INT. J. REMOTE SENSING, 10–20 APRIL, 2004,
VOL. 25, NO. 7–8, 1453–1457

Deriving phytoplankton biomass in the Marginal Ice Zone from satellite observable parameters

O. ENGELSEN*†, H. HOP†, E. N. HEGSETH‡, E. HANSEN† and S. FALK-PETERSEN†

†Norwegian Polar Institute, N-9296 Tromsø, Norway
‡Norwegian College of Fishery Science, University of Tromsø, N-9037 Tromsø, Norway

Abstract. Water mass properties and sea ice history have a significant impact on the vertical distribution of phytoplankton in the Marginal Ice Zone of the northern Barents Sea. A method is suggested to identify the phase and magnitude of the phytoplankton bloom based on satellite observable values of chlorophyll-*a*, temperature, salinity and sea ice history. For each bloom phase, formulae are provided for calculation of the chlorophyll-*a* column from satellite-equivalent measurements of chlorophyll-*a*.

1. Introduction

The onset of plankton blooms in the Marginal Ice Zone (MIZ) of the Barents Sea is directly related to the seasonal availability of incident light and stratification of water masses due to melting of sea ice. Following the receding ice edge, these algal blooms sweep across the entire northern Barents Sea. The total annual production for this area can become relatively large (40–50 $\mathrm{g\,C\,m^{-2}}$, Hegseth 1998), i.e. comparable to that of the North Atlantic shelf and Norwegian fjords.

Estimates of water column phytoplankton biomass and biomass-dependent primary production are important biological parameters derived from interpretations of water-reflected radiance, measured by ocean colour satellite sensors. However, only measurements of near-surface concentrations of chlorophyll-*a* are available operationally from satellite data. In order to estimate the full chlorophyll-*a* column (as a measure of total phytoplankton biomass) from satellite measurements, assumptions on the overall vertical chlorophyll-*a* distribution must be made.

In this study the vertical distribution of chlorophyll-*a* in relation to the sea ice and water mass properties in the MIZ is determined. In contrast to previous studies (e.g. Moline and Prézelin 2000), the focus is on different bloom phases and ways are proposed to identify them from surface conditions observable from satellite. Equations for calculation of the chlorophyll-*a* column from satellite-equivalent

*Present address: Norwegian Institute for Air Research, N-9296 Tromsø, Norway; e-mail: ola.engelsen@nilu.no

An updated version of a paper originally presented at *Oceans from Space 'Venice 2000' Symposium,* Venice, Italy, 9–13 October 2000.

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160310001592436

values are presented for the different bloom phases: homogeneous water masses (no bloom), pre-bloom/bloom and post-bloom.

2. Materials and methods

In situ data were collected during cruises in the Barents Sea in the MIZ from March to October, dating back to 1986 (Hegseth 1992, 1997, Falk-Petersen *et al.* 1999, 2000, Engelsen *et al.* 2002). The vertical distribution of chlorophyll-*a* was determined fluorimetrically from water samples. Temperature and salinity were recorded with CTD (conductivity–temperature–density) sondes.

Satellite-equivalent chlorophyll-*a* (C_{sat}) was approximated as (Gordon and Clark 1980):

$$
\begin{aligned}
C_{\mathrm{sat}} &\approx \int_0^{Z_{90}} C(z) g(z) \mathrm{d}z \bigg/ \int_0^{Z_{90}} g(z) \mathrm{d}z, \\
g(z) &= \exp\left[-2 \int_0^{z} K(z') \mathrm{d}z' \right], \\
g(z_{90}) &= 0.1
\end{aligned}
\tag{1}
$$

where all necessary chlorophyll-*a* values, $C(z)$, at all depths z were interpolated from the measured chlorophyll-*a* profiles. Profiles of the irradiance attenuation coefficients (Kz) were computed at 445 nm wavelength according to Morel and Maritorena (2001) using $C(z)$.

Sea ice concentrations originate from Special Sensor Microwave Imager (SSM/I) data. The National Aeronautics and Space Administration (NASA) Team Algorithm (Cavalieri *et al.* 1997) was used in the computation of mean sea ice concentrations from daily brightness temperatures. By collecting a time-series of SSM/I data from the Barents Sea, the history of the total ice concentrations was determined for each station before the *in situ* measurements.

3. Data analysis

The different phytoplankton bloom phases had the following characteristics. In the homogeneous phase, the water masses are not yet stratified and little chlorophyll-*a* exists in general. The water column salinity is typically around 34.7–35.2 psu and the temperature near the freezing point (-1.8°C). During the bloom phase, the phytoplankton biomass is concentrated near the surface (figure 1(*a*)). In the transition from bloom to post-bloom, the phytoplankton biomass sinks downwards and is also grazed by zooplankton. This results in a decrease in surface concentration and a deep chlorophyll maximum near the pycnocline (figure 1(*b*)).

The history of sea ice cover partly explains the shape of vertical chlorophyll-*a* profiles (figure 2). Homogeneous conditions occurred when ice concentrations were either increasing or were high and stable. At the onset of blooms, the ice concentrations inside the ice zone had decreased over time. Blooms occurred in the low density upper melt water layer, with higher sea surface temperature (SST) and lower sea surface salinity (SSS) than for homogeneous water masses. Post-bloom scenarios generally occurred after the ice had receded. The ambient conditions of the different bloom phases are discussed thoroughly in Engelsen *et al.* (2002). Bloom stages may be roughly separated by analysing parameters measurable from satellite, such as chlorophyll-*a*, ice concentration, ice concentration history (gradient), SST and SSS (table 1).

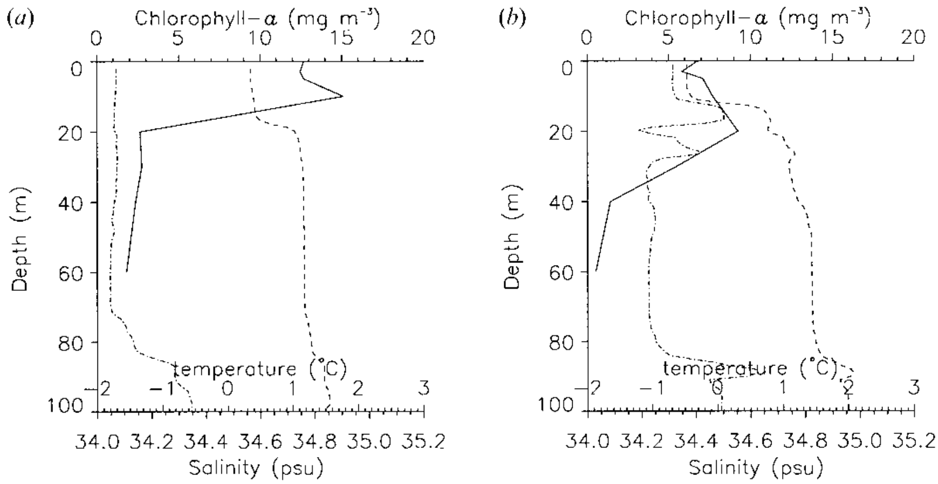

Figure 1. Examples of vertical profiles of chlorophyll-*a*, temperature and salinity inside the Marginal Ice Zone (MIZ). Solid line: chlorophyll-*a* (mg chl-*a* m^{-3}); dashed line: salinity (psu); dashed-dotted line: temperature (°C). (*a*) Bloom: N76°48.9′ E32°49.2′. Date: 11 May 1999, inside the MIZ. (*b*) Late bloom: N76°29.6′ E27°42.7′. Date: 21 May 1999, near open water.

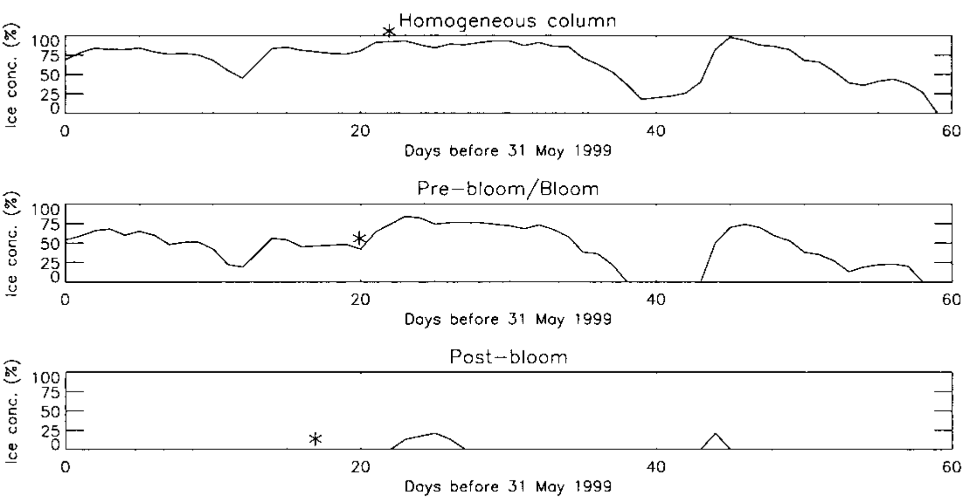

Figure 2. Total ice concentration history for the homogeneous water column, pre-bloom/bloom and post-bloom scenarios. The star (*) on each plot indicates the actual time of measurements.

Table 1. Synthesis of levels and gradients (Δ) of sea ice concentration, surface temperature (SST), sea surface salinity (SSS) and chlorophyll-*a* for different bloom stages in the Marginal Ice Zone of the northern Barents Sea.

Growth phase	Ice conc./Δ (%)	SST/Δ (°C)	SSS/Δ (PSU)	Chl-*a*/Δ ($mg\,m^{-3}$)
Homogeneous water masses	[0, 100]/+	$<-1.6/0$	$>34.1/0$	$<4/0$
Pre-bloom/Bloom/Late Bloom	[0, 70]/−	$>-1.8/+$	$<35.0/-$	$>2/+$
Post-bloom	0/0	$>-1.8/0,+$	$<35.0/0,-$	$<1/-$

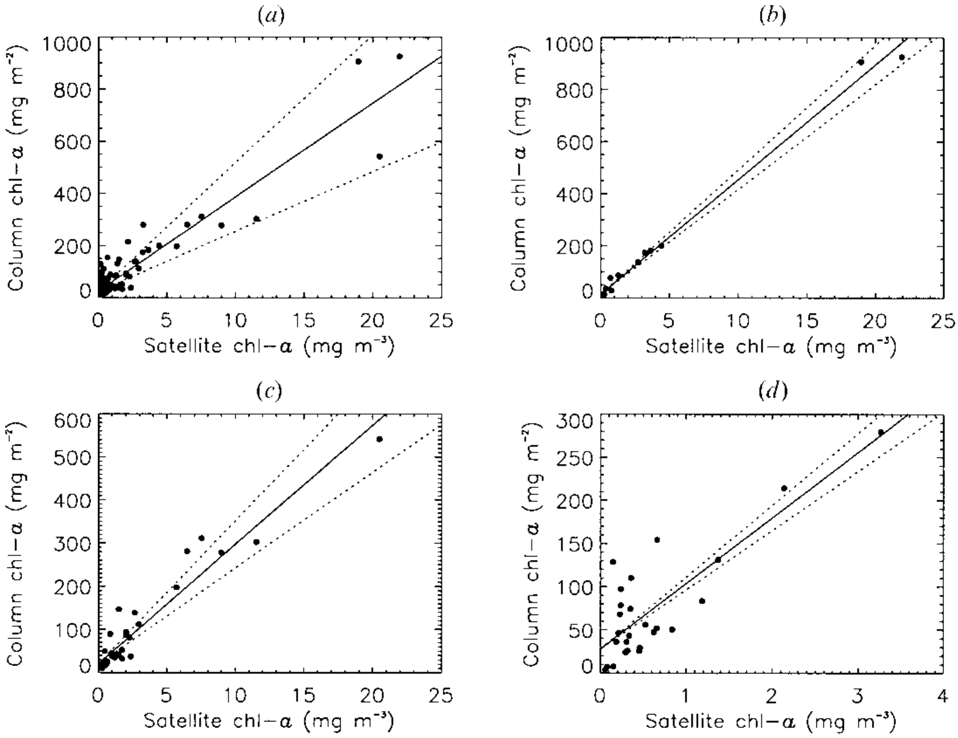

Figure 3. Relationships between satellite-equivalent chlorophyll-*a* concentrations C_{sat} (mg Chl-*a* m^{-3}) and chlorophyll columns C_{column} (mg chl-*a* m^{-2}), measured at different times of the year in the Barents Sea. The dotted lines illustrate 95% confidence interval. (*a*) All data both in open and ice-covered water [$C_{column} = 36.085 \times (C_{sat} + 25.142)$, $R^2 = 0.941$]. (*b*) Homogeneous water masses [$C_{column} = 44.076 \times (C_{sat} + 13.343)$, $R^2 = 0.997$]. (*c*) Pre-bloom/bloom phase [$C_{column} = 27.676 \times (C_{sat} + 20.075)$, $R^2 = 0.961$]. (*d*) Post-bloom phase [$C_{column} = 75.981 \times (C_{sat} + 27.686)$, $R^2 = 0.829$].

Given that the particular bloom phase is identified, the next step is to estimate the chlorophyll-*a* column (C_{column}) from satellite equivalent chlorophyll-*a* measurements (C_{sat}). This is followed by determination of the regression parameters *a* and *b* in the equation $C_{column} = aC_{sat} + b$, based on *in situ* chlorophyll-*a* measurements for the three phases (figure 3). In the case that a bloom phase cannot be determined, an overall regression equation for the column chlorophyll-*a* is provided. This formula is likely to yield good results except for the summer conditions when post-blooms prevail; in this case total biomass tends to be underestimated.

4. Conclusions

Phytoplankton blooms occur in different phases: homogeneous water column (i.e. no bloom), pre-bloom/bloom and post-bloom. From satellite measurements of near-surface chlorophyll-*a*, ice concentration, ice concentration history, SST and, possibly, SSS, the three bloom phases can be identified. For each bloom phase, formulae are provided to derive chlorophyll-*a* values for the water column from satellite-equivalent measurements.

Acknowledgments

We thank Józef Wiktor, Institute for Oceanology, Polish Academy of Sciences, for participation in the collections of water samples. This project was partly funded by the partners of the Barents Sea Production Licenses 182, 225 and 228 (i.e. Norsk Hydro, Statoil, Petoro, Agis, Chevron, Fortum, Enterprise). The SSM/I data were obtained from the National Snow and Ice Data Center, USA.

References

CAVALIERI, C., PARKINSON, L., GLOERSEN, P., and ZWALLY, H. J., 1997, Arctic and Antarctic sea ice concentrations from multichannel passive-microwave satellite data sets: October 1978 to September 1995, User's Guide. NASA Technical Memorandum 104627.

ENGELSEN, O., HEGSETH, E. N., HOP, H., HANSEN, H., and FALK-PETERSEN, S., 2002, Spatial variability of chlorophyll-*a* in the Marginal Ice Zone of the Barents Sea, with relations to sea ice and oceanographic conditions. *Journal of Marine Systems*, **35**, 79–97.

FALK-PETERSEN, S., HOP, H., BUDGELL, W. P., HEGSETH, E. N., KORSNES, R., LØYNING, T. B., ØRBÆK, J. B., KAWAMURA, T., and SHIRASAWA, K., 2000, Physical and ecological processes in the Marginal Ice Zone of the northern Barents Sea during the summer melt period. *Journal of Marine Systems*, **27**, 131–159.

FALK-PETERSEN, S., PEDERSEN, G., KWASNIEWSKI, S., HEGSETH, E. N., and HOP, H., 1999, Spatial distribution and life-cycle timing of zooplankton in the marginal ice zone of the Barents Sea during the summer melt season in 1995. *Journal of Plankton Research*, **21**, 1249–1264.

GORDON, H. R., and CLARK, D. K., 1980, Remote sensing optical properties of a stratified ocean: an improved interpretation. *Applied Optics*, **19**, 3428–3430.

HEGSETH, E. N., 1992, Sub-ice algal assemblages of the Barents Sea: Species composition, chemical composition, and growth rates. *Polar Biology*, **12**, 485–496.

HEGSETH, E. N., 1997, Phytoplankton of the Barents Sea – the end of a growth season. *Polar Biology*, **17**, 235–241.

HEGSETH, E. N., 1998, Primary production of the northern Barents Sea. *Polar Research*, **17**, 113–123.

MOLINE, M. A., and PRÉZELIN, B. R., 2000, Optical fractionation of chlorophyll and primary production for coastal waters of the Southern Ocean. *Polar Biology*, **23**, 129–136.

MOREL, A., and MARITORENA, S., 2001, Bio-optical properties of oceanic waters: A reappraisal. *Journal of Geophysical Research*, **106**, 7163–7180.