

1 Diatom evidence of 20th Century ecosystem change in Lake 2 Baikal, Siberia

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22 **Highlights:**

- 23 • This study tests predictions that regional atmospheric warming would result in substantial
24 shifts in diatom communities in Lake Baikal, characterised by an increase in lighter, littoral
25 diatom species (including cosmopolitan varieties) at the expense of endemic, heavily silicified
26 open water species.
- 27 • In the south basin of Lake Baikal, we find significant change in diatom assemblages over the
28 past 40+ years, consistent with predictions of warming surface waters.
- 29 • No discernible change is evident in diatom assemblages in the north basin of the lake over the
30 past 40 years.
- 31 • We find no evidence to date for cultural eutrophication in deep water sediments from Lake
32 Baikal.

33

34 **Abstract**

35

36 Lake Baikal has been experiencing limnological changes from recent atmospheric warming since the
37 1950s, with rising lake water temperatures, reduced ice cover duration and reduced lake water mixing
38 due to stronger thermal stratification. This study uses lake sediment cores to reconstruct recent changes
39 (c. past 20 years) in Lake Baikal's pelagic diatom communities relative to previous 20th century diatom
40 assemblage records collected in 1993 and 1994 at the same locations in the lake. Recent changes
41 documented within the core-top diatom records are in agreement with predictions by Mackay et al
42 (2006) and Moore et al (2009) of diatom responses to warming at Lake Baikal. Sediments in the south
43 basin of the lake exhibit clear temporal changes, with the most rapid occurring in the 1990's with shifts
44 towards higher abundances of the cosmopolitan *Synedra acus* and a decline in endemic species, mainly
45 *Cyclotella minuta* and *Stephanodiscus meyerii* and to a lesser extent *Aulacoseira baicalensis* and
46 *Aulacoseira skvortzowii*. The north basin, in contrast, shows no evidence of recent diatom response to
47 lake warming despite marked declines in north basin ice cover in recent decades. This study also shows
48 no diatom-inferred evidence of eutrophication from deep water sediments. However, due to the
49 localised impacts seen in areas of Lake Baikal's shoreline from nutrient pollution derived from out-
50 dated sewage treatment plants, urgent action is vital to prevent anthropogenic pollution extending into
51 the open waters.

52

53 **1. Introduction**

54

55 In recent decades, lakes around the world have experienced increased surface water temperatures
56 (O'Reilly et al., 2015; Hampton et al., 2018). The impacts of this warming are numerous but include
57 changes in the vertical thermal structure of the water column and longer ice-free seasons, together with
58 shifts in ecosystem structure and function (Smol et al., 2005; Saros et al., 2012, 2013; O'Reilly et al.,
59 2015; Hampton et al., 2017). For example, lakes have experienced community compositional changes
60 such as large-scale shifts in plankton, with increases in taxa (such as picocyanobacteria) which are better
61 adapted to reduced turbulent mixing (Findlay et al., 2001; Bopp et al., 2005; Hampton et al., 2008;
62 O'Beirne et al., 2017; Reavie et al., 2017; Edlund et al., 2017). These changes are not restricted to small
63 – medium sized water bodies. Very large lakes, including the Laurentian Great Lakes, Lake Tahoe
64 (North America) and Lake Tanganyika (East Africa), have also experienced shifts in their biological
65 communities and autochthonous primary production (Winder et al., 2009; Shaw Chraïbi et al., 2014;
66 Cohen et al., 2016; O'Beirne et al., 2017; Reavie et al., 2017; Hampton et al., 2018). At the same time,

67 lake ecosystems are also sensitive to the impacts of climate warming on watershed processes, which
68 can lead to alterations of fluvial inputs, including the flux of nutrients to lakes and the browning of lake
69 waters from increased dissolved organic matter (DOM) input (Magnuson et al., 2000; Yoshioka et al.,
70 2002, Hampton et al., 2008; Edlund et al., 2017; Creed et al. 2018). Such changes can influence
71 autotrophic algal and bacterial communities through changes in nutrient cycling and light availability
72 (Wrona et al., 2006; Attermeyer et al., 2014).

73
74 Lake Baikal, the world's oldest, deepest, and most voluminous lake, is experiencing impacts from
75 climate warming. Atmospheric temperatures in the region around Lake Baikal in southern Siberia have
76 increased significantly in recent decades, with mean annual surface air temperatures in the nearby city
77 of Irkutsk (Figure 1) rising from -5.8°C to 0.3°C over the last 20 years (Shimaraev and Domysheva,
78 2013). Atmospheric temperature data from a climate station in Nizhneangarsk (Figure 1), in the north
79 basin catchment area of Baikal, similarly shows a less pronounced warming trend from -1.27°C to
80 0.48°C between 1952 and 2013 CE (mean annual temperatures; <http://climexp.knmi.nl/>). The scale of
81 recent atmospheric warming, regionally, is unprecedented for the past 1000 years (Davi et al. 2015).
82 Concordant with recent warming, summer surface lake water temperatures have increased by over 2°C
83 over the past 60 years (Hampton et al., 2008; Moore et al., 2009; Izmet'seva et al. 2016), alongside
84 seasonal changes to ice cover dynamics (Todd and Mackay, 2003; Sizova et al. 2013). Shorter ice cover
85 and warmer water temperatures have led to marked increases in chlorophyll-*a* concentrations and
86 summer plankton biomass in the south basin of Lake Baikal over the past 60 years (Hampton et al.,
87 2008; Moore et al., 2009; Hampton et al., 2014; Hampton et al., 2015; Izmet'seva et al., 2016; Silow et
88 al., 2016).

89
90 Further 21st Century warming is predicted to trigger additional plankton community change with a shift
91 from the production of endemic, heavily silicified diatoms towards lighter, littoral diatoms and
92 autotrophic picoplankton (APP) (Popovskaya 2000; Mackay et al., 1998; Fietz et al., 2005; Mackay et
93 al., 2006; Moore et al., 2009). For example, Mackay et al. (2006) predicted that future reductions in ice
94 duration associated with regional warming, would result in enhanced transport of littoral diatoms to
95 pelagic regions, such as *Stephanodiscus meyerii* and *Synedra acus*, concomitant with the decline in
96 endemic pelagic species such as *Aulacoseira baicalensis* and *Cyclotella minuta*. These changes may be
97 enhanced by elevated spring run-off from increased precipitation (IPCC 2014), increasing silicon and
98 other nutrient delivery to the lake, further encouraging the growth of species such as *Synedra acus*
99 (Bradbury et al., 1994; Mackay et al., 2006), while also altering carbon cycling in the lake due to
100 enhanced delivery of dissolved organic carbon (DOC) and particulate organic carbon (POC) (Yoshioka
101 et al. 2002; Moore et al. 2009).

102

103 To date, these predictions at Lake Baikal have largely been made from diatom records collected in the
104 early 1990's (Mackay et al. 1998; 2006). In this paper, we test these predictions and assess whether the
105 diatom flora in Lake Baikal has indeed undergone shifts in community composition in response to the
106 major increases in global and regional atmospheric temperatures over the past 20 years (IPCC 2014).
107 In particular we examine whether there has been a transition from a flora dominated by heavily-silicified
108 endemic species to one that is more cosmopolitan with lighter, less-silicified species (Mackay et al.,
109 2006; Hampton et al., 2008, 2014, 2015; Moore et al., 2009; Izmet'seva et al., 2016).

110

111 **2. Methodology**

112

113 **2.1. Short cores**

114

115 Short cores (< 65 cm) were collected in March and August 2013 from 7 coring stations across the
116 southern and northern basins of Lake Baikal, as well as Maloe More Bay, a relatively isolated bay off
117 the central basin (Figure 1). The codes used to define the locations of these coring sites across Lake
118 Baikal include south basin (SB), nearby the Selenga Delta (SD), at the Buguldieka Saddle (BS), Maloe
119 More bay (MM) and north basin (NB), and these have been applied after the original coring site codes.
120 Cores were collected using a UWITEC corer with PVC-liners (\varnothing 63 mm), which provided complete
121 and undisturbed recovery of the sediment/water interface. All coring stations were > 5 km from the
122 shore with some sites coinciding with previous short cores taken in 1993 and 1994 – see Table 1 and
123 Mackay et al. (1998) for details. Several cores were collected at each station. One core was sub-sampled
124 in the field at a resolution of 0.2 cm and transported to the UK for diatom analyses and ^{210}Pb radiometric
125 dating, and at least one other core was transferred to the Institute of the Earth's Crust (Irkutsk) before
126 being cut, photographed and lithologically described, based on smear slide inspection. A Bartington
127 MS2E High Resolution Surface Scanning Sensor (Bartington Instruments, 1995) was used for non-
128 destructive measurement of magnetic susceptibility (MS), with a resolution of 1 cm and reproducibility
129 of <5%.

130

131 **2.2 Diatom Analysis**

132

133 Surface sediment samples (upper 2 cm) covering at least the last 30 years were analysed for diatoms,
134 enabling overlap with published diatom records covering the interval prior to this (Mackay et al., 1998).
135 Sample preparation followed previous protocols for diatom analysis on Lake Baikal sediment samples
136 with no chemical treatments in order to minimise valve breakage, especially of lightly silicified diatom

137 species (Flower, 1993; Mackay et al., 1998). To calculate diatom concentrations (10^4 valves/g dry
138 weight), a known weight of divinylbenzene microspheres (approximately 1 – 2 g) was added to the
139 cleaned samples (Battarbee and Kneen, 1982). Subsamples of the suspensions were diluted and settled
140 out onto coverslips and fixed onto slides with Naphrax on a hotplate at 130°C. A total of 300 valves
141 were counted at x1000 magnification by using an oil immersion lens and phase contrast under a Zeiss
142 Axioskop 2 plus light microscope.

143

144 Diatom dissolution also plays a role in shaping sedimentary diatom assemblages, because some species
145 are more heavily silicified (*A. baicalensis*) than others (*S. acus*) and consequently more resistant to
146 dissolution (Ryves et al. 2003). Diatom dissolution was estimated by categorising endemic diatom
147 species; *Aulacoseira baicalensis* (Meyer) Simonsen, *Aulacoseira skvortzowii* (Edlund, Stoermer and
148 Taylor), *Cyclotella baicalensis* (Meyer) Skv., and *Cyclotella minuta* (Skv.) Antipova, into three stages
149 of valve preservation. A diatom dissolution index (DDI) (Flower and Likhoshway, 1993) was then
150 calculated to quantify the extent of diatom preservation in every sample (Ryves et al., 2009). A DDI
151 value of 0 indicates that all diatom valves are affected by dissolution, while a DDI value of 1 indicates
152 that all the diatom valves are in a pristine condition. Indices have been combined to express the index
153 as dissolution per sample. There is possibly a third endemic *Cyclotella* species, *Cyclotella ornata*
154 (Flower 1993) of intermediate size between *C. baicalensis* and *C. minuta*. However, Jewson et al.
155 (2015) suggest that it most likely belongs to one of the other two species. Either way, in sedimentary
156 material the centre areas of these valves are often indistinguishable from the central areas of *C. minuta*
157 valves after breakage and dissolution. Here we group potential *C. cf. ornata* valves in with *C. minuta*
158 (*C. minuta* agg.), which also makes comparisons with earlier studies, e.g. Mackay et al. (1998)
159 consistent.

160

161 **2.3 Chronology**

162

163 Dried sediments from cores BAIK13-4F_SB, BAIK13-7A_SB, BAIK13-10A_SD, BAIK13-11C_BS,
164 BAIK13-14C_MM, BAIK13-18A_NB and BAIK13-19B_NB (Figure 1) were analysed for ^{210}Pb , ^{226}Ra ,
165 ^{137}Cs and ^{241}Am , by non-destructive direct gamma spectrometry (Appleby et al., 1986) at the UCL
166 Environmental Radiometric Facility, using an ORTEC HPGe GWL series well-type coaxial low
167 background intrinsic germanium detector. Age-depth models were constructed using polynomial
168 regressions fitted to the ^{210}Pb data with additional degrees added until no improvement occurred in the
169 fitted model under an ANOVA test at the 95% confidence interval.

170

171 **2.4 Statistical Analysis**

172

173 To constrain how diatom assemblages in the core-tops (representing material over the past c. 20 years)
174 have differed through the 19th and 20th Centuries, squared chord distance (SCD) dissimilarity scores
175 were determined for cores BAIK13-7A_SB, BAIK13-11C_BS and BAIK13-18A_NB using R (R Core
176 Team, 2013). These cores overlap with previously published cores BAIK38_SB, BAIK19_BS and
177 BAIK29_NB respectively (Table 1), and the results can be used as a baseline to evaluate whether diatom
178 assemblages have significantly altered since the 1990's (Mackay et al., 1998). Ranging between 0 and
179 5, a SCD score of 0 indicates that the diatom assemblages in two samples are identical, whereas a score
180 of 5 indicates samples are completely different in their diatom assemblage composition. Breakpoint
181 analysis was carried out on the SCD scores in R using the *segmented* library (Muggeo, 2008; R Core
182 Team, 2013).

183

184 Temporal changes in the diatom assemblages were further visualised using principal components
185 analysis (PCA) of major taxa in all core-top samples collected in 2013 together with data from the
186 overlapping cores collected in 1993/1994 (Table 1). Following detrended correspondence analysis
187 (DCA), which demonstrated a linear response based on the gradient length of the first axis, data were
188 reanalysed using PCA with square root transformation of species abundances using Canoco 4.5 (ter
189 Braak and Šmilauer, 2002).

190

191 **3. Results**

192

193 **3.1. Core lithology**

194

195 All cores were dominated by terrigenous material with varying levels of oxidation due to the complete
196 fully oxygenated water column (Figure 2). Turbidites were present in cores BAIK13-4C_SB and
197 BAIK13-18C_NB, but the uppermost turbidites (2.0–5.3 cm in BAIK13-4C_SB; 22.0–49.8 cm in
198 BAIK13-18C_NB) occurred below the samples analysed in this study and are therefore not discussed
199 further.

200

201 **3.2. ²¹⁰Pb age models**

202

203 Total ²¹⁰Pb activity reaches equilibrium with supported ²¹⁰Pb at a depth of 9 cm (BAIK13-4F_SB), 4
204 cm (BAIK13-7A_SB), 13 cm (BAIK13-10A_SD), 10 cm (BAIK13-11C_BS), 7 cm (BAIK13-
205 14C_MM), 3 cm (BAIK13-18A_NB) and 5.5 cm (BAIK13-19B_NB) (Figure 3). At all sites, ²¹⁰Pb

206 dates were calculated using the constant rate of ^{210}Pb supply (CRS) model (Appleby and Oldfield,
207 1978), and where possible, dates independently verified using ^{137}Cs and ^{241}Am data. For example, a
208 well resolved ^{137}Cs activity peak at 5.5-5.7 cm agrees with ^{210}Pb dated sediments at BAIK13-4F_SB.
209 At BAIK13-10A_SD, ^{137}Cs activity shows a broad peak at 6.7-8.5 cm, and because ^{241}Am peaks at 8.3
210 cm, this represents the 1963 CE (common era) peak in radioactive fallout; the ^{210}Pb date at 1963 falls
211 in this range. At BAIK13-11C_BS, ^{210}Pb dating can be confirmed with peaks of ^{137}Cs at both 1986 CE
212 and 1963. At BAIK13-14C_MM, high ^{137}Cs activities in top 4.1cm concur with ^{210}Pb dating that these
213 sediments were deposited since 1963. At BAIK13-18B_NB, the peak in ^{137}Cs activity between 0.7-
214 1.1cm concurs with CRS ^{210}Pb dating of 1986 being between 0.7-1.1cm, so this peak likely represents
215 Chernobyl accident in 1986. At only two sites, BAIK13-7A_SB and BAIK13-19B_NB, were ^{137}Cs and
216 ^{241}Am activities not able to be used to confirm ^{210}Pb dating. For all sites, the final age-depth model
217 shows a good fit to the ^{210}Pb dates with an adjusted $R^2 > 0.99$ (Figure 3). Mean uncertainty in the
218 individual ^{210}Pb dates across all four cores ranges from 2-36 years is: BAIK13-4F_SB: $\bar{x} = 8$, range =
219 2-30; BAIK13-7A_SB: $\bar{x} = 3$, range = 2-6, BAIK13-10A_SD: $\bar{x} = 7$, range = 2-20; BAIK13-11C_BS:
220 $\bar{x} = 12$, range = 2-36; BAIK13-14C_MM: $\bar{x} = 8$, range = 2-26; BAIK13-18A_NB: $\bar{x} = 8$, range = 2-15;
221 BAIK13-19B_NB: $\bar{x} = 11$, range = 2-24 (Figure 3).

222

223 3.3. Diatom profiles

224

225 3.3.1 South basin sites

226

227 In the south basin, at BAIK13-4F_SB (Figure 4) *S. acus* increased from 7% to 22% abundance over the
228 top 2 cm of the core (2006–2013 CE). Over the same interval *A. baicalensis* declined from 26% to 24%,
229 along with *A. skvortzowii* (decrease from 8% to 5%). *C. minuta* agg. varies between 35% to 51% relative
230 abundance and *S. meyerii* varied between 2% to 5%. Diatom concentrations in the upper sediments
231 ranged between 85.1 to 147.1 x 10⁴ valves/g DW over the last decade.

232

233 In the south basin, at site BAIK13-7A_SB (Figure 5) there was a good overlap with the core diatom
234 assemblages from BAIK38_SB in Mackay et al. (1998) between 0.9–1.9 cm. *S. acus* relative
235 abundances in the surface sediment assemblages from BAIK13-7A_SB ranged from 6% to 18%, *A.*
236 *baicalensis* ranged from 25% to 41% relative abundance over the last c. 40 years between 1975 – 2013,
237 and *Cyclotella minuta* agg. ranged between 38% and 24%. Diatom concentrations ranged between 540.8
238 to 98.5 x 10⁴ valves/g DW over the last c. 33 years (1980 – 2013 CE). Diatom dissolution index (DDI)
239 values fluctuated between 0.5 to 0.8.

240

241 In the south basin, at site BAIK13-10A_SD (Figure 4), in the shallow waters off the coast of the Selenga
242 Delta, the diatom assemblage diversity (> 2% abundance) was higher than the core tops in this study,
243 with *Stephanodiscus parvus* (1–3% abundance), *Staurosira construens* var. *venter* (1-3% abundance),
244 *Fragilaria ulna* (2-4% abundance), *Fragilaria capucina* (1-9% abundance), *Achnantheidium*
245 *minutissimum* (1–3% abundance), *Staurosirella pinnata* (1-4% abundance) and *Cocconeis placentula*
246 (1–2% abundance). Over the top 2 cm (2009-2013 CE), percentage abundances remained relatively
247 consistent for *A. baicalensis* (range between 9-17%), *A. skvortzowii* (ranged between 22-31%), *C.*
248 *minuta* agg. (ranged between 13-18%) and *S. acus* (ranged between 10-17%), while *S. meyerii* ranged
249 from 13% to 2% abundance.

250

251 At site BAIK13-11C_BS, in the waters of the Buguldieka Saddle opposite the Selenga Delta (Figure
252 1), there was a good overlap between 2.4–2.6 cm with the diatom assemblages from BAIK19_BS in
253 Mackay et al. (1998) (Figure 5). The upper 2.3 cm in BAIK13-11C_BS showed a decreasing trend in
254 *A. baicalensis* to abundances of c. 14% and *C. minuta* agg. to abundances of c. 20% and increasing
255 abundances of *S. acus* to abundances of > 20% over the last c. 20 years (1993-2013 CE). Diatom
256 concentrations showed a decreasing trend towards the surface sediments, from concentrations of 648.5
257 x 10⁴ valves/g DW to 241.1 x 10⁴ valves/g DW over the last c. 80 years (1930-2013). DDI values
258 fluctuated between 0.4 to 0.7.

259

260 3.3.2 Maloe More Bay

261

262 In Maloe More bay, off of the central basin, at site BAIK13-14C_MM, in the shallow waters of the
263 Maloe More (Figure 4), *A. baicalensis* (range = 13–20%), *A. skvortzowii* (range = 3-8%), *C. minuta*
264 agg. (range = 19-31%), *S. acus* (range = 9-15%) and *Crateriportula inconspicua* (range = 4-6%)
265 remained relatively consistent in abundance over the 2 cm (2002-2013 CE). However, over the same
266 interval *S. meyerii* ranged from 22-13% abundance, and diatom concentrations ranged between 78.7 to
267 486.2 x 10⁴ valves/g DW.

268

269 3.3.3 North basin sites

270

271 In the centre of the north basin, at site BAIK13-18A_NB (Figure 1) there was a good overlap between
272 0.8–1.9 cm with the assemblages from BAIK29_NB in Mackay et al. (1998) (Figure 5). Assemblages
273 within the upper 2 cm of BAIK13-18A_NB showed a decreasing trend in *A. baicalensis* (from c. 60%
274 to c. 50%) and *S. acus* ranged from c. 6% to 1% (Figure 5). *C. minuta* agg. ranged in abundance between
275 c. 20% to 30% over the last c. 80 years (1930–2013 CE). DDI values fluctuated between 0.5 to 0.7 and

276 before the surface sediments, diatom concentrations showed a decreasing trend, from concentrations of
277 129.5 to 12.4 x 10⁴ valves/g DW between c. 1876–1992 CE.

278

279 In the north of the north basin, at site BAIK13-19B_NB (Figure 4), *A. baicalensis* and *C. minuta* agg.
280 varied between 65-74% and 12-17% respectively, while there was little change in both *A. skvortzowii*
281 and *C. inconspicua* (1–4% and 2-3% respectively). *S. meyerii* showed a small decline from 5-1.3% over
282 the top 2 cm (1984-2013 CE) with diatom concentrations ranging between 129.5 to 455.6 (10⁴ valves/g
283 DW) over the last 30 years.

284

285 **3.4. Temporal changes in the diatom assemblages**

286

287 DDI values are > 0.5 in all samples, suggesting that the majority of the valves, which make it into the
288 sedimentary record are well preserved (Ryves et al., 2003). Squared chord distance (SCD) dissimilarity
289 scores (Figure 5) showed that surface sediment diatom assemblages in the south basin (BAIK13-
290 7A_SB) and Buguldieka Saddle (BAIK13-11C_BS) were significantly different from older diatom
291 assemblages determined from BAIK38_SB and BAIK19_BS respectively. In the south basin, the
292 significant change in SCD values occurred at c. 1970 CE ($p < 0.001$; Figure 5). At the Buguldieka
293 Saddle, breakpoint analysis of the SCD scores showed that a significant shift to the modern-day
294 assemblage occurred later, at c. 2000 CE (p value < 0.001) (Figure 5). In contrast, diatom assemblages
295 have changed very little in the north basin over the past 60 years, with no significant breakpoints found
296 in the SCD scores at BAIK13-18A_NB (Figure 5).

297

298 PCA of all diatom assemblages investigated here revealed a difference between the core top samples
299 analysed in this study and all samples in the older, overlapping cores from Mackay et al. (1998). Core
300 tops collected in 2013 contained higher abundances of *S. acus*, *A. skvortzowii* and *S. meyerii*, and lower
301 abundances of *A. baicalensis* (Figure 6). Axis one explained 47% of the variance in the dataset and is
302 driven largely by the pelagic species *A. baicalensis* (species score = +0.98) versus species linked to
303 littoral habitats, mainly *S. acus*, *A. skvortzowii*, (and to a lesser extent *S. meyerii*). Axis two explained
304 24% of the variance in the dataset and is driven by a gradient of pelagic *C. minuta* agg. versus the
305 smaller *C. inconspicua* species (Figure 6).

306

307 **4. Discussion**

308

309 **4.1 Diatom ecology and spatial variability**

310

311 The observed spatial distributions of the most common planktonic diatoms in Lake Baikal surface
312 sediments (summarised by PCA in Figure 6) are linked to complex interactions between lake
313 morphology and chemistry, against a backdrop of a strong climatic gradient associated with the lake
314 spanning over 4 degrees of latitude (Mackay et al., 1998, 2006; Likhoshway et al., 2005). When the
315 lake is frozen (between November and March), and during both spring and autumn turnover periods,
316 siliceous diatoms dominate primary production (Jewson et al., 2009). During summer months however,
317 surface water temperatures increase and lake surface waters stratify, resulting in the seasonal succession
318 to mainly non-siliceous, autotrophic picoplankton. These non-siliceous algae effectively compete for
319 nutrients such as phosphate and nitrate (Belykh & Sorokovikova 2003), making them unavailable for
320 most diatoms growing in the open lake. Picoplankton are well adapted to thrive within summer stratified
321 waters as they are able to adjust their position within the water column, unlike heavy diatoms, and can
322 avoid high solar radiation and move to waters depths with favourable nutrient concentrations and
323 temperatures (Hampton et al., 2008).

324
325 PC1 is dominated by the gradient between *A. baicalensis* (associated with north basin, deep-water
326 surface sediments; species score = +0.98) and *A. skvortzowii* (-0.72), *S. acus* (-0.83) & *S. meyerii* (-
327 0.79) (all associated with the shallow water surface sediments of the Buguldieka Saddle, off the Selenga
328 Delta, and in the Maloe More) (Figure 6). Unlike *A. baicalensis* abundances, Figure 5 reveals that the
329 latter three species have never been abundant in the north basin for at least the last 100 years. Both *A.*
330 *baicalensis* and *A. skvortzowii* thrive in cold water temperatures below 5°C, blooming largely during
331 the spring and decline in abundance when lake waters warm to more than 5-6 °C (Jewson et al., 2008;
332 2010). During the summer therefore as lake stratification commences and surface water warms (Jewson
333 et al., 2009; 2010) and nutrient concentrations decrease (due to the seasonal succession of autotrophic
334 picoplankton), these two species decline. However, each species employs very different adaptations
335 that allow them to avoid high surface water temperatures. *A. baicalensis* grows well in conditions of
336 low light (Jewson et al., 2009), and due to its physiological plasticity competes well under ice through
337 the production of smaller-sized valves, which then sink slowly after ice break up. After ice break up,
338 mixing depths increase and declining light levels induce *A. baicalensis* to form longer, thicker resting
339 cells full of storage products that allow them to survive throughout the period of summer stratification
340 in cooler waters of intermediate depth (c. 50-100m) (Jewson et al. 2010). Formation of the resting cells
341 requires a lot of silica, which is met through remineralisation of silica from dissolving diatoms at
342 moderate depths in the water column (Callender & Granina 1995; Jewson et al., 2010). *A. skvortzowii*
343 avoids higher surface water temperatures also through the production of resting stages, but unlike *A.*
344 *baicalensis*, its cue for the production of resting spores is phosphate utilisation by other algae (e.g.
345 picoplankton) in surface waters (Jewson et al., 2008). Furthermore, *A. skvortzowii* has evolved

346 planktonic and littoral life history stages, such that viable spores remain in coastal sediments down to a
347 depth of 25 m, where they can be resuspended by strong autumn wind-driven waves into the pelagic
348 zone (ibid.) in time to bloom the following spring. In the north basin of Lake Baikal, generally lower
349 primary production during the spring (e.g. Izmet'seva et al., 2016; Panizzo et al., 2018) means that
350 phosphate concentrations rarely fall below the threshold level of 15-23 µg/L needed to induce spore
351 formation, meaning *A. skvortzowii* is unable to grow well in this basin (Jewson et al., 2008). Similarly,
352 later ice off dates (compared to the south and central basins) in the north basin can account for the
353 competitive advantage of *A. baicalensis* species over *A. skvortzowii*.

354

355 *S. acus* is associated with high dissolved silica concentrations (Kilham & Kilham, 1990; Bradbury et
356 al., 1994), which are higher in the south basin than the north basin because of greater river inflow (e.g.
357 the Selenga river), transporting dissolved Si from the catchment to the lake (Bradbury et al., 1994;
358 Shimaraev et al., 2013), and this is reflected in Figure 6 (refer to core BAIK13-10A_SD data). However,
359 recent work has shown that increased silicic acid availability is also strongly controlled via population
360 changes in other diatom taxa (Shimaraev and Domysheva, 2013; Jewson et al., 2015). In particular,
361 when populations of *A. baicalensis* remain high during *Melosira* years, the availability of silicic acid
362 for other species to uptake (such as *S. acus*) declines (Jewson et al., 2015). In addition to water
363 temperature dynamics driving high abundances of *A. baicalensis* populations in north basin sites (see
364 above), it is probable that their high Si demand can also account for the reduced abundances of *S. acus*
365 in north basin sites (Figures 5 and 6).

366

367 *S. meyerii* is a small endemic diatom which has a high temperature optimum of 15 - 17.5 °C (Jewson et
368 al., 2015), and like other *Stephanodiscus* species likely has a high affinity for phosphorus (Bradbury et
369 al., 1994), although its autecology is poorly known. These adaptations likely account for the observed
370 distributions in the surface sediments of Lake Baikal (Figure 6), especially in regions which have high
371 phosphorus loadings (Mackay et al., 2006), such as the shallow waters of the Maloe More and off the
372 coast of the Selenga Delta (Müller et al., 2005).

373

374 *C. minuta* is a co-dominant of the pelagic community in both the north and south basins, although it
375 mainly occupies a different temporal niche than the spring blooming diatoms, which accounts for it
376 being positioned orthogonal to taxa associated with PCA axis 1 (Figure 6). Populations of *C. minuta*
377 also grow under ice during spring, but their main growth occurs during autumn overturn (Jewson et al.,
378 2015). Indeed, they are the only pelagic diatom to bloom in substantial numbers in autumn; they persist
379 in the upper water column for longer because they can tolerate water temperatures up to 11 °C, so that
380 when stratification breaks down at the end of the summer, and nutrient overturn occurs in the photic

381 zone, cells are retrained first, giving them a competitive advantage (Jewson et al., 2015). However, at
382 the finer scale, *C. minuta* abundances are not truly independent of spring blooming species. For
383 example, when *A. baicalensis* blooms are particularly large (e.g. “Melosira bloom years”), dissolved
384 silica becomes depleted for all other diatoms, causing the subsequent autumnal crop of *C. minuta* to be
385 much smaller (Jewson et al., 2015). Unfortunately, we know very little about the ecology of the endemic
386 *C. inconspicua*, and currently can only describe its spatial distribution here as being present in very low
387 relative abundances (< 2%) in the south basin and in the shallow waters off the Selenga Delta, but is
388 persistent (> 2%) in the north basin and the Buguldieka Saddle, which accounts for its strong negative
389 association with axis 2 in Figure 6.

390

391 **4.2. Environmental trends and temporal variability**

392

393 Spring (March to April) air temperatures, from the KNMI Climate Explorer database
394 (<http://climexp.knmi.nl/>) for Irkutsk, close to the south basin of Lake Baikal (World Meteorological
395 Organisation station 30710; 52°16'20"N, 104°18'29"E; elevation = 467 m) increased between 1950-
396 2013 CE (Figure 7). Air temperatures in the south basin of Lake Baikal have increased by c. 1.2 °C per
397 year, significantly higher than global trends, with greatest warming occurring during winter months,
398 especially at the start of the 1950s and again since the early 1970s (Shimaraev & Domysheva, 2013).
399 Increasing air temperatures have resulted in increases in average annual surface water temperatures of
400 c. 2°C across the entire lake between 1977-2003 (Izmest'eva et al., 2016), with warming in the south
401 basin, reaching increases of over 2.4 °C during late summer months (Hampton et al., 2008) and warming
402 also reported in the north basin from 1977 to 2003 CE (Izmest'eva et al., 2016). Warmer atmospheric
403 temperatures have also resulted in marked changes in ice dynamics across the lake; annual ice duration
404 in the south and north basins has declined, as has ice thickness since the start of the 1970s in the south
405 basin (Todd and Mackay 2003; Shimaraev and Domysheva, 2013). Since the 1950s, increased surface
406 water temperatures have resulted in extended summer stratification (Hampton et al., 2014), and
407 increased chlorophyll-*a* concentrations (Moore et al., 2009; Izmest'eva et al., 2016). Total annual river
408 inflow into the lake has increased over the past 100 years due to increased precipitation, bringing with
409 it supplies of nutrients and dissolved silica (Shimaraev and Domysheva, 2013). A key question
410 therefore, is whether this significant and unprecedented regional warming in southern Siberia (Davi et
411 al., 2015; Shimaraev and Domysheva, 2013), led to a measurable impact, either directly or indirectly,
412 on diatom community composition in Lake Baikal in particular.

413

414 Breakpoint analyses reveal that a significant change in diatom assemblage composition in the south
415 basin was already underway by the early 1970s (Figure 5a). Although this trend was initially identified

416 in the diatom record by Mackay et al. (1998), the more recent records show the disappearance of *S.*
417 *meyerii* altogether from (BAIK13-7A_SB) in the south basin. At the Buguldieka Saddle (BAIK13-
418 11C_BS), significant changes occurred c. 2000 CE, a few decades later than the more southern site.
419 Here, the increase in *S. acus* is accompanied by wider changes in the diatom flora (Figure 5b); again *S.*
420 *meyerii* declines to low relative abundance (although it persists in record), while *C. inconspicua* almost
421 disappears from the record. Both sites also show declines in heavily silicified species such as *A.*
422 *baicalensis* and *C. minuta*. These changes are in contrast to no significant changes in the diatom flora
423 from the north basin over the past 100 years (BAIK13-18A_NB).

424

425 Significant change in diatom SCD scores in the south basin core BAIK13-7A_SB (Figure 5a) at c.1970
426 CE occurs soon after significant change in rising summer (July to August) surface water temperatures
427 in the south basin (Figure 7; breakpoint at 1966 CE in the temperature record; p value < 0.001) and the
428 start of declining ice thickness in the south basin (Todd and Mackay, 2003; Sizova et al., 2013).
429 Phytoplankton monitoring studies from the south basin show major changes in the diatom flora
430 consistent with those observed in the stratigraphic record. For example, within phytoplankton samples
431 from the south basin, *A. baicalensis* concentrations have declined from c. 5 to 3 cells L⁻¹ between 1950–
432 2010 (Silow et al., 2016). These changes are likely related to ice cover dynamics and increasing surface
433 water stratification (Hampton et al., 2014). For example, Hampton et al. (2014) demonstrate that
434 monitored diatoms now occur deeper in the water column, likely due to increased surface water
435 temperature, stratification and reduced mixing, causing cells to sink further. For *C. minuta*, this would
436 mean fewer cells being entrained back up into the photic zone during the autumnal overturn, hence the
437 declining valve numbers observed in the south basin (Figure 5a).

438

439 Factors causing the heavily silicified diatoms to decline in abundance may also contribute to observed
440 increases in *S. acus*. *S. acus* is non-endemic to Lake Baikal and has a high temperature optima and fast
441 growth rates (Mackay et al., 1999), so can take advantage of rapidly warming surface waters after ice
442 break-up. It is also able to grow through the summer months (e.g. Ryves et al., 2003; Panizzo et al.,
443 2018) due to its low biovolume and higher surface – volume ratio, enabling it to stay in the photic zone
444 longer than heavily silicified endemic species. So as endemic diatom species find growth in increasingly
445 warmer waters of southern Lake Baikal challenging, *S. acus* is able to flourish under these conditions,
446 especially if availability of dissolved silica also increases (Jewson et al., 2015).

447

448 An additional, notable, finding of this study is the disappearance in the endemic *S. meyerii* off the
449 Vydrino Shoulder (BAIK13-7A_SB) and its marked decline at the Buguldieka Saddle (BAIK13-
450 11C_BS) post c. 2003 CE (Figure 1 and Figure 5). Its decline may be linked to changes towards reduced

451 nutrient availability (including silicon and phosphorus concentrations). As mentioned above, *S. meyerii*
452 may be indicative of more nutrient rich waters. However, in core BAIK13-10A_SD (Figure 4) within
453 the shallow waters off the Selenga Delta, *Stephanodiscus parvus*, a cosmopolitan diatom which is often
454 indicative of cultural enrichment, remains only at low abundance while *S. meyerii* declines in abundance
455 over the past 10 years. High abundances of *S. acus* are seen within the BAIK13-10A_SD core top
456 sediments, which are similar to those observed in BAIK13-4F_SB, BAIK13-7A_SB, BAIK13-11C_BS
457 and BAIK13-14C_MM core tops (Figure 4 and 5). We conclude therefore that *S. acus* may be out-
458 competing *S. meyerii* at these locations.

459

460 Temporal changes in sedimentary diatom assemblages in the north basin (BAIK13-18A_NB) contrast
461 with those from the south (BAIK13-7A_SB and BAIK13-11C_BS) (Figure 7). Hydro-physical
462 parameters in the north basin, such as ice cover, are clearly responding to a warming in global mean
463 temperatures (Jewson et al. pers comm), yet we detected no discernible effect on sedimentary diatom
464 assemblages. We conclude that the magnitude of change in ice cover duration, open water stratification
465 and ice thickness has not yet been sufficient to induce changes in these endemic populations in the north
466 basin, which are uniquely adapted to these cold, low-light environments.

467

468 In addition to direct climate change, changes in the Lake Baikal diatom community may also be driven
469 by changes within the lake's food-web. Since the 1950s, increased surface water temperatures have
470 resulted in changes to zooplankton numbers, including declining abundances of planktonic rotifers, but
471 increased abundances of cladocera (Hampton et al., 2008) and copepods (Izmest'eva et al., 2016). With
472 shorter ice cover duration on the lake, a rise in summer zooplankton biomass (copepods and *Bosmina*/
473 *Daphnia*) has been seen over the last 60 years (Hampton et al., 2008) (Figure 7), with many of these
474 groups also shifting to more shallow waters in the water column for reasons not yet fully understood
475 (Hampton et al., 2014). Increasing zooplankton biomass (largely the endemic copepod *Epischura*
476 *baicalensis*) in the upper 50 m of the water column have also been determined (Silow et al., 2016) from
477 1950 - 2010 CE. The diatom assembly shifts seen in the south basin and Buguldieka sediment core
478 (BAIK13-11C_BS) (Figure 5) could therefore also be affected by increased grazing pressures, both
479 from increasing zooplankton numbers and their shift to shallow water positions, but also an increase in
480 the spatial overlap between phytoplankton and copepods (Yoshii et al., 1999; Hampton et al., 2014).
481 For example, *C. minuta* is a key food source for the zooplankton *Epischura baicalensis* (e.g. Mackay
482 et al., 2006; Hampton et al., 2014; Jewson et al., 2015), while the larger endemic *Cyclotella baicalensis*
483 although too large to be consumed by *E. baicalensis* is instead an important food source for the larger
484 endemic gammarid *Macrohectopus brankcii* (Jewson et al, 2015).

485

486 Finally, we find no evidence in our recent palaeolimnological records to suggest that local
487 anthropogenic pollution has had a detectable effect on planktonic diatom communities. Nevertheless,
488 in the past decade, evidence of cultural eutrophication of benthic and littoral regions of Lake Baikal
489 near towns and tourist resorts is clear (Kravtsova et al., 2014; Timoshkin et al., 2016). Very poor or
490 non-existent sewage treatment has resulted in localised high levels of nutrients (phosphorus & nitrogen)
491 and organic matter (Khodzer et al., 2017). Such eutrophication is causing large blooms of filamentous
492 green algae to form, often far from local sources of pollution (including *Spirogyra* spp. and
493 *Stigeoclonium tenue*), which then rot along the coastlines (Kravtsova et al., 2014; Timoshkin et al.,
494 2016; Ozerksy et al., 2018). As yet there is no chemical monitoring evidence to suggest that littoral
495 eutrophication has spread into the pelagic regions of lake (e.g. Khodzer et al., 2017), nor of a biological
496 impact in the form of increased chlorophyll concentrations or decline in water transparency (Izmest'eva
497 et al., 2016). However, near-shore nutrient pollution can act as a precursor of off-shore disturbance,
498 especially food-web dynamics (Rosenberger et al., 2008). Improvements to water treatment facilities in
499 Lake Baikal are essential as soon as possible to ensure that eutrophication does not reinforce the
500 negative impacts of global warming (Moss et al., 2011) on the Lake Baikal ecosystem.

501

502 **5. Conclusions**

503

504 Palaeolimnological records of changing diatom assemblages over recent decades agree well with
505 phytoplankton monitoring studies; numbers of heavily silicified diatom species in the south basin of
506 Lake Baikal are in decline at the expense of increasing cosmopolitan, lighter, littoral species. These
507 changes are consistent with previous predictions as to what might happen to diatoms in Lake Baikal as
508 global mean temperature continue to increase (Mackay et al., 2006; Moore et al., 2009). Warmer surface
509 waters and increased period of stratification are very inhospitable for endemic taxa such as *A.*
510 *baicalensis*, *A. skvortzowii* and *C. minuta*, while changes in nutrient availability may be restricting the
511 growth of smaller, lighter endemics such as *S. meyerii*. Interactions with increasing numbers of primary
512 consumers, especially endemic copepods such as *Epischura baicalensis* and amphipods such as
513 *Macrohectopus*, are as yet undefined, but likely to be important. *S. acus* on the other hand may be
514 benefiting from a combination of different impacts including shorter ice duration, longer periods of
515 summer stratification, and increased dissolved silica availability from both increased river discharge,
516 but also declining numbers of heavily silicified diatoms. At the moment these changes are confined to
517 the south basin of Lake Baikal, and we have no evidence of warming impacts on sedimentary diatom
518 assemblages in the north basin, despite a marked decline in ice duration in both basins over recent
519 decades. We also have no evidence in our records of increased impact from littoral eutrophication –
520 however, given that littoral regions can act as early indicators of future wide-spread change, urgent

521 action is still needed to stop nutrient pollution from entering the lake. Observed changes in the diatom
522 flora are likely to be affected by several interacting factors which are still in play today, and much more
523 work still needs to be done to unravel these multiple stressors.

524

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526

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533

534 **7. References**

535

536 **Appleby, P.G., Oldfield, F. (1978).** ‘The calculation of ^{210}Pb dates assuming a constant rate of supply
537 of unsupported ^{210}Pb to the sediment.’ *Catena*, **5**, 1-8.

538

539 **Appleby, P.G., Nolan, P.J., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J., Battarbee,**
540 **R.W. (1986).** ‘Pb-210 Dating by Low Background Gamma-Counting.’ *Hydrobiologia*, **143**, 21-27.

541

542 **Attermeyer, K., Hornick, T., Kayler, Z.E., Bahr, A., Zwirnmann, E., Grossartm H-P., Premke,**
543 **K. (2014).** ‘Enhanced bacterial decomposition with increasing addition of autochthonous to
544 allochthonous carbon without any effect on bacterial community composition.’ *Biogeosciences*, **11**,
545 1479-1489.

546

547 **Bartington Instruments (1995).** Operation Manual MS2. Bartington Instruments, Oxford.

548

549 **Battarbee, R.W., Kneen, M. (1982).** ‘The use of electronically counted microspheres in absolute
550 diatom analysis.’ *Limnology and Oceanography*, **27**, 184-188.

551

552 **Belykh, O.I., Sorokovikova, E.G. (2003).** ‘Autotrophic picoplankton in Lake Baikal: Abundance,
553 dynamics, and distribution.’ *Aquatic Ecosystem Health and Management*, **6**, (3), 251-261.

554

555 **Bopp, L., Aumont, O., Cadule, P., Alvain, S., Gehlen, M. (2005).** ‘Response of diatoms distribution
556 to global warming and potential implications: a global model study.’ *Geophysical Research Letters*, **32**,
557 (19), 1-4.
558

559 **Bradbury, J.P., Bezrukova, Y.V., Chernyaeva, G.P., Colman, S.M., Khursevich, G., King, J.W.,**
560 **Likhoshway, Ye. V. (1994).** ‘A synthesis of post-glacial diatom records from Lake Baikal.’ *Journal of*
561 *Paleolimnology*, **10**, 213-252.
562

563 **Callander, E., Granina, L. (1995).** ‘Biogeochemical silica mass balance in Lake Baikal, Russia.’ In:
564 Proceedings 8th International Symposium of Water–Rock Interaction, pp. 341–344. Balkema,
565 Rotterdam.
566

567 **Cohen, A.S., Gergurich, E.L., Kraemer, B.M. McGlue, M.M., McIntyre, P.B., Russell, J.M.,**
568 **Simmons, J.D., Swarzenski, P.W. (2016).** ‘Climate warming reduced fish production and benthic
569 habitat in Lake Tanganyika, one of the most biodiverse freshwater ecosystems.’ *PNAS*, **113**, (34), 9563-
570 9568.
571

572 **Creed, I.F., Bergström, A.-K., Trick, C.G., Grimm, N.B., Hessen, D.O., Karlsson, J., Kidd, K.A.,**
573 **Kritzberg, E., McKnight, D.M., Freeman, E.C., Senar, O.E., Andersson, A., Ask, J., Berggren,**
574 **M., Cherif, M., Giesler, R., Hotchkiss, E.R., Kortelainen, P., Palta, M., Vrede, T., Weyhenmeyer,**
575 **G.A. (2018).** ‘Global change-driven effects on dissolved organic matter composition: implications for
576 food webs of northern lakes.’ *Global Change Biology*, DOI: 10.1111/gcb.14129.
577

578 **Davi, N.K., D’Arrigo, R., Jacoby, G.C., Cook, E.R., Anchukaitis, K., Nachin, B. (2015).** ‘A long-
579 term context (931-2005 C.E.) for rapid warming over Central Asia.’ *Quaternary Science Reviews*, **121**,
580 89-97.
581

582 **Edlund, M.B., Almendinger, J.E., Fang, X., Hobbs, J.M.R., VanderMeulen, D.D., Key, R.L.,**
583 **Engstrom, D.R. (2017).** ‘Effects of climate change on lake thermal structure and biotic response in
584 northern wilderness lakes.’ *Water*, **9**, 1 – 35.
585

586 **Fietz, S., Kobanova, G., Izmesteva, L., Nicklisch, A. (2005).** ‘Regional, vertical and seasonal
587 distribution of phytoplankton and photosynthetic pigments in Lake Baikal.’ *Journal of Plankton*
588 *Research*, **27**, (8), 793-810.
589

590 **Findlay, D.L., Kasain, S.E.M., Stainton, M.P., Beaty, K., Lyng, M. (2001).** ‘Climatic influences on
591 algal populations of boreal forest lakes in the experimental lakes area.’ *Limnology and Oceanography*,
592 **46**, 1784-1793.
593

594 **Flower R.J. (1993).** ‘Diatom preservation: experiments and observations on dissolution and breakage
595 in modern and fossil material.’ *Hydrobiologia*, **269/270**, 473-484.
596

597 **Flower, R.J., Likhoshway, Ye. V. (1993).** ‘Diatom preservation in Lake Baikal.’ In Diatom algae as
598 indicators of the changes of climate and environment. Fifth workshop on diatom algae (ed. M.A.
599 Grachev), pp. 77-78. Irkutsk: Russian Botanical Society Publications.
600

601 **Hampton, S.E., Izmet’eva, L.R., Moore, M.V., Katz, S.L., Dennis, B., Silow, E.A. (2008).** ‘Sixty
602 years of environmental change in the world’s largest freshwater lake – Lake Baikal, Siberia.’ *Global*
603 *Change Biology*, **14**, 1947 – 1958.
604

605 **Hampton, S.E., Gray, D.K., Izmet’eva, L.R., Moore, M.V., Ozersky, T. (2014).** ‘The Rise and Fall
606 of Plankton: Long-term changes in the vertical distribution of algae and grazers in Lake Baikal, Siberia.’
607 *PLOS ONE*, **9**, (2), 1 – 10.
608

609 **Hampton, S.E., Moore, M.V., Ozersky, T., Stanley, E.H., Polashenski, C.M., Galloway, A.W.E.**
610 **(2015).** ‘Heating up a cold subject: prospects for under-ice plankton research in lakes.’ *Journal of*
611 *plankton research*, **0**, (0), 1- 8.
612

613 **Hampton, S.E., Galloway, A.W.E., Power, S.M., Ozersky, T., Woo, K.H., Batt, R.D., Labou, S.G.,**
614 **O’Reilly, C.M., Sharma, S., Lottig, N.R., Stanly, E.H., North, R.L., Stockwell, J.D., Adrian, R.,**
615 **Weyhenmeyer, G.A., Arvola, L., Baulch, H.M., Bertani, I., Bowman, L.L., Carey, C., Catalan, J.,**
616 **Colom-Montero, W., Domine, L.M., Felip, M., Granados, I., Gries, C., Grossart, H-P., Haberman,**
617 **J., Haldna, M., Hayden, B., Higgins, S.N., Jolley, J.C., Kahilainen, K.K., Kaup, E., Kehoe, M.J.,**
618 **MacIntyre, S., Mackay, A.W., Mariash, H.L., McKay, R.M., Nixdorf, B., Nöges, B., Nöges, T.,**
619 **Palmer, M., Pierson, D.C., Post, D.M., Pruett, M.J., Rautio, M., Read, J.S., Roberts, S.L., Rucker,**
620 **J., Sadro, S., Silow, E.A., Smith, D.E., Sterner, R.W., Swann, G.E.A., Timofeyev, M.A., Toro, M.,**
621 **Twiss, M.R., Vogt, R.J., Watson, S.B., Whiteford, E.J., Xenopoulos, M.A. (2017).** ‘Ecology under
622 lake ice.’ *Ecology Letters*, **20**, (1), 98 – 111.
623

624 **Hampton, S.E., McGowan, S., Ozersky, T., Viridis, S.G.P., Vu, T.T., Spanbauer, T.L., Kraemer,**
625 **B.M., Swann, G., Mackay, A.W., Powers, S.M., Meyer, M.F., Labou, S.G., O'Reilly, C.M.,**
626 **DiCarlo, M., Galloway, A.W.E., Fritz, S.C. (2018).** 'Recent ecological change in ancient lakes.'
627 *Limnology and Oceanography*, doi: 10.1002/lno.10938.
628
629 **IPCC (2014).** Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III
630 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing
631 Team, P.K., Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
632
633 **Izmest'eva, L.R., Moore, M.V., Hampton, S.E., Ferwerda, C.J., Gray, D.K., Woo, K.H., Pislegina,**
634 **H.V., Krashchuk, L.S., Shimaraeva, S.V. Silow, E.A. (2016).** 'Lake-wide physical and biological
635 trends associated with warming in Lake Baikal.' *Journal of Great Lakes Research*, **42**, 6 – 17.
636
637 **Jewson, D.H., Granin, N.G., Zhdanov, A.A., Gorbunova, L.A., Bondarenko, N.A., Gnatovsky,**
638 **R.Y. (2008).** 'Resting stages and ecology of the planktonic diatom *Aulacoseira skvortzowii* in Lake
639 Baikal.' *Limnology and Oceanography*, **53**, (3), 1125-1136.
640
641 **Jewson, D.H., Granin, N.G., Zhdarnov, A.A., Gnatovsky, R.Y. (2009).** 'Effect of snow depth on
642 under-ice irradiance and growth of *Aulacoseira baicalensis* in Lake Baikal.' *Aquatic Ecology*, **43**, 673
643 – 679.
644
645 **Jewson, D.H., Granin, N.G., Zhdarnov, A.A., Gorbunova, L.A., Yu, R. (2010).** 'Vertical mixing,
646 size change and resting stage formation of the planktonic diatom *Aulacoseria baicalensis*.' *European*
647 *Journal of Phycology*, **45**, (4), 354 – 364.
648
649 **Jewson, D.H., Granin, N.G., Gnatovsky, R.Y., Lowry, S.F., Teubner, K. (2015).** 'Coexistence of
650 two *Cyclotella* diatom species in the plankton of Lake Baikal.' *Freshwater Biology*, **60**, 10, 2113-2126.
651
652 **Khodzher, T.V., Domysheva, V.M., Sorokovikova, L.M., Sakirko, M.V., Tomberg, I.V. (2017).**
653 'Current chemical composition of Lake Baikal water.' *Inland Waters*, **7**, (3), 250 - 258.
654
655 **Kilham, P., Kilham, S.S. (1990).** 'Endless summer, internal loading processes dominate nutrient
656 cycling in tropical lakes.' *Freshwater Biology*, **23**, 379-389.
657
658 **Kravtsova, L.S., Izhboldina, L.A., Khanaev, I.V., Pomazkina, G.V., Rodionova, E.V., Domysheva,**

659 **V.M., Sakirko, M.V., Tomberg, I.V., Kostornova, T.Y., Kravchenko, O.S., Kupchinsky, A.B.**
660 **(2014).** ‘Nearshore benthic blooms of filamentous green algae in Lake Baikal.’ *Journal of Great Lakes*
661 *Research*, **40**, 4441 – 448.
662

663 **Likhoshway, E.V., Pomazkina, G.V., Kostyukovskaya, A.O., Sergeeva, V.N., Levina, O.V. (2005).**
664 Distribution of diatoms in surficial sediments of Lake Baikal. *Geology and Geophysics*, 46, 34-49. [in
665 Russian].
666

667 **Mackay, A.W., Flower, R.J., Kutmina, A.E., Granina, L., Rose, N.L., Appleby, P.G., Boyle, J.F.,**
668 **Battarbee, R.W. (1998).** ‘Diatom succession trends in recent sediments from Lake Baikal and their
669 relation to atmospheric pollution and to climate change.’ *Phil. Trans. R. Soc. Lond. B.*, **353**, 1011-1055.
670

671 **Mackay, A. W., Battarbee, R. W., Flower, R. J., Jewson, D., Lees, J. A., Ryves, D. B., & Sturm,**
672 **M. (1999).** The deposition and accumulation of endemic planktonic diatoms in the sediments of Lake
673 Baikal and an evaluation of their potential role in climate reconstruction during the Holocene. Final
674 Report to the NERC GR3/10529.: ECRC Research Report 59. 9 pp London: Environmental Change
675 Research Centre, UCL.
676

677 **Mackay, A.W., Ryves, D.B., Morley, D.W., Jewson, D.H., Riouals, P. (2006).** ‘Assessing the
678 vulnerability of endemic diatom species in Lake Baikal to predicted future climate change: a
679 multivariate approach.’ *Global Change Biology*, **12**, 2297 – 2315.
680

681 **Magnuson, J.J., Robertson, D.M., Benson, B.J. (2000).** ‘Historical trends in lake and river ice cover
682 in the northern hemisphere.’ *Science*, **289**, 1743 – 1746.
683

684 **Moore, M.V., Hampton, S.E., Izmet’eva, L.R., Silow, E.A., Peshkova, E.V., Pavlov, B.K. (2009).**
685 ‘Climate Change and the World’s “Sacred Sea” – Lake Baikal, Siberia.’ *BioScience*, **59**, (5), 405 – 417.
686

687 **Moss, B., Kosten, S., Meerhoff, M., Battarbee, R.W., Jeppesen, E., Mazzeo, N., Havens, K.,**
688 **Lacerot, G., Liu, Z., De Meester, L. and Paerl, H., (2011).** Allied attack: climate change and
689 eutrophication. *Inland waters*, **1**, (2), pp.101-105.
690

691 **Muggeo, V.M. (2008).** ‘Segmented: An R package to fit regression models with broken-line
692 relationships.’ *R news*, **8**, 20-25.
693

694 Müller, B., Maerki, M., Schmid, M., Vologina, E.G., Wehrli, B., Wüest, A., Sturm, M. et al. (2005).
695 ‘Internal carbon and nutrient cycling in Lake Baikal: sedimentation, upwelling and early diagenesis.’
696 *Global and Planetary Change*, **46**, 101–124.
697

698 O’Beirne, M.D., Werne, J.P., Hecky, R.E., Johnson, T.C., Katsev, S., Reavie, E.D. (2017).
699 ‘Anthropogenic climate change has altered primary productivity in Lake Superior.’ *Nature*, 1-8.
700

701 O’Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P.,
702 Lenters, J.D., McIntyre, P.B., Kraemer, B.M., Weyhenmeyer, G.A., Straile, D., Dong, B., Adrian,
703 R., Allan, M.G., Anneville, O., Arvola, L., Austin, J., Bailey, J.L., Baron, J.S., Brookes, J.D., de
704 Eyto, E., Dokulil, M.T., Hamilton, D.P., Havens, K., Hetherington, A.L., Higgins, S.N., Hook, S.,
705 Izmet’eva, L.R., Joehnk, K.D., Kangur, K., Kasprzak, P., Kumagai, M., Kuusisto, E.,
706 Leshkevich, G., Livingston, D.M., MacIntyre, S., May, L., Melack, J.M., Mueller-Navarra, D.C.,
707 Naumenko, M., Noges, P., Noges, T., North, R.P., Plisnier, P-D., Rigosi, A., Rimmer, A., Rogora,
708 M., Rudstam, L.G., Rusak, J.A., Salmaso, N., Samal, N.R. (2015). ‘Rapid and highly variable
709 warming of lake surface waters around the globe.’ *Geophysical Research Letters*, **42**, 10,773 – 10,781.
710

711 Ozersky, T., Volkova, E.A., Bondarenko, N.A., Timoshkin, O.A., Malnik, V.V., Domysheva, V.M.
712 and Hampton, S.E., (2018). Nutrient limitation of benthic algae in Lake Baikal, Russia. *Freshwater*
713 *Science*, **37**, (3), pp.000-000.
714

715 Panizzo, V.N., Roberts, S., Swann, G.E.A., McGowan, S., Mackay, A.W., Vologina, E., Pashley,
716 V., Hortswold, M.S.A. (2018). ‘Spatial differences in dissolved silicon utilization in Lake Baikal,
717 Siberia: Examining the impact of high diatom biomass events and eutrophication.’ *Limnology and*
718 *Oceanography*, 1-17.
719

720 Popovskaya, G.I. (2000). ‘Ecological monitoring of phytoplankton in Lake Baikal.’ *Aquatic Ecosystem*
721 *Health and Management*, **3**, 215 – 225.
722

723 R Core Team. (2013). R: A language and environment for statistical computing. R Foundation for
724 Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.
725

726 Reavie, E.D., Sgro, G.V., Estep, L.R., Bramburger, A.J., Shaw Chraïbi, V.L., Pillsbury, R.W.,
727 Cai, M., Stow, C.A., Dove, A. (2017). ‘Climate warming and changes in *Cyclotella sensu lato* in the
728 Laurentian Great Lakes.’ *Limnology and Oceanography*, **62**, 768 – 783.

729
730 **Rosenberger, E.E., Hampton, S.E., Fradkin, S.C. and Kennedy, B.P., (2008).** Effects of shoreline
731 development on the nearshore environment in large deep oligotrophic lakes. *Freshwater Biology*, **53**,
732 (8), pp.1673-1691.
733
734 **Ryves, D.B., Battarbee, R.W., Fri, S.C. (2009).** ‘The Dilemma of Disappearing Diatoms:
735 Incorporating Diatom Dissolution Data into Paleoenvironmental Modelling and Reconstruction.’
736 *Quaternary Science Reviews*, **28**, (1-2), 120-136.
737
738 **Saros, J.E., Stone, J.R., Pederson, G.T., Slemmons, K.E.H., Spanbauer, T., Schliep, A., Cahl, D.,**
739 **Williamson, C.E., Engstrom, D.R. (2012).** ‘Climate induced changes in lake ecosystem structure
740 inferred from coupled neo and paleoecological approaches.’ *Ecology*, **93**, (10), 2155-2164.
741
742 **Saros, J.E., Strock, K.E., Mccue, J., Hogan, E., Anderson, N.J. (2013).** ‘Response of *Cyclotella*
743 species to nutrients and incubation depth in Arctic lakes.’ *Journal of Plankton Research*, **36**, (2), 450-
744 460.
745
746 **Shaw Chraïbi, V.L., Kireta, A.R., Reavie, E.D., Cai, M., Brown, T.N. (2014).** ‘A paleolimnological
747 assessment of human impacts on Lake Superior.’ *Journal of Great Lakes Research*, **40**, 886-897.
748
749 **Shimaraev, M.N., Domysheva, V.M. (2013).** ‘Trends in hydrological and Hydrochemical processes
750 in Lake Baikal under conditions of modern climate change.’ In: Climate change and global warming of
751 inland waters. Impacts and mitigation for ecosystems and societies. Eds Goldman, C.R., Kumagai, M.,
752 Robarts, R.D.
753
754 **Silow, E.A., Krashchuk, L.S., Onuchin, K.A., Pislegina, H.V., Rusanovskaya, O.O., Shimaraeva,**
755 **S.V. (2016).** ‘Some recent trends regarding Lake Baikal phytoplankton and zooplankton.’ *Lakes and*
756 *Reservoirs and Management*, **21**, 40-44.
757
758 **Sizova, L.N., Kuimova, L.N, Shimaraev, M.N. (2013.)** ‘Influence of the atmospheric circulation on
759 ice-thermal processes on Baikal during 1950-2010.’ *Geography and Natural Resources*, **34**, 158-165.
760
761 **Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A., Pienitz, R.,**
762 **Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M-A., Hughes, M., Keatley, B.E.,**
763 **Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R.,**

764 **Rautio, M., Saulnier-Talbot, E., Siltonen, S., Solovieva, N., Weckström, J. (2005).** ‘Climate-driven
765 regime shifts in the biological communities of arctic lakes.’ *PNAS*, **102**, (12), 4397-4402.
766

767 **Ter Braak, C.J.F., Smilauer, P. (2002).** CANOCO Reference manual and CanoDraw for Windows
768 User’s guide: Software for Canonical Community Ordination (version 4.5).
769

770 **Timoshkin, O.A., Samsonov, D.P., Yamamuro, M., Moore, M.V., Belykh, O.I., Malnik, V.V.,**
771 **Sakirko, M.V., Shirokaya, A.A., Bondarenko, N.A., Domysheva, V.M., Fedorova, G.A.,**
772 **Kochetkov, A.I., Kuzmin, A.V., Lukhnev, A.G., Medvezhonkova, O.V., Nepokrytykh, A.V.,**
773 **Pasynkova, E.M., Poberezhnaya, A.E., Potapskaya, N.V., Rozhkova, N.A., Sheveleva, N.G.,**
774 **Tikhonova, I.V., Timoshkina, E.M., Tomberg, I.V., Volkova, E.A., Zaitseva, E.P., Zvereva, Y.M.,**
775 **Kupchinsky, A.B., Bukshuk, N.A. (2016).** ‘Rapid ecological change in the coastal zone of Lake Baikal
776 (East Siberia): Is the site of the world’s greatest freshwater biodiversity in danger?’ *Journal of Great*
777 *Lakes Research*, **42**, (3), 487-497.
778

779 **Todd, M.C., Mackay, A.W. (2003).** ‘Large-Scale climate controls on Lake Baikal ice cover.’ *Journal*
780 *of Climate*, **16**, 3186 – 3199.
781

782 **Winder, M., Reuter, J.E., Schladow, S.G. (2009).** ‘Lake warming favours small-sized planktonic
783 diatom species.’ *Proceedings of the Royal Society*, **276**, 427-435.
784

785 **Wrona, F.J., Prowse, T.D., Reist, J.D., Hobbie, J.E., Levesque, L.M.J., Vincent, W.F. (2006).**
786 ‘Climate Change effects on aquatic biota, ecosystem structure and function.’ *Climate Change Impacts*
787 *on Arctic Freshwater Ecosystems and Fisheries*, **35**, (7), 359 – 369.
788

789 **Yoshi, K., Melnik, N.G., Timoshin, O.A., Bondarenko, N.A., Anoshko, P.N., Yoshioka, T., Wada,**
790 **E. (1999).** ‘Stable isotope analysis of the pelagic food web in Lake Baikal.’ *Limnology and*
791 *Oceanography*, **44**, 502–511.
792

793 **Yoshioka, T., Ueda, S., Khodzher, T., Bashenkhaeva, N., Korovyakova, I., Sorokovikova, L.,**
794 **Gorbunova, L. (2002).** ‘Distribution of dissolved organic carbon in Lake Baikal and its watershed.’
795 *Limnology*, **3**, 159-168.
796

Figure 1: Map of Lake Baikal showing coring station sites across the south and north basin, and within Maloe More Bay, off the central basin. [SB: South basin, SD: Selenga Delta, BS: Buguldieka Saddle, MM: Maloe More and NB: North basin].

Figure 2: Core lithology and magnetic susceptibility profiles for BAIK13-4C_SB, BAIK13-7B_SB, BAIK13-10B_SD, BAIK13-11A_BS, BAIK13-14B_MM BAIK13-18C_NB and BAIK13-19A_NB sediment cores. Lithology key: 1 - pelagic mud, 2 - turbidite, 3 - sandy sediment, 4 - diatoms, 5 - clay, 6 - silt, 7 - sand, 8 - land plant remains. Right column: 9 - oxidized sediment, 10 - Fe/Mn crust, 11 - fragments of Fe/Mn crust, 12 e O₂ reduced sediment. Boundaries between layers: 13 - distinct boundaries between layers, 14 - indistinct boundaries between layers. The lithology for cores BAIK13-4C_SB and BAIK13-7B_SB have previously been published in Swann et al (2018). [SB: South basin, SD: Selenga Delta, BS: Buguldieka Saddle, MM: Maloe More and NB: North basin].

Figure 3: ²¹⁰Pb age models for BAIK13-4F_SB, BAIK13-7A_SB, BAIK13-10A_SD, BAIK13-11C_BS, BAIK13-14C_MM, BAIK13-18A_NB and BAIK13-19B_NB sediment cores. In the upper sediments, turbidites are present between 2.0 – 5.3 cm in the BAIK13-4F_SB sediment core. [SB: South basin, SD: Selenga Delta, BS: Buguldieka Saddle, MM: Maloe More and NB: North basin].

Figure 4: Stratigraphic plots of core top diatom assemblages are shown for [A] BAIK13-4F_SB, [B] BAIK13-18A_NB, [C] BAIK13-10A_SD and [D] BAIK13-14C_MM. Diatom fluxes are shown alongside diatom abundances (species with > 2% abundance). [SB: South basin, SD: Selenga Delta, BS: Buguldieka Saddle, MM: Maloe More and NB: North basin].

Figure 5: Stratigraphic plot of diatom assemblages at [A] BAIK13-7A_SB, [B] BAIK13-11C_BS, [C] BAIK13-18A_NB with core top samples (represented by grey bars) overlapping with diatoms records from Mackay et al (1998) [A] BAIK38_SB, [B] BAIK19_BS and [C] BAIK29_NB (represented by black bars). Diatom Dissolution Index (DDI) and diatom fluxes are shown alongside diatom abundances (species with > 2% abundance). SCD dissimilarity scores are shown for the diatom dataset. The timings of significant breakpoints in the SCD scores are highlighted in grey for BAIK13-7A_SB and BAIK13-11C_BS diatom assemblages. No significant breakpoints were found in the BAIK13-18A_NB diatom assemblage data. [SB: South basin, SD: Selenga Delta, BS: Buguldieka Saddle, MM: Maloe More and NB: North basin].

Figure 6: PCA of diatom species from all core samples. Core top samples (upper 2 cm) are from BAIK13-4F_SB, BAIK13-7A_SB, BAIK13-10A_SD, BAIK13-11C_BS, BAIK13-14C_MM, BAIK13-18A_NB and BAIK13-19B_NB sediment cores collected in 2013. The older sediments (20th century sediments) are from cores BAIK19_BS, BAIK29_NB and BAIK38_SB (Mackay et al.,

1998). Axis one eigenvalue is 0.47 and axis two eigenvalue is 0.24. [SB: South basin, SD: Selenga Delta, BS: Buguldieka Saddle, MM: Maloe More and NB: North basin].

Figure 7: Regional spring Irkutsk air temperatures (March and April average) from a climate station next to the south basin of Lake Baikal (World Meteorological Organisation station 30710; 52°16'20''N, 104°18'29''E; elevation = 467 m) are shown over the period 1950 CE to 2013 CE. Summer surface water temperatures and water temperatures in the upper 25m of the water column (July to August average) are shown for the south basin over the period 1948 CE to 2002 CE (Hampton et al., 2008). Ice cover duration data for the south basin of Lake Baikal is shown between the period 1869 CE to 1996 CE (Todd and Mackay, 2003). Zooplankton summer abundance (1000 cells L⁻¹) for copepods, rotifers and bosmina/daphnia are shown for the period 1950 CE to 2002 CE (data provided by S. Hampton). The stratigraphic plot includes SCD dissimilarity scores, comparing upper core top samples to all samples below in the same core. Timings of significant breakpoints in the SCD scores are also highlighted in grey for BAIK13-7A_SB and BAIK13-11C_BS diatom assemblages. No significant breakpoints were found in the BAIK13-18A_NB diatom assemblage data. [SB: South basin, BS: Buguldieka Saddle and NB: North basin].

Table 1: Location of both the sediment cores collected in August 2013 and the published diatom records at the same coring sites in Lake Baikal collected in 1993/1994 (Mackay et al., 1998). Water depths at each coring site is shown, along with the basin which they were collected from in Lake Baikal. [SB: South basin, BS: Buguldieka Saddle and NB: North basin].

Figure 1:

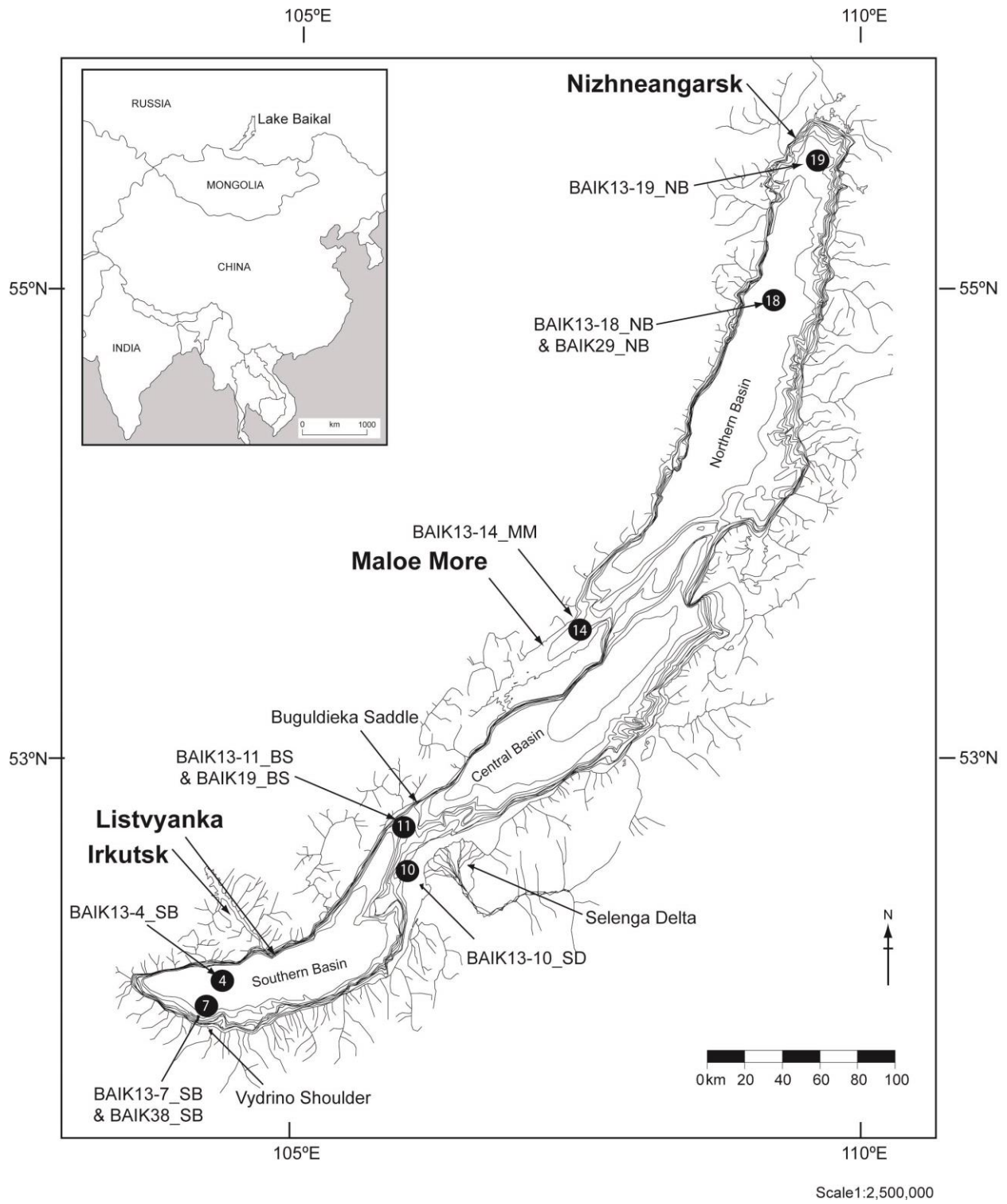


Figure 2:

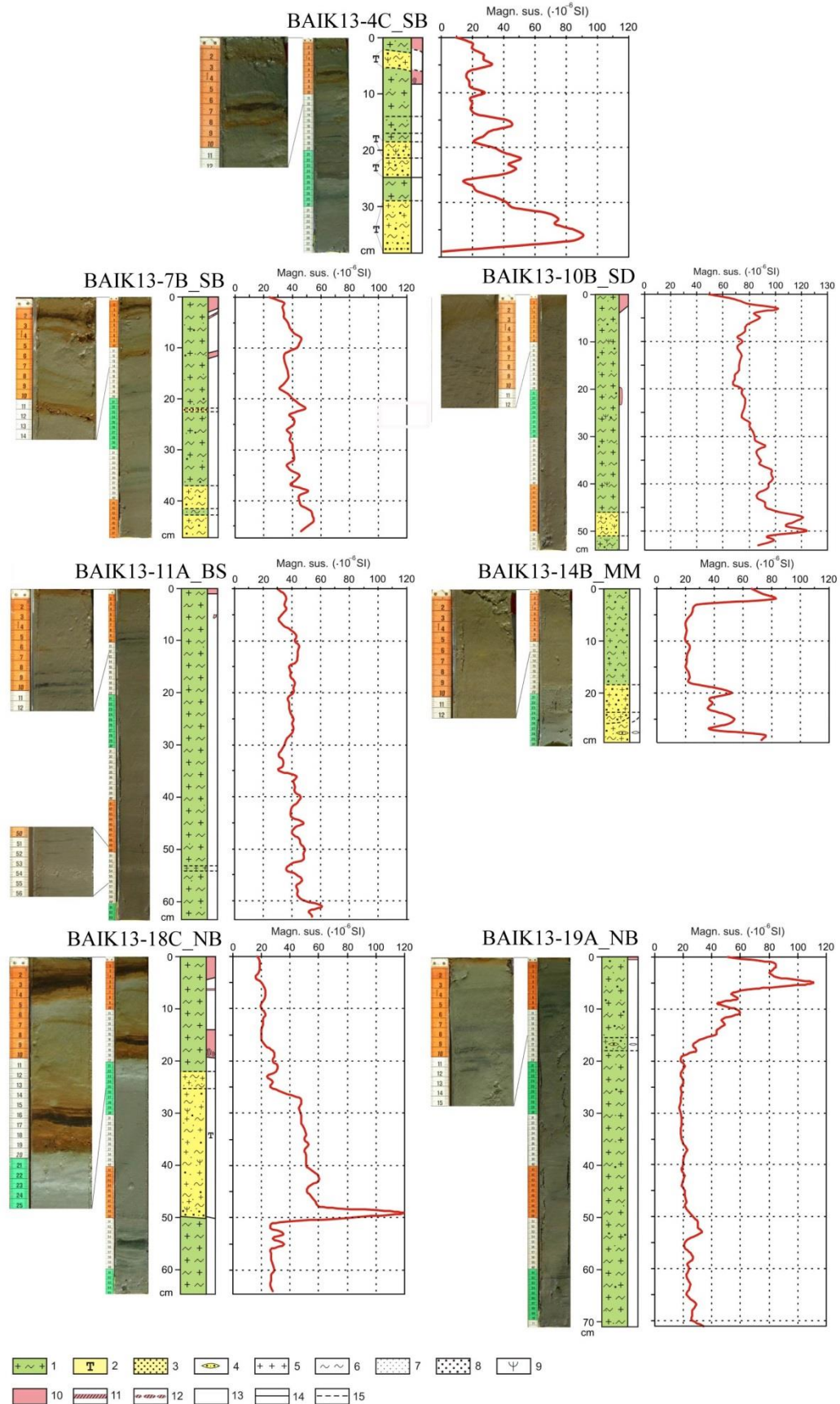


Figure 3:

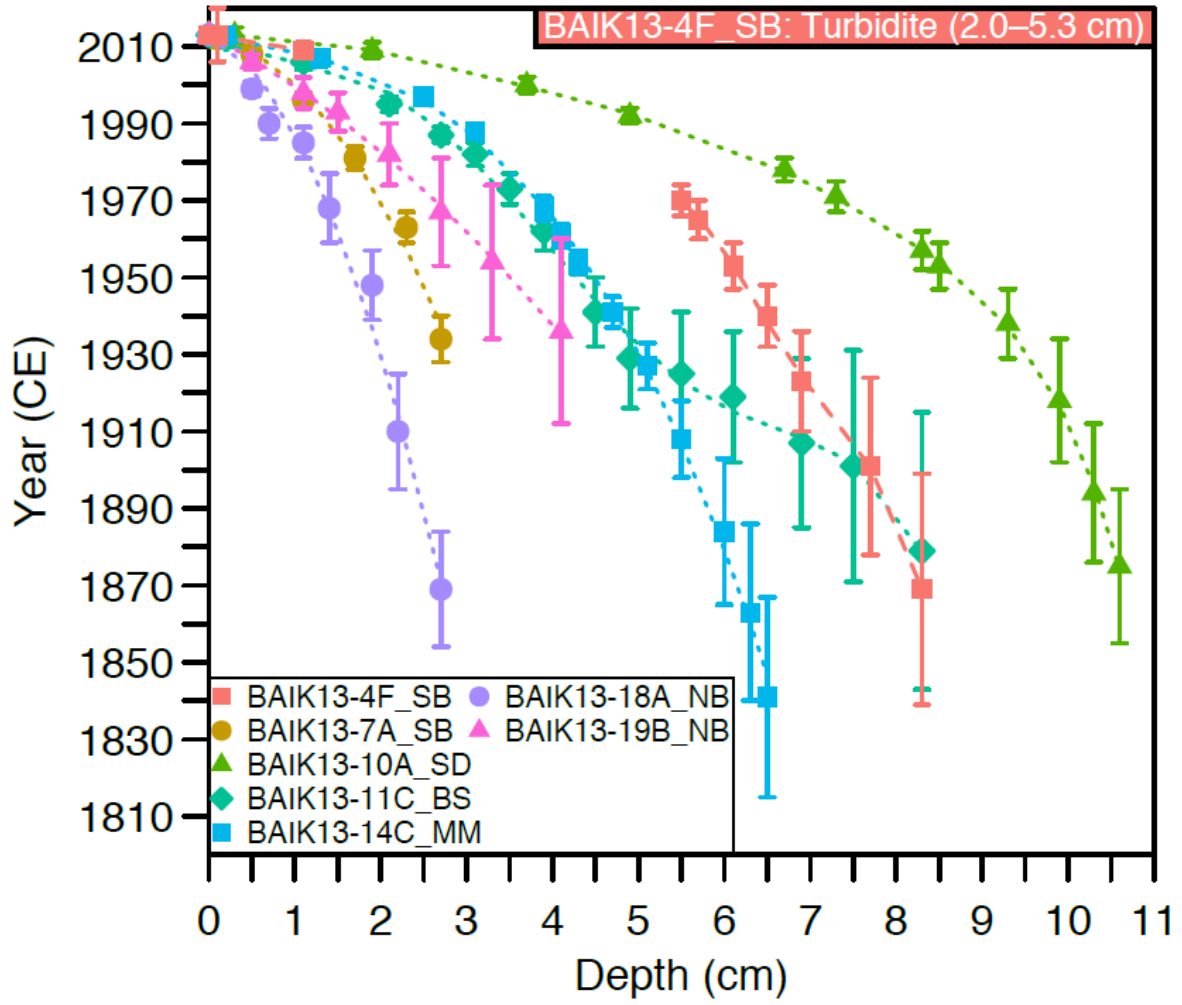
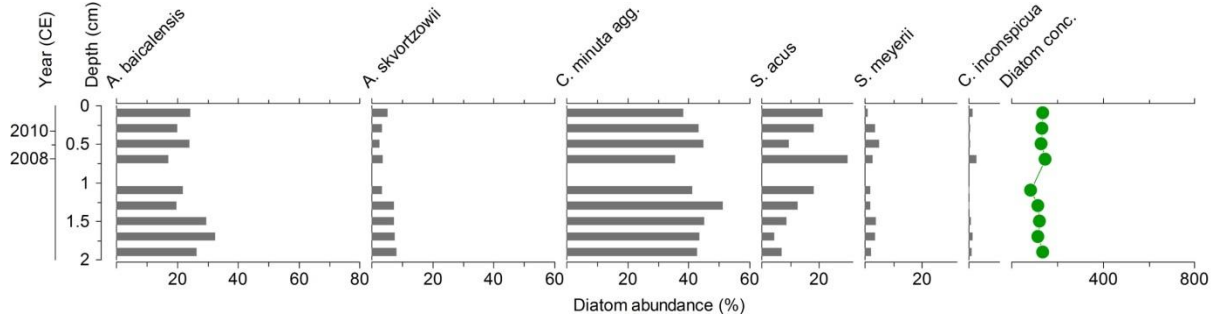
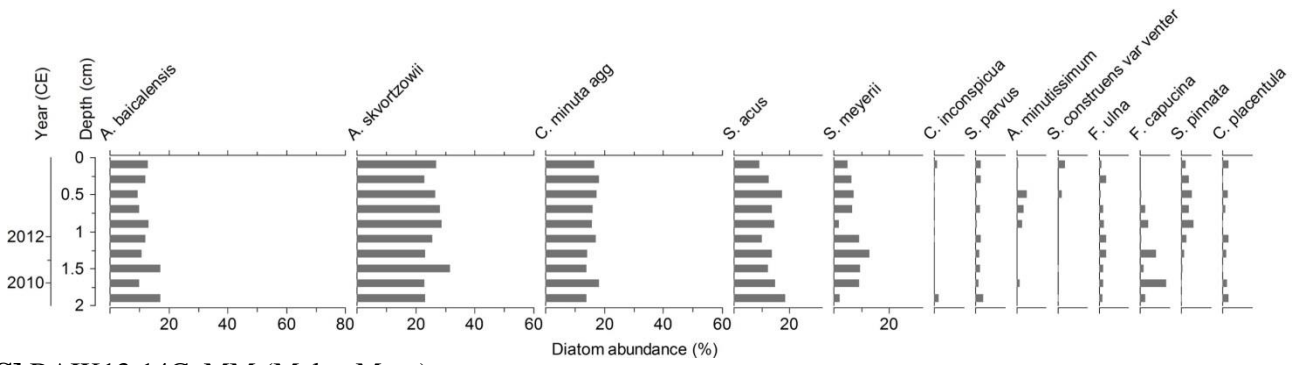


Figure 4:

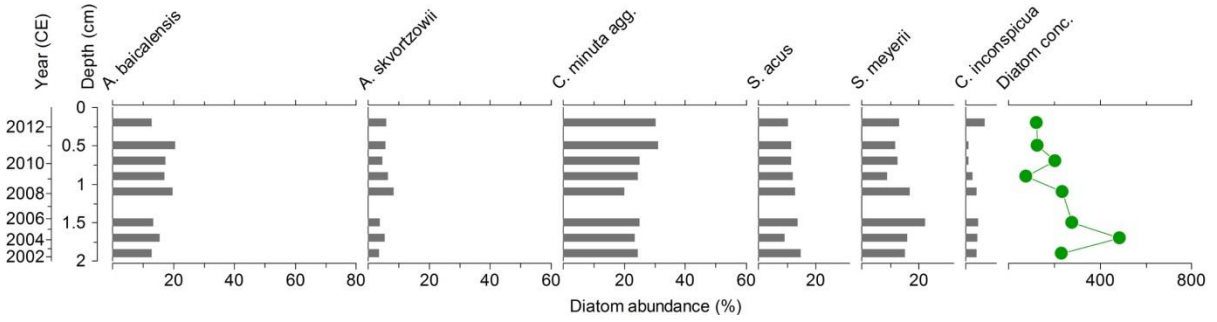
[A] BAIK13-4F_SB (South Basin)



[B] BAIK13-10A_SD (Selenga Delta)



[C] BAIK13-14C_MM (Maloe More)



[D] BAIK13-19B_NB (North Basin)

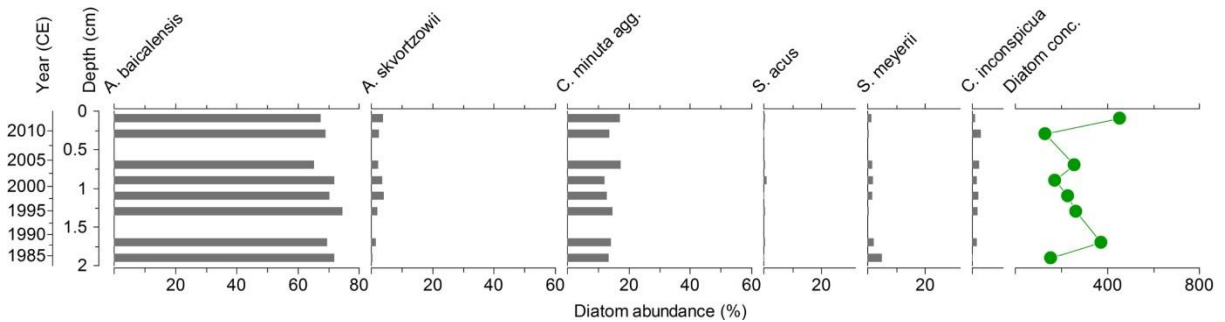
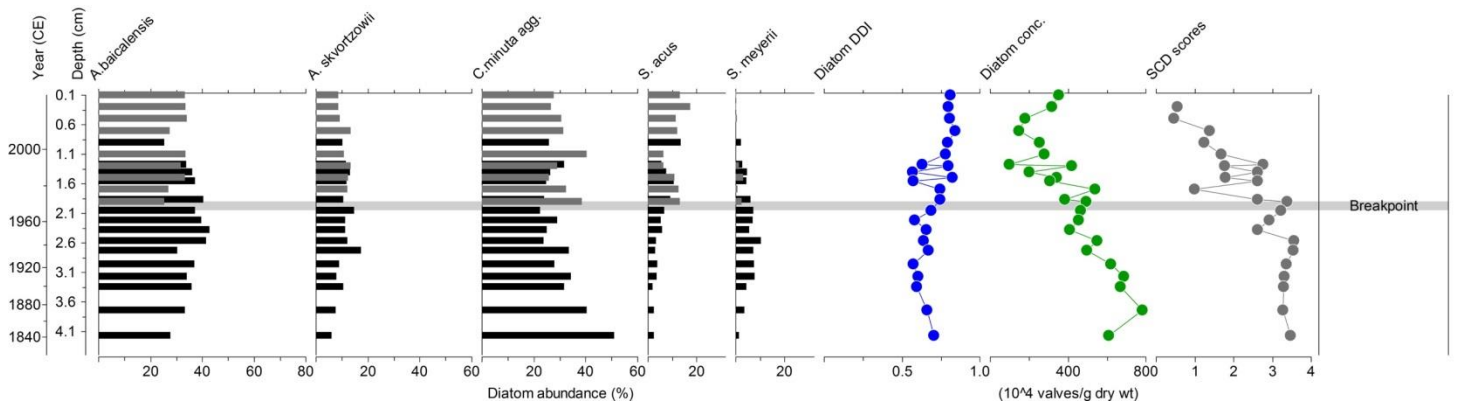
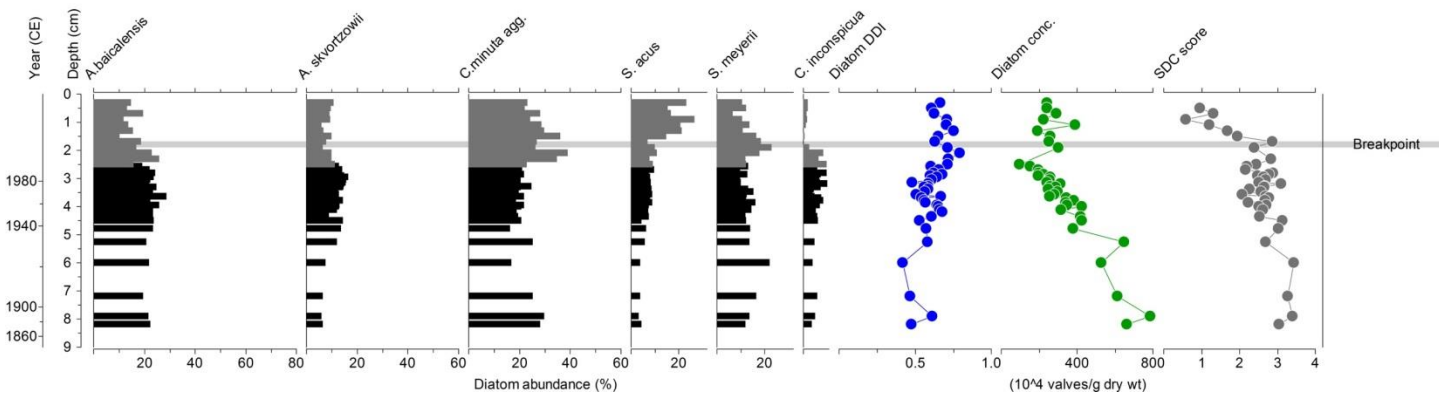


Figure 5:

[A] BAIK13-7A_SB (South Basin)



[B] BAIK13-11C_BS (Buguldieka Saddle)



[C] BAIK13-18A_NB (North Basin)

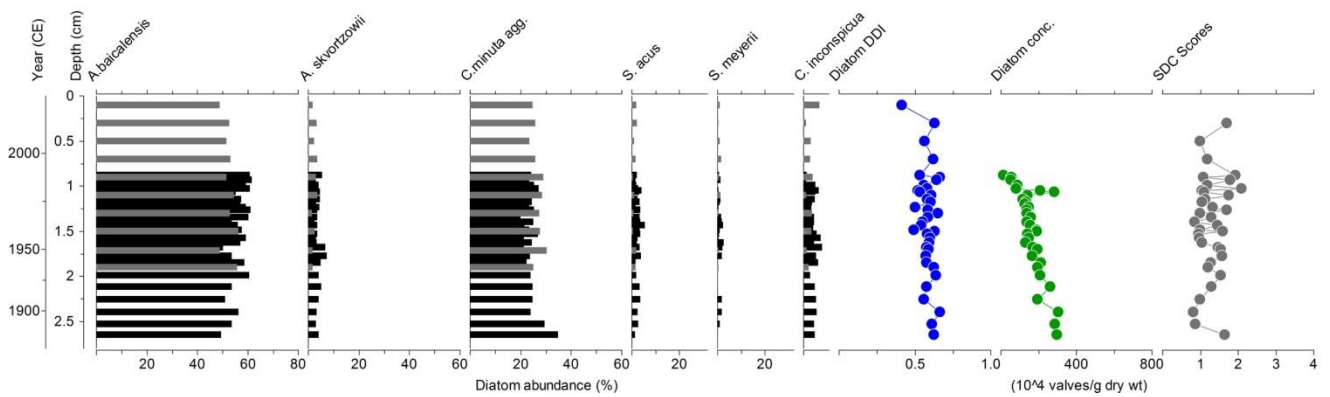


Figure 6:

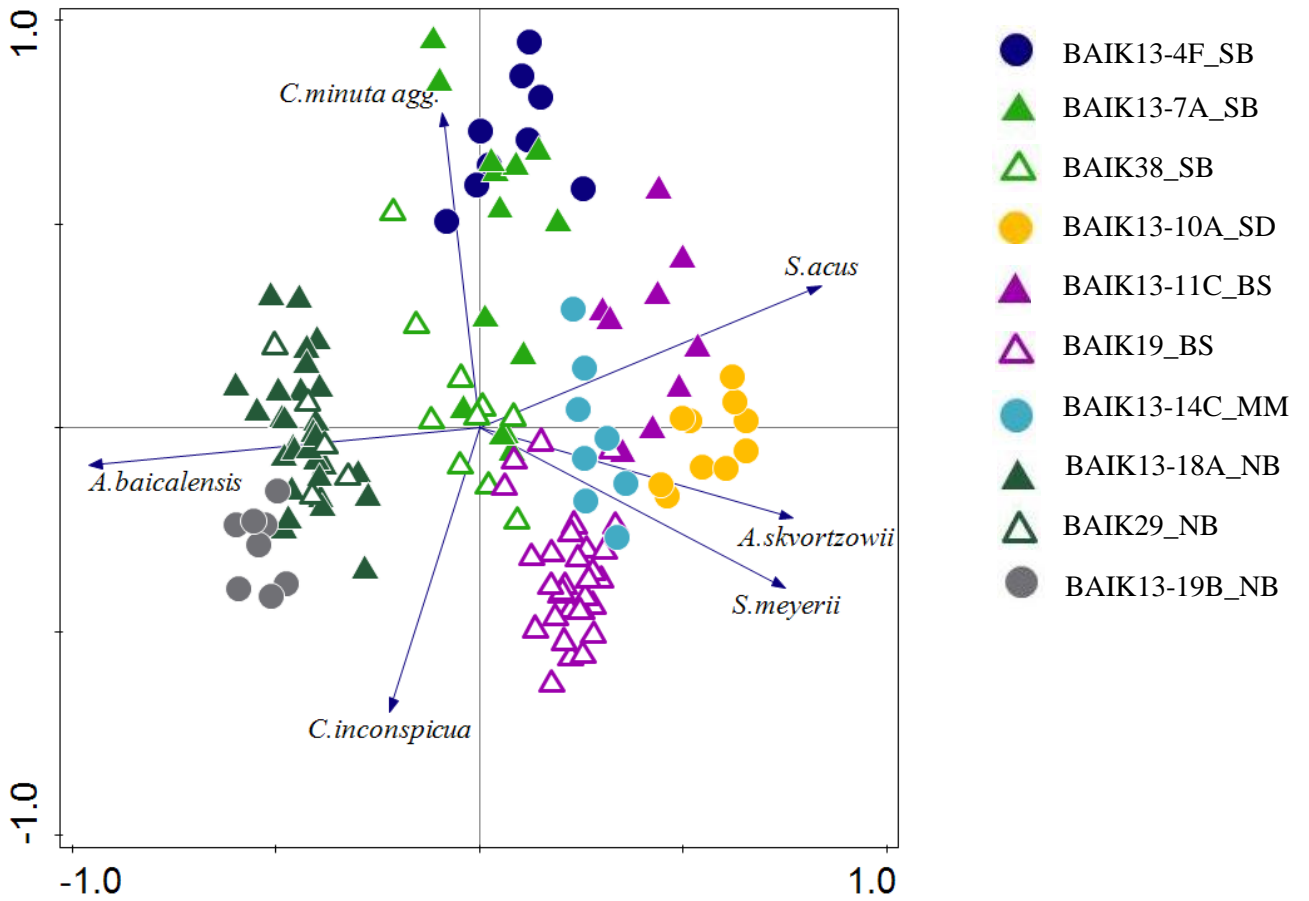


Figure 7:

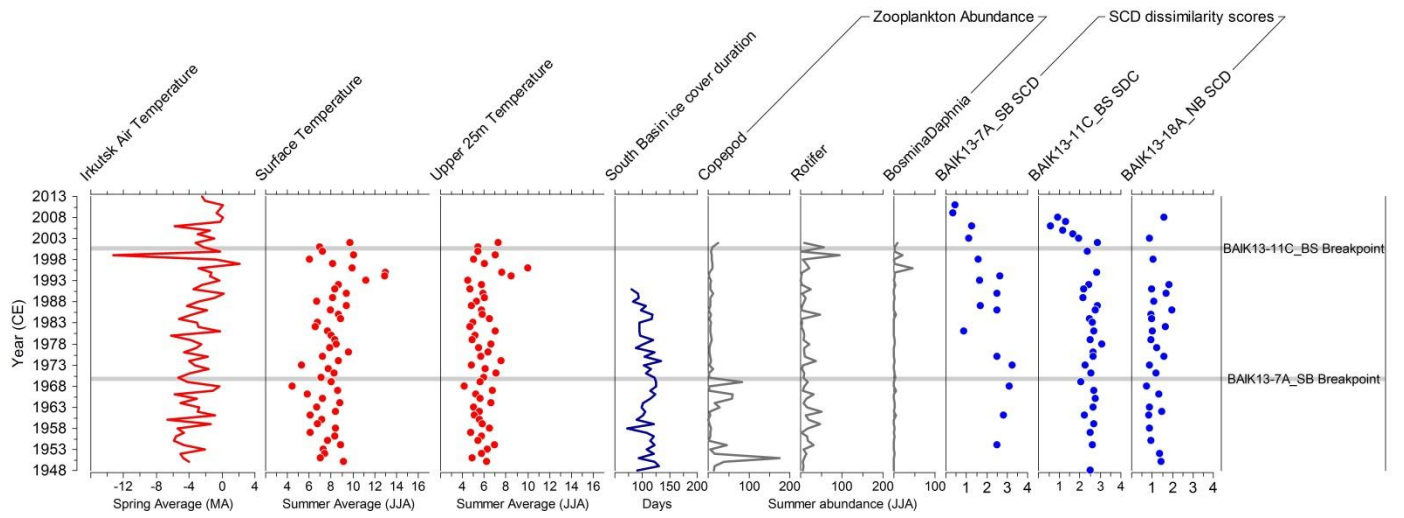


Table 1:

Sediment cores collected in August 2013	Sediment cores published in Mackay et al (1998)	Basin	N	E	Water depth (m)
BAIK13-7A_SB	BAIK38_SB	South	51°34'06"	104°31'43"	1080
BAIK13-11C_BS	BAIK19_BS	South/Selenga	52°27'00"	106°07'32"	345
BAIK13-18A_NB	BAIK29_NB	North	54°47'31.4"	109°14'15.3"	890