Disentangling the environmental signals recorded in Holocene calcite varves based on modern lake observations and annual sedimentary processes in Diss Mere, England.

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Abstract

Diss Mere is a small natural lake located in the centre of the town Diss in Norfolk (England). The lake, which has been exposed to different stressors including climate variability and changing land use, has significant recreational, historical, and environmental value. The Diss Mere sediments are annually-laminated for most of the Holocene (2.1 – 10.3 ka BP), which allows the study of the lake evolution and its response to changing environmental conditions at an exceptionally high resolution. As with many mid-latitude, alkaline lakes, Diss Mere's sediments are formed of biogenic-calcite varves. We have conducted a 3.5-year lake monitoring survey including sediment trapping to identify the main drivers and seasonal processes contributing to lake sedimentation. Our results demonstrate that the modern lake is still producing seasonally-differentiated sediments today, however, are unable to be preserved as varves due to the permanent oxygenation of the lake bottom through gradual lake shallowing. Seasonal sediment fluxes follow a general pattern of i) an early spring diatom bloom ii) spring precipitation of medium-coarse calcite grains; iii) summer precipitation of smaller endogenic calcite grains; and iv) an autumn algal bloom and endogenic calcite precipitation intermixed with benthic diatoms and micrite. Whilst calcite precipitates throughout the whole year, peaks are observed in the epilimnion during the summer. This study shows that a modern analogue approach can be applied to the varves revealing their potential for environmental and climate reconstruction and highlights the significance of monitoring surveys for modern analogue approaches to palaeolimnological research.

Introduction

Palaeoenvironmental and palaeoclimate research based on annually laminated (varved) lacustrine and marine records has increased over the last few decades. When well preserved, varved records can provide robust chronologies and have yielded evidence for past environments at very high temporal resolutions. Such records have been applied to reconstruct, for example, the frequency and magnitude of extreme weather events (Czymzik et al. 2016; Corella et al. 2014), abrupt climate changes (Brauer et al. 2008; Martin-Puertas et al. 2012), decadal climate variability (Lapointe et al. 2020; 2021), ecological responses to changing climate (Lücke and Brauer, 2004) and interactions between humans and environments (Dräger et al. 2017, Sear et al. 2020).

Advantages of lacustrine varves as a palaeoenvironmental archive is that they are globally distributed and preserve high-resolution (seasonal to annual) palaeoenvironmental information. Palaeoenvironmental proxies require careful interpretation as archives act as filters between external environmental variables such as climate, and proxies themselves. In lacustrine settings, this is termed the hydroclimate filter (Cohen et al. 2003). The hydroclimate filter integrates the physical, chemical, and biological processes in lakes, which control and modify the climate and environmental signal recorded in the sediments. Thus, the environmental and climatic interpretation of lacustrine proxies requires both an understanding of the lake system and its catchment (Sturm and Lotter, 1995), and cross-validation with other indicators from the same record through a multi-proxy approach. Based on the composition and structure of laminations, varves are commonly sorted into three types: clastic, organic, and evaporitic varves, according to conceptual models based on general lake response to seasonality in different climatic regions; cold, temperate, and (semi) arid climates, respectively (Zolitschka et al., 2015 and references therein). However, the annual nature of the laminations and the seasonal succession of layers need validation for each individual lake. The most common practice is microscopic analysis of the laminations to identify seasonally cyclic events, such as monospecific diatom blooms, layers of authigenic mineral precipitation, or detrital deposits associated with spring snow melt and increased discharge into the catchment (Brauer et al., 2004). In lakes where varves are preserved at present, it is possible to compare sediments deposited at the lake/sediment interface with observational data of the modern limnology and sediment trapping, providing a deeper understanding of the complex interactions between the internal lake processes controlling the sediment flux (Tylmann et al., 2011; Ojala et al., 2013; Żarczyński et al., 2022). This modern analogue approach provides new insights into varve formation and the calibration of the proxy record from varved sediments (Trapote et al., 2018; Vegas-Villarrubia et al., 2020; Żarczyński et al., 2022). Special emphasis has been put on the study of biogenic-calcite varves, the most common varve type preserved in temperate, alkaline lakes. Although only a few study cases have been published (Tylmann et al. 2011; Bonk et al. 2015; Kienel et al. 2017; Trapote et al. 2018; Apolinarska et al. 2020; Roeser et al. 2021; Zander et al. 2021; Żarczyński et al. 2022), they all provide evidence of a more differentiated view of the classic light calcite/dark organic couplet reflecting the complexity of the biogeochemical annual lake cycle. This emphasises the need to better connect varve formation, the annual limnological cycle, and the external environmental conditions.

One example of a biogenic-calcite varved record is Diss Mere, UK. This site holds the only lake record in the UK published to date that preserves a continuous varved sequence through most of the Holocene from 2.1 – 10.3 ka BP (Martin-Puertas et al. 2021). From 2.1 ka BP at 9 m of sediment depth, varves stop preserving and the sediment record experienced a huge increase in sedimentation rate from 0.4 mm yr^{-1} to 5 mm yr^{-1} (Martin-Puertas et al. 2021). The end of the varved sequence is diffuse and laminations fade out over the last four varves.

The uppermost 9 m of sediments are characterised by massive deposits intercalated by ~1.5 m-thick deposits of fairly-preserved 0.5 cm-thick laminations at 7-6.3 m, 5.5-3.8 m and 2.4-1 m of sediment depth (Martin-Puertas et al., 2021). The laminations might have an annual origin according to the sedimentation rate (Yang et al., 2010; Martin-Puertas et al., 2021), which suggests that the environmental and limnological processes triggering the varve formation in the past may still be controlling the lake sedimentation today but varve preservation conditions are unfavourable and changing through time. This study reports the findings of a 3.5-year lake monitoring survey, including 4 spring-summer, and 3 autumn-winter seasons in Diss Mere, in an attempt to apply a modern analogue approach to the palaeolimnological study of this lake. Our main objectives are to: i) describe the annual lake cycle and identify the environmental processes governing the seasonality of the modern limnology and sedimentation; ii) confirm whether the seasonal material deposited today resembles the composition of the varve sub-layers in the past; and iii) discuss factors limiting varve preservation.

Study site and sediment accumulation process

Regional settings of the modern lake

Diss Mere (52º22’N, 1º6’E, 29 m a.s.l.) is a small freshwater, eutrophic, lake located in the town of Diss, East Anglia, England (Fig. 1a). The lake has a maximum water depth of 6 m with a lake surface area of 0.034 km^2 and a catchment of 1.5 km^2 (Fig. 1b, c). There are no surface inflows or outflows. The mere is situated in the River Waveney Valley, an area formed of chalky till. Drainage is poor around the mere which has resulted in waterlogged calcareous soils. The lake is located 7 km east of a major drainage divide (source of both the River Waveney and Little Ouse), but the topography does not reveal the current lake to be part of any surface water system and it is unclear how much modem surface drainage enters the lake (Bailey, 2005). Local groundwater data from the Waveney Catchment is presented in Supplementary Table 1.

East Anglia is characterised by a relative continental climate (Mayes, 2000). The average climatology records maximum monthly air temperatures in July (17.4 °C) and minimum temperatures in January of 4.4 °C. Total annual precipitation for this region is 626.9 mm with the wettest and driest months being October (64.6 mm) and March (39.3 mm), respectively (Fig. 1d).

The Diss Mere varve models

The Diss Mere varves are shown in Figure 2. One varve typically consists of a pale lamina made of endogenic calcite crystals, and a dark lamina composed of, primarily, chrysophyceae cysts, planktonic centric diatoms, filaments of organic matter and micrite (Peglar et al. 1984). Coarse grains of endogenic calcite also occur in these laminae (Fig. 2b). The calcite layer is made of coarser grains at the bottom and crystal size decreases upwards through the lamina (Bailey, 2005) (Fig. 2b).

Diatom, pollen and chrysophyceae cyst content were described in detail for fourteen individual pale and dark laminae at 10.85 m of sediment depth (ca. 6 ka BP) to identify the phenology of biological cycles and help identify the seasonal succession of layers within a varve (Peglar et al., 1984). The diatom palaeo-community in these sediments is mainly represented (63-99%) by *Lindavia comta* (Kützing) Nakov et al., (2015). Diatoms occur in both the pale and dark layers, but with the greatest concentration in the dark-organic layer, alongside the highest abundance of chrysophyceae cysts. This suggests the formation of the dark lamina begins in late summer and autumn, when the cysts are commonly produced (Tippett, 1964).

The pollen composition of the pale layers is characterised by *Tilia* and Gramineae, whilst *Corylus, Alnus, Ulmus* and *Taxus* pollen is found in the dark layer reflecting a pattern of the phenological season distinguishing between plants flowering from May to July and in early spring, respectively (Peglar et al., 1984). The combination of pollen and chrysophyceae cyst observations reveal that the pale calcite layer might represent lake deposition in late spring and summer (May-July approx.), while the dark organic layer indicates accumulation from late summer to late spring (August-April approx.) (Peglar et al. 1984).

A microscopic sedimentological study of the varve structure through the entire varved sequence reveals, however, changing varve composition (Fig. 2a) possibly reflecting interannual variability of limnological processes inducing calcite precipitation and biological productivity. Three varve types have been recorded in Martin-Puertas et al. (2021). Varve type 1 is the light/dark couplet described above; varve type 2 includes a diatom layer prior to the light calcite layer; and varve type 3 is a couplet of diatom and organic dark layers with no (or very thin) calcite layers (Fig. 2c).

Methods

Lake monitoring survey

This lake monitoring survey at Diss Mere has been carried out monthly between June 2018 and November 2021 to study the modern sediments using sediment traps and physicochemical (temperature, pH, alkalinity, conductivity, dissolved oxygen, major ions) profiles of the lake’s water column.

Physical and chemical properties

The water column physicochemical characteristics were obtained using a Multi 3320 WTW meter equipped with a Tetracon® 325 probe for temperature, conductivity, dissolved oxygen (DO), and pH. Measurements were recorded at 1 m intervals from the lake surface to lake bottom. At each interval, water samples were collected using a Niskin bottle for further chemical analyses: alkalinity was measured in situ with a HACH digital titrator model AL-DT; major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+, NH_4^+) and anions (NO_3^-, PO_4^{3-} Cl^-, SO_4^{2-}) were analysed by ion chromatography with a Metrohm 930 Compact IC Flex equipped with a 919 IC Autosampler after 0.2 µm filtration. Analysis for cations began in May 2019, and anions in September 2019. Total reactive phosphates and acid-hydrolysable phosphorous (TP) were analysed by colorimetry with a Skalar Segmented Flow Analyser following digestion by Microwave assisted method in potassium persulfate/sulphuric acid mixture (Eaton et al, 1995).

Two nKe thermistors were attached to the sediment traps at 1 m and 5.5 m (Fig. 1b). Temperature was recorded every 10 minutes from June 2018 to June 2021 at 1m, and between June 2018 and June 2020 at 6m.

Sediment analyses

Two sets of PVC sediment traps were placed in the lake with the trap openings at 1m (epilimnion) and 5 m (hypolimnion) of lake water depth to analyse the sediment flux and composition (Fig. 1e). Each set of traps contained two PVC tubes each with an active area of 6.3 cm and length of 1 m, and a tap near the base to drain some of the lake water and suspended material collected during trap retrieval. The traps were emptied at each monitoring campaign and content, including the remaining lake water, and settled material in the trap, was stored in plastic bottles at 4 °C prior to analysis for sediment and diatom composition. In the lab, the content from each trap was homogenised and divided for diatom and chemical analysis.

An aliquot of the homogenised sample was filtered at 0.2 μm, dried, and scaled up to the whole volume of the water in the trap and the total mass flux (TMF: g m^{-2} d^{-1}) was calculated following equation 1.

(Equation 1)

$$TMF\ (g\ m^{-2}\ d^{-1}) = \frac{\text{Dry net weight of sediments (g)}}{\text{Active area } (m^2)\ \times\ Time\ between\ trap\ collection\ (d)}$$

Samples for chemical analysis, including organic and inorganic carbon, were filtered with a 0.2 μm GC fibreglass filter using a vacuum pump and then dried. Smear slides and sediment samples for scanning electron microscope (SEM) analysis were carried out to characterise the main components of the sediments. Sediment samples were mounted on aluminium stubs and carbon coated to 6 μm and observed under a Hitachi SU9000 SEM with backscatter and secondary electron modes. Organic and inorganic carbon were quantified using a Thermo Electron Corporation Flash EA 112 Series nitrogen and carbon soil analyser with carbon, hydrogen, nitrogen and sulphur (CHNS) configuration. Amino acid cystine (29.5 %C) was used as a quality control throughout the analysis, returning an overall SD of 1.94 (%C) and a bias of 0.35 (%C). For inorganic carbon, the sediment samples were previously treated with 10% hydrochloric acid overnight to remove the carbonates, they were then rinsed and dried. As carbonates were removed, the measured C can be considered total organic carbon (TOC).

The calcite saturation index (SI) is used here as an indication of favourable conditions for calcite to precipitate in the lake water. SI ≥ 0 indicates supersaturation and thus favourable conditions for precipitation (Roeser et al. 2021).

The SI was calculated using Equation 3 (Langmuir, 1971).

(Equation 2)

$$SI_{calcite} = \log \frac{[Ca^{2+}] \times [CO_3^{2-}]}{K_c}$$

Where [] is the activity of the free ion and K_c is the solubility constant of the calcite at a given temperature. The activity of the free ions was calculated by the products of the specific activity coefficients and concentrations. The activity coefficients were obtained using the conductivity measurements. The carbonate concentration was calculated using the alkalinity, pH and temperature.

To assess the role that phosphates have on the precipitation of calcite in Diss Mere, we sequentially extracted both apatite (phosphorous bound to calcite) and non-apatite (inorganic) phosphorous from the sediments. We followed the Williams method with adaptations recommended by Ruban et al., (1998). Five months were selected from different seasons (October 2019, February, March, July, and October 2020) from both sediment traps to reveal seasonal changes through one year.

Diatom analysis

All water samples from the sediment traps were studied for diatom composition. To concentrate the diatoms, 50 cm^3 of lake water from the traps were first spun down, allowing ~0.1 g sample to be extracted for analysis. Preparation followed an adapted version of the digestion procedure of Battarbee et al., (2001), where organics were removed using H_2O_2, carbonates removed using several drops of 50% HCl, and samples were rinsed at least 4 times, to neutralise the medium. Ammonia (NH_3) was added in the final stages to prevent diatoms clumping. Concentrations were determined with the addition of divinylbenzene (DVB) microspheres, added following the final rinse (Equation 3). Fluxes were calculated to account for varying numbers of days between samples being collected. Samples were pipetted onto cover slips and left to dry before being mounted in Naphrax^{TM} mounting resin (refraction index

1.73). Samples were examined at 1000 x magnification using a Leica DMBL, and where possible, a minimum of 300 diatom valves were counted per sample. Identifications were made following Krammer and Lange-Bertalot (1986; 1991)**,** Lange-Bertalot, (2001), and Krammer (2002), Fritz (1989) and online resources (http://craticula.ncl.ac.uk and https://diatoms.org).

To determine the concentration the following equation was used:

(Equation 3)

$$Diatom\ Concentration = \frac{(\text{ Total Microspheres Added } \times \text{ Total Diatoms Counted})}{\text{Total Microspheres Counted}}$$

Diatom dissolution has been quantified across the samples to produce an F_index to estimate the diatom preservation state and the influence of dissolution on the sample and assemblage (Supplementary Information).

Meteorological data

Meteorological data was obtained from the Tibenham Airfield meteorological station (13 km from Diss Mere). The data collected includes daily mean values for air temperature (°C), wind speed (m s^{-1}), and total precipitation (mm).

Results

Physico-chemical properties of the water column: the annual lake cycle

Diss Mere is characterised by summer thermal stratification and winter mixing reflecting a monomictic mixing pattern (Fig. 3a). Surface temperatures ranged between 3–25 °C through the monitored years with the coldest water (3–5 °C) in February and warmest water (>21 °C) in summer (June-August). Water column mixing began to slow in March, and complete stratification was reached by April (Fig. 3a). Mean surface and bottom waters were 22.7 °C and 12.0 °C, respectively during July, where the maximum thermal gradient was reached, sustaining a thermocline between 2–4 m (Figure 3a). By late August, the thermocline deepened, and intermittent periods of mixing continued until October, when mixing persisted until the following spring.

The annual lake turnover helps to regulate the chemical composition of the lake, where the chemical homogenisation of the water column coincides with the onset of lake mixing (Fig. 3). However, the stratification of different chemical parameters (the differences between the chemical composition of the epi- and hypolimnion) occurred at the same time as the intermittent and weak temperature gradients in March, occurring one month prior to complete thermal stratification (Fig. 3). During lake stratification, surface waters had the highest concentrations of DO ranging between 11 – 15 mg L^{-1} in the epilimnion and 0.9 – 2.8 mg L^{-1} in the hypolimnion (Fig. 3b). The oxycline (the depth at which DO = 2 mg L^{-1}) was located between 4 – 5 m during stratification. The duration of the hypolimnetic hypoxia showed high interannual variability, within one month in 2019 and 2020 to five months in 2021 (Fig. 3b).

Anoxic conditions in the hypolimnion (<1 mg L^{-1}, Nürnberg, 1995) were only observed once in June 2018 (0.6 mg L^{-1}). In the epilimnion, discrete peaks of DO occurred in April and September (Fig. 3b). The beginning of mixing in October marked the full oxygenation of the water column, with an increase from October (4 mg L^{-1}) to March (13 mg L^{-1}).

The equilibrium pH for carbonate lake systems at 8.3 (Ito, 2002) was usually reached in February in Diss Mere, coinciding with the end of the mixing season (Fig. 3c). During stratification, pH remained high in the epilimnion (pH values ~9) coinciding with peaks in DO and drops in alkalinity (Fig. 4a). In the hypolimnion, pH remained stable at 7, and increased slightly towards the end of summer. At lake overturn, pH increased with maxima in September/October (9.3) and March (8.9) (Fig. 3c). The alkalinity ranged 140 – 194 mg L^{-1} as $CaCO_3$ in the epilimnion and 153 – 233 mg L^{-1} as $CaCO_3$ in the hypolimnion (Fig. 4a).

Conductivity remained mostly consistent through the water column, and across most of the year (Fig. 3d) with values ranging between ~ 600 – 720 µS cm^{-1}. Values increased to > 800 µS cm^{-1} below 5 m of depth during the stratified season coinciding with the hypoxic layer.

The most abundant cation was Ca^{2+} (Supplementary Table 2). The vertical distribution of this ion was not as heterogenous as other dissolved substances in the water column (Fig 3 and 4); however, some variability was observed across the year. Maximum concentrations were reached in February and March (> 65 mg L^{-1}) which then decreased until the lowest concentration (55 – 43 mg L^{-1}) between June to August (Fig. 4b; Supplementary Table 2). The concentration of Ca^{2+} increased gradually during the mixed season.

Nutrient concentrations of both dissolved phosphate (PO_4^{3-}) and total phosphate decreased in February and March with the complete absence of PO_4^{3-} at certain depths in March 2021 (Fig. 4c-d). The highest NO_{3-} concentrations were in February (3.9 mg L^{-1}) but were rapidly depleted by March (0.7 mg L^{-1}). During stratification NO_{3-} remained depleted and was replenished following lake overturn in October with an average of 1.4 mg L^{-1} (Supplementary Table 2).

Deposition of modern sediment components

Smear slides and SEM images revealed that the main component of the sediments in the traps was calcite and organic matter remains (Fig. 5, left panel). Calcite grain size varied through the year with larger grains (5 – 15 µm) collected in spring and summer compared to those in autumn (< 5 µm) (Fig. 5c, e). During the autumn-winter samples, *Pediastrum* (green algae) was the dominant component of the sediments forming a matrix together with fine micrite calcite crystals (Fig. 5g, h). Some rhombohedral calcite grains (< 5 µm) were present and were typically attached to diatom valves in the autumn and winter samples (Fig. 5h, i).

Total Mass Flux (TMF)

Figure 6 displays the changes in both the timing and composition of sediment collected in the traps, revealing evidence of seasonal and interannual variability. TMF in the epilimnion and hypolimnion followed the same general pattern, however the amount of material collected at the hypolimnion was greater (Fig 6a). Increases in TMF occurred in Spring (March–May) when the lake began to stratify, a higher flux was recorded in the hypolimnion recording a maximum seasonal flux of 8.1 g m^{-2} d^{-1} in April 2021. A gradual decline in TMF occurred during the summer until August. The largest flux of sediment was recorded at the point of lake mixing in September or October (Fig. 6a). The traps in October 2021 collected the highest flux of the monitoring period (22.2 g m^{-2} d^{-1}).

Organic Matter (OM) flux

Clear seasonal differences exist in the amount of OM collected within the traps (Fig. 6b). During the stratified period OM flux remained stable and low with mean values of 0.8 g m^{-2} d^{-1} in the epilimnion, and 1.3 g m^{-2} d^{-1} in the hypolimnion. It reached its annual maximum in September/October following lake overturn, with the highest flux recorded in October 2021 (7.7 g m^{-2} d^{-1}). Whilst not as substantial as in autumn, there was a secondary flux in spring reaching maximum values of 2.0 g m^{-2} d^{-1} and 2.9 g m^{-2} d^{-1} in the epi- and hypolimnion, respectively. This seasonal pattern of changes in OM flux was consistent through the monitored period except for 2018 when OM remained low consistently through the year (Fig. 6b).

Calcite flux

Similar to OM, calcite flux also demonstrated a seasonal component to its deposition. An initial primary flux was recorded with mean values of 2.4 g m^{-2} d^{-1} and 3.3 g m^{-2} d^{-1} in the epi- and hypolimnion, respectively in spring (March–May) (Fig. 6c). Through the summer months (June-August), calcite flux increased to a maximum of 6.6 g m^{-2} d^{-1} in July 2020. Calcite flux decreased towards the end of summer and a further peak occurred following the demise of thermal stratification at beginning of lake mixing in both the epilimnion (3.4 g m^{-2} d^{-1}) and hypolimnion (4.7 g m^{-2} d^{-1}). Calcite flux was typically greater in the hypolimnion traps through most of the year, except in summer when most of the calcite was collected in the epilimnion (Fig. 6c).

In all the monitored years, except 2018, peaks of calcite precipitation occurred both during the stratified period, and again following lake turnover in autumn. In 2018, the main calcite flux occurred only during lake stratification with no clear increase in autumn (Fig. 6c). The year 2019 was an anomaly with exceptionally low calcite in the traps – the lowest calcite flux of the monitored period was 0.2 g m^{-2} d^{-1} in February 2019, and very low calcite precipitation in summer (0.7 g m^{-2} d^{-1}). Most of the calcite flux collected during this year was in October (Fig. 6c). The amount of apatite phosphate found in the sediments was greatest in the October samples, with a maximum of 17.8 g Kg^{-1} in the hypolimnion (Supplementary Table 3). July recorded the lowest amount of apatite phosphate with 2.2 g Kg^{-1} and 3.2 g Kg^{-1} in the epi- and hypolimnion, respectively.

SI in the epilimnion remained mostly above zero (-0.6 to 1.5), except for September 2020 (-0.6), and November 2021 (-0.1). Peaks of epilimnion SI occurred in early spring and autumn (Fig. 6c). Hypolimnion SI values ranged between –0.6 to 0.9.

Diatoms

Diatom blooms occurred in early spring (February–March) and in autumn (September–November), the latter following lake overturn. Concentrations were generally lower during the summer, especially in July and August 2019 (Fig. 6d). The Diss Mere assemblage consists of

128 diatom species (Supplementary Table 4 and 5). The dominant species is *Cyclostephanos dubius* (Hustedt) Round, 1988, a generally small, but morphologically variable, planktonic, centric species (Bradshaw and Anderson, 2003) (Fig. 5i). The highest concentrations of diatoms were recorded in the epilimnion in spring/early summer, and in autumn for the hypolimnion (Fig. 6d). In general, both the spring and autumn blooms were dominated by *C. dubius*, but smaller fluctuations of other species characterised the seasonal blooms. Short-lived peaks in *Stephanodiscus hantzschii* Grunow, occurred in the spring only, while small concentrations of benthic taxa were observed in the autumn, including *Amphora* species, Naviculoid species and *Achnanathes* species. Diatom preservation varied throughout the samples (Supplementary Information Fig. 1).

Meteorological Data

Air temperatures between 2018 to 2021 followed a seasonal pattern (Fig. 7b). Maximum average monthly temperatures peaked in July/August (19.0 °C), and minimum monthly average temperatures in January (4.3 °C). January 2019 and February 2021 were the coldest months of the monitoring period with the coldest day of the monitoring period recording a daily average of -2.9 °C in February 2021, despite negative temperatures, ice cover on the lake did not occur. Wind speeds during the summer months (June-August) were the lowest, with a mean of 3.7 m s^{-1} which then increased in autumn (September–November) to 4.1 m s^{-1}. February had the highest overall mean at 5.1 m s^{-1} (Fig. 7c). Monthly precipitation during the monitored period showed no clear seasonal pattern, but in general there was an increase in the autumn and winter months, compared to the spring and summer (Fig. 7d).

Discussion

Meteorological impact on the dominant limnological processes

The monomictic mixing regime in Diss Mere is strongly driven by air temperature and windy conditions. Water temperatures closely follow the annual variability of air temperature with thermal stratification driven by spring temperature increases and the decline of temperatures, alongside a general increase in winds in autumn result in lake overturn. The large volume of Diss Mere in relation to its relatively small watershed suggests that the lake ecosystem dynamics might be mainly controlled by the annual water cycle rather than catchment processes such as terrestrial runoff. In addition, the high conductivity of the lake water (~720 μS cm^{-1}) accounts for approximately 90% that of ground water from this locality (~810 μS cm^{-1}, Supplementary Table 2), suggesting groundwater is the main inflow into the lake and only a small proportion of lake water comes from either direct precipitation, or through runoff (Bailey, 2005).

Lake productivity

Peaks in productivity occur twice in the year at Diss Mere, with the first in spring. This is characterised by a diatom bloom and peak in organic matter flux following maximum windspeeds in February and a general increase in surface water temperatures. Despite *C. dubius* remaining the dominant species of the bloom, the springtime diatom assemblage includes higher concentrations of *S. hantzschii,* likely because water temperatures are cooler (<12 °C) throughout February and March (Jung et al., 2009). The presence of *S. hantzschii* and *C. dubius* would explain the depletion of dissolved phosphates in early spring (February and March), followed by the depletion of nitrates in April, a nutrient commonly associated with *C. dubius* (Bradshaw and Anderson, 2003).

During the summer, concentrations of nutrients in the epilimnion are low, with an accumulation of phosphates in the hypolimnion at the sediment-water interface, and very low concentrations of NO_{3-} throughout the water column. The breakdown of thermal stratification in September permits diatom-limiting nutrients to reach the photic zone (Bradshaw and Anderson, 2003; Roeser et al., 2021), and temperatures are still warm enough to allow the occurrence of a diatom bloom, specifically *C. dubius*. The second peak in productivity occurs in autumn, coinciding with the onset of the lake turnover. This peak in productivity is larger than the spring peak, evidenced by the highest OM flux, diatom concentration and presence of *Pediastrium* from September to November.

Both the spring and autumn diatom blooms are influenced by wind-induced lake mixing, recirculating nutrients to the photic zone and allowing smaller planktonic species, such as *C. dubius,* to outcompete others due to its preference for eutrophic conditions and its ability to tolerate low light levels through greater turbidity (Bradshaw and Anderson, 2003). This suggests a lake response encouraged by windy activity and a potential signal in the sediment represented by the deposition of a diatom layer.

Calcite precipitation

Calcite is deposited throughout the year at Diss Mere, however, similarly to the diatom concentrations, calcite precipitation also reveals a seasonal pattern. The annual variability of dissolved Ca^{2+} and the decrease in concentration in the epilimnion between May and October suggests calcite is precipitating during these months. Primary calcite peaks occur during the stratified seasons from late spring to late summer in the epilimnion followed by secondary peaks in autumn, mainly recorded in the hypolimnion. The permanent calcite precipitation in the lake during the whole year is likely a result of calcium oversaturation throughout the water column. Given the composition of the local bedrock and groundwater analyses from the Waveney Catchment (Supplementary Table 2), the water of Diss Mere is likely to be a dilute solution of calcium bicarbonate. This is complimented by almost consistent positive values of SI in the epilimnion, reporting oversaturation, hence favourable conditions for persistent precipitation.

Seasonal calcite peaks, however, could be accentuated by either pH increases, displacing the carbonate equilibrium from organism activity, favourable temperatures, or both (Kelts and Hsü, 1978; Dittrich and Obst, 2004). In Diss Mere, the increases in pH, driven by diatom blooms in early spring, and the general increase in air temperatures, in turn warming the epilimnion, triggers the oversaturation of $CaCO_3$ and facilitates calcite precipitation (Stabel, 1986; Trapote et al., 2019; Żarczyński et al., 2022). It is notable that in years where spring diatom concentrations are higher (April 2019; May 2021), early spring calcite precipitation events occur.

The calcite collected during spring presents large well-developed calcite grains (5-15µm) (Fig. 5c). High concentrations of dissolved phosphates have been shown to limit calcite precipitation leading to the supersaturation of lake water (Kunz and Stumm, 1984; Lotter et al., 1997). Once consumed, the rapid precipitation of large calcite grains can occur (Lotter et al., 1997). This is likely the cause of the larger spring calcite crystals at Diss Mere during these months as the concentration of dissolved PO_4^{3-} from Autumn through the winter remain high (0.7 mg L^{-1}) and are then rapidly depleted in February or March (0.05 mg L^{-1}) coinciding with the first algal bloom of the year.

The summer months are when calcite precipitation is more pronounced at Diss Mere, reflected by the dip in epilimnion Ca^{2+} and alkalinity, and the higher amount of calcite collected in the traps, coinciding with the warmest air temperatures. Saturation index in the epilimnion is also highest, likely from warmer waters. Calcite crystals here are still well-developed from the slow precipitation maintained by temperature (Fig. 5).

The second calcite peak is in autumn and is collected mostly in the hypolimnion and the calcite in the trap is largely dominated by micrite (Fig. 5). However, the autumn is the most productive period of the year, and both the saturation index, and relatively low epilimnion concentrations of Ca^{2+}, suggest that endogenic calcite is still precipitating during this period. The endogenic calcite crystals collected during these months are smaller (< 5µm), likely resulting from the increase in dissolved PO_4^{3-} compared to the spring and summer seasons. The relationship between changing crystals size and phosphate is complimented by the greatest amount of apatite phosphate found in the October sediment samples (Supplementary Table 3). This suggests more phosphate is absorbed into the active growth sites during precipitation, limiting grain size growth (House, 1980; Plant and House, 2002, Lotter et al., 1997). This is not the case however, for the calcite precipitation in the summer when there is much lower apatite phosphate present in the sediments (Supplementary Table 3).

Resuspension

Despite clear evidence showing that the sediment trapped during a single year represents the limnological processes occurring in the water column, some evidence suggests the sediments collected from October to February could also include resuspended material from both the littoral zone and lake bottom (Roeser et al., 2021). This is demonstrated by greater amount of calcite in the hypolimnion trap, as well as minerogenic particles and plant remains deposited during the lake mixing season (Fig. 5g). Whilst this could also be the accumulation of calcite from other depths of the water column below the epilimnion trap opening, the presence of several benthic diatom species in autumn including *Amphora* species, Naviculoids and *Achnanathes* species supports this interpretation (Supplementary Table 5). Layers of resuspended material in organic-calcite varves have been described in other European lakes and associated with site-specific lake morphology promoting the erosion of littoral parts of lakes from surface currents and waves (Roeser et al., 2021). The seasonal resuspension during lake turnover might be also accompanied by an autumn diatom bloom as it has been observed in Lake Czechowskie, which is driven by the redistribution of water column nutrients into the photic zone (Roeser et al., 2021). In Diss Mere the shallow waters (max. depth 6 m) and the morphology of the basin make the lake bottom vulnerable to wind-induced erosion, explaining both the deposition of resuspended material during the mixing season and the main diatom bloom in autumn.

Validation of the varve conceptual model

The main limnological processes identified in a single year in the modern Diss Mere system leaves a trace in the traps consisting of three different depositional phases: i) an early spring diatom bloom; ii) late spring and summer calcite precipitation characterised by calcite grains with an average size of 10 μm; and iii) an autumn diatom bloom, micritic calcite and resuspended material. This seasonal depositional sequence resembles the conceptual model of the varved record at Diss Mere, thereby suggesting that the modern limnology could be applied to the sediment record. Unlike the dominant microfacies recorded in the varved sequence where varve type 1 reflects ~90% of the varves, the seasonality observed in this study is likened to varve type 2 (Fig. 2). Varve type 1 does not present a spring diatom bloom as an independent layer; however, this might be mixed with the calcite layer thus prevents its identification on the thin sections. The calcite layer in the varves show coarse grains at the base and fine calcite grains at the top, representing the decreasing grain size observed from May to October in the sediment traps. The transition between the calcite layer and dark organic layer is diffuse as calcite grains still occur in the dark layer but intermixed with a wide range of diatoms species (including benthic species) and terrestrial organic matter remains (Fritz et al., 1989). This suggests resuspension is one of the dominant deposition processes during this season (Roeser et al., 2021).

Less than the 8% of the Holocene varves in Diss Mere correspond to varve type 3, where the calcite layer is extremely thin or absent. During the monitoring period, we have observed one year (2019) in which the spring and summer calcite is very low and thus may correspond to this varve type. Diatom concentration is high in spring 2019 and Ca^{2+} ions decrease in summer 2019, which suggest that calcite grains might have precipitated, but not collected in the traps. According to the results shown in this study, we find no clear link with the meteorological data, limnology, and diatom productivity to explain the lower precipitation during this summer. We therefore speculate that the occurrence of this varve type may be specific to certain lake conditions not recorded during this monitoring period.

A main issue in studying calcite varves is the deposition of multiple calcite layers (Trapote et al., 2018; Roeser et al., 2021; Żarczyński et al., 2022). Sediment trapping in Diss Mere reveals two calcite pulses, a summer event sustained by temperature, and an autumn event driven by biological productivity. Because these two calcite pulses precipitate in sequential seasons it is likely that the calcite would be deposited as a single layer, leaving a trace characterised by the gradual decrease in the grain size. From the palaeolimnological point of view, this means that multiple calcite precipitation events in a year are recorded as a single layer in the sediments and therefore unlikely to have chronological implications on varve counting. This is validated by the comparison of the varve counts with radiocarbon dates and selected tephra ages, all integrated into a Bayesian age model for the Diss Mere record (Martin-Puertas et al., 2021), but the environmental interpretation of calcite deposition in the sediments might be complex.

Although longer timeseries of monitoring data together with a permanent sediment trap are needed to establish statistically significant relationships between meteorology, limnology and lake sediments, our study suggests that most of the calcite deposited as a layer correspond to the summer and relates to annual maximum temperature; and the autumn precipitation might mark the diffuse transition between the light and the dark layers in the varves. Thus, either the thickness of the calcite layer, the contribution of the calcite layer to the total varve thickness, the Ca^{2+} in the sediments, or all, might potentially be sensitive to summer temperature variability during the Holocene.

Limiting factors for varve preservation

Varves stopped preserving around 2,100 years ago in Diss Mere, with some intermittent periods of preserved laminations over the last two thousand years. Despite a strong seasonality in the sediment deposition, which is the case in the modern Diss Mere system, varve preservation depends on hypoxia preventing bioturbation and the absence of erosive processes at the lake bottom (Ojala et al., 2000; Zolitschka et al. 2015). Much of the global varves preserved today have been preserving for the last few centuries only, which is the result of cultural eutrophication increasing lake productivity, degradation of the organic matter and, consequently resulting in hypoxic hypolimnions (Jenny et al. 2013; Dräger et al., 2016; Haas et al., 2019; Poraj-Górska et al., 2021; Salminen et al., 2021). However, natural varve preservation mainly depends on the catchment and lake morphology, with a low lake surface/depth ratio reducing wind-induced bottom oxygenation and sediment resuspension (Ojala et al., 2000). Recent studies on varved sediment formation and preservation show evidence that permanent hypolimnetic anoxia and meromictic conditions are not essential to preserve varved sediments. Instead, monomictic/dimictic lakes with short periods of available oxygen at the bottom are also able to preserve varves (Bonk et al., 2015; Roeser et al., 2021;

Żarczyński et al., 2022) of which a seasonal layer of resuspended material can be deposited and preserved (Roeser et al., 2021). The fact that the seasonal-defined sediments at Diss Mere are not preserved as varves following cultural eutrophication, and varves stopped preserving two thousand years ago suggests that varve preservation conditions during the Holocene were maintained by an optimal lake surface/depth ratio. The evidence of resuspended material in the varves indicates that the water column might not have been deep enough to sustain meromictic conditions, but periods of lake mixing and ventilation of the lake bottom were short preventing bioturbation thus allowing varve preservation. The end of the varve preservation occurred gradually when varves fade out over a few years (Martin-Puertas et al., 2021) coinciding with forest clearance and farming of the catchment suggesting an intensification of human activities from ca. 2.1 ka BP (Peglar et al., 1993). We suggest that the contribution of these two factors played a role in varve preservation at Diss Mere. Natural infilling of the lake alters the lake surface/depth ratio and may have been intensified by the increase in deforestation and soil use increasing the detrital input, supported by the rapid increase in sedimentation rate (Martin-Puertas et al., 2021). Both, a lake with an optimum surface/depth ratio, and a more open forest would favour longer wind-induced water mixing with available oxygen in the hypolimnion. The monitoring survey reveals that the current lake bottom is oxygenated (>2 mg L^{-1}) for most of the year, explaining the lack of varve preservation even when lake seasonality characterises sediment deposition. The intermittent preservation of laminations in the last two millennia suggest that relative changes in lake level and/or changing intensity of human activities on the catchment could have an impact on preservation conditions.

Conclusions

This study applies a 3.5-year lake monitoring survey on Diss Mere, England to disentangle the main drivers of sediment deposition in the Holocene varved sediments through a modern analogue approach. We found that Diss Mere is a monomictic lake currently forming seasonally defined sediments that consist of i) a spring diatom bloom, ii) calcite precipitation from late spring through summer, and iii) an autumnal diatom bloom with calcite grains bonded to organic matter and resuspended material from the littoral area. This annual pattern is similar to that recorded in the varve record and we conclude that a modern analogue could be applied to understand the seasonal environmental and climate signals recorded in the Holocene varves. The current lake seasonality is driven by air temperature and windiness. Lake productivity is enhanced during lake mixing from autumn to early spring by wind bringing additional nutrients into the photic zone, and most of the calcite precipitates over the summer through favourable temperatures. Although a long-term monitoring survey is needed to establish stronger relationship between meteorology and interannual variability of seasonal sediments (e.g. mass fluxes), this study suggests that the Diss Mere varves might have high potential for palaeoclimate investigations. Despite the seasonally defined sediments deposited today, we find that they are unable to be preserved as varves due to the lack of a stable hypoxic period maintained through the year, likely resulting from the shallow water depth of the lake. One limitation of the modern analogue approach is that it does not capture the influence of the ice cover on varve formation processes, which could induce variability in the lake seasonality during colder climates. As a final message, we highlight the importance of bridging the gap between limno- and palaeolimnology through sediment trapping techniques to develop robust and reliable reconstructions. We emphasise this especially for lakes which experience strong seasonality today and therefore may be potential sites for varve exploration.

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Conflicts of Interest

Authors declare no conflict of interest

Author Contribution

L.B and C.M.P. wrote the main manuscript text. C.M.P. designed the study, L.B and J.V. ran the chemical analyses. A.H. and C.M.P. designed and installed the sediment traps. P.H. extracted and identified the diatoms. All authors were involved in analysing results. All authors contributed to both the writing of the manuscript and to discussions about results. All authors reviewed the manuscript before submission.

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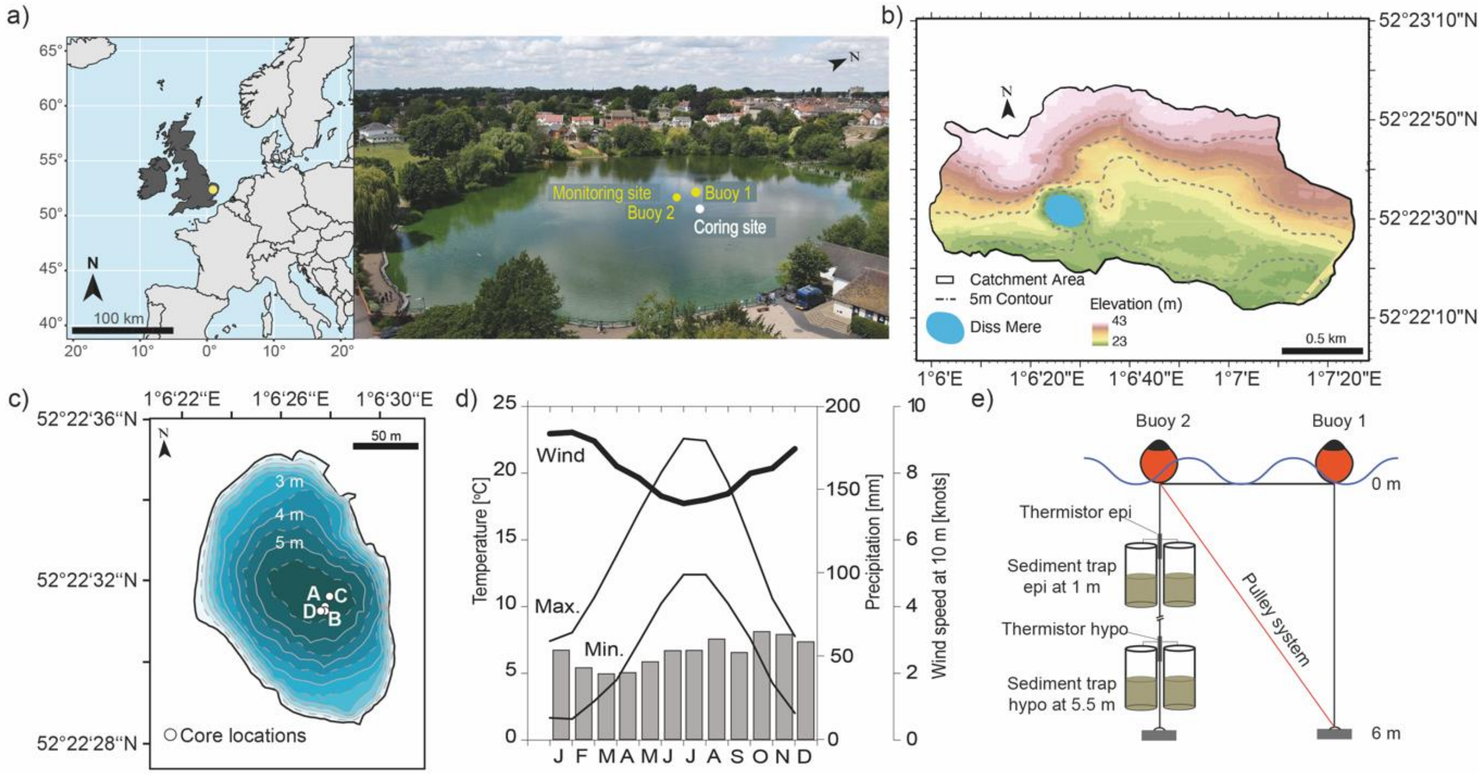

Figure 1. Settings of Diss Mere. a: geographical location and aerial photograph of the lake. b: topography of the catchment area. c: Diss Mere bathymetry and core locations. d: climatograms for East Anglia: maximum and minimum monthly temperature (thin black lines), monthly precipitation (grey bars) and wind speed (thick black line). Data are monthly averaged between 1990-2020. Data source: Met Office at www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/u12cfksmy. e) diagram of the sediment traps based on a pulley system. Epi is used for epilimnion and hypo for hypolimnion.

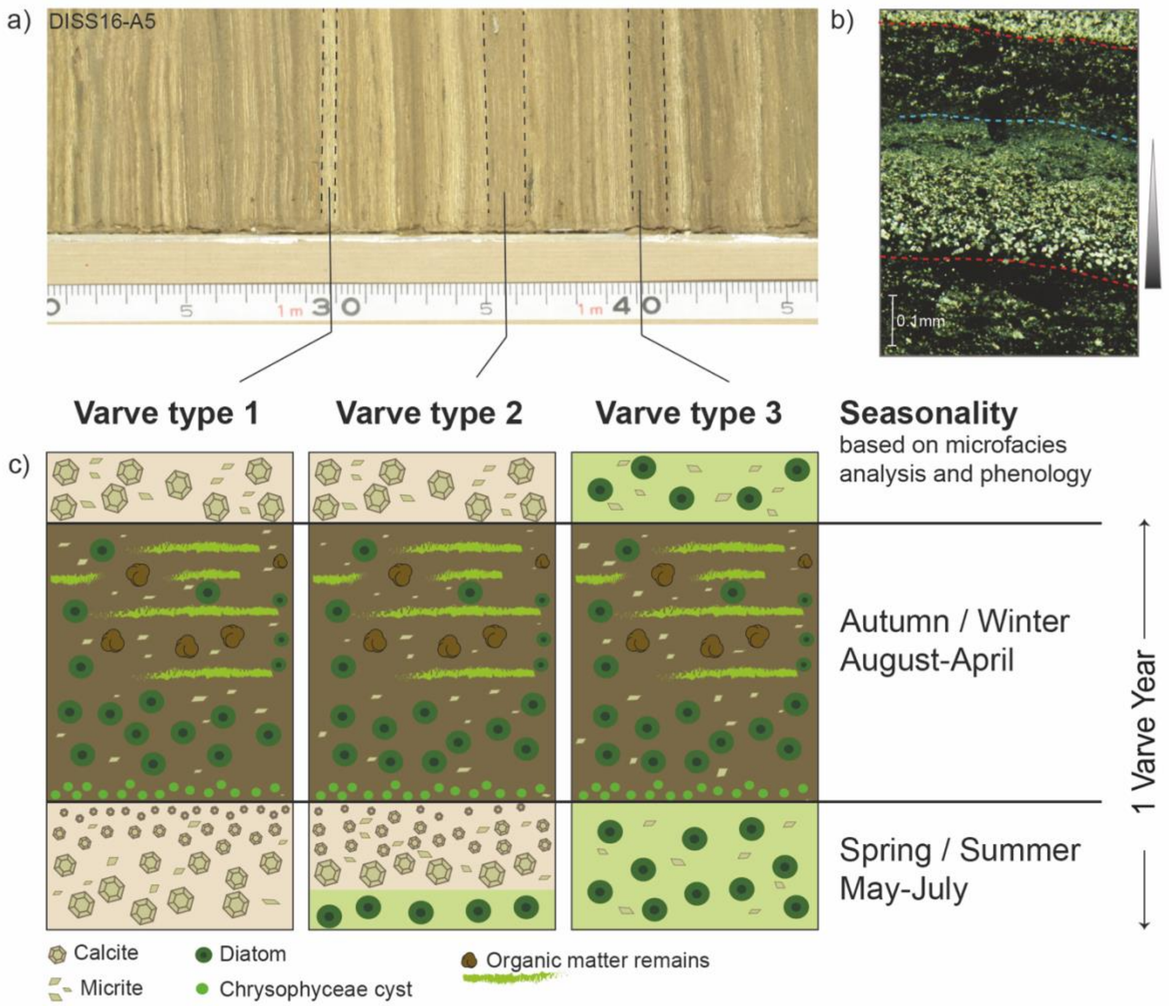

Figure 2. Diss Mere varve models. a: core photo section (DISS16-A5) of varved sediments showing interannual variability along the record as shown by the colour of the sediments. b: microscope image of a varve showing both the calcite (light) and the organic (dark) layers, and the gradient triangle depicts the gradually decreasing calcite grain size through the layer. c: model of the varve types identified in Diss Mere and their seasonality (Peglar et al. 1984; Martin-Puertas et al. 2021).

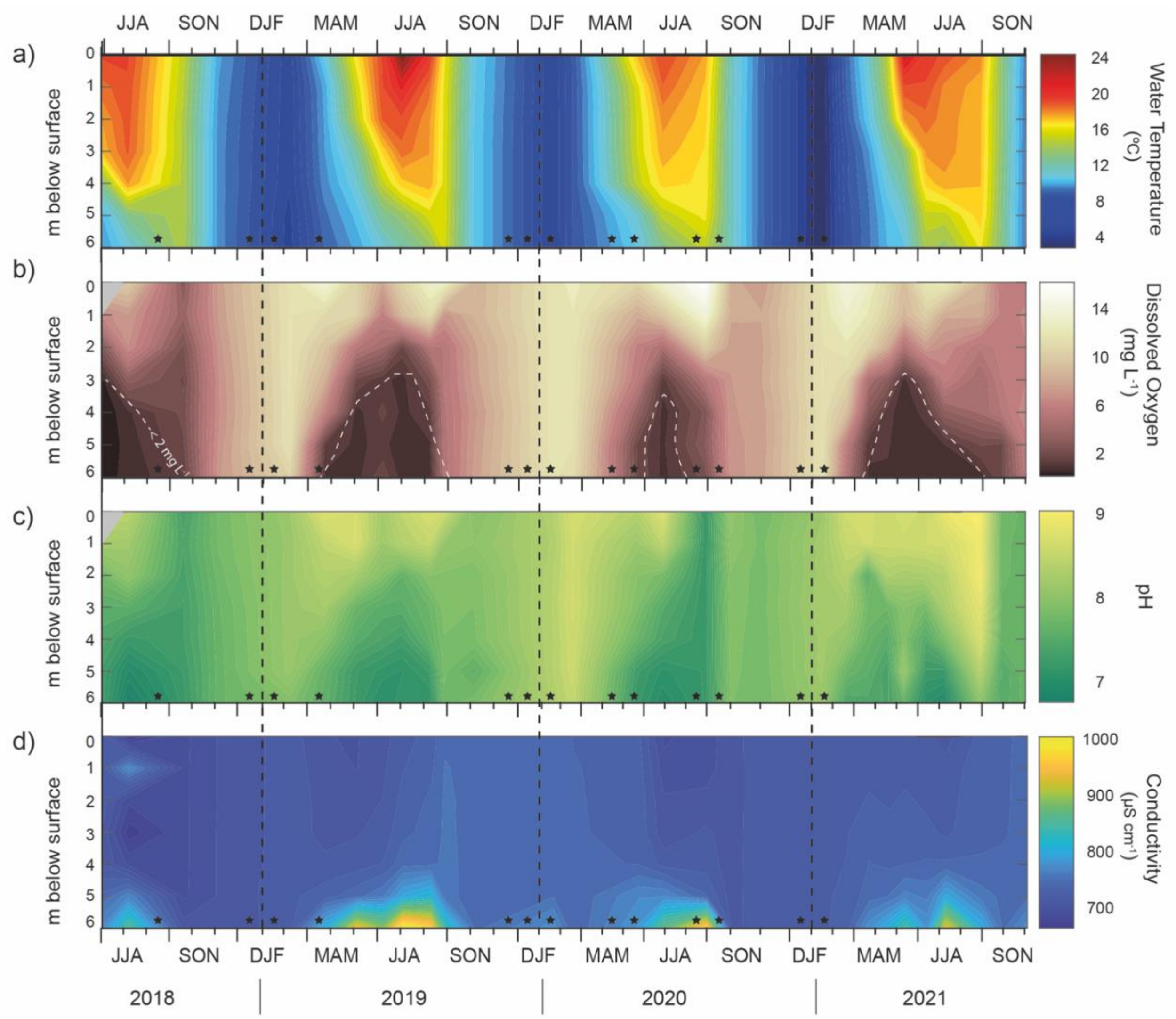

Figure 3. Contour plots of the main physical and chemical limnological variables in the water column over the monitored period (2018-2021). a: temperature. b: dissolved oxygen (DO) with white dashed line indicating the oxycline. c: pH; and d: electrical conductivity. Vertical black dashed lines indicate the beginning of a calendar year. Stars indicate months where data has been interpolated due to missing data. Grey triangles on b and c indicate that no data was collected for the surface water for this month.

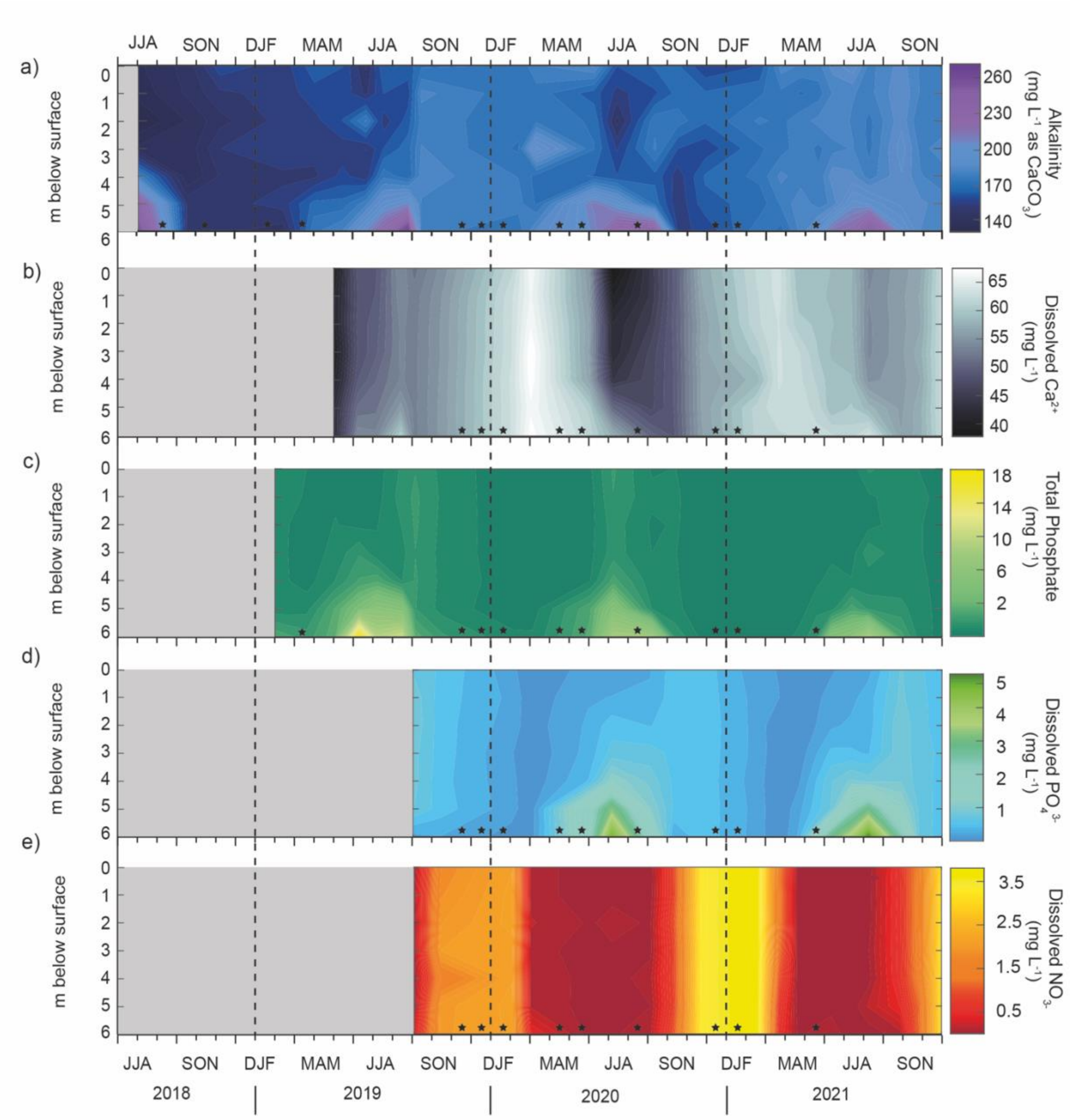

Figure 4. Chemical parameters for the monitored period (2018-2021). a: alkalinity. b dissolved Ca^{2+}, c: total phosphate. d: dissolved PO$_4^{3-}$ and e: dissolved NO^{3-}. Grey boxes indicate the absence of data. Vertical black dashed lines indicate the beginning of a calendar year. Stars indicate months where data has been interpolated due to absent data.

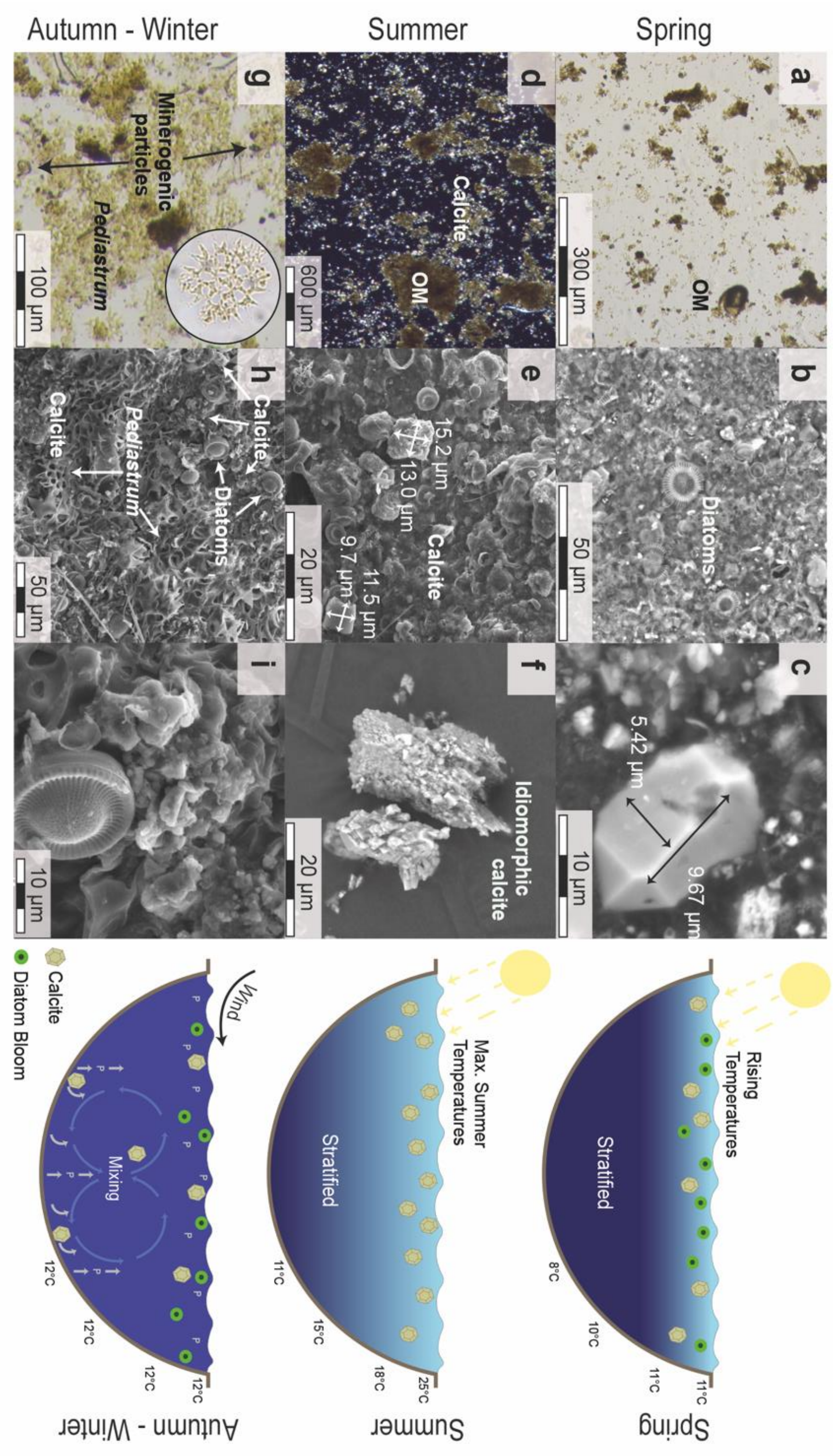

Figure 5. Dominant sediment composition and conceptual lake mixing and stratification cycle for the different seasons at Diss Mere. Left panel a-i: smear slide images (a, d, g) and SEM images (b, c, e, f, h, i) of the main components of the trapped material for each season. Right panel: conceptual model for the annual lake mixing and stratification cycle.

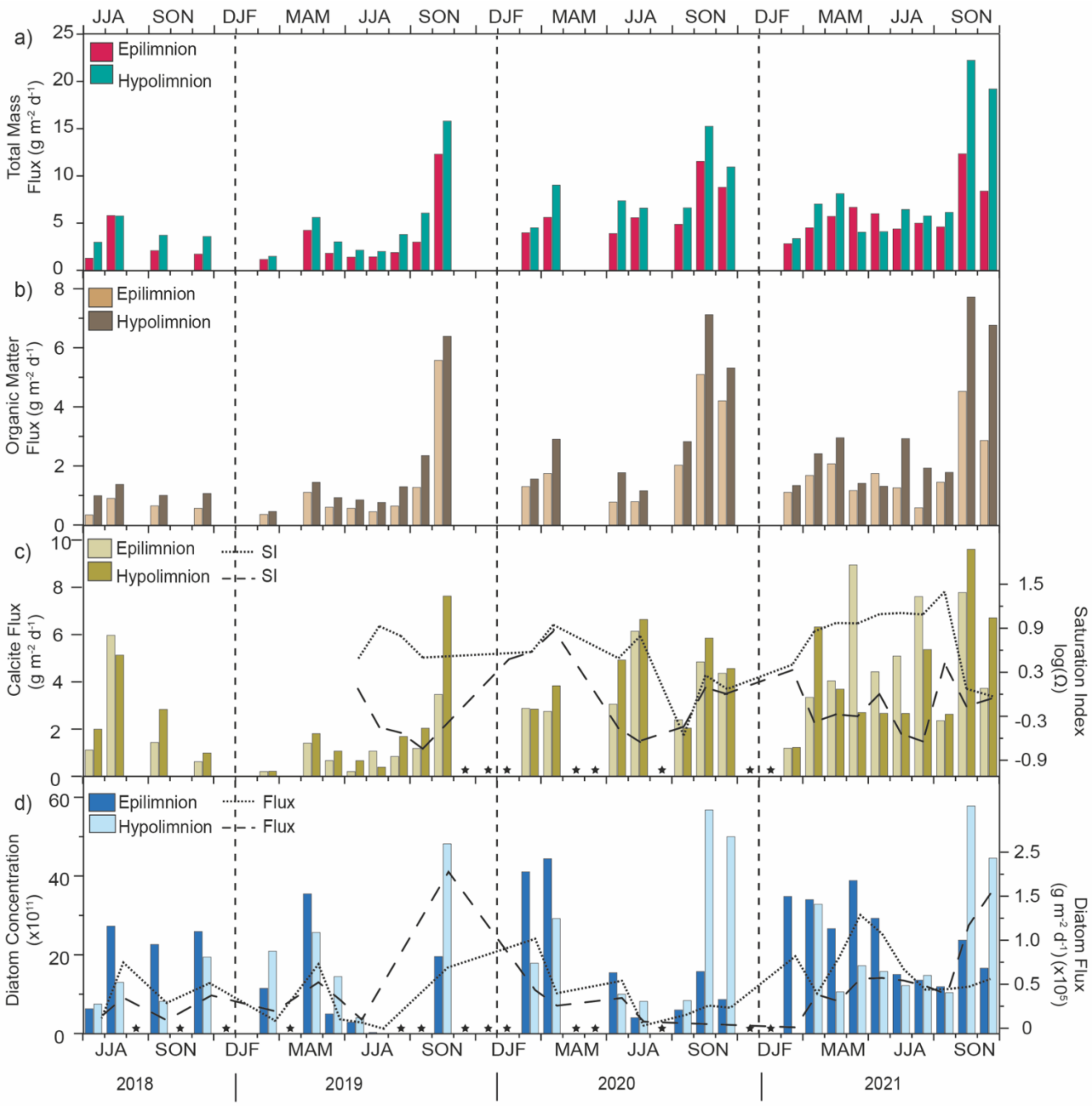

Figure 6. Flux and concentration data for the epi- and hypolimnion traps.

a: total mass flux. b: organic matter flux, c: calcite flux and saturation index (SI) (dashed lines). d: diatom concentrations (bar graphs) and diatom fluxes (dashed lines). c and d contain stars to indicate the months where data has been interpolated due to absent data Vertical black dashed lines indicate the beginning of a calendar year.

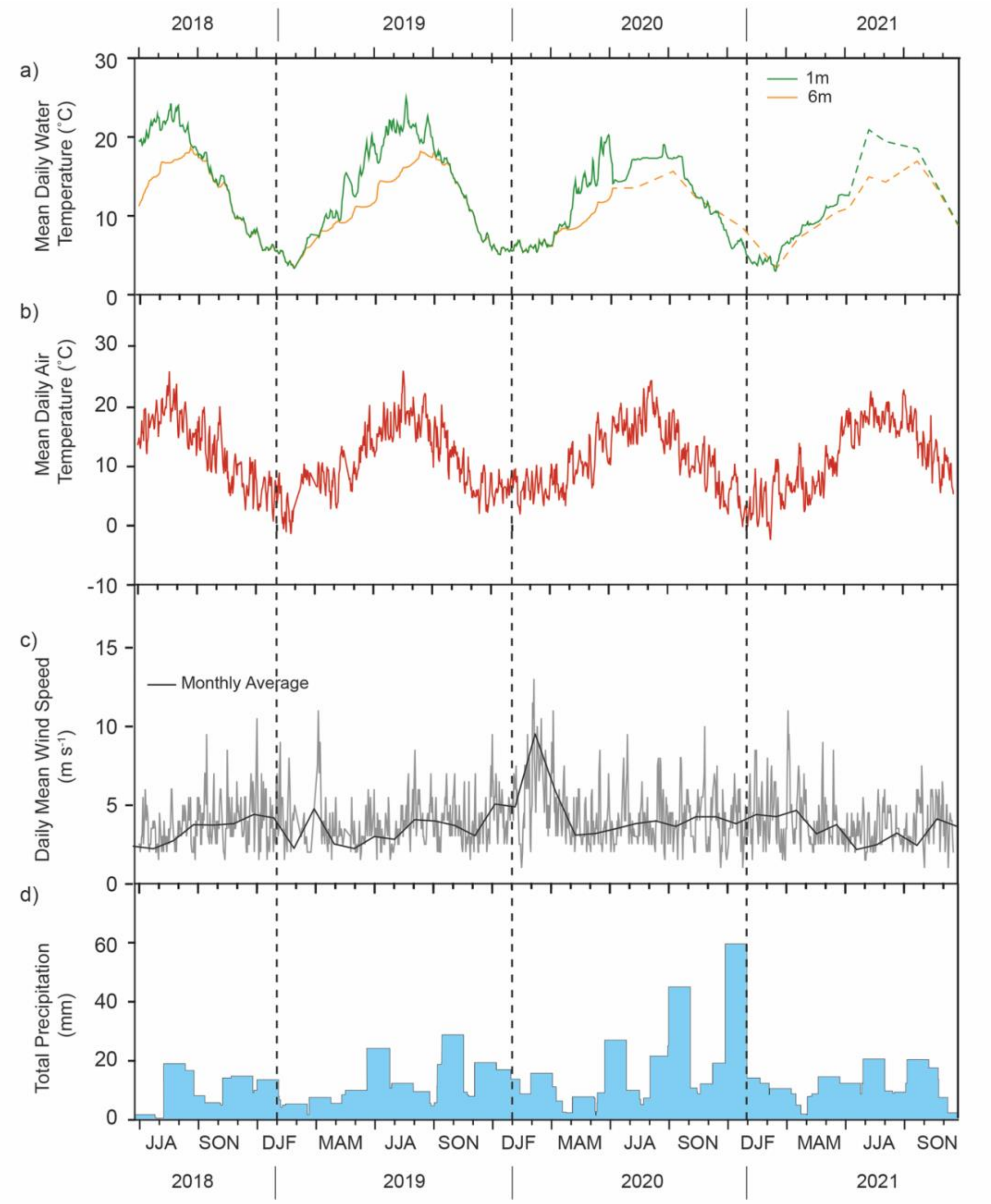

Figure 7. Thermistor timeseries from Diss Mere and meteorological information from the Tibenham Airfield meteorological station between June 2018 and November 2021. a: water temperatures recorded by the in situ thermistors at 1 m (green line) and 6 m (orange line) from Diss Mere, calculated at daily mean intervals. Dashed line indicates when thermistors stopped recording, and monthly temperature recordings are used in place. Stars indicate months where temperature data has been interpolated due to absent data. b: daily mean air temperature. c: daily mean wind speed (m s^{-1}) (grey line) and a monthly moving average (black line). d: total daily precipitation (mm). Vertical black lines indicate the beginning of a new calendar year.