Phototrophic microbial community responses to late-Holocene environmental forcing of Southwest Greenland lakes

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Running title: Phototrophic community responses to environmental forcing in SW Greenland
Summary

1. The biological structure of arctic lakes is changing rapidly, apparently in response to global change processes, such as increasing air temperatures, although altered nutrient stoichiometry may also be an important driver. Equally important, however, are local factors (e.g. landscape setting, hydrological linkages and trophic interactions) that may mediate responses of individual lakes at the regional scale. Despite general acknowledgement of the importance of local factors, there has been little focus on among lake variability in the response to environmental change.

2. Sedimentary pigments, organic carbon and nitrogen and biogenic silica (BSi) in $^{210}$Pb and $^{14}$C-dated sediment cores from three contrasting lakes in the Kangerlussuaq area (~67° N, 51° W) of Southwest Greenland were used to reconstruct algal and phototrophic bacterial ecological change during the late Holocene. Water chemistry for the individual lakes varies in terms of conductivity (range: 30–3000 µS cm$^{-1}$) and stratification regimes (cold monomictic, dimictic and meromictic), linked to their position along the regional climate gradient from the coast and to the present ice sheet margin.

3. Despite essentially similar regional climate forcing over the last ~1000 years, marked differences among lake types were observed in the phototrophic communities and their temporal variability. Considerable short-term variability occurred in an oligosaline, meromictic lake (SS1371), dominated by purple sulphur bacteria, likely due to a tight coupling between the position of the chemocline and the phototrophic community. Communities in a lake (SS86) located on a nunatak, just beyond the edge of the present ice sheet shifted in a non-linear pattern, approximately 1000 cal. yrs BP, possibly due to lake-level lowering and loss of outflow during the Medieval Climate Anomaly. This regime shift was marked by a substantial expansion of green sulphur bacteria.

4. A dilute, freshwater coastal lake (SS49) dominated by benthic algae was relatively stable until ca. 1900 AD when rates of community change began to increase. These changes in
benthic algal pigments are correlated with substantial declines (1.3 to 0.44‰) in δ¹⁵N that are indicative of increased deposition of atmospheric inputs of industrially-derived NOx into the atmosphere.

5. Climate control on lake ecosystem functioning has been assumed to be particularly important in the Arctic. This study, however, illustrates a complex spatial response to climate forcing at the regional scale and emphasizes differences in the relative importance of changes in the mass (m, both precipitation and nutrients) and energy flux (E) to lakes for the phototrophic community structure of low-Arctic Greenland lakes.
Introduction

Arctic ecosystems are changing rapidly in response to global change processes (Overpeck et al., 1997; Post et al., 2009). Much of the evidence for altered biological structure in arctic lakes over the last 50−150 years are derived from the natural archives recorded in lake sediment (Smol et al., 2005). Considerable emphasis has been placed on increased air temperature at high latitude and its impact on lake thermal budgets as a driver of these observed changes (Smol et al., 2005) but other global change processes, such as increased regional N deposition are undoubtedly important (Bergstrom, Blomqvist & Jansson, 2005; Wolfe, Cooke & Hobbs, 2006). While these large scale, hemispheric, processes impact lake functioning, indirect effects, largely mediated through catchment processes such as soil development, vegetation succession, altered nutrient cycling and hydrology can have profound impacts on lakewater chemistry and biological structure (Kane et al., 1992; Battarbee, 2000; Engstrom et al., 2000). The effect of these direct and indirect fluxes of mass and energy on lake response to climate has been highlighted in a conceptual model developed by Leavitt et al. (2009). This model indicates the extent to which direct climate impacts on lakes have to be balanced by consideration of catchment-mediated fluxes of mass ($m$ - water, solutes, and particles) and energy ($E$ - e.g. irradiance [PAR, UVR], wind friction, or transfer of atmospheric heat). This balance may be very important in the Arctic where precipitation is often very low, nutrients are limiting, and there is a strong marked seasonality of energy inputs (Vincent, Hobbie & Laybourn-Parry, 2008).

The area around Kangerlussuaq, Southwest (SW) Greenland (Fig. 1) contains ~20 000 lakes and has a strong regional climate gradient, from a maritime coastal zone to the arid interior, which is in part caused by the strong orographic effect of the Sukkertoppen ice-cap (Fig. 1). Marked differences in precipitation ($m$ flux) and effective solar radiation inputs ($E$ flux) exist between the coast (where summer fog banks are common) and the inland areas. Groundwater flows are minimal in SW Greenland due to permafrost, and so hydrological ($m$) fluxes to lakes reflect the influence of catchment-lake ratios, landscape position and relief. The regional
environmental (climate) gradient influences both contemporary water chemistry (Anderson et al., 2001) and biological structure (Brodersen & Anderson, 2000; Pla & Anderson, 2005; Perren et al., 2009).

Recent palaeolimnological work in the Kangerlussuaq area has focussed on both fresh and oligosaline lakes at the head of the fjord (Fig. 1) where changing effective moisture (i.e. the balance between precipitation and evaporation) has resulted in a number of lakes with evaporatively concentrated ion chemistry (Anderson et al., 2001). McGowan et al. (2008) and Anderson et al. (2008) concluded that lake ontogeny was a significant factor controlling algal communities and biological structure in SW Greenland lakes. The interaction of climate and catchment processes also was highlighted by a terrestrial-aquatic macrofossil study of a small, dilute lake (Heggen et al., 2010). In-lake processes such as the nature and strength of stratification as some of the oligosaline lakes are meromictic (McGowan, Ryves & Anderson, 2003), also can affect lake response to environmental/climate forcing.

Much of the evidence for change within lake communities in the Arctic has focussed on diatoms, but there is also some evidence for altered food web dynamics (Quinlan, Douglas & Smol, 2005) and increased lake productivity derived from reflectance spectroscopy (Michelutti et al., 2005). While diatoms are an important component of arctic lake ecosystems, non-siliceous algae also can be significant (Vadeboncoeur et al., 2003; Bonilla, Villeneuve & Vincent, 2005). Pigments are produced by algae and other phototrophic organisms, some of which are taxonomically specific while others are ubiquitous in most algal groups (Jeffrey, Mantoura & Wright, 1997). Therefore, pigment analysis by High Performance Liquid Chromatography (HPLC) provides important information about a wide range of primary producers and phototrophic bacteria and hence whole-lake responses to environmental forcing (Leavitt & Hodgson, 2001). Analysis of sedimentary pigments is now an important component of palaeolimnological studies (Vinebrooke et al., 1998; Leavitt et al., 1999; Leavitt and Hodgson 2001) but their application to arctic lakes has been relatively limited (Pienitz et al., 2000;
Anderson et al., 2008; Reuss et al., 2010a; Reuss et al., 2010b). In a pigment study of two oligosaline lakes in SW Greenland, McGowan et al. (2008) highlighted the individual and non-linear response of lakes to climate forcing at centennial timescales, perhaps due to differences in lake morphometry and benthic-pelagic productivity. Here we use pigment analysis to address recent ecological change in lake phototrophic communities (i.e. algae and phototrophic bacteria).

Focusing on three lakes positioned along the regional climate gradient in the Kangerlussuaq area (Fig. 1) and with very different hydrological budgets, conductivity and stratification regimes, we evaluate the degree of spatial variability in the extent to which algal and phototrophic bacterial responses to late-Holocene climate change in this area are mediated by changing fluxes in mass \(m\) and energy \(E\) (sensu Leavitt et al., 2009). Closed basin lakes with increased ion-concentration and strong stratification is expected to respond strongly to direct effects of mass and energy flux determining changes in effective moisture (Battarbee, 2000; Leavitt et al., 2009). Previous work on this lake type in the Kangerlussuaq area suggests that the over-riding effect on lake functioning is via direct mass transfer: i.e. the impact of hydrological fluxes on lake levels (McGowan et al., 2003; Aebly & Fritz, 2009; Leavitt et al., 2009). In contrast, freshwater, dilute lakes in this area are more affected by indirect changes in mass flux mediated by the specific catchment properties (Anderson et al., 2008; Heggen et al., 2010).

**Methods**

**Study sites**

Kangerlussuaq (Søndre Stromfjord in Danish) is a 150-km long glacial fjord in SW Greenland (Fig. 1), and the area between the coast and the ice sheet is the widest ice-free land area in Greenland today (~180 km). There are thousands of lakes that are well suited for palaeoclimatic investigations and direct anthropogenic influence is minimal (Anderson et al., 2001); however, as with the majority of arctic lakes, they are impacted by northern hemisphere atmospheric
pollution (Bindler et al., 2001). The area encompasses a strong climatic gradient from the inland continental climate to a more maritime environment at the coast. Annual precipitation at Kangerlussuaq at the head of the fjord is <150 mm yr\(^{-1}\), while precipitation at the coast is >500 mm yr\(^{-1}\). The annual temperature range is greatest at Kangerlussuaq town with average summer/winter temperatures of 10°/–18°C compared to 6°/–12°C at the coast. Estimated evaporation at the head of the fjord is ~300 mm and together with the low precipitation results in negative effective precipitation in the area extending to approximately half way (80 km) to the coast from the ice sheet margin (Hasholt & Søgaard, 1978).

An extensive study of 86 lakes from the Kangerlussuaq area along a transect from the ice sheet to the coast identified the main characteristics of lake chemistry (Anderson et al., 2001). The majority of the lakes are dilute (<300 µS cm\(^{-1}\)), with an mean conductivity of 160 µS cm\(^{-1}\) while the remaining (ca. 10%) of the lakes are oligosaline, have conductivity >800 µS cm\(^{-1}\) and are characterised by Na Mg-CO\(_3\) chemistry (Anderson et al., 2001). These oligosaline lakes (Williams, 1991) are situated well above the marine limit and cannot therefore have been formed by trapping of marine water due to isostatic uplift, which is a common method of oligosaline lake formation in the Arctic and Antarctic (Burton, 1981; Ouellet et al., 1987). The primary cause of elevated salinity in these saline closed-system lakes is most likely evaporation enhanced by inputs of salts from nearby terrestrial sources, brought to the lakes by aeolian activity (Anderson et al., 2001; Willemse et al., 2004).

Details of the physical and chemical characteristics of the three study lakes are given in Table 1. The study lakes are representative of the range of water chemistry (fresh-oligosaline), DOC concentration and thermal stratification (cold monomictic, dimictic and meromictic) found in the Kangerlussuaq area (see Table 1) (Anderson et al., 2001). The lakes are also spatially separated along the geographic gradient from the coast to the inland ice (Fig. 1). Lake SS49 is located ~120 km to the west of the ice sheet at 340 m a.s.l. and is typical of the dilute oligotrophic lakes (< 50 µS cm\(^{-1}\); DOC 12 mg L\(^{-1}\)) found along the coastal margin (Anderson et
al., 2001; Anderson & Stedmon, 2007). SS1371 located ~45 km west of the ice sheet is an oligosaline closed-basin lake, surrounded by extensive fossil shorelines indicative of substantially higher lake levels in the past. SS86 is located on a nunatak, an isolated mountain top that protrudes over the surface of the ice sheet, approximately 5 km inside the ice sheet and has significantly higher conductivity and alkalinity compared to both a neighbouring lake (SS32) (Table 1) and to other freshwater lakes in the Kangerlussuaq area (Anderson et al., 2001). SS86 and SS1371 are fishless but sticklebacks (*Gasterupty sp.*) were observed in SS49.

*Sediment coring*

Sediment cores (22–34 cm in length) were collected in April 2000 by freeze-coring which results in cores with an undisturbed surface layer. The sediments from SS1371 and SS86 were laminated, whereas the core from SS49 had no visible laminations. The cores were shipped to the laboratory frozen and wrapped in black plastic to limit light and oxygen access. Cores were stored undisturbed at –20°C in the dark until sectioning. Sectioning was conducted in a cold room at less than –10°C by removing the outer layers of the core with a wood planer and cutting into 0.5 cm sections using a band saw. The samples were then cleaned with a glass plate and stored at –80°C until freeze-drying and extraction of pigments.

*Sediment chronology*

Cores were dated by means of $^{210}$Pb (Fig. 2), determined using gamma assay (Appleby et al., 1986) and bulk AMS $^{14}$C were determined for selected depths on Russian cores taken at the same time as the freeze cores and within 2 m of the freeze core location. The Russian and freeze cores were readily cross-correlated using distinctive carbon profiles (total carbon or organic carbon wt%, see Fig. 3).

*Pigment analyses*
0.1–0.5 g of homogenized freeze-dried sediment was extracted in 5 ml cold 100% acetone and spiked with an appropriate amount of internal standard β-apo-8-carotenal (25–100µl). The mixture was sonicated, extracted overnight at –20°C, filtered and diluted to a final concentration of 80% acetone to increase peak resolution before run by High Performance Liquid Chromatography (HPLC) (Reuss & Conley, 2005). Quantitative analyses of all pigments were conducted on a Shimadzu HPLC equipped with an on-line photodiode array detector (SPD-M10Avp) for quantification and fluorescence detector (RF-10Axl) for identification purposes only. The run method was a modification of Wright et al. (1991) as described by Reuss & Conley (2005).

Tentative identification of individual pigments was based on a combination of retention time and absorption spectra. The quality of the absorption spectra diminished down core for some pigments, and identification were then primarily based on the retention time. Reference absorbance spectra for identification and quantification of algal pigments were obtained from a single run of standards from DHI Water and Environment, Denmark and (Jeffrey et al., 1997). Absorbance spectra of bacterial pigments were obtained from a standard of okenone provided by A. Lami (CNR.ISE, Italy) and a culture of a green sulphur bacterium Chlorobium phaeobacteroides containing bacteriochlorophyll-e provided by R. Cox (University of Southern Denmark, Denmark). Concentrations of chlorophyll-e and okenone standards were determined at absorbance maxima using specific molar extinction coefficients (467 nm, 10 × 10^4 l mmol⁻¹ cm⁻¹ (Frigaard, Larsen & Cox, 1996), and 487 nm, 13.4 × 10^4 l mmol⁻¹ cm⁻¹ (Züllig, 1985), respectively). Quantification of chlorophyll-a (chl-a) and pheopigment-a’s (ppn-a) was conducted at 666 nm while carotenoids, chlorophyll-b, pheopigment-b’s and bacteriochlorophylls were quantified at 449 nm. Normalisation of concentrations of all samples were conducted by scaling to the highest value of the internal standard, β-apo-8-carotenal, except for the top half of the core from SS86 where the bacteriochlorophylls interfered with the internal standard peak. The ratio of chl-a/ppn-a was calculated to provide a simple preservation index as
chlorophyll-a is readily degraded while its degradation products are much more stable. Three
samples from lake SS49 were excluded from the dataset due to a very irregular injection peak
and chromatogram.

*Carbon (C), nitrogen (N), biogenic silica (BSi) and stable isotope (^15N) analyses*

Carbon and nitrogen content were determined using a CHNS elemental analyzer (CE instruments
EA1110). The total fraction of C and N was measured on freeze-dried samples, while the
inorganic C-fraction was measured on combusted samples (2h at 500°C) and corrected for loss of
organic mass. Organic C was calculated as the difference between the total and inorganic
class. Biogenic silica (BSi) analyses were carried out on every or every other level in SS86,
SS49, and SS1371. BSi was measured using the Demaster (1981)-method as modified by Conley
& Schelske (2001). Quality control of BSi-analyses was carried out by using reference samples
used in an international inter-laboratory comparison (Conley, 1998) and 10% duplicate samples.
Samples for ^15N/^14N at SS49 were analysed at the UC Davis Stable Isotope Facility, California,
USA on Hydra 20-20 or Anca-GSL isotope ratio mass spectrometers. Freeze-dried sub-samples
of sediment were milled to a fine powder using a Retsch mixer mill. Approximately 0.001g of
milled sediment was transferred to pre-weighed tin capsules, which were then sealed. The
isotopic ratio of ^15N/^14N is expressed using the delta (δ) notation in parts per thousand (or per
mille, ‰), where δ^15N (‰) = [(R_{sample} / R_{standard}) - 1] x 1000, where R is the ^15N/^14N ratio in the
measured sample or the appropriate standard. The standard for nitrogen is the δ^15N of
atmospheric nitrogen (commonly referred to as AIR).

*Statistical analyses*

In order to summarize changes occurring in the sediment pigment composition in the three lakes
over time, Principal Component Analysis (PCA) was undertaken using CANOCO for Windows
version 4.5. The analyses were based on log_{10}(x+1) transformed pigment concentrations, which
were centred and standardised prior to analysis. Bacterial chlorophyll-e homologs and their degradation products were grouped into total Bchl-e and Bppn-e before analysis of lake SS86. Because of possible uncertainties in the sediment chronologies, only visual comparisons between the PCA-axis 1 scores and the independent proxies for global environmental change (ice-core temperature inferences, effective precipitation) were undertaken.

**Results**

**Sediment chronology**

The cores used in this study cover a period of approximately 600–1600 years. Unsupported $^{210}\text{Pb}$ activities decline more or less exponentially with depth in SS86 and SS49 (Fig. 2). At SS86, total $^{210}\text{Pb}$ activity reaches equilibrium with the supporting $^{226}\text{Ra}$ at a depth of around 5 cm and at SS49 at 14 cm (Fig. 2). $^{137}\text{Cs}$ activity had a relatively well resolved peak between 2.5–2.75 cm at SS86 and at SS49 at 4.5–5.5 cm. The presence of a clear $^{241}\text{Am}$ peak around 2.5–2.75 cm at SS86 (Fig. 2) provides further support for allocating a bomb-testing date (1963) to these levels. Application of the CRS dating model (Appleby & Oldfield, 1978; Appleby, 2001), to the unsupported $^{210}\text{Pb}$ data, constrained by the $^{137}\text{Cs}$ profiles, suggests a sediment accumulation of $\sim 0.11 \text{ cm y}^{-1}$ over the last $\sim 100$ years at lake SS49. At SS86 the CRS model again indicates a relatively uniform sediment accumulation rate with 5.25 cm depth dating to $\sim 1880$. At SS86 the final chronology was determined using $^{210}\text{Pb}$ activity and extrapolation of simple linear regression of the $^{14}\text{C}$ chronology (Fig. 3). For SS49 only the environmental changes that occur within the period of $^{210}\text{Pb}$ activity are discussed in detail, so only the CRS chronology is referred to in the results and discussion.

$^{210}\text{Pb}$ activity at SS1371 was very low and irregular (P.G. Appleby, pers. comm.), possibly due to the extreme chemical environment of this permanently anoxic basin. As a result, the chronology for the freeze core is based on extrapolation of the $^{14}\text{C}$ chronology using a simple
linear regression fitted to the $^{14}$C dates and sediment surface (~2000 AD) (see Fig. 3 and D'Andrea et al., 2011 for details).

**Carbon, nitrogen and biogenic silica (BSi)**

All three lakes showed changes in organic carbon (OC) content of about 8% and in nitrogen (TN) content of about 1% over time resulting in conspicuous changes in the molar OC/TN ratio with a decline towards the present in SS49 and SS1371 while a very irregular profile was observed in SS86 (Fig. 4). The low-conductivity coastal site (SS49) had a relatively high OC content, 12–19 wt% with a decrease from the base of the core to ~13 cm and a subsequent increase to the top. An increase in TN content towards the top was reflected in a decrease in the molar OC/TN ratio particularly in the top 10 cm. The oligosaline lake, SS1371, and the nunatak lake, SS86, had lower organic carbon content, 4–12 and 3–11 wt%, respectively (Fig. 4). The TN profile at SS86 increased from ~7 cm to the top, while marked changes in the molar OC/TN ratio is observed between 13 and 5 cm.

Biogenic silica (BSi) content exhibited differences of an order of magnitude between the three lakes (Fig. 4). At SS49 the BSi content is high throughout the core (12–22 wt%) indicating high diatom abundance but is low (1–2.4 wt%) at SS1371 possibly due to silica dissolution. At SS86 BSi is more variable, with highest values (3–5 wt%) in the bottom part of the core.

**Sediment pigment record**

Different pigments dominate in the three study lakes and their concentrations differ with an order of magnitude between the relatively dilute lakes (SS49 and SS86) and the oligosaline lake (SS1371) (Fig. 4). Although chlorophyll-a, chlorophyll-b and fucoxanthin are labile compounds, the remainder of the pigments are relatively stable once incorporated into the sediment record. Pigments at the costal lake SS49 (Fig. 4a) indicate dominance of chromophyte algae (fucoxanthin, diatoxanthin, diadinoxanthin-like), as well as the presence of green algae and
higher plants (lutein, pheophytin-b) and cyanobacteria (canthaxanthin, echinenone). The labile pigments, chlorophyll-a and fucoxanthin, increase towards the top of the core. All other pigments have relatively uniform profiles throughout the core. The preservation indicator, chlorophyll-a/pheophytin-a (chl-a/ppn-a) ratio, indicates that no major changes in preservation conditions have occurred throughout the period covered by the core, except for significantly increased preservation (or more likely incomplete degradation) of the labile chlorophyll-a in the top few cm. These changes were reflected in the ordination of the pigments that showed clustering of all samples except for the top samples that diverged from the rest.

The dominant pigment at the oligosaline lake SS1371 is okenone, which increases towards the core top (Fig. 4b) and is specific to phototrophic purple sulphur bacteria, which require photic zone anoxia to thrive (Pfennig 1989). Generally high but fluctuating concentration of all pigments and high values of the preservation indicator (chl-a/ppn-a) indicates that preservation at this site was good, in accordance with the inferred anoxic conditions due to presence of the anoxygenic phototrophic bacteria. The algal pigments indicate dominance of green algae and higher plants (lutein, chlorophyll-b and pheophytin-b) and chromophyte algae (diatoxanthin). Indicators of total algal biomass (β-carotene, chlorophyll-a, pheophytins-a) show no marked trend throughout the core. Profiles of green algae and higher plant pigments (lutein, chlorophyll-b, pheophytins-b) show peak concentration at 14−16 cm and a decreasing trend towards the surface. Ordination of the pigments showed no discernible trends in the samples.

At SS86, located on the nunatak, marked changes in the pigment record occurred around 16−18 cm, with a shift from algal pigments to near complete dominance by bacterial chlorophyll-e (bchl-e) homologs specific to green sulphur bacteria (Fig. 4c). Like the purple sulphur bacteria, green sulphur bacteria require photic zone anoxia to grow (Pfennig 1989). This profile follows that of OC% but with a small lag. Algal pigments exhibited relatively large variation down core with two peaks near the base of the core, a peak at 5−9 cm, and a surface peak. Chromophyte-algal indicators (fucoxanthin, diatoxanthin, diadinoxanthin-like) dominate
the record, but indicators of green algae (lutein, pheophytin-b) are also an important component. Several common algal and higher plant indicators (diatoxanthin, alloxanthin, canthaxanthin and lutein) disappear or were masked by large amounts of bacterial pigments (bchl-e homologs) in the top half of the core. The preservation indicator show periods of increased preservation coinciding with periods of maximum algal pigment concentration, e.g. around 5–9 cm and at the core surface. Ordination of the pigments showed two distinct clusters representing the top and bottom half of the core.

Stable $\delta^{15}$N isotopes at SS49

Stable isotope measurements from SS49 (Fig. 5a) showed that prior to 1920, sediment $\delta^{15}$N measurements, though sparse, were stable around 1.3‰. Subsequently, $\delta^{15}$N values decline by ~1‰ from ~1920, whilst organic C and total N content of sediment samples almost double (Fig. 4a). OC/TN molar ratio exhibits a distinct decrease over the same period. The pigment PCA-I scores follow the observed isotopic trend. The timing of the decline in the lake sediment proxies are well in line with changes in NO$_3$ and $\delta^{15}$N from the Greenland ice cores (Hastings, Jarvis, and Steig 2009, Fig. 5b) while no trend is observed in the temperature trends from Nuuk (Fig. 5c).

Discussion

Changes in the phototrophic communities of three contrasting lakes in the Kangerlussuaq area, SW Greenland revealed very different responses to environmental change over the last 600–1600 years which are interpreted in relation to Leavitt et al.'s (2009) E-m flux model (Fig. 6). At SS1371 and SS86 the main driver is variability of E flux via effects on stratification and light availability for photosynthetic bacteria. At SS86 m flux was also important historically, resulting in lake level lowering, creation of a closed-basin system and the development of chemical stratification. At SS49 m and E fluxes were more constant as medium-term (decadal to
centennial) climate variability reduced, although atmospheric nutrient loading may have increased (Fig. 5). Our interpretations of the observed in-lake changes not only emphasize the varying importance of the mechanisms involved in transferring and filtering environmental forcing into ecological response by phototrophic communities but also that these relationships can themselves change over time.

*Mass flux: precipitation*

The most pronounced impact of the reduced precipitation from around 800 cal. yr BP on the study lakes was observed at the nunatak lake (SS86), where the pigment, carbon and BSi profiles indicate a switch from a freshwater, autotrophic lake to an increasingly chemolithotrophic system within a few decades around 1000 cal. yr BP (Fig. 4). This is concomitant with the latter part of the Medieval Climate Anomaly (Fig. 6) and a lake-level lowering, ultimately falling below the outlet level. This interpretation is consistent with studies of palaeoshorelines in the area indicating that precipitation (and lake levels) decreased briefly prior to 1000 cal. yr BP and then fell sharply to modern levels after ~700 cal. yr BP (Aebly & Fritz, 2009). SS86 has a very small catchment, too small to supply the lake with sufficient runoff to sustain an outflow during a period of negative precipitation balance. The role of lake:catchment ratios is exemplified by the neighbouring lake, SS32, an open basin with a larger catchment and an outflow resulting in different water chemistry characteristics (Anderson *et al.*, 2001; Table 1), that have not undergone the dramatic switches seen at SS86 (Perren *et al.*, 2009).

Closed-basin lakes are thought to be especially sensitive to climate change due to the tight coupling between water level and chemistry, forced by changes in temperature and effective precipitation (Fritz, 1996; Battarbee, 2000). However, the time period covered by the freeze core at SS1371 was too short to include the effect of the lake level lowering inferred for the area from ~1000 cal. yr BP. However, the presence of fossil shorelines around the lake indicate that this site has indeed been subject to lake-level lowering and solute concentration as
well as expansion of purple sulphur bacteria around 1000 cal. yr BP as observed in other lakes (e.g. SS4) in the region (McGowan et al., 2008).

An unquantified but possibly important component of changing m-flux in the Kangerlussuaq area is the increased regional deposition of loess that accompanied increased aeolian activity since the neoglacial cooling (Willemse et al., 2003). The area between SS1371 and the present ice sheet margin (Fig. 1) is subject to considerable aeolian input, sufficient to dilute the organic content of lake sediments particularly during the Little Ice Age (Anderson et al. 2012). The ecological effects of dust loading on remote lakes are well known due to their nutrient content (Field et al., 2010). The input of loess in the Kangerlussuaq area has been shown to have had considerable impact on the biological communities of these lakes (Perren et al., 2012; Bullard et al., submitted).

Mass flux: nutrient influx

The coastal and dilute lake (SS49) shows few changes in algal community composition prior to ~1900 AD (50 cal. yr BP) when pigment concentration increased (Fig. 4). Primary production in oligotrophic arctic lakes is dominated by relatively stable benthic communities, which can contribute substantially (80–98%) to the primary production (Vadeboncoeur et al., 2003). The inference of a substantial benthic community at SS49 is supported by the stratigraphic record with high concentrations of both chromophyte algal pigments and biogenic silica (the latter an order of magnitude higher than the other lakes, Fig. 4), indicating the importance of diatoms. Pigment indicators of green algae, higher plants, and cyanobacteria also likely originate from a benthic community, based on contemporary regional lake surveys. Michelutti et al. (2005) reported production increases in a number of arctic lakes, which they attributed primarily to recent warming although increased nutrient availability is implicit. Oligotrophic lakes are sensitive to even small increases in nutrient input due to the very low initial content (Leavitt et al., 2009) and there is now increasing evidence of the ecological effects of N-deposition at
remote arctic and alpine lakes (Galloway et al., 2008; Holtgrieve et al., 2011). Deposition rate of NOx are not well prescribed for western Greenland, but are low (<0.5 kg N ha yr\(^{-1}\)) although loadings are presumably greater in coastal regions where precipitation is higher (Hasholt & Søgaard, 1978).

The \(\delta^{15}N\) data at SS49 represent a significant change in the N biogeochemistry of the lake initiated at the beginning of the 20\(^{th}\) Century onwards (Fig. 5). The trend towards more-depleted \(\delta^{15}N\) values is comparable with those observed in other Arctic and northern hemisphere mountain lakes (e.g. Wolfe, Edwards & Aravena, 1999; Wolfe et al., 2003; Holtgrieve et al., 2011) and is consistent with increased inputs of anthropogenic N arising from fossil fuel combustion. Such anthropogenic sources are generally isotopically depleted in \(^{15}N\), and ice core records from Greenland document a progressive change from preindustrial \(\delta^{15}N\) values of \(~11\%o\) to ca. \(-1\%o\) in NO\(_3^\text{–}\); concomitant with a doubling in nitrate concentration in deposition during the 20\(^{th}\) Century (Hastings et al., 2009; Fig. 5). The agreement between \(\delta^{15}N\), pigment PCA-1 and the increasing organic C content since \(~1880\) is strongly supportive of a linear change in productivity in response to increased nutrient input.

Both the interpretation of \(\delta^{15}N\) and PCA-1 of the pigments can be affected by diagenesis (Leavitt, 1993; Talbot, 2001; Galman, Rydberg & Bigler, 2009) however, at SS49 the sediment data are inconsistent with a diagenetic effect as the observed changes occur over longer time frames (several decades) than expected with diagenesis. In general, pigments in the top 1-3 cm of lake sediments are interpreted to be affected by post-depositional degradation (Leavitt, 1993). Moreover, the anticipated isotopic effect of such processes would lead to an enrichment trend in \(\delta^{15}N\) (Galman et al., 2009), the converse of that observed. Climate change in recent decades in combination with its effects on changes in the catchment could be posited as a cause for the observed \(\delta^{15}N\) record, however, following statistical analysis of the meteorological data (Simpson, unpublished; Fig.5), no trend in 20\(^{th}\) Century monthly mean temperature (at Nuuk) was observed, a local pattern that is consistent with temperature trends throughout south west
Greenland (Box, 2002). Furthermore, the timing of recent Arctic warming is inconsistent with the observed change in $\delta^{15}\text{N}$ at this site.

Nitrogen accrual is an important process in Arctic ecosystems largely associated with terrestrial vegetation succession and the role of N-fixation by *Dryas* spp. and *Alnus* sp. (Engstrom *et al.*, 2000). However, changes of the in-lake N pool can also result from N-fixation by cyanobacteria which form extensive littoral mats in oligotrophic Arctic lakes. The soil microbial and hydrological processes that can result in N transfer from land to water are complex and highly seasonal due to the relationships between N-mineralization, snow melt and plant uptake (Hobbie, Nadelhoffer & Hogberg, 2002). Moreover, these processes are hypothesized to change with warming of the Arctic but presumably this is not important in the Kangerlussuaq area given the relatively steady temperatures recorded for much of the 20th Century (Fig. 5). The SS49 catchment is sparsely vegetated with thin soils, in contrast to inland catchments with more extensive shrub tundra and thicker soils. The greater precipitation at the coast, coupled with thin soils suggests that the sediment $\delta^{15}\text{N}$ profile of SS49 is reflecting direct deposition of NO$_x$ on to the lake. Interestingly, $\delta^{15}\text{N}$ profiles from sediment cores from inland lakes do not show the characteristic depletion observed in many Arctic lakes (Simpson, unpublished).

**Energy flux**

SS1371 showed considerable short-term variability but little directional changes in phototrophic community composition over time (Fig. 4). The pigment record at indicates input from higher plants and green algae, probably including input from the extensive *Chara* beds in the littoral zone, as well as chromophytes and the dominant phototrophic sulphur bacterial communities. The continual dominance of phototrophic purple sulphur bacteria suggests that the lake was meromictic or had prolonged periods of anoxic bottom water throughout the approximately 650-year period covered by the core. Indicators of phototrophic sulphur bacteria often are observed in both saline and freshwater lakes where light penetrates to anoxic waters and have been used
previously to infer major shifts in lake status (Leavitt, Carpenter & Kitchell, 1989; Vinebrooke et al., 1998; Pienitz et al., 2000; Squier, Hodgson & Keely, 2002; McGowan et al., 2008). The inference of meromictic conditions in the modern lake is supported by temperature thermistors deployed over 5 years at SS1371 (Anderson, unpublished). Strong stratification and good light transparency could promote the high-frequency variability in community structure, due to tight coupling between stratification and the phototrophic community (e.g. Pfennig, 1989; Vila et al., 1998). While the continued negative precipitation balance and resulting decreasing lake level inferred from fossil shorelines (Aebly & Fritz, 2009) over the last ~1000 years is the primary cause of the establishment of closed basin systems in the area it cannot explain the observed variability of the phototrophic community. On the other hand, considerable changes in temperature has been inferred from the ice cores during this period (Dahl-Jensen et al., 1998) and direct E-flux is therefore inferred as the primary controlling mechanism of the lake response (Fig. 6).

At the nunatak lake (SS86), dominance of green sulphur bacterial pigments in the upper half of the sediment core (Fig. 4) also indicate chemical stratification and light penetration into an anoxic hypolimnion (Pfennig 1989). The observed changes in the phototrophic community and geochemical markers suggest a transition from a dilute, oligotrophic lake to one with stronger seasonal chemical stratification, hypolimnic anoxia, and substantial phototrophic bacterial production over the last ~1000 years. A change in the main controlling mechanism of this lake from direct mass (precipitation) to energy (Fig. 6) is inferred in accordance with interpretations of trends at the other lakes in this study.

**Synthesis**

Changes in the phototrophic community in the Southwest Greenland lakes are driven by a combination of factors, including direct and indirect E and m forcing (e.g. radiative forcing, temperature, effective precipitation, ice-free period), mediated by location, catchment:lake ratios,
and in-lake processes (e.g. stratification). Although precipitation levels are low in much of the Arctic, with associated reduced hydrological fluxes from land to lake, catchment processes are still important and will mediate $m$ flux to the lake. For example, Anderson et al. (2008) found significant effects on biological structure associated with the arrival of Betula nana in SW Greenland through sequestration of nutrients. Any assessment of “drivers” of limnological change in the Arctic should include a terrestrial/vegetation component (Wookey et al., 2009) but conceptual models that have been developed to account for recent biological change at high latitudes have tended to downplay alternative hypotheses such as catchment processes (Smol & Douglas 2007). Moreover, as well as changing E and $m$-fluxes, in-lake processes (altered trophic interactions, benthic-pelagic coupling) and other ontogenetic processes (long-term accumulation of salts, dissolved organic carbon) may have considerable influence on biological structure independent of climate (Anderson et al., 2004), therefore making it difficult to infer unambiguously climate from biological remains in lake sediments (Lotter & Birks, 2003). The contrasting responses of the three lakes in this study to global environmental change processes over the last ~1600 years highlights the need to consider greater regional variability as we attempt to disentangle the ecological response of arctic lakes to multiple stressors. This is true even in a relatively small area (<150 km) such as the Kangerlussuaq lake district, which is a reasonably homogenous in terms of geology and vegetation. As highlighted by Kaufman (2012), recognizing the spatial complexity of lakes to regional climate forcing and the associated non-climatic filters is critical if lake sediment records are to be used to reconstruct past-climate variability in the Arctic. There is clearly a need for greater replication at the regional scale to help identify signals of environmental change.

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Table 1. Mean morphological and water chemistry characteristics of the lakes shown in Fig. 1 and other sites referred to in the text (SS32, SS4). For comparative purposes the mean water chemistry of three groups of lakes located along the fjord are given (Fig. 1) (see Anderson et al., 2001; Pla & Anderson, 2003 for details). The formal name for SS4 is Braya Sø.

<table>
<thead>
<tr>
<th>Units</th>
<th>Coastal</th>
<th>Central: head of fjord</th>
<th>Ice margin</th>
<th>Coastal</th>
<th>Oligosaline</th>
<th>Nunatak</th>
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Figure legends

Figure 1. Location of the study sites (SS49, SS1371, SS86) along the Kangerlussuaq fjord (Southwest Greenland) on a transect from the sea to the ice sheet margin, together with the location of two additional lakes referred to in the text (SS4, SS32; see Table 1). The rectangles indicate the approximate location of the three lake groups referred to in Table 1 (coastal, central, ice margin) for comparative purposes.

Figure 2. $^{210}$Pb and $^{137}$Cs profiles for SS49 (left) and SS86 (right). Uppermost panels are total and supported $^{210}$Pb activity; the central panels are unsupported $^{210}$Pb while the lowermost plots show the $^{137}$Cs and $^{241}$Am at SS86, the latter indicating the well resolved radionuclide profiles despite the low sedimentation rates.

Figure 3. Cross correlation of freeze and Russian cores. A: SS86 (Nunatak lake), B: SS1371 (oligosaline lake), C: SS49 (coastal lake). $^{14}$C dates used for constructing an age-depth curve are included in A, while they fall outside the range of the plot in B (for further details see D’Andrea et al., 2011). In C the bottom $^{210}$Pb date and one of two $^{14}$C dates are included in the plot while all three points have been used to construct the age-depth curve for samples below 11cm. Note that SS1371 is correlated by %OC (organic carbon) not %TC (total carbon) since there were significant amounts of inorganic carbon in the sediment from this lake.

Figure 4. Sediment pigment record and geochemical proxies of the study lakes. Biogenic silica (BSi), organic carbon (OC), and total nitrogen (TN) presented as weight percentage, OC/TN as molar ratio. Chlorophylls (chlorophyll-a and b, pheophytins-a and b) and carotenoids (the remainder of the pigments) as concentration in $\mu$mol g$^{-1}$OC. The ratio of chl
a/ppn a is included as a degradation signal. Note different scales on x-axis. A) Coastal lake SS49. B) Oligosaline lake SS1371, Okenone total include the cis- and trans-peak, pheophytins-a and b include pheophytin and pyro-pheophytin as they are both important degradation products in this lake. C) Nunatak lake SS86, Bchl-e total includes 8 homologs of bacteriochlorophyll-e.

Figure 5. A: δ^{15}N and pigment PCA-1 at SS49 plotted against ^{210}Pb timescale; B: δ^{15}N and NO₃ in the Greenland ice core (Hastings et al., 2009) and C: mean annual temperature at Nuuk, showing representative trends in air temperature for SW Greenland since 1860.

Figure 6. Conceptual interpretation of the relative importance of energy (E) and mass (m) in controlling lake response (summarized by PCA axis 1 and BSi) to environmental change according to Leavitt et al., 2009. While direct influx of m through precipitation is inferred to have a strong control of all lakes before ~1000 cal yr BP (A), direct influx of E is inferred to have a greater influence in closed basin systems (SS1371 and SS86 after ~1000 cal yr BP)(B). SS49 has not been included in the plot due to no change in the main controlling factor during the investigated time period. Supplementary palaeolimnological proxies have been included for comparison; the temperature reconstruction from the Greenland GRIP and Dye-3 ice cores (Dahl-Jensen et al., 1998), regional lake-levels (Aebly & Fritz, 2009), and diatom-inferred conductivity from SS4 (McGowan et al., 2003).
Figure 1, Reuss et al.
Figure 2. Reuss et al.
Figure 3, Reuss et al.
Figure 4, Reuss et al.
Figure 5, Reuss et al.

A. PCA axis sample scores

B. Nitrate and δ¹⁵N

C. Mean annual temperature °C

Date

Freshwater Biology
Figure 6, Reuss et al.