Ocean Sci. Discuss., 9, 3567–3591, 2012
www.ocean-sci-discuss.net/9/3567/2012/
doi:10.5194/osd-9-3567-2012

Ocean Science Discussions

From the chlorophyll *a* in the surface layer to its vertical profile: a Greenland Sea relationship for satellite applications

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Received: 14 September 2012 – Accepted: 31 October 2012 – Published: 15 November 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Current estimates of global marine primary production range over a factor of two. At high latitudes, the uncertainty is even larger than globally because here in-situ data and ocean color observations are scarce, and the phytoplankton absorption shows specific characteristics due to the low-light adaptation. The improvement of the primary production estimates requires an accurate knowledge on the chlorophyll vertical profile, which is the basis for most primary production models. To date, studies describing the typical chlorophyll profile based on the chlorophyll in the surface layer did not include the Arctic region or, if it was included, the dependence of the profile shape on surface concentration was neglected. The goal of our study was to derive and describe the typical Greenland Sea chlorophyll profiles, categorized according to the chlorophyll concentration in the surface layer and further monthly resolved. The Greenland Sea was chosen because it is known to be one of the most productive regions of the Arctic and is among the Arctic regions where most chlorophyll field data are available. Our database contained 1199 chlorophyll profiles from R/Vs *Polarstern* and *Maria S Merian* cruises combined with data of the ARCSS-PP database (Arctic primary production in-situ database) for the years 1957–2010. The profiles were categorized according to their mean concentration in the surface layer and then monthly median profiles within each category were calculated. The category with the surface layer chlorophyll exceeding 0.7 $\mathrm{mg\,C\,m^{-3}}$ showed a clear seasonal cycle with values gradually decreasing from April to August. Chlorophyll profiles maxima moved from lower depths in spring towards the surface in late summer. Profiles with smallest surface values always showed a subsurface chlorophyll maximum with its median magnitude reaching up to three times the surface concentration. While the variability in April, May and June of the Greenland Sea season is following the global non-monthly resolved relationship of the chlorophyll profile to surface chlorophyll concentrations described by the model of Morel and Berthon (1989), it deviates significantly from that in other months (July–September) where the maxima of the chlorophyll are at quite different depths. The Greenland Sea

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dimensionless monthly median profiles intersect roughly at one common depth within each category. Finally, by applying a Gaussian fitting with 0.1 mg C m^{-3} surface chlorophyll steps to the median monthly resolved chlorophyll profiles of the defined categories, mathematical approximations have been determined. These will be used as the input to the satellite-based primary production models estimating primary production in Arctic regions.

1 Introduction

Current uncertainty in global marine primary production (PP) estimates is high, with values ranging over a factor of two (Carr et al., 2006). The most challenging regions for PP modeling are poleward of 40° in all basins (Carr et al., 2006), where the range of PP estimates is even higher. In the Arctic Ocean the uncertainties are mainly caused by the unique optical properties of the Arctic waters and the presence of a Subsurface Chlorophyll Maximum (SCM) (Arrigo et al., 2011; Weston et al., 2005; Matsuoka et al., 2007, 2011). The SCM is often not correctly seen by the satellite as it lies below the surface layer visible to the satellite sensor. To include the information on the SCM into primary production models accurately, one needs to find the appropriate relationship between the chlorophyll concentration (CHL) in the surface layer and its vertical profile. There have been a number of methods developed to handle this. The PP model by Behrenfeld and Falkowski (1997) considers the CHL profile to be uniform throughout the water column. The model by Antoine and Morel (1996) and Antoine et al. (1996) goes further by assuming that the CHL profile changes its shape depending on the concentration of the surface layer. On the contrary, the recent Arctic PP model by Arrigo et al. (2011) adopts a fixed shape of CHL profile for a specific month and region.

In this study, although being generally interested in the Arctic primary production, we focused on the Greenland Sea for several reasons: firstly, the Greenland Sea is known to be one of the most productive regions of the Arctic (Reigstad, 2011; Sakshaug, 2004; Arrigo and Van Dyiken, 2011). Secondly, it is one of the few areas in the world where deep convective mixing occurs, possibly transferring significant amounts of carbon dioxide to great depths (Rey et al., 2000). Finally, it is one of the Arctic regions with the most in-situ CHL data available (Arrigo et al., 2011). The Greenland Sea was and is in the focus of hydrographic studies of the Alfred-Wegener-Institute (AWI), and transects across the Fram Strait have been run repeatedly for many years (e.g. Budeus and Ronski, 2009; Schauer et al., 2008). During these cruises measurements of in-situ CHL were carried out regularly. In this study, CHL data from R/V *Polarstern* and *Maria S Merian* 1991–2010 cruises were combined with data from the Arctic primary production database ARCSS-PP (Matrai et al., 2010).

The Greenland Sea is a highly dynamic area in terms of water mass exchange, where warmer surface waters of relatively high salinity advected to the area from the North Atlantic meet fresher and colder waters of Arctic origin (Rudels and Quadfasel, 1991). It is also the area where most of the Arctic drifting sea ice is advected. The complex hydrography and the sea ice drift provide conditions (in terms of nutrients, stratification and presence of sea ice) which differ significantly within the Greenland Sea. This in turn implies that the phytoplankton vertical profiles of the Greenland Sea vary significantly, having though a clear seasonal cycle (Rey et al., 2000). To capture such variability, we combine the methods of Morel and Berthon (1989) and Arrigo et al. (2011), by looking for the relationship describing (1) the change of the CHL profile depending on its surface concentration, and (2) the seasonal cycle of the CHL profile. Finally, we are also interested in identifying the differences between the Greenland Sea relationship of this study and the global one by Morel and Berthon (1989).

2 Methods

2.1 Data description

The borders for the Greenland Sea sector of the Arctic were chosen as in Arrigo et al. (2010): north to the Arctic circle at 66°33′39′′ N and between 45° W and 15° E. We

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combined the CHL data from R/Vs *Polarstern* and *Maria S Merian* 1991–2010 cruises with the ARCSS-PP database (1957–2003). The data covered the months from April till October.

The samples of R/V *Polarstern* and *Maria S Merian* cruises were collected for 6 depths in Niskin bottles, 0.5–2.0 L of water were filtered through Whatman GF/F glasfibre filter, stored at -18° C and afterwards analysed in the Alfred-Wegener-Institute laboratory. The filters were extracted in 90 % acetone and analysed with a spectrophotometer for higher values and with a Turner-Design fluorimeter for lower values according to the methods described in Edler (1979) and Evans and O'Reily (1984). The values from the fluorimeter were calibrated with the values obtained from the spectrophotometer. In addition, calibration of the fluorimeter was carried out with Sigma chlorophyll *a*. The samples were taken both during the movement of the ship (surface sampling) and during the stops (vertical profile sampling, further on called stations). In this study we considered only the samples from the stations as we are interested in the information on vertical profile. See Matrai et al. (2010) for details on ARCSS-PP database.

2.2 Data quality control and preprocessing

The data quality control procedure consisted of filtering out all profiles which either had less than three depths or belonged to the month of October since the number of October data points was below 20. In case of several profiles measured at one location in one day we took only the profile with the most sampled depths. If either the location or the day changed we considered it to be the new profile. Profiles that did not reach the surface were extrapolated to the surface as described below. To avoid negative values we put 0.01 mg C m^{-3} as the lowest value for the surface. Finally, we increased the resolution of the extrapolated profiles to 1 m increments for the further statistical analysis.

By linearly extrapolating the profiles with a steep change between the two shallowest measurements additional errors could be possibly introduced. Therefore, we additionally investigated three other ways of handling the difficulty of the majority of profiles

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not reaching the surface. These included: (1) taking the value of the shallowest depth as the surface CHL; (2) extrapolating only those profiles which changed with a rate less than 0.1 $\mathrm{mg\,C\,m^{-1}}$ between the 2 shallowest measurements and treating other profiles as described in point 1; (3) as in point 2, but with a stricter rate threshold of 0.05 $\mathrm{mg\,C\,m^{-1}}$. Comparing the results of these three different extrapolation methods showed that there was hardly any influence on the shape of the final median profiles. We therefore decided to apply the simple linear extrapolation to the profiles by using the change between the two shallowest measurements.

2.3 Calculation of the main profiles parameters

For each profile we calculated the parameters essential for further analysis. Firstly, we estimated the depth of the euphotic layer (Z_{eu}) according to Eq. (1a, b) and of Morel and Berthon (1989). Z_{eu} is the depth where the downwelling photosynthetically available irradiance is reduced to 1 % of its value at the surface. Profiles which did not reach Z_{eu} were excluded. Then we obtained the penetration depth (Z_{pd}) as Z_{eu} divided by 4.6. Z_{pd} is the depth of the upper ocean layer where 90 % of optical remote sensing information originates from (Gordon and McCluney, 1975). Using Z_{pd} we calculated the CHL value to be seen by satellite sensor – the mean CHL concentration for the penetration depth (C_{pd}). The parameters which describe the total CHL content for the water column, C_{tot} (CHL integrated for Z_{eu}) and C_{zeu} (mean CHL for Z_{eu}), were also computed.

The dimensionless profiles (obtained to compare our results to those of Morel and Berthon, 1989) were computed as following: the dimensionless depth as the actual depth values divided by Z_{eu}, and the dimensionless CHL as the actual CHL values divided by C_{zeu}. Thus the shape of the vertical profiles (for different stations) could be compared regardless to their absolute magnitude (Morel and Berthon, 1989).

2.4 Selection of the representative surface layer chlorophyll categories and statistics

According to the method by Morel and Berthon (1989) and based on the histogram of C_{pd} we divided all data into six categories with an equal number of profiles. After that, we organized the data within each category into monthly bins and calculated the median profiles inside each bin. These median profiles were used in the further analysis as the representative profiles for the certain C_{pd} in a certain month, because as opposed to the mean profiles, the median gives less attention to outliers. To have an idea on the spread of the initial data, we plotted half of the interquartile range together with the median. We additionally calculated the mean, standard deviation, depth of the CHL maximum and its magnitude for each category as they provided a more detailed view on the variation of the data within each category.

With a subset of the data (R/V *Polarstern* and R/V *Maria S Merian* 2000–2009 data only) we additionally investigated the different ways of categorizing the profiles (e.g. by latitude, longitude, temperature or salinity of the surface layer). However, the selection of categories based on the CHL in the surface layer and month showed the least variability within a category.

Keeping in mind that we plan to use the results of this study as representative CHL profiles of the Greenland Sea for a certain month and surface concentration with the least computational effort, we were interested in having equations describing the profiles. Thus we took the processed median profiles and fitted a Gaussian to each of the median profiles in the least squares sense (see Eq. 1). Median profiles had been linearly extrapolated and interpolated in the range of surface CHL from 0 till 5 $\mathrm{mg\,C\,m^{-3}}$ with 0.1 $\mathrm{mg\,C\,m^{-3}}$ steps. The deviation of the fitted curves from the original data was estimated as the root mean square averaged for the water column and surface CHL concentration. The Gaussian shape was chosen for fitting as the vertical profiles of bio-optical profiles such as the chlorophyll maximum layer have been shown to be well defined using this shape (Arnone et al., 2007).

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3 Results

3.1 Data quality control and preprocessing

Our initial CHL database for the Greenland Sea consisted of 1676 profiles, with 548 profiles derived from the unpublished database of R/V *Polarstern* and R/V *Maria S. Merian* cruises and the rest from the ARCSS-PP database. After applying quality control procedures 1472 profiles were left. In addition, nearly 300 profiles didn't reach the euphotic depth and thus were excluded. Our database after preprocessing consisted of 1199 profiles.

Figure 1 shows a clear relationship between C_{pd} (mean CHL within the penetration depth) and C_{pd} (total CHL in the water column) for the Greenland Sea from our database (left) and for the global database from Morel and Berthon (1989), which is based on the analysis of 2811 profiles (right). Both scatter plots have similar slopes and generally have nearly no difference in the high C_{pd} values related to C_{tot}. The differences between the two datasets are visible at low C_{pd} values which for the Greenland Sea correspond to a wider range of C_{tot} as compared to the global relationship. We attribute this difference to the various magnitudes of SCM in our data. Specifically, very low values of C_{tot} (in the range of 1–10 mg C m^{-2}, below the one-to-one line on Fig. 1) are present in our dataset only. The clear relationship between C_{pd} and C_{tot} for the Greenland Sea proved that a mathematical dependency between these two parameters can be expected.

3.2 Selection of the representative surface layer chlorophyll categories and fitting of Gaussians

Based on the histogram of C_{pd} (Fig. 2) we defined six ranges of C_{pd} with roughly 200 profiles per range. The histogram shows that most of the profiles have low values in the upper ocean layer (C_{pd} lower than 1 mg C m^{-3}). The obtained C_{pd} (mg C m^{-3}) ranges are: (1) < 0.3; (2) 0.3–0.45; (3) 0.45–0.7; (4) 0.7–1; (5) 1–1.5; (6) > 1.5. The median of

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the profiles for each range (see Sects. 2.3–2.4) showed that the profiles for the ranges 4 to 6 are nearly identical. Therefore we combined those into one range (> 0.7 mg C m^{-3}) which covers 600 profiles.

Figure 3 illustrates monthly resolved median profiles for the final four C_{pd} ranges. For all C_{pd} ranges the CHL maximum shallows towards the end of the season. The SCM for the majority of the months is most pronounced in the lowest C_{pd} range, where it is also deeper than in other ranges. Within this range the April–May maximum has the same or even a greater magnitude as the shallower one in September. May to July, having no clear maximum, show the transitional state between the two seasons. The relative spread of the maxima is highest in this range (see Appendix, Fig. 1). In the second and third C_{pd} range the SCM is more difficult to be distinguished (except for the August profiles), there is rather a gradual shift of the maximum towards the surface from April to September. In the fourth and maximum C_{pd} range the maxima mostly occur exactly at the surface. It is the only range with most months reaching maximum values at the surface. The forth range shows a clear seasonal cycle of the data, with values gradually decreasing from April to September.

Fitting the Gaussians to the median profiles resulted in much smoother curves which have a single pronounced maximum (see Fig. 4). Some of the original median profiles. that are quite different, are nearly identical as fitted Gaussians (such as April–May of the lowest C_{pd} range). However, main features of the median profiles (such as the propagation of the maximum towards the surface in September, as the season goes by) are also present in the fitted curves. The deviation of the fitted curves from the original data averaged for the water column and surface CHL concentration ranged between 0.03 mg C m^{-3} in July and 0.06 mg C m^{-3} in May with other months showing the intermediate values. The table with the coefficients A, σ and μ for the Eq. (1) of the Gaussians fitted with 0.1 mg C m^{3} surface CHL resolution is given in Fig. A1.

$$\mathrm{CHL} = Ae^{-\frac{(z-\mu)^2}{2\sigma^2}} \quad (1)$$

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3.3 Statistical analysis

In addition to the above presented figures, Table 1 gives more details on the basic statistics and CHL maximum characteristics of the dataset (Table 1). Table 1 enables the comparison of the features of different C_{pd} ranges (vertically) and of different months (horizontally). The median, mean, inter-quartile range and standard deviation are values averaged for the whole water column.

The profiles with low concentration in the surface layer, the lower C_{pd} ranges, are always showing a SCM (see the depth of the CHL maximum for the first two ranges). Median values rise towards the maximum C_{pd}, pointing out that the SCM does not critically influence the median CHL in the water column. In case of low surface concentration, however, the relative contribution of SCM to the total CHL is important, with its maximum reaching three times the surface value (see e.g. April for the lowest C_{pd} range). Median and mean for all the C_{pd} ranges show a clear seasonal cycle with the bloom weakening from April till September (also in Fig. 3, but for the highest range only). The CHL maximum does not show the same clear seasonal cycle, e.g. the third C_{pd} range with all months except August having about the same CHL maximum. Generally, the mean is mostly higher than the median, signifying that most of the outliers are higher than the median. The spread of the data (interquartile range) is usually highest in the lowest C_{pd} range. September is the month with the least spread.

3.4 Summary of the results

In summary, the general patterns of the median profiles are: (1) low surface values are usually a sign for SCM; (2) the relative contribution of SCM to the total CHL in case of low surface concentration can be important, with its maxima reaching three times higher values than the surface CHL; (3) the percentage spread of the data (interquartile range) is highest in case of the lowest surface concentration; (4) profiles propagate towards surface as the season goes by; in the highest C_{pd} range this is visible by the profiles “sticking” to the surface towards September; (5) when averaged for the whole

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water column, median values show a clear seasonal cycle, with bloom weakening from April to September; the CHL maximum values do not show such a cycle; (6) Gaussians fitted to the median profiles generally reproduce the magnitude and position of the CHL maximum.

4 Discussion

Based on the clear correlation of C_{pd} to C_{tot} for the Greenland Sea, it is in principle possible to estimate the CHL in the whole water column based on the CHL in the surface layer only. Both the scatter of C_{pd} versus C_{tot} and the histogram of C_{pd} (Figs. 1 and 2, respectively) showed the majority of profiles having low CHL values in the surface layer. In the following, the specifics of Greenland Sea CHL profiles and C_{tot} and their comparison to the global approximation by Morel and Berthon (1989) are further discussed in respect to the specific hydrographic conditions and other studies focusing on phytoplankton dynamics in the Arctic region (Sects. 4.1 and 4.2, respectively).

4.1 Special features of the Greenland Sea chlorophyll profiles

For the surface CHL lower than 1 mg C m^{-3}, total phytoplankton varies much more in the Greenland Sea than for the global case. As is the case for most Arctic waters, the Greenland Sea has pronounced water column stratification by salinity. The stratification here is influenced by the melting sea ice moving through the Fram Strait as it is the major gateway for the sea ice to leave the Arctic Ocean. The amount of drifting sea ice varies throughout the year and so as well does the strength of the stratification. Nutrient supply to the ocean surface layer (critical for the phytoplankton growth) depends on the stratification and therefore differs as well during the season. Thus the depth and the magnitude of the phytoplankton maximum are highly variable here and differ at the respective months for the different years, explaining the big range of C_{tot} values corresponding to the low surface CHL.

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We observed two different scenarios of phytoplankton distribution in the water column and through the season, depending if the CHL of the surface layer is higher or lower than 0.7 mg C m^{-3}. In case of the low surface concentration (first three C_{pd} ranges) there is always a SCM (though its magnitude for some profiles is quite small). This case could be typical for regions of sea ice melting in the Greenland Sea characterized by strong stratification and therefore lack of nutrients in the surface layer. The case of surface layer concentration higher than 0.7 mg C m^{-3} shows the clear seasonal cycle of the bloom with a month-to-month gradual decrease from April onwards. Such a decrease of the bloom could be caused by either the phytoplankton using up the nutrients or the grazing pressure getting stronger. We do not observe a bloom limitation by light, keeping in mind that the daylight at these latitudes is increasing from April to June (while we observed a bloom decrease for these months). As mentioned in the introduction, the Greenland Sea is an inhomogeneous region in terms of water masses properties. It has parts with cold and fresh waters as well as warmer and salty ones, and the sea ice drift adds to the complexity of the region. As a result, here at the same month in the top layer, both small phytoplankton concentrations (most likely stratified waters) and blooms (most likely non-stratified waters) are observed.

Considering the seasonal cycle, both previous satellite (Arrigo et al., 2011) and in-situ (Rey et al., 2000) data analyses are showing that blooms start with the increase of daylight in spring and the peak of the bloom is in May–June, with a rapid decrease afterwards. Compared to that, blooms in our analysis appear to happen earlier, in April. The sampling period of Rey et al. (2000) however, is quite different to that of our database. Rey et al. (2000) sampled in the months May–July only in 1993–1995, while most of data used here were sampled after 1995 and for all months between April and September. Satellite-based work by Arrigo et al. (2011) also showing the May–June peak, dealt with the net primary production only, which can be quite different from the CHL values. There is yet another point of view on the subarctic Atlantic phytoplankton seasonal cycle. Recent work by Behrenfeld (2010) shows that the bloom initiation occurs in winter

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when the Mixed Layer Depth is at maximum. This is in line with what we observed in April, being the maximum of the bloom which starts to decrease afterwards.

Within our study, the SCM only contributes significantly to C_{tot} within the lowest surface CHL range ($< 0.3\,\mathrm{mg\,C\,m^{-3}}$). The relative spread of the data is greatest for this range, showing a highly variable position and magnitude of SCM, which is most probably caused by differences in the nutrient conditions. In accordance to Tremblay et al. (2012) study based on the in-situ data of Canadian Arctic, we observed that the SCM is a long-lived (present from April till September) and wide-spread biological structure, which needs to be monitored carefully. In the future, freshening of the Arctic waters caused by the increasing sea ice melt due to climate change, coupled with the atmospheric circulation patterns that favour advection of the sea ice out of the Arctic Ocean (Rigor and Wallace, 2004; Liu et al., 2007; Maslanik et al., 2007) should lead to stronger water stratification. Thus the cases of low surface CHL with SCM may become even more frequent, because the nutrients will not reach the top layer.

4.2 Comparison of the Greenland Sea chlorophyll profiles with those of the global ocean

To compare our results to the global relationship by Morel and Berthon (1989), we derived the dimensionless profiles from the data. The mean profiles for the selected low ($0.15 < C_{pd} < 0.3$) and high ($1.5 < C_{pd} < 5$) ranges introduced by Morel and Berthon (1989) are presented in Fig. 5. The examples for these two ranges are shown as they clearly present two different trophic situations. Other ranges are variations of the two mentioned above, for the Greenland Sea generally showing two different patterns of the CHL profile for April–June and August–September, and the spread of both depth and value of CHL maxima decreasing as the C_{pd} range rises. July is the “deviating” profile, in some ranges behaving like April–June, and like August–September in others.

One has to keep in mind, that dimensionless profiles magnify the shape of the actual profile, giving the largest values to the steepest changes of the profile. (Therefore the CHL maximum values on Fig. 5 are not comparable with those of the median profiles on

Fig. 3.) In the low range, the Greenland Sea April–June CHL maxima correspond to the global annual maximum. Later in the season, in July–August, the CHL maximum value almost matches that of the global relationship, but the location is much shallower. In the high range as well, the April–June CHL maxima are alike the global maximum, while in the later months both values and the depth of the Greenland Sea CHL maxima are not represented by the global relationship. To sum up, although the Morel and Berthon (1989) relationships are global and exclude all the high latitudes (thus did not account for any data of the Greenland Sea) and in addition did not account for the seasonality, they agree well with the Greenland Sea CHL maxima early in the season, whereas the months after June are not correctly represented. Our results show that for the correct parametrization of CHL content in the water column at the high latitudes we need both the monthly- and surface chlorophyll-resolved relationship. A remarkable feature of our dimensionless profiles is the intersection at one depth of all the monthly profiles. It is especially visible around depths 0.5 in the high C_{pd} range (Fig. 5, bottom left), but was observed for all the ranges. As mentioned above the dimensionless profiles give the attention to the shape of the CHL maxima, but do not reproduce the magnitude of the CHL maxima correctly, which made us decide for the profiles having "natural" dimensions as the output of the current effort.

Comiso (2010) found small inter-annual variability of the CHL in the Greenland Sea and Pabi et al. (2008) observed that the Greenland Sector (geographically the same as our area of investigation) had the lowest inter-annual variability of primary production of all the Arctic Ocean. Small inter-annual variability implies that the relationship we observed may be used for any year with a minimum risk of year-to-year change.

5 Conclusion

In this study we derived the relationship between the CHL in the surface layer and its vertical profile for the Greenland Sea. Median profiles and their Gaussian fittings reducing the computational effort were obtained. The relationship is resolved in terms of CHL content in the surface layer as well as in terms of seasonal cycle. As in the global study by Morel and Berthon (1989), we observed principally different patterns of CHL profile for the low and high concentration in the surface layer, which showed the need to account for the surface value when calculating the shape of the profile. Since the Morel and Berthon (1989) relationship is seasonally averaged, it captured only the early months of the Greenland Sea season, suggesting the need to use the monthly resolved relationship for the region. The analysis of the relationships derived here showed a clear seasonal cycle (most evident in high concentration range) with CHL lowering from April to August and the CHL maxima coming closer to the surface. The Subsurface Chlorophyll Maximum was significant for the low surface CHL. The dimensionless profiles of all specific surface layer CHL ranges showed a point of intersection between all monthly profiles. The obtained mathematical fits are to be used to obtain the CHL profile based on the satellite CHL value (which coincides to the C_{pd} value). This CHL profile is in turn meant as an input to a primary production model for improving the primary production estimates in the Arctic Ocean.

Supplementary material related to this article is available online at: http://www.ocean-sci-discuss.net/9/3567/2012/osd-9-3567-2012-supplement.zip.

Acknowledgements. Current work was supported by POLMAR Helmholtz Graduate School for Polar and Marine research, AWI and Helmholtz Impulse and Network Fond (HGF Young Investigators Group Phytooptics). We thank D. Antoine for helpful discussions, C. Lorenzen and S. Murawski for chlorophyll *a* measurements in the laboratory and all students and scientists who did the water filtration on board the research vessels.

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From the chlorophyll *a* in the surface layer to its vertical profile

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Table 1. Characteristics of the chlorophyll profiles categorized according to the mean chlorophyll in the surface layer (C_{pd}), and then binned into the monthly bins. Roman numbers indicate the four ranges of C_{pd} (mg C m^{-3}): (I) <0.3; (II) 0.3–0.45; (III) 0.45–0.7; (IV) >0.7. The corresponding mean total chlorophyll content in the water column over all months (mean C_{tot}, mg C m^{-2}) for the four ranges is: (I) 20.4; (II) 24.9; (III) 27.5; (IV) 46.0. The median, mean, inter-quartile range and standard deviation are values averaged for the whole water column.

		Apr	May	Jun	Jul	Aug	Sep
Median (mg C m^{-3})	I	0.25	0.26	0.12	0.18	0.16	0.19
	II	0.61	0.31	0.30	0.26	0.30	0.19
	III	0.52	0.44	0.34	0.30	0.35	0.24
	IV	1.04	0.89	0.61	0.49	0.48	0.37
Interquartile range (%)	I	75	81	134	62	64	56
	II	39	47	31	60	54	22
	III	23	46	25	41	30	24
	IV	53	52	46	45	46	27
Depth of CHL max (m)	I	38	37	28	26	25	29
	II	65	27	23	28	21	8
	III	1	1	25	16	17	5
	IV	2	2	3	11	1	1
Value of CHL max (mg C m^{-3})	I	0.60	0.49	0.27	0.31	0.30	0.53
	II	0.88	0.45	0.48	0.63	1.30	0.41
	III	0.59	0.60	0.65	0.68	0.90	0.62
	IV	1.95	1.61	1.32	1.28	1.47	1.19
Mean (mg C m^{-3})	I	0.43	0.46	0.33	0.30	0.23	0.25
	II	0.68	0.42	0.41	0.42	0.35	0.20
	III	0.52	0.60	0.41	0.38	0.37	0.26
	IV	1.18	1.17	0.78	0.66	0.60	0.40
Standard deviation (%)	I	102	131	145	116	92	93
	II	41	80	87	113	58	34
	III	34	79	68	70	44	33
	IV	66	79	72	88	65	42

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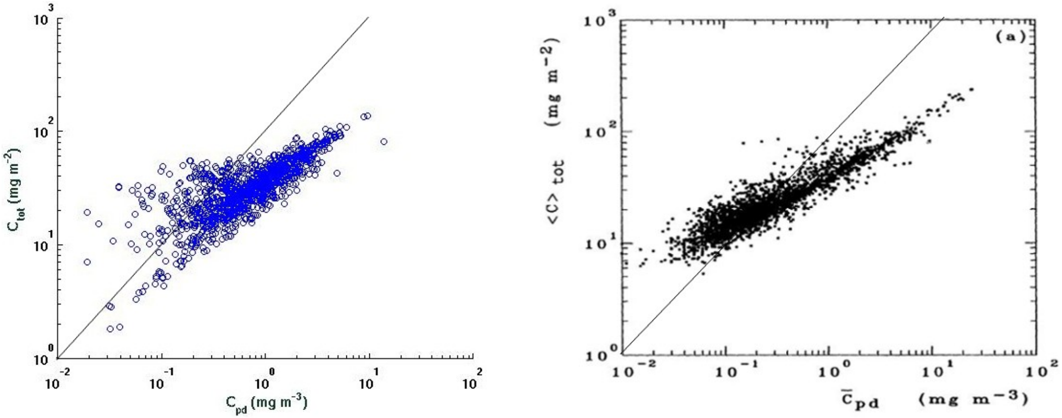

Fig. 1. Total chlorophyll content within the euphotic layer (C_{tot}) versus mean chlorophyll within the surface layer (C_{pd}). The black line is the one-to-one line. Left: for the Greenland Sea, this study, $R = 0.82$, $N = 1208$, significant correlation ($p < 0.0001$). Right: from the global study by Morel and Berthon (1989).

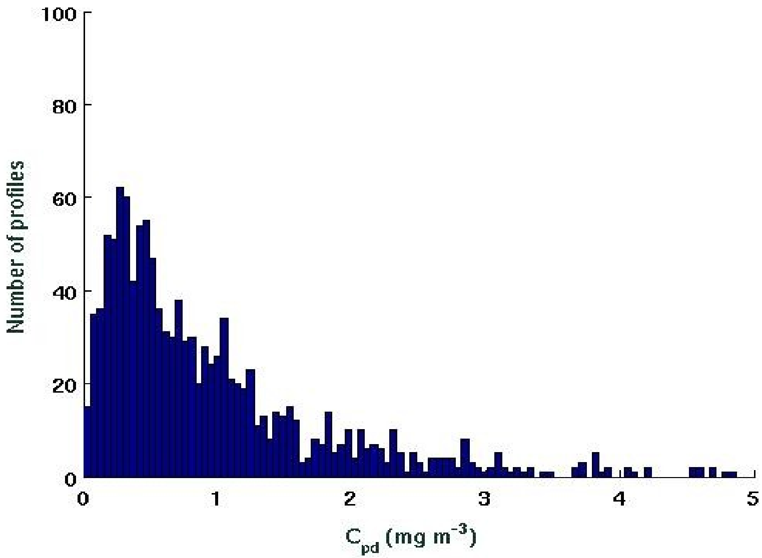

Fig. 2. Histogram describing the distribution of the mean chlorophyll within the surface layer (C_{pd}) over the 1200 chlorophyll profiles.

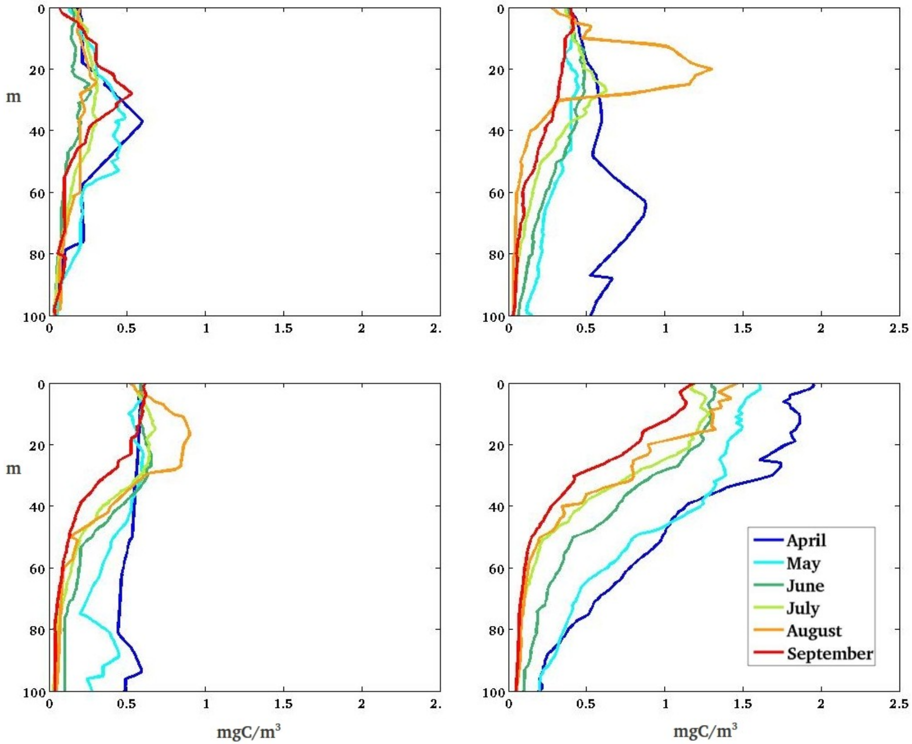

Fig. 3. Median monthly chlorophyll profiles obtained for the four ranges of mean chlorophyll within the surface layer (C_{pd}, mg C m^{-3}). Ranges (from top left to bottom right, range 2 is top right and range 3 is bottom left): (1) <0.3; (2) 0.3–0.45 (3) 0.45–0.7 (4) >0.7. Data of R/V *Polarstern* and *Maria S Merian* cruises (unpublished), and from ARCSS-PP database, 1957–2010.

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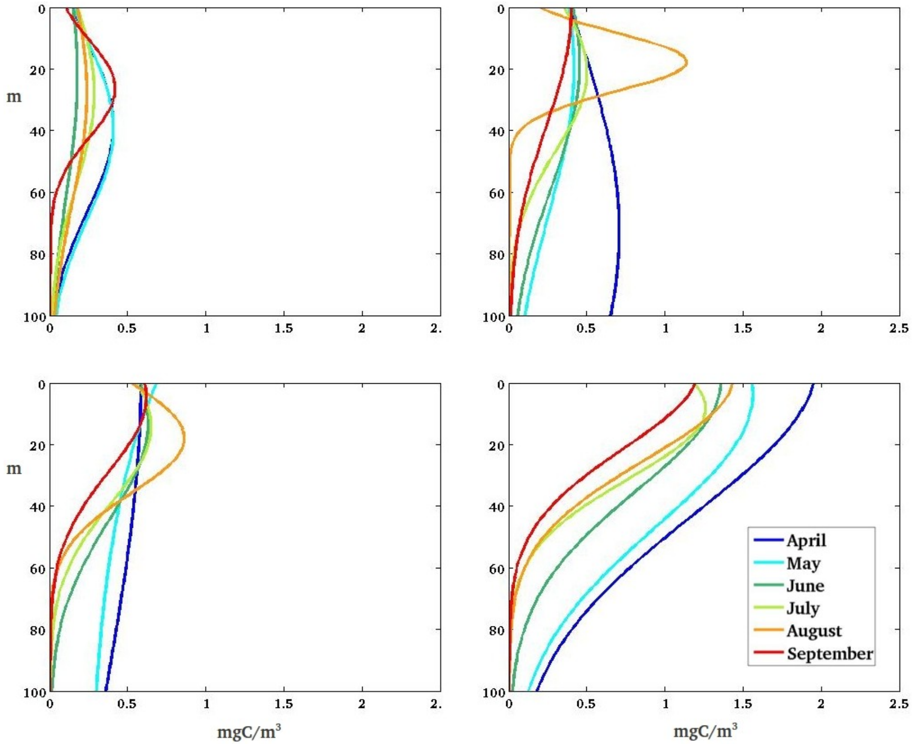

Fig. 4. Gaussians fitted to the median monthly chlorophyll profiles obtained for the four ranges of mean chlorophyll within the surface layer (C_{pd}, $mg\,C\,m^{-3}$). Ranges (from top left to bottom right, range 2 is top right and range 3 is bottom left): (1) < 0.3; (2) 0.3–0.45 (3) 0.45–0.7 (4) > 0.7. Data of R/V *Polarstern* and *Maria S Merian* cruises (unpublished), and from ARCSS-PP database, 1957–2010.

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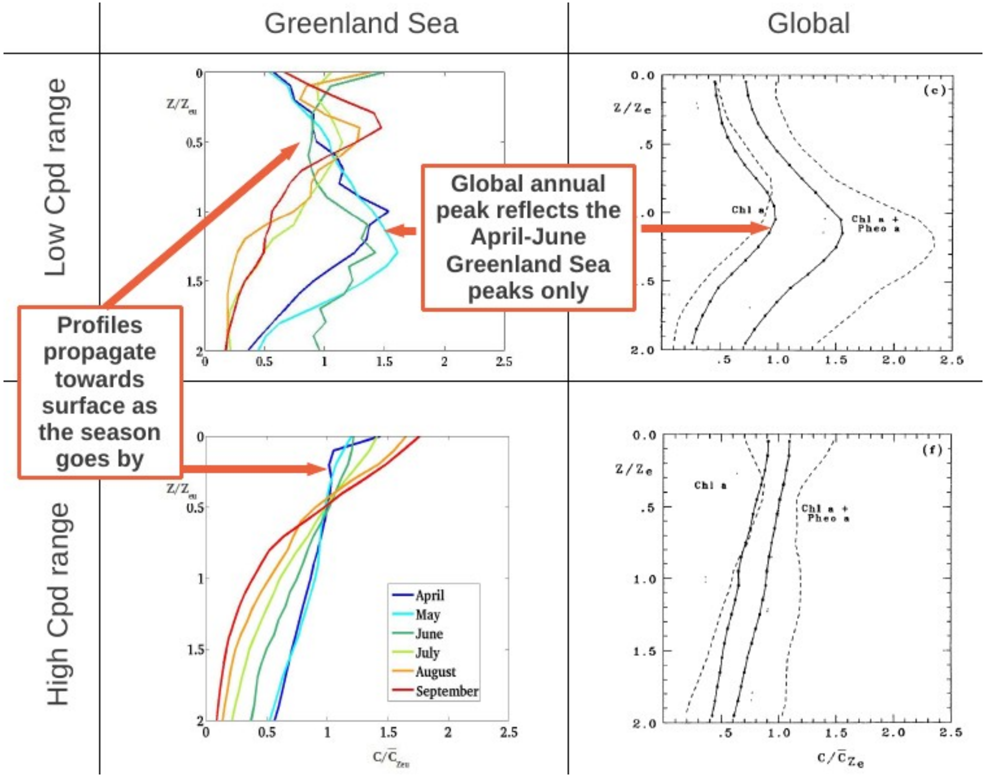

Fig. 5. Dimensionless chlorophyll profiles categorized according to their chlorophyll within the surface layer (C_{pd}). Two C_{pd} ranges out of seven computed are shown. Vertical axis shows depth divided by the euphotic layer depth (Z_{eu}). Horizontal axis shows chlorophyll divided by the mean chlorophyll for Z_{eu}. Left: Greenland Sea monthly mean profiles computed in this study. Right: from global relationship (Morel and Berthon, 1989), we are interested in solid line marked CHLa (mean chlorophyll profile). Top is low C_{pd} range ($0.15 < C_{pd} < 0.30$), bottom is high C_{pd} range ($1.5 < C_{pd} < 5$).

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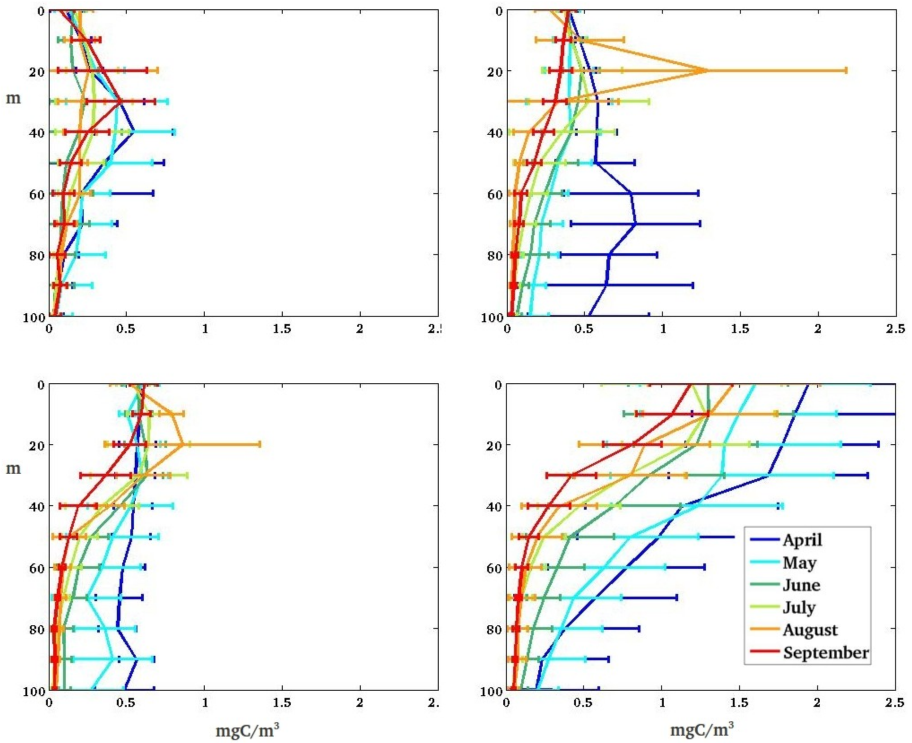

Fig. A1. Interquartile ranges of the monthly chlorophyll profiles for the four ranges of mean chlorophyll within the surface layer (C_{pd}, mg C m^{-3}). Ranges (from top left to bottom right, range 2 is top right and range 3 is bottom left): (1) < 0.3; (2) 0.3–0.45 (3) 0.45–0.7 (4) > 0.7. Data of R/V *Polarstern* and *Maria S Merian* cruises (unpublished), and from ARCSS-PP database, 1957–2010.