



Ultraviolet radiation exposure of a high arctic lake in Svalbard during the Holocene

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Long-term fluctuations in lake-water optical properties were examined using a Holocene sediment sequence and multi-proxy palaeolimnological approach in Lake Einstaken, Nordaustlandet, Svalbard. UV-absorbance of sedimentary cladoceran remains provided information on underwater UV exposure and changes in lake-catchment coupling processes were inferred from sediment geochemistry. In addition, aquatic community succession was used as an indicator for lake-water bio-optical properties and a Holocene record of sun activity (sunspots) was utilized to evaluate long-term solar forcing. The results indicated that the UV-absorbance of cladoceran remains was highest (i.e. maximum UV-induced pigmentation) for a short period during the early Holocene and for several millennia during the mid-Holocene. Sun activity was high during these time intervals, probably impacting the UV intensities, but it is probable that the amount of UV-attenuating compounds (e.g. dissolved organic carbon (DOC)) also significantly affected the underwater UV environment and were low during high UV exposure. Benthic autotrophic communities also responded to the millennial changes in lake-water optical properties. UV-resistant *Nostoc* cyanobacterial colonies were established during the mid-Holocene, indicative of high underwater UV intensities, and *Fontinalis* mosses thrived during the early Holocene, indicating a highly transparent water column. The results further suggested that underwater UV exposure decreased during the late Holocene, which is probably attributable to increased DOC and decreased solar forcing. Owing to the location of Lake Einstaken and its catchment in the periglacial barren landscape of the polar desert, the fluctuations of bio-optical lake-water properties were apparently forced by postglacial environmental processes and Holocene climate development. These factors controlled sea shoreline proximity, water discharge, ice-cover duration and littoral-benthic primary production and further affected the underwater UV environment. Although the role of solar forcing cannot be underestimated, the current record emphasizes the role of climate-mediated lake-catchment interactions in impacting bio-optical properties and UV exposure of high arctic aquatic systems.

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Organic carbon is an important functional component in aquatic lake ecosystems, playing a central role in the flow of energy and trophic structure and altering the composition and productivity of aquatic communities. Allochthonous organic carbon of terrestrial origin, resulting from lake-catchment coupling processes, plays a significant role in aquatic biogeochemical cycles, solar radiation attenuation (including UV radiation) and food-web composition (Schindler *et al.* 1996; Pienitz & Vincent 2000; Berggren *et al.* 2010), thus affecting the structure and functioning of lakes. Aquatic organic carbon in lake waters and sediments participates significantly in the global carbon cycle because inland aquatic systems receive 1.9–2.7 billion metric tonnes of organic carbon from their catchments (Cole *et al.* 2007; Battin *et al.* 2009) and the burial of organic carbon in lake sediments is similar to or even exceeds that of the ocean and the ocean floor (Tranvik *et al.* 2009). Accordingly, lakes and lake-catchment coupling processes connect directly to the climate system and are important in climate change discussion and research.

Over the late 20th and early 21st centuries, dissolved organic carbon (DOC) has increased in waters of glaciated landscapes in eastern North America and central and northern Europe and future predictions imply that DOC levels will continue to increase (Monteith *et al.* 2007). In contrast to the recent increases of organic carbon, some studies have provided data on recent opposite trends indicating decreasing concentrations of organic carbon (Schindler *et al.* 1997; Cunningham *et al.* 2011). The factors that control lake-water organic carbon concentrations and long-term trends are complex and region-specific or even local. Temporal and regional changes in DOC have been associated with, for example, climatic factors including temperature and precipitation, topography and vegetation (Sobek *et al.* 2007; Weyhenmeyer & Karlsson 2009), solar radiation (Hudson *et al.* 2003), and atmospheric deposition and recovery from acidification (Monteith *et al.* 2007).

Limnological monitoring does not extend back in time to record natural variability of organic carbon at longer temporal scales (centuries to millennia) and

prior to human disturbances or its relationships with UV responses in lakes. Moreover, in remote areas, such as in the high arctic regions, observational records are rare and usually even shorter. For example, some freshwater sites at the Canadian arctic islands have been monitored for some decades (Smol & Douglas 2007a) whereas lakes and ponds in the northernmost island of the Svalbard Archipelago, Nordaustlandet, are completely unexplored. To elucidate the relationships amongst climate-related drivers, UV regimes and organic carbon in arctic aquatic ecosystems, a long-term palaeolimnological perspective is required to understand natural fluctuations under climatic and lake ontogenic processes (cf. Smol 2008). Previous palaeolimnological investigations on long-term trends in aquatic organic carbon have been conducted mainly from boreal and sub-arctic lakes in North America (e.g. Pienitz *et al.* 1999; Saulnier-Talbot *et al.* 2003; Bouchard *et al.* 2013) and northern Europe and Russia (e.g. Rosén 2005; Jones *et al.* 2011; Rosén *et al.* 2011). These studies have emphasized the importance of climate-mediated catchment characteristics, mainly related to vegetation composition and soil development, for long-term lake-water organic carbon trends. However, there are no records of long-term variability of photobiological environments in lakes located in the arctic desert far north of the tree line with barren catchments. In high arctic lakes, which are often small and shallow and therefore closely connected to terrestrial and atmospheric processes, temporal fluctuations of lakes' bio-optical properties and organic carbon amounts and sources are probably mediated through periglacial catchment processes and ice cover through direct climatic forcing (cf. Rouillard *et al.* 2012) and, in some cases, superimposed on seabird impact that enhances allochthonous carbon transport (cf. Keatley *et al.* 2009; Luoto *et al.* 2014a, b).

The palaeolimnological inferences in examining carbon-related lake optics have mainly been based on sedimentary diatom assemblages (e.g. Pienitz & Vincent 2000). In addition to diatoms, new spectroscopic methods including visible-near-infrared and Fourier-transform infrared techniques and their calibration in space have been introduced to infer past lake-water organic carbon concentrations from lake sediments (Rosén & Persson 2006; Rouillard *et al.* 2011, 2012). Additionally, a recently introduced method utilizing spectroscopic UV-absorbance of cladoceran sedimentary remains has been used as an indirect proxy for palaeo-optical lake-water properties, including DOC (Nevalainen & Rautio 2014). In this method, the UV-screening melanin pigmentation in cladoceran exoskeletons, which is synthesized under intensive UV exposure (Rautio & Korhola 2002) and preserved in ancient cladoceran remains (Rautio 2007; Nevalainen & Rautio 2014), is measured spectroscopically allowing interpretations of past pigmentation of cladoceran

populations. Changes in pigmentation throughout time may then be used to infer underwater UV-exposure and lake-water optical properties.

In the current study, our aim was to examine palaeo-optics of a high arctic lake (Lake Einstaken) in Nordaustlandet, Svalbard, and to provide knowledge on natural variability of UV-radiation regimes in a climatically extreme aquatic system with respect to lake-catchment coupling and solar forcing. We used UV-absorbance values of sedimentary cladoceran remains to provide indications on lake-water optical properties (UV exposure and DOC) and sediment geochemistry to give information on carbon accumulation and sources and compared the environmental inferences to a Holocene record of sun activity. We presumed that the long-term interglacial development of underwater UV environment generally reflects inherent lake-water properties through the impacts of postglacial lake ontogenic processes and the regional Holocene climate succession.

Study site

Lake Einstaken (latitude 79°58'12"N, longitude 18°42'46"E, altitude 54 m a.s.l.) is located in Nordaustlandet, Svalbard (Fig. 1A), and lies between the Vestfonna glacier (~8 km) and Isvika bay (~0.5 km) in the southern Murchisonfjorden (Fig. 1B). Lake Einstaken drains into Isvika bay and is occasionally connected to adjacent Lake Krystallvatnet (64 m a.s.l.) by a small inlet (Fig. 1B). The bedrock consists of dolomites, limestones, shales and sandstones, and the catchment is characterized by highly weathered substrates, discontinuous till patches, and periglacial features with extremely scarce vegetation (scattered *Saxifraga*, *Dryas* and mosses) and undeveloped soils. Mean annual and July air temperatures in the region are -8 and +2°C, respectively (Pohjola *et al.* 2011).

Material and methods

The sediment succession from Lake Einstaken was sampled with a Livingstone piston corer using a small boat. Water depth at the sampling site was 6.8 m (Fig. 1C). The 154-cm-long core contained marine sediments in the bottom part and the lacustrine section was 132 cm long. According to the deglaciation and shoreline displacement history of the region (Kaakinen *et al.* 2009), and a tentative ¹⁴C-based age-depth model of the sediment core based on bulk sediment samples (terrestrial plant macrofossils absent), the lake was isolated from the sea roughly around 12 500 calibrated years before present (cal. a BP) and the lacustrine section of the sediment sequence covers the Holocene (Luoto *et al.* 2011). The rate of deposition for the top section

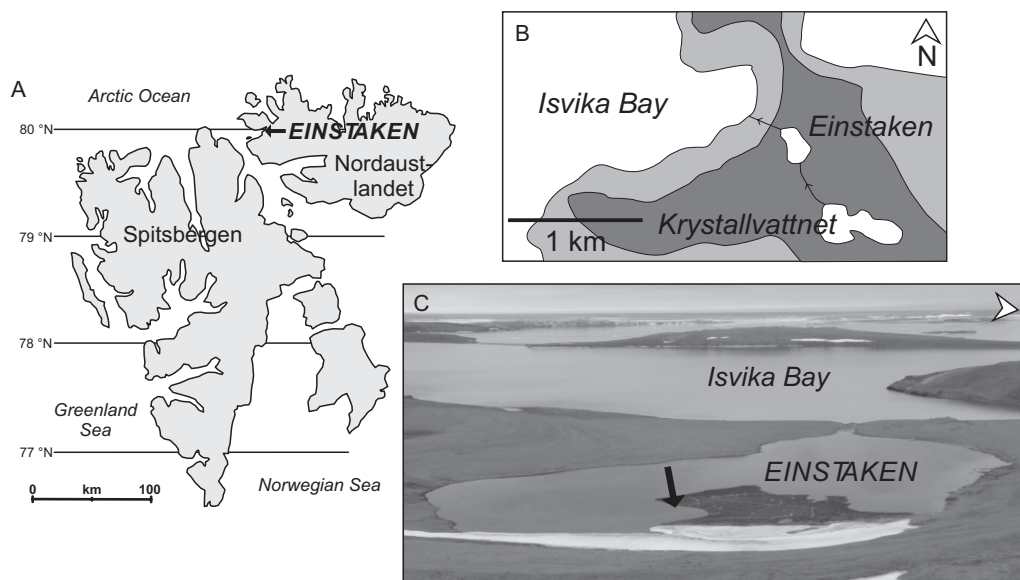


Fig. 1. Location of Lake Einstaken in Nordaustlandet, Svalbard (A), local topographic features (dark grey ≥ 50 m a.s.l., light grey ≤ 50 m) and hydrographical settings (B) and photograph of the lake at the time of sediment sampling (C), where the arrow indicates the point of sediment coring.

(0–9 cm) of the sediment core was estimated based on artificial ^{137}Cs accumulation. The ^{137}Cs analysis was performed at the Geological Survey of Finland with an EG&G Ortec ACETM-2 k gamma spectrometer equipped with a 4-inch NaI/Tl detector. The general stratigraphical subdivision of the core into early, mid- and late Holocene follows Walker *et al.* (2012). More detailed descriptions of the study site and sediment lithology were provided by Luoto *et al.* (2011).

A previously published cladoceran stratigraphy of Einstaken indicated that *Chydorus cf. sphaericus* was abundant throughout the Holocene (Luoto *et al.* 2011) and therefore this abundant taxon was subjected to extensive carapace absorbance measurements. Spectral absorbance from visible light to UV wavelengths (700–280 nm) of *Chydorus* carapaces at randomly selected sediment depths was measured to determine whether *Chydorus* carapaces contain melanin (cf. Rautio 2007; Nevalainen & Rautio 2014). UV-absorbance of cladoceran carapaces (i.e. inference of UV protective melanin pigment in the carapaces) was measured at 4-cm intervals using the methodology introduced by Nevalainen & Rautio (2014). Ten *Chydorus* carapaces from each subsample were hand-picked from a sieved (100 μm) sediment–water solution under a binocular microscope with fine forceps. The carapaces were individually attached to a specifically designed adapter and their UV-absorbance (at 305 and 340 nm) was measured with a Shimadzu UV/VIS-2401PC dual-beam spectrophotometer (Shimadzu Corporation, Kyoto, Japan). The same protocol was used to measure UV-absorbance of *Daphnia* (two samples, $n=3-4$) and *Alona cf. bergi* (three samples, $n=6-9$)

ephippia in the lowest sequence. Presence or higher abundance of cyanobacterial *Nostoc* colonies was estimated simultaneously from the same samples when hand-picking the cladoceran remains under the binocular microscope. The higher abundance of *Nostoc* was approximated by observing >10 colonies (i.e. *Nostoc* balls) per subsample.

Weight percentages (sediment dry weight) of total organic carbon (TOC), total nitrogen (TN) and total sulphur (TS) were determined at 3-cm intervals with an elemental analyser and ratios of TOC to TN (C/N) and to TS (C/S) were calculated. Approximately 250 mg freeze-dried sediment was weighed and inorganic (carbonate) carbon was removed by rinsing in 10% HCl, following the methodology of Brodie *et al.* (2011). Then, 10–20 mg of the carbonate-free sediment material was weighed into tin capsules and the elemental content was analysed with a Vario Micro Cube CNS Analyzer (Elementar, Hanau, Germany).

Organic matter (OM) of the sediment and relative abundances of a clear-water chironomid taxon *Micropsectra radialis*-type and the most abundant cladoceran taxa (*Daphnia* spp., *C. cf. sphaericus*, and *Alona cf. bergi*) were used as additional proxies for the palaeoenvironmental interpretations. These data were originally published by Luoto *et al.* (2011). A Holocene record of sun activity (sunspot numbers) by Solanki *et al.* (2004) was used as an indicator for solar forcing, available at the National Oceanic and Atmospheric Administration Paleoclimatology branch database (<http://www.ncdc.noaa.gov/paleo/paleo.html>).

Table 1. ^{137}Cs accumulation in the topmost section (0–9 cm) of the Lake Einstaken core with remarks on sample size and age (recent refers to the past 50–60 years).

Depth (cm)	^{137}Cs (Bq kg $^{-1}$)	Remarks
0	216	Small sample, recent
1	19	Recent
2	0	
3	0	Small sample
4	29	Mixing?
5	0	
6	0	Small sample
7	0	
8	0	
9	0	Small sample

Results

^{137}Cs accumulation was high only in the surface sediment sample (0 cm) and decreased markedly in the next sample (1 cm), from 216 to 19 Bq kg $^{-1}$ (Table 1). In other analysed samples, besides at depth 4 cm (29 Bq kg $^{-1}$), ^{137}Cs was zero. Note that sample size was small at depths 0, 3, 6 and 9 cm (Table 1).

Spectral absorbance measurements of *Chydorus* carapaces from the randomly selected sediment depths were similar to each other and to synthetic melanin (Fig. 2). *Chydorus* carapace absorbance of each measured *Chydorus* carapace increased slightly and steadily under visible light wavelengths (700–400 nm), and more pronounced under UV radiation (<400 nm) as the wavelength shortened. Absorbance values of each measured carapace reached their maximum at the shortest wavelength 280 nm (UV-B) within the measured wavelength range.

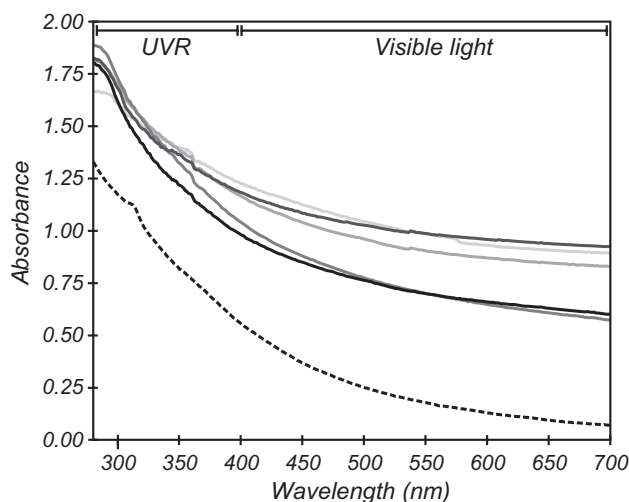


Fig. 2. Absorbance spectra of fossil *Chydorus* carapaces from the Lake Einstaken core at different sediment depths (from black to light grey: 112, 100, 64, 44 and 0 cm). The absorbance spectrum of synthetic melanin (Sigma-Aldrich M8631 with a concentration of 5 mg L $^{-1}$) in the 280–700 nm wavelength range is indicated with a dashed line.

Mean stratigraphical UV-absorbance of *Chydorus* carapaces varied between 1.4 and 2.0 (relative absorbance unit) for 305 nm and 1.3 and 1.7 for 340 nm (Fig. 3). Lowest UV-absorbance values were recorded for the early Holocene (100–96 cm) and topmost sediment samples, as there was a decreasing trend in the values during the late Holocene. In general, carapace absorbance values were highest during the mid-Holocene, with peak values at 80, 64 and 44 cm core depth. *Nostoc* colonies were observed constantly in the sediments from the mid-Holocene onward (Fig. 3), with higher abundances at 68 cm and in the top sediments (12–4 cm). *Daphnia* ephippia UV-absorbance was high (around 4 at 305 nm) in both samples, whereas *Alona* ephippia absorbance values increased from ~1 (124 cm) to 1.8 (116 cm).

TOC fluctuated between 7.1 and 24.7%, TN between 0.6 and 2%, and TS between 0.3 and 2.3% in the sediment core. TOC had a general decreasing trend throughout the Holocene, being highest during the early and mid-Holocene (132–78 cm), and increasing again in the uppermost sediment section (Fig. 3). The lowest TOC percentages were recorded in the Pleistocene–Holocene transition and during the late Holocene (15–6 cm). TN increased from the lowest sediment sections toward the mid-Holocene, with the highest values being observed between 93 and 75 cm, after which a long-term decreasing trend began except for the top sediments where it increased again (Fig. 3). TS decreased throughout the Holocene (Fig. 3), being highest at the Pleistocene–Holocene transition and during the mid-Holocene (96–69 cm).

The proportion of organic matter (OM) in the sediment varied between 15 and 50% (Fig. 3). The lowest proportions of OM occurred in the lowest sample, after which it increased in the early Holocene and had a trend during the Holocene toward lower values. OM increased from <20 to >30% in the topmost sample. The chironomid *Micropsectra radialis*-type was abundantly (10–90%) present throughout the core but an increase in its relative proportion was observed during the mid-Holocene (Fig. 3). In cladocerans, a succession from *Daphnia*, which was the dominant during the Pleistocene–Holocene transition, to *Alona* cf. *bergi* and later to *Chydorus* cf. *sphaericus* was observed (Fig. 3). *Fontinalis* mosses were abundantly present in the core during the early Holocene and at top of the sequence and *Nostoc* colonies appeared in the stratigraphy during the early Holocene and increased in the topmost sediment sections (Fig. 3).

The C/N ratio fluctuated between 9 and 24 and the C/S ratio between 4 and 32 (Fig. 4). C/N ratios were generally stable throughout the core, but higher values were recorded during the early Holocene (126–114 cm), whereas the lowest values (ratio <10) occurred during the mid-Holocene. The C/S ratio generally increased throughout the Holocene, as it was lowest in the

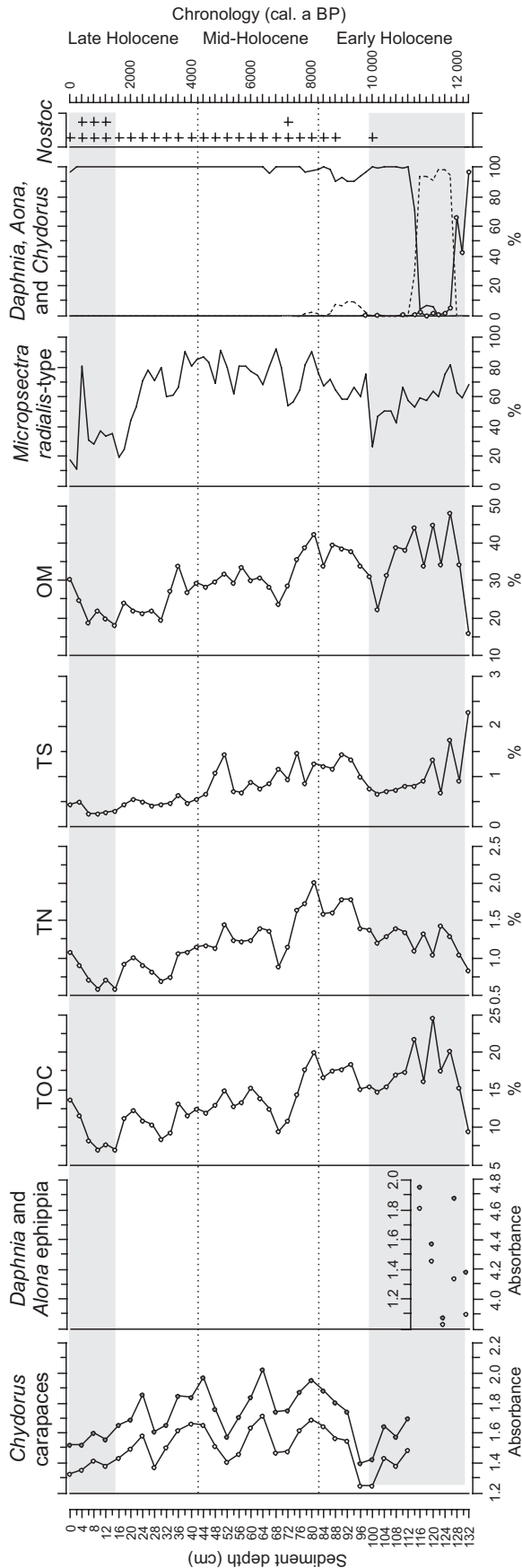


Fig. 3. UV-absorbance of *Chydorus cf. sphaericus* carapaces (white dots at 340 nm and grey dots at 305 nm), UV-absorbance of the *Daphnia pulex* group (at depths of 132 and 128 cm) and *Alona cf. bergi* ephippia (at depths of 124, 120 and 116 cm), sedimentary total organic carbon (TOC), total nitrogen (TN) and total sulphur (TS) and organic matter (OM) in the Lake Einstaken succession. In addition, relative percentages of the chironomid *Micropsectra radialis*-type, which is associated with clear-water environments, and the cladocerans *Daphnia* (black line with white dots), *Alona cf. bergi* (dashed line) and *Chydorus cf. sphaericus* (solid black line) are shown. Plus signs indicate presence (+) or higher abundance (++) of *Nostoc* cyanobacterial colonies and the grey bands indicate periods with high abundance of *Fontinalis* macrofossils. Horizontal dotted lines indicate the formal stratigraphical boundaries from the early to mid-Holocene (8200 cal. a BP) and mid- to late Holocene (4200 cal. a BP) following Walker *et al.* (2012). Organic matter and invertebrate community succession data were originally published by Luoto *et al.* (2011).

bottom sample and clearly increased during the early (129–99 cm) and late Holocene (45–0 cm), having slightly lower values during the mid-Holocene.

Discussion

Chronology

Establishing a reliable chronology for high arctic lake sediment cores is a common problem, also discussed in detail in the previous palaeolimnological study from Lake Einstaken (Luoto *et al.* 2011). As terrestrial

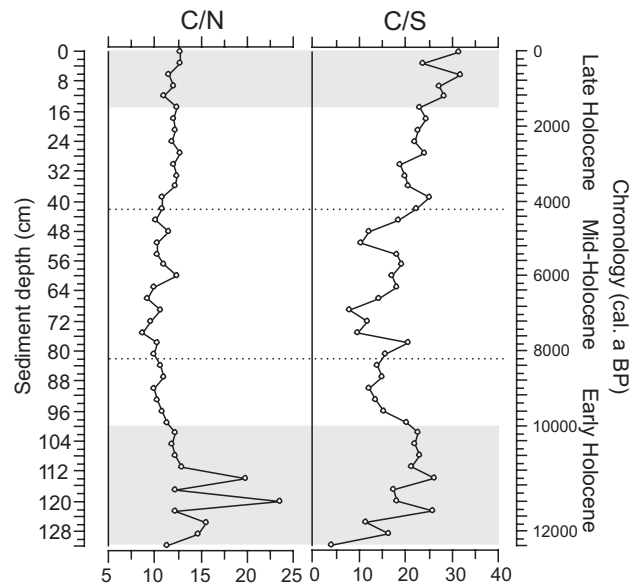


Fig. 4. Ratios of organic carbon to nitrogen (C/N) and sulphur (C/S) in the Lake Einstaken succession throughout the Holocene. The grey bands indicate periods with high abundance of *Fontinalis* macrofossils and the horizontal dotted lines indicate the formal stratigraphical boundaries from the early to mid-Holocene (8200 cal. a BP) and mid- to late Holocene (4200 cal. a BP) following Walker *et al.* (2012).

macrofossils were not found and bulk sediments had to be used, the original tentative chronology for the core relies on the assumptions that the marine–lacustrine contact occurred at ~12 500 cal. a BP and that the surface sediment represents the modern age (Luoto *et al.* 2011). The results of this study give supporting evidence for the latter assumption, as ^{137}Cs fall-out indicates a very low rate of sedimentation where only the topmost sediment samples (0–1 cm) represent the modern age (Table 1), approximately the past 50–60 years. As a clear Cs-peak related to the 1960s nuclear weapon testing could not be observed, the topmost sediment layers may be slightly mixed with respect to ^{137}Cs , probably because of a high water content and disturbance of the loose uppermost sediment during the coring. In addition, it is probable that a low rate of sedimentation has hidden the 1960s Cs-peak within the topmost samples, and that we were unable to subsample the core with a required resolution to detect a clear peak in ^{137}Cs stratigraphy with sufficient amount of material.

The sedimentological properties of the Einstaken core are depicted in detail in the original publication by Luoto *et al.* (2011) but it is worth mentioning here that we did not detect any sedimentary unconformities, such as erosion horizons or slumping structures, which would indicate periods of anomalous decrease or increase of sedimentation. Although the results above only provide suggestive evidence to support the original age-depth model by Luoto *et al.* (2011), they indicate a low and fairly stable rate of sedimentation within the basin during the Holocene. Therefore, throughout the following discussion, we utilize the tentative age estimates from the original publication by referring to the general chronological subdivision of the core to early, mid- and late Holocene, following Walker *et al.* (2012).

DOC and UV exposure in arctic lakes

High arctic freshwater lakes have extrinsic characteristics that make them naturally low in organic carbon including, for example, their high latitude location, barren catchments, long ice-cover season and persistent permafrost. DOC is generally controlled by topographic and climatic factors through catchment vegetation, surface runoff and temperature (Sobek *et al.* 2007; Weyhenmeyer & Karlsson 2009). According to a wide geographical survey, median DOC concentration in lakes at barren tundra is below 5 mg L^{-1} , although concentrations of $10\text{--}15 \text{ mg L}^{-1}$ have also been reported (Sobek *et al.* 2007). Anomalously high DOC concentrations in high arctic sites are related to impacts of bird colonies transporting nutrients or to local lush vegetation (Antoniades *et al.* 2003; Keatley *et al.* 2009; Michelutti *et al.* 2010). Given the low DOC concentrations, long day length during summer seasons and shallowness of most arctic lake basins, these ecosystems are

exposed to intensive UV radiation that also has a strong influence on ecosystem functioning (Vincent & Pienitz 1996).

Unfortunately, DOC was not measured during the field campaign and therefore the modern lake-water DOC of Einstaken is not known. However, the water was visually transparent during the sediment coring in August 2009 and the bottom of the lake was visible at the coring site. Based on this observation it is estimated that the secchi depth of the lake reaches the bottom (6.8 m). Previous results from other lakes in Svalbard (Ellis-Evans *et al.* 2001) suggest typical DOC concentrations of $<2 \text{ mg L}^{-1}$ in the region. Schindler *et al.* (1996) suggested a DOC threshold of $2\text{--}3 \text{ mg L}^{-1}$ to be significant for potentially harmful underwater UV penetration in lakes, and high arctic lakes in Svalbard would thus be highly UV sensitive.

In the current study, melanin pigmentation of *Chydorus* was utilized in detecting long-term changes in the underwater bio-optical environment (Figs 2, 3) to provide proxy evidence of DOC fluctuations. The current results suggest that, in addition to arctic *Daphnia* (e.g. Rautio & Korhola 2002; Rautio *et al.* 2009), other cladoceran taxa (i.e. Chydoridae) utilize photoprotection and respond to intensive UV radiation in highly exposed arctic sites by carapace (melanin) pigmentation (Fig. 2). As there exists a strong negative relationship between lake-water DOC and cladoceran carapace melanization in northern lakes (Rautio & Korhola 2002), also detected previously in sediment cores (Nevalainen & Rautio 2014), carapace UV-absorbance (i.e. the amount of pigmentation) throughout sediment successions may serve as an indicator for aquatic UV environment and UV-screening compounds (e.g. DOC) in lake-waters.

Pleistocene–Holocene transition

Lake Einstaken was isolated from the sea c. 12 500 cal. a BP (Luoto *et al.* 2011) and the lowest lacustrine core samples were indicative of the newly developed lake basin near the sea shore. This was particularly clearly shown in the high sulphur content of the sediment (Fig. 3) and low C/S ratios (Fig. 4). Sedimentary TOC in Einstaken was concurrently low, indicating that the burial of organic carbon was low in the early phase of lake ontogeny (Fig. 3).

Environmental conditions in Einstaken were unique during the initial phase of lake ontogeny c. 12 500–12 000 cal. a BP owing to the isolation, close proximity of the sea, and periglacial environmental settings following the retreat of the Vestfonna ice margin. These palaeoenvironmental settings probably represented conditions in which terrigenous carbon input from the barren catchment was low. The presence and high abundance of *Daphnia ephippia* (i.e. resting egg capsules) in the lowest samples of the sequence (Fig. 3;

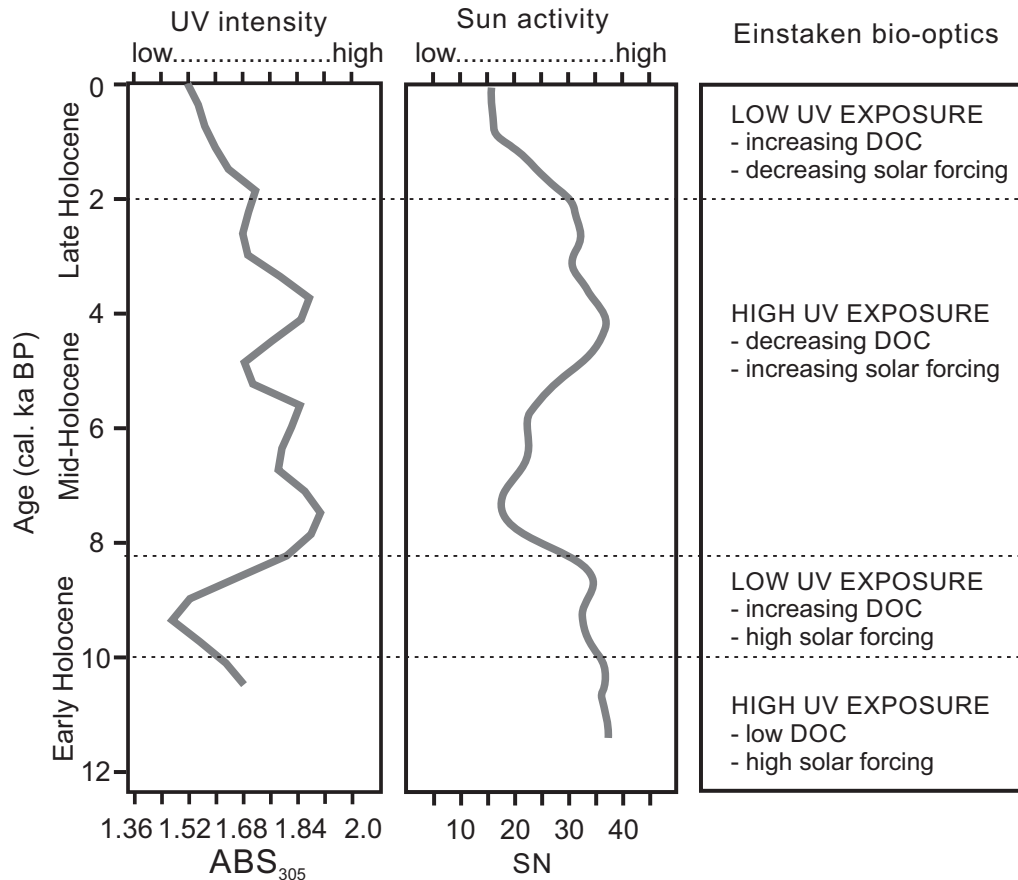


Fig. 5. Holocene reconstructions of relative UV intensity in Lake Einstaken based on UV-absorbance of *Chydorus* carapaces at 305 nm (ABS_{305}) and of sun activity (as sunspot numbers, SN) by Solanki *et al.* (2004). The data series were smoothed with LOESS (smoothing factor of 0.15). The last panel summarizes the relative UV regimes and bio-optical settings related to them.

Luoto *et al.* 2011) indicate that in-lake production and phytoplankton or microbial communities flourished in the lake until 12 000 cal. a BP, providing autochthonous carbon in the system. It is possible that the newly exposed sea floor after the marine shoreline retreat provided nutrients for the autotrophs (Luoto *et al.* 2011).

The presence of *Daphnia* may reflect water-column turbidity and a more shaded underwater environment. A species of the *Daphnia longispina* group, which does not utilize UV protection through strong carapace pigmentation, is known to prefer low-transparency lakes in the Himalayas (Manca *et al.* 1998). Therefore, it is possible that the presence of *Daphnia* in the initial phase of Lake Einstaken was indicative of water-column turbidity, which was caused by high amounts of glacial meltwaters from the retreating glacier front, and may have resulted in a more UV-protected environment allowing *Daphnia* to survive. However, based on ephippial morphology, the species present in Lake Einstaken was typical of arctic lakes (a species of the *D. pulex* group) having adapted to the high-latitude environmental regimes through heavy pigmentation. Accordingly, UV-absorbance measurements of

Daphnia ephippia from the Einstaken succession indicated strong pigmentation (Fig. 3) and it is presumed that *Daphnia* pigmentation during the isolation phase was a response to high UV exposure of the newly developed lake basin under transparent water and high solar forcing (Fig. 5).

Early Holocene

TOC, TN and OM increased from the isolation phase and *Daphnia* was replaced by the chydorid taxon *Alona* cf. *bergi* (Fig. 3), suggesting a clear change in limnological conditions during c. 12 000–11 000 cal. a BP. These changes were probably driven by nutrient depletion in the catchment through leaching of the fertile sea-floor sediments and periglacial processes in the exposed arctic ground, decreasing planktonic primary production and suppressing *Daphnia*. It is therefore likely that lake water was transparent (i.e. low DOC), providing light for benthic primary production. In agreement, *Fontinalis* macrofossils were found abundantly in the sequence during this clear-water period, which, together with the presence of the vegetation-

associated *Alona* (Nevalainen *et al.* 2012), suggests that the littoral–benthic zone was widely covered by aquatic bryophytes. Sedimentary TOC and OM were high, having several peaks during 12 000–11 000 cal. a BP (Fig. 3) and these values probably represent the burial of OM originating mainly from the *Fontinalis* stands. UV-absorbance of *Alona* ephippia showed increasing values, suggesting intensified UV exposure that was probably driven by high lake-water transparency.

C/N ratios increased markedly during two separate periods of the early Holocene, indicating a short but significant supply of allochthonous carbon from the catchment (Fig. 4), but these pulses of terrigenous material were not reflected in the lake-water optics (Fig. 3). The Arctic Atlantic sector generally experienced early Holocene climate amelioration after the glacial period (reviewed by Humlum 2005) and temperatures reached their Holocene maximum *c.* 9000 years ago at the earliest, although the early Holocene climatic oscillation in Svalbard is yet to be examined in detail. Therefore, the trends in lake-water transparency and sedimentary organic carbon are not easily explained by climatic events of the early Holocene. We assume that the postglacial warming resulted in more abundant vegetation in the catchment of Lake Einstaken, thereby increasing the input of terrigenous OM into the lake as indicated by the high C/N ratios typical of vascular plants (Meyers & Teranes 2001).

A period of concurrent changes was evident in most of the proxies (Fig. 3) *c.* 10 000 cal. a BP when *Fontinalis* disappeared from the sequence and cyanobacterial *Nostoc* colonies, which are known to be tolerant to intensive UV radiation in arctic lakes (Vincent 2000), were established for a short period of time. Faunal communities of Lake Einstaken changed as *Chydorus* replaced the moss-inhabiting *Alona* and the clear-water chironomid *Micropsectra radialis*-type (cf. Luoto 2014) decreased. In addition, UV-protective melanin pigmentation in the *Chydorus* community (Fig. 2) was reduced (Fig. 3), suggesting that the underwater UV doses decreased. As sun activity was high during the early Holocene (Fig. 5), it is possible that the observed changes were driven by a photobiological underwater environment where higher DOC reduced light penetration, thereby modifying autotrophic and heterotrophic communities, and the need for pigmentation in cladocerans.

According to the decreasing C/N ratios, carbon sources shifted toward autochthonous production (Fig. 4), which may have resulted from the establishment of *Nostoc* colonies as they are efficient N-fixers. However, this does not explain the temporary decrease in UV exposure (i.e. increased DOC) because permanent *Nostoc* colonies were observed from *c.* 9000 cal. a BP onward in the Einstaken core (Fig. 3). High DOC concentrations have been observed in arctic lakes as a result of bird-driven nutrients and lush catchment veg-

etation (e.g. Antoniadou *et al.* 2003; Keatley *et al.* 2009). Therefore, it is possible that the Einstaken basin was impacted by bird guano or by increased catchment vegetation (or both), causing higher lake-water DOC and lower underwater UV exposure. At that time, the sea shoreline was closer to the lake and it is therefore possible that birds may have bred and/or grazed in the catchment, increasing nutrients and impacting catchment vegetation and limnological properties. In fact, in a nearby shallow freshwater pond (Kvalrosslaguna) in the Murchisonfjorden, this scenario occurred during the 20th century (Luoto *et al.* 2014a). In common with the Einstaken record, Rouillard *et al.* (2012) described high DOC concentrations in a freshwater lake in high arctic Canada during the early Holocene and they associated this DOC maximum with lush catchment vegetation and aquatic bryophytes. However, reduced sedimentary TOC and OM in Einstaken do not support this, suggesting that lake productivity did not increase (Fig. 3). In addition, C/N ratios do not indicate significant carbon input from the catchment (Fig. 4).

As Lake Einstaken is periodically connected to Lake Krystallvatnet, which is located at higher altitude and drains to Einstaken (Fig. 1B), it is possible that the reduction in underwater UV (i.e. increasing DOC) was a result of increased runoff from the upper lake and from the catchment. In common with this assumption, Luoto *et al.* (2011) described biostratigraphical changes of Chironomidae, i.e. an increase in *Thienemannimyia*-type, which favours turbulent habitats and streams. This change may have been caused by increased precipitation and the subsequently more extensive winter meltwater or summer runoff. However, as the palaeoclimatic records from Svalbard are sparse, there is no other evidence in support of a moist early Holocene in northern Svalbard, and existing data rather suggest that the North Atlantic sector at lower latitudes was dry during the early Holocene (Shuman & Plank 2011), although this may not be the case at high-latitude locations such as Nordaustlandet, which are under polar climatic influences. Apparently, this period was characterized by rising air temperatures in Svalbard (Svendsen & Mangerud 1997; Humlum 2005) that could have caused higher in-lake production, affecting DOC and underwater light in the basin.

Mid-Holocene

During the mid-Holocene *c.* 8000 cal. a BP, *Micropsectra radialis*-type and *Chydorus* carapace UV-absorbance values generally increased, suggesting higher water transparency and UV exposure of the underwater environment. In conjunction, sun activity showed an increasing trend throughout the mid-Holocene (Fig. 5), suggesting that, in addition to the decreasing amount of UV-absorbing compounds, solar forcing also intensified the increasing UV radiation. In

addition, *Nostoc* colonies were observed to have been continuously present since *c.* 9000 cal. a BP, which is probably indicative of the highly transparent water column and intensive UV radiation. The presence of *Nostoc* in high-latitude lake sediments has previously been attributed to warmer climate conditions (Keatley *et al.* 2006; Rouillard *et al.* 2012). Likewise, previous investigations from western Spitsbergen in Svalbard (Birks 1991; Svendsen & Mangerud 1997) and the arctic Atlantic sector (Humlum 2005) have suggested that air temperatures reached their Holocene maximum during the mid-Holocene between *c.* 9000–5000 cal. a BP. Sedimentary TOC and OM slightly increased during 9000–8000 cal. a BP together with TN (Fig. 3), which may be attributed to climate amelioration through enhanced in-lake production, as also evident from the slight decrease in C/N (Fig. 3). In support of this, the previous chironomid record from the lake showed an increase in thermophilous taxa during the mid-Holocene (Luoto *et al.* 2011).

The stable phase of higher underwater UV exposure (lower DOC) continued throughout the mid-Holocene until *c.* 4000 cal. a BP and is generally opposite to previous inferences of DOC in high latitude lakes. For example, Pienitz *et al.* (1999) indicated that DOC increased during the mid-Holocene in Canadian tree-line lakes, Rosén (2005) showed similar TOC responses in lakes across northern Scandinavia and comparable results were also presented by Jones *et al.* (2011) from the Russian tundra. As these changes were related to the development of tree-catchment vegetation and soils and tree-line oscillations, it is apparent that Lake Einstaken, located in the high arctic landscape, did not respond to Holocene climate amelioration in a similar manner because of the scarcity of catchment vegetation and poor soil development. Owing to the decreasing trends in TOC and OM during the mid-Holocene (Fig. 3), it is presumed that burial of organic carbon decreased through time as a response to the stabilization of the lake catchment basin, which favoured the development of a clear-water arctic lake with low productivity.

It is also possible that the higher UV exposure and lower DOC concentrations during the mid-Holocene were driven by periglacial processes, such as permafrost development after the early Holocene environmental changes, which would have trapped organic carbon compounds within the ground. However, permafrost was absent in Svalbard near the sea-level during the early and mid-Holocene (Humlum 2005), whereas extensive permafrost developed during the late Holocene cooling, covering presently ice-free coastal areas including Murchisonfjorden (Humlum *et al.* 2003). Therefore, it is likely that other mechanisms besides or in addition to permafrost, which were related to the stable barren catchment and long period of climate stability during the Holocene climatic optimum, kept

the Einstaken lake-water highly transparent. Apparently carbon in Einstaken was mostly of autochthonous origin during the mid-Holocene, as indicated by the slightly decreasing C/N ratios (Fig. 4), and was probably fixed by the autotrophic benthic communities (e.g. *Nostoc* and algae) that are typical for high arctic lakes (cf. Chételat *et al.* 2010).

Late Holocene

Late Holocene climatic cooling began in Svalbard about 5000–4000 cal. a BP (Birks 1991; Svendsen & Mangerud 1997; Humlum 2005) and this is clearly reflected in some of the examined proxies. Based on Isvika Bay marine sediment stratigraphy, the climatic optimum terminated with a probable glacier re-advance event occurring as early as 5800 cal. a BP, and this was followed by a shift towards colder and more stratified conditions in marine environment (Ojala *et al.* 2014). *Chydorus* carapace UV-absorbance and abundance of *Micropsectra radialis*-type decreased from *c.* 4000 cal. a BP (Fig. 3). The absorbance values appear to be in agreement with decreasing solar forcing (Fig. 5), yet it is presumed that UV-attenuating carbon compounds also modified the underwater UV environment. There was a slight increase in C/N values referring to higher inputs of terrigenous organic matter (Fig. 4), although the trends in elemental abundances (TOC, TN, TS) and OM showed continuous decreases (Fig. 3). The onset of a climate cooling trend probably created environmental conditions under which allochthonous carbon transport from the catchment increased slightly, which in turn may have resulted in higher lake-water DOC and lower underwater UV intensities. This may have been favoured again through increases in surface runoff received from the upstream Lake Krystallvatnet catchment following moister climate conditions.

A similar late Holocene DOC increase in a palaeolimnological record occurred in the high Arctic Canadian Archipelago, albeit the recent increase was not entirely supported by the currently low DOC in the lake (Rouillard *et al.* 2012). Late Holocene DOC records from the northern Canadian tree line by Saulnier-Talbot *et al.* (2003) and Bouchard *et al.* (2013) showed contrasting DOC developments toward the present, emphasizing the importance of local geographical settings, e.g. vegetation succession and thermokarst-related limnological processes, for long-term fluctuations of organic carbon in high-latitude lakes. As the long-term UV exposure in the Einstaken basin cannot be attributed to vegetation or soil succession, it is possible that, for example, moss patches in the catchment increased as a response to the late Holocene climate development altering limnological properties of the lake and causing higher DOC concentrations.

The algal (diatom) communities shifted and species richness increased in the topmost sediments (Luoto *et al.* 2011), suggesting altered limnological regimes in the late Holocene, and these shifts were coupled with the re-emergence of *Fontinalis* moss and an increase in *Nostoc* colonies in the succession (Fig. 3). In addition, reversed trends occurred in sedimentary TOC, TN and OM (Fig. 3) as they increased in the top sediments. The general biostratigraphical shifts in Einstaken are consistent with many other high arctic palaeolimnological studies from Canada showing, for example, distinct top core changes in diatom assemblages (Douglas *et al.* 1994; Smol *et al.* 2005) and increases in *Nostoc* (Keatley *et al.* 2006) that have been attributed to recent climate warming in the Arctic. Specifically, the in-lake processes of arctic freshwater environments are driven by changes in ice-cover thickness and duration that control habitat structure and diversity for algae and aquatic plants (Smol & Douglas 2007b), thereby regulating lake functioning and carbon pathways. The shifts also correlate rather well with other findings from Svalbard that indicate large palaeolimnological changes in the most recent lacustrine sediment deposits representing the time interval since the Little Ice Age (Guilizzoni *et al.* 2006; Jiang *et al.* 2011). Due to the lack of good chronological control and slow sediment deposition in the Einstaken succession (Luoto *et al.* 2011), the shifts in the top sediments cannot be precisely aligned with either the Little Ice Age or with the post-1850 climate warming.

The systematic trends in the biotic and geochemical proxies, which prevailed during most of the Holocene, appear to be decoupled in the very topmost sediment section of the Einstaken core (Fig. 3). Specifically, TOC and OM increased and were probably related to increased *Fontinalis* and *Nostoc*, but carapace absorbance decreased. The C/N ratios slightly increased in accordance with lower UV exposure (Figs 3, 4). It is possible that these changes were caused by increased seabird colonies in the lake's catchment, as also suggested by Luoto *et al.* (2011) based on the changes in chironomid assemblages. The increased proportions of organic matter and carbon and nitrogen (Fig. 3) could also be explained by increased number of birds causing higher nutrient inputs. However, bird colonies were not observed in the catchment during the sediment coring, although a seashore pond (Kvalrosslaguna) near Lake Einstaken has developed toward a more productive system owing to recent bird guano deposits (Luoto *et al.* 2014a). The impacts of birds on lake productivity are superimposed on recent climate warming and may potentially trigger cascading effects in high arctic freshwater ecosystems and result in completely new limnological regimes (Luoto *et al.* 2014a, b). Therefore, it is possible that the lower UV exposure and possibly higher DOC in the topmost sediment section of Lake Einstaken, representative of the recent centuries, was a

response to climate warming and longer growing season.

Conclusions

The present study suggests that ecologically significant long-term fluctuations of UV exposure have occurred throughout the Holocene in the high arctic Lake Einstaken. The UV fluctuations inferred for Lake Einstaken show a pattern in which the lowest underwater UV exposure occurred during the early Holocene and the most recent period of the succession, whereas the highest intensities prevailed during the mid-Holocene. The lake-water optical properties (i.e. UV-screening compounds) impacting the underwater UV environment were probably forced by postglacial processes and Holocene climate variability controlling sea shoreline proximity, water discharge, ice-cover length, as well as littoral–benthic primary productivity. In addition to in-lake and lake-catchment processes affecting water transparency, solar forcing has probably contributed to the millennial-scale UV regimes of Lake Einstaken.

The Lake Einstaken sediment record provides reference information on millennial-scale UV radiation regimes and lake-water bio-optical properties (e.g. DOC) for remote high arctic aquatic ecosystems and emphasizes the role of lake ontogenic processes in understanding these natural fluctuations. The importance of unravelling natural UV radiation regimes and other bio-optical components (e.g. DOC dynamics) of high latitude lake-waters comes from the facts that shallow arctic lakes and ponds are closely linked to terrestrial and atmospheric processes, are major components of arctic landscapes and respond sensitively to climate changes, providing useful long-term records for global change assessment.

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