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Advances in understanding calcite varve formation: new insights from a dual lake monitoring approach in the southern Baltic lowlands

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We revise the conceptual model of calcite varves and present, for the first time, a dual lake monitoring study in two alkaline lakes providing new insights into the seasonal sedimentation processes forming these varves. The study lakes, Tiefer See in NE Germany and Czechowskie in N Poland, have distinct morphology and bathymetry, and therefore, they are ideal to decipher local effects on seasonal deposition. The monitoring setup in both lakes is largely identical and includes instrumental observation of (i) meteorological parameters, (ii) chemical profiling of the lake water column including water sampling, and (iii) sediment trapping at both bi-weekly and monthly intervals. We then compare our monitoring data with varve micro-facies in the sediment record. One main finding is that calcite varves form complex laminae triplets rather than simple couplets as commonly thought. Sedimentation of varve sub-layers in both lakes is largely dependent on the lake mixing dynamics and results from the same seasonality, commencing with diatom blooms in spring turning into a pulse of calcite precipitation in summer and terminating with a re-suspension layer in autumn and winter, composed of calcite patches, plant fragments and benthic diatoms. Despite the common seasonal cycle, the share of each of these depositional phases in the total annual sediment yield is different between the lakes. In Lake Tiefer See calcite sedimentation has the highest yields, whereas in Lake Czechowskie, the so far underestimated re-suspension sub-layer dominates the sediment accumulation. Even in undisturbed varved sediments, re-suspended material becomes integrated in the sediment fabric and makes up an important share of calcite varves. Thus, while the biogeochemical lake cycle defines the varves' autochthonous components and micro-facies, the physical setting plays an important role in determining the varve sub-layers' proportion.

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Annually laminated (varved) lake sediments are valuable terrestrial palaeoenvironmental archives, as they provide both precise chronologies and seasonally resolved proxy data (e.g. Kemp 1996; Brauer *et al*. 2007; Martin-Puertas *et al*. 2012a, 2017; Neugebauer *et al*. 2012; Amann *et al*. 2014). Worldwide, lakes holding certain types of varves tend to occur in geographical clusters, i.e. under comparable regional climate and catchment geology (Ojala *et al*. 2012). Varved lake sediments have been reviewed for geographical location or types of annual laminations (e.g. O'Sullivan 1983; Tylmann *et al*. 2013; Zolitschka *et al*. 2015), for their timely occurrence in the geological record (Anderson & Dean 1988), for aspects of building varve chronologies (Ojala *et al*. 2012; Brauer *et al*. 2014), and for their palaeoclimatic relevance (Brauer 2004).

In mid-latitudes and temperate climate, endogenic calcite varves are the most common varve type in sediments of stratified alkaline lakes and have been frequently studied (e.g. Kelts & Hsü 1978; Lotter & Lemcke 1999). Such sediments are particularly well documented in mid to northern latitudes, between approx. 35°N and 65°N (Ojala *et al*. 2012; Tylmann *et al*. 2013). The predominant components of calcite varves result from autochthonous sediment production in the lacustrine biogeochemical cycle. The latter is controlled by seasonal changes in air temperature and the lake mixing dynamics, which affect nutrient and elemental distribution in the water column (Wehrli *et al*. 1997; Bluszcz *et al*. 2008). The major sediment components of typical calcite varves are planktonic and/or benthic diatom frustules and endogenic calcite crystals of different sizes, sometimes intermixed in an organic matrix (Table 1). Other autochthonous components are water plant remains, amorphous organic material, chrysophyte cysts and a fine amorphous matrix. Calcite varves in lakes of the southern Baltic lowlands com-

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Table 1. Sub-layer succession of calcite varves in different European lakes and selected lake characteristics (n.a. = data or information were not available)

Lake	Location		Monitoring period and/or palaeo-reconstruction	Max. depth (m)	Mean depth (m)	Surface area (km^2)	Catchment size (km^2)	Surface inlet	Calcite varve sub-layer succession	Other intercalated sub-layers	References
Tiefer See near Klocksin (this study)	N 53°35.5’ E 12°31.8’	Germany	2012–present, sediment record	62	18.5	0.75	5.5	Minor	Diatoms; graded calcite; re-suspension (benthic and planktonic diatoms, plant fragments, calcite patches)	–	This study; Kienel *et al.* (2013), Dräger *et al.* (2017)
Czechowskie (this study)	N 53°52.4’ E 18°14.3’	Poland	2014–present, sediment record	30	8.1	0.73	19.7	Minor	Diatoms; graded calcite; re-suspension (benthic and planktonic diatoms, plant fragments, calcite patches)	Older sections up to 5 sub-layers	This study; Ott *et al.* (2016), Ott *et al.* (2017)
Belau	N 54°6’ E 10°15.1’	Germany	1989–1994, sediment record	25.6	9	1.1	4.5	Yes	Planktonic diatoms; graded calcite; benthic + planktonic diatoms + reworked calcite + organic + minerogenic particles; clay	–	Schernewski (2003), Zahrer *et al.* (2013)
Woserin (subbasin)	N 53°40’ E 12°1.1’	Germany	Sediment record	39	15	2.2	75.8	n.a.	Diatoms; calcite; organic	–	Czymzik *et al.* (2016)
Sacrow	N 52°26.4’ E 13°5.8’	Germany	2003–2005, sediment record	35	20	1.1	7.9	Minor	Light calcareous and dark organic couplets	Minerogenic layers	Lüder *et al.* (2006), Bluszcz *et al.* (2008), Enters *et al.* (2010)
Palaeolake Rehwiese	N 52°25’47.7” E 13°11’58.4”	Germany	Sediment record	n.a.	n.a.	0.22	n.a.	n.a.	Diatoms; graded calcite; organic material	Monospecific diatom sub-layers between graded calcite	Neugebauer *et al.* (2012)
Ammersee	N 48°00’ E 11°07’	Germany	1984–2016, sediment record	81.1	37.6	47	45.36	Yes	Light calcite layers (evtl. graded); dark layers: detrital + amorphous organic, diatom layers (evtl. monospecific);	Flood event layers	Alefs & Müller (1999), Czymzik *et al.* (2010), Bueche (2016)
Perty	N 54°16.5’ E 22°53.9’	Poland	Sediment record	32.6	7.4	0.2	n.a.	Yes	Calcite (two or three sub-layers); mixed layer (diatoms, amorphous organic matter, chrysophyte and calcite)	–	Tylmann *et al.* (2016)
Kamenduł	N 54°16’ E 22°52’	Poland	Sediment record	26.2	7	0.25	n.a.	Yes	Pale calcite + centric diatoms; mixed: pennate + centric diatoms, calcite, organic material + clastics	Monospecific pennate diatoms as black sub-laminae	Tylmann *et al.* (2016)
Szurpiły	N 54°13.8’ E 22°53.5’	Poland	Sediment record	46.2	20	0.81	11.14	Yes	Carbonate-rich; organic-carbonate	Small scale slump deposits	Kinder *et al.* (2019)
Żabińskie	N 54°7.9’ E 21°58.9’	Poland	2011–2013, sediment record	44.4	15	0.416	2.3 (24)	Minor	Diatom (+ fine calcite, several pulses possible); mineral-organic	–	Bonk *et al.* (2015), Żarczyński *et al.* (2018, 2019)

(continued)

Table 1. (continued)

Lake	Location		Monitoring period and/or palaeo-reconstruction	Max. depth (m)	Mean depth (m)	Surface area (km^2)	Catchment size (km^2)	Surface inlet	Calcite varve sub-layer succession	Other intercalated sub-layers	References
PalaeoLake Trzechowskie	N 53°52.3’ E 18°13.1’	Poland	Sediment record	n.a.	n.a.	0.3	19.7	Minor	Diatoms; calcite; mixed: littoral diatoms and pyrite	–	Słowiński *et al.* (2017)
Głęboczek	N 53°52.1’ E 18°12.4’	Poland	Sediment record	18	5.33	0.07	0.65	Minor	Calcite + planktonic diatoms; planktonic + epiphytic diatoms + organic debris	–	Ott *et al.* (2017)
Jelonek	N 53°45.9’ E 18°23.5’	Poland	Sediment record	13	4.1	0.2	1.11	Minor	Calcite + planktonic diatoms; planktonic + epiphytic diatoms + organic debris	–	Ott *et al.* (2017)
Gościąż	N 52°34’59” E 19°20’25”	Poland	Sediment record	25.8	4.97	0.469	5.88	Yes	Light & dark layers; light: calcite, diatom + calcite; dark: organic matter, Fe or Fe + Mn rich	–	Churski (1998), Goslar (1998a, b)
Kierske	N 52°27’ E 16°47’	Poland	2015–2016	35		2.86	70.6	Yes	Light & dark couplets	–	Apolinarska *et al.* (2020)
Nylandssjön	N 62°57’ E 18°17’	Sweden	2002–2014	17.5		0.28	0.95	n.a.	Light spring layer; dark winter layer	–	Maier *et al.* (2018)
Zürich	N 47°14.7’ E 8°40.6’	Switzerland	1972–1974	137		88		Yes	Diatom blooms; large calcite polyhedra; micrite; organic	–	Kelts & Hsü (1978), Minder-Zürich (1922)
Baldegg	N 47°11’55” E 8°15’38”	Switzerland	Sediment record	60		5.2	67.8	Yes	Diatom; graded calcite; re-suspension	Flood event layers	Lotter *et al.* (1997), Wehrli *et al.* (1997), Wirth *et al.* (2013)
Soppensee	N 47°5.3’ E 8°4.8’	Switzerland	1980–1993	27	16	0.235	1.6	Minor	Light (diatoms + graded calcite); dark (chrysophyte cysts + organic detritus)	–	Lotter & Lemcke (1999), Gruber *et al.* (2000)
Mondsee	N 47°48’ E 13°23’	Austria	2011–2013	68		14	247	Yes	Diatom; calcite; mixed	Flood event layers	Lauterbach *et al.* (2011), Kämpf *et al.* (2020)
Pianico	N 45°48’ E 10°02’	Italy	Sediment record	n.a.	n.a.	n.a.	n.a.	n.a.	Graded calcite (up to 4 sub-layers); winter layer	–	Brauer *et al.* (2008b), Mangili *et al.* (2010)
Albano	N 41°44.4’ E 12°39.6’	Italy	Sediment record	175		6		No	Diatom (spring and autumn); summer calcite; winter detrital material	–	Lami *et al.* (1994), Ariztegui *et al.* (2001)
Montcortès	N 42°19.5’ E 0°59.41’	Spain	2013–2015, sediment record	30		0.14	1.39	Minor	Graded calcite (large crystals also in winter); organic	Turbidite/flood event deposits	Corella *et al.* (2014), Trapote *et al.* (2018)

monly include only minor amounts of detrital particles from the catchment due to limited erosion in the flat relief of this landscape (e.g. Bonk *et al.* 2015; Czymzik *et al.* 2016; Tylmann *et al.* 2016).

Calcite varves have been referred to under different names, such as nonglacial varves (Kelts & Hsü 1978), biogeochemical varves (Amann *et al.* 2014), biochemical calcite (Enters *et al.* 2010; Kienel *et al.* 2013; Czymzik *et al.* 2016), biogenic (calcite) varves (e.g. Ojala *et al.* 2012; Bonk *et al.* 2015; Trapote *et al.* 2018), or carbonaceous-biogenic varves (Zolitschka *et al.* 2015). Commonly, light-dark or pale-dark couplets of laminae have been described macroscopically, with the light sub-layer identified as endogenic calcite formed during spring–summer in epilimnion waters (e.g. Lotter *et al.* 1997; Dean *et al.* 2002; Zolitschka *et al.* 2015). Much attention has been given to the processes of calcite precipitation and the underlying chemical and biological triggers (e.g. Kelts & Hsü 1978; Koschel *et al.* 1983), whereas the processes leading to the formation of the dark sub-layer remain less well understood.

Spring lake warming in association with high nutrient availability favours phytoplankton blooms. With increasing summer temperatures, phytoplankton photosynthetic activity further exploits CO_2 from the epilimnion acting as a trigger to reach carbonate saturation (Minder-Zürich 1922; Brunskill 1969; Koschel *et al.* 1983; Gruber *et al.* 2000; Bluszcz *et al.* 2008). Subsequently, calcite crystals are precipitated from the water column (Kelts & Hsü 1978; Koschel *et al.* 1983; Koschel 1990) as long as warming and biological productivity persist, and provided that Ca^{2+} ions are available (Koschel 1990). Concomitant blooms of *Phacotus lenticularis* are known from hardwater lakes worldwide and commonly observed in the southern Baltic lake district (Schlegel *et al.* 1998). Sometimes, a sub-layering of coarser and fine-micrite calcite crystals is observed (Table 1) and related to the nutrient content in the lake water and the degree of supersaturation (Mangili *et al.* 2010; Trapote *et al.* 2018). It must be further considered that not all precipitated calcite crystals are deposited because of eventual dissolution in the hypolimnion due to undersaturation, e.g. because of decreasing pH by CO_2 release during decomposition of organic matter in the lower water column (Dean 1999; Ramisch *et al.* 1999; Ohlendorf & Sturm 2001; Bluszcz *et al.* 2008, 2009; Katz & Nishri 2013). In autumn, a second phytoplankton bloom can be facilitated by transport of dissolved nutrients from the bottom to the surface waters (Bonk *et al.* 2015).

The dark sub-layer of calcite varves is often described as organic or diatom-organic (e.g. Lami *et al.* 1994; Bonk *et al.* 2015; Tylmann *et al.* 2016) and may include a variety of mixed components including amorphous organic matter, diatom frustules, organic detritus and various amounts of minerogenic detritus (Table 1). Generally, this layer is interpreted as an autumn to winter layer but, in contrast to the many studies of calcite sub-layer formation, the detailed processes leading to the deposition of the dark sub-layer remain unravelled. A common hypothesis explaining detrital matter flux assumes catchment erosion (Zolitschka *et al.* 2015) but sediment re-deposition as a possible trigger is also suggested (Nuhfer *et al.* 1993; Zahrer *et al.* 2013; Czymzik *et al.* 2016). In some cases, calcite varves have also been described as triplets rather than couplets including a diatom-rich sub-layer, a sub-layer of endogenic calcite and an amorphous organic sub-layer (Kelts & Hsü 1978; Lüder *et al.* 2006; Czymzik *et al.* 2016).

The thickness and composition of endogenic calcite varves and of the sub-seasonal layers have been used for palaeoclimatic and palaeoenvironmental reconstructions (Table 1; e.g. Dean 1993; Brauer *et al.* 2008a; Martin-Puertas *et al.* 2012b). Moreover, variations in varve and/or sub-layer thickness have been related to different climatic and environmental parameters. For example, the calcite sub-layer thickness has been interpreted as a proxy for the annual precipitation sum (Czymzik *et al.* 2016) and the sum of summer days and average summer temperature (Zahrer *et al.* 2013). Increased deposition of diatoms in spring has been connected to mild winters and prolonged lake mixing in spring (Dreßler *et al.* 2011; Bonk *et al.* 2015), increased productivity due to more elevated temperatures or enhanced nutrient load (Koutsodendris *et al.* 2017), as well as to a later lake overturn in spring due to prolonged lake ice coverage followed by a rapid increase in temperatures (Kienel *et al.* 2017). Total calcite varve thickness has also been interpreted as a proxy for aeolian deposition (Dean *et al.* 2002) and for periods of enhanced drought (St-Jacques *et al.* 2008). Total varve thickness in combination with calcite median size and phosphorous concentrations have been used to infer lacustrine eutrophication (Lotter *et al.* 1997).

In this context, we provide information about the fundamental sedimentation processes and their timing for the seasonal succession of sub-layers that form calcite varves. Such understanding is essential in the search for climate variables that potentially could be recorded in sub-layer thickness. Our overall goal is to unravel limnological factors and their external drivers controlling the formation of seasonal sub-layers in calcite varves through a novel approach of parallel monitoring of sedimentation processes at two lakes in the same climate zone.

Dual lake monitoring approach

In order to comprehensively understand seasonal sedimentation processes and their controlling factors that result in calcite varve formation, we apply for the first time a high-resolution concurrent lake monitoring in two alkaline lakes in the southern Baltic lowlands, located ~380 km from each other. This approach allows differentiation between local and regional factors that determine calcite varve formation in these lakes. Previous sediment core investigations have proven preservation of varves both at the present time and other intervals during the Holocene in Lake Tiefer See (NE Germany; Kienel *et al.* 2013, 2017; Dräger *et al.* 2017) and Lake Czechowskie (N Poland; Ott *et al.* 2016, 2017; Słowiński *et al.* 2017).

Lake settings and regional climate

Lake Tiefer See (near Klocksin, TSK; latitude 53°35.5'N, longitude 12°31.8'E; altitude 62 m a.s.l.) and Lake Czechowskie (Jezioro Czechowskie, JC; 53°52.4'N, 18°14.3'E; 108 m a.s.l.) are located in the southern Baltic lowlands on an east–west transect within the Pomeranian terminal moraine of the Weichselian glaciation at a distance of about 380 km (Fig. 1). Both lakes are situated in subglacial channels. The catchment area of Lake Tiefer See (5.5 km^2) is dominated by glacial till of the Pomeranian terminal moraine, with locally occurring overlaying glaciofluvial sediments, also of Weichselian age (Kienel *et al.* 2013). The catchment has long been largely used for agriculture except for a narrow band of trees surrounding the shoreline, comprising stands of large alder, ash, and oak trees (Theuerkauf *et al.* 2015). Most of the catchment area of Lake Czechowskie (19.7 km^2; Ott *et al.* 2017) is characterized by pine forest growing on deposits of the glacial outwash plain with the exception of the glacial till of the Pomeranian moraine in the north, which is used for agriculture (Błaszkiewicz 2005; Błaszkiewicz *et al.* 2015; Słowiński *et al.* 2017). Despite the differences in catchment area (Fig. 1, Table S1), the surface area of both lakes is of similar size (TSK: 0.75 km^2; JC: 0.73 km^2), but Lake Tiefer See is twice as deep with 62 m maximum depth as compared to Lake Czechowskie with 32 m. The transport of detrital sediments into both lakes is very low due to the lack of major inflows. A former surface connection of Lake Tiefer See to the northern Lake Flachersee was piped during railway constructions in the years of 1884–1886 (Kienel *et al.* 2013), and is in modern times mostly dry, while a southern connection to the small neighbouring Lake Hofsee is through a wetland (Fig. 1B). Lake Czechowskie is situated at the lowest part of a lake chain comprising also Lake Głęboczek and the palaeolake Trzechowskie (now grassland), and has two small inflows entering the basin at its northwestern corner and a small outflow towards the east (Ott *et al.* 2017). The longest inflow (~1 km) originates from Lake Głęboczek and has been altered for irrigation purposes. Both lake basins are oval-shaped, Lake Tiefer See is N–S oriented while Lake Czechowskie is W–E oriented (Fig. 1B, C). Both lakes can be classified as mesotrophic, with trophic state indices (calculated from phosphorous concentrations; Carlson 1977) varying seasonally from 27 to 54 (Tiefer See) and from 37 to 64 (Czechowskie) for summer and winter, respectively (Table S1).

Climate conditions of the region are warm-temperate and humid. The predominant wind direction is WSW with highest wind activity during winter. At Lake Tiefer See mean monthly air temperatures range from 0 °C in January to 18 °C in July with a mean annual precipitation of 560 mm (meteorological data from DWD Station Schwerin AD 1890–2016; 80 km to the west of the lake). The climate at Lake Czechowskie is slightly more continental with mean monthly air temperatures ranging from −2.5 °C in January to 17 °C in July. Total annual precipitation is on average 580 mm (meteorological data provided from the climate station Chojnice, 50 km west of the lake, for the period 1951–2011 and operated by the Institute of Meteorology and Water Management – IMGW).

Material and methods

Surface sediment cores

At Lake Tiefer See a 112-cm-long surface sediment core was recovered in January 2018 at 51 m water depth, close to the sediment trap location, using a 90-mm UWITEC gravity corer (Fig. 1B; core TSK18-SC2; 53°35.623'N, 12°31.818'E). At Lake Czechowskie, a 100-cm-long sediment core was retrieved in October 2019 at 32 m water depth also close to the sediment trap location using the identical coring equipment (Fig. 1C; core JC19-SC2; 53°52.468'N, 18°14.346'E). Both cores recovered a well-preserved sediment–water interface. Before any further core handling, and in order to preserve the varves of the uppermost cm, the surface cores were left vertically drying at 4 °C for approximately 2 weeks, and checked several times in between for their water content. Only after this procedure were the cores split. Large-scale thin sections (10×2 cm) were prepared according to a standard procedure including freeze-drying and impregnation with epoxy resin (Brauer & Casanova 2001). Microscopic analysis comprised investigation of varve structure, single measurement of varve thicknesses, and varve counting using a petrographic microscope with parallel and polarized light and 50 to 400× magnifications (Carl Zeiss Axioplan).

Monitoring of modern sediment deposition

We established a dual lake monitoring concept with similar sampling intervals at both lakes, which is ongoing. At Lake Tiefer See, the sediment traps have been placed at two water depths since March 2012 (Fig. 1B). At the metalimnion (12 m water depth) sediment has been collected with a 4-cylinder trap (KC Denmark A/S; total active area 0.0163 m^2 for the four cylinders) at monthly intervals. Due to ice cover, some periods could

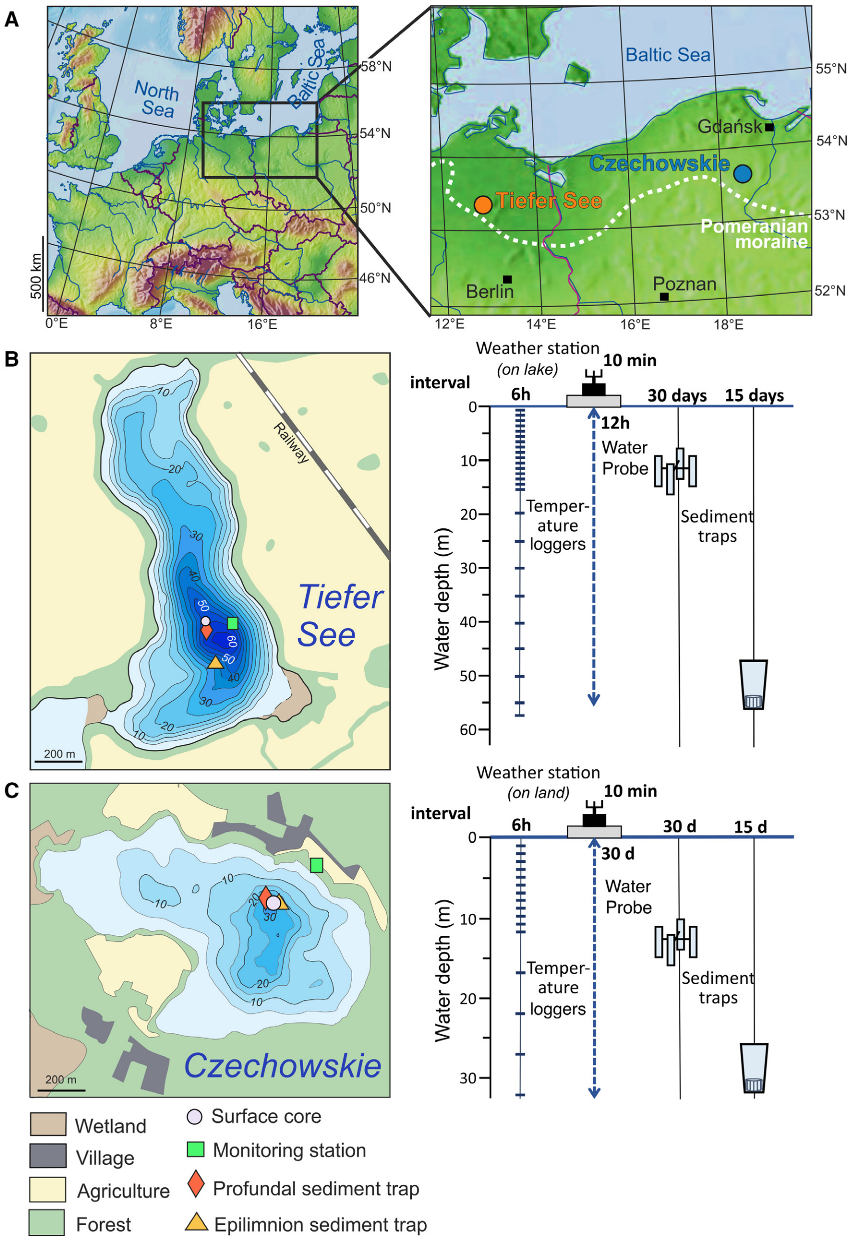

Fig. 1. Regional and local settings of Lakes Tiefer See (TSK) and Czechowskie (JC). A. Location of both lakes in the southern Baltic lowlands. B, C. Bathymetric maps of TSK and JC, respectively, with the position of the meteorological station, stationary temperature loggers, multiparameter water quality probe, sediment traps and the surface sediment cores TSK18-SC2 and JC19-SC2. The graphics on the right illustrate the monitoring setup at the respective lake. [Colour figure can be viewed at www.boreas.dk]

not be sampled (Jan–Apr 2013; Mar–Apr 2014; Kienel *et al.* 2017). An automated sequential trap (Technicap PPS 3/3; active area 0.125 m^2) equipped with 12 sample bottles has been used for collecting hypolimnion particulate matter (50 m water depth). To set up, sample containers are filled with distilled water and the sampling period is set to a 2-week interval. Following deployment of all 12 bottles, the trap is retrieved and equipped with new sample containers at intervals of 180 days. Because of technical issues, the periods from 9–20 September 2012 and 3–15 May 2013 were not sampled (Kienel *et al.* 2017). Sediment yields for these gaps were estimated from sediment yields in a back-up double cylinder trap with monthly resolution through re-calculation of fluxes under consideration of the different active areas of the traps. The segmentation of monthly data into 2-week intervals was estimated based on relative distribution in other years.

Monitoring of sediment deposition at Lake Czechowskie follows a similar approach using identical equipment with a 4-cylinder trap in the metalimnion (12 m water depth) and one automatic sequential trap in the hypolimnion (32 m water depth; Fig. 1C). The hypolimnion trap has been operating continuously since October 2014 and the metalimnion trap has been maintained since September 2012. In parallel to Lake Tiefer See, the sampling intervals in Lake Czechowskie range from ~2 weeks (hypolimnion) to monthly (metalimnion), respectively. The sampling intervals for the sequential sediment traps have been synchronized between the two lakes.

Trapped-sediment preparation and analyses

The sediment material from the traps was freeze dried and weighed to determine the areal dry deposition per day (sediment flux: g m^{-2} d^{-1}). Afterwards, the samples were ground and homogenized. Total carbon (TC) was analysed from 0.2 mg replicate aliquots weighed in Sn capsules, using an elemental analyser (NC2500). Prior to determination of total organic carbon (TOC) 0.2 mg sample aliquots were in situ decalcified in Ag capsules (20% HCl and drying at 75 °C), also in replicates. The TOC content was measured with an elemental analyser (NC2500). $CaCO_3$ contents were calculated by obtaining the total inorganic carbon content (TIC = TC – TOC) and multiplying by 8.33, referring to the percentage molecular weight of inorganic carbon in the calcium carbonate structure.

From the total sediment trap material, the fractions of organic material and calcite were measured as TOC and $CaCO_3$ contents. The remaining fraction is given by the difference between organic matter and calcite from the total sediment. This fraction is predominantly composed of diatom frustules but also includes scattered silt and clay-sized mineral grains (mostly quartz). Due to the small amount of minerogenic particles this sediment fraction was not further quantitatively separated. For microscopic inspection of the trap material through smear slides, each sample was carefully homogenized using a glass stirring rod without damaging any components. Afterwards, an aliquot of 2 mg of the homogenized sample was suspended in 5 mL of purified water using mild ultrasonic treatment. An aliquot of 400 µL of the sample suspension was spread over a round coverslip, allowed to dry overnight at room temperature and mounted with Naphrax.

Monitoring of physical properties and water chemistry

Physicochemical parameters (temperature, pH, oxygen concentrations) in the water column have been measured at Lake Tiefer See using a multi-parameter water quality probe (YSI 6600 V2): (i) from March 2012 to October 2013 at 1-m intervals between 1 and 15 m water depth and at 8-m intervals between 15 and 52 m water depth, and, (ii) since March 2014 at 1-m intervals throughout the entire water column (Fig. 1B). Measurements were conducted with a resolution ranging in 2012 between 8 and 60 days (on average 34 days) and in 2013 to 2017 between 0.5 and 45 days (on average 1.5 days). Additionally, the water temperature has been measured continuously since March 2012 at 6-h intervals, close to the position of the deepest water depth using 26 stationary data loggers (HOBO Water Temp Pro v2) in 1-m steps from 0 to 15 m and in 5-m steps from 15 to 55 m water depth (Fig. 1B). Because of technical problems, no data were collected between 4 April and 6 June 2014, and from 9 September to 18 December 2014 only monthly data were recorded.

At Lake Czechowskie the same limnological parameters have been measured monthly since 2015 with a multi-parameter water quality probe (Hanna HI 9829) at 1-m depth intervals. Continuous water temperature measurements have been based on 17 stationary data loggers (HOBO Water Temp Pro v2) covering the entire water column in 1-m increments from 0 to 12 m water depth and in 5-m increments from 12 to 32 m water depth (Fig. 1C). Temperature has been documented on a daily basis since mid-April 2013.

Element concentrations were determined in water samples retrieved from both lakes at different water column depths at monthly intervals from January 2013 to December 2017 in Lake Tiefer See and from October 2014 to December 2017 in Lake Czechowskie. At Lake Tiefer See waters were sampled at 1, 3, 5, 7, 10, 20, 40, 45 and 50 m water column depth. At Lake Czechowskie waters were sampled at 0, 5, 10, 15, 20, 25 and 28 m water column depth. Due to technical problems no data were collected at Lake Czechowskie in January and February 2015, from November 2015 to February 2016, and between August 2016 and May 2017. Generally, different water aliquots have been sampled. For the purposes of the present study, the concentrations of calcium, total dissolved phosphorous (TDP) and silicon were relevant. For elemental analysis, the water samples were immediately filtered using 0.45-µm filters (Sartorius) and acidified with HNO_3 to a pH of 2. For Lake Tiefer See waters, Ca and TDP were analysed after acid addition and adequate dilutions using ICP-AES (iCAP 6000 series, Thermo Electron Corporation). External calibration was based on mixed element standards that were prepared from commercial single element standards (Spex, Merck). Silicon was measured separately with ICP-AES after appropriate dilutions of unstabilized and filtered water samples. Results are averaged for at least two emission lines and triple measurements. Typical detection limits are ~0.5 µg L^{-1} for Ca, ~50 µg L^{-1} for P and ~20 µg L^{-1} for Si. For Lake Czechowskie waters, Ca was determined within 48 h of sampling, using ion chromatography (Dionex ICS 1100) and TDP was determined by spectrophotometry (DR2800) preceded by sample

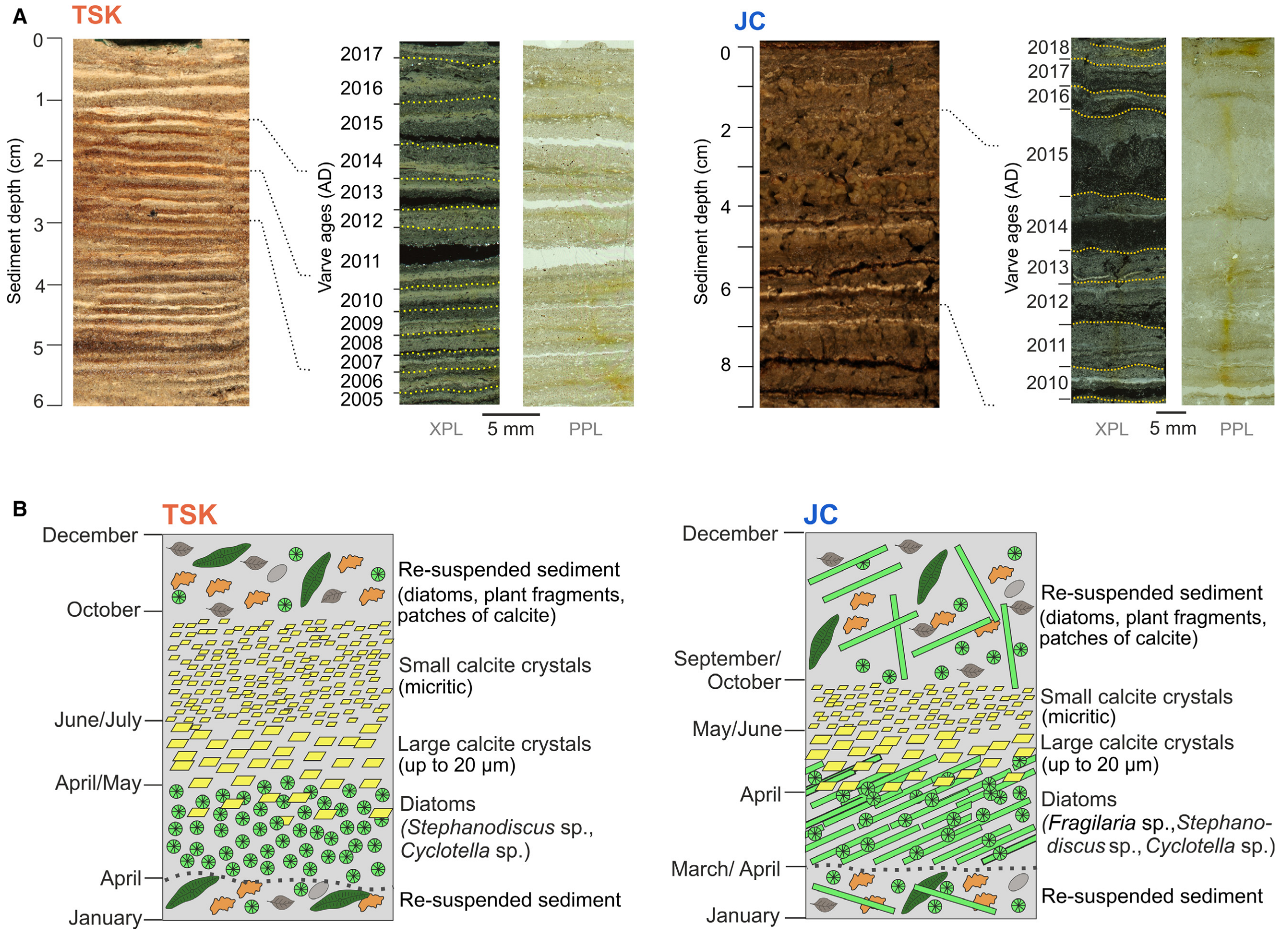

Fig. 2. Varve documentation and varve models for Lakes Tiefer See (TSK) and Czechowskie (JC). A. Core pictures and thin-section scans under cross- (XPL) and plane polarized light (PPL) of the uppermost centimetres of cores TSK18-SC2 and JC19-SC2. Dotted yellow lines indicate the varve boundaries. (Note that the black intervals in the XPL thin sections are gaps rather than sub-layers.) B. Varve models for both lakes according to micro-facies observations. Dotted grey lines indicate the beginning of a new varve year. [Colour figure can be viewed at www.boreas.dk]

preparation with Hach Lange tests LCK 349 (range: 0.05–1.50 mg L^{-1} PO_4-P) and LCS 349 (range: 0.01–0.50 mg L^{-1} PO_4-P; heater LT-200).

Carbonate equilibria

The saturation of lake waters with respect to calcite was calculated using the software PHREEQC (version 3.6.2), and the respective database (Parkhurst & Appelo 2013). The applied input parameters were temperature, pH (both measured on site), and Ca^{2+} for both lakes. In addition, for Lake Tiefer See alkalinity was measured within 24 h of sampling, by endpoint titration with HCl. For Lake Czechowskie, dissolved inorganic carbon (DIC) was measured with a portable UV-VIS DR2800 spectrophotometer (Hach) using Hach Lange cuvette tests (LCK 380). Calcite saturation indices are given by [$SI_{calcite}$ = (log IAP) – (log K_T)]; where IAP = ion activity product between $\{Ca^{2+}\}\{CO_3^{2-}\}$, and K_T = equilibrium constant at a given temperature. (Super)saturation conditions are given when $SI_{calcite} \geq 0$.

Monitoring of meteorological conditions on site

Measurements of meteorological conditions include air temperature, rainfall and wind speed. These have been measured at Lake Tiefer See at 10-min intervals since June 2013 at a weather station installed on the lake (Fig. 1B). Due to technical problems no data were collected in May 2014 and in October 2014. At Lake Czechowskie, the meteorological conditions have been measured at 10-min intervals since July 2013 at a similar weather station, located at the northeastern shore. Due to technical problems no wind speed data were collected at Lake Czechowskie from March 2015 to May 2017. For representation purposes, data gaps of 2014 are completed with data from the meteorological station Waren, Müritz (Deutscher Wetterdienst, https://opendata.dwd.de).

Results

Varves and sub-layers

Varve deposition in the collected surface sediment cores was preserved in Lake Tiefer See until late autumn 2017 and in Lake Czechowskie until early summer 2019 (Fig. 2A). Varve micro-facies analyses and varve thickness measurements were carried out on the uppermost 4 and 8 cm from thin sections for both lakes, encompassing 19 varves in the Tiefer See core and 13 varves in the Czechowskie core. The mean varve thickness of Czechowskie varves (6.1±2.8 (σ) mm) is more than triple than that of Tiefer See varves (1.8±0.78 (σ) mm). Although it cannot be excluded that the difference in thickness might be to some degree biased by possibly different water contents of the sediments (see Material and methods section) it is obvious that mass accumulation rates in Lake Czechowskie are clearly higher than in Lake Tiefer See. The internal varve structure (Fig. 2B, Fig. S1) and sub-layer succession (micro-facies) in both lakes is largely the same and includes three sub-layers: (i) planktonic diatoms deposited in spring (Lake Tiefer See: predominantly *Stephanodiscus* sp. and *Cyclotella* sp.; Lake Czechowskie: predominantly *Fragilaria* sp. and *Stephanodiscus* sp.), (ii) graded coarse- to fine-grained idiomorphic calcite crystals on the base to some extent intermixed with planktonic diatoms, and (iii) a third sub-layer of sediments comprising planktonic and benthic diatoms, plant fragments and calcite patches (Fig. 2B), thus mainly re-suspended matter. For both lakes, all sub-layers show considerable variations in thickness. In Lake

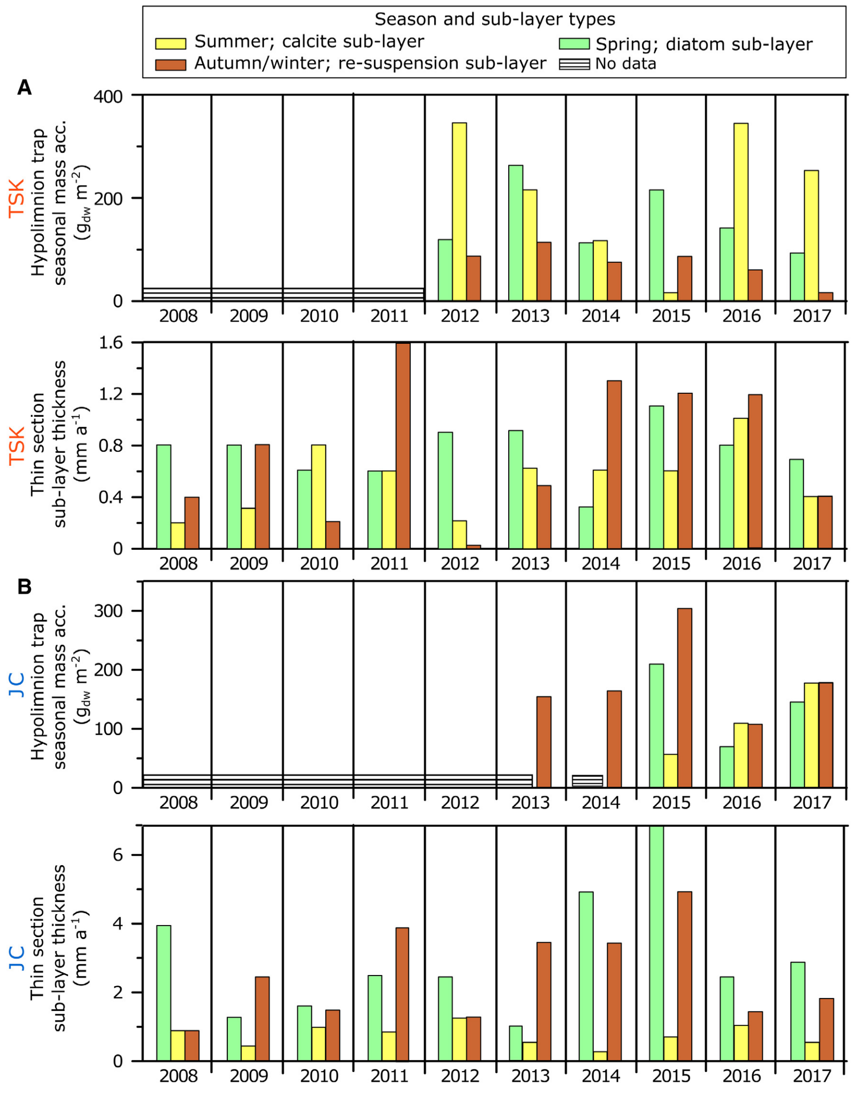

Fig. 3. Comparison between seasonal sedimentation rates in the hypolimnion traps and the sub-layer thickness in thin sections of the surface sediment cores in Lakes (A) Tiefer See (TSK) and (B) Czechowskie (JC). Details for flux calculations are given in the Material and methods section. [Colour figure can be viewed at www.boreas.dk]

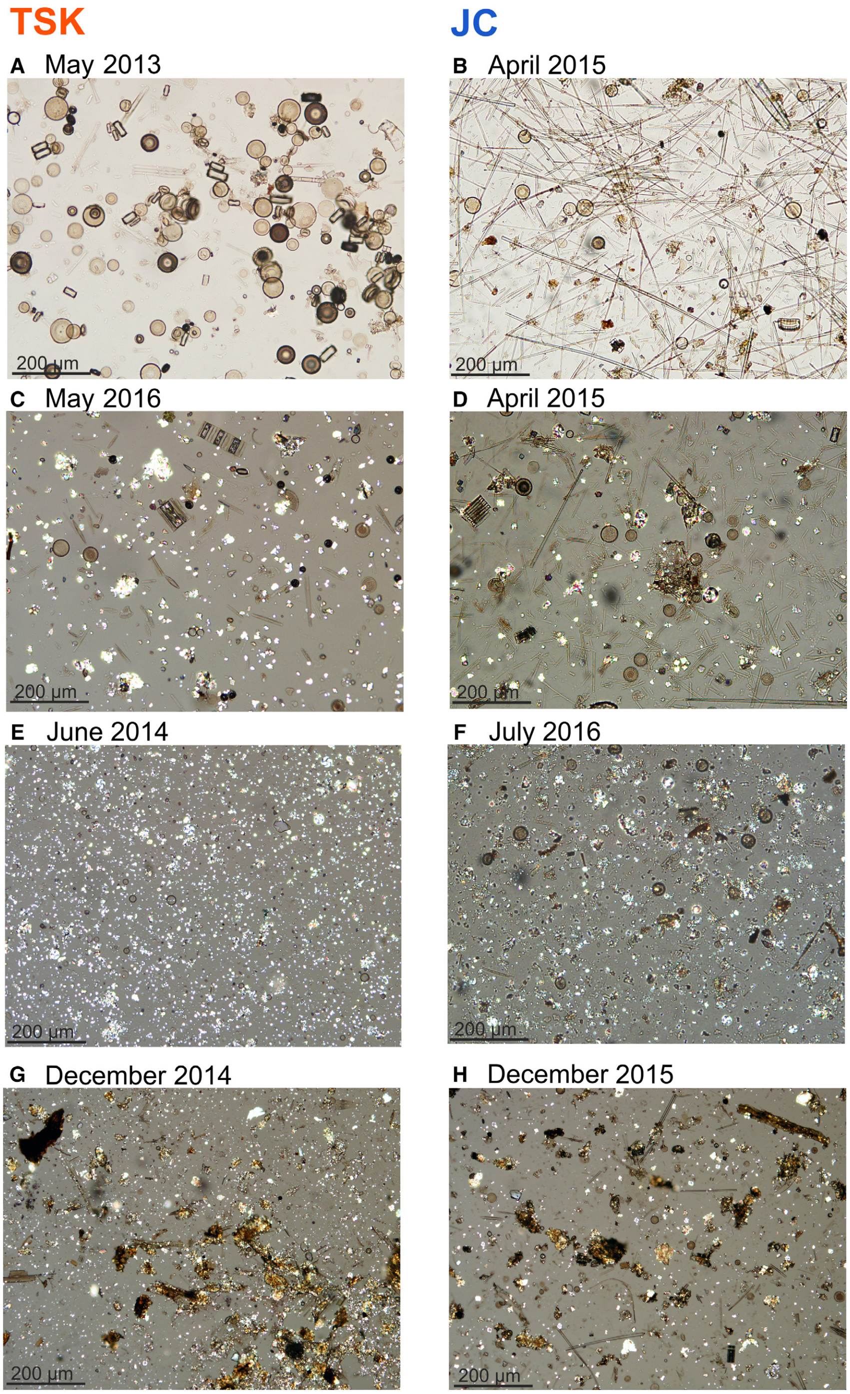

Fig. 4. Smear slide images of sediment trap material collected in the hypolimnion of Lakes Tiefer See (TSK) and Czechowskie (JC) showing the major seasonal sediment components. A, B. Planktonic diatoms. C, D. Planktonic diatoms and coarse-grained precipitated calcite crystals of up to 20 µm. E, F. Fine-grained (micritic) precipitated calcite crystals and *P. lenticularis*. G, H. Re-suspended calcite patches from the littoral zone, plant fragments and benthic diatoms. [Colour figure can be viewed at www.boreas.dk]

Tiefer See, the mean thickness of the diatom sub-layer is 0.7±0.23 (σ) mm; while the calcite sub-layer is 0.50±0.22 (σ) mm and the re-suspension sub-layer is 0.71±0.46 (σ) mm thick. In Lake Czechowskie, the mean thickness of the diatom sub-layer is 2.9±1.9 (σ) mm; the calcite sub-layer 0.6±0.3 (σ) mm and the re-suspension sub-layer 2.5±1.3 (σ) mm. The main difference between the calcite varves in the two lakes is the dominance of the relative thicker re-suspension sub-layers throughout the years in the Lake Czechowskie varves. This sub-layer contains a considerably higher number of planktonic diatoms (*Fragilaria* sp., Fig. 2), and together with the spring

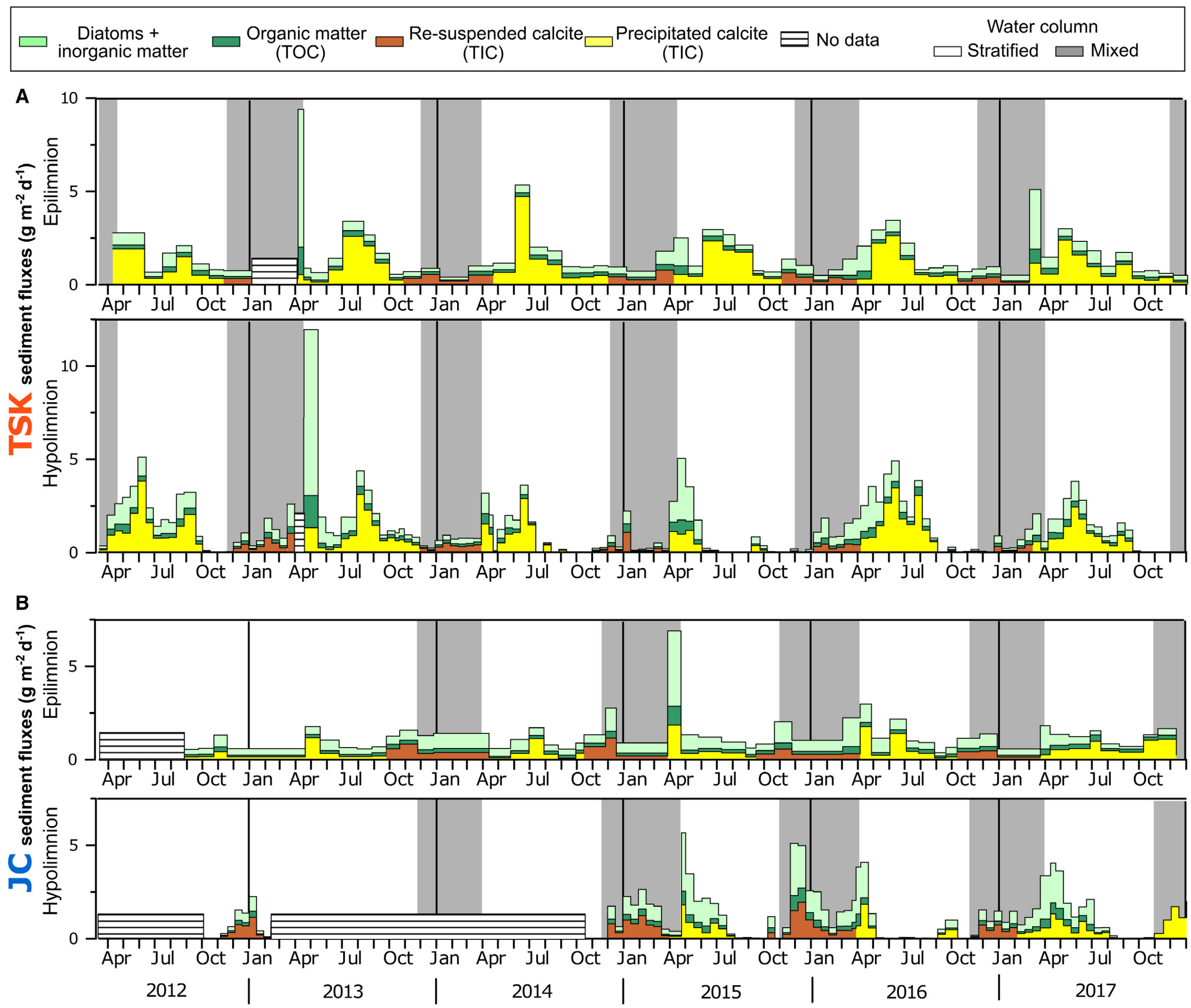

Fig. 5. Sediment fluxes (g m^{-2} d^{-1}) of the epilimnion and hypolimnion of Lakes (A) Tiefer See (TSK) and (B) Czechowskie (JC). The distinct sediment fractions correspond to precipitated calcite (total inorganic carbon – TIC, yellow), re-suspended calcite (total inorganic carbon –TIC, brown), total organic carbon (TOC, dark green), and the remaining fraction corresponds mainly to diatoms summed to eventual inorganic sediment (light green). Further details are given in the Material and methods section. [Colour figure can be viewed at www.boreas.dk]

diatom sub-layer, dominates the annual sediment yield in Lake Czechowskie from 2010 to 2018. By contrast, the relative contribution of each sub-layer to the total annual sedimentation in Lake Tiefer See varies from 2005 to 2017 (Figs 2, 3).

Deposition in sediment traps

Although the annual sedimentation cycle as documented from the composition of trapped sediments is similar in both lakes (Fig. 4), the amount of sediment in the hypolimnion traps representing particle flux to the lake bottom reveals some pronounced seasonal differences (Fig. 3).

In both lakes, diatom frustules dominate the sediment composition in early spring (Fig. 4A–D), but they represent different taxa. At Lake Tiefer See, the main diatoms are *Stephanodiscus* sp. and *Cyclotella* sp. and to a lesser extent *Aulacoseira* sp., and *Fragilaria* sp. (e.g. Fig. 4A, C), while the dominant diatom species in Lake Czechowskie are *Fragilaria* sp. and to a lesser extent *Stephanodiscus* sp. and *Cyclotella* sp. (Fig. 4B, D). In late spring/early summer, when diatoms are still being deposited, calcite crystals with a size of up to 20 µm form in both lakes (Fig. 4C, D). Small micritic calcite crystals dominate the sedimentation from May/June until September/October (Fig. 4E, F). In addition, blooms of *Phacotus lenticularis* regularly occur in both lakes in July and August (Fig. 4E, F). Based on trapped sediments, the largest difference between the two lakes appears from September until March. At Lake Tiefer See, the sedimentation flux to the hypolimnion is greatly

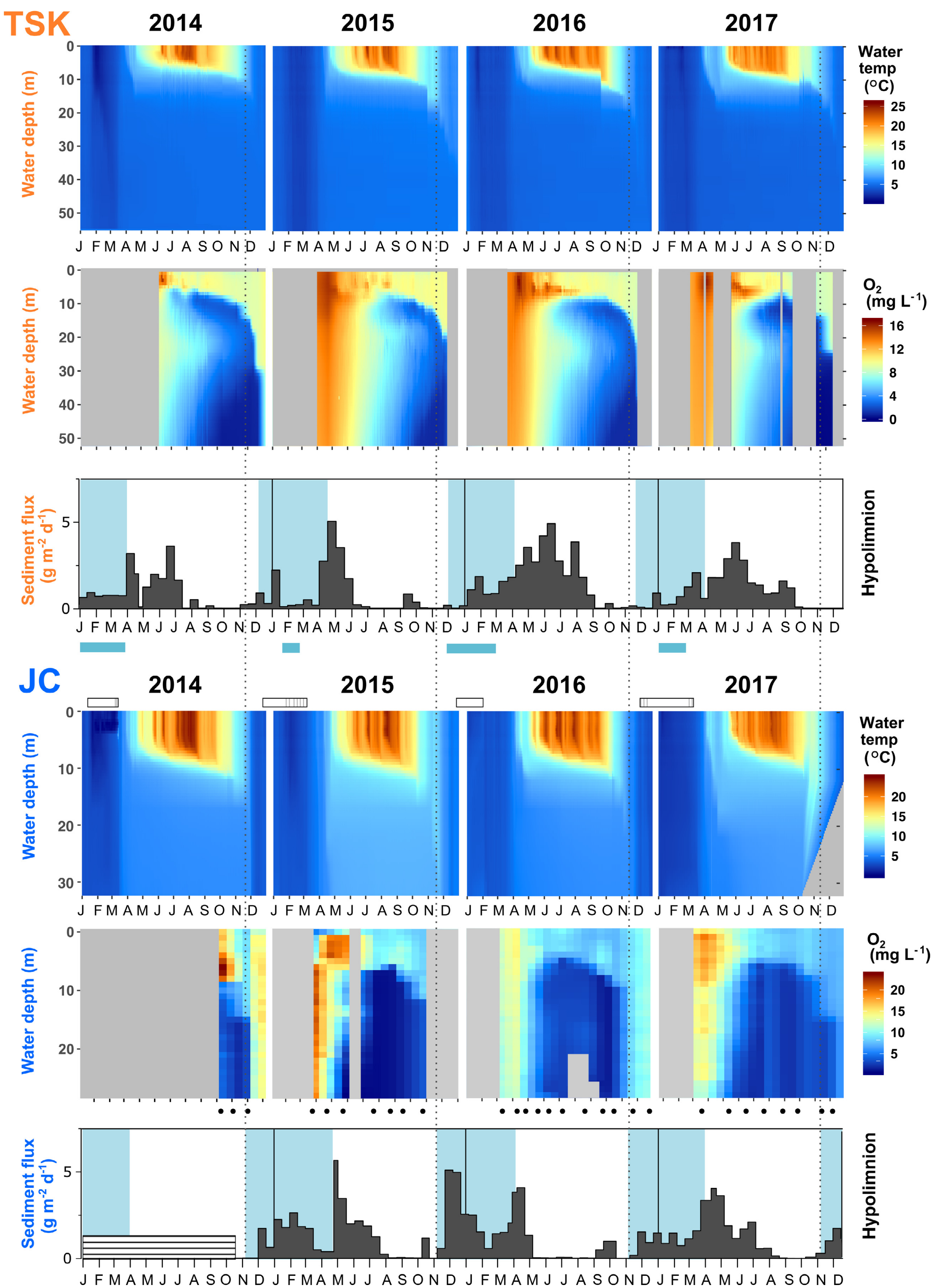
TSK
2014
2015
2016
2017
Water depth (m)
Water temp (°C)
O2 (mg L-1)
Sediment flux (g m-2 d-1)
Hypolimnion
J F M A M J J A S O N D
JC
Water depth (m)
Water temp (°C)
O2 (mg L-1)
Sediment flux (g m-2 d-1)
Hypolimnion

Fig. 6. Mixing dynamics (water temperature and dissolved oxygen) and total hypolimnion sediment fluxes for Lakes Tiefer See (TSK) and Czechowskie (JC) from 2014 to 2017. Vertical blue bars indicate periods without thermal stratification. Vertical dotted lines indicate the onset of an isothermal water column in Lake JC. Horizontal blue bars indicate periods of frost days for the region (T_{air} < 0 °C). Horizontal white bars, and grey hashes therein, indicate periods with complete or partial ice cover for Lake JC. Lake TSK had substantial ice cover only in 2014. Sampling and data resolution are given in the Material and methods section. For both lakes, T (°C) was interpolated to 1 day and 0.5 m water depth. Oxygen data were interpolated to 1 day, 1 m water depth for Lake TSK, and 15 days and 0.5 m for Lake JC. Detailed components of sediment fluxes are given in Fig. 5. [Colour figure can be viewed at www.boreas.dk]

reduced during this time and comprises littoral calcite patches, plant fragments as well as benthic and planktonic diatoms, the latter mostly broken and fragmented (Fig. 4G). In contrast, at Lake Czechowskie the hypolimnion sedimentation flux rises again in November and these sediments comprise littoral calcite patches, plant fragments and benthic diatoms (Fig. 4H).

At Lake Tiefer See, the sedimentation rates in the metalimnion and hypolimnion exhibit a single annual sedimentation maximum lasting from April to August (Fig. 5A), dominated by precipitated calcite. In contrast, at Lake Czechowskie two distinct sedimentation maxima are observed during one year – the first likewise from April to August and an additional second from December to March. Both maxima in Lake Czechowskie have enhanced calcite fluxes, but are likely triggered by different deposition processes (Fig. 5B). At Lake Tiefer See, in some years the summer epilimnion carbonate fluxes exceed the hypolimnion carbonate fluxes by 4 to 9 g m^{-2} d^{-1} (April to October sum), e.g. 2014 and 2015, suggesting calcite dissolution during settling. In other years, the fluxes are comparable, or even higher in the hypolimnion by 3 to 11 g m^{-2} d^{-1}, e.g. 2012, 2013, suggesting further calcite precipitation. At Lake Czechowskie, the sediment fluxes in the water column are more differentiated in autumn and winter, with higher hypolimnion fluxes compared to the metalimnion (Fig. 5B). This higher sediment yield in the hypolimnion trap during mixing of the water column points to lateral sediment flux from lake internal re-suspension. Detrital catchment material is rare or even absent.

The fluxes of planktonic diatoms at Lake Tiefer See were highest and reached up to 11 g m^{-2} d^{-1} in April/May 2013, while at Lake Czechowskie the highest diatom flux of up to 7 g m^{-2} d^{-1} was recorded in April 2015 (Fig. 5). Higher abundances of *P. lenticularis* are usually recorded in July and August, accounting for a maximum of ~20% of the deposited calcite (Fig. 4F). At Lake Tiefer See, nearly no calcite is found in the hypolimnion after September, except in the anomalous year 2013. Cyanobacteria remains were noted in Lake Tiefer See epilimnion traps especially in 2014 and 2015. At Lake Czechowskie, the highest deposition of re-suspended sediment was recorded in the winter season 2015/2016 (Fig. 3). Furthermore, in autumn 2015 a second bloom of planktonic diatoms was recorded in the Czechowskie metalimnion sediment traps of up to 1 g m^{-2} d^{-1}.

Water column physico-chemical properties

Thermal stratification for both lakes has its onset with increasing water temperatures in spring of each year (Fig. 6). The timing of the onset of lake stratification for both lakes is very similar and differs by less than one week. In contrast, the end of lake stratification occurs up to 30 days earlier in Lake Czechowskie. In autumn, at the end of October and early November, convective mixing lowers the thermocline by about 5 metres in both lakes, before an overturn of the water column takes place first in late November/December in Lake Czechowskie and in late December/January in Lake Tiefer See. The period between the onset of water isothermy in late autumn and the beginning of the next summer stratification varied in Lake Tiefer See between 119 days (winter 2013/2014) and 150 days (winter 2012/2013). In Lake Czechowskie this period varied by only 8 days with a maximum duration of 155 days in winter 2015/2016. It is noticeable that in both lakes the water body during winter is mostly characterized by isothermal conditions, except during short periods, days to weeks, in February when an eventual inverse thermal stratification with gradients of ~1 °C developed (Fig. 6). Lake Czechowskie remains isothermal for long periods also below an ice cover.

During early spring, enhanced oxygen concentrations in the epilimnion clearly indicate algal blooms in both lakes. With the development of temperature stratification in spring, oxygen becomes gradually depleted in the hypolimnion waters of both lakes, as a result of organic matter decomposition and reaches a minimum in late autumn (Fig. 6). The boundary between oxygen rich upper waters and oxygen deficient lower waters during summer stratification is sharp in Lake Czechowskie at ~7 m water depth, whereas in Lake Tiefer See a metalimnetic oxygen minimum zone develops between ~7–15 m water depth (Fig. 6).

Concentrations of dissolved silicon and calcium are lower in the epilimnetic waters during diatom blooms and calcite precipitation, respectively, as these elements are retrieved from the dissolved to the particulate phase. At Lake Tiefer See, the retrieval of Si from the epilimnion precedes the retrieval of Ca^{2+} often by more than 4 weeks, reflecting a clear succession between the diatom blooms and calcite precipitation (Figs S2, S3), the latter likely induced by other primary producers. In both lakes, the spring diatom

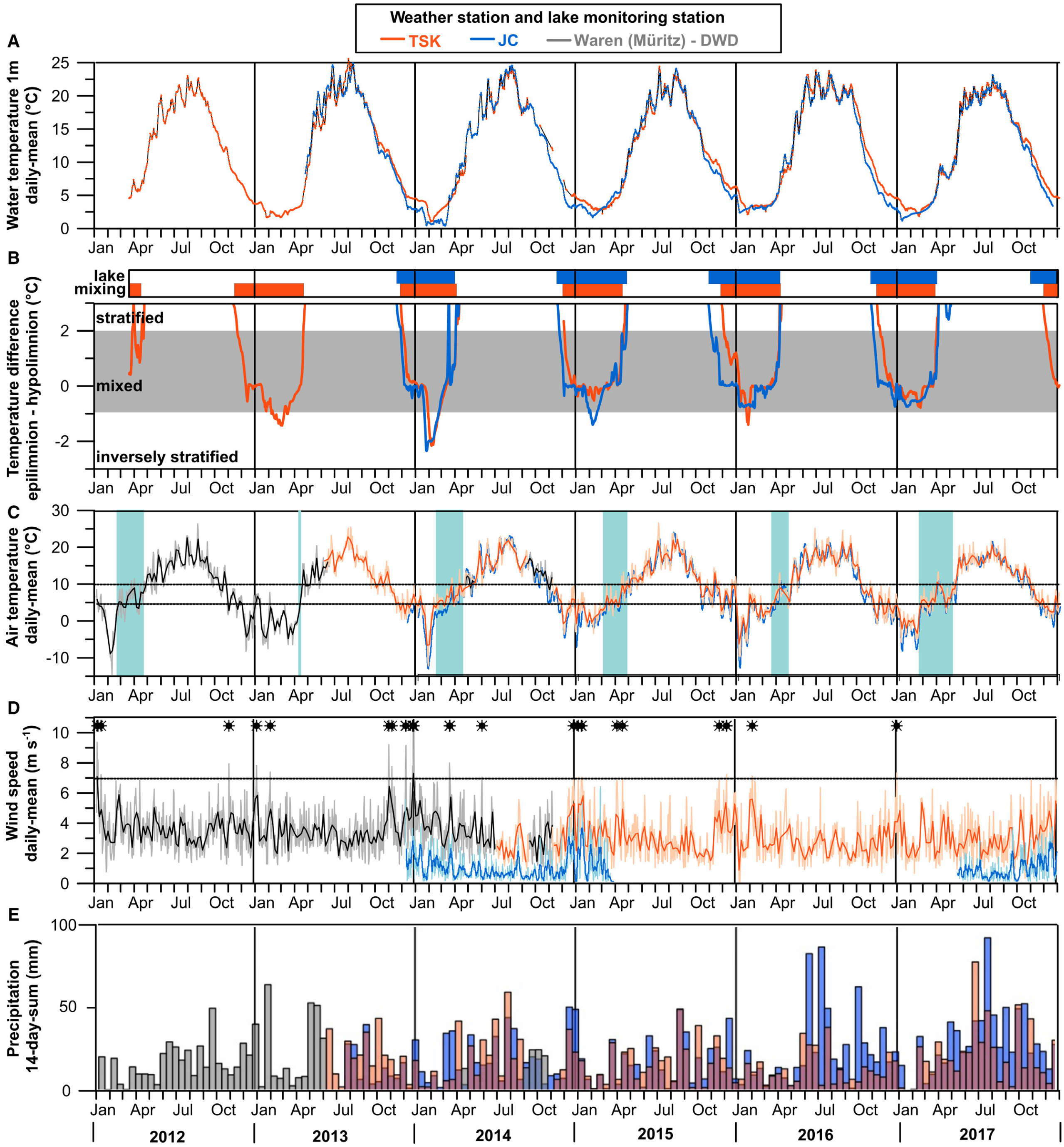

Fig. 7. Water column properties of Lakes Tiefer See (TSK; orange) and Czechowskie (JC; blue) from 2012 to 2017, and meteorological conditions at both sites. A. Water temperature at 1 m water depth. B. Temperature difference between epilimnion and hypolimnion (calculated from the maximum temperatures obtained for the uppermost and lowermost 5 m of the water column, respectively). C. Daily-mean air temperature (thin lines) and 5-day-mean air temperature (bold lines); the duration of spring warming from 5 to 10 °C is shown by the turquoise vertical bars. D. Daily-mean wind speed (thin lines) and 5-day-mean wind speed (bold lines); days of mean wind speed higher than 7 m s^{-1} are indicated by the black asterisks. E. 14-day-sum of rainfall. [Colour figure can be viewed at www.boreas.dk]

blooms are concomitant with the first increase in water temperatures in April (Figs 5, 6).

In both lakes the concentrations of dissolved silicon and a fraction of redox sensitive phosphorous gradually become enhanced in the bottom waters throughout the year, as dissolved substances accumulate during lake stratification (Figs S2, S3). With lake mixing in late autumn and early winter, nutrients and other dissolved substances are re-distributed in the water columns of both lakes, favouring the diatom blooms in the following spring. In both lakes, concentrations of total dissolved P in March, shortly before the spring diatom bloom, were higher in 2015 as compared to 2016 (Figs S2, S3). This is reflected in the following algal bloom, and consequently the thickness of the diatom sub-layers of both lakes for the years 2015 and 2016.

Carbonate saturation

During the stratified summer season, calcium concentrations are also higher in the hypolimnion than in the epilimnion of both lakes, although they do not follow the stepwise evolving oxygen depletion in the lower water column. Lower Ca^{2+} concentrations in the upper water column show ion removal by calcite precipitation (Fig. S2). During summer, available Ca^{2+} concentrations in the epilimnion of both lakes are still about ~65 mg L^{-1} in Lake Tiefer See, and ~50–40 mg L^{-1} in Lake Czechowskie. Epilimnion waters of both lakes are saturated with respect to calcite throughout the year (Table S2). With the onset of stratification, in the epilimnion the calcite saturation index increased from spring towards summer (Table S2). In general, the first increase of the saturation index was observed in spring, was pH driven, and initiated precipitation of the coarser calcite grains. A second increase in saturation towards summer was temperature driven and caused precipitation of micritic calcite grains (Table S3). With onset of lake stratification, the colder hypolimnion waters tend to become gradually undersaturated also due to small decreases in the value of pH, reaching maximum undersaturation during late autumn. During winter, calcite saturation conditions are nearly constant with only slight variations throughout the water column of Lake Tiefer See. Notably, the year 2015 showed the highest winter calcite saturation at Lake Czechowskie following very high pH values, which additionally sustains formation of the re-suspension sub-layer, as the latter also contains reworked patches of calcite. At Lake Tiefer See, in 2016 the strongest supersaturation of epilimnion waters occurred already during spring (1.16), leading to the thickest calcite sub-layer (Fig. 3), despite strong undersaturation of bottom waters in late autumn (−0.22).

Meteorological conditions

Maximum daily mean air temperatures higher than 25 °C at both study sites were reached during July and/or August (Fig. 7, Table S4). The time interval during which air temperature increased from 5 to 10 °C at the transition from winter to spring lasted on average 40 days, and was exceptionally short in 2013, taking only 5 days (blue bars in Fig. 7C).

Daily wind speed for both sites had the same relative pattern during the study period, with higher values during the autumn and winter months (Fig. 7D). Maximum values were higher than 9 m s^{-1} at Lake Tiefer See, and about 6 m s^{-1} at the more continental Lake Czechowskie. Major wind directions recorded from the stations at both lakes were very similar, mainly W for Lake Tiefer See, and SW for Lake Czechowskie.

The 14-day sum of precipitation was generally higher during the summer and autumn months and lower during winter and spring at both lakes. The annual precipitation amount from 2013 to 2015 was similar between the two study sites, whereas in 2016 and 2017 ~200 mm more annual rainfall was recorded at Lake Czechowskie.

Discussion

Seasonal sedimentation cycle and calcite varve structure

The seasonal succession of sediment formation and deposition as recorded in sediment traps is generally well reflected by the sub-layer succession forming calcite varves in the sediment record of both lakes. The seasonal cycle of sediment formation is generally the same in both lakes and proceeds as follows.

High deposition rates of diatom frustules in April/May mark the onset of biological productivity. The timing of first diatom blooms is seen from removal of dissolved silicon in the epilimnion and concurs with the increases in air temperature and development of lake stratification. The spring diatom bloom is favoured by the increased nutrient availability due to the preceding water column mixing (Bluszcz *et al.* 2008; Bonk *et al.* 2015; Maier *et al.* 2018). Interestingly, in Lake Tiefer See in 2013 and 2016, enhanced nutrient availability led the diatom bloom to precede temperature stratification of the lake water by 4 to 8 weeks. Still during the first phytoplankton blooms, alongside the increase in calcite saturation index, Ca^{2+} concentrations in the epilimnion begin to decrease at a rate of about 2 mg L^{-1} due to precipitation of coarse-grained calcite crystals, with up to 20 μm size. The blooms increase the pH value of the water, e.g. typically from ~8 (winter) to 8.6 (spring), leading to saturation indices of 0.88–1.16 in spring (Table S2). Therefore, our data suggest that the spring increase in carbonate saturation is pH driven and triggered by algal blooms (Table S3). The coarse calcite grains form slowly due to the inhibition of calcite precipitation by higher phosphorous concentrations (Raidt & Koschel 1988; Koschel 1990). Continuing calcite precipitation is well reflected by a depletion of Ca^{2+} ions from the epilimnion. Supersaturation continues to increase, maintained by temperature, and as soon as dissolved nutrients are further removed due to phytoplankton growth, smaller calcite crystals precipitate and between June/July and September micritic calcite crystals dominate the deposition in both lakes. As the first calcite crystals formed during spring begin to sink, they act as a downward transport of alkalinity. The temperature-maintained supersaturation of the epilimnion favours further pulses of calcite precipitation.

During late autumn when colder temperatures and enhanced wind lead to the onset and development of water column mixing (late December/January in Lake Tiefer See; late November/December in Lake Czechowskie), we observed higher contributions of benthic diatoms, calcite patches formed in the littoral zone, and few minerogenic particles and plant remains in the hypolimnion traps, suggesting lake-internal sediment re-suspension from the shallow water area into the deep basins. The assumption is confirmed by two- to sixfold higher flux in the hypolimnion traps in comparison to the metalimnion trap, especially in Lake Czechowskie. Parallel to the deposition of re-suspended littoral sediments an increase in planktonic diatom deposition suggests a second algal bloom in October especially in Lake Czechowskie. This productivity phase is likely caused by the redistribution of water column nutrients into the photic zone during mixing of the shallower lake zones and the release of nutrients by sediment re-suspension (Bonk *et al.* 2015; Maier *et al.* 2018). In some years, additional silicon retrieval from the epilimnion waters of Lake Tiefer See in October/November also suggests a second diatom bloom in autumn. However, in the sediment traps planktonic diatoms are found only sporadically after September until the onset of mixis. In summary, sediment trap observation reveals a consistent annual succession of three main depositional processes including (i) spring diatom blooms followed by (ii) endogenic calcite formation in two sub-phases with a decrease from larger crystal sizes at the beginning to smaller sizes in the later stage, and, finally (iii) lake-internal sediment re-suspension that can be accompanied by a second diatom bloom (Figs 2, 5).

All three deposition phases and even details of the transitions are well reflected in the varve micro-facies of the sediment record obtained in cores. The spring diatom sub-layer sometimes appears monospecific (e.g. pure *Stephanodiscus* sp. in spring 2013 at Lake Tiefer See) and often includes in its upper part large idiomorphic calcite crystals up to 20 μm reflecting the time overlap of the onset of calcite precipitation and the diatom bloom. The overlying calcite sub-layer exhibits the same shift from larger (up to 20 μm) to micritic grain sizes observed in the sediment traps. Multiple discrete summer calcite pulses reported elsewhere (Brauer *et al.* 2008b; Bonk *et al.* 2015; Trapote *et al.* 2018) were not observed in either of the presently studied lakes during the observation period. The fine-grained calcite layer is followed by a third sub-layer that appears as a diffuse mixture of amorphous organic matter, patches of calcite, benthic and not only epiphytic but also planktonic diatoms, reflecting re-suspension processes during the period of water isothermy in autumn and winter. The transition from the preceding calcite layer is usually sharp and clearly visible, while the transition to the following spring diatom layer, which marks the begin of the 'new varve year', is often diffuse and only recognizable in thin sections. Macroscopically, both the autumn/winter re-suspension and the spring diatom layer together appear as the 'dark' organic, or mixed, layer of the 'light-dark couplet' according to how calcite varves are commonly interpreted (Table 1; e.g. Minder-Zürich 1922; Kelts & Hsü 1978; Lotter & Lemcke 1999). Although sediment re-suspension is recognized as a typical lake-internal process during autumn (e.g. Lüder *et al.* 2006; Czymzik *et al.* 2016), it is commonly not considered as causing deposition of a distinct sub-layer. The re-suspension of sediments that form this third season sub-layer is proven by hypolimnion sediment fluxes and constrained to water column mixing in late autumn and early winter. The distinction of the re-suspension sub-layer from the following spring diatom layer is not trivial and requires in-depth knowledge of seasonal deposition processes from high-resolution sediment monitoring and parallel thin section analyses of the resulting sediment succession (e.g. Fig. 2, Fig. S1).

Overall, the seasonal autochthonous sediment production and deposition in Lake Tiefer See and Lake Czechowskie are representative for alkaline lakes in humid climate zones that form and preserve varves. Aspects that become more evident from the dual lake monitoring data are (i) identification of a discrete re-suspension sub-layer that easily can be overlooked if no thin sections are available, (ii) calcite supersaturation is maintained by pH in spring, and by temperature in summer, and (iii) calcite grain-size decreases from spring to summer, although the absolute size of calcite grains may vary among lakes.

Differences in seasonal deposition

Despite largely common lake-internal processes in alkaline lakes with varved sediments, outlined above, we identified patterns that have implications for the interpretation of the resulting varve record in terms of climate and environmental proxies. The main difference between the two lakes is that Lake Tiefer See exhibits only one distinct sedimentation maximum during summer, whereas Lake Czechowskie shows a distinct second maximum during the autumn/winter season (hypolimnion fluxes). In addition, the seasonal contribution of the single components to the total annual sediment yield differs between both lakes. While in Lake Tiefer See spring diatom (up to 300 g m^{-2} a^{-1}) and summer calcite (up to 350 g m^{-2} a^{-1}) deposition predominantly contribute to the yearly sedimentation, the Lake Czechowskie sediments are dominated by the re-suspension (up to 300 g m^{-2} a^{-1}) and diatom fluxes (up to 200 g m^{-2} a^{-1}).

The strength of the re-suspension processes particularly in Lake Czechowskie that lead to a second

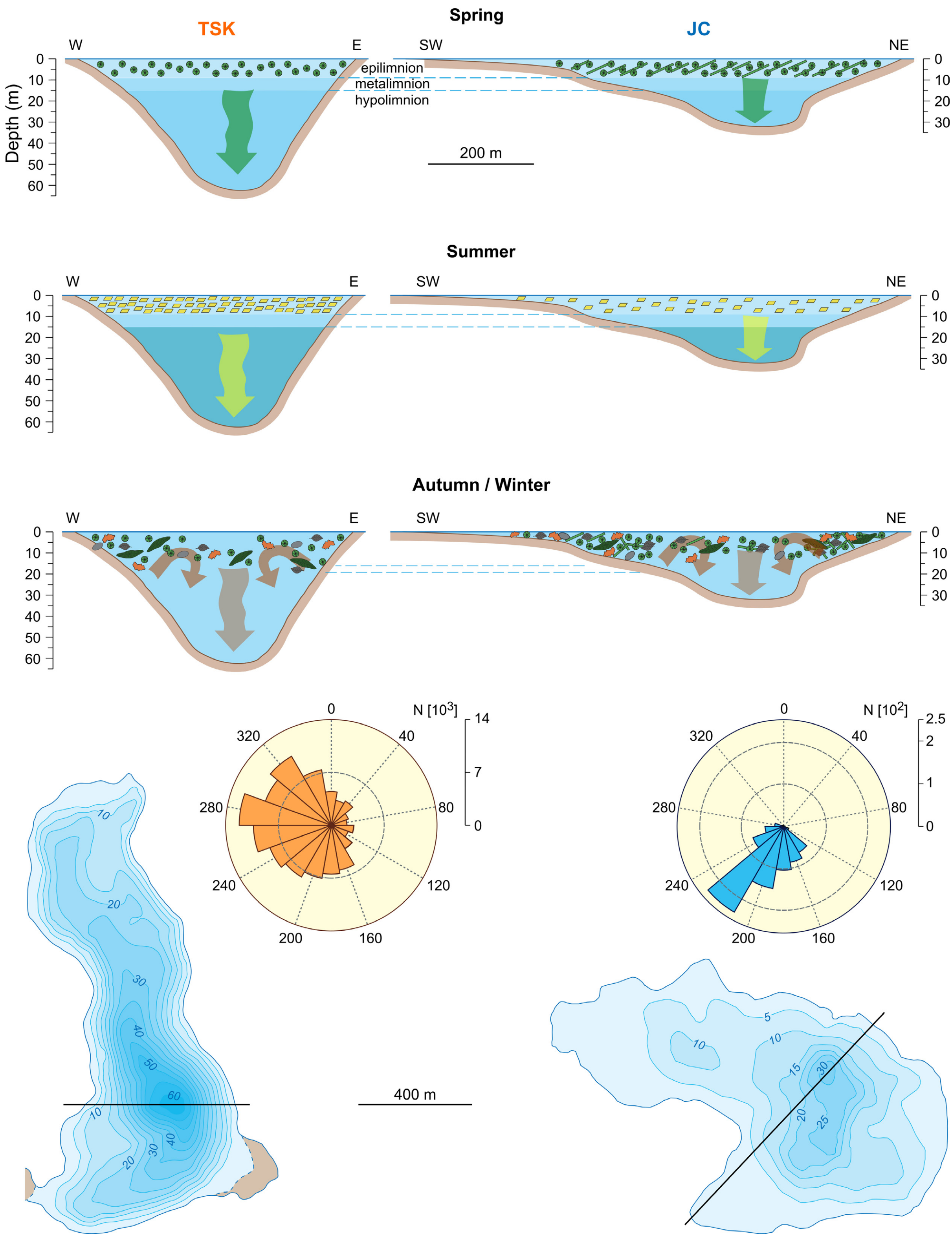

Fig. 8. Conceptual model of varve formation in alkaline temperate lakes. The three deposited sub-layers correspond to the three main deposition phases. Differences in the sediment yield of the single sediment components are affected by local factors. Given wind direction data are for wind speeds higher than 2.0 m s^{-1}, and originate from the meteorological stations placed by the lakes; at Lake TSK data resolution of 10 min, time interval 2013–2016; at Lake JC hourly data from 2013–2015, 2017. [Colour figure can be viewed at www.boreas.dk]

sedimentation maximum in late autumn and early winter can be explained by the following site-specific bathymetry and morphology, affecting timing and lake turnover. (i) Lake Czechowskie is only half as deep as Lake Tiefer See and thus the transport path from the shallow water area, where sediment re-suspension occurs, to the depot centre is shorter. (ii) The ratio between the shallow water area (<10 m water depth) and the depot centre of the basins is twice as high in Lake Czechowskie (Fig. 8) so that a larger area is affected by re-suspension through surface currents and waves (*sensu* Hilton *et al.* 1986; Bloesch 1995). This further extends the duration of re-suspension because the process starts already before complete lake turnover as soon as the convective mixing lowers the epilimnion to 10 m water depth. (iii) The Lake Czechowskie basin has a longer cross-section oriented along the main local wind direction leading to a longer wind fetch in comparison to the N–S oriented basin of Lake Tiefer See, which is perpendicularly oriented to the main local wind direction (Fig. 8). Consequently, wind impact particularly on the eastern shore of Lake Czechowskie close to the depot centre is stronger and reinforces re-suspension from the shallow regions and deposition at the coring site (Eadie *et al.* 1984; Blais & Kalff 1995; Kelderman *et al.* 2012). The influence of wind induced re-suspension on the eastern shore is confirmed by the different steepness of the eastern and western slopes of the basin (Fig. 8). (iv) Sediment re-suspension at Lake Czechowskie is additionally reinforced by the up to 30 days earlier onset of mixing in comparison to Lake Tiefer See, which provides more effective time for sediment re-suspension. This earlier onset of lake mixing is a consequence of the hypolimnion being up to 2 °C warmer in the shallower Lake Czechowskie. Thus, because of the smaller temperature gradient between upper and lower water-masses the shallower lake basin can respond much faster to wind forcing. For instance, at the end of November, the water column in Lake Czechowskie is already isothermal, while the larger water body of the 60-m-deep Lake Tiefer See requires up to a month more time to become isothermal.

In combination, these four site-specific factors lead to a more sensitive response of sedimentation in Lake Czechowskie to wind. This is especially documented by the high deposition rate of re-suspended sediment at the end of the stratification period in autumn 2015, following the earlier than usual onset of lake mixing in this year, in late November. The earlier onset of mixing likely was favoured by the longer consecutive period of enhanced wind speed, and additionally by the warmer hypolimnion in this year, which caused an earlier attainment of an equal temperature in the water column.

The second major difference in the sedimentation between Lake Tiefer See and Lake Czechowskie is the higher amount of precipitated calcite in Lake Tiefer See, which, in some years, reaches about 300 g m^{-2} while in Lake Czechowskie it never exceeds around 160 g m^{-2}. This difference is mirrored in the sediment record that in Lake Tiefer See exhibits a very clear and conspicuous calcite sub-layer, while in Lake Czechowskie this layer appears less distinct. Calcite precipitation at Lake Tiefer See occurs in the upper 5 metres of the water column, as evidenced by the retrieval of dissolved Ca^{2+}. As both lakes have similar surface areas, it can be assumed that the epilimnion water volume from which calcite precipitates is not significantly different. Both lakes also have similar concentrations of dissolved inorganic carbon (DIC) in the epilimnion waters. However, Ca^{2+} concentrations in Lake Tiefer See epilimnion waters are about 80 mg L^{-1} and in Lake Czechowskie about 60 mg L^{-1} before summer depletion. Higher Ca^{2+} contents in the lake water of Lake Tiefer See explain the more elevated supersaturation indices at Lake Tiefer See during the spring/summer season compared to Lake Czechowskie and are the likely cause for the higher amount of calcite precipitation (e.g. Kelts & Hsü 1978; Koschel 1990). Also, thriving cyanobacteria might further enhance calcite precipitation in Lake Tiefer See by regulating the partial pressure of CO_2 in the epilimnion. As for the hypolimnion waters, Lake Tiefer See shows gradually increasing undersaturation with respect to calcite during the annual cycle, culminating in autumn. For Lake Czechowskie this trend is the same. Consequently, in some years calcite is absent from August to October in the hypolimnion traps in both lakes. Calcite dissolution in Lake Tiefer See in comparison to Lake Czechowskie is promoted in the ~30 m thicker hypolimnion. The calcite crystals have a longer travel time to the deepest part of the basin and are, thus, exposed to the undersaturated waters for longer. For the sediment deposition and sub-layer structure it is important to note that calcite dissolution rates in Lake Tiefer See do not compensate for the higher precipitation rates such that the yield of calcite in the sediment record is still higher than in Lake Czechowskie resulting in a thicker calcite sub-layer in the sediment record.

Another difference in the seasonal sediment cycle between the two lakes is the occurrence of a discrete second diatom bloom in Lake Czechowskie during autumn that is not observed in Lake Tiefer See. This second distinct diatom bloom in Lake Czechowskie is likely caused by the aforementioned earlier lake overturn resulting in enhanced nutrient transport into the surface water and/or increased light availability in the water column. A higher nutrient availability during autumn is further related to sediment re-suspension that facilitates nutrient release in the shallower parts of the basin (Nuhfer *et al.* 1993). At Lake Tiefer See, retrieval of dissolved silicon in the epilimnion and sporadic occurrence of diatoms in traps during autumn might also suggest a second diatom bloom but only in some years, such as 2015. Although the occurrence of a second diatom sub-layer in older sediments from the Lake Tiefer See record has been reported (Kienel *et al.* 2013), this has not been observed during our monitoring period. The reason for this lack of a distinct second annual diatom bloom in Lake Tiefer See is unclear, but one might argue that either diatoms are outcompeted by increased growth of (cyano-)bacteria that assimilate phosphate and/or nitrogen better than the phytoplankton (Amin *et al.* 2012) or that diatom frustules are dissolved during settling, e.g. due to enhanced alkalinity in the bottom waters (*sensu* Ryves *et al.* 2009).

Conclusions

In this study, we reviewed the conceptual model of calcite varves and re-investigated seasonal sedimentation through a monitoring setup in two lakes located 380 km apart. Lakes Tiefer See and Czechowskie are both located in the southern Baltic lowlands, a region containing a large number of alkaline lakes with varved sediments. The comprehensive monitoring approach allowed us to identify a common seasonal deposition cycle controlled by the lake mixing dynamics, and to distinguish subtle but important local differences in sedimentation.

Our results point towards a more differentiated view on calcite varves than previously assumed. Rather than the commonly described light/dark laminae couplets, we clearly identified a succession of three sediment deposition pulses forming calcite varves: (i) a spring diatom bloom followed by (ii) endogenic calcite precipitation, sometimes sub-divided into an initial phase of medium silt-sized calcite followed by micritic calcite, and (iii) re-suspension of shallow water sediments during the autumn/winter lake mixis. The calcite crystal size is related to the distinct saturation drivers: pH in spring, and temperature in summer. Although sediment re-suspension has also been recognized earlier as a process contributing to the annual sediment yield, its role as a varve-forming process so far has been underestimated likely because macroscopically the re-suspension sub-layer appears together with the spring diatom sub-layer as one dark lamina.

We arrive at three major conclusions: (i) although alkaline lakes show a common sub-layer succession within calcite varves, there is no uniform climate–layer relationship for all lakes, (ii) the autochthonous sedimentation is determined by the yearly pace of lake mixing, and (iii) site-specific lake morphology exerts an important influence on the water circulation regime, leading to differences in the relative dominance of calcite varve sub-layers. In Lake Tiefer See calcite precipitation constitutes the main deposition phase. In contrast, sediment re-suspension is the predominant sedimentation process in Lake Czechowskie. These differences in depositional processes explain the different calcite varve micro-facies found in the sediment records of the two lakes.

In more general terms, the commonly accepted paradigm that varves are formed and preserved solely under conditions of constant stratification and hypoxic bottom waters needs careful verification. An in-depth knowledge of seasonal depositional processes in combination with micro-facies analyses of sediment profiles is a valuable approach for a better understanding of varve formation and preservation and required for a robust interpretation of varve data.

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References

Alefs, J. & Müller, J. 1999: Differences in the eutrophication dynamics of Ammersee and Starnberger See (Southern Germany), reflected by the diatom succession in varve-dated sediments. *Journal of Paleolimnology 21*, 395–407.

Amann, B., Lobsiger, S., Fischer, D., Tylmann, W., Bonk, A., Filipiak, J. & Grosjean, M. 2014: Spring temperature variability and eutrophication history inferred from sedimentary pigments in the varved sediments of Lake Żabińskie, north-eastern Poland, AD 1907–2008. *Global and Planetary Change 123*, 86–96.

Amin, S. A., Parker, M. S. & Armbrust, E. V. 2012: Interactions between diatoms and bacteria. *Microbiology and Molecular Biology Reviews 76*, 667–684.

Anderson, R. Y. & Dean, W. E. 1988: Lacustrine varve formation through time. *Palaeogeography, Palaeoclimatology, Palaeoecology 62*, 215–235.

Apolinarska, K., Pleskot, K., Pełechata, A., Migdałek, M., Siepak, M. & Pełechany, M. 2020: The recent deposition of laminated sediments in highly eutrophic Lake Kierske, western Poland: 1 year pilot study of limnological monitoring and sediment traps. *Journal of Paleolimnology 63*, 283–304.

Ariztegui, D., Chondrogianni, C., Lami, A., Guilizzoni, P. & Lafargue, E. 2001: Lacustrine organic matter and the Holocene paleoenvironmental record of Lake Albano (central Italy). *Journal of Paleolimnology 26*, 283–292.

Blais, J. M. & Kalff, J. 1995: The influence of lake morphometry on sediment focusing. *Limnology and Oceanography 40*, 582–588.

Błaszkiewicz, M. 2005: Późnoglacjalna i wczesnoholoceńska ewolucja obniżeń jeziornych na Pojezierzu Kociewskim (wschodnia część Pomorza). Prace Geograficzne, 201, Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warszawa, 192 pp.

Błaszkiewicz, M., Piotrowski, J., Brauer, A., Gierszewski, P., Kordowski, J., Kramkowski, M., Lamparski, P., Lorenz, S., Noryśkiewicz, A., Ott, F., Słowiński, M. & Tyszkowski, S. 2015: Climatic and morphological controls on diachronous postglacial lake and river valley evolution in the area of Last Glaciation, northern Poland. *Quaternary Science Reviews 109*, 13–27.

Bloesch, J. 1995: Mechanisms, measurement and importance of sediment resuspension in lakes. *Marine & Freshwater Research 46*, 295–304.

Bluszcz, P., Kirilova, E., Lotter, A. F., Ohlendorf, C. & Zolitschka, B. 2008: Global radiation and onset of stratification as forcing factors of seasonal carbonate and organic matter flux dynamics in a hypertrophic hardwater lake (Sacrower See, Northeastern Germany). *Aquatic Geochemistry 14*, 73–98.

Bluszcz, P., Lücke, A., Ohlendorf, C. & Zolitschka, B. 2009: Seasonal dynamics of stable isotopes and element ratios in authigenic calcites during their precipitation and dissolution, Sacrower See (northeastern Germany). *Journal of Limnology 68*, 257–273.

Bonk, A., Tylmann, W., Amann, B., Enters, D. & Grosjean, M. 2015: Modern limnology and varve-formation processes in lake Żabińskie, northeastern Poland: comprehensive process studies as a key to understand the sediment record. *Journal of Limnology 74*, 358–370.

Brauer, A. 2004: Annually laminated lake sediments and their palaeoclimatic relevance. *In* Fischer, H., Kumke, T., Lohmann, G., Flöser, G., Miller, H., von Storch, H. & Negendank, J. F. (eds.): *The Climate in Historical Times: Towards a Synthesis of Holocene Proxy Data and Climate Models*, 109–128. GKSS School of Environmental Research, Springer, Berlin.

Brauer, A. & Casanova, J. 2001: Chronology and depositional processes of the laminated sediment record from Lac d' Annecy, French Alps. *Journal of Paleolimnology 25*, 163–177.

Brauer, A., Allen, J. R. M., Mingram, J., Dulski, P., Wulf, S. & Huntley, B. 2007: Evidence for last interglacial chronology and environmental change from Southern Europe. *Proceedings of the National Academy of Sciences of the United States of America 104*, 450–455.

Brauer, A., Hajdas, I., Blockley, S. P. E., Ramsey, C. B., Christl, M., Ivy-Ochs, S., Moseley, G. E., Nowaczyk, N. N., Rasmussen, S. O., Roberts, H. M., Spötl, C., Staff, R. A. & Svensson, A. 2014: The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval. *Quaternary Science Reviews 106*, 47–66.

Brauer, A., Haug, G. H., Dulski, P., Sigman, D. M. & Negendank, J. F. W. 2008a: An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period. *Nature Geosciences 1*, 520–523.

Brauer, A., Mangili, C., Moscariello, A. & Witt, A. 2008b: Paleoclimatic implications from micro-facies data of a 5900 varve time series from the Pianico interglacial sediment record, southern Alps. *Palaeogeography, Palaeoclimatology, Palaeoecology 259*, 121–135.

Brunskill, G. J. 1969: Fayetteville Green Lake, New York. II. Precipitation and sedimentation of calcite in a meromictic lake with laminated sediments. *Limnology and Oceanography 14*, 830–847.

Bueche, T. 2016: The mixing regime of Lake Ammersee. *Journal of the Geographical Society of Berlin 147*, 275–283.

Carlson, R. E. 1977: A trophic state index for lakes. *Limnology and Oceanography 22*, 361–369.

Churski, Z. 1998: Bathymetry and morphometry of Lake Gościąż. *In* Ralska-Jasiewiczowa, M., Goslar, T., Madeyska, T. & Starkel, L. (eds.): *Lake Gościąż, Central Poland. A Monographic Study. Part 1*, 37–39. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Corella, J. P., Benito, G., Rodriguez-Lloveras, X., Brauer, A. & Valero-Garcés, B. L. 2014: Annually-resolved lake record of extreme hydro-meteorological events since AD 1347. *Quaternary Science Reviews 93*, 77–90.

Czymzik, M., Dreibrodt, S., Feeser, I., Adolphi, F. & Brauer, A. 2016: Mid-Holocene humid periods reconstructed from calcite varves of the Lake Woserin sediment record (north-eastern Germany). *The Holocene 26*, 935–946.

Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R. & Brauer, A. 2010: A 450 year record of spring-summer flood layers in annual laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research 46*, W11528, https://doi.org/10.1029/2009WR008360.

Dean, W. E. 1993: Physical properties, mineralogy, and geochemistry of Holocene varved sediments from Elk Lake, Minnesota. *In* Bradbury, J. P. & Dean, W. E. (eds.): *Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States: Boulder, Colorado*, 135–157. *Geological Society of America, Special Paper 276*.

Dean, W. E. 1999: The carbon cycle and biogeochemical dynamics in lake sediments. *Journal of Paleolimnology 21*, 375–393.

Dean, W. E., Forester, R. M. & Bradburry, J. P. 2002: Early Holocene change in atmospheric circulation in the Northern Great Plains: an upstream view of the 8.2 ka cold event. *Quaternary Science Reviews 21*, 1763–1775.

Dräger, N., Theuerkauf, M., Szeroczyńska, K., Wulf, S., Tjallingii, R., Plessen, B., Kienel, U. & Brauer, A. 2017: Varve microfacies and varve preservation record of climate change and human impact for the last 6000 years at Lake Tiefer See (NE Germany). *The Holocene 27*, 450–464.

Dreßler, M., Schwarz, A., Hübener, T., Adler, S. & Scharf, B. W. 2011: Use of sedimentary diatoms from multiple lakes to distinguish between past changes in trophic state and climate: Evidence for climate change in northern Germany during the past 5,000 years. *Journal of Paleolimnology 45*, 223–241.

Eadie, B. J., Chambers, R. L., Gardner, W. S. & Bell, G. L. 1984: Sediment trap studies in Lake Michigan: resuspension and chemical fluxes in the southern basin. *Journal of Great Lakes Research 10*, 307–321.

Enters, D., Kirilova, E., Lotter, A. F., Lücke, A., Parplies, J., Jahns, S., Kuhn, G. & Zolitschka, B. 2010: Climate change and human impact at Sacrower See (NE Germany) during the past 13,000 years: a geochemical record. *Journal of Paleolimnology 43*, 719–737.

Goslar, T. 1998a: Record of laminae thickness of the Lake Gościąż sediments, and its correlation with absolutely dated tree-ring width sequences. *In* Ralska-Jasiewiczowa, M., Goslar, T., Madeyska, T. & Starkel, L. (eds.): *Lake Gościąż, Central Poland. A Monographic Study. Part 1*, 104–110. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Goslar, T. 1998b: Late-Glacial sediments of Lake Gościaż. *In* Ralska-Jasiewiczowa, M., Goslar, T., Madeyska, T. & Starkel, L. (eds.): *Lake Gościąż, Central Poland. A Monographic Study. Part 1*, 119–121. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Gruber, N., Wehrli, B. & Wüest, A. 2000: The role of biogeochemical cycling for the formation and preservation of varved sediments in Soppensee (Switzerland). *Journal of Paleolimnology 24*, 277–291.

Hilton, J., Lishman, J. P. & Allen, P. V. 1986: The dominant processes of sediment distribution and focusing in a small, eutrophic, monomictic lake. *Limnology and Oceanography 31*, 125–133.

St-Jacques, J.-M., Cumming, B. F. & Smol, J. P. 2008: A 900-year pollen-inferred temperature and effective moisture record from varved Lake Mina, west-central Minnesota, USA. *Quaternary Science Reviews 27*, 781–796.

Kämpf, L., Plessen, B., Lauterbach, S., Nantke, C., Meyer, H., Chaplingi, B. & Brauer, A. 2020: Stable oxygen and carbon isotopes of carbonates in lake sediments as paleoflood proxy. *Geology 48*, 3–7.

Katz, A. & Nishri, A. 2013: Calcium, magnesium, and strontium cycling in stratified, hardwater lakes: Lake Kinneret (Sea of Galilee), Israel. *Geochimica et Cosmochimica Acta 105*, 372–394.

Kelderman, P., Angweya, R. O., de Rozari, P. & Vijverberg, T. 2012: Sediment characteristics and wind-induced sediment dynamics in shallow Lake Markermeer, the Netherlands. *Aquatic Sciences 74*, 301–313.

Kelts, K. & Hsü, K. 1978: Freshwater carbonate sedimentation. *In* Lerman, A. (ed.): *Lakes: Chemistry, Geology, Physics*, 295–323. Springer, Berlin.

Kemp, A. E. S. 1996: Laminated sediments as palaeo-indicators. *Geological Society, London, Special Publications 116*, vii–xii.

Kienel, U., Dulski, P., Ott, F., Lorenz, S. & Brauer, A. 2013: Recently induced anoxia leading to the preservation of seasonal laminae in two NE-German lakes. *Journal of Paleolimnology 50*, 535–544.

Kienel, U., Kirillin, G., Brademann, B., Plessen, B., Lampe, R. & Brauer, A. 2017: Effects of spring warming and mixing duration on diatom deposition in deep Tiefer See, NE Germany. *Journal of Paleolimnology 57*, 37–49.

Kinder, M., Tylmann, W., Bubak, I., Fiłoc, M., Gąsiorowski, M., Kupryjanowicz, M., Mayr, C., Sauer, L., Voellering, U. & Zolitschka, B. 2019: Holocene history of human impacts inferred from annually laminated sediments in Lake Szurpiły, northeastern Poland. *Journal of Paleolimnology 61*, 419–435.

Koschel, R. 1990: Pelagic calcite precipitation and trophic state of hardwater lakes. *Archiv für Hydrobiologie, Fundamental and Applied Limnology 33*, 713–722.

Koschel, R., Benndorf, J., Proft, G. & Recknagel, F. 1983: Calcite precipitation as a natural control mechanism of eutrophication. *Archiv für Hydrobiologie, Fundamental and Applied Limnology 98*, 340–408.

Koutsodendris, A., Brauer, A., Reed, J. M., Plessen, B., Friedrich, O., Hennrich, B., Zacharias, I. & Pross, J. 2017: Climate variability in SE Europe since 1450 AD based on a varved sediment record from Etoliko Lagoon (Western Greece). *Quaternary Science Reviews 159*, 63–76.

Lami, A., Niessen, F., Guilizzoni, P., Masaferro, J. & Belis, C. A. 1994: Paleolimnological studies of the eutrophication of volcanic Lake Albano (Central Italy). *Journal of Paleolimnology 10*, 181–197.

Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D. L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Obremska, M., von Grafenstein, U. & DECLAKES participants 2011: Environmental responses to Lateglacial climatic fluctuations recorded in the sediments of pre-Alpine Lake Mondsee (northeastern Alps). *Journal of Quaternary Science 26*, 253–267.

Lotter, A. F. & Lemcke, G. 1999: Methods for preparing and counting biochemical varves. *Boreas 28*, 243–252.

Lotter, A. F., Sturm, M., Teranes, J. L. & Wehrli, B. 1997: Varve formation since 1885 and high-resolution varve analyses in hypertrophic Baldeggersee (Switzerland). *Aquatic Sciences 59*, 304–325.

Lüder, B., Kirchner, G., Lücke, A. & Zolitschka, B. 2006: Palaeoenvironmental reconstructions based on geochemical parameters from annually laminated sediments of Sacrower See (northeastern Germany) since the 17th century. *Journal of Paleolimnology 35*, 897–912.

Maier, D. B., Gälman, V., Renberg, I. & Bigler, C. 2018: Using a decadal diatom sediment-trap record to unravel seasonal processes important for the formation of the sedimentary diatom signal. *Journal of Paleolimnology 60*, 133–152.

Mangili, C., Plessen, B., Wolff, C. & Brauer, A. 2010: Climatic implications of annual to decadal resolution stable isotope data from calcite varves of the Pianico interglacial record, Southern Alps. *Global and Planetary Change 71*, 168–174.

Martin-Puertas, C., Brauer, A., Dulski, P. & Brademann, B. 2012a: Testing climate-proxy stationarity throughout the Holocene: an example from the varved sediments of Lake Meerfelder Maar (Germany). *Quaternary Science Reviews 58*, 56–65.

Martin-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C., Aldahan, A., Possnert, G. & van Geel, B. 2012b: Regional atmospheric circulation shifts induced by a grand solar minimum. *Nature Geoscience 5*, 397–401.

Martin-Puertas, C., Tjallingii, R., Bloesma, M. & Brauer, A. 2017: Varved sediment responses to early Holocene climate and environmental changes in Lake Meerfelder Maar (Germany) obtained from multivariate analyses of micro X-ray fluorescence core scanning data. *Journal of Quaternary Science 32*, 427–436.

Minder-Zürich, L. 1922: Über biogene Entkalkung im Zürichsee. *Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verhandlungen 1*, 20–32.

Neugebauer, I., Brauer, A., Dräger, N., Dulski, P., Wulf, S., Plessen, B., Mingram, J., Herzschuh, U. & Brande, A. 2012: A Younger Dryas varve chronology from the Rehwiese palaeolake record in NE-Germany. *Quaternary Science Reviews 36*, 91–102.

Nuhfer, E. B., Anderson, R. Y., Bradbury, J. P. & Dean, W. E. 1993: Modern sedimentation in Elk Lake, Clearwater County, Minnesota. *In* Bradbury, J. P. & Dean, W. E. (eds.): *Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States: Boulder, Colorado*, 96–118. *Geological Society of America, Special Paper 276*.

O'Sullivan, P. E. 1983: Annually-laminated lake sediments and the study of Quaternary environmental changes – a review. *Quaternary Science Reviews 1*, 245–313.

Ohlendorf, C. & Sturm, M. 2001: Precipitation and dissolution of calcite in a Swiss High Alpine Lake. *Arctic, Antarctic, and Alpine Research 33*, 410–417.

Ojala, A. E. K., Francus, P., Zolitschka, B., Besonen, M. & Lamoureux, S. F. 2012: Characteristics of sedimentary varve chronologies – A review. *Quaternary Science Reviews 43*, 45–60.

Ott, F., Kramkowski, M., Wulf, S., Plessen, B., Serb, J., Tjallingii, R., Schwab, M., Słowiński, M., Brykała, D., Tyszkowski, S., Putyrskaya, V., Appelt, O., Błaszkiewicz, M. & Brauer, A. 2017: Site-specific sediment responses to climate change during the last 140 years in three varved lakes in Northern Poland. *The Holocene 28*, 464–477.

Ott, F., Wulf, S., Serb, J., Słowiński, M., Obremska, M., Tjallingii, R., Błaszkiewicz, M. & Braue, A. 2016: Constraining the time span between the early Holocene Hässeldalen and Askja-S Tephras through varve counting in the Lake Czechowskie sediment record, Poland. *Journal of Quaternary Science 31*, 103–113.

Parkhurst, D. L. & Appelo, C. A. J. 2013: Description of input and examples for Phreeqc version 3: a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. *U.S.Geological Survey Techniques and Methods 6 - A43*, 497 pp. available at https://pubs.usgs.gov/tm/06/a43/

Raidt, H. & Koschel, R. 1988: Morphology of calcite crystals in hardwater lakes. *Limnologica 19*, 3–12.

Ramisch, F., Dittrich, M., Mattenberger, C., Wehrli, B. & Wüest, A. 1999: Calcite dissolution in two deep eutrophic lakes. *Geochimica et Cosmochimica Acta 63*, 3349–3356.

Roeser, P., Dräger, N., Brykała, D., Ott, F., Pinkerneil, S., Gierszewski, P., Lindemann, C., Plessen, B., Brademann, B., Kaszubski, M., Fojutowski, M., Schwab, M. J., Słowiński, M., Błaszkiewicz, M. & Brauer, A. 2021: *TERENO Monitoring data from Lake Tiefer See and Lake Czechowskie (2012–2017)*. GFZ Data Services. https://doi.org/10.5880/GFZ.4.3.2020.003.

Ryves, D. B., Battarbee, R. W. & Fritz, S. C. 2009: The dilemma of disappearing diatoms: Incorporating diatom dissolution data into palaeonvironmental modelling and reconstruction. *Quaternary Science Reviews 28*, 120–136.

Schernewski, G. 2003: Nutrient budgets, dynamics and storm effects in a eutrophic, stratified Baltic lake. *Acta Hydrochimica et Hydrobiologica 31*, 152–161.

Schlegel, I., Koschel, R. & Krienitz, L. 1998: On the occurrence of Phacotus lenticularis (Chlorophyta) in lakes of different trophic state. *Hydrobiologia 369*, 353–361.

Słowiński, M., Zawiska, I., Ott, F., Noryśkiewicz, A. M., Plessen, B., Apolinarska, K., Rzodkiewicz, M., Michczyńska, D. J., Wulf, S., Skubała, P., Kordowski, J., Błaszkiewicz, M. & Brauer, A. 2017: Differential proxy responses to late Allerød and early Younger Dryas climatic change recorded in varved sediments of the Trzechowskie palaeolake in Northern Poland. *Quaternary Science Reviews 158*, 94–106.

Theuerkauf, M., Dräger, N., Kienel, U., Kuparinen, A. & Brauer, A. 2015: Effects of changes in land management practices on pollen productivity of open vegetation during the last century derived from varved lake sediments. *The Holocene 25*, 733–744.

Trapote, M. C., Vegas-Vilarrubia, T., Lopez, P., Puche, E., Gomà, J., Buchaca, T., Cañellas-Boltà, N., Safont, E., Corella, J. P. & Rull, V. 2018: Modern sedimentary analogues and integrated monitoring to understand varve formation in the Mediterranean Lake Montcortès (Central Pyrenees, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology 496*, 292–304.

Tylmann, W., Kinder, M., Żarczyński, M. & Poraj-Górska, A. 2016: Preliminary characteristics of laminations in recent sediments from lakes Kamenduł and Perty in the Suwałki Landscape Park, northeastern Poland. *Limnological Review 16*, 237–245.

Tylmann, W., Zolitschka, B., Enters, D. & Ohlendorf, C. 2013: Laminated lake sediments in northeast Poland: distribution, preconditions for formation and potential for paleoenvironmental investigation. *Journal of Paleolimnology 50*, 487–503.

Wehrli, B., Lotter, A. F., Schaller, T. & Sturm, M. 1997: High-resolution varve studies in Baldeggersee (Switzerland): project overview and limnological background data. *Aquatic Sciences 59*, 285–294.

Wirth, S., Glur, L., Gilli, A. & Anselmetti, F. 2013: Holocene flood frequency across the Central Alps – solar forcing and evidence for variations in North Atlantic atmospheric circulation. *Quaternary Science Reviews 80*, 112–128.

Zahrer, J., Dreibrodt, S. & Brauer, A. 2013: Evidence of the North Atlantic Oscillation in varve composition and diatom assemblages from recent, annually laminated sediments of Lake Belau, northern Germany. *Journal of Paleolimnology 50*, 231–244.

Żarczyński, M., Szmanda, J. & Tylmann, W. 2019: Grain-size distribution and structural characteristics of varved sediments from Lake Żabińskie (Northeastern Poland). *Quaternary 2*, 8, https://doi.org/10.3390/quat2010008.

Żarczyński, M., Tylmann, W. & Goslar, T. 2018: Multiple varve chronologies for the last 2000 years from the sediments of Lake Żabińskie (northeastern Poland) – comparison of strategies for varve counting and uncertainty estimations. *Quaternary Geochronology 47*, 107–119.

Zolitschka, B., Francus, P., Ojala, A. E. K. & Schimmelmann, A. 2015: Varves in lake sediments – a review. *Quaternary Science Reviews 117*, 1–41.

Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

Fig. S1. Detailed micro-facies of selected sub-layers and season transitions under cross- (XPL) and plane polarized light (PPL).

Fig. S2. Selected biogeochemical cycles for Lake Tiefer See (TSK) from 2012 to 2017: water temperatures, dissolved oxygen, calcium, silicon, phosphorous and total hypolimnion sediment fluxes.

Fig. S3. Selected biogeochemical cycles for Lake Czechowskie (JC) from 2014 to 2017: water temperatures, dissolved oxygen, calcium, phosphorous and total hypolimnion sediment fluxes.

Table S1. Geomorphological features of Lake Tiefer See (TSK) and Lake Czechowskie (JC) and ranges of selected physicochemical parameters during the monitoring interval.

Table S2. Calcite saturation indices ($SI_{calcite}$) for selected months in different seasons in Lake Tiefer See (TSK) and Lake Czechowskie (JC).

Table S3. Water parameters used for determining $SI_{calcite}$ for the two lakes.

Table S4. Differences in length and intensity of warm season during the observation period, measured at Lake Tiefer See meteorological station.