Original article

Recent shift in diatom record from Lake Rabbvatnet: response to global warming or solar variability?

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ABSTRACT

Within the last decades, phytoplankton biomass has significantly risen in many lakes worldwide. Global warming was proposed as the most probable cause of the discovered effect. In this work, attention was paid to other drivers than just global warming, in particular, variability in solar radiation to explain this unexpected diatom shift. Here, we use a combination of paleolimnological, dendrochronological and meteorological datasets, as well as local pollution information, to analyze the recent growth of diatom total abundance in Lake Rabbvatnet (69.7º N, 30.5º E, Northern Norway). The results show that the diatoms of the genus *Aulacoseira* were most abundant in the top layers of the sediment core. On the contrary, the biomass of small-sized *Cyclotella* species, which, as a rule, should grow simultaneously with warming, has decreased over the past decades. We suggest basing on the experimental data analysis (comparison of diatom abundance with solar irradiance and heavy metals, testing of air temperature trends) that the recent growth of the total diatom abundance observed in the subarctic Rabbvatnet Lake could be mainly due to an increase in photosynthetically active spectral solar irradiance fluxes in the visible and infrared ranges.

Keywords: Diatom response, palaeolimnological data, climate warming, solar radiation, Arctic lake.

Introduction

Diatom microalgae are important constituents of phytoplankton communities and widespread in freshwater ecosystem. These unicellular species with sizes ranging from 2 to 500 μm and significantly contribute to the Earth's carbon cycle by absorbing carbon dioxide against producing nearly 25% of our planet's oxygen through photosynthesis, contributing to Earth's carbon cycle (Reynolds 2006; Winder *et al*. 2009;

Kirk 2011; Ruhland *et al*. 2015; Benoiston *et al*. 2017). Diatoms are an effective proxy for climate variability due to their high sensitivity to any changes in the natural environmental factors such as air temperature, solar radiation, ice cover, wind, rain, thermal stratification, lake mixing patterns and nutrient resources (Reynolds 2006; Adrian *et al*. 2009; Winder and Sommer 2012; Ruhland *et al*. 2015). Over thousands of years, diatom frustules settle to the bottom of the lakes and become part of the sediment record, allowing for valuable palaeoclimate reconstructions (Korhola *et al*. 2000; Velle *et al*. 2010).

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Interactions between climate change and freshwater diatom assemblages are extremely complex because other factors such as basin-specific lake characteristics, nutrient and light resource availability, thermal stability and stratification patterns all affect diatom composition abundance and dynamics in some way (Winder *et al.* 2009; Winder & Sommer 2012; Ruhland *et al.* 2015; Kuefner *et al.* 2020; Oleksy *et al.* 2020).

Increases in phytoplankton biomass have been observed over the past decades, mainly in arctic and subarctic lakes (Larsen *et al.* 2006; Lehnherr *et al.* 2018; Anneville *et al.* 2019). On occasion, phytoplankton biomass continued to increase even in lakes experiencing a decrease in nutrients concentrations or re-oligotrophication (Anneville *et al.* 2019). In some studies, recent global warming was considered to be a probable cause of this phytoplankton shift (Larsen *et al.* 2006; Elliot 2010; Lehnherr *et al.* 2018). Indeed, lake surface temperatures have increased in the past decades worldwide in line with increasing air temperature (Schneider *et al.* 2009; Schneider & Hook 2010; Fink *et al.* 2014; O'Reilly *et al.* 2015; Schmid & Koster 2016; Woolway *et al.* 2017). Also, diatom responses to climate change will considerably vary depending on geographic location and lake characteristics with amplified effects at high latitudes due to a variety of feedback mechanisms (Smol *et al.* 2005, Adrian *et al.* 2009; Ruhland *et al.* 2015; Kuefner *et al.* 2020), e.g. climate-driven external nutrient loadings (Larsen *et al.* 2006; Lehnherr *et al.* 2018). Some results indicate that surface temperatures of many lakes warm faster than regional air

temperatures (Schneider & Hook 2010; O'Reilly *et al.* 2015; Schmid & Koster 2016). This is especially true for Arctic ice-covered lakes (O'Reilly *et al.* 2015).

Arctic lakes are extremely responsive to climate changes because even slight warming leads to a decrease in ice cover, and therefore a longer growing season for algae (Smol *et al.* 2005). Phytoplankton spring blooms observed under clear ice in Arctic lakes indicate that low temperature does not prevent phytoplankton growth, and solar radiation appears to play a significant role in its initiation (Sommer & Lengfellner 2008; Vehmaa & Salonen 2009; Winder & Sommer 2012; Ruhland *et al.* 2015; Deng *et al.* 2018; Winslow *et al.* 2018; Anneville *et al.* 2019).

Our study is based on the hypothesis that other aside from global warming, in particular, solar radiation could cause the observed diatom shift in high-latitude lakes. In this study, we used a long-term diatom record from subarctic Lake Rabbvatnet (69.7º N, 30.5º E, Northern Norway) in conjunction with environmental records to investigate the possible causes of the recent diatom assemblage shift.

Material and methods

Site description

Rabbvatnet Lake (69.7º N, 30.5º E) is a small subarctic lake with an oligotrophic status located at an elevation of 83 m.a.s.l. on the Barents Sea coast (Jarfjord, Norway, Fig. 1).

Figure 1. Map showing the location of Lake Rabbvatnet (69.7º N, 30.5º E, Northern Norway). Locations of Nikel (69.4º N, 30.3º E) and Zapolarny (69.4º N, 30.8º E) Pechenganikel smelters and meteorological station at Kirkenes (69.7° N, 29.9° E) are shown by black circles and square, respectively.

The lake has a surface area of 0.4 km^2 and a maximum depth of 10 m. Catchment geology belongs to the Baltic crystalline shield, composed of ancient rocks of the Archean, Lower and Middle Proterozoic. The bedrock is covered by Quaternary deposits of glacial genesis, and the eluvial-deluvial deposits are developed on the surrounding heights. Catchment vegetation belongs to the forest-tundra ecotone with a predominance of *Parvo-Betuletum cladinosum* associations and *Empetrum-Cladina* birch forest type.

Since 1939, the lake ecosystem has been exposed to atmospheric emissions of sulphur dioxide (SO_2) and heavy metals from the Nikel (69.4° N, 30.3° E) and Zapolyarny (69.4° N, 30.8° E) Pechenganikel smelters (a Russian "Norilsk Nikel" enterprise) (Ylikorkko *et al.* 2015). Both enterprises are located at a distance of ~ 30 km from the lake. The increase of the content of Ni, Cu and Co in lake sediments already started in the 1960s as a result of mining and metal processing in the region (Ylikorkko *et al.* 2015). The total emission of SO_2 was more than 400 000 t per year during this period, and now the emissions have been reduced about 100 000 t per year due to using of local ore rather than ores from Siberia (Ylikorkko *et al.* 2015). In the lake, total organic carbon, phosphorus and nitrogen concentrations were on average 2.5-2.6 µg/l, 2.9-3.1 µg/l and 90-170 µg/l, respectively, which are typical for high latitude lakes (Ylikorkko *et al.* 2015). We used monthly averaged summer (June-August, Ts), May (Tm) and September (Tse) temperature data from the Norwegian station Kirkenes (69.7° N, 29.9° E) from 1965 to 2012 (Lenssen *et al.* 2019; GISTEMP Team 2020), located ~ 20 km from the lake to assess the climatic situation in the region. This selection was due to the situation that the rest of the time the monthly mean air temperature was negative. In Nikel, the mean annual air temperature is +0.2 °C. January is the coldest and July is the warmest month with mean air temperatures of -10.7 °C and +13.1 °C, respectively (Ylikorkko *et al.* 2015). In winter, the prevailing wind directions are south and south-west, while in summer northern and north-eastern winds prevail. The average annual precipitation in Nikel is 515 mm (Ylikorkko *et al.* 2015). In the summer months the amount of precipitation (183 mm) is larger than in winter (169 mm), autumn (103 mm), and spring (60 mm). Since the middle 1970's an increasing trend of annual precipitation amount has been observed in all seasons (2.4 mm/month for 10 years) with the largest increase in autumn (6 mm/month for 10 years), but these changes were statistically insignificant (Ylikorkko *et al.* 2015). The annual mean wind speed in Nikel is 3.8 m/s (Ylikorkko *et al.* 2015). The time interval from November 20 to January 20 (62 days) is a period of polar night and total absence of sunlight in the area.

Sample processing

We obtained a 44 cm long sediment core from the deepest 10 m part of the lake in 2013 using a gravity corer with an 8.5 cm diameter tube and automatic closing diaphragm. The gravity corer was made of plexiglass according to the model developed by Skogheim (1979). The sediment core was separated into 1 cm layers and freeze-dried for diatom analysis and dating. Preparation of sediments was carried out according to the standard generally accepted methods (Battarbee 1986; Battarbee *et al.* 2001; Ylikorkko *et al.* 2015; Vokueva & Denisov 2021). Microfossil identification and cell counts were determined with a microscope at 1000x magnification. At least 500 valves per sample were counted. All diatom valves have been identified at least to the species level and, if possible, to intraspecific taxonomic categories. Species composition was identified according to diatom taxonomic sources (Krammer & Lange-Bertalot 1986-1991; Krammer 2002; 2003). The taxonomy and nomenclature were harmonized with the International Algae Base data set (Guiry *et al.* 2014). The total amount of diatoms (Nd) was calculated (million cells g dry weight^{-1}) using the weight (g) data of sediment material from each layer. Changes in diversity were evaluated by the Shannon-Wiener Index (H') (Shannon 1948):

$$H' = -\sum P_i \cdot \log_2 P_i \, ,$$

where P_i – proportion of individuals of i-th species in a whole community; $P_i = N_i/\sum N_i$, where N_i – individuals of a given type/species, $\sum N_i$ – total number of individuals in community. Indices were calculated on an individual basis. In the literature calculations of phytoplankton diversity based on biomass are now being used more frequently (Figueredo & Giani 2001). In this study, because of using diatom analysis of lake sediments, diatom valves (or individuals) were the best units suitable for calculating the Shannon-Wiener index.

The diatom-inferred value of the pH has been calculated with the following equation (Moiseenko & Razumovsky 2009):

$$\mathrm{pH} = \frac{\sum ph_i \cdot k}{\sum k} \, ,$$

where ph_i is the individual numeric value of each indicator taxon and k is the relative abundance of this taxon.

We dated the sediment core by ^{210}Pb and ^{137}Cs at the Vernadsky Institute of Geochemistry and Analytical Chemistry (Moscow, Russia) (Ylikorkko *et al.* 2015; Travkina *et al.* 2017). Dating of sediments by ^{210}Pb covers the time interval of about the past 150 years. Collection and processing of the sediment chronologies were carried out on the pulse analyzer DSA-1000 (USA). DSA-1000 is a complete integrated multi-channel analyzer with a resolution of 16K channels, built based on modern digital signal processing. In conjunction with the analyzer DSA-1000, the Germanium detector BEGe3825 forms a complete installation of spectrometry for undertaking recruitment and analysis of the spectra with the highest quality (Travkina *et al.* 2017). Genie 2000 software (version 2.1) has been used to process the recorded spectra (Travkina *et al.* 2017). The

complex is regularly checked in the State Scientific Centre of the Russian Federation "VNIIFTRI". Low background apparatus for measuring gamma activity of samples are certified and used in a specialized laboratory for radiation control, which is accredited by the State Standard of Russia (accreditation number SARK RU.0001.441438). A CRS model (Constant Rate of Supply, Appleby 2001) has been applied to determine the age of the sedimentation.

Concentrations of heavy metals (Ni and Cu) in sediments were analyzed by atomic absorption spectrophotometer (Perkin Elmer 460 and 560) using the standard addition technique (Dauvalter 2003). Data on ozone total content (OTC) averaged poleward of latitude 63º N in the springtime spanning 26 years (1980-2006) (McKenzie *et al.* 2007) were used to characterize the variability of DNA-damaging UV-B (280-320 nm) solar irradiance. Data on spectral solar irradiance (SSI) from the Solar Radiation and Climate Experiment (SORCE) satellite were used to characterize variations of the photosynthetically active solar radiation (https://lasp.colorado.edu/home/sorce). The yearly means of sunspot number *W* were obtained from the WDC-SILSO, Royal Observatory of Belgium, Brussels.

Statistical analysis

To evaluate the relationship between the variables, we calculated the Spearman's correlation coefficients using the MATLAB software package (Software Company: MathWorks, www.mathworks.com). The statistical significance of the correlation coefficients was calculated with the *t*-test. A correlation was considered significant at $p \leq 0.05$.

The Kendall-Theil robust line (Sen's slope) was used for trends analysis using a KTRLine software developed by the U.S. Geological Survey (USGS) (Granato 2006). The Kendall-Theil robust line belongs to nonparametric methods and, therefore, is insensitive to the effects of outliers and normality of data distribution (Granato 2006). The slope of the line was calculated as the median of all possible pairwise slopes between points, and the intercept was calculated so that the line will run through the median of input data. The statistical significance of the trends was assessed with a nonparametric Mann-Kendall test and its homogeneity (or regime shift) with a Pettitt test using the XLSTAT 2020 statistical software. The Pettitt's test is a nonparametric adaptation of the Mann-Whitney test that allows identifying the time (a breakpoint year) at which the abrupt regime shift occurs (Pettitt 1979). For all tests, XLSTAT 2020 provides *p*-values and confidence intervals using Monte-Carlo resamplings.

We estimated trends in air temperatures before (1965-2002) and after the breakpoint (2002-2012) in the diatom abundance using a Kendall-Theil robust regression line. Trends were considered significant at $p \leq 0.05$ (Mann-Kendall test).

Results

The 44 cm sediment core spanned 687 years with an average sedimentation rate of 0.65 mm/year (Ylikorkko *et al.* 2015). In the analysis of the diatom complexes in the Rabbvatnet core, we identified 255 taxa to species level or below. Diatom assemblages were characterized by significant changes both in their diversity and in the quantitative characteristics (Fig. 2). The most common diatoms were planktic cyclotelloid taxa (*Cyclotella ocellata* Pantocsek, *C. rossii* Håkansson, *C. schumannii* (Grunow) Håk., *C. bodanica var. lemanica* (Mull. ex Schrot.) Bachm.), tychoplanktic *Aulacoseira* (*A. alpigena*
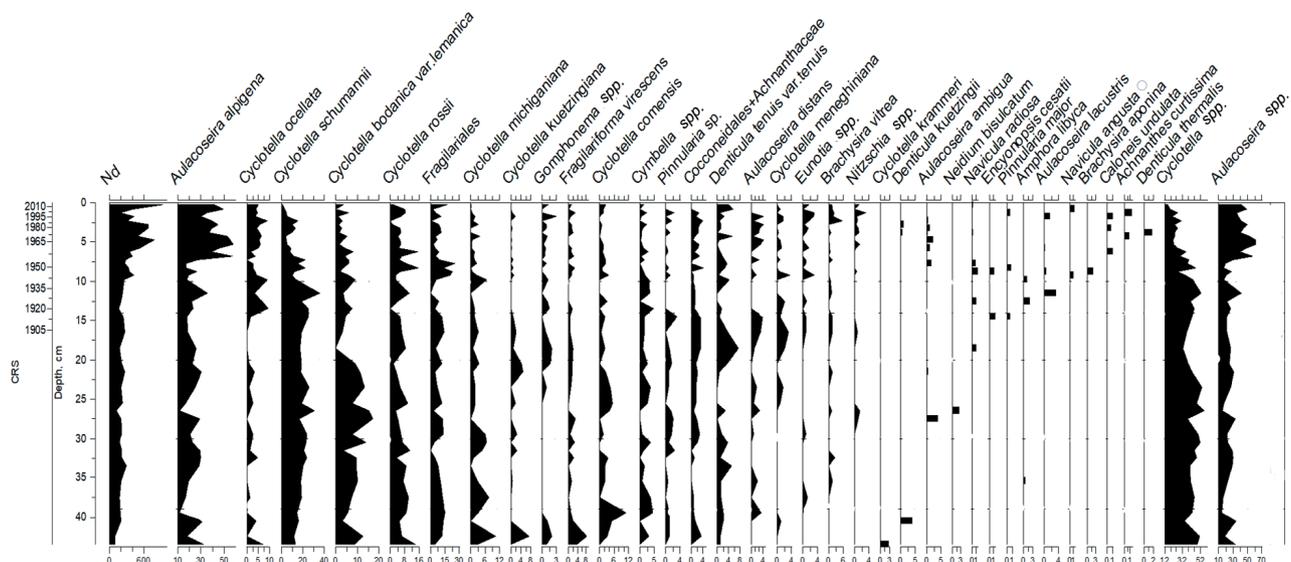
Figure 2. Total diatom abundance *N*d (million cells g dry weight^{-1}), relative abundances (%) of the main diatom species identified in Lake Rabbvatnet sediment.

(Grun.) Krammer, *A. distans* (Ehrenberg) Simonsen) and *Fragilaria* (*Fragilariforma virescens* (Ralfs) D.M. Williams and Round, *Pseudostaurosira brevistriata* (Grun.) D.M. Williams and Round, *Staurosira construens* Ehrenberg) species. Non-planktic, benthic species were also present in the sediments, mainly *Denticula tenuis var. tenuis* Kütz. and *Brachysira* spp. (*B. brebissonii* R. Ross, *B. vitrea* (Grun.) R.Ross in Hartley). The typical diatoms in the oldest layers (40-44 cm) of the column were *F. virescens*, *A. alpigena* and *Cyclotella* species, however, the total abundance was relatively low (~ 60 million cells g dry weight^{-1}). *C. krammeri* Håkansson was observed only in this layer. In the middle part (10-40 cm) of the core, the dominant species were *Denticula tenuis var. tenuis*, *A. alpigena* and *Cyclotella* species. In this layer, the proportion of benthic diatoms varied from 29 to 43%. In the top layers (0-10 cm), *Aulacoseira alpigena* was dominant (>50%). The minimum benthic diatom abundance was recorded in the 6-7 cm sediment layer formed in the 1960s. In this period, some new species were identified in the diatom assemblages: *Navicula angusta* Grunow, *Brachysira aponina* Kütz., *Caloneis undulata* (Gregory) Krammer, *Achnanthes curtissima* J.R. Carter and *Denticula thermalis* Kütz. (Fig. 2). *A. alpigena* and tychoplanktic/benthic *Fragilariales* were present throughout the entire core though more consistently present in the top 10 cm (1939 – 2012, Figs. 2, 3D). Otherwise, major *Cyclotella* species were abundant (>40%) before 1950 but they decreased subsequently, especially since 1990 (Figs. 2, 3D). The total diatom abundance *N*d increased significantly with a rate of 1.2% per year (Mann-Kendall test, $p < 0.05$) from 1895 to 2002 (Fig. 3E). The mean *N*d value was 157.9±20.9 million cells g^{-1} dry weight from 1895 to 2002. The total diatom abundance from 1963 to 2002 showed a declining trend, but then it increased more than 400% from 2002 (94 million cells g^{-1} dry weight) to 2012 (478 million cells g^{-1} dry weight) with a rate ~ 37% per year, though it was not statistically significant due to insufficient number of measurements (Fig. 3E). These changes were accompanied by a restructuring of species structure and diversity of the diatom complexes, but no net change in the Shannon-Wiener species diversity index *H'* (Fig. 3C). Whereas the rate of N_D increase was 30 times higher than before 2002, some benthic species simultaneously increased by > 5 times, such as *Denticula tenuis* (Fig. 3E).

Diatom-inferred pH values ranged between 6.99-7.11 without any statistically significant trend with respect to the Mann-Kendall and Pettitt homogeneity tests, meaning that the lake water was characterized by near-neutral values over the whole time interval (1895-2012) (Fig. 3B). A similar absence of trend was also observed in the Shannon-Wiener species diversity index. Its value did not change significantly and was close to an average (*H'*=2.41±0.09) from ~ 1970 to 2012 (Fig. 3C).

Variations of nickel (Ni) and copper (Cu) concentrations in the sediments are shown in Fig. 3A. These concentrations increased significantly (Mann-Kendall test, $p < 0.0001$) with rates of 3.7% per year in Ni and 1.3% per year in Cu from 1895 (Ni: 36.2 µg g^{-1} dry weight, Cu: 62.5 µg g^{-1} dry weight) to 2002 (Ni: 166 µg g^{-1} dry weight, Cu: 203 µg g^{-1} dry weight). The highest concentrations of Ni (247 µg g^{-1} dry weight) and Cu (315 µg g^{-1} dry weight) occurred in 2012 (Fig. 3A). Also, Ni and Cu experienced a post-2002 increasing trend (4.4% in Ni and 5% per year in Cu) that exceeded insignificantly the increasing rate calculated before 2002. The highest and significant correlations were found only for *A. alpigena* (Ni: $r=0.74$, $p=0.001$, Cu: $r=0.68$, $p=0.004$) and *C. schumannii* (Ni: $r=-0.75$, $p=0.0009$, Cu: $r=-0.76$, $p=0.0006$).

Average ozone total content poleward of latitude 63° N in the springtime varied between 1980-2006 (McKenzie *et al.* 2007; Fig. 4A). Values were initially high in 1980 (459 DU), but decreased significantly (~ 20%) from 1980 to 1997 with a rate of 1.1% per year (Mann-Kendall test, $p < 0.05$), and then increased to almost the same level (422 DU) in 2006 (Fig. 4A). No statistically significant trends with respect to the Mann-Kendall test were observed in *T*s and *T*se air temperatures before and after the breakpoint in diatom abundance). However, a significant increasing trend (0.32 °C decade^{-1}) was detected in September temperatures for the entire period from 1965 to 2012 (Figs. 4B, D). A significant increasing trend in May air temperature (0.8 °C decade^{-1}) was found before the breakpoint (1965-2002) and no trend after the breakpoint (2002-2012) (Fig. 4C). Homogeneities of the temperature series were as well analyzed with the Pettitt's test. *T*s time series were homogeneous with respect to the Pettitt's test, while some shifts were observed in *T*se and *T*m in 1987 (Pettitt's test, $p=0.03$). Note this quasi-breakpoint is other than the diatom abundance breakpoint (2002). Thus, this result confirms the results of the Mann-Kendall test.

Consequently, according to the slope analysis, local air temperature did not demonstrate a sharp rise from 2002 to 2012, although the May temperature is characterized by a gradual increase before the breakpoint from 1965 to 2002 (0.88 °C decade^{-1}, Figs 4b-d).

Recent direct measurements of SSI onboard the SORCE satellite showed that from 2004 to 2007, over the declining phase of the 11-year solar cycle 23, the changes in the visible and infrared spectral ranges were opposite to those in the UV-range and total solar irradiance (Harder *et al.* 2009; Haigh *et al.* 2010). That is, according to the SORCE data, the observed fluxes in the visible and infrared ranges increased, while the solar activity level decreased. SSI at a wavelength of 500.08 nm increased significantly with a rate of 0.18% per decade (Mann-Kendall test, $p < 0.05$) from 2003 to 2012, diatom abundance *N*d (million cells g^{-1} dry weight) increased substantially over this same time period (Fig. 4E).

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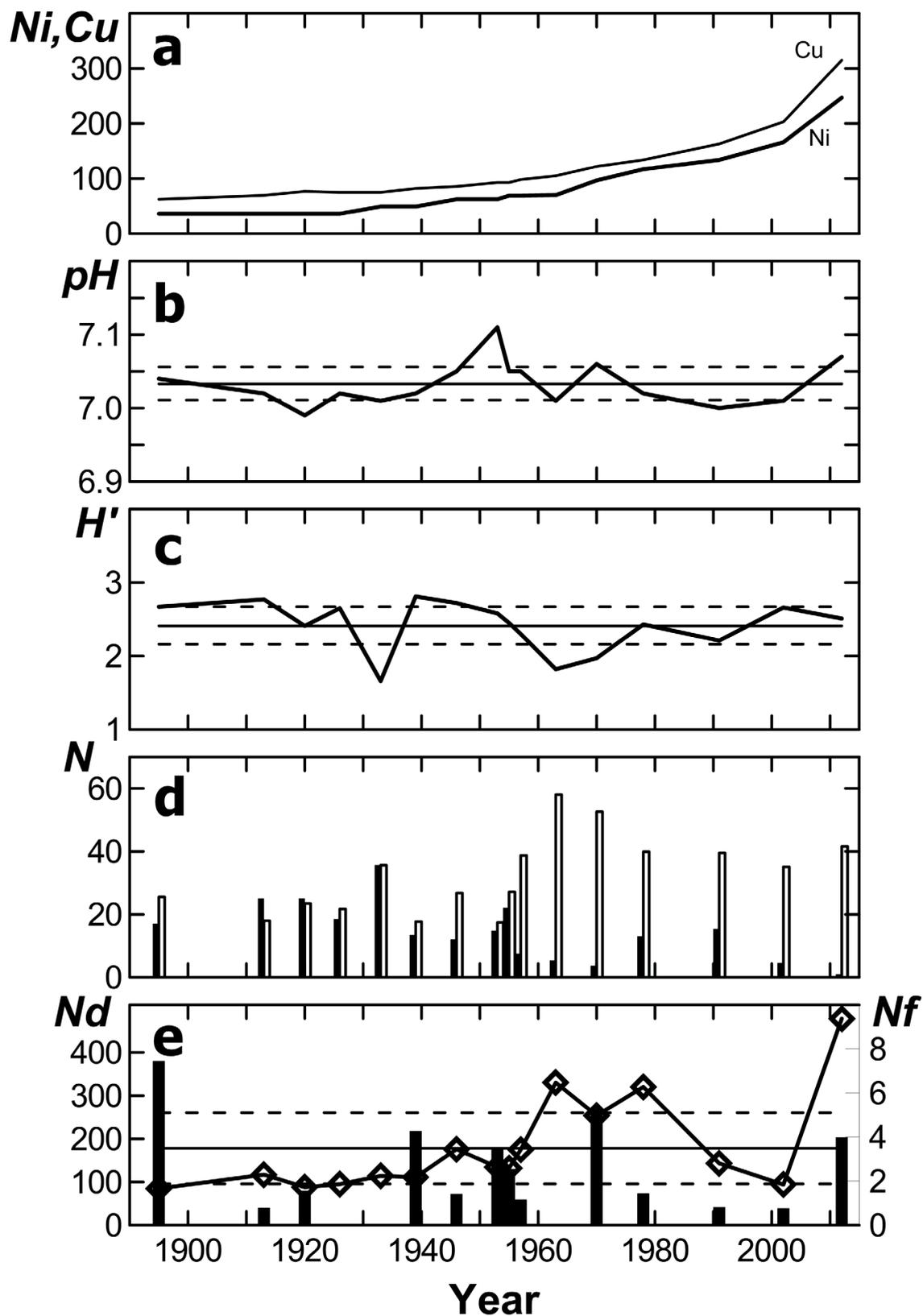
Figure 3. Distribution of different variables in the dated sediment record from Rabbvatnet Lake spanning the period 1895-2012 AD: (a) Cu and Ni concentrations µg g^{-1} dry weight, (b) diatom-inferred pH, (c) Shannon-Wiener Index (*H'*), (d) relative abundances (%) of the dominant diatom species *Aulacoseira alpigena* (light bars) and *Cyclotella schumannii* (black bars), (e) total diatom abundance *N*d (million cells g dry weight^{-1}, line) and relative abundance of benthic *Denticula tenuis* *N*f (%, black bars). Horizontal lines in Figs 3b,c,e indicate mean values (thin line) with 99% interval confidence intervals (dashed lines).
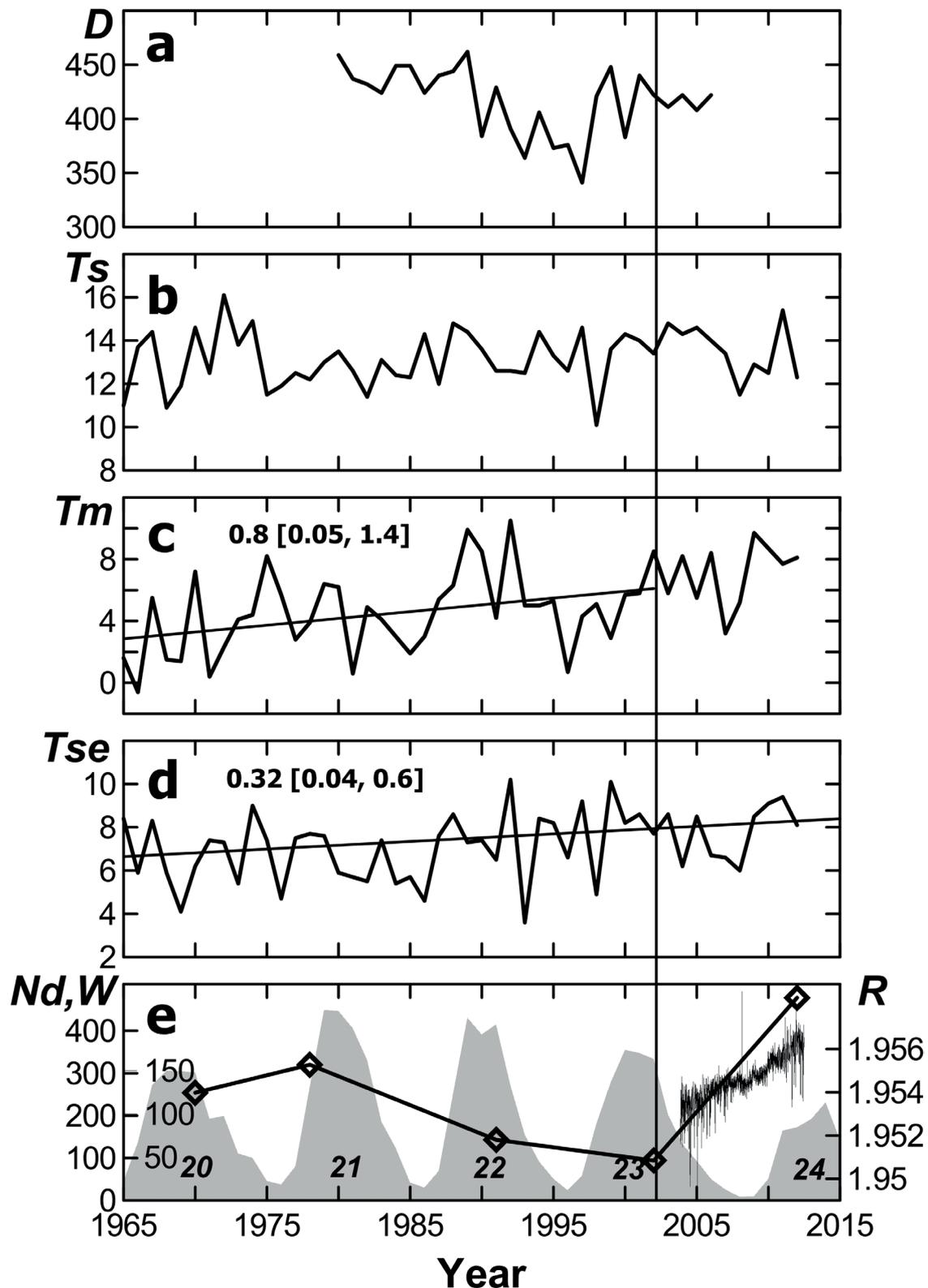
Figure 4. (a) changes in ozone total content (OTC) averaged poleward of latitude 63° N in the springtime spanning 26 years from 1980 to 2006 (*D* in Dobson units) (McKenzie *et al* 2007), (b-d) variations of mean summer (June-August) *T*s, May *T*m and September *T*se monthly air temperatures (°C) at Kirkenes (1965-2012), (e) variations of the diatom total abundance *N*d (million cells g dry weight^{-1}) in Rabbvatnet Lake from 1970 to 2012 (bold line with diamonds), spectral solar irradiance *R* (W m^{-2} nm^{-1}) at a wavelength of 500.08 nm from 2003 to 2012 according to the SORCE satellite data (thin line) and yearly means of sunspot number *W* (shaded area) with solar cycle numbers in italic. The straight lines in Figs 4c,d show Kendall-Theil trends (thin lines), numbers indicate slopes (°C decade^{-1}) with 95% confidence interval in brackets. The vertical line indicates the start year of the shift in diatom abundance *N*d (2002).

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Discussion

Lake Rabbvatnet's diatom abundance has shifted significantly from 2002 to 2012, while local air temperature generally remained constant. A similar absence of trend was also observed in the Shannon-Wiener species diversity index and pH values. Similar phytoplankton biomass increases have been observed in other arctic and subarctic lakes over the last decades (Larsen *et al*. 2006; Lehnherr *et al*. 2018; Anneville *et al*. 2019). Several studies have suggested that the main reason for observed diatom shifts is a global air temperature warming and various climate-driven processes such as longer growing seasons, reduced ice cover, external nutrient loadings, thermal stratification and habitat change (Larsen *et al*. 2006; Lehnherr *et al*. 2018; Anneville *et al*. 2019). Recently, other non-temperature effects (e.g., decreases in wind speed and increases in solar radiation) on phytoplankton communities in large lakes have received increasing attention (Jiang & Xia 2017; Deng *et al*. 2018). In addition, in our study of Rabbvatnet Lake, warming air temperatures alone do not appear to be the primary driver of changes in diatom assemblages.

We posit that changing light conditions, such as solar radiation, day length, cloud and ice cover, water column transparency may contribute significantly to the observed recent diatom shift in freshwater ecosystems (Sommer & Lengfellner 2008; Vehmaa & Salonen 2009; Winder & Sommer 2012; Ruhland *et al*. 2015; Schmid & Koster 2016; Deng *et al*. 2018; Winslow *et al*. 2018; Anneville *et al*. 2019). UV-B (290-320 nm) radiation affects phytoplankton biomass through photosynthesis inhibition and damaging DNA, and it is strongly (~ 95%) absorbed by atmospheric ozone (Smith *et al*. 1992; Williamson 1996; Lavaud 2007; McKenzie *et al*. 2007). Other trace gases (SO_2, NO_2) and aerosols also contribute to the absorption of UV-B radiation, but at a lesser extent (Chubarova 2006). Shumilov *et al*. (2005) showed that solar activity, mainly UV radiation, in combination with other human-caused stresses can significantly affect zooplankton productivity in Imandra Lake located on the Kola Peninsula. We hypothesize that the N_D decrease from 1978 to 2002 seemed to be caused by a reduction of OTC and the damaging effect of UV-B radiation.

Diatom complexes actively absorb solar radiation in the visible range from 400 to 700 nm (photosynthetically active radiation) in the process of photosynthesis (Kirk 2011; Chen *et al*. 2015). High-resolution analysis of lake sediment from southwestern Alaska revealed variations in diatom abundance at multicentennial time scales, which coincided with known solar cycles (Hu *et al*. 2003). According to SORCE satellite observations, in the early 2000s solar activity level decreased while observed fluxes in the visible and near-infrared ranges increased. This unusual behavior of SSI in visible and near-infrared ranges seemed to be a manifestation of a long-term centennial cycle of solar activity (Gleissberg cycle). Indeed, the last 11-yr solar cycle

(cycle 24) was the weakest cycle of the past ~ 100 years (Zharkova 2020). According to satellite data, TSI during the past three decades showed the 11 yr solar cycle variation of about 0.1%, positively correlated with solar activity, but it was lower by about 25% of its typical cycle amplitude during the minimum in late 2008 (Frohlich 2013). Note that Kasatkina *et al*. (2019) compared solar activity and tree-ring width variations and found that SSI in the visible and near-infrared bands could be one of the main solar agents affecting tree growth during Grand Solar Minima, like Maunder minimum (1645-1715 AD). All this, together with other evidences, seem to indicate the approach of new Grand Solar Minima with Little Ice Age climatic conditions (Lockwood *et al*. 2011; Abdussamatov 2013; Frohlich 2013; Kasatkina *et al*. 2019; Zharkova 2020).

Variations of diatom-inferred pH showed that over the whole period the water was characterized by near-neutral values and fluctuations were insignificant (Fig. 3B). Although we do not have proxies that indicate changing nutrient conditions, Rabbvatnet Lake is highly oligotrophic and does not show indication of rising carbon, nitrogen, or phosphorus concentrations.

Of course, the ecosystem of Rabbvatnet Lake has been exposed to high emissions of SO_2 and heavy metals (Ni and Cu) from Pechenganikel smelters since 1939 (Ylikorkko *et al*. 2015). In the last decade, the concentrations of Ni and Cu in lake sediments reached their maximum values in 2012 (247 and 315 µg g^{-1} dry weight, respectively) (Fig. 3A). According to the research results, one of the effects of emissions such as those from Pechenganikel smelters may be a decline in small cyclotelloid and weakly silicified *Cyclotella* species (Cattaneo *et al*. 2008). Although a significant negative relationship was found between *C. schumannii* abundance and concentration of Ni and Cu, a sharp decrease in the relative amount of this algae from 22% (1955) to 7.5% (1957) occurred long before the breakpoint in 2002 (Fig. 3D). A similar, but opposite (positive) significant relationship was found for *A. alpigena*. However, it is considered unlikely that the sharp increase in the total diatom abundance N_D observed in 2002-2012 could be related to heavy metals.

Conclusion

We conclude that the recent growth of the total diatom abundance observed in Rabbvatnet Lake in 2002-2012, and possibly in other polar and subpolar lakes, could be mainly due to an increase in photosynthetically active spectral irradiance fluxes in the visible and near-infrared ranges recorded by SORCE measurements. Regional air temperature seemed not to be the dominant reason for the recent diatom shift detected. Further investigation concerning diatom assemblages in Arctic lakes seems to open new aspects of their application in light trapping nanotechnologies and paleoclimatology.

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