and (c) are from core BDP-96-2 extracted from the Academician Ridge (Karabanov et al., 2000b). The solid line in (a) represents a 5-point moving average, and the arrows with corresponding codes LBKZ-1 to LBKZ-6 indicate episodes of lower diatom biomass. Profile (d) is off a non-arboreal pollen record from central France (Touveny et al., 1994). Profile (e) exhibits reconstructed SSTs in the Norwegian Sea (Cortijo et al., 1994). Profiles (b)–(d) adapted from Karabanov et al. (2000b).

record to the peak insolation at 65 °N. Prokopenko et al. (2002a) suggested that the last interglacial lasted about 12 ka, from 127 ka to 115 ka (Fig. 5), a figure in between estimates of approximately 10.5 ka in northern Europe (e.g. Turner, 2002) and 15 ka in southern Europe (Tzedakis et al., 2003). [Under the new astronomically-tuned age model, the last interglacial starts at 128 ka BP (Prokopenko et al., 2006)]. However, recent work, undertaken as part of the EU *Continent* program (http://continent.gfz-potsdam.de/front_content.php), used geomagnetic palaeointensities (tuned to a well constrained reference curve from ODP 984 site) (Demory et al., 2005) to establish a robust independent chronology. Centennially resolved records for diatom-inferred increases in productivity and pollen-inferred increases in precipitation, both place the beginning of the interglacial at c. 128 ka cal BP (Granoszewski et al., 2005; Rioual and Mackay, 2005; Tarasov et al., 2005) and indicate that the switch from glacial into interglacial conditions was rapid. The same records also suggest that the Kazantsevo terminated at c. 117 ka cal BP (cf. c. 115 ka BP under the astronomically tuned age model by Prokopenko et al. (2006), which agrees well, considering the uncertainty associated with interpolation over 23 ka intervals (ibid.)), due to the dramatic decline in Northern Hemisphere insolation resulting in the growth of continental glaciers and concomitant start of the last glacial inception. These dates are comparable with records from northern Europe (e.g. Turner, 2002), but differ from records for southern Europe and the Mediterranean (e.g. Shackleton et al., 2003; Tzedakis et al., 2003), and from other regions, including western Australia (Stirling et al., 1995), Devil's Hole, Nevada (Winograd et al., 1992) and Antarctica (Jouzel et al., 1993). These findings confirm persistent teleconnections between northern Europe and Lake Baikal during the last interglacial, given that the biological responses to changing conditions in both regions are so similar.

Spatial variability between regions is also apparent with regard to the termination of the Kazantsevo (i.e. the MIS 5e/d boundary). Based on the orbitally tuned BioSi records, Prokopenko et al. (2002a) suggested the end of the Kazantsevo was abrupt, with the return to full glacial conditions at the start of MIS5d (c. 115 ka BP). In the Lake Baikal records, cooling actually begins slightly before this date, at c. 119 ka BP, which agrees well with the independent record of biovolume productivity in the north basin, which reaches minimum values by 117 ka BP. The reduction in forest cover and diatom productivity are linked therefore to changes in orbital parameters after 120 ka BP (Crucifix and Loutre, 2002) as decline of the North Atlantic thermohaline circulation did not occur until the marine coldwater episode C24, c. 107 ka BP (McManus et al., 2002). During the onset of glacial conditions, the detailed diatom records by Rioual and Mackay (2005) indicate that although BioSi and biovolume productivity metrics were at their minimum, low abundances of *C. minuta* and benthic diatoms including *Fragilaria sensu lato* persisted through this stage. Thus, while productivity in the open water was greatly reduced, diatoms associated both with autumnal waters (when the lake is free from ice) and littoral, shallow water environments, were still able to grow (i.e. while niches of certain species may have become much more restricted, they had not disappeared altogether). It is worth noting here that *C. minuta* is the species least susceptible to dissolution, at least as far as we are able to determine from extant taxa (Table 1; Battarbee et al., 2005). It may well be therefore that some species have been removed from the sedimentary record during the onset of glacial conditions by dissolution processes.

The last interglacial is seen as a period of relatively stable climate (e.g. McManus et al., 1994), although millennial-scale variability has been recorded, especially in marine sediments (e.g. Curry and Oppo, 1997; Bond et al., 2001) and seems to be geographically dependent (Bigg and Wadley, 2001). Floristically, the diatom evidence in Lake Baikal (i.e. the continued presence of large *Stephanodiscus* spp.) is indicative of climatic conditions able to promote deep spring mixing; these large-celled species generally require low light, high phosphorus and moderate silica levels (e.g. Bradbury et al., 1994).

Table 1

Average diatom fluxes observed from the water column for the dominant species found in phytoplankton samples between 1994 and 1998, and for BAIK38, a core taken from a shoulder region in the south basin in 1994 (valves cm^{-2}) (Fig. 1)

Water column	*A. skvortzowii*	*A. baicalensis*	*C. minuta*	*S. meyerii*	*S. acus*	*N. acicularis*	Total
Average 1994–1998	1,847,868	1,375,303	385,548	1,157,408	3,745,882	3,481,749	12,021,832
BAIK38							
Average flux of valves from surface sediment	12,942	38,038	35,562	3264	5514	0	11,1620
Difference factor	× 143	× 36	× 11	× 355	× 680	NA	× 108
Preservation factor	0.007	0.028	0.092	0.003	0.001	NA	0.009

Full details of this table are in Battarbee et al. (2005).

Moreover, the presence of *Cyclotella* cf. *operculata* (Agardh) Kützing (Rioual and Mackay, 2005) suggests that summer conditions were warm and sunny enough to ensure thermal stratification of the water column during summer months (e.g. Fahnenstiel and Glime, 1983). However, the diatom BVAR records show significant variability, with several distinct reductions in diatom biomass productivity occurring throughout the Kazantsevo. During the first half of the interglacial (between c. 128 and 122 ka cal BP) BVAR generally increases, although there is evidence in the record for four centennial-scale reductions in diatom biomass, which occur approximately every 1.5 ka, a pacing similar to Bond cycles determined for the Holocene (Campbell et al., 1998; Nesje et al., 2005) and for cooling cycles in North Atlantic ocean marine records (Bond et al., 2001). These reductions in diatom biomass coincide with small, but distinct reductions in pollen-inferred temperature of the coldest month from the same core material (Tarasov et al., 2005). Cool, cyclical episodes (with a frequency of c. 1.5 ka) have also recently been observed during the last interglacial from a European pollen record in southwest Germany (Müller et al., 2005). These cold episodes are linked to reductions in mean winter temperatures, although mean summer temperatures were relatively stable. It is therefore apparent that biological impacts of climate variability do exist within this interglacial, with similarly-paced episodes of diatom biomass reduction in Lake Baikal and cool climate events in North Atlantic regions. I have labeled these Lake Baikal diatom biomass reduction events LBKZ-1 to KBKZ-6, as potential tie-points to assist regional correlation with other high resolution studies both within Lake Baikal, or within the central Asian region itself, as longer, more detailed profiles become available.

During the latter stages of the Kazantsevo episodes of diatom biomass reduction intensify, and there is a major biomass reduction event at c. 120 ka cal BP (120.6–119.6 ka cal BP) (LBKZ-5; Fig. 5a; Rioual and Mackay, 2005, and several studies from around the world have reported the occurrence of a late intra-Eemian cold event (e.g. in European lakes (Field et al., 1994 and the Chinese loess (Zhisheng and Porter, 1997)) that lasted approximately 400 years (Maslin and Tzedakis, 1996). In a further development using annually laminated lake sediments in Germany, Sirocko et al. (2005) describe the occurrence of a late Eemian aridity pulse (LEAP), which persisted for 468 years, and is characterised by containing over 50 dust layers. The occurrence of an intra-Eemian cool event in Lake Baikal was first proposed by Karabanov et al. (2000b), who document a decline in BioSi concentration at c. 122 ka BP (Fig. 5b) (subsequently dated by Prokopenko et al. (2002a) at c. 120 ka BP, while no specific mention of this event is mentioned in Prokopenko et al. (2006)). Similar to the non-arboreal pollen records in central France (Touveny et al., 1994), this decline was relatively short lived, and BioSi records suggested that the climate in the Lake Baikal region returned to conditions as warm as before the intra-Eemian cooling until the end of the interglacial. This LBKZ-5 reduction in diatom biomass is likely to be concurrent with the decline in biogenic silica documented by Karabanov et al. (2000b) given the discrepancies in dating techniques and overall interpolation uncertainly with the SPECMAP age model. However, there are several differences between these two proxies. Diatom productivity inferred from BVAR does not drop as dramatically as the BioSi record and like summer SSTs determined for the Norwegian Sea during (Fig. 5e), does not return to peak values found earlier during the climatic optimum at c. 124–122 ka. Terrestrial records from European sites suggest that this late Eemain cool episode was of low amplitude (Touveny et al., 1994; Rioual et al., 2001; Tzedakis et al., 2003), and this is confirmed by recent semi-quantitative pollen-inferred precipitation reconstructions (Tarasov et al., 2005). At this time, while quantitative estimates of pollen-inferred summer temperatures were high (in agreement with Karabanov et al., 2000b), quantitative estimates of winter temperatures and precipitation show distinct declines, and it may well be that this increase in aridity associated with the late Kazantsevo diatom biomass reduction event (LBKZ-5) is related to the LEAP event determined by Sirocko et al. (2005). Increased aridity is associated with a synchronous attenuation of monsoon circulation and cooling in the region (Tarasov et al., 2005) linked to reduced insolation (Berger et al., 1996) and increasing ice volume (McManus et al., 2002). However, the duration of LBKZ-5 is c. 1000 yrs, approximately twice that determined for the LEAP event (Sirocko et al., 2005), which suggests that impacts on the Lake Baikal ecosystem, at least with regard to recovery in diatom productivity were greater than comparative impacts in northern Europe. Changes in diatom numbers in BDP-98 at this time exhibit similar trends to changes in BVAR from Continent Ridge, suggesting that the biological responses in Lake Baikal are consistent, at least in the north basin of the lake (Fig. 5c), although again likely impacts of dissolution are largely unaccounted for.

3.3. Abrupt climate changes: Heinrich events

Imprinted within paleolimnological responses to orbital forcing are abrupt changes in climate, associated with complexity between systems (e.g. the atmosphere, ice sheets, oceans, land-masses), which result in non-linear responses crossing climatic thresholds (Bard, 2002). That climate can change so dramatically within a period of decades is now increasingly recognized as a significant feature of paleoecological records, especially during the latter period of the Quaternary (Taylor et al., 1993). Over the last 115 ka, several forms of abrupt changes in climate have been described (Adams et al., 1999). These include Heinrich events (H) linked to ice-rafting pulses into the North Atlantic ocean from the Laurentide ice sheet, which were extremely cold and punctuated the paleo record (e.g. Heinrich, 1988; Andrews, 1998; Hemming, 2004), and interstadials (IS) which are characterized by short periods of warm climate occurring during overall cooler conditions. The impacts of such abrupt changes have a global impact (Hemming, 2004 and refs. contained therein), although evidence from remote continental regions is relatively sparse (Alverson and Oldfield, 2000), and on Lake Baikal itself, has only recently been recognized (Prokopenko et al., 2001a,b; Swann et al., 2005). Over the last c. 70 ka, Heinrich events have been shown to occur approximately every 7.2 ka (+/−2.4 ka), up until the start of the Holocene (Sarnthein et al., 2001). Here, I will focus on the evidence for abrupt climate impacts on the Lake Baikal ecosystem during interstadial MIS 3, which lasted c. 59–29 cal ka BP, and was punctuated by Heinrich events H2–H5 (Prokopenko et al., 2001a,b; Swann et al., 2005). In this region of Siberia, MIS 3 is also called the Karginsky interstadial.

The first study to implicitly link abrupt changes in the Lake Baikal ecosystem to changes in the North Atlantic ocean associated with ice-rafting events was by Prokopenko et al. (2001a,b). Initially comparisons were made between cores extracted from two very contrasting sites: the Buguldeika Saddle (opposite the Selenga Delta) and the Academician Ridge (Fig. 1). Sedimentation in the Buguldeika Saddle is significantly affected by sediment deposition from the Selenga River, Baikal's largest tributary, while sedimentation at the Academician Ridge is mainly pelagic. North Atlantic cooling cycles result in a decline in diatom productivity, recognized in Lake Baikal records in the form of decreased diatom concentrations and changes to the C/N composition of bulk sediments (reflecting input of fluvial material) (Prokopenko et al., 2001a). However, records also highlight that sedimentary evidence for North Atlantic cooling is site specific within Lake Baikal. For example, where pelagic sedimentation dominates the environment, e.g. at the Continent Ridge in the north basin, North Atlantic cooling results only in decreased diatom concentrations, indicative of a fall in diatom productivity in the lake, while C/N ratios did not change because influence of fluvial input to this location is small (Swann et al., 2005). At Continent Ridge, H5 (c. 51.5–50.2 ka BP) is expressed only by a fall in diatom concentration (Fig. 6), coincident with glacier readvancement in the catchment (Back et al., 2000). Heinrich 5 marks the very abrupt end to the early MIS 3 warm phase (c. 54–51.5 ka BP), which is characterized by high diatom concentrations, dominated by the endemic *C. gracilis*. In diatom profiles from the Buguldeika Saddle, this early MIS 3 warm phase is also dominated by *C. gracilis* (Edlund and Stoermer, 2000) although increases in fluvial sediments brought in via the Selenga River are also apparent (Prokopenko et al., 2001a).

In a recent investigation of previously published Lake Baikal MIS 3 sequences, Swann and Mackay (2006) demonstrate that in regions of slow accumulating sediments, such as Continent Ridge or the Academician Ridge (Fig. 1) interstadial conditions (e.g. between ca. 53.3 and 51.5 ka BP) are recorded by increases in diatom concentrations and diatom biovolumes, but not by biogenic silica. However, for the same period, but at a faster sedimentation site (Buguldieka opposite the Selenga Delta region) this interstadial is faithfully recorded by both diatom concentrations and biogenic silica analysis (Colman et al., 1999; Edlund and Stoermer, 2000). Through comparison of diatom and biogenic silica records in all three sites (Swann and Mackay, 2006), no relationship is observed to exist between BioSi and diatom concentrations during MIS 3 in slow sedimentation sites, in contrast to sites with faster accumulation and associated higher burial rates of diatoms away from the surface sediment/water interface where dissolution processes are most intense (Ryves et al., 2003). Implications for paleoclimatic studies on Lake Baikal are such that analyses of biogenic silica records alone during glacial periods appear to be sensitive to sediment accumulation rates, and therefore site selection needs to be carefully considered (e.g. Charlet et al., 2005).

3.4. Abrupt climate changes: millennial-scale cycles

Related to Heinrich events are Dansgaard–Oeschger (D–O) events, which are more frequent and occur every c. 1.5 ka (1470 yrs). D–O events are smaller in amplitude than Heinrich events (Dansgaard et al., 1993), but they also penetrate into interglacial periods, notably the Holocene (e.g. Bond et al., 1997; Campbell et al., 1998) and the last interglacial (Curry and Oppo, 1997; Müller et al., 2005; this study). While their cause is still uncertain,

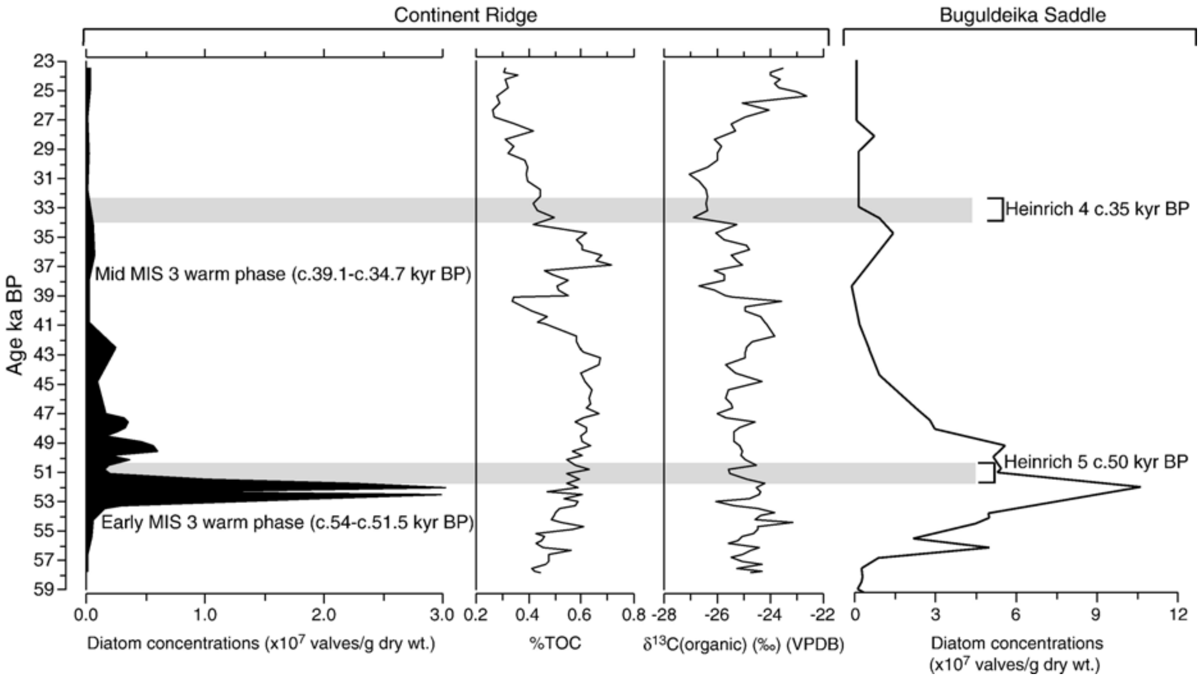

Fig. 6. Correlation of diatom concentrations (10^7 valves/g dry wt.), $\delta^{13}C_{(organic)}$, and %TOC at Continent Ridge core CON01-603-5 (Swann et al., 2005) with diatom concentrations at the Buguldeika Saddle (Prokopenko et al., 2001a,b) during the Early (c.54–c.51.5 kyr BP) and Mid (c.39.1–c.34.7 kyr BP) MIS 3 warm phases in Lake Baikal and during ‘Kuzmin’/Heinrich events 5 (c.50 kyr BP) and 4 (c.35 kyr BP) (shaded grey). Reproduced from Swann et al. (2005).

recent evidence suggests that they may be triggered by the product of two solar cycles (210 yrs and 81 yrs) acting on freshwater input into the North Atlantic, synchronizing the c. 1470-year cyclicity (Braun et al., 2005). Events with a periodicity of c. 1.5 ka have been determined in Lake Baikal paleomagnetic susceptibility records, with all but one of the nine episodes described by Bond et al. (2001) recognized in the paleoclimatic record (Witt and Oberhänsli, unpublished). Recent developments in paleoclimatic research have started to interpret previously described short-term climatic fluctuations such as the GS-1 (Younger Dryas) (e.g. Mayewski et al., 1997), and the “Little Ice Age” c. 500–300 years ago (Campbell et al., 1998), within the context of these millennial-scale cycles. Given the evidence synthesized above so far, the responses of Lake Baikal diatoms and diatom silica to large amplitude changes are not in doubt. Perhaps less well explored are the responses of diatoms and BioSi to lower amplitude events and associated non-linear climate dynamics. It is within this context therefore, that I provide a synthesis of paleoclimatological events reconstructed from diatoms and BioSi since the late glacial up to the present day. This section focuses on: (i) a major episode during Termination 1 at the end of the last glacial (the GS-1 or Younger Dryas or event), (ii) evidence for centennial-scale cooling through the early to mid-Holocene; and (iii) climate fluctuations during the last millennium. While the cause of millennial-scale periodicities is still under debate, they provide a useful and coherent framework on which to discuss relatively recent ecosystem responses to climate variability in central Asia.

3.4.1. GS-1/Younger Dryas

The transition from the end of the last glacial into the Holocene (Termination 1) was rapid in Lake Baikal (only c. 4 ka, comparable with other regions around the world) as the climate system underwent significant re-organization. There is still debate however, as to whether Termination 1 events such as the Younger Dryas or GS-1 (Mangerud et al., 1974; Björck et al., 1998 respective terminologies) were synchronous around the world, or whether significant leads and lags exist due to local and regional influences. Part of the uncertainty is due to the difficulties of achieving robust chronologies from many sites (e.g. Lowe et al., 2001). Another factor is undoubtedly due in part to inappropriate use of classification schemes first proposed by e.g. Mangerud et al. (1974) and the related Blytt–Sernander sequence, which were not originally designed for such high resolution and spatially diverse sites.

An independent event stratigraphy has recently been established, based on the GRIP core with chronology ss08c from the Greenland ice sheet (Björck et al., 1998), with which to compare regional stratigraphic schemes, and any resulting concomitant leads, lags or otherwise between records (Lowe et al., 2001). While this is not the place to provide a summary of the two schemes, impacts of past climate on the Lake Baikal ecosystem are likely to be substantially different from those occurring in Scandinavia, from which the original Mangerud classification was devised. However, recent paleoclimate studies of Termination 1 based on Lake Baikal sediments have tended to use the old Mangerud classification (e.g. Younger Dryas and Bølling), including studies based on BioSi (Colman et al., 1999), diatom abundances (Karabanov et al., 2000a) and pollen (Demske et al., 2005). Moreover, complex problems with radiocarbon dates obtained from recently deposited sediments have been widely reported by the BDP team (e.g. Colman et al., 1996), which for these studies may preclude high resolution comparisons with the INTIMATE GRIP event stratigraphy. However, new radiocarbon chronologies, based on pollen extractions, are significantly more accurate and permit well dated, high resolution stratigraphies in at least two contrasting sites in Lake Baikal–Vydrino Shoulder in the south of the lake, and Continent Ridge in the north (Fig. 1) (Piotrowska et al., 2004; Demske et al., 2005). In this synthesis therefore, both schemes are used where necessary.

BioSi and diatom concentration trends provided the first evidence that GS-1 resulted in the depression of diatom productivity in Lake Baikal (Colman et al., 1999; Karabanov et al., 2000a; c. 10–11 ka) (Fig. 7) confirming other evidence that this rapid but abrupt return to glacial conditions was experienced throughout Central Asia. However, given the potential problems with the BDP ^{14}C chronologies, detecting leads and lags between the INTIMATE event stratigraphy and diatom productivity changes occurring in Lake Baikal remained uncertain. A decline in total organic carbon, total chlorophyll *a* and total carotenoids between c. 11 and 12 ka BP indicates that not only diatom productivity decreased during GS-1, but possibly all algal productivity underwent a significant reduction (Tani et al., 2002; Soma et al., 2007).

Perhaps the best resolved profile to date has been carried out by Morley (2005), Morley et al. (2005) and Morley et al. (in review) from the Vydrino shoulder in the south basin. Here the LBGS-1 (Lake Baikal GS-1) stage occurs at c. 12.64 cal ka BP, which agrees remarkably well with the record from GRIP (12.65 cal ka BP; Fig. 8a),

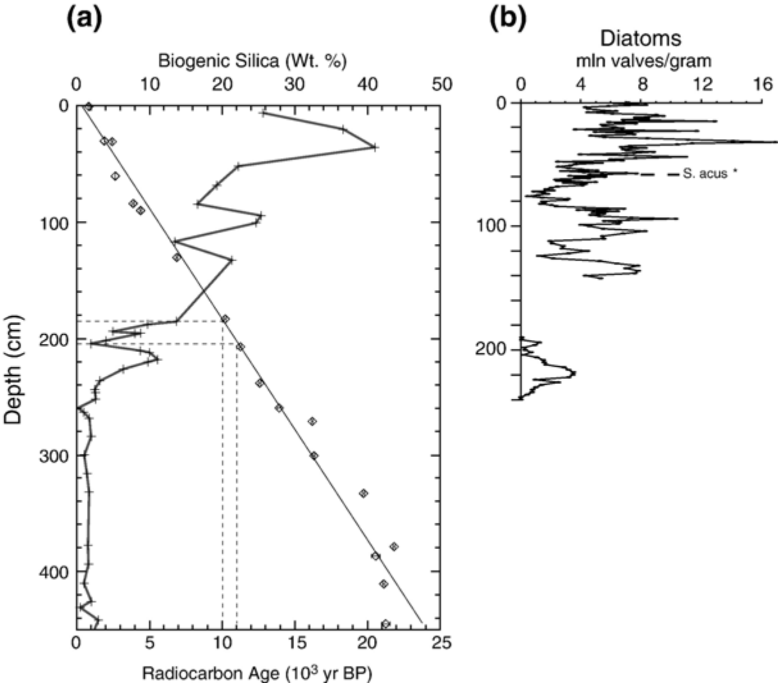

Fig. 7. Profile (a) details biogenic silica values for the last 25 ka from BDP93-1 and 02, taken at the Buguldieka Saddle (Colman et al., 1999). Radiocarbon ages are plotted as diamonds, and a least-squares best fit line has been plotted as a straight line through the dates. Dash lines are projected from 10 and 11 ^{14}C ka on the age scale to the age-depth curve and then to the depth scale. This period represents the conventional age limits for the Younger Dryas event. Redrawn from Colman et al. (1999). Profile (b) shows associated diatom numbers from BDP-93-2 and the monospecific laminae of *S. acus* (redrawn from Karabanov et al., 2000a).

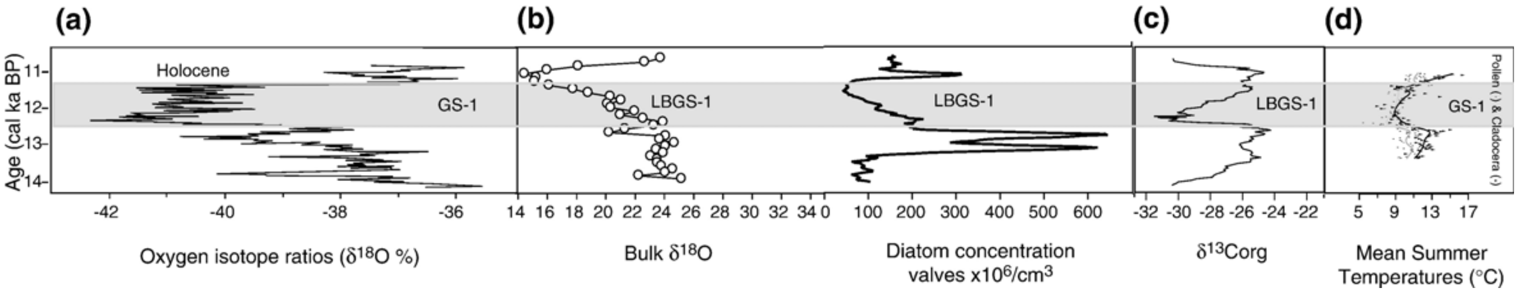

Fig. 8. Proxy evidence for late glacial cooling during the GS-1 event. (a) Oxygen isotope record from GRIP ice cores (Johnsen et al., 1992); (b) bulk $\delta^{18}O_{\mathrm{diatom}}$ and diatom concentration of sediments before cleaning for a core taken from the Vydrino Shoulder, Lake Baikal (Fig. 1); (c) $\delta^{13}C_{\mathrm{ORG}}$ (Morley et al., in review); (d) pollen- and cladoceran-inferred mean summer temperature records from Gerzensee (Switzerland) lake sediments (data redrawn from Lotter, 2003). The GS-1 cooling event is highlighted by grey shading. Profiles are plotted against cal ka BP (left axis).

suggesting that weakening of the Atlantic meridional circulation and decline in the rate of deepwater formation in the North Atlantic ocean formation impacted significantly on the Lake Baikal ecosystem with negligible lag time. Both diatom concentrations and organic isotopes ($\delta^{13}C_{ORG}$) point to distinct reductions in productivity at this time, linked to regional cooling. However, it is worth noting that $\delta^{13}C_{ORG}$ values tend to increase before diatom numbers recover (Morley et al., in review) which may either reflect a regain in productivity due to other algal groups, or that dissolution is impacting on the diatom record during this cold episode (Swann and Mackay, 2006).

Morley et al. (2005) sought to exploit the technique of oxygen isotope analysis of diatom silica, thereby providing a complementary, yet independent proxy climate signal to either diatoms or BioSi. This technique is proving invaluable in the context of Lake Baikal paleoclimate studies because carbonates are only extremely dilute in the lake, making oxygen isotope analysis of carbonates unviable. There is the possibility of both indirect and direct influences of diatom dissolution on $\delta^{18}O_{diatom}$ values. For example, dissolution preferentially removes certain species from the sedimentary assemblage, which theoretically could influence the isotope signal by biasing potential vital effects, although such vital effects are likely to be smaller than overall analytical error Leng and Barker (2006). A recent experimental study on the direct impacts of dissolution of diatom valves on $\delta^{18}O_{diatom}$ found that while enrichment of $\delta^{18}O_{diatom}$ values occurred when diatom dissolution took place at high pH (pH 9.0), there was no significant change on $\delta^{18}O_{diatom}$ values at near neutral pH (Moschen et al., 2006). In Lake Baikal therefore, it is unlikely that dissolution will have had a significant effect on the $\delta^{18}O_{diatom}$ values observed.

Interpretations of changing $\delta^{18}O_{diatom}$ rely on knowledge of (i) the contemporary system and relative inputs from northern basin and southern basin rivers (provided mainly by Seal and Shanks (1998)) and (ii) potential confounding factors with the methodology for the technique (Morley et al., 2004). The decline in $\delta^{18}O_{diatom}$ values during GS-1 is interpreted as a relative increase in northern basin river discharge (e.g. Upper Angara, which is fed by isotopically low winter precipitation and snowmelt) and a concomitant reduction in south basin river discharge, e.g. the Selenga (Fig. 8b). These shifts in fluvial patterns are consistent with shifts in atmospheric circulation over central Asia during periods of intense cold. Extended Eurasian spring snow cover results in the weakening of the East Asian monsoon and a strengthening of the Siberian High, which causes increased aridity across the catchment of rivers to the south of Lake Baikal, including the Selenga River (Bartlett et al., 1988; Lui and Yanai, 2002; Morley et al., 2005). An increase in more arid conditions during LBGS-1 in the region to the south of Lake Baikal concurs well with pronounced expansion of more steppe-like vegetation communities, e.g. *Artemisia* and Chenopodiaceae, indicative of cooler and drier conditions at this time (Bezrukova et al., 2003; Demske et al., 2005). The hemispheric nature of this event is seen in other proxy records. For example, mean summer temperatures (reconstructed from pollen and benthic cladoceran transfer functions) from Gerzensee lake in the European Alp dropped by between 2 and 4 °C in response to slowing down of ocean circulation in the North Atlantic (Lotter, 2003).

3.4.2. Centennial cooling events in the early–late Holocene

Paleoclimate studies in the Northern Hemisphere demonstrate that after GS-1, the early to mid-Holocene was a period of warmer climate than the present day, while cooling began to occur in the last 4000–3000 years BP, and that these changes are synchronous with orbital changes and received solar insolation. Centennial cooling events associated with millennial-scale cycles have been identified (e.g. Bond et al., 1997), and are increasingly being found in archive sequences from around the world (e.g. Campbell et al., 1998; deMenocal et al., 2000; Heiri et al., 2004; Mayewski et al., 2004; Nesje et al., 2005). These cooling events during the early to mid-Holocene have been associated with pulses of freshwater discharge from the Laurentide ice sheet slowing North Atlantic THC (Teller et al., 2002), although changes in solar insolation have also been implicated (Bond et al., 2001). The existence of these cycles and events is having great resonance in current debates on global warming, hence, high priority needs to be given to understanding their causes and impacts from archives around the world.

Holocene studies from the Lake Baikal region have to date tended to still focus on phases of apparent warming according to the Blytt–Sernander stratigraphy (e.g. Karabanov et al., 2000a; Anisimov et al., 2002), but as discussed above, terms such as Atlantic and Boreal are considered to be overly restrictive and of limited value outside of western Europe (Bradbury et al., 1994). Moreover, in comparison to other regions, empirical evidence for millennial-scale cycles and centennial cooling events from sites in central Asia are under-represented. In this synthesis therefore, I adopt a different direction from previous Lake Baikal Holocene studies by assessing diatom and oxygen isotope records from BioSi in the context of centennial-scale cooling events during early to mid-Holocene. These cooling events are compared with other regions across the NH by reference to several recent studies investigating Holocene climate variability (Fig. 9).

Shortly after the LBGS-1 event, there are several other notable episodes of lower $\delta^{18}O_{diatom}$ values in the Lake Baikal isotope record (Morley et al., 2005; Fig. 9). The first occurs between c. 10.2 and 10.4 ka cal yr BP, when values decline from c. 24‰ to 20‰. This is coincident with the prominent cooling event seen at c. 10.35–10.15 ka cal yr BP in several archives from the North Atlantic and Greenland ice cores (see Björck et al., 2001 for a synthesis), was caused by a weakening of the North Atlantic THC and the southwards extension of polar waters. The cause of this change in ocean circulation is linked to reduced solar activity, as the cooling event is coincident with one of the most significant increases in ^{10}Be fluxes determined for the Holocene (Fig. 9b). Potassium records from GISP2 indicate at this time a significant strengthening of the Siberian High (Fig. 9d) (Mayewski et al., 2004) — the evidence here suggests therefore that weakening of the THC in the North Atlantic at this time has also had substantial and perhaps almost simultaneous impact on the Lake Baikal ecosystem through intensification of the Siberian High.

An extended cooling episode is evident from the Lake Baikal Holocene record, from between c. 6.6 and 5.5 ka cal yr BP; lowest values of $\delta^{18}O_{diatom}$ (c. 20.8‰) are found at 6.1 ka cal yr BP. These findings are coincident with increasing GISP2 Na^+ (ppb) (indicative of a deepening Icelandic Low (Mayewski et al., 2004)) and GISP2 K^+ (ppb) (indicative of a more intense Siberian High pattern (Mayewski et al., 1997)) concentrations. Furthermore, this cooling occurred at the same time as major glacier readvancement in central Asia (Mayewski et al., 2004), a very prominent increase in ice-rafting debris being deposited in the North Atlantic (Bond et al., 2001), and a small decline in July air temperature and arboreal pollen in the Swiss Alps (Heiri et al., 2004) (Fig. 9 b–d). Mayewski et al. (2004) suggest that this episode may also be caused by solar forcing, as there is no evidence of other major forcing factors especially freshwater input into the North Atlantic. This minimum suggests that maximum cooling was caused by an intensification of the Siberian High, altering fluvial input into the lake (Morley et al., 2005). Diatom concentrations (Fig. 9) and phytoplankton biomass estimates (Shimaraev and Mizandrontsev, 2003) also exhibit marked declines at this time, suggesting a drop in productivity linked to prevailing colder climate and extended ice cover. As well as shifts in fluvial sources in the Lake Baikal region, this cooling phase may also have had an impact on diatom production in the lake, as there is evidence of a decline in BioSi values (Colman et al., 1999).

Archive records from around the NH suggest a period of rapid-climate change and associated cooling between c. 3.2 and 2.5 ka cal yr BP, and like the event above, coincides with increasing GISP2 K^+ and Na^+ concentrations, indicative of strengthened Siberian High and Icelandic Low systems (Mayewski et al., 2004). Also apparent is a small but distinct increase in lithic grains in North Atlantic ocean sediments (Bond et al., 1997) and significant advancement of central Asian glaciers (Fig. 9). A decline in diatom concentration from c. 3 to 2.5 ka cal yr BP reflects this period of regional cooling. However, the Lake Baikal $\delta^{18}O_{diatom}$ record does not respond to this cooling event until later (c. 2.8 ka cal yr BP), representing a possible lag in the response of hydrological changes in the lake.

Towards the top of the profiles highlighted in Fig. 9, there is a major decline in $\delta^{18}O_{diatom}$ values (of about 5‰) at c. 0.6 ka cal yr BP, which occurs at the same time as the largest increase in K^+ concentrations in the GISP2 for almost 10 ka. In central Asia therefore, the Siberian High was at its strongest between 600 and 200 years ago, resulting in major hydrological changes in the Lake Baikal catchment. These changes coincide with well documented records of climate variability in the northern hemisphere during the last millennium, and these records are discussed in greater detail below.

3.4.3. Climate variability over the last millennium

In the NH over the last c. 1000 years, three distinct phases of climate are often classified in the literature: the Medieval Warm Period (MWP), the Little Ice Age (LIA) and recent warming since c. 1850 AD (see Jones and Mann, 2004 for a critical review of using these terms). These terminologies are rather simplistic and certainly overly restrictive, because they assume that 'warm' and 'cold' episodes occurred synchronously across at least the NH, although paleoclimate records increasingly show distinct regional variation (e.g. Nesje et al., 2005). While these terms still predominate throughout the literature, Jones and Mann (2004) suggest that paleoclimatologists should instead use calendar ages to precisely date where possible changes in climate of interest. In this section, both calendar ages are used where possible, but as the literature on paleoclimate over this timeframe also uses the terms MWP and LIA, these are used where necessary.

There is still debate as to the actual causes of cold episodes during the 16th–18th centuries (associated with the 'LIA'). This is especially true in relation to the relative roles of volcanic forcing (Free and Robock, 1999; Crowley, 2000), solar forcing (Shindell et al., 2001; Muscheler et al., 2007), changes in thermohaline circulation (Broecker, 2000; Lund et al., 2006) and its place as

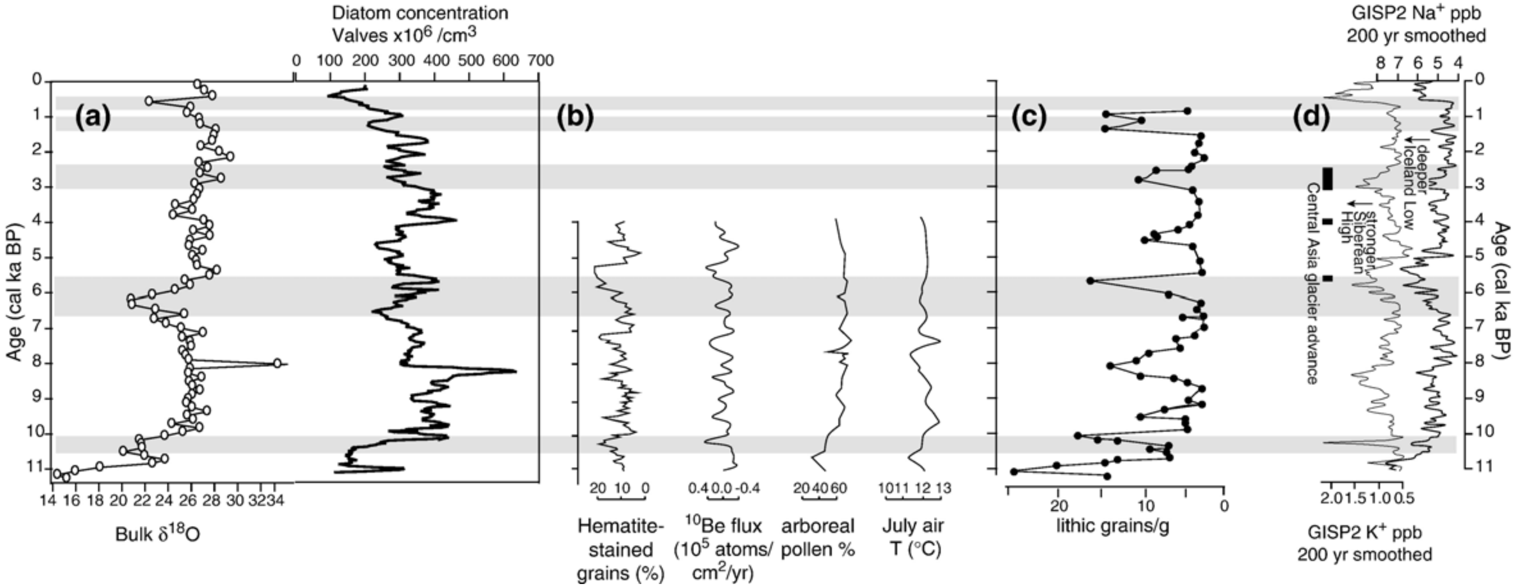

Fig. 9. Synthesis of Holocene paleoclimate records from Lake Baikal, and other records from across central Asia, northwest Europe and the North Atlantic ocean. All profiles are scaled to calendar years BP. Fig. 9(a) shows Holocene profiles for bulk $\delta^{18}O_{diatom}$ and diatom concentration of sediments for a core taken from the Vydrino Shoulder, Lake Baikal (adapted from Morley et al., 2005); (b) ice-rafted hematite stained grains in sediments from the core VM29-191 extracted from the North Atlantic ocean, off the coast of western Ireland; smoothed and detrended ^{10}Be flux in Greenland Summit ice cores; arboreal pollen from Gouillé Rion, Swiss Alps; smoothed chironomid-inferred July air temperatures from Hinterburgsee, Swiss Alps (adapted and redrawn from Heiri et al., 2004); (c) Holocene record of concentration of lithic grains (/g) again from core VM29-191 (from Bond et al., 1997); (d) Gaussian smoothed (200 yr) GRIP2 Na$^+$ (ppb) ion proxy for the Icelandic Low; Gaussian smoothed (200 yr) GRIP2 K$^+$ (ppb) ion proxy for the Siberian High; episodes of distinct glacial advances in central Asia (all adapted and redrawn from Mayewski et al. (2004)). Grey bands represent cooling events determined from the Lake Baikal $\delta^{18}O_{diatom}$ and diatom concentration records.

part of the most recent millennial-scale cycle (Campbell et al., 1998). For example, one of the coldest periods during the last 1000 years (and indeed the whole Holocene) is the Maunder Minimum (1645 AD–1715 AD), coincident with reduced sunspot activity and total solar irradiance. Mid- to high-latitude continental regions such as Lake Baikal, experience much lower temperatures than sites at similar latitude near to the North Atlantic (Bradley, 2003). Thus while global temperatures were on average only slightly lower during the 17th and 18th centuries, cooling over continental regions is estimated to be up to 5 times as great (Shindell et al., 2001). It is reasonable therefore to put forward the hypothesis that this cooling had a significant biological impact on the aquatic ecosystem of Lake Baikal.

In Lake Baikal, several empirical paleoclimate studies have focused on reconstructing change during the last 1000 years, either semi-quantitatively (e.g. Edlund et al., 1995; Mackay et al., 1998) or quantitatively (Mackay et al., 2005). Even at these relatively short timescales, distinct diatom responses to prevailing climate conditions are apparent. For example, the dominance of the autumnal blooming *C. minuta* (in core 324 extracted from the north basin) between c. 1640 AD into the early 19th century is coincident with the beginning of the Maunder Minimum, and the LIA in general (Edlund et al., 1995). They suggested that during this period of colder climate, ice and snow cover on the lake will have acted to suppress diatom communities which begin to grow under the ice in spring, resulting in the dominance of autumnal blooming taxa such as *C. minuta*. In a separate study, similar changes were shown to occur throughout the length of the lake, but that these changes were conclusively not linked to pollution of the ecosystem or to catchment processes resulting from human interference (Mackay et al., 1998). At least in a qualitative sense, prevailing climate was invoked as the main driving factor linking these basin-wide responses (ibid.).

More recently, a quantitative approach was taken, and a diatom-inferred model of snow thickness on the frozen Lake Baikal was constructed using transfer function methodologies (Mackay et al., 2003). This model was then applied to a short core extracted from the south basin, spanning the last 1200 years (Mackay et al., 2005). As detailed in Section 2, diatom dissolution is a significant process in Lake Baikal, and an attempt was made to improve bias in the model by using correction factors established for the dominant phytoplankton in the lake: *C. minuta*, *A. baicalensis*, *A. skvortzowii*, *S. meyerii* and *S. acus* (Battarbee et al., 2005) (Table 1; Fig. 10). Based on diatom composition alone, three significant zones could be recognized, coincident with the broad features of the MWP, the LIA and the period of recent warming. Ecological and quantitative interpretations demonstrated that between c. A.D. 850 and 1200, *S. acus* dominated the assemblage, most likely due to prevailing warmer and wetter climate that occurred in Siberia at this time (Fig. 10), which is reflected in high early summer temperatures derived from tree ring studies (Naurzbaev and Vaganov, 2000). These conditions will have benefited net growth of this opportunistic species over heavier, larger cells of *A. baicalensis*. Bradbury et al. (1994) outline how *S. acus* may indicate climatic conditions that result in earlier ice break-up, coupled with increased fluvial input and concomitant nutrient supply to the lake. A proxy series of Siberian High sea-level pressure (SLP) reconstructions, based on GISP2 K^+ concentrations highlights that at this time, the Siberian High was at its weakest during the last 1000 years (Meeker and Mayewski, 2002) (Fig. 10).

Between c. A.D. 1200 and 1400, spring diatom crops growing under the ice decline in abundance, due in part to increased winter severity and snow cover on the lake (Edlund et al., 1995; Mackay et al., 2005), which is reflected in cooler early Siberian summers (Fig. 10) (Naurzbaev and Vaganov, 2000). This period is associated with a weakening in the NAO, allowing the expansion of the Siberian High across central Asia (e.g. Krenke and Chernavskaya, 2002) (as indicated by increasing GISP2 K^+ concentrations; Fig. 10 (Meeker and Mayewski, 2002)), resulting in increased anticyclonic activity in the region. Intensification of the Siberian High is confirmed by a decline in $\delta^{18}O_{\text{diatom}}$ values from c. 27‰ to 22‰ at this time (Fig. 9; Morley et al., 2005). The diatom-inferred snow model suggests significantly increased snow cover on the lake between A.D. 1200 and 1775, which mirrors for the large part increases in snow cover in China during AD 1400–1900 (Zhang and Crowley, 1989). Thick, accumulating snow cover inhibits light penetration through the ice, thereby having negative effects on cell division rate and the extent of turbulence underneath the ice (Granin et al., 1999), a factor that helps diatom cells to avoid sinking down through the water column. Consequently, only taxa that whose net growth occurs during autumn overturn (e.g. *C. minuta*) predominate in the lake at this time. Estimates of diatom concentrations and fluxes during this period suggest that overall diatom productivity at this time was low (Mackay, unpublished data).

In recent decades, the impacts of global warming are increasingly being identified in lakes around the world, especially in remote regions such as the arctic (Douglas et al., 1994; Smol et al., 2005). In this respect Lake Baikal is no exception (Livingstone, 1999; Magnuson et al.,

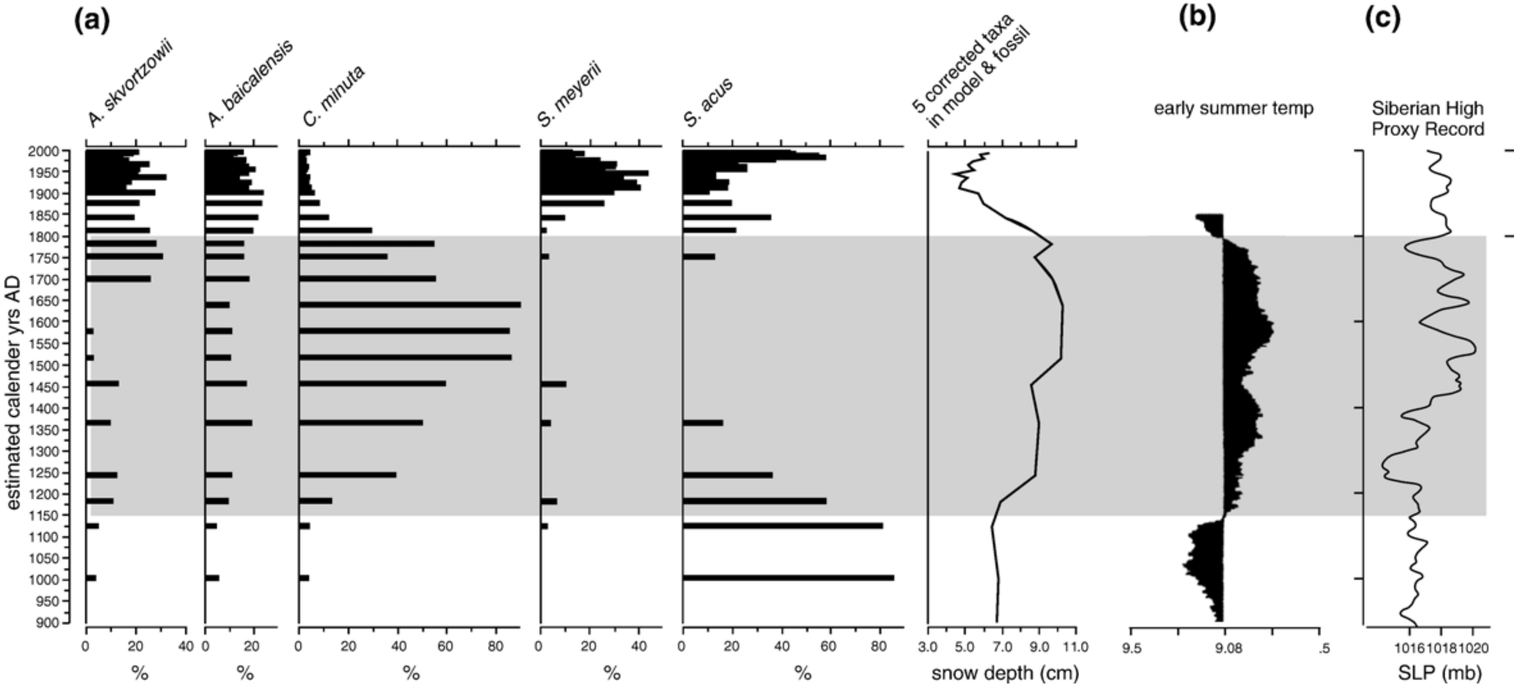

Fig. 10. Quantitative estimates of recent climate variability over the last millennium. (a) Relative percentage diatom profile using corrected values for dominant phytoplankton in core BAIK38 in the south basin of Lake Baikal, recalculated to sum to 100% and diatom-inferred snow accumulation values (Mackay et al., 2005) based on data using correction factors derived from Battarbee et al. (2005); (b) reconstructed early summer temperature (with 300-year smoothing) from tree ring variability from east Taymir and Putoran in northern Siberia spanning the last 1000 years (Naurzbaev and Vaganov, 2000); (c) Siberian High sea-level pressure GISP2 log(continental-source non-seasalt K) proxy record (Meeker and Mayewski, 2002).

2000; Shimaraev et al., 2002; Todd and Mackay, 2003). However, records of recent global warming need to be contextualised especially with respect to the extent and intensity of climate variability over the last 1000 years. Diatom census data and reconstructions of snow accumulation suggest that changes in the influence of the Siberian High in the Lake Baikal region started as early as c. 1750 AD, with a shift from taxa that bloom during autumn overturn to assemblages that exhibit net growth in spring after ice break-up (Mackay et al., 2005) (Fig. 10). The data here mirror instrumental climate records from Fennoscandia for example, which also show over the last 250 years positive temperature trends (e.g. Jones, 2001) and increasing early summer Siberian temperature reconstructions (Naurzbaev and Vaganov, 2000). Warming in the Lake Baikal region commenced before rapid increases in greenhouse gases, and at least initially, is therefore a response to other forcing factors such as insolation changes during this period of the most recent millennial cycle (e.g. Beer et al., 1996).

4. Prospectus

It is evident that over the last decade there has been great progress in reconstructing paleoclimates from Lake Baikal sediments using diatoms and biogenic silica. Over the Quaternary, insolation changes due to shifts in orbital parameters and non-linear responses to global ice volume and changes in oceanic thermohaline circulation processes have had major impacts on the aquatic ecosystem over glacial–interglacial cycles. These impacts are responsible for dramatic shifts in diatom productivity in the lake and in driving speciation of endemic pelagic diatoms. Increasingly, higher resolution studies of both interglacial, interstadial and termination periods show that the lake has responded to abrupt and rapid shifts in climate caused by the reorganization of North Atlantic ocean circulation, highlighting the importance of teleconnections between these two distant regions. However, diatoms are prone to secondary processes such as dissolution, and where possible these need to be accounted for, especially when using species composition within sediments to make semi-quantitative and quantitative estimates of past climate variability (e.g. Mackay et al., 2005). So, what does the future hold for paleoclimate research in Lake Baikal with respect to diatoms?

4.1. Improved ecological information

In order to better understand the ecological characteristics of diatom species in Lake Baikal, three approaches have been taken. The first of these is a laboratory approach, and involves culturing the main phytoplankton species to identify their nutrient and biophysical requirements (temperature and light) (Richardson et al., 2000; Bondarenko and Guselnikova, 2002; Jewson et al., unpublished). However, the majority of species have not been investigated in this way, yet are important components of the phytoplankton during earlier time periods. For example, *Crateriportula inconspicua* (Mak. & Pom.) Flower & Håkansson is a major component of the diatom assemblage in the south basin from early to mid-Holocene (Morley, 2005) and also dominant for most of the Holocene at Continent Ridge in the north basin, yet its ecology is still poorly known, limiting paleoenvironmental interpretations. A second approach involves spatial and temporal monitoring studies of diatoms. Phytoplankton in Lake Baikal has been monitored for many decades now (e.g. Rychkov et al., 1989; Bondarenko, 1999; Popovskaya, 2000), yet the majority of these studies are restricted in their location (invariably in the south basin). The results of a long-term intensive monitoring programme (15 years) covering the whole of the lake are currently being collated and analyzed and these data will provide important information with respect to diatom populations, seasonal succession, grazing and relationships with hydrophysical and hydrochemical variables (e.g. Granin et al., 1999; Morley, 2005). Third, the use of multivariate techniques such as ordination and the construction of training sets encompassing environmental gradients of interest can provide useful information on variables that significantly account for spatial differences in diatoms around the lake (Mackay et al., 2003). These models can be improved upon using remote sensing of snow and ice cover, together with advanced multiple regression techniques such as generalized linear models (Morley, 2005; Mackay et al., 2006). Taking all these together, there are still substantial in-roads to be made to improve our understanding of the ecological characteristics of the common diatom species in the lake. These inroads are made particularly challenging due to taxonomic complexities of Lake Baikal diatoms. For example, many taxa are yet to be formally described, especially for (i) 'small' benthic taxa that occur in the littoral regions of the lake, and (ii) for both planktonic and benthic taxa which have been found in pre-Holocene sediments, and which now are extinct. There is great scope for more taxonomical work to be undertaken, if even for a modern comprehensive diatom flora to be published.

4.2. Establishing chronologies for high resolution reconstructions

Developing coherent and robust chronologies for paleoclimate studies from Lake Baikal sediments has proved challenging. Methods applied to Lake Baikal sediments include: ^{210}Pb dating for the most recently deposited sediments (Edgington et al., 1991; Appleby et al., 1998; Carroll et al., 1999), ^{14}C dating using AMS techniques (Colman et al., 1996; Piotrowska et al., 2004), palaeomagnetic dating and core correlation (Sakai et al., 2000; Demory et al., 2005), U-series dating (Goldberg et al., 2000), luminescence dating (Rogalev et al., 1998), ^{10}Be (Sapota et al., 2004), correlation to SPECMAP (e.g. Peck et al., 1994; Colman et al., 1995; Williams et al., 1997) and astronomically tuning (Prokopenko et al., 2006). Here is not the place to provide a critique of the strengths and limitations of each of these techniques, but it is useful to focus briefly on radiocarbon dating, as the time-span which this technique covers is of immense relevance to human dispersal and occupation in central Asia within the timeframe of e.g. rapid and abrupt periods of climate change (Chlachula, 2001). Pelagic sediments in Lake Baikal contain relatively low concentrations of organic matter (<c. 1%), no authigenic carbonates and very few plant macrofossils, which makes radiocarbon dating challenging. For example, contamination by older carbon can have a relatively larger impact, resulting in non-zero surface ages (Colman et al., 1996). Although corrected ages have been developed, e.g. for BDP-98 extracted from Buguldeika Saddle to the south of the lake (Colman et al., 1996), comparisons between some Holocene BDP studies has proved difficult because other studies, e.g. Karabanov et al. (2000a) revert to using uncorrected ages to reconstruct paleoclimate variability. In an attempt to improve radiocarbon dating, and as recommended by Colman et al. (1996), Piotrowska et al. (2004) extracted pollen grains for AMS analysis from narrow bands of sediments from three selected sites in Lake Baikal (Vydrino Shoulder, Posolsky Bank and Continent Ridge; Fig. 1), which has led to decreased uncertainty in terms of accuracy and precision. These advancements are important because they allow more refined questions to be asked with respect to: (i) rapid and abrupt periods of climate change (Alverson and Oldfield, 2000), (ii) the regional complexity of warm and cold periods, getting away from broad uninformative terms such as LIA and MWP (Jones and Mann, 2004), and (iii) the impact of quasi-periodic climate cycles on remote ecosystems (Witt and Schumann, 2005). However, while advancements are being made with respect to constructing chronologies for Late Glacial–Holocene sediments, accurately dating diatom-inferred paleoclimates during previous interstadials and interglacials is much more challenging. Few absolute dates exist prior to c. 40 ka BP, and although techniques such as luminescence dating have been shown to be possible (Rogalev et al., 1998), problem of quartz grains being contaminated by feldspars is still a problem. There is therefore a greater need to improve both resolution in sedimentary profiles and chronology reconstruction to enable increasingly sophisticated research questions to be addressed.

4.3. High resolution reconstructions

Both endemic and cosmopolitan diatoms in Lake Baikal respond quickly to changes in climate. Contemporary monitoring studies have for many years now characterized the population succession trends between diatom species, and a notable feature of these studies is the occurrence of '*Melosira*' years. '*Melosira*' years are characterized by large increases in the number of *A. baicalensis* cells every 2–4 years. However, even in sediments sectioned at continuous 2 mm intervals (corresponding to 2–3 years deposition) (Mackay et al., 1998) these fluctuations are not apparent, most likely due to low-level bioturbation (Martin et al., 2005) and dissolution (Ryves et al., 2003) on the bottom sediments. An alternative approach to investigating diatom trends in Lake Baikal sediments has been taken by Francus and Karabanov (2000) and Boës et al. (2005), using thin sectioning techniques. These approaches highlight the fact that occasionally in the sediment record, monospecific laminae and lenses are apparent, e.g. *A. baicalensis* and *S. acus* (Francus and Karabanov, 2000; Karabanov et al., 2000a; Fig. 7b) suggesting that conditions were sometimes suitable for rapid deposition and burial of diatom valves, before bioturbation and dissolution had a major impact. As yet, the significance of these occurrences are not well understood, although they may be related to rapid deposition events, such as '*Melosira*' years described above.

Boës et al. (2005) constructed grey scale measurements from Lake Baikal thin-sections, thereby deriving very high resolution archives of c. 20 µm (<1 year resolution) covering the late glacial, Termination 1 and the Holocene. Increases in grey scale values are related to concentrations of diatoms in the sediments, and are suggested to be indicative of periods of warmer prevailing climate in the Lake Baikal region. There is great potential to exploit this technique further, to investigate abrupt changes in climate at decadal to pluriannual scales during other time-periods of interest, including glacials, associated terminations, interstadials and interglacials. Although such changes will help our understanding of species responses to abrupt climate change, until chronologies are further improved for pre-Holocene sequences, the debate on whether Lake Baikal climate responses lag those of e.g. the North Atlantic will still be affected by uncertainty.

4.4. Multiproxy reconstructions

The majority of paleoclimate work utilizing Lake Baikal sediments has been mono-proxy studies, focusing on e.g. only diatoms, or BioSi or pollen. Increasingly however, multiproxy studies offer the potential to provide independent lines of evidence for paleoclimatic reconstruction (Birks and Birks, 2006). This synthesis has focused only on diatoms and BioSi, but chemical analysis of the sediments indicates that it is possible to reconstruct the presence of other algal groups using breakdown products of photosynthetic pigments (Fietz et al., 2005) and major lipid classes of *n*-alkanes, fatty acids and sterols (Russell and Rosell-Melé, 2005). Assessing these compounds down core, together with diatoms, pollen and molecular marker compounds such as lignin oxidation products (Orem et al., 1993) will build a much more complete picture of biological productivity in and around the lake throughout the year, and not just during periods of overturn (Popovskaya, 2000). Ideally, different proxies ought to be extracted from the same samples because of known problems of core correlation in any lake, although this can pose problems in terms of quantities of sediment material available. Two other potential avenues of research involves the reconstruction of silicon isotopes from diatom silica in Lake Baikal sediments and the recently developed TEX_{86} ratio as a proxy for paleotemperature (Schouten et al., 2002).

Increasingly the silicon isotope composition of diatoms is being explored as a potential proxy of past environmental conditions, such as changes to silicon cycling in the Southern Ocean between the last glacial maximum and the Holocene (e.g. De La Rocha et al., 1998). However, the composition of silicon isotopes in freshwater environments is poorly understood, although recent work has been carried out on the Yangtze River, China (Ding et al., 2004), Lake Tanganyika (Alleman et al., 2004) and a pilot project on Lake Baikal itself as part of the EU Continent programme (Alleman, unpublished data). Given the nature of silica recycling in Lake Baikal, the importance of BioSi for paleoclimatic reconstructions, and the problems of diatom dissolution at the sediment surface–water interface make the use of δ^{29}Si isotope analysis to reconstruct paleoproductivity a potentially very important methodology. Work is ongoing as part of the EU *Continent* programme to reconstruct the relative abundances of different lipid membranes (TEX_{86}) (Escala et al., 2007) of Crenarchaeota organisms which are widely found in marine and lake ecosystems (Powers et al., 2004). This technique offers great potential is providing past temperature reconstructions, which will complement hydrological-inferred changes derived from $\delta^{18}\mathrm{O}_{\mathrm{diatom}}$ values especially in interglacial sequences.

A major goal for paleoclimate researchers is to relate modeled changes in climate to impacts on the Lake Baikal ecosystem. This can be done qualitatively by comparing proxy records with modeled climate. However, a more sophisticated approach would involve constructing a ‘forward model’ of Lake Baikal diatoms, which can be driven by a range of physical and climatic parameters. Recent attempts have been made to model the impact of anthropogenic disturbance on the lake's biota using an ecosystem disturbance model (Silow et al., 2001). Initial results suggest all components of the planktonic communities become disturbed, especially under-ice diatom communities, together with an overall increase in nutrient concentration and increase in summer phytoplankton biomass. These changes are similar to those predicted by future climate variability (Mackay et al., 2006) and it is now important therefore that refined models are developed to take account of interactions between localized eutrophication and climate change impacts on the lake's ecosystem.

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