ELSEVIER

Deep-Sea Research II 51 (2004) 1323–1331

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Temporal and spatial distribution of chlorophyll-*a* in surface waters of the Scotia Sea as determined by both shipboard measurements and satellite data

O. Holm-Hansen[a,*], M. Kahru[a], C.D. Hewes[a], S. Kawaguchi[b,1], T. Kameda[b], V.A. Sushin[c], I. Krasovski[c], J. Priddle[d,2], R. Korb[d], R.P. Hewitt[e], B.G. Mitchell[a]

[a]*Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093, USA*
[b]*National Research Institute of Far Seas Fisheries, 5-7-1 Orido, Shimizu, Shizuoka-pref. 424-8633, Japan*
[c]*Atlantic Scientific Research Institute for Marine Fisheries and Oceanography (AtlantNIRO) 5, Dmitry Donskoy St., Kaliningrad, 236000, Russia*
[d]*British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 OET, UK*
[e]*Southwest Fisheries Science Center, National Oceanic and Atmospheric Administration, P.O. Box 271, La Jolla, CA 92038, USA*

Accepted 18 June 2004
Available online 16 September 2004

Abstract

Chlorophyll-*a* (Chl-*a*) concentrations in surface waters were measured at 137 hydrographic stations occupied by four research vessels participating in the CCAMLR 2000 Survey and the values were compared to estimates from data acquired by the SeaWiFS satellite. The Chl-*a* concentrations measured on board ship ranged from 0.06 to 14.6 mg m^{-3}, a range that includes most surface Chl-*a* concentrations during mid-summer in the Southern Ocean. Owing to persistent cloud cover over much of the Southern Ocean, it was necessary to acquire multi-day composites of satellite data in order to obtain reliable estimates of Chl-*a* at each of the hydrographic stations. The correlation between the median value for the eight-day composites and the Chl-*a* concentrations measured on board ship had an R^2 value of 0.82, with the satellite data under-estimating the values obtained on board ship at high Chl-*a* concentrations and slightly over-estimating the shipboard data at Chl-*a* concentrations of <0.2 mg m^{-3}. For Chl-*a* concentrations of <1.0 mg m^{-3}, the ratio of the satellite estimates divided by the shipboard values was 0.89 ± 0.45 ($n = 50$). As the mean Chl-*a* concentration in most pelagic Antarctic waters is close to 0.5 mg m^{-3}, satellite estimates for Chl-*a* concentrations in surface waters are thus close to shipboard measurements, and offer the advantage of providing synoptic maps of Chl-*a* distribution over extensive areas of the Southern Ocean. Satellite Chl-*a* images for the months preceding (December 1999) and following (February 2000) the CCAMLR 2000 Survey cruises showed that the general pattern of Chl-*a* concentration in the Scotia Sea and adjoining waters was similar in all three months, but that the phytoplankton biomass was generally

*Corresponding author.
E-mail address: oholmhansen@ucsd.edu (O. Holm-Hansen).
[1]Present address: Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia.
[2]Present address: Science Training and Education Partnership, Scolt House, 59 High Street, Barrington CB2 5QX, UK.

0967-0645/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.dsr2.2004.06.004

lowest in December, reached maximal values in January, and started to decline in February. In contrast, Chl-*a* concentrations in Drake Passage declined progressively from early December through February.
Published by Elsevier Ltd.

1. Introduction

One limitation of shipboard-acquired data in attempting to determine the distribution of phytoplankton over a large area is that the spatial coverage per day is relatively small. When the study period extends over several weeks or more in a physically dynamic area such as the Scotia Sea, there may be considerable error in attempting to describe the synoptic distribution of chlorophyll-*a* (Chl-*a*). This can be overcome by the use of satellite data as this can provide synoptic information on the distribution of Chl-*a* over an entire study area. At high latitudes such as the Scotia Sea, polar-orbiting satellites may view an Earth location more than once each day. An additional advantage is that satellite data may be acquired for a region much larger than the shipboard sampling grid, which makes it possible to observe eddies or other water masses intruding into the sampling area. One limitation of satellite data, however, is that estimates of Chl-*a* concentration pertain to surface waters (the upper 5–10 m) only, and ecological studies generally require information about the distribution of Chl-*a* throughout the entire euphotic zone. However, previous studies in the Bransfield Strait region (Holm-Hansen and Mitchell, 1991) have shown a good correlation between surface Chl-*a* concentrations and depth-integrated values ($R^2 = 0.91$, $n = 331$) in Antarctic waters. A more important limitation of satellite data is caused by clouds, and these are especially prevalent at high latitudes.

Understanding the distribution of phytoplankton and concomitant rates of primary production in the Scotia Sea is of much importance, as this region has historically been one of the richest areas for the harvest of krill (Everson and Miller, 1994; Priddle et al., 1988). Except for the shallow shelf areas of the North and South Scotia Ridge and the South Sandwich Islands, most Scotia Sea waters are deep (>2000 m) and thus generally considered to be oligotrophic with regard to phytoplankton biomass (El-Sayed, 1988). The Scotia Sea, however, differs from most deep circumpolar waters due to the inflow and mixing of continental shelf waters from the Weddell Sea, Bellingshausen Sea, Bransfield Strait, and Argentine Shelf with Drake Passage waters. Foster and Middleton (1984) have shown that a clearly defined front between Drake Passage waters and water outflow from the Weddell Sea can be observed in a limited region to the northwest of the South Orkney Islands, and is associated with the formation of eddy-like structures which persist as they flow northeast through the Scotia Sea. Southward transport of nutrient-rich waters from the Argentine Shelf into the Scotia Sea may also be important (Davis et al., 1996). These dynamic oceanographic features result in considerable temporal and spatial variability in both the physical and biological characteristics of the Scotia Sea, which makes it difficult to obtain a reliable synoptic description of phytoplankton distribution in this area from shipboard observations.

The outcome of a coordinated survey in the Scotia Sea by vessels from four CCAMLR member countries (UK, Russia, Japan, USA) in January and early February 2000 (Watkins et al., 2004), combined with ocean-color data from the SeaWiFS satellite, made it possible to evaluate the reliability and utility of using satellite data to describe temporal and spatial variability in Chl-*a* concentrations in Antarctic waters. Frequent cloud cover over much of the Southern Ocean makes it necessary to combine satellite data obtained over periods of many days or weeks to obtain spatial estimates of Chl-*a* concentration. If surface Chl-*a* concentrations change rapidly (e.g., over periods of days), it would be expected that shipboard data would not correlate well with weekly or monthly averaged Chl-*a* concentrations estimated from satellite data. The degree to which shipboard data correlate with estimates from satellite data is examined in this paper. Monthly averaged maps of Chl-*a* distribution estimated from satellite data are shown for the Scotia Sea for the months preceding, during, and after the CCAMLR 2000 Survey. These are compared with the monthly and eight-day averaged estimates of surface Chl-*a* concentration at all stations based on shipboard measurements. The primary purposes of this paper are: (1) to show that the distribution patterns of Chl-*a* in the Scotia Sea as estimated from satellite data are fairly similar over a three-month period, but that the time of maximal phytoplankton biomass may vary between December and February in some local areas, and (2) to verify that Chl-*a* concentrations estimated from satellite data are reasonably close to the concentrations determined on board ship by direct analysis of Chl-*a* in seawater samples.

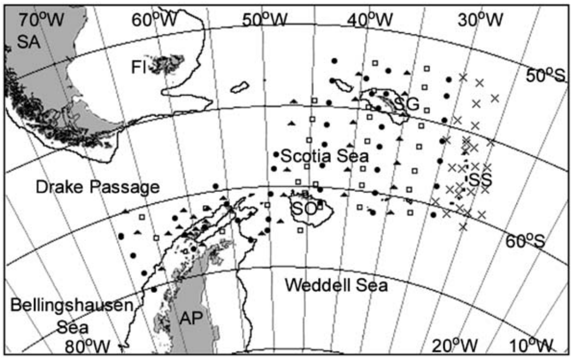

Fig. 1. Hydrographic station locations where Chl-*a* concentrations were measured during the CCAMLR 2000 Survey. Crosses (×) show the 27 stations occupied by the R.V. *Atlantida* from 1/17/00 to 2/1/00. Filled triangles (▲) show the 38 stations occupied by the R.V. *Kaiyo Maru* from 1/11/00 to 2/6/00. Filled circles (●) show the 41 stations occupied by the R.R.S. *James Clark Ross* from 1/16/00 to 2/11/00. Open squares (□) show the 31 stations occupied by the R.V. *Yuzhmorgeologiya* from 1/16/00 to 2/4/00. Transects were generally north–south, starting in the east and moving west. The black line shows the 1000 m isobath. SA: South America; FI: Falkland Islands; AP: Antarctic Peninsula; SO: South Orkney Islands; SG: South Georgia; SS: South Sandwich Islands (the South Sandwich Islands comprise many small islands extending from ~56.3 to 59.4° S and 27.6 to 27.2° W. The 1000 m isobath is too close to these islands to show on this map).

2. Materials and methods

2.1. Ship tracks and station locations

Fig. 1 shows the location of all hydrographic stations at which Chl-*a* measurements were made during the CCAMLR 2000 Survey. Although most occurred within the Scotia Sea, some were located to the north of South Georgia, to the east of the South Sandwich Islands, in the northern Weddell Sea, in Bransfield Strait, and in Drake Passage waters. All sampling occurred between January 11 and February 11, 2000.

2.2. Water samples

Water samples were obtained at standard depths using Niskin bottles attached to the CTD-profiling units. Although the sampling depths varied slightly between the four vessels, most of the samples discussed here were from approximately 1 (surface water), 6, 10, 20, and 30 m. No pre-filter was used when taking water from the Niskin bottles for Chl-*a* determination.

2.3. Measurement of chlorophyll-a

Water samples, which varied from 100 to 500 ml depending on the expected Chl-*a* concentration, were filtered either through Whatman GF/F glass fiber filters (USA, UK, Japan) or through cellulose acetate filters of Synpor #6 type with 0.45 μm pores or Sartorius filters with 0.45 μm pores (Russia). A differential vacuum of 25 cm Hg or less was used in all filtrations. Photosynthetic pigments were extracted by immersion of the filters in 10 ml of 90% acetone. After storage in the dark for more than one hour, the samples were shaken and centrifuged. Concentrations of Chl-*a* and phaeophytin in the supernatants were determined by measuring the fluorescence before and after acidification (Holm-Hansen et al., 1965). All fluorometers were calibrated against purified Chl-*a* standards.

2.4. Satellite data

Satellite estimates of surface Chl-*a* concentrations were obtained from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; McClain et al.,

1998) using the standard OC4v2 chlorophyll algorithm (O'Reilly et al., 1998, 2000). Monthly and eight-day composited satellite data were produced by the Distributed Active Archive Center at the NASA Goddard Space Flight Center using global (GAC) data at 4 km resolution (Campbell et al., 1995). These binned data sets were mapped onto a global map at approximately 9 km resolution and used for match-ups with the in situ Chl-*a* data. Both the estimated Chl-*a* value for the nearest pixel to the sample site as well as various statistics relating to the 3×3 pixel window centered at the nearest pixel in the image were used in the match-up data sets. Frequent cloud cover is the main reason why compositing of individual satellite passes is required in order to obtain a matching value for a particular point in the ocean. While a longer compositing interval increases the probability that a particular point has a valid Chl-*a* estimate, it also increases the temporal bias between the near-instantaneous in situ measurement of Chl-*a* and the estimate derived from the composited satellite data.

3. Results

Fig. 2 shows the monthly averaged distribution of Chl-*a* determined from satellite data for December 1999, January 2000, and February 2000. These images show that:

- the same general pattern of Chl-*a* distribution occurs in all three months, but with Chl-*a* concentrations increasing over time in some areas (e.g., the shelf area to the south of South Georgia) and decreasing over time in others (e.g., the shelf areas around the South Orkney Islands);
- the lowest Chl-*a* concentrations occur in Drake Passage and extend into the northwestern Scotia Sea. There is also a progressive decrease in Chl-*a* in this area between December and February;
- low Chl-*a* concentrations also occur to the east of the South Sandwich Islands, in the Weddell Sea, and in the Atlantic Ocean near 50° S;
- high Chl-*a* concentrations occur over much of the continental shelf region (e.g., the Argentine

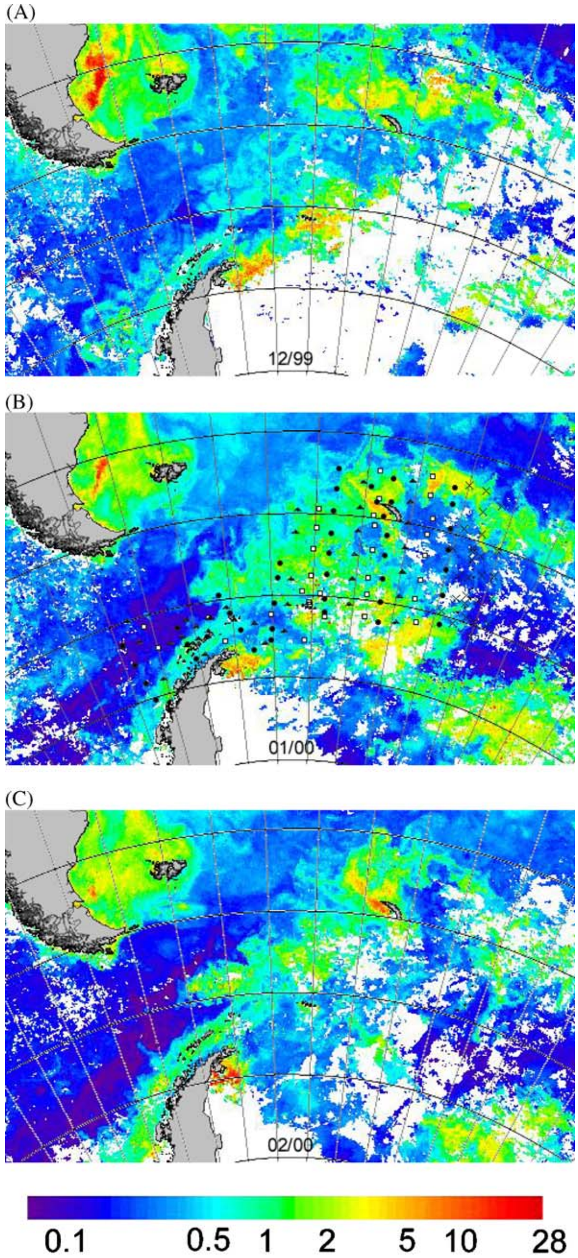

Fig. 2. Satellite maps of monthly averaged Chl-*a* concentration in the Scotia Sea and adjoining waters preceding (A, December 1999), during (B, January 2000), and after (C, February 2000) the CCAMLR 2000 Survey. A Lambert Conformal Conic Projection was used in the preparation of these images. White areas represent either sea ice or open-water areas with insufficient data owing to cloud cover. The color bar shows estimated Chl-*a* concentration in mg m^{-3}. The symbols in B indicate the location of hydrographic stations where Chl-*a* samples were obtained (symbols as in Fig. 1).

shelf, sections of the Scotia Arc, and the shelf regions near the Antarctic Peninsula);

- most of the Scotia Sea shows intermediate concentrations of Chl-*a*, with occasional patches of low Chl-*a* concentration. Concentrations appear to be lowest in December (Fig. 2A), highest in January (Fig. 2B), and then decline slightly in February (Fig. 2C);
- the hydrographic stations occupied by the four vessels include those in areas with the lowest Chl-*a* concentrations (purple areas, with Chl-*a* $<0.1\,\mathrm{mg\,m^{-3}}$) and the highest Chl-*a* concentrations (red areas, with Chl-*a* $>10\,\mathrm{mg\,m^{-3}}$).

The correlation between Chl-*a* concentrations measured on board ship and Chl-*a* concentrations estimated from satellite data for each station is shown in Fig. 3. In order to minimize the differences between Chl-*a* concentrations measured at sea and those estimated from satellite data, it is necessary to use satellite data for the pixel that most closely corresponds to the station location and which was obtained as close as possible in time to the time of sampling at sea. Owing to extensive and often persistent cloud cover over Antarctic waters, it is usually necessary to combine satellite data of many days and to use data from more than one pixel. When the median value of Chl-*a* within a 3×3 pixel area ($\sim27\times27\,\mathrm{km}$) for 30-day satellite composites is used, the correlation with the shipboard measurements is significant ($R^2=0.54$), but the satellite data underestimate the higher Chl-*a* concentrations and overestimate the lower Chl-*a* concentrations (Fig. 3A). When the median values within a 3×3 pixel area for eight-day satellite composites are used (Fig. 3B), the correlation with the shipboard measurements improves ($R^2=0.81$), but the slope of the line remains similar to that for the 30-day composites. Table 1 indicates the magnitude of the differences in Chl-*a* concentration between the shipboard data and the satellite estimates from eight-day composites. For Chl-*a* concentrations $<\sim0.7\,\mathrm{mg\,m^{-3}}$, the agreement between the measured and the estimated concentrations is excellent. At the highest Chl-*a* concentrations ($>4\,\mathrm{mg\,m^{-3}}$), the satellite estimates are approximately 40% of the shipboard values.

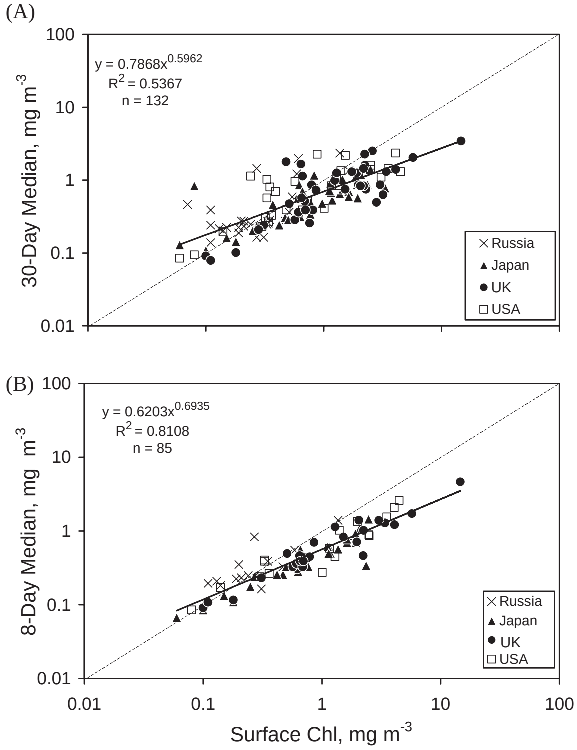

Fig. 3. The correlation between Chl-*a* concentrations measured on board ship and those estimated from satellite data for each hydrographic station. A, median values within the 3×3 pixel area of 30-day composites of satellite data regressed against the Chl-*a* concentrations in the uppermost water sample at each station. B, median values within the 3×3 pixel area of eight-day composites of satellite data regressed against the Chl-*a* concentrations in the uppermost water sample at each station. Owing to persistent cloud cover, the 30-day composites resulted in no data being available for 5 of the 137 stations; the eight-day composites resulted in no data being available for 52 of the 137 stations.

One limitation of using satellite data to provide information on phytoplankton standing stock and productivity is that the estimates are heavily weighted to the upper few meters of the water column. For food web considerations, however, it is desirable to obtain estimates for the entire euphotic zone, or at least for the upper mixed layer. The upper mixed layer in the Scotia Sea is usually around 30–50 m deep (Mitchell et al., 1991) and has fairly uniform Chl-*a* concentrations (Holm-Hansen et al., 1997; Rönner et al., 1983). The correlation between surface Chl-*a*

Table 1
Ratios (mean ± S.D.) of Chl-*a* values estimated from eight-day composited satellite data to measured concentrations of Chl-*a* in surface waters. Owing to cloud cover, satellite data were available for only 85 of the 137 stations

N	Range of Chl-*a* ($mg\,m^{-3}$)	Ratio
13	<0.2	1.09 ± 0.34
37	0.2–1.0	0.82 ± 0.47
30	1.0–4.0	0.48 ± 0.18
5	>4.0	0.40 ± 0.13

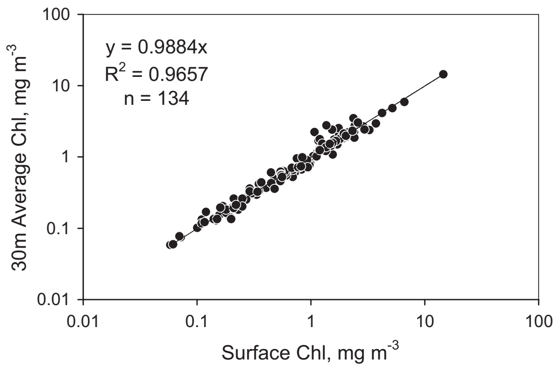

Fig. 4. Correlation between concentrations of Chl-*a* in the uppermost water sample (0–6 m) and the mean concentrations of all water samples obtained from 0 to 30 m. Three of the 137 stations had surface water samples only and hence were deleted from the data set.

concentrations and the mean concentrations for all water samples between the surface and 30 m depth for all stations sampled during the CCAMLR 2000 Survey is shown in Fig. 4. This shows that there is an excellent agreement between the two data sets ($R^2 = 0.99$) and hence surface Chl-*a* concentrations appear to be a reliable estimator for the mean Chl-*a* concentration in the upper mixed layer.

4. Discussion

Studies on the dynamics of the food web in Antarctic waters and the food resources available to support higher trophic levels (e.g., krill, fish, birds, whales) require data on the rate of production of organic carbon by autotrophic microorganisms. Such data are based on direct measurements of photosynthetic rates in shipboard experiments or on remotely sensed information from which productivity rates can be estimated. Shipboard measurements are costly in terms of the time and effort required and so are limited in both duration and area of the field observations. Satellites, in contrast, can be used to obtain data on Chl-*a* concentration, incident solar irradiance, and water temperature over extended spatial and temporal scales, from which it is possible to estimate phytoplankton standing stocks as well as rates of primary production. Mitchell and Holm-Hansen (1991) first reported that the algorithms used to calculate Chl-*a* concentration from satellite data are biased in the Southern Ocean compared to tropical or temperate regions. The CCAMLR 2000 Survey offered the opportunity to determine the reliability of estimating Chl-*a* concentration using standard global algorithms—developed predominately with low latitude data sets (O'Reilly et al., 2000)—in this ecologically important and physically dynamic region of the Southern Ocean.

SeaWiFS standard products do not include a Southern Ocean algorithm. The intention of the match-up analysis reported here was to evaluate the standard SeaWiFS algorithm using the unique, large, synoptic data set acquired during the CCAMLR 2000 Survey. Since the agreement for Chl-*a* concentrations of less than ~1 mg m^{-3} was ±20% of the in situ data (Table 1), it appears that the SeaWiFS algorithm is appropriate for the open waters of the Scotia Sea. The alternate algorithms developed with data from the Ross Sea polynya (Arrigo et al., 1998) or the predominantly coastal waters of the Antarctic Peninsula region (Dierssen and Smith, 2000) differ by up to 2× relative to the NASA algorithm. Spectral reflectance data, required to create alternative Chl-*a* algorithms, were not collected during the CCAMLR 2000 Survey and there are no known published bio-optical data for the Scotia Sea. As pointed out by Arrigo et al. (1998) for the Ross Sea, at high Chl-*a* concentrations there can be large algorithm differences for different taxonomic groups, and detailed information on phytoplankton taxa is not available for the CCAMLR 2000 Survey. Also, the various algorithms published for the Southern Ocean result in relative differences that are at least as great as the differences between the ship data for Chl-*a* concentrations of $<1\,mg\,m^{-3}$ and the SeaWiFS estimate. In addition, the alternative algorithms mentioned above used three different filter types and these could introduce biases for the in situ Chl-*a* data. It is not justified choosing one of the previously published algorithms that were based on data collected in predominantly coastal waters or the Ross Sea polynya without independent verification based on in situ spectral reflectance measured simultaneously with Chl-*a* concentrations. This paper thus is based on the standard SeaWiFS algorithm and focuses on the large-scale patterns of Chl-*a* distribution, which can be achieved without elaborate re-processing and re-binning of the SeaWiFS data.

The correlation between measured Chl-*a* concentrations and the values estimated from satellite data highlights several points. Firstly, there is a good correlation between the two data sets, although at high Chl-*a* concentrations the estimated values from satellite data are lower than the measured values and at low Chl-*a* concentrations the estimated values from satellite data are slightly higher than the measured concentrations. Secondly, owing to persistent cloud cover in the Antarctic, it was necessary to generate multi-day composites of satellite observations in order to estimate pigment concentrations at most of the hydrographic stations sampled. With eight-day composites, Chl-*a* estimates could be made at only 85 of the 137 stations, compared to 132 of the 137 stations for 30-day composites. Thus, estimates from satellite data cannot be expected for every hydrographic station. Thirdly, the ratio of the satellite derived estimates divided by the measured Chl-*a* concentrations for all stations with Chl-*a* concentrations of $<1.0\,mg\,m^{-3}$ was 0.89 ± 0.45 ($n = 50$). As the mean Chl-*a* concentration in surface pelagic Antarctic waters is about $0.5\,mg\,m^{-3}$ and in coastal waters is generally between 1 and $2\,mg\,m^{-3}$, the use of satellite data to estimate Chl-*a* concentrations in surface waters of the Southern Ocean should be quite reliable. In a similar match-up between US JGOFS data and the OC2v2 algorithm, Moore et al. (1999) found SeaWiFs to underestimate Chl-*a* concentrations by about 30%. Since the global SeaWiFS algorithm was developed with few Southern Ocean data, improved satellite estimates could be expected by using components of alternative algorithms (e.g., Arrigo et al., 1998; Dierssen and Smith, 2000; Mitchell and Holm-Hansen, 1991; Sullivan et al., 1993).

In addition to time aliasing, there is a discrepancy in spatial scale between an in situ sample taken from a few liters of water and a satellite estimate based on a sensor that is averaging over a pixel that has a minimum dimension of approximately $1\,km^2$. Using composit data mapped at 9 km resolution further increases the spatial area of the satellite estimate versus the in situ sample. Spatial variability at scales less than the 9-km global map of the satellite estimate is equivalent to the spatial average of a statistically representative number of in situ samples within the composited pixel. Use of a 3×3 pixel matrix ($27 \times 27\,km$) further aliases the spatial scale. It is thus to be expected that the satellite estimate has a tendency to underestimate in situ Chl-*a* values if the patchiness of high Chl-*a* areas is less than the effective area of the satellite estimate ($27 \times 27\,km$). As surface chlorophyll in the ocean is often distributed log-normally (Campbell and O'Reilly, 1988) with a few very high values versus the background of many relatively low values, the satellite estimate is expected to underestimate the high in situ values owing to the averaging effect on the sub-pixel spatial variability. Similarly, match-ups with infrequent very low in situ chlorophyll concentrations can be expected to be over-estimated by the satellite. The exact nature of this satellite/in situ discrepancy due to different scales of the estimate depends on the statistical properties of the spatio-temporal distribution of chlorophyll concentration in the ocean. These discrepancies are solely due to differences in the spatio-temporal sampling between the satellite and in situ estimates, and not related to errors in the bio-optical algorithm, sensor calibration, and/or atmospheric correction that are independent factors that contribute to the observed discrepancy between the satellite and in situ estimates. Using the five-year Coastal Zone Color Scanner (CZCS) climatology of chlorophyll from ocean color, and a multi-decade data set of ship estimates of Chl-*a* concentration, Sullivan et al. (1993) demonstrated that the algorithm of Mitchell and Holm-Hansen (1991) shifted the frequency distribution of CZCS chlorophyll estimates higher and made them more consistent with ship data. Thus, the discrepancies shown in Fig. 3 are likely to be related to both algorithm issues and spatio-temporal aliasing.

The satellite images shown in Fig. 2 illustrate that while the overall pattern of phytoplankton distribution remains quite similar over the three months, the temporal changes in Chl-*a* concentration vary considerably in different areas. The rich blooms in Argentine coastal waters and to the northeast of South Georgia are highest in December and decline progressively through January and February. In contrast, the ice-edge bloom to the northeast of the Antarctic Peninsula moves progressively southward and intensifies from December through February. Most of the Scotia Sea, however, shows low Chl-*a* concentrations in December and maximal concentrations in January, after which concentrations start to decrease. This temporal trend in Chl-*a* concentration in pelagic waters of the Scotia Sea is similar to that described by Clarke (1988) for the Southern Ocean. It is also seen from Fig. 2 that the lowest Chl-*a* waters (e.g., in Drake Passage and to the east and southeast of South Georgia) get progressively lower in Chl-*a* concentration between December and February.

Although the correlation between Chl-*a* concentrations estimated from satellite data and by shipboard studies deviates slightly from a 1:1 relationship, particularly at the lowest and highest Chl-*a* levels, the agreement is sufficiently good that satellite data can provide reasonable estimates of phytoplankton biomass for any region at temporal scales of eight days or more. Cloud cover will continue to limit the observations at shorter time scales. In addition to estimating Chl-*a* concentration in surface waters, satellite data can provide the information needed for calculating depth-integrated rates of primary production in terms of organic carbon (e.g., Behrenfeld and Falkowski, 1997). Such estimates, which can be obtained throughout the year, are important for understanding food web dynamics and in assessing the availability of food resources for higher trophic levels. The most accurate estimates of Chl-*a* or productivity from satellites, however, will require the use of chlorophyll algorithms that are based on in situ optics and Chl-*a* data from the region under consideration.

References

Arrigo, K.R., Robinson, D.H., Lizotte, M.P., Worthen, D.L., Schieber, B., 1998. Bio-optical properties of the southwestern Ross Sea. Journal of Geophysical Research 103, 21683–21695.

Behrenfeld, M.J., Falkowski, P.G., 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography 42, 1–20.

Campbell, J.W., O'Reilly, J.E., 1988. Role of satellites in estimating primary productivity on the northwest Atlantic continental shelf. Continental Shelf Research 8, 179–204.

Campbell, J.W., Blaisdell, J.M., Darzi, M., 1995. Spatial and temporal binning algorithms. National Aeronautics and Space Administration Technical Memorandum 32 (104566), 73pp.

Clarke, A., 1988. Seasonality in the Antarctic marine environment. Comparative Biochemistry and Physiology 90B, 461–473.

Davis, R.E., Killworth, P.D., Blundell, J.R., 1996. Comparison of Autonomous Lagrangian Circulation Explorer and fine resolution Antarctic model results in the South Atlantic. Journal of Geophysical Research 101 (C1), 855–884.

Dierssen, H.M., Smith, R.C., 2000. Bio-optical properties and remote sensing ocean color algorithms for Antarctic Peninsula waters. Journal of Geophysical Research 105 (C11), 26301–26312.

El-Sayed, S.Z., 1988. Productivity of the Southern Ocean: a closer look. Comparative Biochemistry and Physiology 90B, 489–498.

Everson, I., Miller, D.G.M., 1994. Krill mesoscale distribution and abundance: results and implications of research during the BIOMASS programme. In: El-Sayed, S.Z. (Ed.), Southern Ocean Ecology. Cambridge University Press, Cambridge, pp. 129–143.

Foster, T.D., Middleton, J.H., 1984. The oceanographic structure of the eastern Scotia Sea – I. Physical Oceanography. Deep-Sea Research 31, 529–550.

Holm-Hansen, O., Mitchell, B.G., 1991. Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region. Deep-Sea Research 38, 961–980.

Holm-Hansen, O., Lorenzen, C.J., Holmes, R.W., Strickland, J.D.H., 1965. Fluorometric determination of chlorophyll.

Journal du Conseil International pour l'Exploration de la Mer 30, 3–15.

Holm-Hansen, O., Hewes, C.D., Villafañe, V.E., Helbling, E.W., Silva, N., Amos, T., 1997. Distribution of phytoplankton and nutrients in relation to different water masses in the area around Elephant Island, Antarctica. Polar Biology 18, 145–153.

McClain, C.R., Cleave, M.L., Feldman, G.C., Gregg, W.W., Hooker, S.B., Kuring, N., 1998. Science quality SeaWiFS data for global biosphere research. Sea Technology 39 (9), 10–16.

Mitchell, B.G., Holm-Hansen, O., 1991. Bio-optical properties of Antarctic Peninsula waters: differentiation from temperate ocean models. Deep-Sea Research 38, 1009–1028.

Mitchell, B.G., Brody, E.A., Holm-Hansen, O., McClain, C., Bishop, J., 1991. Light limitation of phytoplankton biomass and macronutrient utilization in the Southern Ocean. Limnology and Oceanography 36, 1662–1677.

Moore, J.K., Abbott, M.R., Richman, J.G., Smith, W.O., Cowles, T.J., Coale, K.H., Gardner, W.D., Barber, R.T., 1999. SeaWiFS satellite ocean color data from the Southern Ocean. Geophysical Research Letters 26, 1465–1468.

O'Reilly, J.E., Maritorena, S., Mitchell, B.G., Siegel, D.A., Carder, K.L., Garver, S.A., Kahru, M., McClain, C., 1998. Ocean color chlorophyll algorithms for SeaWiFS. Journal of Geophysical Research 103, 24937–24953.

O'Reilly, J.E., Maritorena, S., Siegel, D.A., O'Brien, M.C., Toole, D., Mitchell, B.G., Kahru, M., Chavez, F.P., Strutton, P., Cota, G.F., Hooker, S.B., McClain, C.R., Carder, K.L., Muller-Karger, F., Harding, L., Magnuson, A., Phinney, D., Moore, G.F., Aiken, J., Arrigo, K.R., Letelier, R., Culver, M., 2000. Ocean color chlorophyll a algorithms for SeaWiFS, OC2, and OC4: version 4. In: Hooker, S.B., Firestone, E.R (eds.), SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3. National Aeronautics and Space Administration Technical Memorandum 2000-206892, vol. 11, pp. 9–23.

Priddle, J., Croxall, J.P., Everson, I., Heywood, R.B., Murphy, E.J., Prince, P.A., Sear, C.B., 1988. Large-scale fluctuations in distribution and abundance of krill—a discussion of possible causes. In: Sahrhage, D. (Ed.), Antarctic Ocean and Resources Variability. Springer, Berlin, pp. 169–182.

Rönner, U., Sörensson, F., Holm-Hansen, O., 1983. Nitrogen assimilation by phytoplankton in the Scotia Sea. Polar Biology 2, 137–147.

Sullivan, C.W., Arrigo, K.R., McClain, C.R., Comiso, J.C., Firestone, J., 1993. Distributions of phytoplankton blooms in the Southern Ocean. Science 262, 1832–1837.

Watkins, J.L., Hewitt, R.P., Naganobu, M., Sushin, V.A., 2004. The CCAMLR 2000 Survey: a multinational, multi-ship biological oceanography survey of the Atlantic sector of the Southern Ocean. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2004.06.010].