Proc. NIPR Symp. Polar Biol., **10**, 66–76, 1997

ESTIMATION OF VERTICAL PROFILE OF CHLOROPHYLL CONCENTRATION AROUND THE ANTARCTIC PENINSULA DERIVED FROM CZCS IMAGES BY THE STATISTICAL METHOD

Noritsugu KIMURA and Yoshihiro OKADA

Department of Ocean Engineering School of Marine Science and Technology, Tokai University, 20–1, Orido 3-chome, Shimizu 424

Abstract: The vertical profile of chlorophyll concentration in waters around the Antarctic Peninsula was estimated using a statistical method (Empirical Orthogonal Function Analysis: EOF Analysis), analyzing more than 200 ship observations from the surface to 150 m. Also a method is established to predict the vertical profile from CZCS-derived concentration. The comparison in terms of vertical profile demonstrates good agreement (relative error=40%) between CZCS prediction and ship-observation. The prediction by the model only needs one input, surface chlorophyll concentration, which can be easily derived from the satellite remote sensing data.

1. Introduction

Due to the importance of monitoring a vast amount of resources in the Antarctic Ocean such as the Antarctic krill (*Euphausia superba*), the biological process and production assessment in this region has become a matter of world wide concern. However, field oceanographic investigation in the Antarctic Ocean involves many difficulties (*e.g.* icebergs, low temperature and strong wind). In recent years, the visible remote sensing (Nimbus-7/CZCS: Coastal Zone Color Scanner) has proved to be a promising method for the estimation of phytoplankton pigment concentration and hence of primary production by virtue of its spatial and temporal capability. An algorithm for the atmospheric scattering (atmospheric correction) was established by GORDON *et al.* (1983). It has provided the impetus to examine low and middle latitude imagery. The atmospheric correction with multiple scattering (GORDON *et al.*, 1988) extends the application of CZCS data in the polar area.

Using CZCS data, MAYNARD and CLARK (1987) studied spring blooming in Bering Sea shelf waters, it appears that the standard algorithm gave an underestimate. With CZCS and SMMR (Scanning Multichannel Microwave Radiometer) data from Nimbus-7 combined with in situ measurements of pigment and sea ice concentration, the dynamic interaction between recession of pack ice and occurrence of ice edge blooms of phytoplankton in the Antarctic Ocean was investigated by SULLIVAN *et al.* (1988). COMISO *et al.* (1990) reported that ice edge phytoplankton blooms were not simply an austral spring-summer feature but extended into the austral autumn and that they might contribute significantly to regional productivity.

The estimation of the primary production from satellite derived pigment concentration requires knowledge of the vertical chlorophyll profile pattern, which is characterized by the area and the seasonal variation. PLATT *et al.* (1988) proposed a normal distribution of chlorophyll with depth superimposed upon a constant background, and the primary production of the water column calculated by this structure was in good agreement with in situ data. However, the model of PLATT *et al.* (1988) is not adaptable to waters around Japan (MATSUMURA and SHIOMOTO, 1993). They improved the model of PLATT *et al.* (1988), and found that the normal distribution was not superimposed on a constant background, but on a slope decreasing with depth.

The Atlantic sector of the Antarctic Ocean is classified into the sub-Antarctic and the Antarctic region. That area can be classified into the Scotia Sea and the Weddell Sea. A confluence exists between the Scotia Sea and the Weddell Sea. All these areas have their own characteristic vertical profiles of chlorophyll concentration.

The bio-optical algorithms of GORDON *et al.* (1983) were established using optical data and phytoplankton pigment concentration data from ship measurements in the seas adjoining America. MULLER-KARGER *et al.* (1990) reported that region-specific bio-optical algorithms are required for proper quantitative interpretation of remote sensing data from the Bering Sea. KIMURA *et al.* (1992) reported that they developed bio-optical algorithms for the Antarctic Ocean using optical data and chlorophyll concentration data obtained in the fifth Antarctic Expedition of R/V KAIYO-MARU, Japan Fisheries Agency, in the seas adjoining the Antarctic Peninsula. They reported that the bio-optical algorithm (three-channel algorithm) could estimate to within a relative error of 30%. KIMURA *et al.* (1994) reported that they estimated the vertical profile of chlorophyll concentration (hereafter VPCC) from CZCS-derived surface chlorophyll concentration (relative error=43%) by applying the estimation model developed by MATSUMURA and SHIOMOTO (1993) for the Antarctic Ocean.

The purpose of this study is to develop an estimated model from satellite-derived surface pigment concentration using a statistical method (Empirical Orthogonal Function Analysis : EOF Analysis). This paper is composed of three elements as follows:

(1) Establish the model using EOF-Analysis.

(2) Validate the model.

Ship-observed surface chlorophyll concentration is applied to the model. This section compares ship-observed data with estimated VPCC using ship-observed surface chlorophyll concentration.

(3) Application of the estimation model to satellite images.

This section compares CZCS-derived VPCC with ship-observed VPCC at three points.

2. Data and Method

Surface concentrations and vertical profile at 202 observed stations are in situ data obtained around the Antarctic Peninsula area during the fourth (1984–1985), the fifth (1987–1988) and the sixth (1990–1991) Antarctic Expeditions of R/V KAIYO-MARU, Fisheries Agency and R/V PROFESSOR SIEDLECKI of the Institute of Ecology

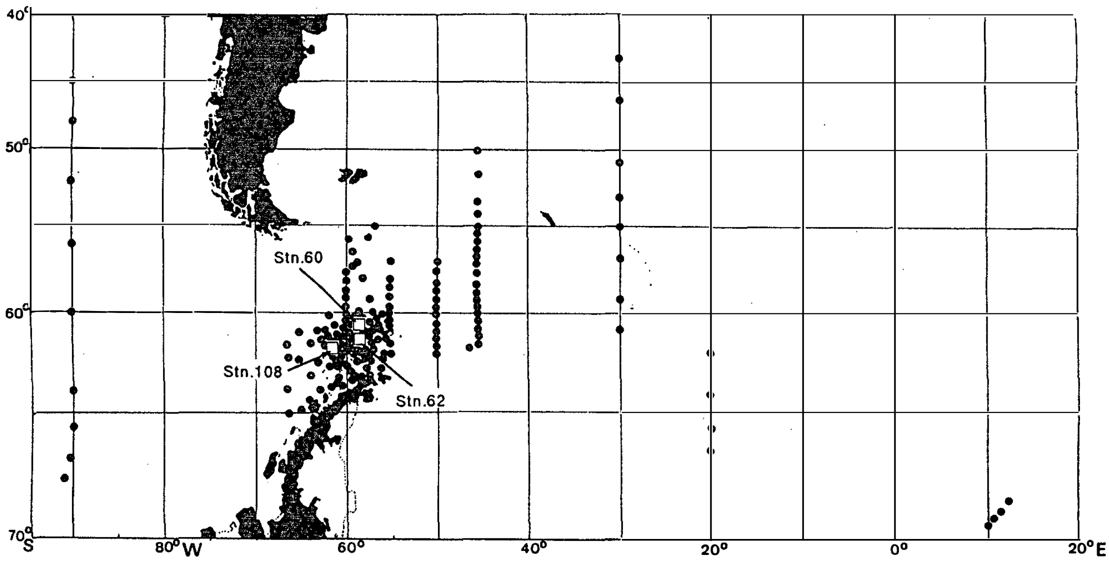

Fig. 1. The location of ship-observed chlorophyll concentrations. Black circles are observed stations of chlorophyll concentration. 202 observed stations are obtained from the fourth, the fifth, the sixth Antarctic Expeditions of R/V KAIYO-MARU of Japan Fisheries Agency and the R/V PROFESSOR SIEDLECKI of the Institute of Ecology PAN and Sea Fisheries Institute of Poland. Stn. 60 at 60°42.4′S 58°30.0′W and 62 at 60°48.9′S 58°32.2′W are used to make a comparison with CZCS image. Stn. 108 at 63°34.3′S 62°21.3′W is used by the validated model and to make a comparison with CZCS image.

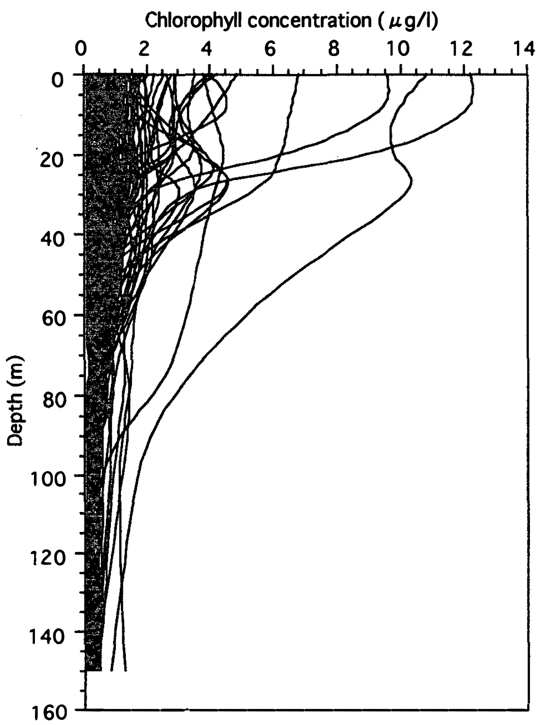

Fig. 2. VPCC at 202 ship-observed stations in Fig. 1. 202 observation points are obtained from the fourth, the fifth and the sixth Antarctic Expeditions of R/V KAIYO-MARU of Japan Fisheries Agency and the R/V PROFESSOR SIEDLECKI of the Institute of Ecology PAN and Sea Fisheries Institute of Poland.

PAN (Polska Akademii Nauk) and the Sea Fisheries Institute of the Poland. The variation of chlorophyll concentration with depth was measured at 202 observation points as shown in Fig. 1. Figure 2 shows VPCC at these points. Most observed chlorophyll concentrations were almost observed less than 2.0 $\mu g/l$. This study establishes the algorithm for estimating VPCC. This study assumes that the estimated chlorophyll concentration consists of an average that (the first term on the right side) to the changeable element (the second term on the right side). VPCC is interpolated to 8 standard depths from the surface to 150 m.

This study employes eqs. (1) and (2) to estimate VPCC using EOF-Analysis.

$$\mathrm{Chl}\,(z) = \overline{\mathrm{chl}\,(z)} + \sum_{i=1}^{2} \phi i(z) AFi(z), \tag{1}$$

where Chl (z) is the estimated chlorophyll concentration at z meters depth, $\overline{\mathrm{chl}\,(z)}$ is the mean chlorophyll concentration at z meters depth, $\phi 1(z)$ and $\phi 2(z)$ are the first and second empirical orthogonal functions and AFi are amplitude functions. AFi are characteristic of ship-observed stations, which the ϕi characterize observation layers.

$$AFi\ (z) = b_{0i} + b_{1i}DC + b_{2i}DC^2 + b_{3i}DC^3 + \cdots + b_{ni}DC^n, \tag{2}$$

where AFi is an amplitude function and b_{0i}, b_{1i}, b_{2i}, b_{3i}, $\cdots$ and b_{ni} are coefficients of correlation. DC is the mean deviation of chlorophyll concentration.

3. Results and Discussion

3.1. Establish the model

Figure 3 shows the average chlorophyll concentration profile, calculated from all observation data in Fig. 1. El-Sayed (1968) reported that the surface average chlorophyll concentration was 0.89 mg/m^3 and the surface standard deviation that was 1.31 mg/m^3 in the Atlantic sector of the Antarctic Ocean. Our average concentration agrees approximately with his. Table 1 shows mean, variance, standard deviation,

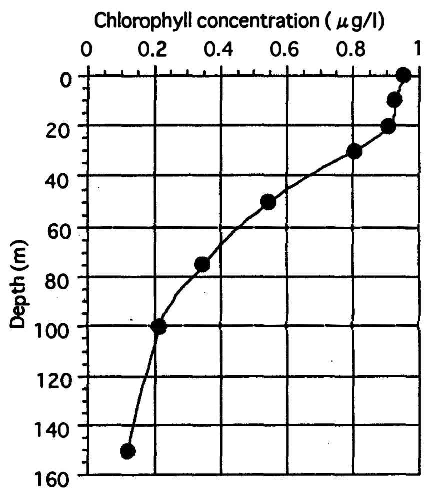

Fig. 3. The average chlorophyll concentration profile at 202 ship-observed stations.

Table 1. Mean, variance, standard deviation, maximum and minimum values of the chlorophyll data set used in this study are shown for reach layer. The data set was obtained around the Antarctic Peninsula area during the forth (1984–1985), the fifth (1987–1988) and the sixth (1990–1991) Antarctic Expedition of R/V KAIYO-MARU and R/V PROFESSOR SIEDLECKI. These locations were shown in Fig. 1.

Depth (m)	Mean	Variance	S.D.	Minimum	Maximum
0	0.956	2.364	1.537	0.050	12.160
10	0.927	2.096	1.448	0.060	11.860
20	0.910	1.639	1.280	0.050	9.750
30	0.807	1.133	1.064	0.050	10.100
50	0.548	0.386	0.622	0.070	6.660
75	0.348	0.112	0.334	0.080	3.300
100	0.218	0.034	0.185	0.031	1.680
150	0.119	0.015	0.123	0.000	1.230

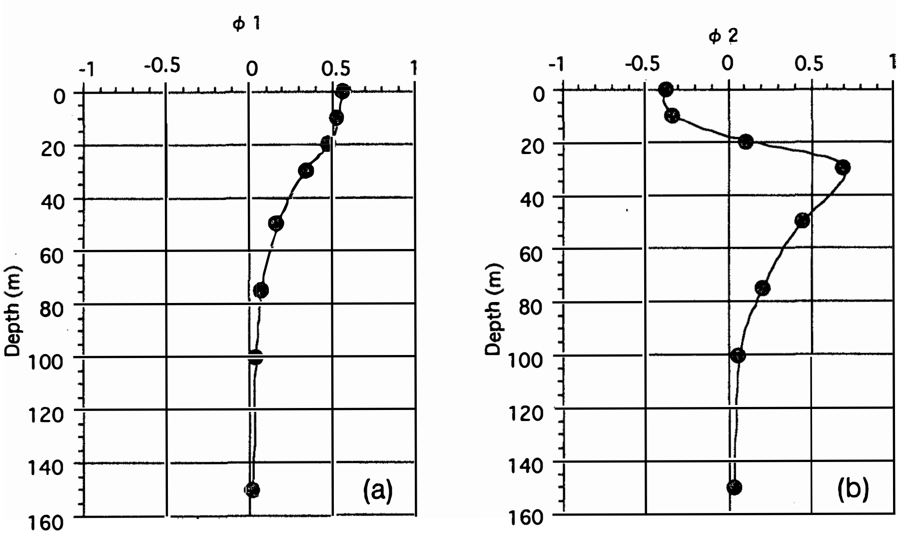

Fig. 4. The result of EOF-Analysis. (a) The first empirical orthogonal function, (b) the second EOF. The proportion of variation accounted for by the first EOF is 86%. The proportion accounted for by the second EOF is 10%. The proportion accounted for by the first and second EOF together is 96%.

minimum and maximum values of chlorophyll concentrations in each layer.

In the first step, this paper calculated the mean deviation of chlorophyll concentration as shown in Fig. 1. Next, this study carried out EOF Analysis on the mean deviation of chlorophyll concentration. The results of EOF Analysis for the first mode ($\phi 1(z)$) and the second mode ($\phi 2(z)$) are shown in Fig. 4a, b, with the first mode accounting for 86%, and the second mode for 10%, so that the first mode and the second mode together account for 96%. This study analyzes VPCC using the only first mode and the second mode. Regression eqs. (3) and (4) were obtained from Fig. 5a, b.

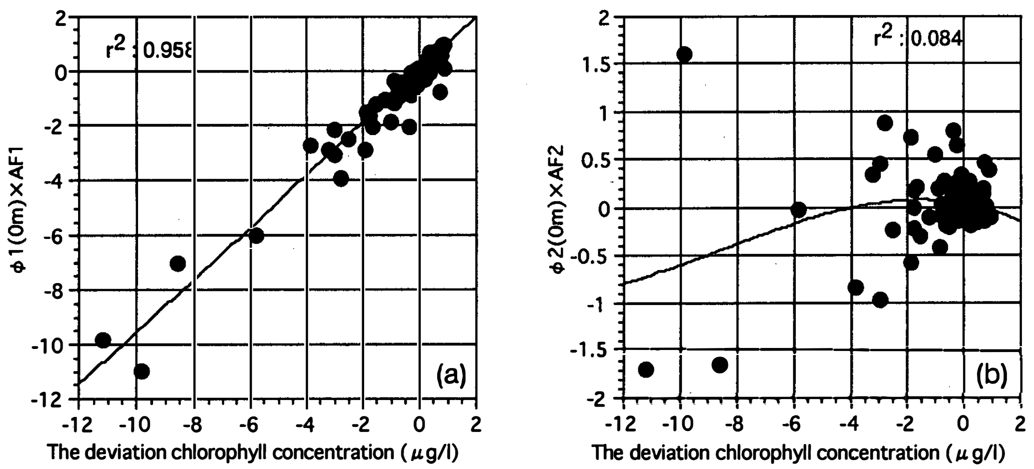

Fig. 5. Relationships between the deviation of surface chlorophyll concentration and φi (0)×AFi. (a) The first EOF. (b) The second EOF. φi (0) is the its empirical orthogonal function at the surface. AFi is the its amplitude function.

$$\phi 1(0)\times AF1(0)=1.68\times DC-1.46\times 10^{-4}, \tag{3}$$

$$\phi 2(0)\times AF2(0)=-7.38\times 10^{-4}\times DC^3-1.91\times 10^{-2}\times \mathrm{DC}^2-5.27\times 10^{-2} \times DC+3.25\times 10^{-2}. \tag{4}$$

Equations (3) and (4) are divisible by $\phi 1(0)$ and $\phi 2(0)$ respectively (see Fig. 4a, b).

$$AF1(0)=(1.68\times DC-1.46\times 10^{-4})/\phi 1(0), \tag{3$'$}$$

$$AF2(0)=(-7.38\times 10^{-4}\times DC^3-1.91\times 10^{-2}\times DC^2-5.27\times 10^{-2}\times DC +3.25\times 10^{-2})/\phi 2(0). \tag{4$'$}$$

Sea-surface amplitude functions ($AFi(0)$) of eq. (3)′ or (4)′ are used to estimate the chlorophyll concentration in each year.

For example, the estimated model and the calculated process at 20 m depth are shown as follows:

$$DC/\phi 1(20)=AF1(0)-1.25\times 10^{-7}, \tag{5}$$

$$DC/\phi 2(20)=-1.19\times 10^{-1}\times AF2(0)^3-3.80\times AF2(0)^2 +5.16\times 10^{-1}\times AF2(0)+2.14, \tag{6}$$

where DC is the deviation value concentration, and $\phi i(20)$ are empirical orthogonal functions at 20 m depth. Equation (5) is derived from Fig. 6a. Equation (6) is obtained from Fig. 6b.

$$CE1(20)=DC/\phi 1(20), \tag{7}$$

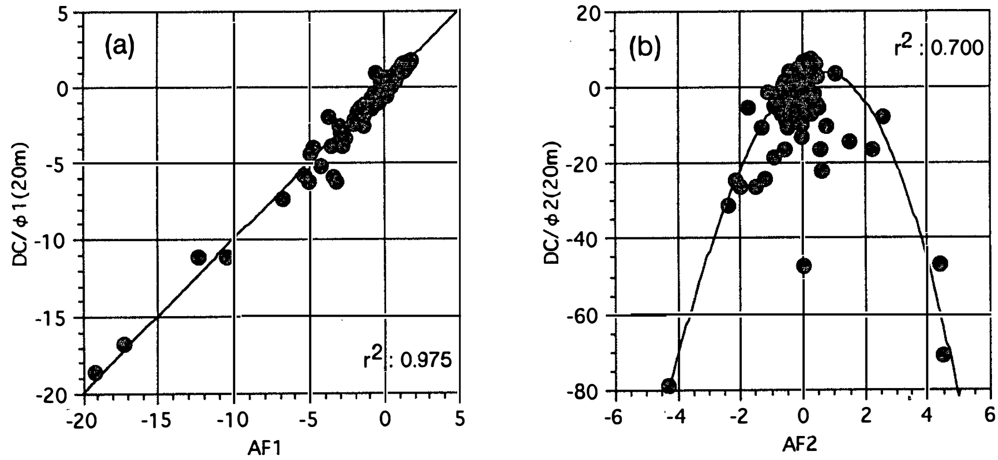

Fig. 6. *Relationship between DC/ϕi (20) and AFi. (a) The first EOF. (b) The second EOF. DC is the deviation concentration. ϕi(20) is the its empirical orthogonal function at 20 m depth.*

Table 2. The result of the coefficient of determination (r^2) for the least squares fits of the first mode (ϕ 1) and the second mode (ϕ 2) amplitudes.

Depth (m)	ϕ 1	ϕ 2
0	0.958	0.084
10	0.962	0.767
20	0.975	0.700
30	0.885	0.747
50	0.756	0.775
75	0.736	0.611
100	0.688	0.400
150	0.523	0.203

$$CE2(20)=DC/\phi 2(20), \tag{8}$$

where $CE1(20)$ and $CE2(20)$ are the changeable elements of the first mode and the second mode at 20 m depth. The total deviationfrom the average is $CE1(20)$ to $CE2(20)$. The estimated concentration is the average plus the deviation. The results of the coefficient of determination (r^2) for the least squares fits to the first mode ($\phi 1$) and the second mode ($\phi 2$) are shown in Table 2. Estimated concentrations are finally interpolated by spline functions.

3.2. *Validate the model*

The estimated model is applied to ship-observed sea-surface chlorophyll concentration. This section compares the model VPCC with ship-observed VPCC.

The ship-measurements of chlorophyll data were observed he R/V PROFESSOR SIEDLECKI in 1981 during the International FIBEX program (LIPSKI, 1982). Figure 7 shows the result of comparison of ship-observed concentration at Stn. 108 on March

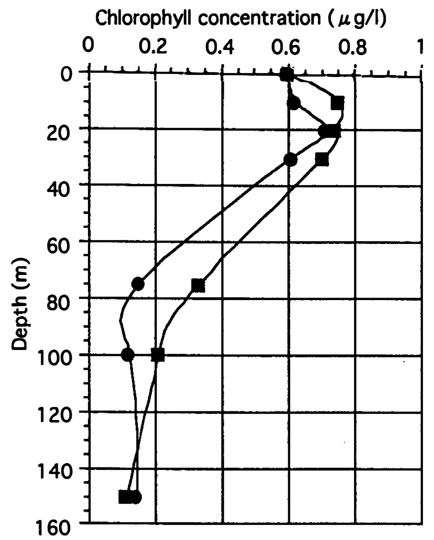

Fig. 7. The result of comparison of results from the model with in situ data. The method applies ship-observed sea surface concentration to the estimated model. Circles are ship-observed values. Squares are obtained from estimated values.

12, 1981, at 63°34.3′S 62°21.3′W with the result of estimated concentration. The relative error is calculated for truth data of ship observations in each layer. This can understand to estimate VPCC to a relative error of 20%, thus confirming that VPCC can be estimated from the sea surface concentration

3.3. *Application of the estimation model to satellite images*

The estimation model developed in the present study was implemented in image processing system, and finally CZCS-derived values were validated with available ship-observed chlorophyll concentrations. As CZCS imagery scanned at solar elevations below 35° angle is of questionable quality (Barale *et al.*, 1986), we did not use any CZCS imagery of "gain4" for our study, because these data were usually scanned at less than a 30° angle at very low sun elevations. Very little light is transmitted into the water due to the low sun angle. The Rayleigh correction is questionable because of multiple scattering on such an image. We analyzed synchronous CZCS images and in situ ship data between October and March. This study assumes that the ship measurements and CZCS imagery are coincident, if the time lag is less than 12 hours. We could find only two CZCS images on 27 February (Fig. 8) and 12 March (Fig. 9) 1981, that satisfy to this condition, to compare with ship-derived chlorophyll concentrations. CZCS imagery were kindly provided by NASA Goddard Space Flight Center (NASA/GSFC). Two CZCS images are processed by the original resolution in regard to pixel and line. Two CZCS images were first corrected for atmospheric effects to obtain the radiance emitted from the water using the algorithm reported by Gordon *et al.* (1988). They were converted to chlorophyll concentration images using the three channel algorithm for the Antarctic Ocean established by Kimura *et al.* (1992). CZCS chlorophyll images were finally remapped to polar stereo projection.

Figure 10 shows a comparison of ship-observed data with the estimated VPCC

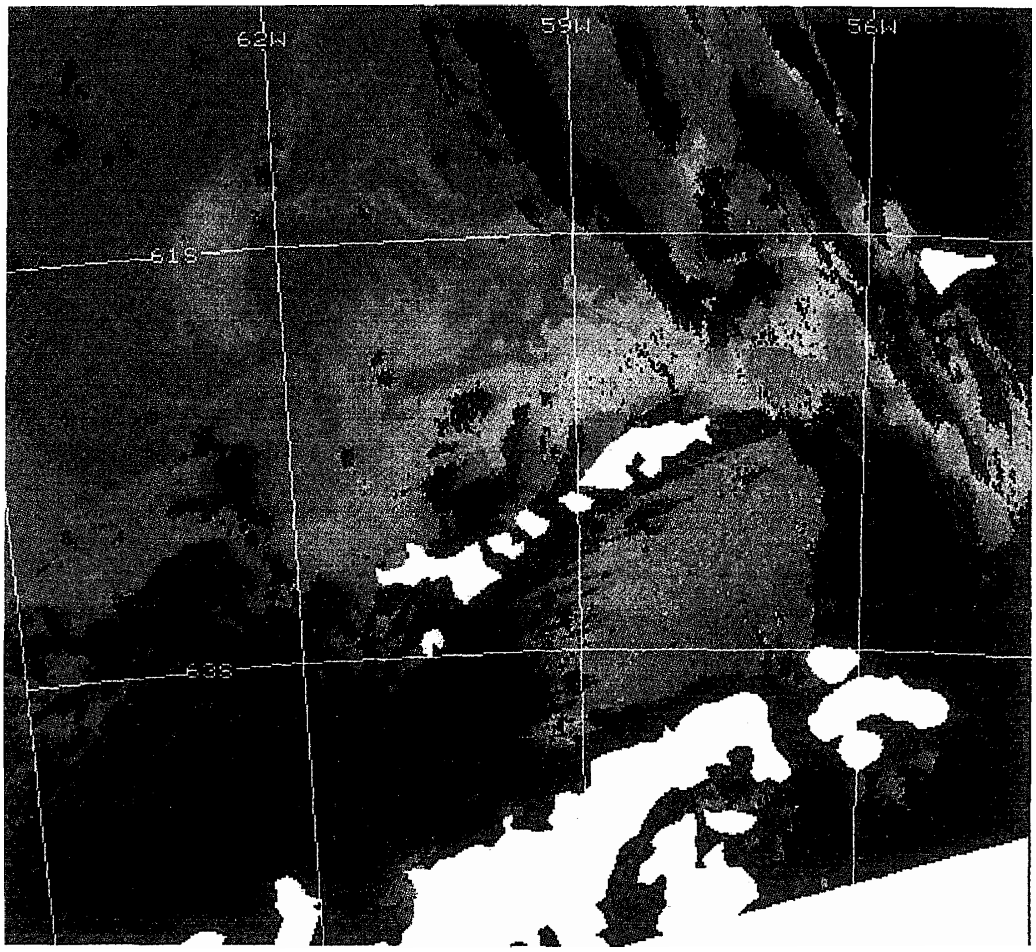

Fig. 8. CZCS image of chlorophyll concentration on 27 February 1981. Darker tones represent lower concentration.

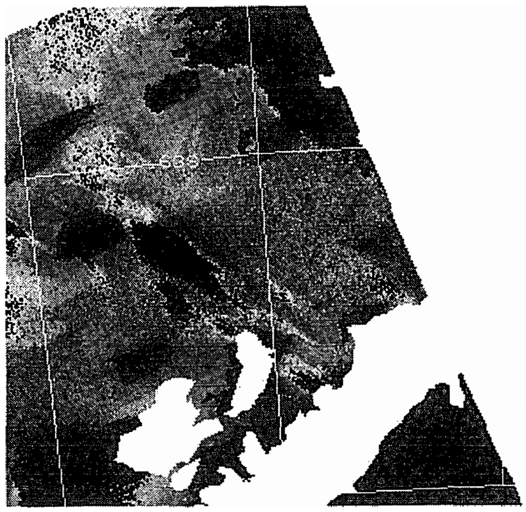

Fig. 9. CZCS image of chlorophyll concentration on 12 March 1981. Darker tones represent lower concentration.

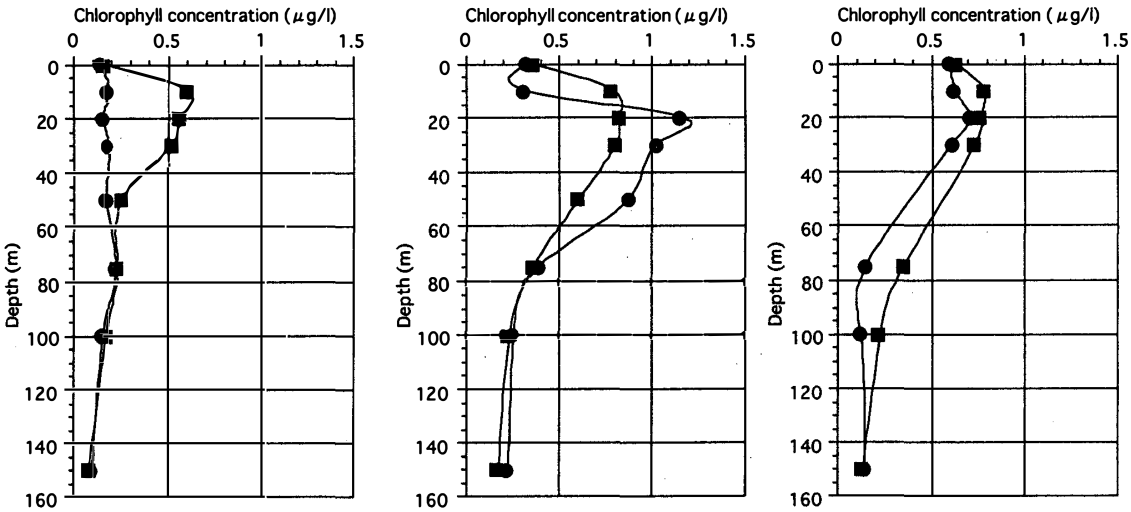

Fig. 10. Comparison of a ship-observed vertical profile with the corresponding vertical profile derived from CZCS using the estimation model. (a) Stn. 60, (b) Stn. 62, (c) Stn. 108. Circles are observed values. Squares are estimated from the model using CZCS-derived concentration.

derived from two CZCS images. The observed VPCC of Stn. 108 on March 12, 1981, at 63°34.3′S 62°21.3′W agrees with the estimated VPCC obtained from the CZCS image. The result of Stn. 60 on February 27, 1981, at 60°42.4′S 58°30.0′W led to noticeable error from extremely differ the observed chlorophyll concentration. The estimated model assumes that the estimated chlorophyll concentration is the average chlorophyll concentration plus the deviation. From this assumption, it seems that an area of low or high chlorophyll concentration leads to noticeable error.

3. Summary

The purpose of this paper is to establish the estimation model and compare results obtatined from it with ship-observed data. The relative error is calculated for truth data of ship observations in each layer. This model calculates a relative error of 40%. The model gives from a noticeable error when the ship-observed and the averaged data are considerably. These results suggest the feasibility and validity of this model to estimate VPCC from the sea surface concentration derived from CZCS imagery. This paper compares in situ data with VPCC estimated from CZCS at three points. We hope to now apply our EOF-Analysis model using vast data sets of ADEOS/OCTS which has been operating since August 17, 1996.

Acknowledgments

We wish to thank Dr. Satsuki MATSUMURA and Mr. Taro ICHII of the National Research Institute of Far Seas Fisheries, Japan for providing the biological data.

References

BARALE, V., MCCLAIN, C. R. and MALANOTTE-RIZZOLI, P. (1986): Space and time variability of the surface color field in the northern Adriatic Sea. J. Geophys. Res., **91**, 12957–12974.

COMISO, J. C., MAYNARD, N. G., SMITH, W. O. and SULLIVAN, C. W. (1990): Satellite ocean color studies of Antarctic ice edges in summer and autumn. J. Geophys. Res., **95**, 9481–9496.

EL-SAYED, S. Z. (1968): Primary productivity. Primary Productivity and Benthic Marine Algae of the Antarctic and Subantarctic, ed. by V.C. BUSHNELL. New York, Am. Geogr. Soc., 1–6.

GORDON, H. R., CLARK, D. K., BROWN, J. W., BROWN, O. B., EVANS, R. H. and BROENKOW, W. W. (1983): Phytoplankton pigment concentrations in the middle Atlantic bright: Comparison of ship determinations and CZCS estimates. Appl. Opt., **22**, 20–36.

GORDON, H. R., BROWN, O. B., EVANS, R. H., BROWN, J. W., SMITH, R. C., BAKER, K. S. and CLARK, D. K. (1988): A semianalytic radiance model of ocean color. J. Geophys. Res., **93**, 10909–10924.

KIMURA, N., OKADA, Y., MATSUMURA, S. and SUGIMORI, Y. (1992): Estimation of phytoplankton pigment concentration distributions in the Antarctic Ocean obtained from the remote sensing of visible bands. Proceedings of the Pacific Ocean Remote Sensing Conference, Australia, 1992, 243–249.

KIMURA, N., OKADA, Y. and FUKUSHIMA, H. (1994): Estimation of vertical profile of chlorophyll concentration around the Antarctic Peninsula derived from the satellite image (Nimbus-7/CZCS). PICES-STA Workshop or Monitoring Subarctic Pacific Ocean, Nemuro, 102–108.

LIPSKI, M. (1982): The distribution of chlorophyll *a* in relation to the water masses in the southern Drake Passage and the Bransfield Strait BIOMASS-FIBEX, February–March 1981. Pol. Polar Res., **3**, 143–152.

MATSUMURA, S. and SHIOMOTO, A. (1993): Vertical distribution of primary production function ϕ (II): For the estimation of primary productivity using by satellite remote sensing. Bull. Nat. Res. Inst. Far Seas Fish., **30**, 227–270.

MAYNARD, N. G. and CLARK, D. K. (1987): Satellite color observations of spring blooming on Bering sea shelf waters during the ice edge retreat in 1980. J. Geophys. Res., **92**, 7127–7139.

MULLER-KARGER, F. E., MCCLAIN, C. R., SAMBROTTO, R. N. and RAY, G. C. (1990): A comparison of ship and Coastal Zone Color Scanner mapped distribution of phytoplankton in the south eastern Bering Sea. J. Geophys. Res., **95**, 11483–11499.

PLATT, T., SATHYENDRANATH, S., CAVERHILL, C. M. and LEWIS, M. R. (1988): Ocean primary production and available light: Further algorithms for remote sensing. Deep-Sea Res., **35**, 855–879.

SULLIVAN, C. W., MCCLAIN, C. R., COMISO, J. C. and SMITH, W. O. (1988): Phytoplankton standing crops within and Antarctic ice edge assessed by satellite remote sensing. J. Geophys. Res., **93**, 12487–12498.

(Received March 27, 1996; Revised manuscript accepted November 1, 1996)