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Causes and effects of long periods of ice cover on a remote high Alpine lake

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ABSTRACT

The response of the physical and chemical limnology of Hagelseewli (2339 m a.s.l.) to local meteorological forcing was investigated from 1996 to 1998 using an automatic weather station, thermistor chains, water samples and sediment traps. On-site meteorological measurements revealed the paramount importance of local topographic shading for the limnology of the lake. A high cliff to the south diminishes incident radiation by 15% to 90%, resulting in a long period of ice cover. Hence, the spring and summer seasons are extremely condensed, allowing only about 2 months per year for mixing, oxygen uptake, nutrient inflow, water exchange and phytoplankton growth. Regular measurements of water temperature, chemistry and diatom composition show that Hagelseewli responds very rapidly to changes in nutrient concentrations and light conditions. This response is restricted mainly to an extremely short productivity pulse, which takes place as soon as the lake is completely free of ice. Ice-free conditions are indicated by the occurrence of planktonic diatoms. In contrast to most low-altitude lakes, maximum productivity occurs in the middle of the water column (6-9 m), where first light, and then soluble reactive phosphorus (SRP), are the limiting factors. During the period of thawing, large amounts of ammonium enter the lake. Nevertheless, allochthonous nutrient input is not important because SRP, the limiting nutrient for algal growth, originates from the sediments. Water chemistry data and data from sediment traps show that, although autochthonous calcite precipitation does occur, the calcite crystals are redissolved completely in the bottom waters during the extended period of ice cover. Thus, the most important factor for changes in the nutrient budget, primary production and preservation of calcite is the bottom water oxygen status, which is governed by the occurrence of an ice-free period. We hypothesise that the duration of the ice-free period is of minor importance for the generation of particles that might be archived in the sedimentary rec??ord as proxy climate indicators. Such particles are produced mainly during times of peak primary production, which last only for a few days before production decreases again to very low levels. Therefore, with respect to the type of climatic signal that might be recorded in Hagelseewli, we presume that what is most likely to be archived in the sedimentary record is the mere occurrence, rather than the duration of the ice-free period.

Key words: high Alpine lakes, ice cover, meteorological data, water chemistry, diatoms, sediment traps

1. INTRODUCTION

The study of abiotic and biotic responses to climate change is of great importance for the assessment of possible risks associated with climate change. Biotic responses to climate change, as well as natural climate variability in the past, may be assessed by studying environmental archives such as lacustrine sediments. Remote lakes at high altitudes or latitudes are considered to represent the most pristine natural environments existing in Europe today. Their sediments show only a low level of human influence (such as land use) and should, therefore, reflect the direct and indirect effects of climate on biotic and abiotic factors. However, as many factors involved in the transfer of climatic signals from the atmosphere via the water column to the sediments are not yet fully understood, these processes need to be studied in more detail. The present study gives an overview of the physical, chemical, and biological processes involved in mediating the reactions of a high-altitude lake to climatic variability. In particular, the importance of ice cover for the limnology of high-altitude lakes is discussed.

In comparison to most other remote high Alpine lakes investigated within the framework of the interdisciplinary project MOLAR (MOuntain LAke Research), Hagelseewli (2339 m a.s.l.) experiences unusual climatic conditions. After 28 months of monitoring local meteorology and limnology, we characterize these conditions and discuss how they affect the limnology of the lake. The translation of water column processes into sedimentary signatures is accomplished by the formation of particles within the lake and the lake catchment which are then preserved in the sedimentary record. The analysis of sediment trap data yields information about how changes in limnological conditions can potentially be archived in the sediments of the lake. These sediments are the subject of the palæolimnological studies

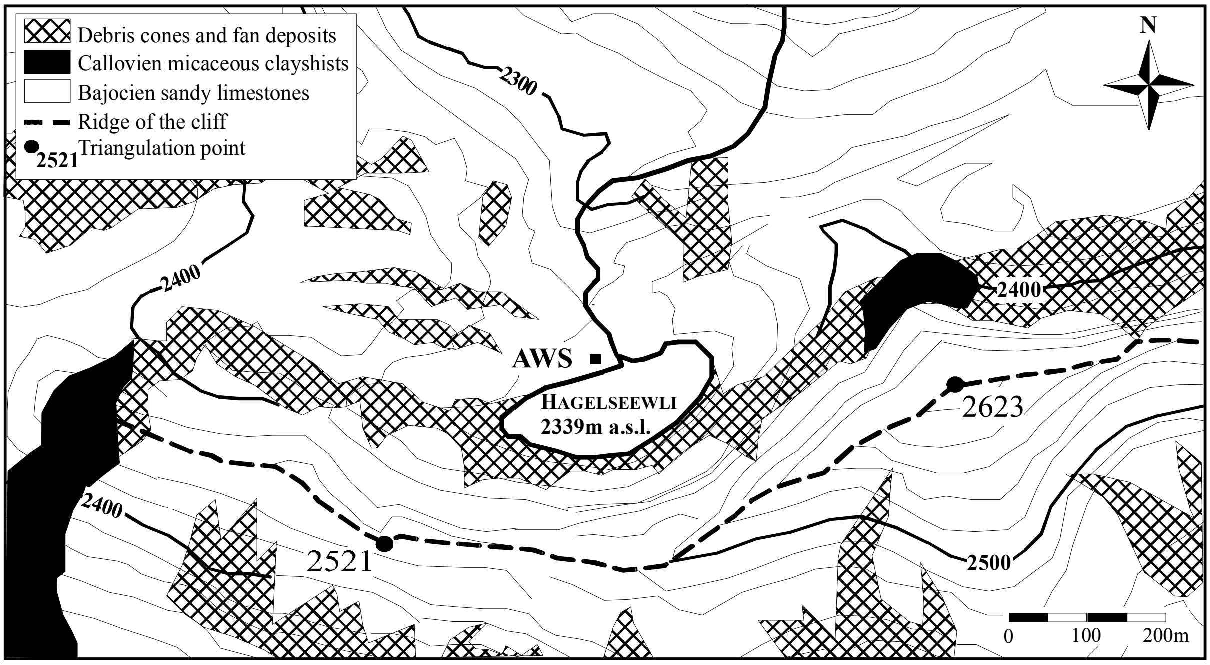

Fig. 1. Topographic and simplified geological map of the Hagelseewli catchment area, showing the high cliff face to the south. All altitudes and contours are given in m a.s.l. The position of the automatic weather station (AWS) is indicated by a black square.

described by Lotter *et al*. (2000, this issue). A preliminary analysis of the first part of the data discussed in this paper has been presented by Goudsmit *et al*. (2000).

2. SITE DESCRIPTION

Hagelseewli (46°40'N, 8°02'E) is located at 2339 m a.s.l. in a north-facing corrie of the Bernese Alps, Switzerland (Fig. 1). It is an elliptically-shaped lake with a maximum depth of 18.5 m and a surface area of only 24,000 m^2 (see Lotter *et al*. 2000, this issue, for more details). The lake catchment (0.3 km^2) is dominated by a high cliff face to the south of the lake (Fig. 1). The area to the north is relatively flat, with alpine meadows and snow-bed vegetation. The lake is supplied with water mainly by diffuse flows from the cliff face and from the surrounding flatter land. There is only one minor inflow at the western shore and a small outflow to the north.

Geologically, Hagelseewli is situated in middle Jurassic (Bajocien/Callovien) sedimentary rocks of a Helvetic Alpine nappe (Axen-Decke), that represent the northern Tethian margin (Fig. 1). In the Hagelseewli region, synclines consisting of Callovien micaceous clay schists (Erzegg Formation) were squashed between isoclinal anticlines formed by Bajocien sandy limestones (turbidites) during Alpine orogeny (Günzler-Seiffert 1938; Pilloud 1990). In the lake catchment only the latter unit outcrops to the surface. The cliff to the south (Fig. 1) is made of clayey, schistous, brittle marls interbedded with fine-grained siliceous limestone beds (thickness: 20-30 cm) with a $CaCO_3$ content of 14% and 40%, respectively. The tectonic situation of Hagelseewli in a narrow syncline indicates that the lake basin was carved into the softer micaceous clay schists by glaciers during the last glaciation. These rocks outcrop 200 m to the east and 500 m to the west of the lake (Fig. 1), and probably also below the lake bottom.

3. MEASUREMENTS AND METHODS

Seasonal meteorological variability at Hagelseewli was assessed on the basis of measurements made from 16 June 1996 to 21 September 1998 using an Aanderaa 2700 automatic weather station (AWS) installed on a slight rise about 5 m from the north shore of the lake (Fig. 1). Air temperature, solar and net radiation, relative humidity, precipitation, wind speed and wind direction were measured every 10 min at the standard meteorological height of 10 m. In the case of air temperature, solar radiation and wind speed, duplicate sensors allowed data quality to be checked; in all three cases, this was found to be satisfactory. As the automatic rain gauge on the AWS was unheated and therefore did not record precipitation at negative air temperatures, it was supplemented by a totalising rain gauge, installed on 17 September 1996, which allowed the total precipitation falling between sampling dates to be determined regardless of air temperature.

Lake water temperatures were measured quasi-continuously at a resolution of 0.023 K and a sampling interval of 30 minutes using two thermistor chains (Aanderaa, Bergen, Norway), each consisting of 11 evenly-spaced sensors. To avoid disturbing the sediment, the two thermistor chains (0.5 to 5.5 m and 0.5 to 15.5 m) were not moored to the lake bottom, but were suspended from two separate sets of floats attached to a positioning rope spanning the lake from shore to shore. Additionally, the surface temperature was measured every 15 min by a small Minilog thermistor (Vemco Ltd., Shad Bay, Nova Scotia, Canada) with a resolution of 0.1 K, attached to a surface buoy.

Information on the presence or absence of ice on the lake was noted during each visit to the lake for sampling purposes, and additional information relevant to the timing of freezing and thawing was obtained from the thermistor chain measurements.

To study how lake chemistry and biological communities respond to changes in ice cover, light penetration, temperature, stratification and mixing, essential water column data were collected at bi-weekly to monthly intervals during the ice-free season, and at bi-monthly intervals during the period of ice cover. Physical, chemical and biological analyses were carried out on water samples collected at 3 m intervals from 0 to 15 m depth using Niskin bottles. All chemical parameters were determined according to standard procedures (DEW 1996). The following parameters were measured: temperature, salinity (as electrical conductivity), pH, alkalinity, and the concentrations of NH_4^+, NO_3^-, NO_2^-, SiO_2, P-PO_4 (soluble reactive phosphorus = SRP), total phosphorus (TP), dissolved phosphorus (DP), dissolved organic carbon (DOC), Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe(II)/Fe(III), Mn(II)/Mn(IV), Cl^-, SO_4^{2-}, O_2, phytoplankton, zooplankton and chlorophyll-*a*. Diatoms in the water column were analysed based on the monthly water samples by integrating over the whole water column; in addition, analyses were carried out of the diatoms found in sediment traps and in the surficial sediments (Lotter & Bigler 2000).

Two moored, open sediment traps (EAWAG-130) with an active surface area of 130 cm^2 were installed at 2 m and 17 m water depth. Between June 1996 and September 1998, 10 samples were collected during both the ice-free and ice-covered periods to assess the total sediment flux as well as the seasonal variability in the composition of particles and diatoms in the water column.

Several sediment cores were taken with a 63 mm diameter gravity corer (Kelts *et al.* 1986). The uppermost 37 cm of sediment was sub-sampled at 5-mm intervals to provide an average sample resolution of 5-10 y. The sediment chronology was assessed using ^{137}Cs and ^{210}Pb dating. See Lotter *et al.* (2000, this volume) for a discussion of the sediment analysis.

4. RESULTS AND DISCUSSION

4.1. Local climate and topographic shading

The meteorological data obtained by the AWS (Figs 2a-h) give a good overview of the seasonal variability in the local weather conditions prevailing at Hagelseewli. As would be expected in view of its altitude, coupled with the fact that it is shaded from the sun by the high cliff to the south (Fig. 1), these conditions are generally harsh. Daily mean air temperatures (Fig. 2a) can fall below 0 °C even in summer, and monthly mean temperatures lie below 0 °C during about 6 months of the year. During the period of observation, daily mean air temperatures varied between –15 °C and +16.3 °C. The latter value, which occurred during the unusually warm summer of 1998, is, however, unlikely to be representative of the lake during the recent past; maximum daily mean air temperatures in 1996 and 1997, which did not exceed 12.5 °C, are likely to be more representative. Monthly mean air temperatures at Hagelseewli from 1961-90, the standard IPCC 30-y baseline period, were estimated by correcting the air temperatures measured at the nearby (15 km) Jungfraujoch meteorological station to the altitude of the lake using surface air temperature lapse rates calculated from data measured at 8 high-altitude meteorological stations in the northern Swiss Alps (Tab. 1). Over this 30-y period, mean monthly air temperatures were estimated to range from –7.5 °C in January to +7.4 °C in July, with an annual mean of –0.4 °C. A comparison of the air temperatures measured by the AWS at the lake with those expected on the basis of the calculated high-altitude lapse rates revealed the discrepancy to be extremely slight, implying that local topographic shading has essentially no effect on the local air temperature at the lake, although it has a considerable effect on the lake surface water temperature (Livingstone *et al.* 1999). This is presumably because the large-scale movement of air masses reduces local control of air temperature to insignificance, whereas the temperature of the "trapped" lake water is controlled much more by the local radiation balance.

Tab. 1. Monthly mean air temperatures at Hagelseewli (1961-90; AT) with corresponding standard deviations (±σ), estimated from the air temperature measured at Jungfraujoch (3580 m a.s.l.) corrected to the altitude of Hagelseewli (2339 m a.s.l.) using the high-altitude lapse rates listed. These lapse rates, which are based on 25 y (1972-97) of monthly mean air temperature data from 8 high-altitude (>1500 m a.s.l.) meteorological stations in the northern Swiss Alps, are largely unaffected by winter temperature inversions.

	Lapse rate (°C km^{-1})	AT ±σ (°C)
January	5.22	-7.5 ±2.4
February	5.48	-7.4 ±2.4
March	6.20	-5.6 ±2.1
April	6.38	-3.1 ±1.8
May	6.47	1.3 ±1.5
June	6.64	4.9 ±1.2
July	6.68	7.4 ±1.3
August	6.61	7.3 ±1.1
September	6.33	5.4 ±1.6
October	5.87	2.1 ±2.3
November	5.42	-3.4 ±1.8
December	4.99	-6.3 ±2.2
Annual mean	6.02	-0.4±0.6

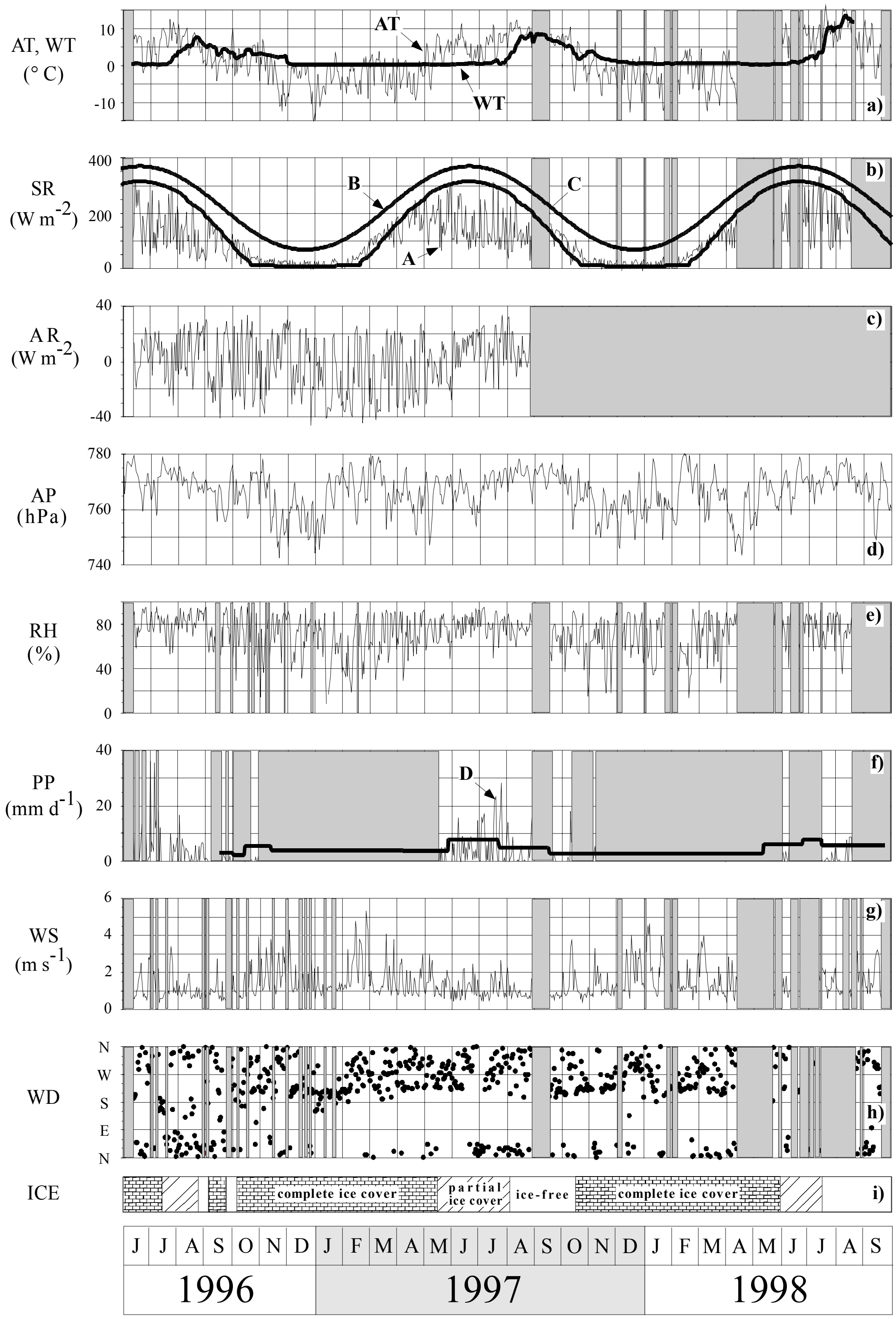

Fig. 2. Meteorological measurements and observations of ice cover made at Hagelseewli, June 1996 – September 1998. The measured variables were: **a)** air temperature (AT) and water temperature at 0.5 m depth (WT); **b)** short-wave solar radiation (SR); **c)** net long-wave atmospheric radiation (AR); **d)** air pressure (AP); **e)** relative humidity (RH), **f)** precipitation (PP); **g)** wind speed (WS); **h)** vector-averaged wind direction (WD); and **i)** ice cover (ICE). In b), in addition to the measured data (A), the calculated clear sky solar radiation is shown, unmodified (B) and modified by the local skyline (C). In f), both daily measurements from the automatic weather station (D) and longer-term measurements from the totalising rain gauge (E) are presented. The grey panels indicate periods of no measurement.

Daily mean values of solar radiation incident on the lake (Fig. 2b) can vary from less than 5 W m^{-2} on some winter days to over 300 W m^{-2} on cloudless summer days. Livingstone *et al*. (1999) and Goudsmit *et al*. (2000) explained the long period of low solar radiation at Hagelseewli in winter as the result of shading by the high cliff face to the south, which prevents direct solar radiation reaching the lake at all from the end of October to the end of February (Fig. 3). This was investigated quantitatively by modelling the clear sky solar radiation at the latitude and altitude of Hagelseewli at 10-min intervals for each day of the year, based on the approach described by Brock (1981), and using the atmospheric transmission coefficients of Hottel (1976). A modification to this approach allowed the influence of the local topography on the clear sky incident solar radiation to be calculated. As can be seen in figure 2b, the local topography – essentially the high cliff face to the south – is predicted to cause a substantial diminution in the amount of solar radiation which can potentially be received by the lake. This diminution (between 55 W m^{-2} and 125 W m^{-2}, depending on the season) corresponds to about 15% in summer, but can be as much as 90% in late autumn and winter, when the sun is below the local skyline and only diffuse solar radiation (with a predicted daily mean of <15 W m^{-2} in winter) can reach the lake. The good agreement between the predicted seasonal variation of the clear sky radiation and that of the measured solar radiation is apparent in figure 2b; the modelled curve closely follows the envelope of the measured data. Deviations between the computed clear sky solar radiation and measured solar radiation are due mainly to cloud cover. In summer, cloud cover causes a reduction in incident solar radiation because of absorption, reflection and scattering; in winter, however, when the sun is below the local skyline, increased scattering in response to cloud cover results in an increase in incident diffuse radiation on the lake to above the predicted values (this tendency can be enhanced by the re-reflection of radiation reflected upwards by snow in the surrounding landscape). The presence of the high cliff face to the south of the lake is thus of paramount importance for the radiation balance at the surface of Hagelseewli in winter.

The daily mean net atmospheric (long-wave) radiation at the site (Fig. 2c) ranges from –45 W m^{-2} to +34 W m^{-2}. Although the net long-wave radiation shows a tendency to be negative in winter and positive in summer, seasonal variation about the overall mean of –2 W m^{-2} (July 1996 – June 1997) is slight, with monthly mean values ranging from –15 W m^{-2} (January 1997) to +13 W m^{-2} (August 1996). The net long-wave atmospheric radiation exceeds or is comparable in magnitude to the incident short-wave radiation only from October to February, during the period of complete ice cover. During the open-water period the incident short-wave radiation dominates, so that the net long-wave radiation is unlikely to play an important role in determining the heat budget of the lake. The emission of long-wave radiation from the cliff face to the south and from the other surrounding terrain higher than the lake surface is likely to enhance the net long-wave radiation measured at the site, but the magnitude of this enhancement is difficult to estimate.

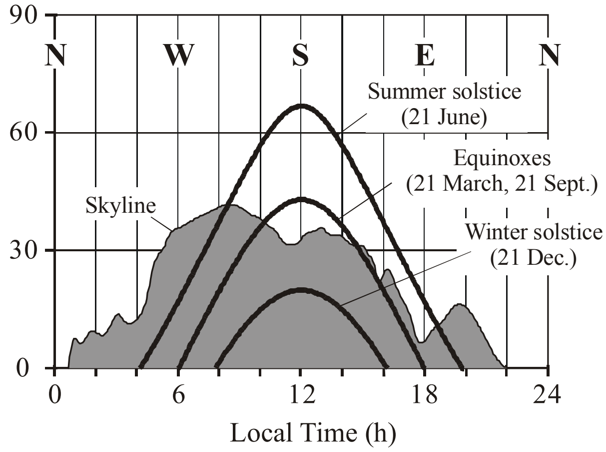

Fig. 3. Local skyline at Hagelseewli (shaded grey). The path of the sun is shown at the solstices and equinoxes. Note that Hagelseewli does not receive direct solar radiation during at least 2 months before and 2 months after the winter solstice.

Air pressure data were available from Jungfraujoch meteorological station for the entire period during which the Hagelseewli AWS was recording. Corresponding air pressures at Hagelseewli (Fig. 2d) were calculated from these data using the usual exponential barometric formula. (The mean air temperatures between Jungfraujoch and Hagelseewli required by this formula were obtained from the Jungfraujoch air temperatures and the high-altitude lapse rates listed in table 1). Based on data from 1 January 1996 to 31 December 1998, the air pressure at the lake varies from a mean of 762.9 hPa in winter to 770.3 hPa in summer. The annual mean air pressure at the lake (± one standard deviation) is estimated to be 765.5 ±7.5 hPa. Applying the empirical formula of Bührer and Ambühl (1975), this implies a saturation O_2 concentration at 4 °C of 9.9 ±0.1 g O_2 m^{-3} for Hagelseewli.

Relative humidity (Fig. 2e), although very variable in the short term, exhibits a tendency to substantially higher values in summer than in winter. Based on all available AWS data, the mean relative humidity ranges from 63% in winter to 79% in summer, with values of 68% and 73% for autumn and spring, respectively. The annual mean is 72%.

Based on the period 17 September 1996 to 21 September 1998, a value of 1658 mm was obtained from the totalising rain gauge for the mean annual precipitation at Hagelseewli (Fig. 2f). This compares well with the mean annual value (1970-91) of 1740 mm y^{-1} given by Wolfensberger (1994) for the precipitation at First, located at 2170 m a.s.l. in a neighbouring valley 2 km to the south-east. The AWS measurements show that during periods of high rainfall, over 30 mm of rain can fall within one day.

Wind conditions (Fig. 2g) can vary from calm to fairly stormy, with daily mean wind speeds upwards of 5 m s^{-1} and individual wind gusts exceeding 25 m s^{-1}.The overall mean measured wind speed was 1.44 m s^{-1}. The prevailing wind directions (Fig. 2h), assessed in terms of vector-averaged daily means, are west (39%) and north (34%). Despite the presumed sheltering effect of the cliff, winds from the south are also common (23%); east winds, however, are rare (4%).

4.2. Lake ice and epilimnetic temperatures

Because of the low prevailing air temperatures and the lack of direct solar radiation due to the local topography, Hagelseewli is completely or partially ice-covered during most of the year (Fig. 2i), and in fact aerial photographs taken every five years during the month of August suggest that the lake often remains frozen throughout the entire year (e.g. 1946, 1981, 1987). During the 1996-98 observation period, there were two main periods of complete ice cover, both of which lasted about 7.5 months and during which ice thicknesses of up to 2 m were encountered. The thawing of Hagelseewli is a complex process, made very heterogeneous by the fact that, because of the presence of the cliff face to the south, the northern part of the lake receives more solar radiation than the southern part, and also receives this radiation earlier in the year. Thawing thus begins along the northern shore, and open water here can co-exist with a thick sheet of ice (>1 m) overlain with snow in the centre of the lake, and especially along the southern shore, for over 2 months. The ice-free period is correspondingly short. In 1997 and 1998, the lake was completely ice-free for slightly longer than 2 months. In 1996, the ice-free period was confined to two brief periods with a total duration of two or three weeks, separated by a period in which the lake was covered by a layer of black ice only 2-3 cm thick. The duration of the period of complete or partial ice cover suggests that climatic influence on this lake is more likely to be indirect, i.e. mediated by ice cover, than direct.

Livingstone *et al*. (1999) have shown that surface water temperatures in Hagelseewli tend to be decoupled from the air temperature for much of the summer, in contrast to other neighbouring lakes which are not subject to the same degree of local topographic shading. This has implications for palaeolimnological studies: climatic effects on the ecology of Hagelseewli during the ice-free period may possibly be affected more by the air temperatures prevailing during the thawing of the ice than by those prevailing during the summer itself.

To compare air temperature with water temperature here, only the measurements from the uppermost thermistor, installed 0.5 m below the lake surface and assumed to reflect the epilimnetic temperature of the lake, will be briefly described (Fig. 2a). The complete water temperature profile in Hagelseewli is discussed below and has already been described by Goudsmit *et al*. (2000). Extensive information on the surface water temperature of the lake has been given by Livingstone *et al*. (1999). The maximum epilimnetic temperatures attained each year were 7.6 °C on 21 August 1996, 8.9 °C on 27 August 1997 and 13.5 °C on 11 August 1998. During the period previous to the maximum, epilimnetic temperatures were always considerably lower than the corresponding air temperatures, presumably to a large extent because of the effect of local topographic shading and partial ice cover (cf. Livingstone *et al*., 1999; Goudsmit *et al*. 2000). The epilimnetic temperature exceeds 1 °C only during about 4-5 months of the year. It rose above 1 °C on 24 July 1996, 17 July 1997 and 21 June 1998, and fell below 1 °C on 1 December 1996 and 2 December 1997. The effects of the exceptionally warm summer of 1998 are therefore noticeable not only in increased temperatures of the air and the lake epilimnion, but also in the extended duration of the period during which the epilimnetic temperature exceeded 1 °C.

In general, epilimnetic temperatures can be thought of as representing a smoothed response to atmospheric forcing. During the open-water phase, the epilimnetic temperature was found to exhibit a similar temporal structure as the mean of the previous 31 d of air temperature. This implies the existence of a time lag of about 15 d between air and water temperatures, which, along with the effects of partial ice cover, results in a tendency for the epilimnion of Hagelseewli to be colder than the overlying air from the time of thawing to the time the epilimnetic temperature reaches its maximum in August, but warmer thereafter.

4.3. Profiles of water temperature, O_2 and pH

The water temperature profiles (Fig. 4a) reflect the fact that the water body is essentially decoupled from atmospheric influences during most of the year as a result of complete or partial ice cover. Only during the very short period when the lake is completely ice-free does surface water warming occur, but this is much less pronounced than would be expected due to shading by the high cliff (Livingstone *et al*. 1999). Warmer (>6 °C) surface water in summer reaches down to a depth of 2-9 m. At the end of the ice-free period a temperature anomaly starts to develop, i.e., the warmest water is found between 4 m and 14 m depth, sandwiched between cooler water above and below. The reason for this anomaly is the relatively strong salinity gradient, which prevents the mixing of deep water and surface water. During the period of ice-cover, deep water is replaced by cool dense water that sinks to the bottom along the slopes (Goudsmit *et al*. 2000). Nevertheless, the temperature anomaly persisted throughout the entire ice-covered period in 1996/97, decaying only during the

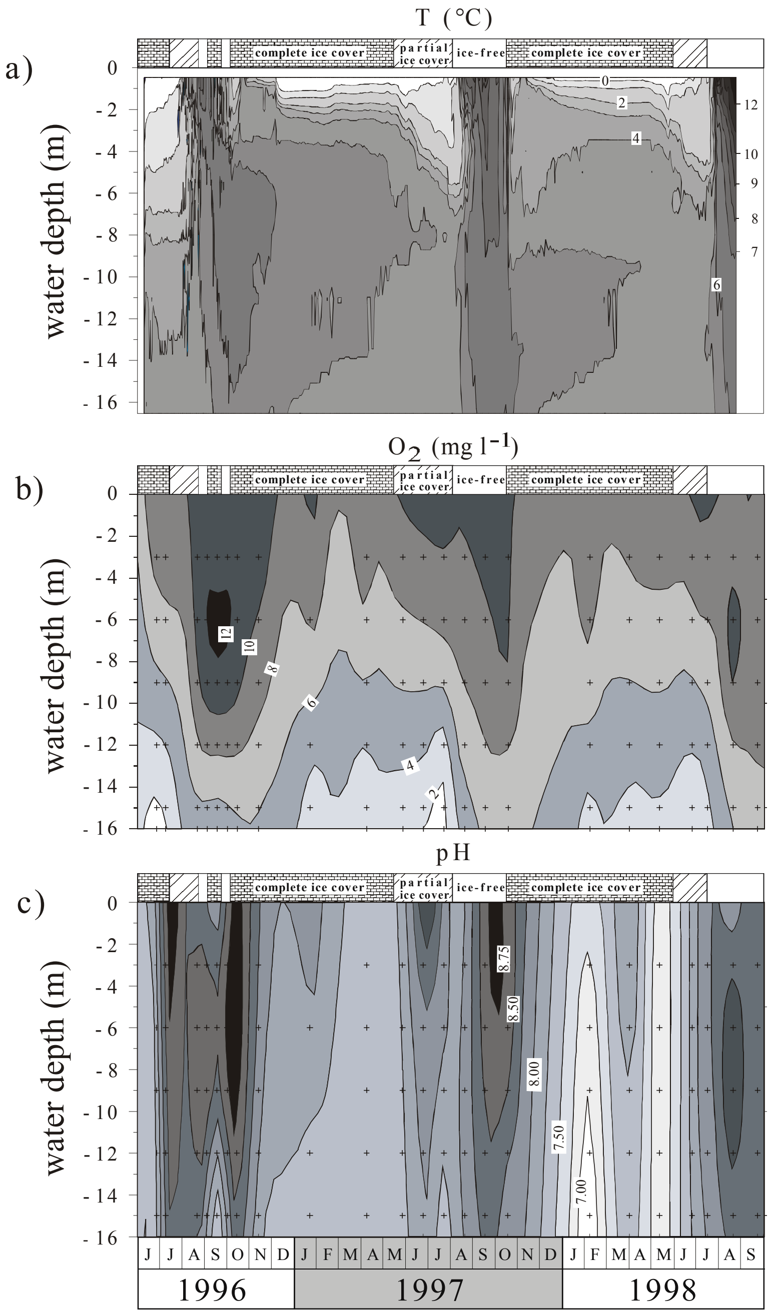

Fig. 4. Physical and chemical measurements made in the water column of Hagelseewli shown in relation to the ice cover status. Isoplots of **a)** water temperature, T (°C); **b)** oxygen concentration, O_2 (mg l^{-1}) and **c)** pH are shown. Measured values used in calculating the isopleths are indicated by crosses.

thawing period. In 1997/98 it was not as pronounced as in the year before and decayed earlier, i.e., during the last third of the ice-covered period. The persistence of the temperature anomaly in 1996/97 may be the result of the fact that the 1996 ice-free period was short and was even interrupted by a brief period of thin ice cover. This may have caused warm water to have been trapped in the lake, as the exchange of heat between lake and atmosphere would have been interrupted by the developing ice-cover. In contrast, in 1997/98 the ice-free period was longer and uninterrupted, thus allowing more complete cooling and deeper mixing of 4 °C water (down to 7 m) by the end of the ice-free period. A maximum surface water temperature of 8.9 °C was attained around the end of August 1997. After this, the lake water cooled down during >60 days in free exchange with the atmosphere, until ice-cover started in mid October 1997. In the previous year, this cooling period had lasted less than 40 days. In 1997/98 the resulting anomaly was therefore much less pronounced and also less persistent. At the onset of thawing, cool (<4 °C) surface water began to mix downwards in response to increasing wind forcing as the ice cover decayed. In 1997 and 1998 cool water mixed down to 6-7 m, whereas in 1996 it reached a depth of 13-14 m. However, complete mixing of the water column never occurred during the whole period of observation.

In Hagelseewli the uptake of atmospheric oxygen is prevented on average during 7-8 months a year by complete ice cover. In addition, photosynthetic oxygen production is inhibited during most of this time by a thick covering of snow which prevents penetration of light into the water column. Despite this fact, oxygen concentrations in the surface water never dropped below 8.0 mg O_2 l^{-1} even under ice (Fig. 4b). Concentrations exceeding 10 mg O_2 l^{-1} occur in the surface water as soon as the ice begins to thaw, and extend down to 10 m depth in the middle of the ice-free period. During the period of observation the highest concentrations of >11.0 mg O_2 l^{-1} always occurred between 6 m and 9 m depth in the middle of the ice-free period. The pH values (Fig. 4c) show the same pattern, except in 1997 where the maximum values occurred in the surface layer. The highest O_2 concentrations (12.7 - 13.3 mg O_2 l^{-1}) were measured in mid-September and mid-October 1996 in a water depth of 6 m, when the lake was covered with black (transparent) ice that allowed light penetration to occur.

High O_2 concentrations coincide with high pH values (up to 9.1) indicating maximum photosynthetic activity (CO_2 uptake) at these times (Figs. 4b, c). As a result of incomplete turnover (cf. temperature profiles), bottom-water O_2 concentrations reach their maximum values of 7.0 mg O_2 l^{-1} in the middle of the ice-free period. When the lake starts to freeze over, bottom-water O_2 depletion starts to develop as a result of the mineralisation of organic matter. Values below 2.0 mg O_2 l^{-1} are observed in the middle of the ice-covered period. This results in a decrease in pH (<7.1) due to increasing CO_2 concentrations. The lowest O_2 concentrations (<1.0 mg O_2 l^{-1}) are reached during thawing. We expect that anoxic conditions develop at the sediment water interface. Bottom-water O_2 concentrations remain low until the lake is completely ice-free, but subsequently undergo a rapid increase.

4.4. Major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}), conductivity and alkalinity

Since the rocks in the Hagelseewli catchment area contain between 14% and 40% $CaCO_3$, the lake water composition is typical of that of a hardwater lake with Ca^{2+}, HCO_3^- and Mg^{2+} as major ions. The major event in the annual rhythm of the lake that governs temporal variations in all biogeochemical processes is best visible in the profiles of the major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}), alkalinity, and conductivity, represented here by Ca^{2+} (Fig. 5a) and alkalinity (Fig. 5b). All ion-related parameters show a minimum in the surface water that develops at the beginning of the thawing period and persists until the beginning of freeze-over. The lowest values in all parameters occur at the end of the thawing period as a result of dilution of the lake water with relatively ion-poor meltwater from the lake ice and from snowcover in the catchment area. This dilution effect is detectable down to 6 m; below this depth all profiles show increases in concentration with depth that vary only slightly with time.

In view of the water chemistry of Hagelseeewli, biogenic calcite precipitation would be expected to occur in the surface waters of the lake during times of high productivity, as is the case in the hardwater lakes of the Swiss Plateau. However, calculations of the degree of calcite saturation occurring at different depths in the water column at different times of the year (Ohlendorf & Sturm, in prep.) reveal that, although biogenically induced calcite precipitation does indeed occur between the end of August and the middle of October, it occurs not in the surface water, but between 6 m and 9 m depth. This reflects maximum productivity, i.e. the assimilation of CO_2 and shifting of pH to high values (see above). Even under a thin cover of black ice, Hagelseewli water at 6-9 m can be up to 8.4 times supersaturated with respect to calcite. In contrast, during the period of winter ice-cover and the subsequent period of thawing, the whole water column, especially the bottom water, is strongly undersaturated with respect to calcite. Therefore, freshly precipitated calcite is redissolved from the sediment during the extended period of ice cover. Since advective mixing is unlikely to occur under ice, released Ca^+ and HCO_3^- ions accumulate in the bottom water (Fig. 5) resulting in an additional stabilisation of the stratification of the water column.

These findings are supported by sediment trap data (Fig. 8a). Autochthonous calcite precipitates consisting of particles of up to 30 µm in diameter were found in the lower sediment trap (17 m water depth) from 28.08.-17.09.96 and 06.08-19.08.98, but never in the upper trap that was installed at 2 m water depth (Ohlendorf & Sturm, in prep.). The fact that the calcite content of the sediments in Hagelseewli is always below the limit of detection, i.e., 0.5% (Lotter *et al.* 2000, this issue), also suggests that calcite is being redissolved.

*4.5. Nutrients (soluble reactive phosphorus (SRP), dissolved phosphorus (DP), SiO_2, NH_4^+, NO_3^-, NO_2^-) and chlorophyll-*a

Concentrations of SRP in the water column (Fig. 6a) vary between 0 and 45 µg P l^{-1}. Except during the period of thawing, surface water concentrations are always below 4.0 µg P l^{-1}. In contrast, bottom-water concentrations are generally higher. There, SRP values start to increase when the lake begins to freeze over, as soon as the oxygen above the sediment has been totally depleted by the mineralization of organic matter. Highest SRP values are attained during the thawing period, when O_2 concentrations are at their lowest. Oxygen depletion (Fig. 4b) and low redox potential at the sediment/water interface may cause the chemical reduction and dissolution of phosphorus bound in the sediments, which then diffuses into the bottom water (Gächter & Wehrli 1998). Within 14 days after the SRP maximum, at the begin-

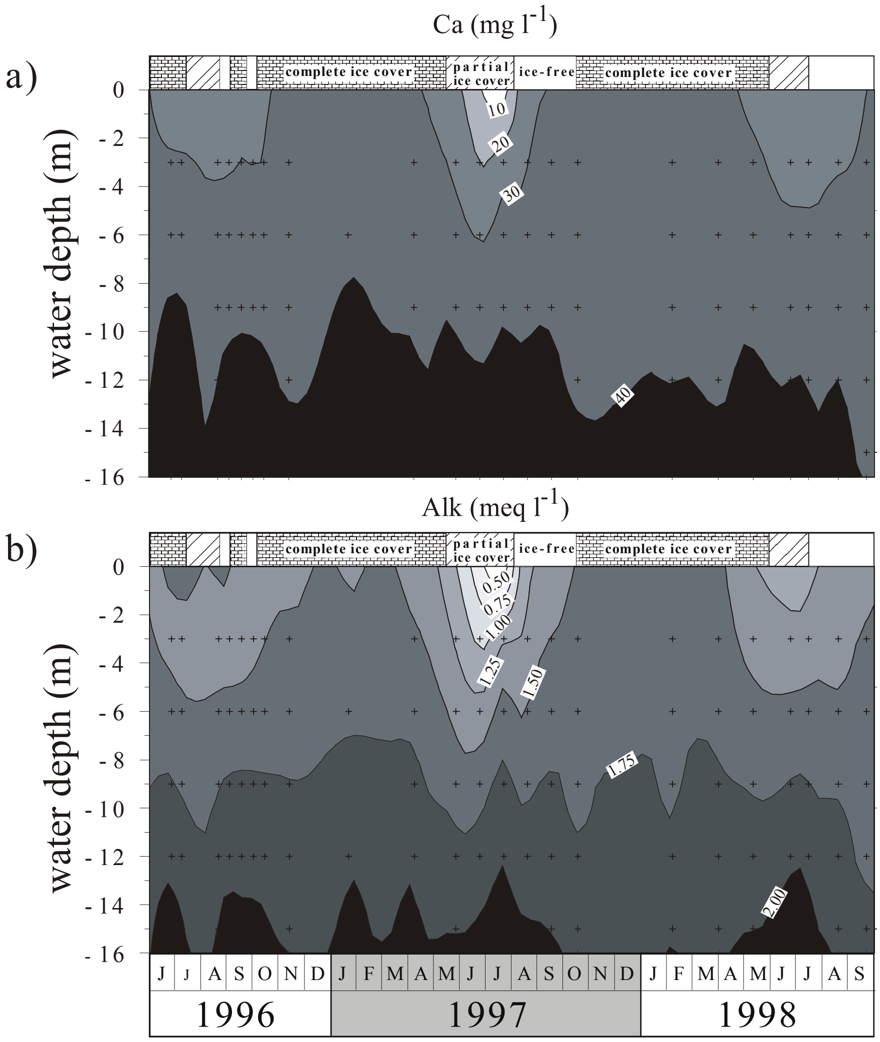

Fig. 5. Chemical measurements in the water column of Hagelseewli shown in relation to ice-cover status. Isoplots of **a)** calcium concentrations, Ca (mg l^{-1}) and **b)** alkalinity, Alk. (meq l^{-1}) are shown. Measured values used in calculating the isopleths are indicated by crosses.

ning of the ice-free period SRP values drop very rapidly below the limit of detection (1.0 µg P l^{-1}). Apparently, as soon as the penetration of light into the lake is no longer impeded by the presence of ice cover, the rate of photosynthesis increases tremendously, leading to the consumption of all available SRP within a few days. The release of phosphorus from the sediments is also apparent in the DP profiles (Fig. 7c), but, in addition, DP shows a surface water maximum during the 1997 thawing period which does not occur in the SRP profiles. This points to an allochthonous input of phosphorus that is bound in organic complexes and probably originates from soil pore waters.

In the same time interval when SRP values drop rapidly, chlorophyll-*a* values (Fig. 6b) increase sharply, reaching a maximum of 22.6 µg P l^{-1} in 15 m. Only 2-4 weeks later, chlorophyll-*a* values are again at very low levels. One exception to this is in mid October 1996, when slightly higher chlorophyll-*a* values indicate that during the period of black ice, light penetration was sufficient to allow algal growth, which was then constrained by higher pH and O_2 values (Figs. 4b, c). The fact that maximum chlorophyll-*a* values occur within a very narrow time window during the open-water period close to the lake bottom (12 m - 16 m depth) and not in the epilimnion, demonstrates that primary production is limited by the availability of light. Once the ice has thawed completely, due to the very clear water (the Secchi depth always exceeded 6 m) enough light is available to allow photosynthesis throughout the entire water column. The high SRP concentrations prevailing below 6 m therefore allow a short algal bloom in the deeper water until the SRP is used up and becomes limiting. Although chlorophyll-*a* concentrations are below the limit of detection during the period of thawing, the increased surface water O_2 concentrations observed then suggest that primary production sets in at the northern rim of the lake as soon as the ice there has thawed, making light available. We observed algal and insect growth at the rim of the lake as soon as open water conditions existed there.

The observation that highest chlorophyll-*a* values occur at the lake bottom, whereas the pH and O_2 maxima occurring at the same time were detected be-

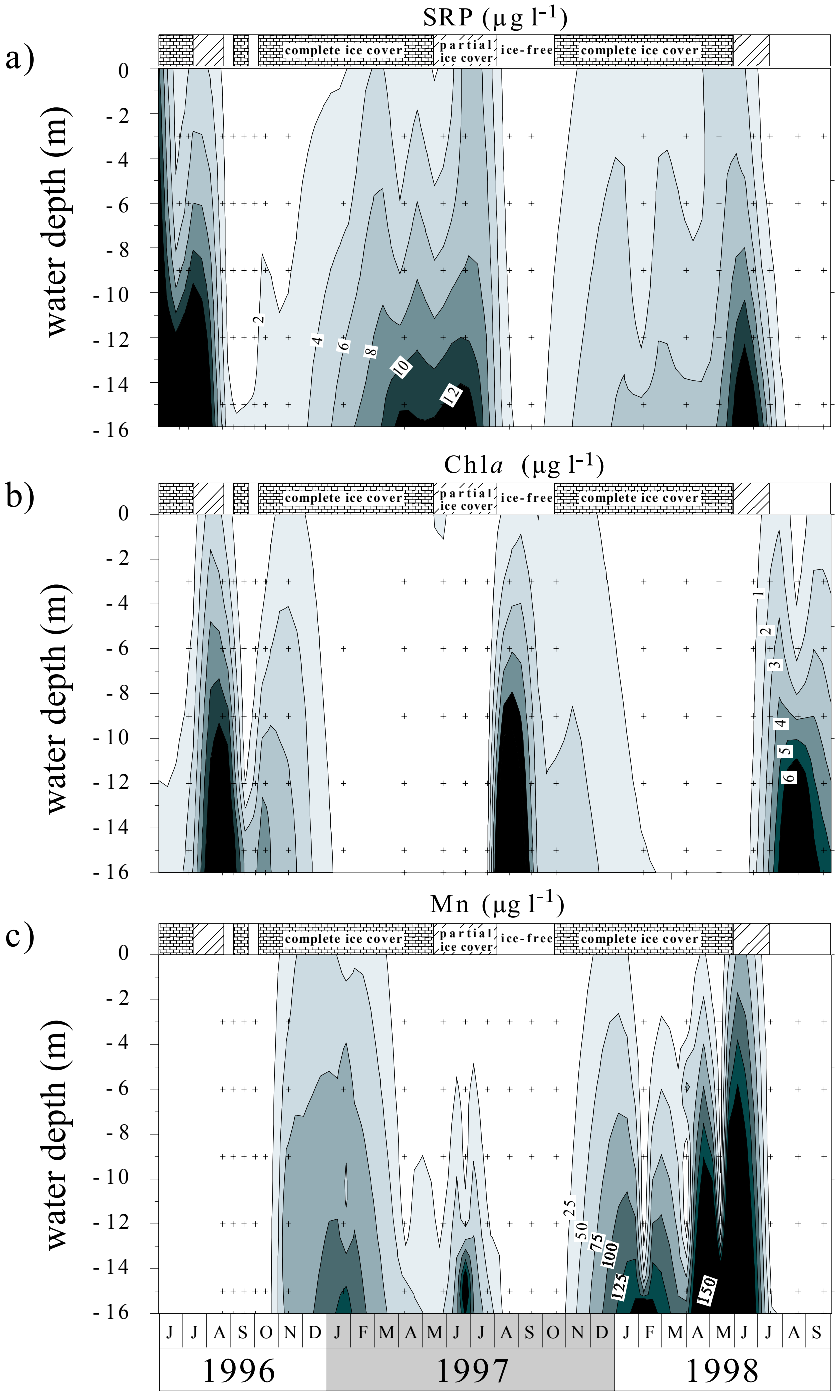

Fig. 6. Chemical measurements in the water column of Hagelseewli shown in relation to ice-cover status. Isoplots of **a)** soluble reactive phosphorus, SRP (µg l^{-1}); **b)** chlorophyll-*a*, Chl-*a* (µg l^{-1}) and **c)** manganese, Mn (µg l^{-1}) are shown. Measured values used in calculating the isopleths are indicated by crosses.

tween 6 m and 9 m depth, might indicate that the algal bloom was already over and that the algae had settled to the bottom by the time of sampling. Chlorophyll-*a* is a measure of particulate matter (algal remains), whereas pH and O_2 are measured in solution and thus monitor the effect of primary production where it occurs. However, high chlorophyll-*a* values might also be the result of picoplankton activity in the bottom water (Hodell *et al*. 1998). Maximum primary production takes place in the middle of the water column as a result of a compromise between the two limiting factors, light and SRP, that have their "sources" at opposite ends of the water column.

SiO_2 as another macronutrient shows a steady increase in concentration from the surface to the bottom during all seasons. Lowest concentrations occur in the epilimnion during summer, when the surface water is diluted by meltwater and most of the SiO_2 is incorporated into diatom frustules. As in the case of SRP, bottom-water SiO_2 concentrations were found to increase during the period of winter ice-cover and during the period of thawing, due to the mineralization and dissolution of diatom frustules. However, in view of concurrent low bottom-water pH values (Fig. 4c), substantial diatom dissolution seems unlikely (e.g. Schwalb *et al.* 1998; Barker *et al.* 1994). In addition, diatom assemblages in the surficial sediments of Hagelseewli, as well as in older sediments, show no signs of substantial dissolution (Lotter & Bigler 2000). The seasonal transport of SiO_2 to the lake bottom, the short ice-free time, which does not allow complete mixing, and the additional stabilisation of the stratification by high concentrations of Ca^+ and HCO_3^- induce and support the characteristic depth profile of SiO_2.

In contrast, the distribution of NH_4^+ is completely different to that of the other nutrients. During most of the year, NH_4^+ concentrations in Hagelseewli (Fig. 7a) are below 20 µg N l^{-1}, whereas at the beginning of thawing, very high concentrations (>100 µg N l^{-1}, i.e., >7.1 10^{-6} mol N l^{-1}) are observed in the surface water. Goudsmit *et al.* (2000) suggest that the high NH_4^+ input at the beginning of thawing may originate from atmospheric deposition in the snow cover (Barica 1970; Barica & Armstrong 1971) as well as from soil porewater. For mean precipitation in the Alps, Camarero *et al.* (1995) give average values of 35 10^{-6} mol N l^{-1} for NH_4^+. Moreover, Psenner (1999) points out that Saharan dust, a frequent phenomenon in the Alps, can increase NH_4^+ concentrations in snow by an order of magnitude. NO_3^- concentrations (not shown) increase in parallel to the NH_4^+ values, attaining maximum values of 304 µg N l^{-1} (22 10^{-6} mol N l^{-1}) in the surface water due to nitrification of NH_4^+. NO_2^-, which is a short-lived intermediate product of nitrification, shows a slight increase at the surface during this time too (Fig. 7b). Short-term increases in NO_2^- concentrations also occur in the surface water during the ice-free season. These originate from the nitrification of NH_4^+, which is released from decaying phytoplankton during that time. Maximum NO_2^- concentrations of 10.3 µg N l^{-1} (0.74 10^{-6} mol N l^{-1}), however, occur during a short time interval in the middle of the ice covered periods between 6 m and 9 m depth.

The high input of NH_4^+ within a very short time interval demonstrates the importance of ice cover for this particular high-altitude ecosystem. This has also been stressed by Catalan (1989) based on investigations on Lake Redó (Pyrenees). Nevertheless, it is obvious that the allochthonous (probably atmospheric) input of NH_4^+ does not affect primary production in Hagelseewli, because it is not a limiting nutrient. This latter role is taken on by SRP, the source of which is internal to the lake, since it is released from the sediments during the period of stagnation under ice cover.

4.6. Redox-sensitive elements (Mn and Fe)

Mn (Fig. 6c) shows a distribution that is comparable to that of SRP. For most of the time, Mn concentrations are below 20 µg l^{-1}. Only when the O_2 in the water layer immediately above the sediment is entirely depleted, do Mn values increase significantly. This happens in the bottom water during the winter ice-cover period and persists until the middle of the thawing period. This distribution pattern indicates that Mn is released from the sediments under O_2-deficient conditions during the winter ice-cover period. Mn dissolution, i.e., the reduction of Mn(IV) to Mn(II), occurs when the redox potential is below approximately 500 mV. The highest Mn concentrations (up to 800 µg l^{-1}) were determined at a depth of 16 m in May 1998 at the beginning of thawing. This was also the only date where significantly higher DOC concentrations (a maximum of 6.5 µg l^{-1} at 16 m) occurred, which points to intense microbial respiration and, therefore, oxygen consumption at that time.

Dissolved Fe (not shown) was detected occasionally in the bottom water of Hagelseewli. Concentrations of up to 82 µg l^{-1} only occurred at the end of May 1997, when thawing began.

4.7. Sediment traps

The exposure times of the sediment traps were very varied due to the long period of ice cover (Fig. 8), ranging from 11 days under ice-free conditions to 313 days under ice cover. Nevertheless, the mean total accumulation rate in the lower trap of 15 mg cm^{-2} y^{-1} (Fig. 8a) compares well with the mean sediment accumulation rate of 11 mg cm^{-2} y^{-1} based on ^{137}Cs-dated sediment cores (Lotter *et al.* 2000, this issue). The highest sediment accumulation rates were determined during the long ice-covered periods. However, this observation is somewhat misleading, because the long exposure times always also include the period of thawing and/or part of the ice-free period. Most of the particles found in these traps are periphytic diatoms, chrysophyte cysts, detrital minerals and amorphous organic matter that was washed into the lake with meltwater during thawing. Sediment traps exposed during the ice-free period show low particle fluxes, mainly of diatoms. Traps were changed at intervals of approximately 14 days during the ice-free period between mid July and mid September 1998. As seen in the chlorophyll-*a*, pH and O_2 data (see above), a productivity peak occurred between August 1998 and September 1998. During this time, the sediment accumulation rates also showed maximum values and endogenic calcite precipitates were found in the lower trap, as discussed above (Fig. 8a).

4.8. Modern diatoms

Analyses of diatoms from water samples integrating over the whole water column (Fig. 9) showed blooms of planktonic *Cyclotella* species occurring mainly during the summer open-water season. The onset of the bloom may take place while the lake is still partly ice-covered, as, for instance, in 1998 (see Fig. 9). Periphytic diatoms such as certain *Fragilaria* species did not play an important role in the water column. Other pennate diatoms

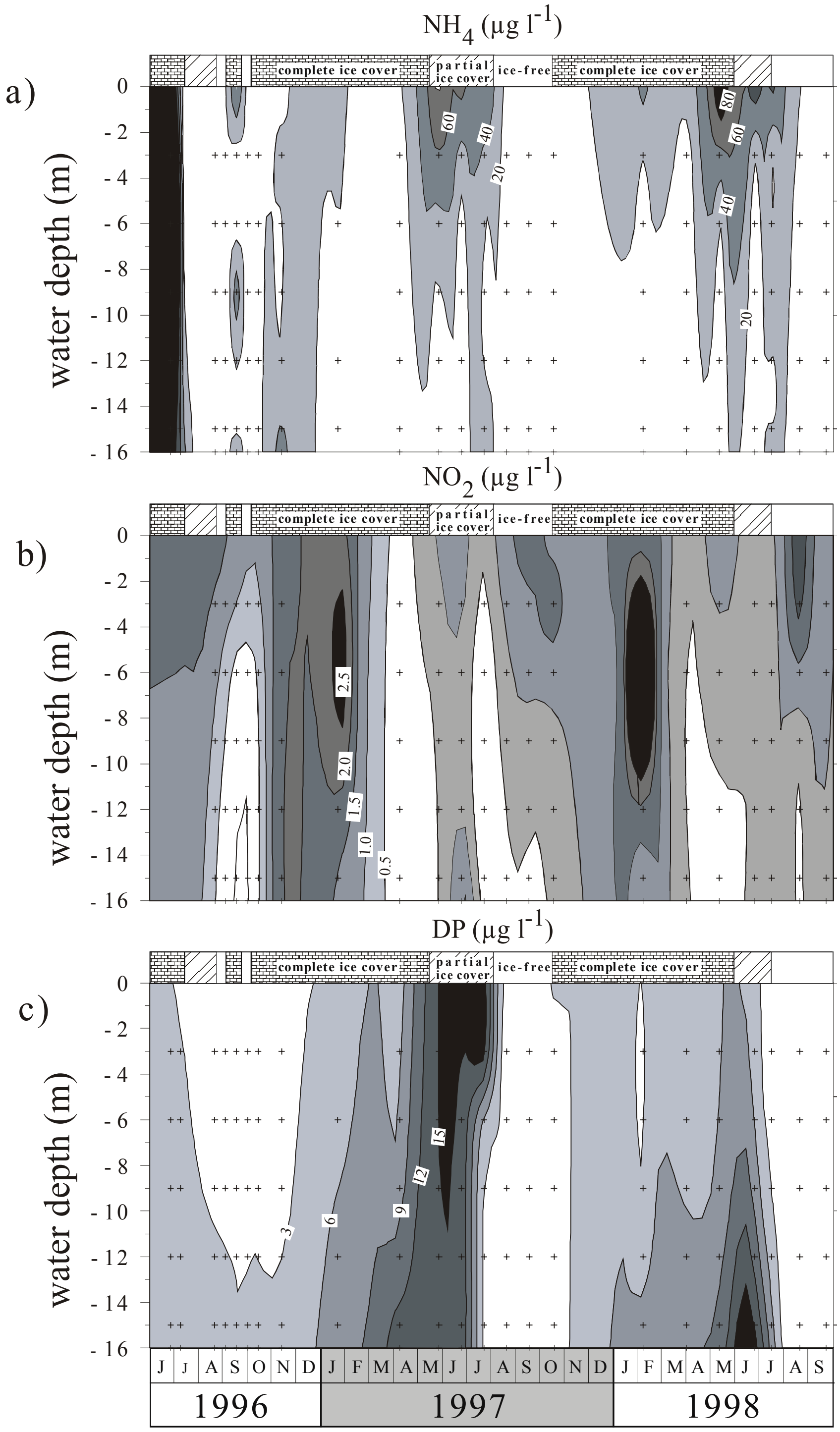

Fig. 7. Chemical measurements made in the water column of Hagelseewli shown in relation to ice-cover status. Isoplots of **a)** ammonium, NH_4 (µg l^{-1}); **b)** nitrite, NO_2 (µg l^{-1}) and **c)** dissolved phosphorus, DP (µg l^{-1}) are shown. Measured values used in calculating the isopleths are indicated by crosses.

sampled in higher quantities in the water column (e.g. *Achnanthes minutissima*) might be considered as tychoplanktonic.

Large differences in diatom composition and accumulation were observed between the two sediment traps (Fig. 8b). Throughout most of the time the samples in the upper sediment trap (at 2 m) were dominated by *A. minutissima*. Given the high water transparency, the transparent trap provided an ideal substrate for periphytic diatoms, and thus represents the periphyton rather than the planktonic diatom component in the water column. The assemblages in the lower sediment trap (at 17 m) were dominated by planktonic *Cyclotella comensis* most of the time. As a result of the long period of ice cover and the thickness of the ice (up to 2 m), it was not possible to assess the timing of diatom blooms at high temporal resolution during the period of winter ice-cover or during the period of thawing. However, the

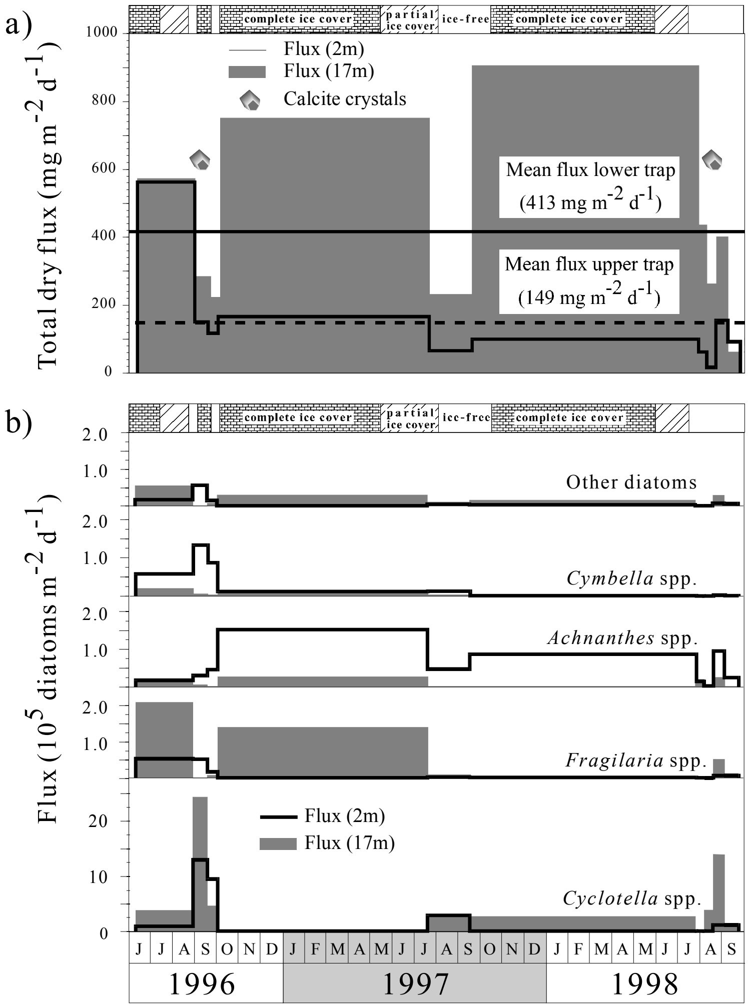

Fig. 8. Hagelseewli sediment trap data shown in relation to ice-cover status. The plots show **a)** total sediment flux in the lower (17 m) and upper (2 m) traps (mg m^{-2} d^{-1}); **b)** Diatom assemblage compositions and fluxes for each trap (diatoms m^{-2} d^{-1}). In **a)** the occurrence of endogenic calcite crystals in the lower trap is indicated by pentagons.

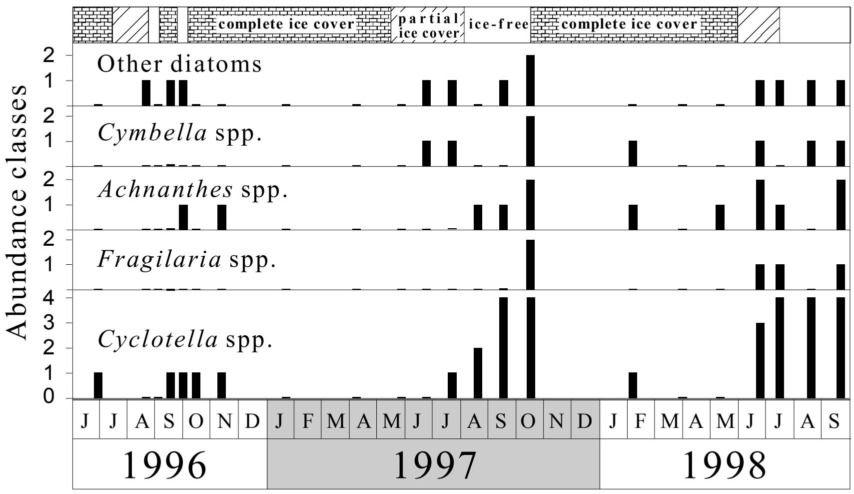

Fig. 9. Composition of diatom assemblages in the water column of Hagelseewli shown in relation to ice-cover status. The data were obtained from mixed water samples integrating over the whole water column.

trap data do reflect the dynamics prevailing during the ice-free period (Fig. 8b). The relative abundance and the accumulation rates of diatom frustules correspond well. The blooms of *C. comensis*, as evidenced by the high accumulation rates and relative abundance of this taxon in both traps, took place during the summer ice-free period. During complete and partial ice-cover, especially in the first two winters, periphytic *Fragilaria* species (in particular *F. pinnata* var. *pinnata*) and other periphytic taxa accumulated in the lower trap.

The sediment trap data support the water column observation of open water blooms of centric diatoms. The high percentages and accumulation rates of *Cyclotella* throughout summer 1997 and winter 1997/98 are probably an artefact of the long period of trap exposure.

Analyses of diatoms in Hagelseewli surface sediments (Lotter & Bigler 2000; Bigler 1998) revealed that water depth is the most important explanatory variable for the distribution of diatom assemblages. As a result of the high water transparency, however, periphytic diatoms may also live in the deepest part of the lake.

5. CONCLUSIONS

To test the suitability of high Alpine lake sediments for palaeoclimate reconstruction, the effect of long-lasting ice cover on Hagelseewli (2339 m a.s.l.) was investigated based on on-site meteorological measurements and on water column, sediment trap and sediment data.

The on-site meteorological measurements document the harsh climatic conditions prevailing at Hagelseewli with monthly mean temperatures below 0 °C during about 6 months of the year. They reveal that the high cliff face to the south is of great importance for the energy budget of the lake. Whereas local air temperature is not influenced by the topographic shading, water temperature is significantly lower than would be expected from average water temperature lapse rates (Livingstone *et al*. 1999). Because of the cliff, Hagelseewli receives only 10-85% of the theoretically possible solar radiation, which is the main reason for the low surface water temperatures. The long period of ice-cover and the heterogeneous thawing of the lake are probably the most important consequences of the reduced radiation balance. The water body is essentially decoupled from the atmosphere during most of the year because of the persistent ice-cover. Only during the ice-free period, i.e., during approximately 2 months of the year, are lake water temperatures correlated with air temperatures, which they lag by about 15 days. The biogeochemical cycles in Hagelseewli are therefore primarily affected by freezing and thawing processes rather than by direct climatic forcing.

Based on the ice-cover data, the annual cycle can be divided into three distinctly different phases: 1) the time of snowmelt when the ice thaws (1 to 2 months); 2) the time when the lake surface is free of ice for 6 to 8 weeks each year; and 3) the time of complete ice cover which lasts 8 to 9 months.

1) As soon as the ice at the northern rim of the lake begins to thaw, phytoplankton, zooplankton and macroinvertebrates are observed along the shore and littoral habitats become available for diatom growth. Lateral water movement and sediment focusing may transport periphytic diatoms, mainly *Fragilaria* species, to the deepest part of the basin, as shown by the sediment trap data. At this time, cold (<4 °C), oxygen-rich meltwater with a low salt content stratifies on top of denser (warmer) water. With continuing thawing, this cold water is pushed down to a depth of 6 to 13 m as the amount of cold meltwater at the surface increases. A characteristic feature of the thawing period is the surficial input of high quantities of ammonium into the surface water. This ammonium is derived mainly from atmospheric deposition in snow and/or from soil porewaters, where it occurs together with dissolved phosphorus. Nitrification of ammonium also causes short-term increases in nitrate and nitrite concentrations in the surface water. Since nitrogen is not the limiting nutrient, its allochthonous input only has a minor effect on primary production.

2) When the lake is free of ice, wind can access the lake surface and introduce mixing energy. Oxygen-rich water can then mix down to the lake bottom, although during the observation period, O_2 concentrations did not reach saturation levels because the density stratification was never entirely overcome. Evidence supporting this interpretation is also seen in profiles of temperature and major ions. The relatively high concentrations of dissolved ions in the hypolimnion that stabilise the stratification of the water column are the result of the dissolution of particles in the hypolimnion and of redissolution from the sediments during the preceding long period of ice cover (see below).

The most dramatic event in the annual cycle of the lake is the moment when it is completely free of ice for the first time. At this point, light penetration into the deeper water of the lake causes a very short but intense productivity pulse. All available SRP is consumed by phytoplankton in less than 2 weeks. The sinking remains of this algal bloom are found in the form of very high concentrations of chlorophyll-*a* just above the lake bottom. In contrast to other lakes, the most intense photosynthesis, indicated by the occurrence of the highest O_2 and pH values, occurs between 6 m and 9 m depth. This happens because the limiting nutrient (SRP) is released from the sediments during the period of ice-cover and the period of thawing, whereas light penetrates from the surface. Primary productivity thus peaks at 6-9 m, where both factors are optimally available. Because Hagelseewli is a hard-water lake, the water at 6-9 m can be up to 8.4 times supersaturated with respect to calcite as a result of photosynthetic CO_2 uptake. This causes the biogenically induced precipitation of large calcite crystals of up to 30 µm in diameter that are found in the sediment traps at that time (Ohlendorf & Sturm, in prep.). Owing to the high transparency of Hagelseewli, the depth in the water column also represents a gradient in light availability. Down to 8-10 m, diatom assemblages are dominated by periphytic taxa, especially *Fragilaria* species, whereas below 10 m planktonic taxa (*C. comensis*) are predominant. This is also seen in the diatom assemblages of the surficial sediments of Hagelseewli (Lotter & Bigler 2000).

3) At the beginning of freeze-over (usually in mid October) a temperature anomaly develops. The warmest water is found in the middle of the water column. This situation may persist under the ice cover until the next thawing period. The anomaly is more pronounced when early freeze-over hampers energy exchange with the atmosphere. Primary production usually stops with the commencement of freeze-over, unless black ice develops. Under black ice, primary production can be just as intense as in open water conditions. The most important feature for the chemistry of Hagelseewli is the development of deep-water anoxia that persists throughout the period of ice-cover and also during the thawing period. Soon after the O_2 is completely depleted, free phosphate is detected in the bottom water. Phosphate concentrations increase with time, and phosphate diffuses upwards in the water column. At the same time, substantial amounts of dissolved Mn and sometimes even Fe diffuse from the sediment into the bottom water. Nutrient redissolution from the sediments is crucial for primary production in Hagelseewli, because such redissolution is virtually the only source of phosphate (SRP), which is the nutrient limiting algal growth. In response to strong undersaturation with respect to $CaCO_3$ - pH can drop below 7 in the bottom waters - autochthonous calcite precipitates are redissolved from the surface sediments. As a consequence of today's very low sedimentation rates (0.65 mm y^{-1}), calcite redissolution is complete, so that the sediments contain no calcite whatever. Together with other macronutrients such as SiO_2, Ca accumulates in the hypolimnion, thereby stabilising the density stratification of the lake and thus preventing complete overturn after the ice has thawed.

Thus, because it regulates the bottom-water oxygen concentration, the occurrence or non-occurrence of an ice-free period is probably the most important single physical factor affecting the nutrient budget, primary production and the preservation of calcite in Hagelseewli. However, since peak primary production only lasts for a few days and decreases again to very low levels when all available SRP is taken up, we assume that the duration of the ice-free period, if it occurs, is of comparatively minor importance. This implies that the duration of the ice-free period is unlikely to be archived in the sedimentary record. It is hypothesised that only years during which there was no open-water period will show up in the sediment record (e.g., in the form of changes in the composition of diatom assemblages). As long as the centre of the lake is covered with ice and snow, planktonic diatoms will not develop in the water column in significant amounts. The ratio of planktonic diatoms to periphytic *Fragilaria* species may therefore yield some information on the presence or absence of ice-cover of alpine and arctic lakes in individual years (see also Smol 1988; Douglas & Smol 1999).

Bottom-water oxygen replenishment seems to be critical for phosphorus redissolution and (in conjunction with high sedimentation rates) for the preservation of calcite. It is hypothesised that phosphorus may have been retained, and calcite preserved, in older Hagelseewli sediments deposited during warmer, wetter summers that would have favoured longer ice-free periods and more catchment erosion, resulting in better circulation and higher allochthonous input of clastic particles. In this case, the sediment calcite content would be a potentially useful indicator of past changes in lake circulation and/or allochthonous input.

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