Late Holocene changes in ultraviolet radiation penetration recorded in an East Antarctic lake

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Abstract

Late Holocene changes in the ultraviolet radiation (UVR) penetration in a lake in the Larsemann Hills (East Antarctica) were reconstructed using sediment core proxies based on fossil pigments (scytonemins and its derivatives) and siliceous microfossils. The influence of changes in lake depth on the UVR proxy was excluded by applying a correction, based on the non-linear relation between modern scytonemin concentrations and lake depth in a regional reference data set, and the record of past lake depths inferred using a diatom based transfer function in the sediment core. Results showed four well-defined maxima in the UVR proxy during the last 1600–1800 years, centred around 1820–1780, 1580–1490, 790–580 and 680–440 AD. Several mechanisms may account for these observed changes in UVR penetration, including past variability in cloud cover, atmospheric turbidity, ozone column depth, snow cover on the lake ice, DOM concentrations and lake-ice thickness and transparency resulting from temperature fluctuations. Although some gaps remain in our knowledge of scytonemin production in relation to the limnology of Antarctic lakes, the results highlight the importance and potential of the sediments in these highly transparent water bodies as archives of changes in past UVR receipt at the Earth’s surface.

Introduction

Since the discovery of the Antarctic spring-time ozone hole (Farman et al. 1985), there have been many studies dealing with the depletion of the ozone layer and the impact of increased ultraviolet radiation (UVR) transmission on the biota of high-latitude terrestrial and aquatic ecosystems (e.g., Newsham et al. 2002; Arrigo et al. 2003; Robinson et al. 2003). However, it is still unclear if the biota are experiencing higher UVR during recent times (i.e., since the discovery of the ozone hole; Farman et al. 1985) than they have in the period before instrumental measurements of ozone started (in 1957). Reconstructions of longer-term changes in UVR flux are only recently becoming available and are based on a combination of historical, indirect measurements (sunspots; Rozema et al. 2002) and direct proxy data, including flavonoids in pollen and p-coumaric acid content in sporopollenin (Rozema et al. 2001).

Paleolimnological approaches can also be used to reconstruct past UVR receipt. Recent studies in the Northern Hemisphere based on fossil pigments and diatoms in lake-sediment cores have, for example, revealed that historically the biological UVR penetration in boreal and Arctic lakes has sometimes been greater than during the recent
period of anthropogenic stratospheric ozone depletion (Leavitt et al. 1997; 2003; Pienitz and Vincent 2000). Changes in the UVR environment of these lakes were directly linked with in-lake processes, namely variations in the concentration of chromophoric dissolved organic matter (cDOM) instead of variations in UVR flux in the atmosphere (Pienitz and Vincent 2000; Leavitt et al. 2003). In East Antarctic lacustrine ecosystems, low turbidity and low concentrations of DOM in the lakes due to the absence of vegetation in the catchments, give rise to very transparent waters and very low vertical attenuation coefficients (Kd_{PAR} 0.18–0.47 m^{-1}, Kd_{UVRa} 0.21–0.28 m^{-1}, Kd_{UVRb} 0.27–0.35 m^{-1}; Ellis-Evans et al. 1998). The effect of cDOM on the UVR flux can thus expected to be relatively low in these lakes in contrast to lakes with extensive vegetation in the catchment area. For example, in studies of a representative selection of lakes in the Larsemann Hills it has been shown that a substantial percentage of the incident UVR (35–45%) can penetrate through the lake-ice. These data suggest that, in the absence of snow cover on the lake ice, at least 10% of the incident UVR can penetrate up to 3.5–6 m depth in ice-covered lakes (Ellis-Evans op. cit.). Collectively, this implies that these water bodies are particularly well-suited to the reconstruction of past atmospheric UVR flux, provided that past variations in lake-specific properties affecting the light climate, such as lake depth, snow cover, lake-ice properties and DOM concentrations, can be accounted for. The Antarctic region is particularly relevant to reconstructions of past UVR fluxes, as it is currently subject to the most severe ozone depletion on Earth during the spring-time ozone hole, which has resulted in an increase in UVR-B fluxes of 6–14% since 1980 (WMO 2002).

The aim of this study is to infer changes in past UVR penetration during the Late Holocene, using proxies based on fossil pigments and siliceous microfossils in a radiocarbon-dated sediment core from a shallow freshwater lake in the Larsemann Hills.

Site description

The Larsemann Hills consists of two main peninsulas, Stornes and Broknes, together with a number of scattered offshore islands in Prydz Bay (Figure 1). The hills are bounded by the continental ice sheet (polar plateau) to the south, which discharges west into the Publications Ice Shelf, and east into the Dâlk Glacier. An extensive description of the geology, physiography and climate of

![Figure 1. Map of the Larsemann Hills showing the location of Pup Lagoon.](image-url)
the Larsemann Hills is given in Hodgson et al. (2001).

Pup Lagoon (76°03′ E–69°25′ S) is a shallow lake, which became isolated from the sea at c. 2002–2307 cal yr BP (2150 ± 45 14C yr BP) due to regional isostatic processes (Verleyen et al. 2004a). The lake is located c. 100 m from the coast of Stornes and c. 2250 m from the continental ice sheet. The sill height is approximately 4 m above present sea level. An outflow stream is present, but was covered with snow and not active during the time of sampling (December 1997–January 1998). The lake has a maximum recorded depth of 4.6 m, which is approximately at the ecological threshold of 2-4 m where benthic cyanobacteria produce scytonemin, an extra cellular pigment produced in response to high UVR (Garcia-Pichel et al. 1993; Sihna et al. 2001), but deeper than the 2 m threshold of abundant scytonemin production, as recorded in a reference data set of 56 lakes from the region (Hodgson et al. 2004; Figure 2). The cyanobacterial flora consists mainly of filamentous *Leptolyngbya* species and the diatom flora consists almost exclusively of *Stauroforma inermis* (Sabbe et al. 2003, 2004). The pigment and dissolved organic carbon (DOC) concentrations in the water column are extremely low (0.7 and 2500 µg/l respectively), indicating a sparse phytoplankton community and limited re-suspension of benthic communities (cf. Vincent et al. 2004). This is in agreement with similar lakes in the nearby Vestfold Hills, where DOC is mainly autochthonous and extremely low all year round (i.e., below 3000 µg/l, with one exception in June of >4000 µg/l; Laybourn-Parry et al. 2004). The annual lake ice in the region is generally very transparent, because it lacks the air bubbles and inorganic occlusions which reduce light penetration (Ellis-Evans et al. 1998), as reported from multi-year lake ice in the Dry Valleys (McKay et al. 1994). Snow cover persists on some of the lakes in the Larsemann Hills in summer and can restrict light levels during spring when the growing season starts (and nutrient levels are relatively high; Ellis-Evans et al. 1998). In general, a moat forms around the Larsemann Hills lakes in late-December and in some lakes, the ice can fully break up by mid-January. The ice-free period typically ends after late February.

**Methods**

A 302 cm long sediment core was extracted from the deepest point of Pup Lagoon using a combination of a Glew gravity corer (Glew 1991) for surface sediments and a modified Livingstone corer (Wright 1967) for intermediate to supposed basal sediments. The core was photographed, macroscopically described, sectioned into 1 cm slices in the field and frozen at below −20 °C until analysis. The upper 120 cm of this core, which fall within the lacustrine sediment sequence (Verleyen et al. 2004a), was analysed in the present study.

![Figure 2](image.png)

*Figure 2.* Non-linear regression linking modern TScyt/TCC<sub>mod</sub> content to lake depth, based on 28 lakes from the Larsemann Hills (Hodgson et al. 2004). The lakes were grouped in lake-depth classes. Lake-depth and Tscyt/TCC<sub>mod</sub> in each class were subsequently averaged in order to reduce the influence of outliers.
Radiocarbon dating

Five samples from the upper lacustrine sediment sequence in the core were dated using AMS $^{14}$C by the UK Natural Environment Research Council Radiocarbon Laboratory (Hodgson et al. 2001). Samples were derived from discrete biological remains of cyanobacterial mats and their associated algal communities. Dates are reported as conventional radiocarbon years BP and as calibrated years BP (cal yr BP relative to AD 1950) using the Intcal 98 dataset (Stuiver et al. 1998) in the CALIB 4.4 programme (Stuiver and Reimer 2000). The calibrated dates in the text are reported as the minimum and maximum value (in cal yr BP) of the ranges, reported in Table 1. These ranges ensure that at least 95% (2 sigma) of the total area defined by the probability distribution is being enclosed. A linear sedimentation rate was assumed in order to interpolate ages between the radiocarbon dated samples; both the minimum and the maximum of the ranges of these calibrated dates were used; interpolated dates are rounded to the nearest 10 years.

Pigments analyses

Pigments were extracted from thawed bulk core sediment layers using acetone, methanol and water (80:15:5 v.v.) and sonication procedures described earlier (Hodgson et al. 1997, 1998; Leavitt and Hodgson 2001). High performance liquid chromatography (HPLC) was performed using a Kromasystem 2000 HPLC with a Kontron pump, auto sampler and diode array detector. Separation was achieved using a Waters Spherisorb ODS2 cartridge column (25 cm x 4.6 mm; 5 μm) protected by a Phenomenex Guard cartridge (ODS2; 3 x 4.6 mm; 3 μm). The 30 min gradient elution programme, using a solvent system comprising methanol, ammonium acetate, acetonitrile and ethyl acetate, is described elsewhere (Method B, Wright et al. 1991). We now recommend new extraction and analytical methods specifically developed for the examination of sedimentary deposits (Airs et al. 2001). Pigments were calibrated to reference cultures following SCOR protocols (Jeffrey et al. 1997) and expressed as organic-matter-specific concentration (ng/g TOC), because comparisons of long-term monitoring studies of lake plankton with the resulting varved fossil record indicates that this metric most accurately captures variations in algal abundance and community composition (Leavitt and Findlay 1994; Leavitt et al. 1997).

Microfossil analyses

Sub-samples for microfossil analysis in the core were taken at 1 cm intervals in the upper 20 cm and at 5 cm intervals from 20 cm to 120 cm. Organic matter was digested with $\text{H}_2\text{O}_2$ (30%) and $\text{CH}_3\text{COOH}$ (95%) following a slightly modified protocol by Renberg (1990). A solution of microspheres was added to permit absolute diatom counts (Battarbee and Kneen 1982) and Naphrax® was used as mounting medium. At least 400 valves (>2/3 intact) and/or chrysophyte

Table 1. AMS $^{14}$C dates and calibrated ages using Intcal98 in CALIB4.4 (Stuiver et al. 1998).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Conventional $^{14}$C age (yr BP ± 1σ)</th>
<th>Publication code</th>
<th>Sample Material</th>
<th>$^{14}$C enrichment (% Modern ± 1σ)</th>
<th>Carbon content (% by wt)</th>
<th>Calibrated age (cal yr BP)</th>
<th>area enclosed under probability curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>modern</td>
<td>AA-35718 C</td>
<td>C</td>
<td>104.45±0.51</td>
<td>21.3</td>
<td>modern</td>
<td>0.485</td>
</tr>
<tr>
<td>20</td>
<td>675±40</td>
<td>AA-35748 C DE</td>
<td>91.93±0.46</td>
<td>36</td>
<td></td>
<td>554–608</td>
<td>0.515</td>
</tr>
<tr>
<td>50</td>
<td>1270±40</td>
<td>AA-35749 C DE</td>
<td>85.39±0.44</td>
<td>26</td>
<td></td>
<td>1080–1112</td>
<td>0.068</td>
</tr>
<tr>
<td>100</td>
<td>1590±45</td>
<td>AA-35750 C DE</td>
<td>82.02±0.49</td>
<td>8.2</td>
<td></td>
<td>1353–1364</td>
<td>0.014</td>
</tr>
<tr>
<td>150</td>
<td>2150±45</td>
<td>AA-35751 O DE</td>
<td>76.53±0.41</td>
<td>13</td>
<td></td>
<td>2002–2183</td>
<td>0.681</td>
</tr>
</tbody>
</table>

Sample material: C = filamentous cyanobacteria, O = unknown organic fraction, DE = degraded.
stomatocysts were counted in each sample. Diatom taxonomy was mainly based on Roberts and McMinn (1999) and Sabbe et al. (2003). The surface area (\(\mu m^2\)) of each diatom was calculated using the BIOVOL ver. 2.1 software (Kirschtel 1996). Because the height of most frustules was difficult to measure, the surface area was used as an approximation for biovolume. Total diatom biovolume (TDB) in each sample was calculated as the product of total diatom surface area and total valve concentration (g\(^{-1}\) dry weight), divided by 2 to express abundance as whole cells (cf. Verleyen et al. 2004b).

**Processing of pigment and microfossil data**

In order to evaluate pigment preservation in the core, total diatom biomass (TDB) was compared with total diatom carotenoid concentration (TDC) in each sample (cf. Verleyen et al. 2004b). TDC was estimated as the sum of concentrations of the biomarkers fucoxanthin (and its derivatives), diatoxanthin and diadinoxanthin.

A proxy for photosynthetic active radiation (PAR) and UVR intensity was developed by dividing the total concentration of the photoprotective pigment zeaxanthin (Zea; Holt et al. 2005), present in cyanobacteria and green algae in the lakes in the Larsemann Hills, by total chlorophyll a concentrations (TChla) to exclude the influence of the organic-matter-specific concentration.

A proxy for light intensity in the UVR wavelengths was based upon the scytonemin concentration and its derivatives (TScyt). Scytonemin is a sheath pigment of certain cyanobacteria which absorbs in the UV spectrum of light and is formed as a protection against harmful UVR (Proteau et al. 1993; Brenowitz and Castenholz 1997). Scytonemin occurs in these Antarctic microbial mats in oxidized (yellow-green) and reduced (red) forms, both of which are effective photo-protectants, in vivo and (Castenholz and Garcia-Pichel 2000) and under laboratory conditions (Ehling-Schulz et al. 1997). Although scytonemin (\(\lambda_{max} = 252, 278, 300, 386\) nm; Proteau et al. 1993) absorbs both PAR and UVR, scytonemin is preferentially induced in laboratory experiments involving step-wise increases in UVR exposure, whereas it is not detected in cultures grown without UVR (Ehling-Schulz et al. 1997). The UVR proxy was obtained by dividing TScyt by the total cyanobacterial carotenoid concentration (TCC) in order to exclude the influence of the organic-matter-specific concentration and changes in the abundance between cyanobacteria and the co-dominant algal groups (e.g., green algae and diatoms). TCC was estimated as the sum of concentrations of the cyanobacterial biomarkers (including, where present, nostoxanthin, echinenone, canthaxanthin and anthaxanthin). A ratio with similar products has been shown to be correlated to the depth of penetration of UV radiation within lakes and has been successfully applied in sediment cores from lakes in the Northern Hemisphere (Leavitt et al. 1997, 2003).

Comparison between the UVR and UVR + PAR proxies throughout the sediment core, were used to estimate the relative changes in UVR in relation to total incoming light intensities. Coincident changes in both proxies are likely linked with changes in factors affecting both PAR and UVR penetration, such as changes in lake-ice properties, snow cover, DOM concentrations and cloud cover, rather than changes exclusively affecting the UVR penetration (e.g., ozone column depth).

Lake depth has previously been identified as the major environmental variable influencing the scytonemin concentration of in situ Antarctic cyanobacteria, probably mainly because the depth of the water column drives the light environment experienced at the bottom of the lakes (Hodgson et al. 2004). Therefore, historical changes in lake depth in Pup Lagoon were inferred with a weighted averaging partial least squares (WA-PLS) transfer function (Verleyen et al. 2003) using CALIBRATE 1.01 (Juggins and ter Braak 1997–2001). The transfer function is based on a reference data set of modern diatom assemblages and environmental data from 55 oligo-saline (salinity < 2\(^{o/0}\)) lakes in East Antarctica. The model has a jack-knifed \(r^2\) of 0.76 and a RMSEP of 0.22. The influence of lake depth on the UVR proxy was excluded by a simple correction based on a non-linear regression linking modern scytonemin: cyanobacterial carotenoids ratios (TScyt:TCC\(_{mod}\)) with lake depth in 28 lakes in the Larsemann Hills (Hodgson et al. 2004). The 28 lakes were grouped in eight lake-depth classes, namely 0–0.5, 0.6–1, 1.1–2, 2.1–3, 3.1–4, 4.1–5, 5.1–10 and 10.1–34 m. Lake-depth and Tscyt:TCC\(_{mod}\) in each class were subsequently averaged in order to reduce the influence of...
outliers. An exponential growth curve in Statistica 6.0 fitted the data well (i.e., 99% of the variance was explained). The resulting equation (TScyt/TCC_{mod} = 0.237317 + \exp (5.05566 - 2.6568*C0^{2.6568*lake depth}); Figure 2) was then applied to the diatom-inferred lake depth (calculated using the diatom-based transfer function (Verleyen et al. 2003)), to calculate the expected TScyt/TCC_{exp} ratio in each section of the core. The corrected TScyt/TCC_{corr} was subsequently obtained by subtracting the calculated TScyt/TCC_{exp} (using the transfer function and the modern relation between TScyt/TCC in the 28 lakes) from the measured TScyt/TCC (using HPLC) in each core level.

Salinity similarly influences scytonemin production as shown in laboratory experiments with a member of the *Chroococcidiopsis* genus (Dillon et al. 2002). Historical changes in lake-water salinity were reconstructed using a weighted averaging (WA) transfer function, which was based on the above-mentioned reference data set from 55 oligo-saline lakes, combined with a similar dataset from 56 meso- to hypersaline lakes in East Antarctic oases (Verleyen et al. 2003). The model has a jack-knifed $r^2$ of 0.83 and a RMSEP of 0.31.

All data were logarithmically transformed before correlation analyses in Statistica 6.0.

Results

Stratigraphy and paleo-environmental setting

Linear age depth models were applied to the minimum and maximum calibrated $^{14}$C dates from the Pup Lagoon core in order to interpolate the ages of major changes in the sediment proxies (Table 1, Figure 3). Lacustrine sediments in the Pup Lagoon core, deposited after isostatic uplift and subsequent isolation of the basin from the sea, are dominated by freshwater diatoms (e.g., *Stauroforma inermis* and *Pinnularia microstauron*) and consist of laminated undisturbed microbial mats (Verleyen et al. 2004a). Inferred lake depth and salinity, both known to influence scytonemin production (Dillon et al. 2002; Hodgson et al. 2004), were variable during the first ~450–390 years of the lacustrine phase (Verleyen et al. 2004a). Therefore, the UVR proxy was only considered in the core sections from c. 160–400 AD until the present. During this period, diatom inferred lake depth was very constant, with a maximum variation of less than 0.6 m (Figure 4). Diatom inferred salinity was also relatively constant throughout this period, with the exception of a brief marine incursion at 100 cm (Verleyen et al. op. cit.).

Changes in the UVR proxy

Overall, four well-defined maxima of higher TScyt/TCC_{corr} (and TScyt/TCC) are present at 6, 14, 65 and 85–90 cm depth and three moderately high values at 16–17, 30–35 and 100 cm, the latter is coincident with the rise in salinity associated with the brief marine incursion (Figure 4). The maxima correspond, after application of the age-depth model, with higher values of UVR penetration around 1820–1780, 1580–1490,

![Figure 3. Age depth model of the lacustrine section in the Pup Lagoon core; both maximum and minimum calibrated ages are shown.](image)
Figure 4. (a) Variations in inferred lake depth (m) using the diatom based WA-PLS transfer function (Verleyen et al. 2003) and TScyt/TCC, (b) Variations in inferred salinity (ppt) using the diatom based WA transfer function (Verleyen et al. op. cit.) and TScyt (ng/g TOC), y-axis of the latter on logarithmic scale, (c) variations in the UVR proxy (TScyt/TCCcorr) and the proxy for PAR + UVR (Zea/TChla), (d) variations in TDC/TDB (y-axis on logarithmic scale) and TScyt/TChla in order to evaluate preferential pigment preservation in the core.
790–580 and 680–440 AD, respectively (Figure 4). Periods of elevated light intensity can be inferred based on the Zea/TChla ratio between 80–100 cm (Figure 4). The proxy for UVR and the proxy for UVR + PAR follow a similar pattern between 0 and 4 cm and between 85 and 105 cm. Both proxies are weakly correlated \((r^2 = 0.4315, p < 0.005)\) but the correlation breaks down when the samples between 0 and 4 cm (past 110–135 years) and between 85 and 105 cm (310–680 AD) are excluded from the correlation analysis \((r^2 = 0.0177, p < 0.925)\).

Values in the UVR proxy \((TScyt/TCC_{corr})\) are negative in the majority of the core levels (Figure 4), implying that past TScyt/TCC in the Pup Lagoon core has, in general, been lower than the TScyt/TCC value in the modern lakes in the Larsemann Hills (Hodgson et al. 2004). This is probably due to the extensive snow cover in the catchment area and on the lake ice, which is situated on Stornes (Figure 1), where an ice dome and more extensive snow cover influence the local albedo and thus the duration and extent of summer melting of the lake ice and snow banks.

### Control of pigment preservation on the UVR proxy

Preferential pigment preservation is unlikely to be of major importance as evidenced by the comparison of the biovolume (TDB) of specific groups that leave reliable morphological fossils (diatoms, chrysophyte stomatocysts) against concentrations of their corresponding biomarker pigments (TDC), which provides an independent evaluation of pigment preservation (cf. Verleyen et al. 2004b). The ratio of TDC/TDB was subsequently calculated; no significant relation between the UVR proxy and TDC/TDB is evident \((r^2 = -0.0784; p < 0.626)\). Moreover, TScyt/TCC and TScyt/TChla show a similar trend and are positively correlated \((r^2 = 0.9011; p < 0.0001)\), which is an additional indication that the variation in the UVR proxy is probably not related to preferential pigment preservation (Figure 4).

### Discussion

Within the context of present-day global climate and ecosystem changes, it is of urgent importance to gain a better understanding on how UVR receipt has changed during the past. Reconstructions of past UVR are, for example, needed to evaluate the effect of ozone depletion on climate changes and vice versa, as it was recently shown that ozone depletion has had a distinct impact on climate in the stratosphere (Staehelin et al. 2001) and at the Earth’s surface (Gillett and Thompson 2003; Shindell and Schmidt 2004). Knowledge of the past UVR environment is also needed to establish a framework within which the effect of elevated UVR on organisms living under the Arctic and Antarctic spring ‘ozone holes’ can be evaluated (Leavitt et al. 2002). In aquatic ecosystems in particular, the interactive effects of global change on the biogeochemistry of DOM, DOM-degrading acidic precipitation, and ozone depletion on UVR penetration (e.g., Zepp et al. 2003) are believed to have a significant impact on aquatic ecosystem integrity and function (e.g., Schindler 1998, 2001).

We developed a proxy for UVR using fossil pigments and diatoms, which is likely to be independent of in-lake properties, such as changes in water depth and variations in pigment preservation conditions. By combining pigments and diatoms, rather than using them separately, variations in lake depth were partialed out using a diatom based transfer function (Verleyen et al. 2003) and a pigment calibration dataset (Hodgson et al. 2004). In the Pup Lagoon core this correction was optional because modelled lake depth was virtually constant and in any case deeper than the 2 m depth threshold, at which an exponential increase in TScyt/TCC occurs in response to increasing UVR stress in the modern lakes in the region (Hodgson et al. 2004; Figure 2). The original data TScyt/TCC and the corrected data TScyt/TCC_{corr} thus follow a similar pattern in this section of the core (Figure 4). As there is no significant relation between TDC/TDB and the UVR proxy and as TScyt/TChla and TScyt/TCC are highly correlated, the UVR proxy is also unlikely to be mainly related to pigment preservation conditions.

Community structure and organisation of the microbial mats are similarly unlikely to be the overriding factors in determining the changes in the proxy, because changes in cyanobacterial species composition are expected to be induced by environmental changes. Lake-water depth was shown to be the structuring environmental factor
of the cyanobacterial communities in the modern lakes in the Larsemann Hills (Sabbe et al. 2004). No evidence for significant changes in lake-water depth is present in this section of the core (Figure 4), implying that changes in cyanobacterial community structure are similarly unlikely. In some cases, microbial mats can colonise the bottom of the lake ice. This change in habitat type of the microbial communities is however probably of little importance for the scytonemin concentration in the sediments, because the under-ice mats become in general entrained in the mixing layer during the ice-free season in summer, deposited on the lake shore and blown away. All this implies that changes in the light proxies in the majority of the core are probably not related to changes in the community structure of the biota living in the lake. In contrast, at 100 cm, changes in the environmental setting of the lake and the cyanobacterial community structure might be influencing the UVR proxy. Here, a brief marine incursion (and salinity rise detected by fossil diatom analysis) is expected to have directly affected the biota present in the lake and possibly the scytonemin production, which has been shown to be inhibited by increasing salt concentrations (Dillon et al. 2002). Therefore, changes in the light proxies in this core section might be related to different factors than in the rest of the core.

Overall, four well-defined maxima of elevated UVR penetration can be identified in the core, dated at 1820–1780, 1580–1490, 790–580 and 680–440 AD, which are likely to be independent of the above-mentioned processes. Several mechanisms may explain these maxima, including within-lake processes and processes affecting atmospheric UVR transmission. Changes in snow cover and lake-ice properties are likely to be the most important within-lake factors. In contrast, changes in DOM concentrations are expected to be of minor importance, because DOM and lake-water pigment concentrations are low (and hence cDOM), and water transparency is high, as previously reported in similar lakes in the region (Ellis-Evans et al. 1998). A first attempt was made to differentiate changes in UVR from variations in total incoming light (UVR + PAR). Proxies for UVR and for UVR + PAR co-vary in some parts of the sediment core, namely between 0 and 4 cm and between 85 and 105 cm, implying that factors influencing the total light climate in the lakes are likely to be most important in these sections of the core. These factors include variations in cloud cover and changes in lake-specific properties such as lake-ice thickness, transparency and duration of snow and ice cover. The proxy for PAR + UVR is furthermore extremely high between 80 and 100 cm, which corresponds to the period between 390 and 710 AD, coincident with a climate optimum detected in Antarctic ice cores (e.g., Masson et al. 2000). Higher temperatures during this period might possibly have lead to an earlier start of the snow- and ice-free season of the lakes in the Larsemann Hills, which in turn would have influenced the benthic light climate. The high UVR penetration between 680–440 AD (85–90 cm) might thus be related to changes which affect the total light climate. Throughout the rest of the core, both proxies are weakly correlated, and the correlation breaks down when the above-mentioned sediment layers are excluded from the analysis. This is likely to imply that factors other than changes in lake-ice properties, DOM concentrations and cloud and snow cover are driving variations in the UVR proxy through the majority of the sediment core. We will consider these below.

Variations in atmospheric transmission are a possible mechanism for the inferred changes in UVR penetration, which are a combined function of cloud cover, atmospheric turbidity, and stratospheric ozone column depth and its interactions with cosmic rays (Haigh 2003). High surface albedo (for example from extended snow and ice-cover which have albedos ranging from 75 to 100% (Blumthaler and Webb 2003)) can additionally moderate attenuation by cloud cover, and increase surface UVR, as a result of multiple scattering between the surface and cloud base. This effect is of particular importance at high latitudes where ice and snow may persist during the summer months (Nichol et al. 2003).

Changes in ozone concentration in the atmosphere depend both on atmospheric dynamics and chemistry (see Staehelin et al. 2001 for a review). Variations in solar output, including changes in the solar flux in different regions of the light spectrum (e.g., ratios of UVR-A to UVR-B) may for example lead to changes in ozone column depth and may thus affect UVR at the Earth’s surface (Rozema et al. 2002). The relationship whereby reduced solar activity leads to increased
UVB at the Earth’s surface can be summarised as follows (cf. Reid 1999). Oxygen in the stratosphere absorbs short wavelength solar radiation (UVC) to form oxygen atoms, which combine with additional O_2 to produce ozone (O_3). During solar minima, UVC radiation is low (Rozema et al. 2002), leading to a decline in stratospheric ozone production, which in turn leads to an increase in damaging UVB reaching the Earth’s surface directly. The changing thickness of the ozone layer may, in addition, indirectly influence the light climate at the Earth’s surface through atmospheric processes. Less ozone results in less absorption of heat in the stratosphere, which affects stratospheric and tropospheric circulation patterns (van Geel et al. 1999; Hartmann et al. 2000; Haigh 2003). Changing tropospheric circulation patterns may, for example, increase the stability and persistence of the Polar Vortex (Schoeberl and Hartmann 1991). A more stable and longer persisting Polar Vortex, a longer persisting ozone hole (Staehelin et al. 2001).

Interestingly, several of the periods of high UVR coincide (within the error of the chronological model) with solar minima as reconstructed from historical records and proxy data. Minima of solar activity are found at the Dalton Minimum (1795–1820 AD), Maunder Minimum (1645–1715 AD), Sporer Minimum (1416–1534 AD), Wolf Minimum (1282–1342 AD) and Oort Minimum (1010–1090 AD; Camuffo et al. 2000) and as recently compiled by Pang and Yau (2002) based upon Asian historical records, around c. 580–800, 400–500 and 200–300 AD. This may possibly imply that changes in UVR are to some extent related to changes in solar activity, yet this link is far from certain. A higher resolution study with sufficient radiocarbon dates could potentially be compared with records of past temperature change and solar activity (e.g., the cosmogenic nuclides ^{14}C and ^{10}Be in ice cores; Bard et al. 1997; Bond et al. 2001). Such approaches would permit us to test hypotheses on the influence of solar activity, and other competing factors influencing the light climate in Antarctic lakes.

What is also required is quantitative information on the effect of interacting environmental variables on scytonemin production in the lakes. Possible factors influencing annual scytonemin production (other than incoming light) are the interaction in time between the start of the growing season, when nutrient levels are relatively high, and factors controlling the light climate throughout the growing season. The light climate is a result of the incoming light intensity and its spectral composition and the complex interaction between the time of candling and melting of the lake ice, the start and duration of the snow-free season and changes in DOM concentration and composition. Although more research is needed concerning some of these uncertainties about scytonemin production, the results here highlight the potential of East Antarctic lake sediments for the reconstruction of changes in past UVR penetration.

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