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# Springtime coupling between chlorophyll *a*, sea ice and sea surface temperature in Disko Bay, West Greenland

M.P. Heide-Jørgensen [a,*], K.L. Laidre [a,d], M.L. Logsdon [b], T.G. Nielsen [c]

[a] *Greenland Institute of Natural Resources (GINR), c/o Danish Polar Center, Strandgade 100H, DK-1401, Copenhagen K, Denmark*
[b] *University of Washington, School of Oceanography, Box 357940, Seattle, WA 98195, USA*
[c] *National Environmental Research Institute, Box 358, Frederiksborgvej 399, DK-4000 Roskilde, Denmark*
[d] *Polar Science Center, Applied Physics Laboratory, University of Washington, 1013 NE 40th St., Seattle, WA 98105, USA*

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## Abstract

Alterations in sea ice and primary production are expected to have cascading influences on the food web in high Arctic marine ecosystems. This study spanned four years and examined the spring phytoplankton production bloom in Disko Bay, West Greenland (69°N, 53°W) (using chlorophyll *a* concentrations as a proxy) under contrasting sea ice conditions in 2001 and 2003 (heavy sea ice) and 2002 and 2004 (light sea ice). Satellite-based observations of chlorophyll *a*, sea ice and sea surface temperature were used together with in situ depth profiles of chlorophyll *a* fluorescence collected at 24 sampling stations along the south coast of Disko Island (5–30 km offshore) in May 2003 and 2004. Chlorophyll *a* and sea surface temperatures were also obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS: EOS-Terra and AQUA satellites) between March 2001 and July 2004. Daily SMMR/SSMI sea ice data were obtained in the same years. An empirical regional algorithm was developed to calibrate ratios of remotely sensed measurements of water leaving radiance with in situ chlorophyll *a* fluorescence. The optimal integration depth was 0–4 m, explaining between 70% and 91% of the variance. The spatial development of the phytoplankton bloom showed that the southwestern corner of the study area had the earliest and the largest spring phytoplankton bloom. The eastern part of Disko Bay, influenced by meltwater outflow from the glaciers, shows no signs of an early phytoplankton bloom and followed the general pattern of an accelerated bloom soon after the disappearance of sea ice. In all four years the coupling between phytoplankton and sea ice was bounded by average open water between 50% and 80%, likely due to the combined availability of light and stable open water. The daily incremental growth in both mean chlorophyll *a* density (chlorophyll *a* per volume water, $\mu g\, l^{-1}$) and abundance (density of chlorophyll *a* extrapolated to ice free areas, tons) estimated by linear regression (chlorophyll *a* vs. day) between 1 April and 15 May was highest in 2002 and 2004 (light ice years) and lowest in 2001 and 2003 (heavy ice years). In years with late sea ice retreat the chlorophyll *a* attained only slightly lower densities than in years with early sea ice retreat. However, the abundance of chlorophyll *a* in light ice years was considerably larger than in heavy ice years, and there was an obvious effect of more open water for light-induced stimulation of primary production. This observation demonstrates the importance of estimating chlorophyll *a* abundance rather than density in sea ice covered areas. This study also presents the first regional calibration of MODIS chlorophyll *a* data for Arctic waters.

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[*] Corresponding author. Tel.: +45 72488131; fax: +45 32880101.
*E-mail address:* mhj@dpc.dk (M.P. Heide-Jørgensen).

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## 1. Introduction

The cascading effects of changing climate on biophysical pathways in Arctic and sub-Arctic seas are of concern, as these ecosystems are particularly susceptible to perturbations from alterations in sea ice cover or physical and biological oceanography. Annual sea ice cover influences the solar penetration, stratification, nutrient availability, and water temperature, and most importantly changes the energy flux and productivity during the spring phytoplankton bloom. Over the past 30 years, Arctic sea ice has shown a declining trend (Parkinson, 2000). This trend was regionally reversed in West Greenland and Baffin Bay where the extent of sea ice increased between the 1950s and 2002 (Stern and Heide-Jørgensen, 2003; Heide-Jørgensen and Laidre, 2004). However, declines in sea ice were observed in West Greenland in 2003 and 2004 (GINR, unpubl. data).

A critical component of the link between the extent and residency of sea ice and the production of fisheries resources is the feeding conditions of the herbivorous copepods (Hansen et al., 2002). During the spring period, the sea ice presumably leaves a 'footprint' in the sea surface temperature. The break up of the sea ice with increased sunlight exposure of the water column triggers the spring phytoplankton bloom that enters into an exponential increase. The exponential phase is short and ends abruptly when nutrients above the pycnocline in the euphotic zone are exhausted. Models of the pelagic food chain suggest that the timing of the break-up of sea ice is directly linked to the efficiency of the trophic transfer of the spring bloom production to higher trophic levels (Hansen et al., 2002). Indirect effects and effects transported up to the top of the food chain are less well understood. It is likely that the increase in sea ice, together with lower spring sea water temperatures, directly alters the coupling between primary production and forage fish biomass in West Greenland (Pedersen and Kanneworf, 1995).

Disko Bay (Fig. 1) is a polynya located in West Greenland between sub-Arctic waters of southwest Greenland and the high Arctic waters of Baffin Bay. It is influenced by both the northward warm West Greenland current of Atlantic origin and the southward current of polar origin in Baffin Bay. Annual sea ice is an important initial structuring agent for springtime conditions in Disko Bay. Sea ice usually forms early in winter, generally in January, and reaches its peak coverage in March. It retreats in April and May and is completely melted by June. No perennial sea ice is found in Disko Bay, except for icebergs from the highly productive Jakobshavn glacier in the eastern part of the bay.

The sea ice coverage in Disko Bay is extensive even in light ice years, covering most of the bay. Stretches of open water however may form and persist throughout the winter period. These open water fields may be caused by wind, upwelling, currents, movements of icebergs, or advection of warm water of Atlantic origin (particularly in the southwestern part of the Bay).

The pattern of sea ice formation and decay is relatively predictable, although there are occasional years with unusually severe ice formation or large fluctuations in formation and coverage. An example of the latter is the sea ice conditions that occurred in Disko Bay between 2001 and 2004. In the winters of 2001 and 2003, sea ice cover was more extensive than the average conditions for the previous 20 years. However, in 2002 and 2004, sea ice cover was far below average conditions. This variability provides a uniquely contrasting situation for examining how the spring bloom is manifested in Disko Bay under different ice regimes.

Disko Bay is a relatively deep basin (>400 m) (Fig. 1), and sedimentation of phytoplankton begins shortly after the peak bloom phase (Nielsen and Hansen, 1995). Extreme wind force is necessary to reintroduce nutrients from below the pycnocline. During winter, the water column is well mixed and both the lack of daylight and ice coverage prevents net growth of the phytoplankton. Various studies have examined the phytoplankton bloom in northern Disko Bay by in situ sampling at one coastal station (Andersen, 1977, 1981a,b; Levinsen et al., 2000; Madsen et al., 2001), but no attempts have been made to examine the phytoplankton bloom and its relation to sea ice production at multiple stations, or at larger spatial scales covering the entire Disko Bay.

Contrasts between different regions of the Arctic are necessary in order to make generalizations about the effect of sea ice on spring phytoplankton. The timing of the spring phytoplankton bloom on the southeastern

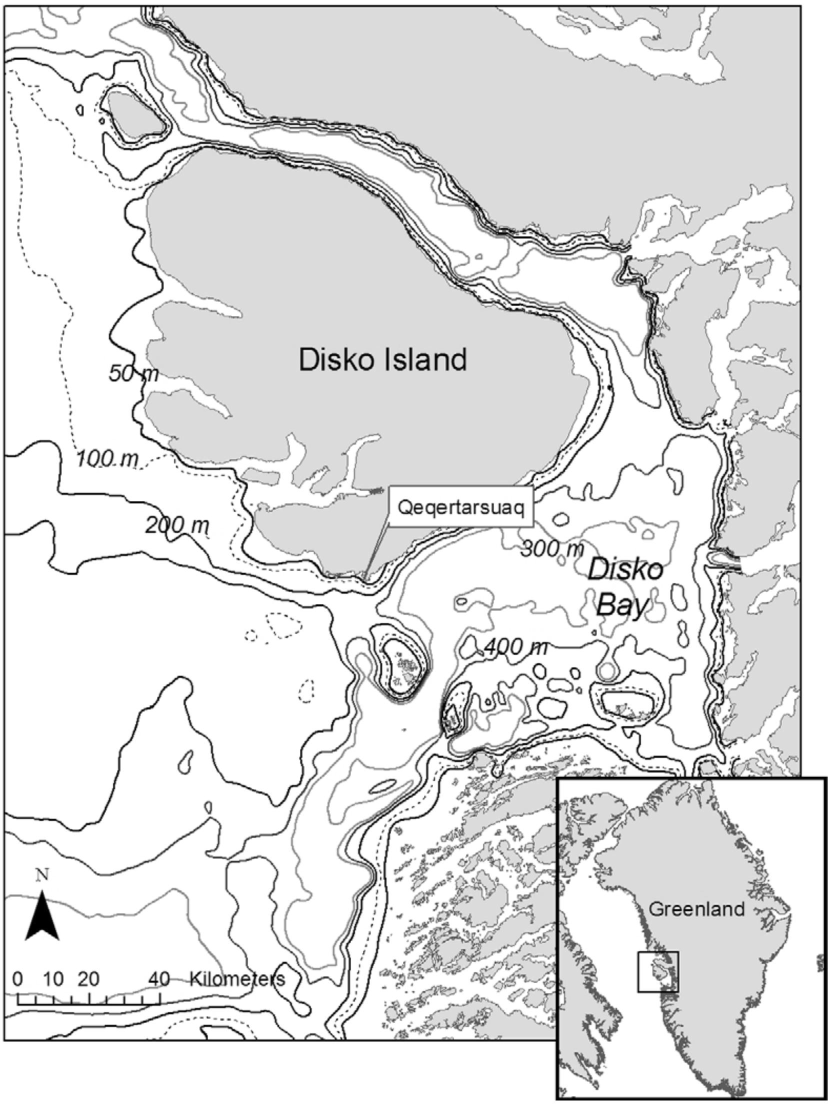

Fig. 1. Bathymetry, names of localities and sampling stations in the study area.

shelf of the Bering Sea seems to be tightly related to the timing of the sea ice retreat. If the sea ice retreats before mid-March, then the spring bloom is delayed until May or June when thermal stratification stabilizes the water column (Stabeno et al., 2001; Hunt et al., 2002; Stabeno and Hunt, 2002). If sea ice persists after mid-March, then an early season spring bloom occurs in cold water (<0 °C) in association with and right after the disappearance of the ice.

We have examined how contrasting sea ice conditions in 2001 and 2003 (heavy ice years) and 2002 and 2004 (light ice years) manifest themselves as constraints on the spring phytoplankton production in West Greenland. To facilitate broader spatial coverage, in situ samples collected at standard sampling stations were coupled with remote satellite-based observations of chlorophyll *a*, sea ice, and sea surface temperature.

## 2. Data and methods

### 2.1. In situ measurements of fluorescence

Depth profiles of chlorophyll *a* fluorescence were recorded in May of both 2003 and 2004 at stations along the south of Disko Island (Fig. 1), approximately 5–30 km offshore in Disko Bay ($n = 24$ in 2003, $n = 8$ in 2004) from the R/V *Porsild* (Arctic Station, Copenhagen University, Fig. 2). A SeaBird 25 CTD (V 4.0a)

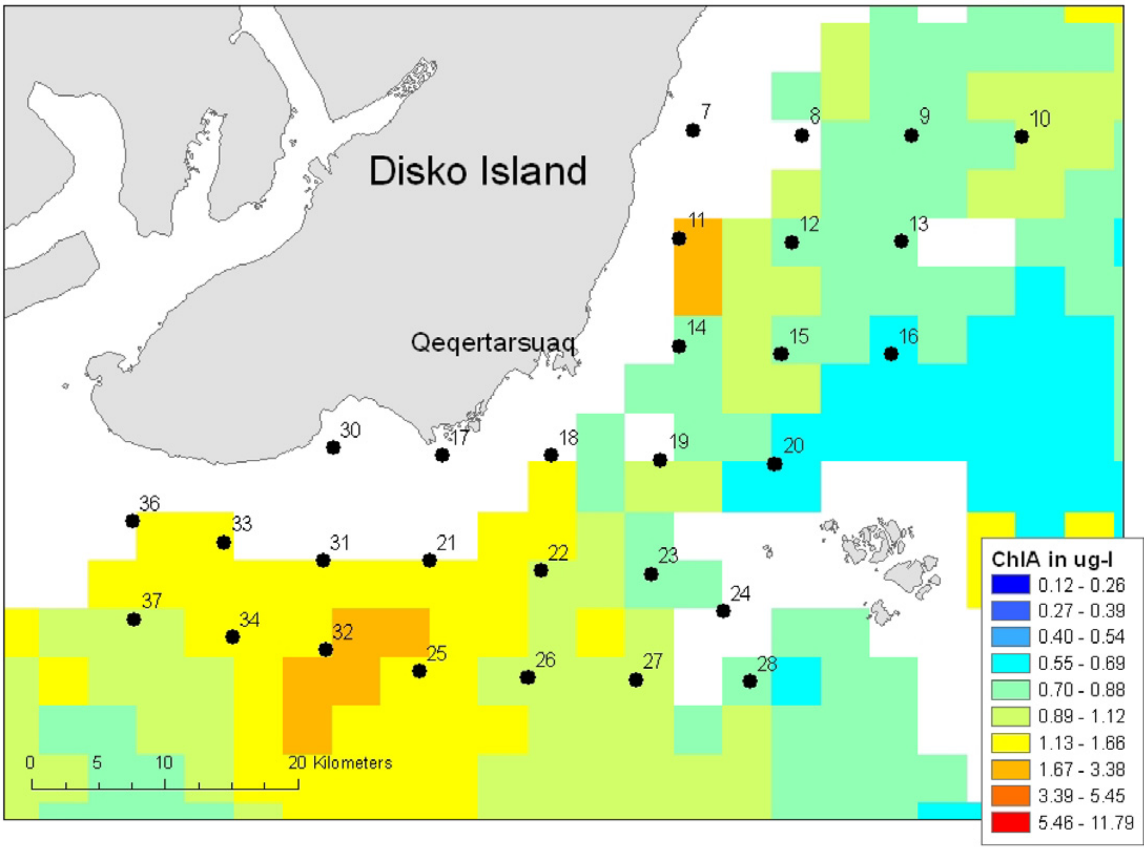

Fig. 2. Standard stations where data were collected during in 2003 and 2004. MODIS level 3 chlorophyll a data are shown behind the grid.

equipped with a Chelsea Aquatrack III fluorometer was used to monitor depth, temperature, salinity, and fluorescence between the surface and the maximum depth at each station (ranging from 26 to 97 m in 2003 and 39 to 228 m in 2004). Chlorophyll *a* was measured on 100–500 ml triplicate samples filtered onto GF/F filters, extracted for 24 h in 96% ethanol (Jespersen and Christoffersen, 1987) and analyzed on a Turner 770h fluorometer (Turner Designs Inc., Sunnyvale CA, USA), calibrated against a chlorophyll *a* standard (for further details see Sejr et al., in press). Chlorophyll *a* concentration was integrated over intervals between 0 and 10 m and from 0 to the maximum depth recorded at each station.

### 2.2. Conversion of in situ fluorescence to chlorophyll a

The fluorescence measurements were calibrated against in situ chlorophyll *a* concentrations in samples taken at a standard station just outside the Qeqertarsuaq grid (Fig. 2) over a four day period between 28 April and 5 May 2003 (Sejr et al., in press). The correlation between average measurements of down- and upcast fluorescence readings and density of chlorophyll *a* at depths of 1, 5, 10, 15, 20, 25, 30, 35, 40 and 45 m was described by an exponential function:

$$\text{Chl}\ a = 0.1027^{*}\text{e}^{(2.2447*V)}$$

where Chl *a* is the measured chlorophyll *a* in $\mu\text{g}\,\text{l}^{-1}$ and $V$ is the voltage reading from the fluorometer ($r^2 = 0.65$). This equation was used to calculate depth averaged (0–10 m) chlorophyll *a* density at all stations in Disko Bay where fluorescence was sampled (Fig. 2).

### 2.3. Ocean color and ocean temperature

Data were obtained from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS: EOS-Terra and AQUA satellites). Data products included MODIS level 3 chlorophyll *a* (MOD26, SeaWIFS analog

OC3M) and sea surface temperature (4 micrometer, MOD37). Level 3 data products were examined at weekly time intervals (8-day means) and provided at a coarse (4 km) spatial resolution (Campbell et al., 1995; Carder et al., 2003). Additional estimates of chlorophyll *a* in Disko Bay were obtained from MODIS level 2 data products and through the development of a simple empirical regional algorithm based upon the water-leaving radiance obtained by the sensor and corresponding daily in situ measurements. The standard level 2 data processing of the satellite data occurred over daily time intervals and at a 1 km resolution. The processing of level 2 estimates of water-leaving radiance at the wavelengths of 421, 443, 488, 531, and 551 nm include atmospheric correction and geo-registration, and a global algorithm (OC3M) to provide chlorophyll *a* estimates ($\mu g\, l^{-1}$), (Martin, 2004; O'Reilly et al., 2000; Gordon and Wang, 1994).

All data were obtained in Hierarchical Data Format (HDF) from the Goddard Earth Sciences Distributed Active Archive Center (GES DAAC) and converted to ESRI ArcINFO 9 grid format for each weekly mean across the time series, where the center of each cell received the estimate of average (or maximum) chlorophyll *a* concentration ($\mu g\, l^{-1}$) or sea surface temperature (°C) for that week. Only good quality data (quality code 0) were used. Level 3 data were available from the Terra satellite during 2001–2003 and from the Aqua satellite for 2003–2004. Discontinuation of the Terra satellite in 2003 required a bridge calibration between the Terra and Aqua satellites to make the values comparable. For the period between mid March and end of June 2003 mean weekly values were calculated for both instruments and a simple regression was conducted between the Terra and Aqua measurements (Fig. 3). Values were well correlated and the Terra values were nearly doubled to match the Aqua values.

A time series geodatabase of the in situ measurements and the remotely sensed level 2 data was constructed in the ESRI ArcGIS® grid format. Level 2 image data were converted directly from the Hierarchical Data Format (HDF) and were processed with WimSoft®. Individual pixel values from the same day and close to the sampling location of the in situ samples of chlorophyll *a* were extracted. Thus direct in situ measurements of chlorophyll *a* density ($\mu g\, l^{-1}$) were spatially comparable with daily remotely sensed estimates of water-leaving radiance and chlorophyll *a* at a 1 km resolution for all cloud free days, and at a 4 km resolution for chlorophyll *a* alone over the associated week.

### 2.4. Cloud cover

Partial or complete cloud coverage potentially obstructs satellite sensing of ice-free pixels during the satellite's passage. Clear sky or cloud coverage below a certain threshold cannot be expected during all satellite passes, and thus cloud coverage must be evaluated during the study period. Daily observations of proportional cloud cover were collected from a research station at Qeqertarsuaq (Fig. 1), at the south end of Disko Island over looking Disko Bay. Cloud cover observations were collected each day at 10:00, 15:00 and 20:00

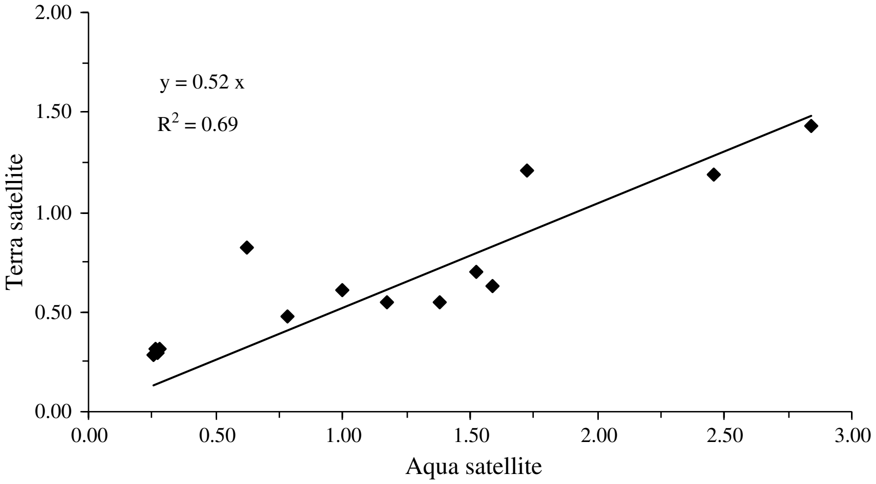

Fig. 3. Linear regression of weekly mean MODIS level 3 values of chlorophyll *a* ($\mu g\, l^{-1}$) from the Terra satellite vs. the means from the Aqua satellite.

GMT during routine monitoring of weather conditions. Average daily cloud cover was calculated for each day between March 2001 and June 2004.

In this study, a threshold of $<21\%$ cloud cover was assumed to allow for a complete census of ice-free pixels on the sea surface by the MODIS instrument. This threshold was considered a conservative approach to ensure that ocean color readings were not obstructed by clouds. A higher threshold value might introduce a bias, since cloud coverage and open water usually are highly correlated in the Arctic. We calculated the total number of days in each week for which $<21\%$ average cloud coverage was observed throughout the study period. For each 8-day MODIS summary period, if at least one day was determined to have $<21\%$ cloud coverage, the week was assumed to be a valid representation of either the maximum daily cloud-free pixel value for the week, or the average of the cloud-free pixel values for the week. Periods that did not meet the 'cloud-free' criteria were removed from the analysis, even if MODIS data were available. We assumed that if enough cloud-free sky was available for MODIS sensors, those pixels not identified as chlorophyll *a* were covered by sea ice.

### 2.5. Spatial analysis

Chlorophyll *a* and sea surface temperature pixels within the defined study area (Fig. 1) were extracted from each 8-day time series between 2001 and 2004. Weekly chlorophyll *a* density was calculated based on the number of pixels and unique chlorophyll *a* concentrations (or temperature values) observed during that week, or weekly mean density ($D_w$):

$$\overline{D}_w = \left(\sum_{i=1}^{h}(\mathrm{PC} * \mathrm{IC})\right) \Big/ PN_w$$

where *i* indexes the lowest chlorophyll *a* value observed for the week in Disko Bay to *h*, the highest chlorophyll *a* value observed for the week, IC is a specific chlorophyll *a* value (to 0.01 resolution), PC is pixel count for each specific chlorophyll *a* value, and $\mathrm{PN}_w$ is the total number of pixels observed within the study area for that week. Densities ($\overline{D}_w$) were weighted by the spatial area in number of pixels observed for the week to calculate a potential measure of weekly chlorophyll *a* abundance ($A_w$) within the study area (tons of chlorophyll *a*), using:

$$A_w = (k * \overline{D}_w)/PN_w$$

where *k* is the product of the area of each pixel (4 $\mathrm{km}^2$) and the depth to which the density was integrated. This depth was decided to be 4 m based on the calibration between the in situ measurements and MODIS level 1 data.

Chlorophyll *a* abundance estimates for weeks without chlorophyll *a* measurements (due to prohibitive cloud cover and consequent lack of MODIS data) were linearly interpolated from 8-day averages using values from adjacent weeks. Weekly estimates of chlorophyll *a* density and abundance and sea surface temperatures were examined as a time series. Estimates were weighted by sampled area in each year in proportion to the entire Disko Bay study area (46,000 $\mathrm{km}^2$).

In situ chlorophyll *a* values were correlated to 1 km level 1 MODIS chlorophyll *a* and band ratios when data were available. Band ratios were calculated between the 551 wavelength and 412, 443, 488, and 531 on each date when data were available. Band ratios were correlated with in situ chlorophyll *a* values and non-linear fits were calculated for each ratio to produce regionally specific realizations of reflectance values in Disko Bay. Fits were produced for each of 7 integration depths where in situ chlorophyll *a* abundance was summed across the water column.

### 2.6. Sea ice data

Sea ice concentration data were obtained from passive microwave telemetry available from the Defense Meteorological Satellite Programs Special Sensor Microwave/Imager dataset. Sea ice concentration (1% resolution) was derived using the Bootstrap algorithm following Comiso (1995), where daily sea ice concentrations for the Northern Hemisphere were mapped to a polar stereographic projection (true at 70°N) at a 25 km resolution. Sea ice data obtained from the NSIDC were converted from raw binary to ASCII format using a program written in Compaq Visual Fortran 90 and imported into a geographic information system (ESRI ArcINFO 9) as raster grids. The center of each cell received the estimate of average sea ice concentration in that 625 km$^2$ area and pixels were consistently classified as land or sea ice across all years. Daily ice cover between 1 March and 30 June was extracted and the fraction (or percentage) of open water was calculated as:

$$F = \left(\sum_{i=1}^{h} \mathrm{PC} * (1 - (\mathrm{IC}/100))\right) \Big/ \mathrm{MHA}$$

where $i$ indexes the lowest sea ice concentration in Disko Bay to $h$, the highest sea ice concentration, IC is specific sea ice concentration calculated in full integer units and recorded as a percent, PC is pixel count for each specific sea ice concentration, and MHA is the area in the defined study area in number of pixels. Statistical significance was determined at the 5% level.

## 3. Results

### 3.1. Cloud cover

There was no statistically significant relation between the average weekly cloud coverage (all weeks with <21% cloud cover were assumed to be ‘cloud free’) and the number of pixels with chlorophyll *a* or sea surface temperature sensed by MODIS (ANOVA, $p > 0.10$). There was, however, a significant positive relation of week number with the number of chlorophyll *a* pixels for all four years, illustrating that as weather improved during spring, the number of pixels available to be detected increased.

The months of March, April, and May were considered the critical period for spring bloom development and mean weekly cloud coverage ranged between 20% and 92% during this time (2001–2004, Table 1). During these three months, only six 8-day periods did not meet the <21% cloud cover threshold and were excluded. In one case, all weeks met the criteria and were used (i.e., 2001). After filtering for cloud conditions, 44 8-day time periods of chlorophyll *a* or sea surface temperature were used in the analysis.

Table 1
Weekly overview of cloud coverage and MODIS level 3 pixels for chlorophyll *a* and sea surface temperature

| Week | Julian day | Days with <21% clouds | | | | Average cloud coverage | | | | Number of Chl *a* pixels | | | | Number of sea surface temperature pixels | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2001 | 2002 | 2003 | 2004 | 2001 | 2002 | 2003 | 2004 | 2001 | 2002 | 2003 | 2004 | 2001 | 2002 | 2003 | 2004 |
| 1 | 65 | 1 | 5 | 3 | 0 | 30 | 67 | 42 | 71 | 0 | 0 | 0 | 197 | 29 | 0 | 2216 | 77 |
| 2 | 73 | 4 | 4 | 1 | 3 | 52 | 36 | 81 | 48 | 89 | 0 | 1531 | 60 | 522 | 0 | 1814 | 32 |
| 3 | 81 | 5 | 3 | 2 | 1 | 49 | 21 | 52 | 70 | 16 | na | 271 | 488 | 44 | na | 342 | 473 |
| 4 | 89 | 6 | 3 | 3 | 1 | 46 | 21 | 59 | 70 | 52 | 66 | 220 | na | 149 | 132 | 278 | 643 |
| 5 | 97 | 0 | 1 | 1 | 3 | 65 | 92 | 57 | 39 | 412 | 590 | 52 | 733 | 80 | 732 | 198 | 1200 |
| 6 | 105 | 0 | 0 | 2 | 4 | 55 | 77 | 67 | 34 | 489 | 772 | 2379 | 752 | 1396 | 679 | 2590 | 1836 |
| 7 | 113 | 0 | 5 | 2 | 1 | 51 | 73 | 67 | 53 | 329 | 1512 | 1992 | 2261 | 604 | 2211 | 2246 | 1488 |
| 8 | 121 | 0 | 1 | 2 | 3 | 46 | 70 | 52 | 67 | 445 | 1639 | 2701 | 2403 | 452 | 2406 | 2655 | 2728 |
| 9 | 129 | 1 | 1 | 1 | 3 | 58 | 72 | 86 | 31 | 1217 | 1398 | 2194 | 3342 | 1546 | 1672 | 2206 | 1580 |
| 10 | 137 | 1 | 5 | 1 | 5 | 37 | 72 | 74 | 39 | 1487 | 1827 | na | 2803 | 2389 | 2283 | 2582 | 2664 |
| 11 | 145 | 1 | 3 | 3 | 4 | 46 | 66 | 54 | 20 | 986 | 2197 | na | na | 1567 | 2681 | 2672 | 2374 |
| 12 | 153 | 2 | 0 | 4 | 0 | 85 | 80 | 39 | 86 | 1883 | 1004 | 3636 | na | 2578 | 1788 | 2640 | na |
| 13 | 161 | 3 | 2 | 6 | 2 | 84 | 37 | 28 | 55 | 2223 | 1059 | 4034 | 3942 | 2642 | 2665 | 2660 | na |
| 14 | 169 | 1 | 1 | 3 | 2 | 71 | 77 | 41 | 53 | na | 1172 | 3987 | 4003 | na | 2500 | 2578 | na |
| 15 | 177 | 1 | 0 | 2 | 1 | 60 | 58 | 50 | 66 | na | 2006 | na | na | na | 2249 | 2587 | na |
| 16 | 185 | 5 | 2 | 4 | 0 | 66 | 36 | 27 | 68 | 2252 | 2215 | 3223 | 3199 | 2666 | 2618 | 2586 | na |
| 17 | 193 | 4 | 0 | 1 | 1 | 76 | 30 | 71 | 85 | 2209 | 2175 | 3941 | 1764 | 2504 | 2394 | 2572 | na |
| 18 | 201 | 4 | 1 | 1 | 1 | 66 | 43 | 78 | 79 | 2235 | 2135 | 3547 | 3035 | 2645 | 2511 | 2285 | na |
| 19 | 209 | 0 | 0 | 1 | 0 | 80 | 63 | 28 | 54 | 2228 | 1847 | na | na | 2664 | 2668 | 2723 | na |

### 3.2. In situ measurements of water column properties

In early May the water column in Disko Bay shows a characteristic stratification with low salinity and positive temperatures in the surface layer, extending down to a pycnocline just above 20 m (Fig. 4). The shallow freshwater-influenced layer results from the sea ice melt and the warmer surface temperature from solar radiation. Fluorescence peaks above the pycnocline at about 10 m and declines rapidly from 15 m to the bottom. The surface temperature was higher in May 2003 than in 2004 (Table 2, Fig. 4).

The correlation between the in situ chlorophyll *a* measurements and the weekly level 3 MODIS observations were very weak but positive ($\log(\text{MODIS level 3}) = 0.251 + 0.053(\log \text{ in situ chl } a \text{ 0–10 m})$, $r = 0.19$). Overall a poor relationship existed between these data and in situ measurements at all depths. Similarly, the correlation between in situ chlorophyll *a* and daily 1 km MODIS observations was weak and negative ($\log(\text{MODIS level 1}) = -0.276 + 0.276(\log \text{ in situ chl } a \text{ 0–10 m})$, $r = 0.19$). Neither correlation was significant at the 0.05 level.

### 3.3. Chlorophyll a and sea surface temperature spatial patterns

In April, monthly sea surface temperatures ranged between −1.8 and 1 °C (Fig. 5). Temperatures increased rapidly in May with the disappearance of sea ice, rising to 3 °C. By June, most of the southern part of Disko Bay was at least 3 °C, with lower temperatures observed farther to the west and offshore. Sea surface warming progressed from south to north, reaching Disko Island then extending eastward into the bay. Interannual comparison of the temperature patterns suggests the largest contrast occurred between 2002 and 2003, where

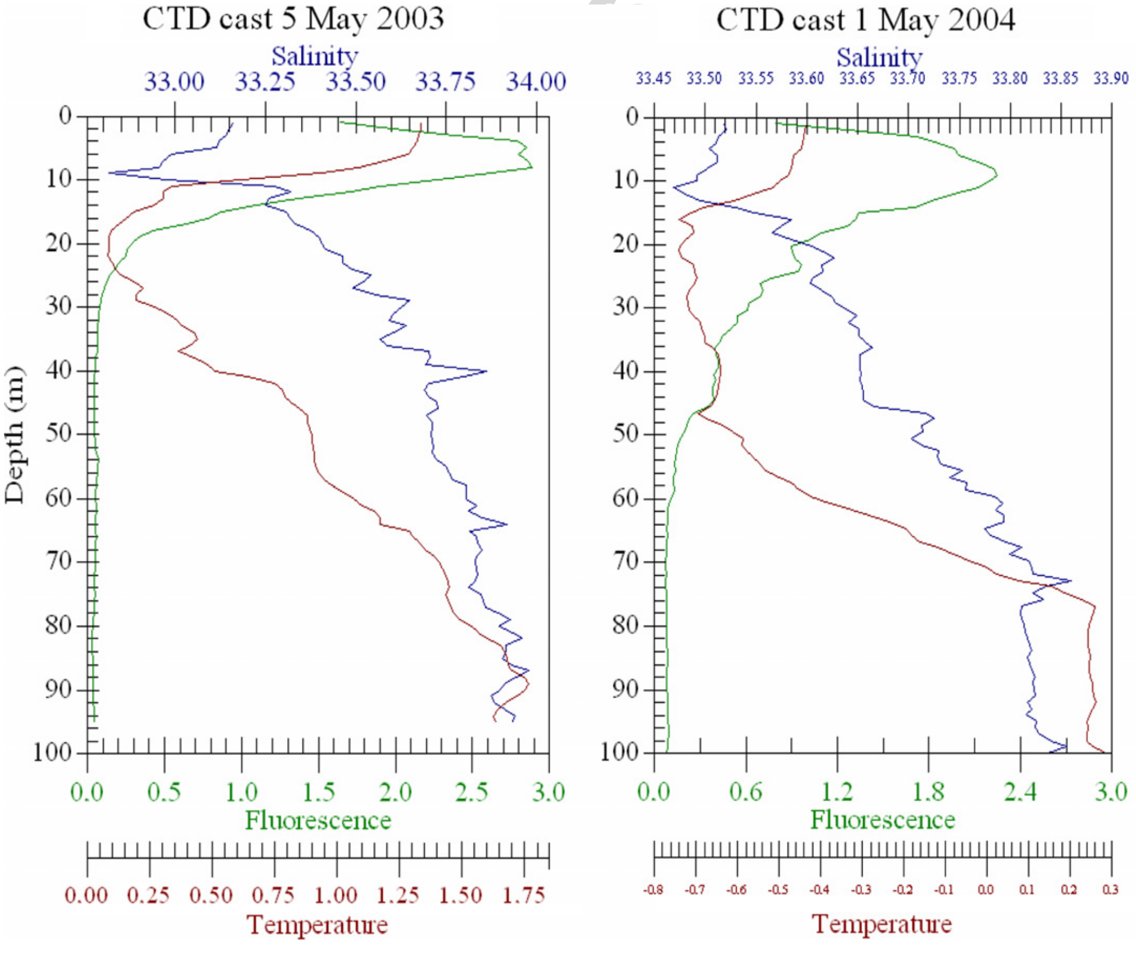

Fig. 4. Examples of temperature (°C), salinity (pss) and fluorescence (∼Chl *a* $\mu g\, l^{-1}$) profiles from May 2003 and 2004.

Table 2
Timing of sea ice coverage, sea temperature increase, and chlorophyll *a* (MODIS level 3) weekly density and abundance between 2001 and 2004 in Disko Bay, West Greenland

| | 2001 | 2002 | 2003 | 2004 |
|---|---|---|---|---|
| Date for 50% retreat of sea ice | 28 April | 25 April | 28 April | 18 April |
| Date for 80% retreat of sea ice | 12 June | 21 May | 12 June | 23 May |
| Sum of ice coverage per day (March–May) | 58.12 | 52.63 | 49.84 | 46.22 |
| Average ice coverage in March | 0.82 | 0.92 | 0.60 | 0.71 |
| Average ice coverage in April | 0.67 | 0.53 | 0.62 | 0.53 |
| Average ice coverage in May | 0.40 | 0.26 | 0.41 | 0.27 |
| Date for sea surface temperature above 2 °C | 6 June | 28 June | 6 June | 24 May |
| Week for peak chlorophyll *a* density (day nr) | May 3 week (137) | May 2 week (129) | June 1 week (153) | May 2 week (129) |
| Density of chlorophyll *a* at peak ($\mu g\, l^{-1}$) | 3.88 | 4.37 | 2.80 | 4.53 |
| Week for peak abundance of *chlorophyll a* (day nr) | May 3 week (137) | May 4 week (145) | June 1 week (153) | May 2 week (129) |
| Abundance of chlorophyll *a* at peak (tons$*10^3$) | 92 | 134 | 79 | 242 |
| Linear growth in chlorophyll *a* density between day 97 and 137 | 0.06 | 0.08 | 0.03 | 0.09 |
| Linear growth in chlorophyll *a* abundance between day 97 and 137 | 916 | 1227 | 512 | 2429 |
| Sea surface temperature at peak chlorophyll *a* abundance | 0.2 °C | 1.5 °C | 0.5 °C | 0.5 °C |
| Sum of monthly abundance values of chlorophyll *a* (tons$*10^3$) | 674 | 767 | 518 | 1560 |
| In situ chlorophyll *a* determinations | na | na | 5–17 May | 5 May |
| Depth of peak chlorophyll *a* density (SD) | na | na | 10.5 (4.2) | 8.9 (4.5) |
| Average temperature at 5 m depth | na | na | 0.58 (0.40) | −0.65 (0.01) |
| Average salinity at 5 m depth | na | na | 33.25 (0.55) | 33.52 (0.04) |
| Mean wind speed April m$^{-1}$ (normal = 3.0 m$^{-1}$) | 3.4 | 4.8 | 4.4 | 3.9 |
| Mean wind speed May m$^{-1}$ (normal = 2.9 m$^{-1}$) | 3.2 | 4.1 | 4.0 | 3.7 |
| Mean cloud coverage April% (normal = 62) | 92 | 79 | 94 | 74 |
| Mean cloud coverage May% (normal = 70) | 86 | 61 | 75 | 61 |

rapid sea surface warming took place between May and June 2003 resulting in nearly all of the bay >4 °C. In 2002, however, warming was slower and temperatures in June were well below those in 2003 (Fig. 5).

The average monthly chlorophyll *a* densities progress from the southern corner of the bay, extending north and east with the retreat of the sea ice (Fig. 6). In general, the largest chlorophyll *a* densities are found in the western part of the bay, but generally no more than about 5 $\mu g\, l^{-1}$. Densities remain low north of Disko Island and in southeastern Disko Bay (about 0.4–1.7 $\mu g\, l^{-1}$) (Fig. 6). Interannual differences in monthly chlorophyll *a* densities indicate large variability. In spring 2001, densities were low (peak <4 $\mu g\, l^{-1}$) and highest densities were concentrated in the western part of the bay. In 2002, the bloom was more widely dispersed and values above 5 $\mu g\, l^{-1}$ were detected west of Disko Bay. In 2003, peak densities above 5 $\mu g\, l^{-1}$ were concentrated in central Disko Bay in a relatively small area. Finally, in spring 2004, the bloom was both temporally and spatially extended and included some of the highest density values observed during the study period. Highest chlorophyll *a* densities were reached in 2002 and 2004, the two years with the least extensive and shortest duration of ice coverage (Table 2).

### 3.4. Chlorophyll a density and abundance

Mean chlorophyll *a* densities calculated from available 8-day average MODIS pixels indicate that beginning in mid-March (Julian day 65), densities rise rapidly from nearly zero (Fig. 7a). This increase continues through approximately Julian day 110 and peaks between 3.5 and 4.5 $\mu g\, l^{-1}$ in the 2nd or 3rd week of May (Julian days 120–140). Density rapidly declines after this peak period (between days 140 and 170) and becomes asymptotic at approximately 1 $\mu g\, l^{-1}$ by June. Upon examination of the deviations in annual phytoplankton density, MODIS data allowed for a clear detection of a secondary peak in chlorophyll *a* density during the light ice years. In 2001, the chlorophyll *a* density peaked at day 138, followed by a monotonic decline. Both in 2002 and 2004, the peak occurred around day 128, also followed by a monotonic decline; however, a secondary peak was observed at day 145 in 2002. In 2003, the spring bloom showed a decline after day 110 to

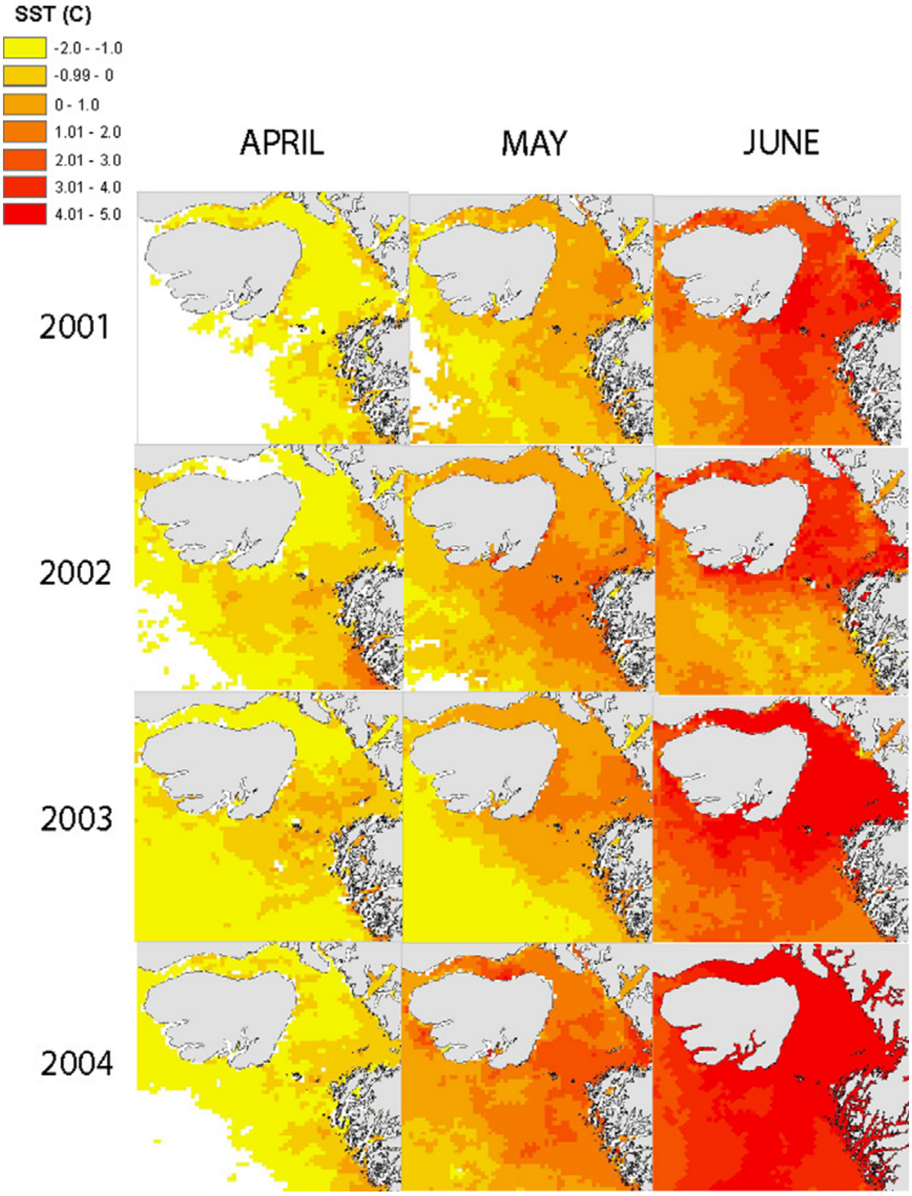

Fig. 5. Monthly progression of sea surface temperature (°C) in Disko Bay, West Greenland between 2001 and 2004. Data are presented as monthly averages from MODIS level 3 Terra. White areas are ice covered.

unusually low levels for the season, but a secondary peak was reached at day 155 resembling the levels observed during the decline in the other years. In 2004, the usual decline was not detected until day 185, after which a new increase that peaked around day 195 was detected (Fig. 7a).

Abundance of chlorophyll *a* (Fig. 7b) followed patterns similar to those of chlorophyll *a* density with exponential increase to a peak and descent to an asymptotic value in June. However, after accounting for the total area comprising density estimates, it is clear that total amount of chlorophyll *a* in Disko Bay remains very low ($\leqslant$600 tons) until Julian day 90, after which total chlorophyll *a* increases to over 80,000 tons in approximately 40 days,. After day 150, a decrease occurs to around 40,000 tons. Interannual differences in abundance show that the ascent and peak in 2004 were the highest for the 4 years in the study period. The years 2001 and 2003 were similar to each other, and 2002 values were intermediate between those of 2001–2003 and 2004 (Fig. 7b).

The daily incremental increase in both chlorophyll *a* density and abundance, estimated by simple linear regression vs. date between 1 April (day 97) and 15 May (day 137) was highest in 2002 and 2004 (light ice years) and lowest in 2001 and 2003 (heavy ice years) (Table 1).

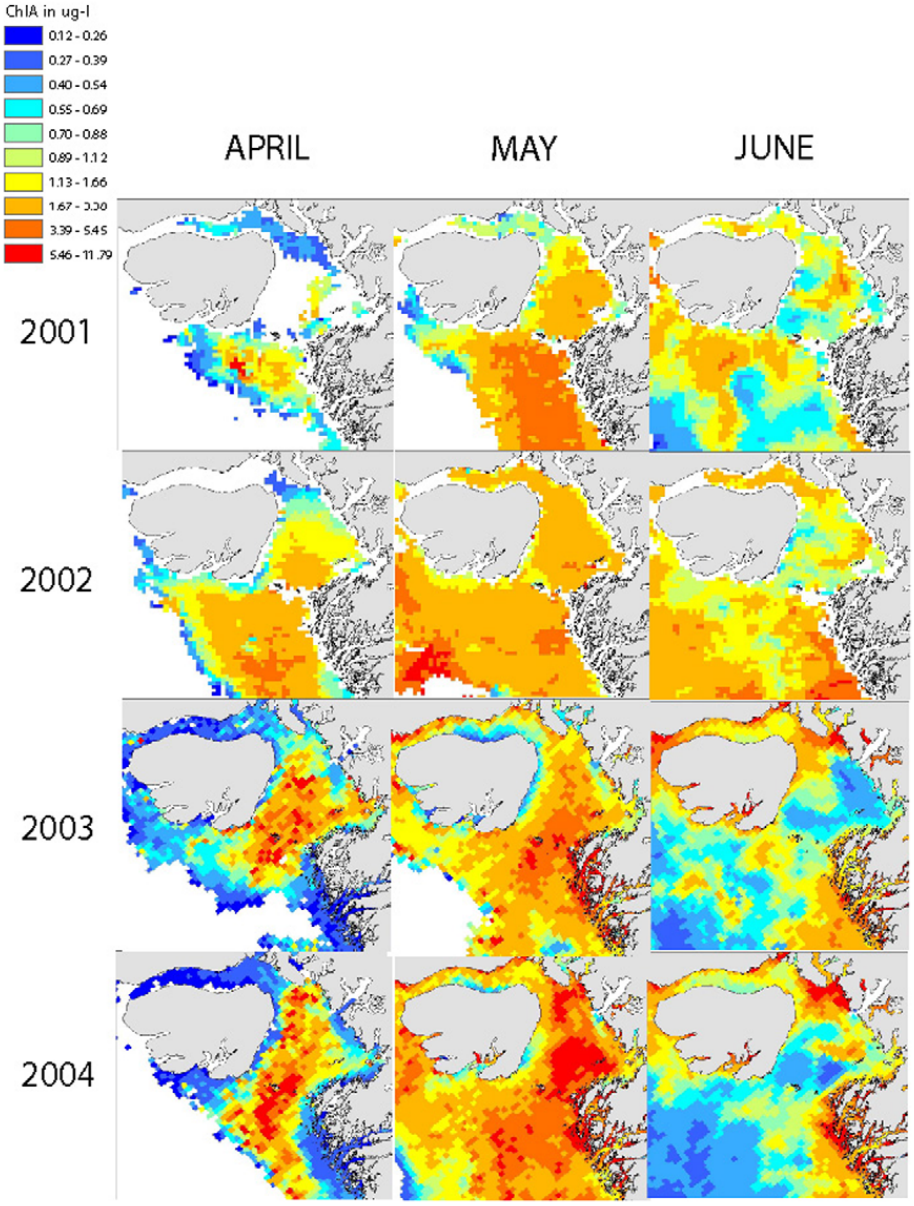

Fig. 6. Monthly progression of chlorophyll *a* production in Disko Bay, West Greenland between 2001 and 2004. Data are presented as monthly averages from MODIS level 3 Terra (2001 and 2002) and level 3 Aqua (2003 and 2004) with adjustment of the Terra data to ensure compatibility. White areas are ice covered.

### 3.5. Chlorophyll a and sea ice coupling

Interannual patterns of sea ice formation in Disko Bay between 2001 and 2004 demonstrate that springtime reduction of sea ice occurs over approximately 100 days (between day 60 and 160) (Fig. 8, Table 2). The fraction of open water in March (ranging from 0.1 to 0.3) increases to 0.9 by June, and asymptotic values of 0.8–0.9 open water were similar in all years. In 2003, an opening in sea ice occurred between day 60 and 80 reaching open water fractions as high as 60%. This open water rapidly declined at day 90 and equilibrated at open water levels similar to 2001 and 2002. Similarly in 2004, ice coverage was lighter than previous years but with a slightly delayed opening of the sea ice between day 85 and 100, where fractions of open water reached >50% by day 90. The year with the longest duration of sea ice coverage (50% ice retreat) was 2001, followed by 2003 and 2002, with 2004 as the lightest ice year (Table 2).

The opening in the sea ice in early March 2003 (Fig. 8) did not trigger an early phytoplankton bloom (Fig. 7a). In all four years (2001–2004) there was low phytoplankton abundance while 50% or more of the area

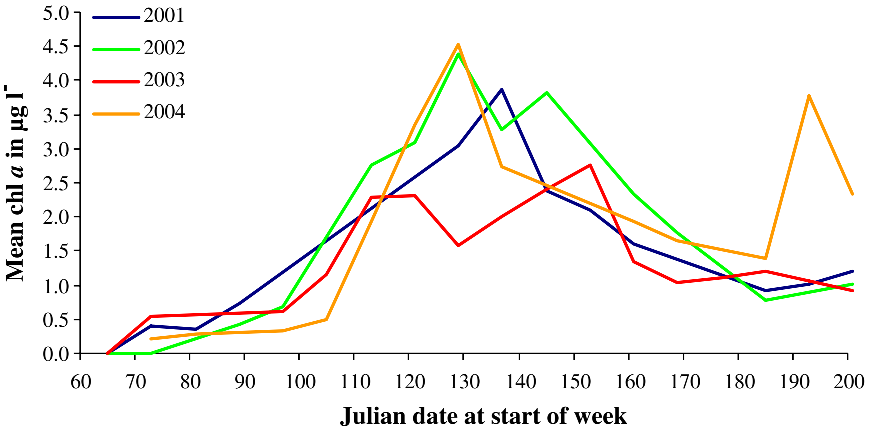

Fig. 7a. Development of weekly chlorophyll *a* density during spring in Disko Bay, 2001–2004. Data are presented as weekly averages from MODIS level 3 Terra.

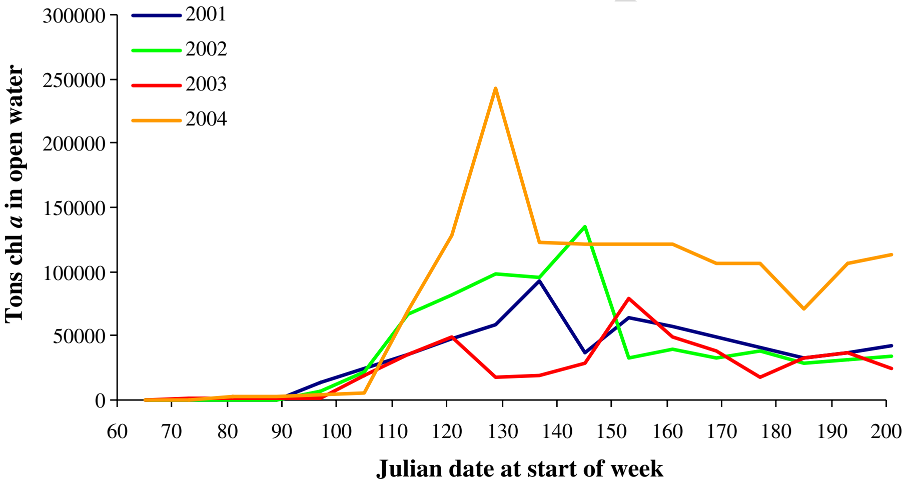

Fig. 7b. Development of chlorophyll *a* abundance during spring in Disko Bay, 2001–2004. Data are presented as weekly averages from MODIS level 3 Terra.

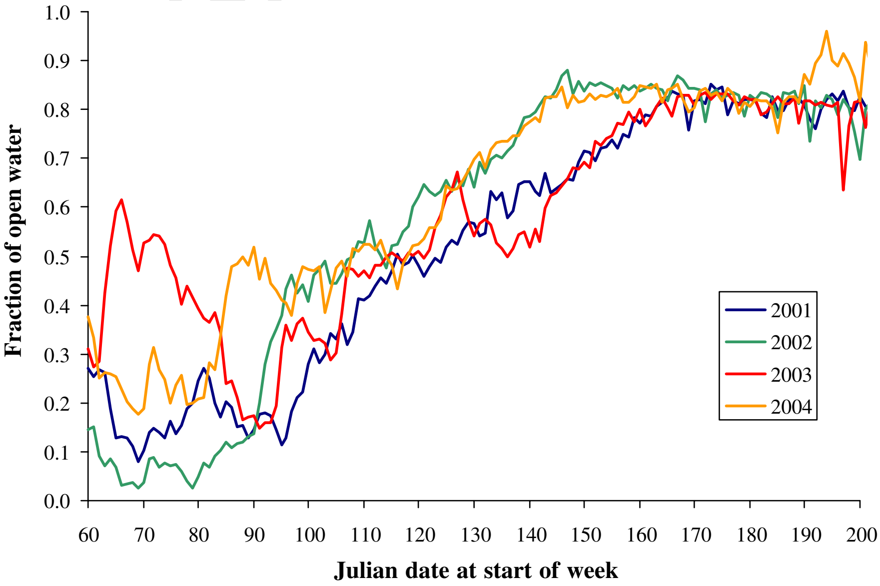

Fig. 8. Interannual patterns of sea ice decrease in Disko Bay between 2001 and 2004, taken from daily SSMI data.

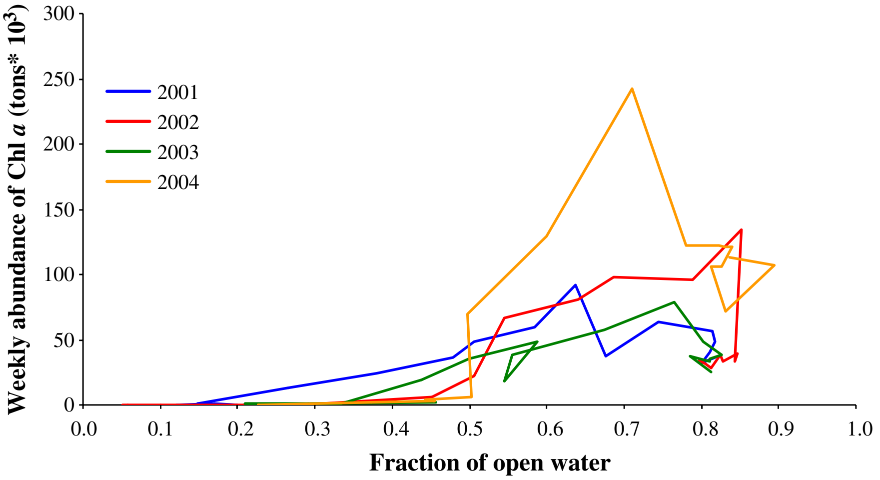

Fig. 9. Development of weekly chlorophyll *a* abundance estimates relative to weekly average open water in Disko Bay 2001–2004. Data are presented as averages from MODIS level 3 Terra and SSMI.

was ice covered (Fig. 9). The spring bloom developed rapidly when more than 50% of the bay was ice-free, which usually happened between 15 and 27 April (Table 2). When approximately 80% of the bay was ice-free, the phytoplankton bloom was terminated and surface densities reached similar levels in all four years (Fig. 9).

An analysis of the effect of weekly sea ice coverage on sea surface temperature (with week as covariate) revealed a significant effect of sea ice on sea surface temperature (ANCOVA, $F = 14.2$, $p < 0.001$). No effect of sea surface temperature on chlorophyll *a* density could be detected, but both density and abundance of chlorophyll *a* were highly correlated with the fraction of open water.

### 3.6. Regionalized chlorophyll a algorithm

An empirical regional algorithm was developed by calibrating ratios of remotely sensed water-leaving radiance with in situ samples. Band ratio values derived from level 2 water leaving reflectance were available for eight stations on day 125 or 126 in 2003 and 2004. Correlations were derived with a power function for seven

Table 3
Relationship between in situ chlorophyll *a* integration depth and daily MODIS level 2 data bandwidth ratios

| In situ depth | 412/551 ratio | 443/551 ratio | 488/551 ratio | 531/551 ratio |
|---|---|---|---|---|
| 0–1 m | $y = 23.639x^{-0.9904}$<br>$R^2 = 0.6284$ | $y = 18.265x^{-1.0012}$<br>$R^2 = 0.7395$ | $y = 13.437x^{-0.9601}$<br>$R^2 = 0.8445$ | $y = 10.58x^{-0.9263}$<br>$R^2 = 0.8923$ |
| 0–2 m | $y = 29.479x^{-1.0865}$<br>$R^2 = 0.6761$ | $y = 22.019x^{-1.088}$<br>$R^2 = 0.7806$ | $y = 15.637x^{-1.0279}$<br>$R^2 = 0.8653$ | $y = 12.11x^{-0.9929}$<br>$R^2 = 0.9165$ |
| 0–3 m | $y = 35.285x^{-1.1586}$<br>$R^2 = 0.6925$ | $y = 25.751x^{-1.1556}$<br>$R^2 = 0.7932$ | $y = 17.836x^{-1.0853}$<br>$R^2 = 0.8688$ | $y = 13.61x^{-1.0465}$<br>$R^2 = 0.917$ |
| 0–4 m | $y = 39.775x^{-1.1996}$<br>$R^2 = 0.7027$ | $y = 28.688x^{-1.1959}$<br>$R^2 = 0.804$ | $y = 19.582x^{-1.1199}$<br>$R^2 = 0.8756$ | $y = 14.785x^{-1.0738}$<br>$R^2 = 0.9138$ |
| 0–5 m | $y = 43.396x^{-1.1937}$<br>$R^2 = 0.6624$ | $y = 31.455x^{-1.1939}$<br>$R^2 = 0.7629$ | $y = 21.515x^{-1.1205}$<br>$R^2 = 0.8346$ | $y = 16.279x^{-1.0814}$<br>$R^2 = 0.8824$ |
| 0–10 m | $y = 29.348x^{-0.5489}$<br>$R^2 = 0.3547$ | $y = 26.092x^{-0.5848}$<br>$R^2 = 0.4634$ | $y = 21.811x^{-0.5609}$<br>$R^2 = 0.5295$ | $y = 19.009x^{-0.5477}$<br>$R^2 = 0.573$ |
| 0–30 m | $y = 21.951x^{-0.4021}$<br>$R^2 = 0.2476$ | $y = 20.413x^{-0.4444}$<br>$R^2 = 0.348$ | $y = 17.923x^{-0.437}$<br>$R^2 = 0.4181$ | $y = 16.094x^{-0.4252}$<br>$R^2 = 0.4492$ |

Data were fit with a power function to the bandwidth value in a 1 km cell for eight stations where in situ and cloud-free MODIS values were available.

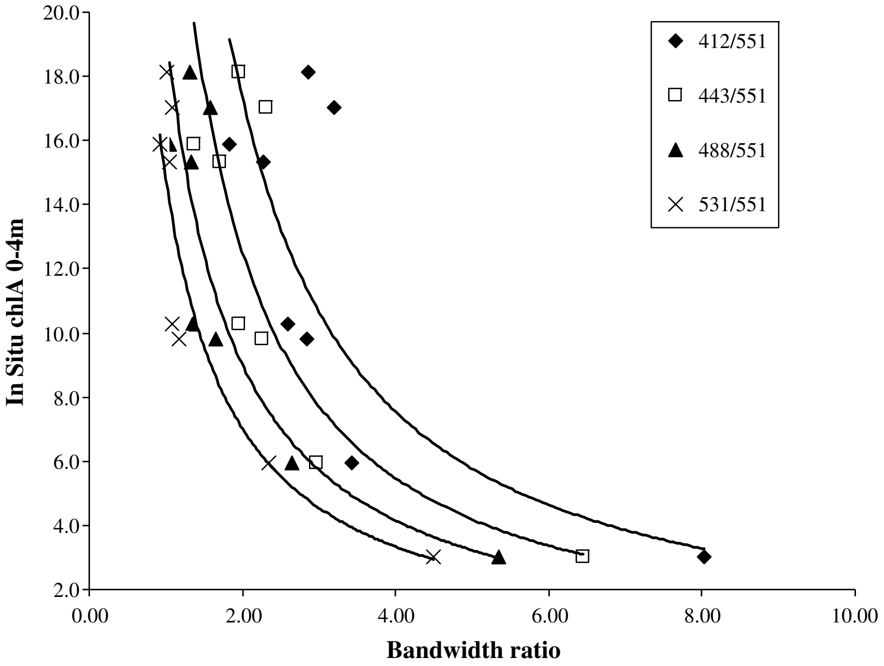

Fig. 10. Bandwidth ratio correlation with in situ chlorophyll *a* based on 1 km level 2 MODIS data. Best fit (0–4 m integration depths) is shown. See Table 3 for fits to all integration depths.

different integrated depths and the best fit of each model was evaluated by corresponding $r^2$ values. Although most fits between 0 and 5 m were good, the optimal integration depth was 0–4 m where between 70% and 91% of the variance could be explained (Table 3, Fig. 10).

## 4. Discussion

### 4.1. Analytical approach

Data gaps as a result of excessive cloud cover are difficult to assess because the MODIS observations are averaged over 8 days and cloud cover is estimated at one locality each day within the study area. In reality, there are likely enough cloud-free ‘windows’ during most 8-day periods to allow for precise chlorophyll *a* observation. However in this study, a conservative approach was taken, where at least one day with <21% cloud cover was required to allow for that period to be included in the study.

A good correlation was found between the chlorophyll *a* estimates from the Aqua and Terra instruments in 2003 (Fig. 3). Terra estimates were approximately 50% lower than those from Aqua in the same 4 km pixel. This was accounted for in the 2004 data series and made the time series compatible. The correlation of MODIS level 3 Terra and Aqua results was conducted over a narrow range of values (0.25–3.00 μg l$^{-1}$ for MODIS values, Fig. 3) which fall within what could be considered an asymptote on the MODIS calibration curve (http://seabass.gsfc.nasa.gov/matchup_results.html).

Similar to past studies (Miroslaw and Stramski, 2004; Sathyendranath, 2000; Carder et al., 1999) the correlation between the global algorithms (MODIS level 3) and regional in situ measurements of chlorophyll *a* were poor and weak. These global algorithms are designed for less optically complex open ocean environments than high Arctic coastal waters. Traditional instrument calibration regressions of MODIS and in situ measurements span a larger range of values than in this study which reduces the effect of variability on the correlation. The optically complex coastal waters of the high Artic experience rapid changes in phytoplankton abundance and in concentrations of both terrestrial and marine colored dissolved organic matter (CDOM). Averaging MODIS data for the development of weekly estimates of chlorophyll *a* can be expected to underestimate the dynamic nature of the spring bloom in these waters. Finally, the depth distribution of the chlorophyll *a* will affect the ability to predict concentration from remote sensing because the volume of water absorbing backscattered light increases with a deeper fluorescence peak. Consequently, even with the same concentration values, the locality where the concentration was near the surface will be upward biased relative to localities where the fluorescence peak was located deeper. Consequently, high variability may be expected, even within a small sampling window (on the order of days), and good correlations may be hard to attain.

Despite the relatively disappointing correlation, both the relative magnitude and the spatial pattern of inter- and intra-annual comparisons of phytoplankton production from MODIS level 3 are expected to be internally consistent and can be considered a useful index of both density and abundance of phytoplankton.

The development of a regionalized calibration for chlorophyll *a* based on level 2 bandwidth values is among the first for high Arctic waters and the first developed for coastal Greenland. The relationships that we derived between the wavelength ratios and in situ chlorophyll *a* follow patterns similar to those used in the development of global calibrations (Martin, 2004) and are built upon decades of improving understanding of how light attenuation in the ocean is affected by chlorophyll *a* concentrations. These regional correction models were developed for a series of integration depths (0–30 m) and it was determined that integration between 0 and 30 m provided the optimal correlation with remotely sensed wavelength ratios in Disko Bay (Table 3, Fig. 10). This regionalized algorithm, while greatly improving the chlorophyll *a* estimate from water leaving radiance, is specific to the waters of Disko Bay and to the use of band ratios in estimation of chlorophyll *a*. For the current study it was not possible to use the MODIS level 2 data because the images were only sporadically available and often cloud-covered. However, for comparison of patterns in space and time series relative values from MODIS level 3 are equally useful.

### 4.2. Ecological significance

The spring phytoplankton bloom is the single most important event in the production cycle in Arctic waters. The bloom is associated with the break up of the sea ice when stratification prevents mixing of phytoplankton below the euphotic zone. When initiated, the exponential growth of phytoplankton quickly depletes the surface layer nutrients and starts to sediment to the sea bed (Nielsen and Hansen, 1995).

The spatial development of the phytoplankton bloom shows that the southwestern corner of the study area has the earliest and the largest spring phytoplankton bloom. In this area sea depths drop from 50 m to more than 400 m over few kilometers (Fig. 1). Such bank areas are often sites of enhanced biological production due to establishment of frontal structures and upwelling of nutrients. This is also observed at Store Hellefiske Bank in West Greenland (68°N 55°W), known to be a highly productive area with significant populations of sea birds and marine mammals (Heide-Jørgensen and Laidre, 2004) and exploited fish and shrimp stocks. The eastern part of Disko Bay, influenced by melt-water outflow from the glaciers, shows no signs of an early phytoplankton bloom and seems to follow the general pattern of accelerated bloom soon after the disappearance of sea ice. Although the freshwater outflow from the Jakobshavn glacier provides a source for early stratification of the water column, this apparently does not affect the local phytoplankton bloom, at least not to an extent that can be observed on the MODIS images. The bloom is more pronounced in offshore areas, and there is no evidence for increased spring phytoplankton production in eastern Disko Bay in years with early ice retreat.

In Disko Bay melting sea ice provides some salinity-based stratification of the water column early in spring. It is however not until mid-June and early-July that extensive freshening of the surface layer is established from inflow and melting of glacial ice and land run-off (Andersen, 1981a,b). Aside from salinity, the solar heating changes temperatures from $<-1$ °C in April to 4 °C in June and strengthens the stratification of the bay during late spring/summer.

The spring phytoplankton bloom is intense and lasts for only a few weeks between the months of April and June (Juul-Pedersen et al., 2006). After this interval, the nutrients in the euphotic zone have been depleted and the strong thermoclines and haloclines prevent vertical mixing that could replenish the surface layer with nutrients (Nielsen and Hansen, 1995, 1999).

In all four years the coupling between phytoplankton and sea ice was bounded by average open water between 50% and 80%, likely due to the combined availability of light and stable open water. This is further supported by the observations in 2003, when a large area of open water occurred early yet no bloom was detected due to low light levels and an unstable water column. The interannual variability that occurred between these bounds is caused by nutrient availability, water column stratification, and sea ice coverage. In all four years the abundance of chlorophyll *a* equilibrated at similar levels.

Spring phytoplankton were concentrated in the upper water column at depths <15 m. In years with late sea ice retreat (2001 and 2003), chlorophyll *a* attained only slightly lower densities than those years with early sea ice retreat (2002 and 2004). However, the abundance of chlorophyll *a* in the light ice years was considerably larger than in the heavy ice years, and there was an obvious effect of the larger available area of open water for light-induced stimulation of primary production. This finding demonstrates the importance of estimating abundance of chlorophyll *a* rather than only its density in regions where the available open water varies with sea ice coverage. The spring bloom development in Disko Bay, West Greenland, is directly coupled to the retreat of sea ice, and the primary bloom does not exhibit a delay in years with an early sea ice retreat as reported for the Bering Sea (Stabeno et al., 2001).

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