Distribution of chlorophyll-*a* and sea surface temperature in the marginal ice zone (20˚E–60˚E) in East Antarctica determined using satellite multi-sensor remote sensing during austral summer

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Abstract: We investigated the distribution of chlorophyll-*a* (Chl-*a*) and sea surface temperature (SST) off the sea ice region south of 64˚S in East Antarctica between 20˚E and 60˚E during austral summers, 1998–2002. We used satellite multi-sensor remote sensing datasets including ocean color Chl-*a*, SST and sea ice concentration. High concentrations of Chl-*a* (>0.5 mg m^{-3}) were generally observed in colder water below 0˚C. Phytoplankton blooms were extended into shallow areas along the isobath. SST distribution exhibited two patterns. In the first pattern, warm water located to the north of this region associated with polynya in early spring. The second pattern was characterized by distribution of cold water throughout the study area. A shift of the Antarctic Circumpolar Current (ACC) is considered to affect this difference between SST distributions. The cold water from the Antarctic coastal current mixed with meltwater was expected to provide vertical stability of the water column for phytoplankton blooms. These results suggest that the phytoplankton blooms in this study area during austral summer can be attributed to water conditions affected by melting sea ice, movement of the ACC and sea floor topography.

key words: ocean color remote sensing, sea surface temperature, phytoplankton, East Antarctica, sea ice

Introduction

Sea ice extent and dynamics have a great influence on biomass in the Southern Ocean. The marginal ice zone in the Southern Ocean has been shown to be a region of enhanced biological activity (Smith and Nelson, 1985). Furthermore, a major phytoplankton bloom was observed close to the ice edge as the ice receded in austral autumn (Comiso *et al*., 1990, 1993). Antarctic coastal polynyas are areas of reduced sea ice cover within the pack ice. Their associated surface waters have been observed to sustain enhanced levels of biological production during the spring and summer (Arrigo and Van Dijken, 2003a).

The retreat of sea ice that occurs in the region results in the input of significant volumes

of meltwater, creating vertical stability for a period sufficient to permit growth and accumulation of phytoplankton within the Antarctic ice edge (Sullivan *et al*., 1988). In addition to sea ice, physical processes like wind and oceanic currents also influence biological productivity in the marginal ice zone during spring-summer. Fiala *et al*. (2002) suggested that factors such as wind could induce a rapid horizontal dispersion of meltwater that would prevent phytoplankton enhancement in exposed open-ocean regions.

Higher primary productivity is associated with the Upper Circumpolar Deep Water (UCDW) in the Antarctic Circumpolar Current (ACC) (Tynan, 1998), while Nicol *et al*. (2000) found enhanced biological activity south of the southern boundary of the ACC. The ACC is dominated by a thick layer of warm, saline, oxygen-poor and macronutrient-rich water with the UCDW located at depths of approximately 200–500 m, where wind-induced divergence and upwelling bring high concentrations of phosphate, nitrate, and silicate to the Antarctic Surface Water (Sievers and Nowlin, 1984). Given that nutrients are generally not considered to be limiting for phytoplankton growth in Antarctic waters, any assessment of phytoplankton and sea surface temperature (SST) distribution must consider the influence of warm water from the ACC and cold water derived from melting ice (Comiso *et al*., 1993).

Sharp poleward shifts of the ACC have been observed through the broad gap in the Southwest Indian Ridge between 20˚E and 30˚E with marked clockwise subpolar circulation between 20˚E and 60˚E (Orsi *et al*., 1995). A large extent of seasonal ice have been observed in the Indian sector off Lützow-Holm Bay (Comiso and Zwally, 1989). This region is normally characterized by relatively low biomass compared with other parts of the southern ocean (Fukuchi, 1980). The Adélie penguin colonies near Lützow-Holm Bay are among the smallest in eastern Antarctica (Arrigo and Van Dijken, 2003a). However, a highly significant relationship exists between the mean annual primary production of a post-polynya in this region, and the mean size of its associated Adélie penguin colonies (Arrigo and Van Dijken, 2003a). Sperm whales are concentrated at high latitudes in the Indian Ocean and track the increasing southward penetration of the Southern Boundary between 20˚E and 60˚E off Lützow-Holm Bay (Tynan, 1998).

In spite of the low phytoplankton biomass in the region off Lützow-Holm Bay, the structure of the ecosystem can be highly dependent on the relationship that exists among the biomass, sea ice and the ACC. Consequently, it is important to investigate the relationship between the physical environment and the distribution of phytoplankton in ecosystem studies such as that of the marginal ice zone off Lützow-Holm Bay where a large decrease in sea ice and marked poleward shift of the ACC have been observed. In order to understand the relationship between variations of phytoplankton biomass and the physical environment within the marginal ice zone, it is necessary to examine the spatial and temporal distributions of phytoplankton, sea ice and SST. Satellite data are very effective in investigating the temporal and spatial variability of phytoplankton and the physical environment.

Previous studies on phytoplankton, sea ice and SST distributions using satellite data in the Southern Ocean have focused on high productivity regions such as the Weddell Sea, Ross Sea and the Polar Front, or on mesoscale activity surrounding Antarctica. Comiso *et al*. (1990) observed phytoplankton blooms about 200 km wide that extended several hundred kilometers along the ice edge using Coastal Zone Color Scanner (CZCS) satellite data in the marginal ice zone of the Weddell Sea . Their results showed that the effect on the spatial distribution of the phytoplankton due to movement of ocean and sea ice is significant. Arrigo

and Van Dijken (2003b) showed that the calving of large icebergs off the face of the Ross Ice Shelf has resulted in high sea ice cover during the spring and summer, diminishing phytoplankton blooms in the region dramatically and reducing primary production by more than 90% relative to normal years using the Sea-viewing Wide Field of View Sensor (SeaWiFS). SeaWiFS has also been used to investigate phytoplankton bloom dynamics at the Antarctic Polar Front (PF), elevated Chl-*a* within the PF often appears as a narrow band that occupies only a portion of the SST (Moore and Abbott, 2002). The Ocean Color and Temperature Sensor (OCTS) has shown a strong correlation of sea ice and ice algae to primary production and to the regionally heterogeneous Chl-*a* distribution in drifting Chl-containing ice to melting spots in the Antarctic Ocean using sea surface temperature and ice cover ratios (Meguro *et al.*, 2004). However, the relationship between the physical environment and phytoplankton distribution off Lützow-Holm Bay has not been known well yet.

We analyzed the distributions of Chl-*a* concentration, SST and sea ice concentration using multi-satellite remote sensing between 20°E and 60°E during 1997–2002 in austral summer. The purpose of this study is to understand the phytoplankton bloom patterns in relation to the SST distribution within the marginal ice zone in this region. The influence of physical environments on the distribution of phytoplankton is discussed.

Materials and methods

Satellite observations were conducted from December to March from 1997 to 2002. The study area is located at the marginal ice zone off the eastern Antarctic continent south of 64°S and between 20°E and 60°E (Fig. 1). Chl-*a* concentrations were derived from SeaWiFS data obtained from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC). We used the
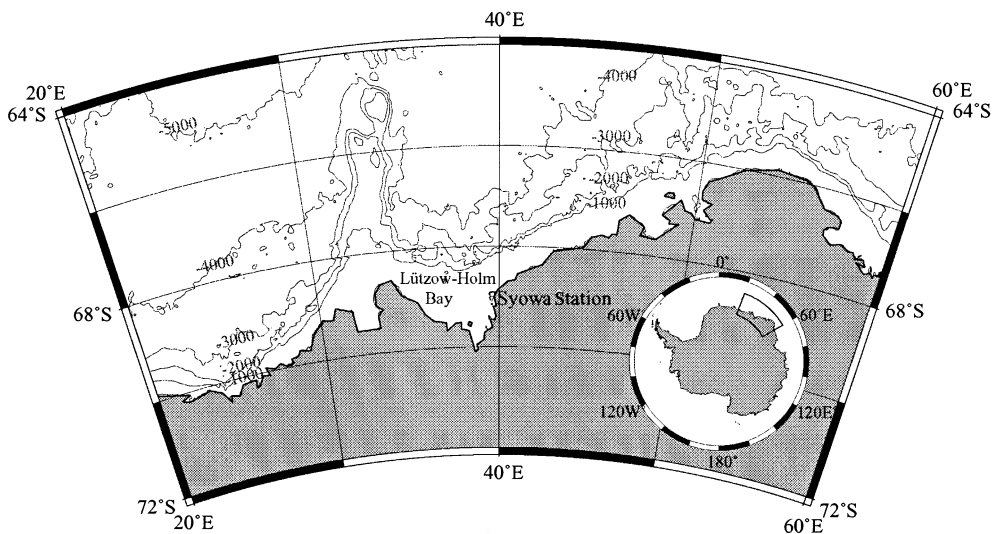

Fig. 1. Map of this study area and sea floor topography of the east Indian sector in the Southern Ocean. Sea floor topography refers to Smith and Sandwell (1997).

SeaWiFS Data Analysis System (SeaDAS) Version 4.0 developed by NASA to generate Chl-*a* products. We applied default atmospheric corrections and the OC4v4 bio-optical algorithms (O'Reilly *et al*., 2000) to SeaWiFS High Resolution Picture Transmission (HRPT) and daily global area coverage (GAC) data. The HPRT and GAC data had a spatial resolution of about 1×1 km and 4×4 km, respectively. The HRPT data were received at Syowa Station, Antarctica during January 1999–March 2002. We used GAC data to cover the period before January 1999. The 8-days, monthly geometric mean Chl-*a* concentrations and the mean Chl-*a* concentration between January and March in each year were calculated except missing data.

SST distribution and variability were investigated using Advanced Very-High Resolution Radiometer (AVHRR) data of National Oceanic and Atmospheric Administration (NOAA) satellites during January to March, 1998–2002. We obtained 8-day mean data sets (spatial resolution$=9 \times 9$ km) from NASA's Jet Propulsion Laboratory (JPL) Physical Oceanography (PO)–DAAC Pathfinder database. The mean SST values between January and March in each year were calculated.

Daily sea ice concentration data (spatial resolution$=25 \times 25$ km) were derived from the Special Sensor Microwave Imager (SSM/I) on the Defense Metrological Satellite Program (DMSP) using a Bootstrap algorithm (Comiso, 1990) during January to March, 1998–2002 and December 1997–2001. These data were obtained from the U.S. National Snow and Ice Data Center (NSIDC).

In order to analyze the influence of sea ice on phytoplankton distribution, the study area was divided into three zones, heavy pack ice zone, marginal ice zone and open ocean. The boundary between the heavy pack ice zone and marginal ice zone was defined as 50% concentration of sea ice. Namely, those three zones were defined as follows: 1) heavy pack ice zone between the coastline and the contour line for sea ice at a 50% concentration; 2) marginal ice zone between the heavy pack ice and approximately 1˚ of latitude from the heavy pack ice, and 3) the open ocean. The 8-day geometric mean Chl-*a* concentrations and the geometric mean Chl-*a* concentrations between January and March in each year in each zone were calculated.

Results

The distribution of sea ice concentration is shown in Fig. 2. Sea ice receded rapidly southward during December and January, and then more slowly until the end of February every year. The extent of sea ice recession in March 1998, 2001 and 2002 was larger than that observed in March 1999 and 2000. Polynyas appeared at 66˚S, 35˚E in December 2000, and 66.5˚S, 20˚E in December 1997 and 2001.

The distribution of monthly averaged SST is shown in Fig. 3. The monthly averaged SST was observed to reach maximum values in February of every year. The distribution of SST exhibited two patterns. The first pattern was characterized by SST less than 1.0˚C except in the north-west (62–64˚S, 20–30˚E). This pattern was observed in 1999 and 2000. The other pattern was characterized by SST more than 1.5˚C in the northern part of the study region. This pattern was observed in 1998, 2001 and 2002. The cold water region (100–200 km wide) below 0˚C along the coast was narrower than that (200–400 km) observed in the first pattern.
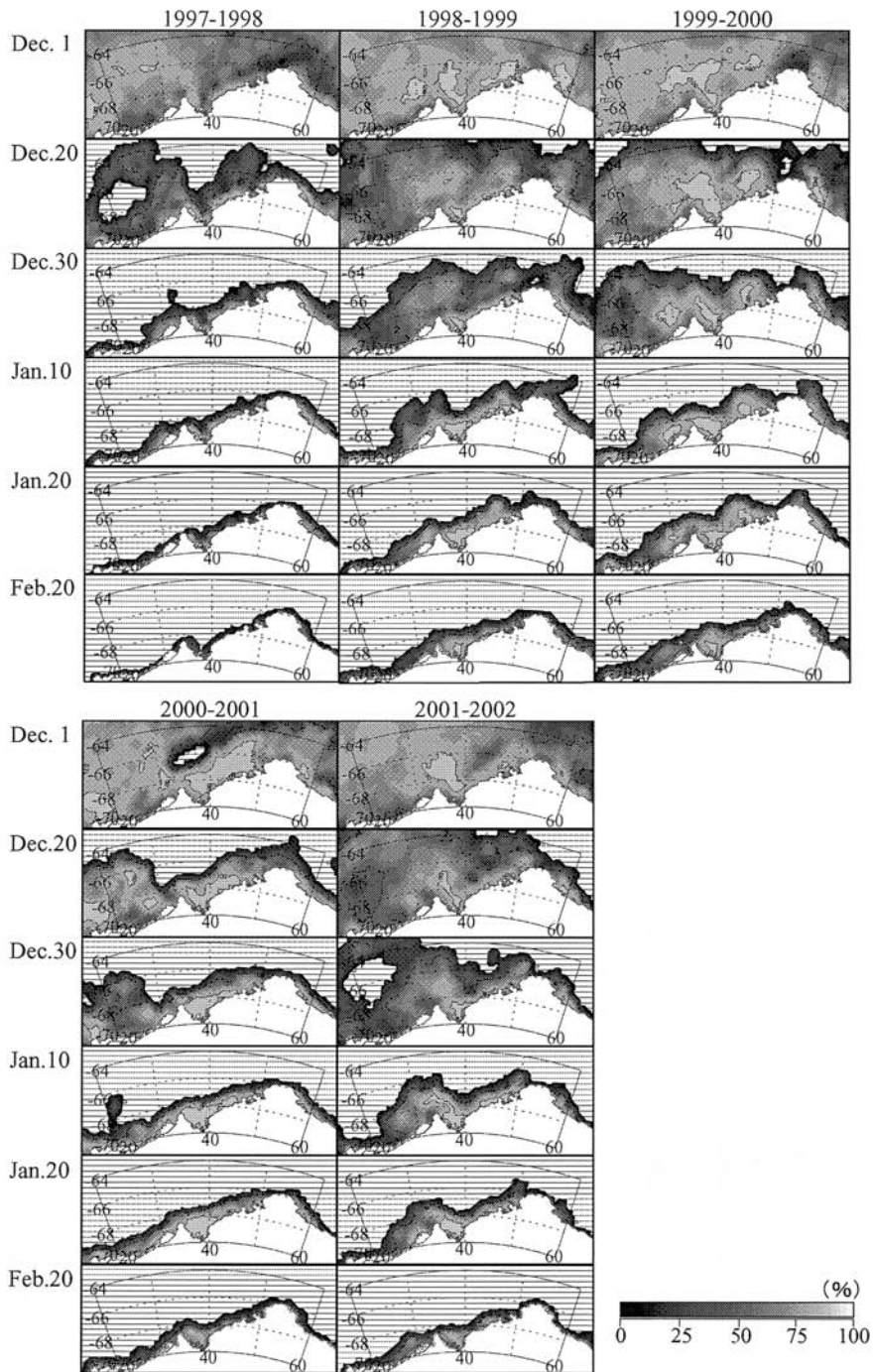
Fig. 2. The distribution of sea ice concentration during austral summer (December to March) from 1997 to 2002 observed by SSM/I.
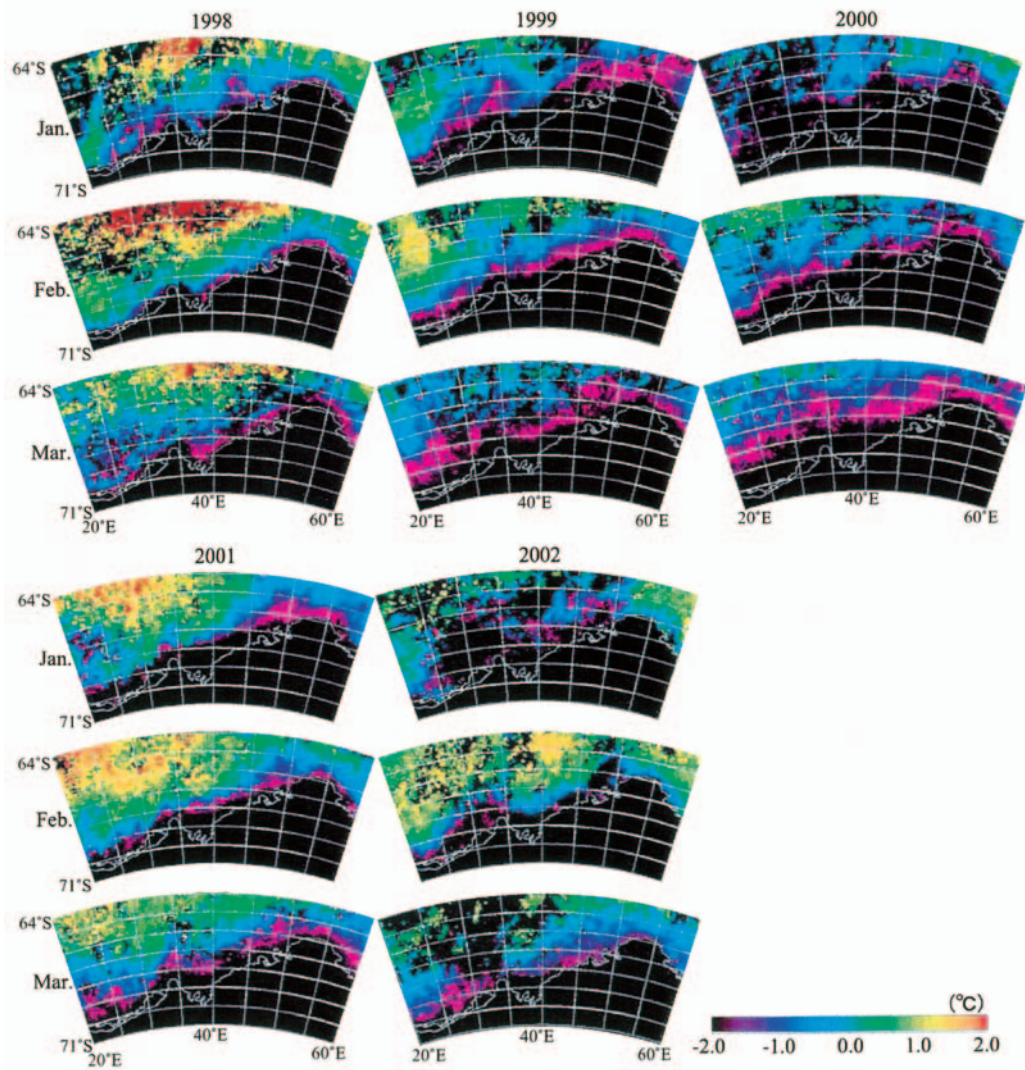
Fig. 3. Monthly mean SST images during austral summer (January to March) from 1998 to March 2002. Black color indicates cloud, sea ice missing data and land.

The distribution of monthly averaged Chl-*a* concentrations is shown in Fig. 4. Very high Chl-*a* concentrations more than 5.0 mg m^{-3} were observed near the ice edge. However, these high concentration of Chl-*a* were not observed in the same region every year, they were observed at 20–25˚E, 30–35˚E and 25–30˚E in 1999, 2000 and 2001 respectively. The distribution of Chl-*a* concentrations more than 0.5 mg m^{-3} exhibited two patterns. The first pattern, observed in 1998, 2001 and 2002, was characterized by having high Chl-*a* concentration distributed in a narrow area near the coast. The other pattern, observed in 1999 and 2000, was characterized by high Chl-*a* concentration over a larger area.
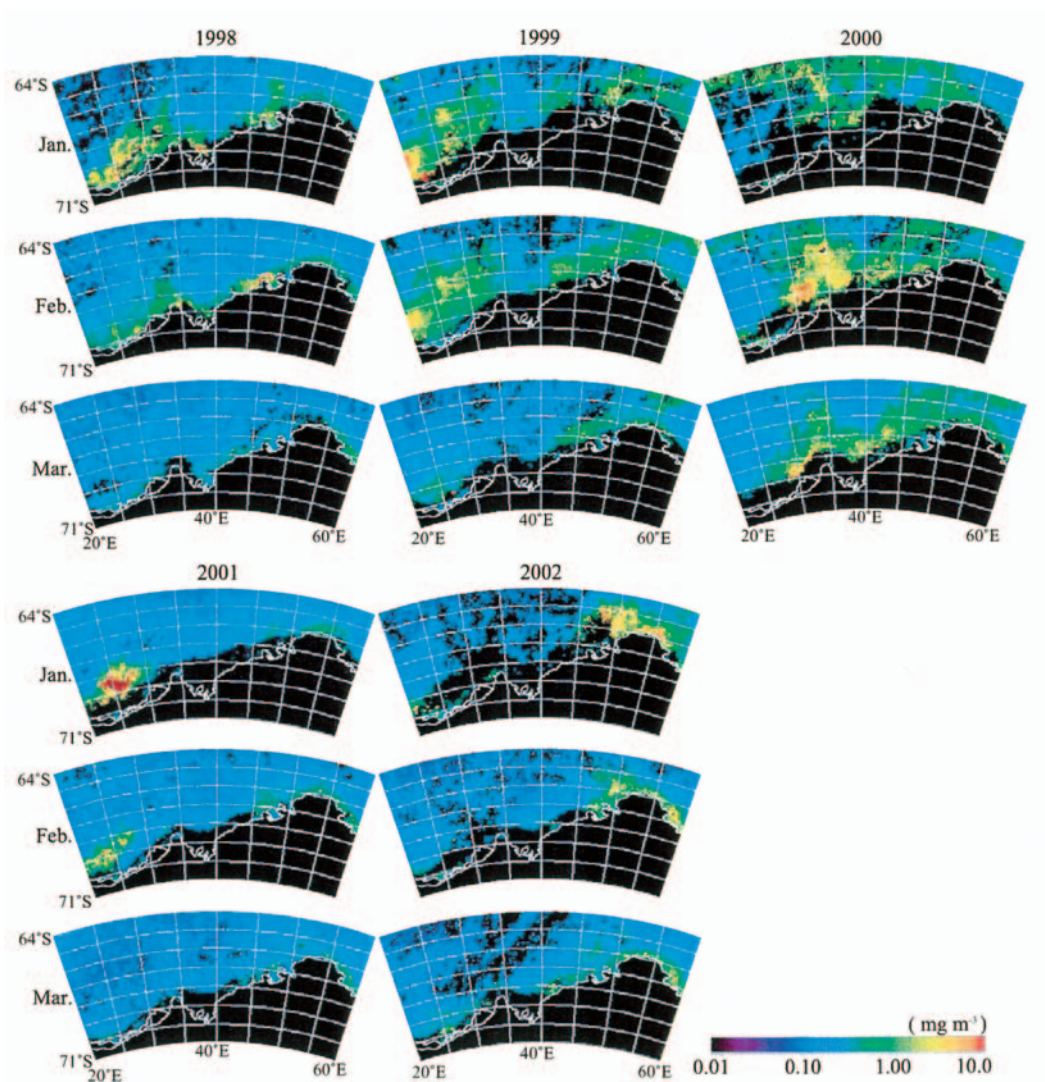
Fig. 4. Monthly mean Chl-*a* images during austral summer (January to March) from 1998 to March 2002. Black color indicates cloud, sea ice missing data and land.

    The average concentration of Chl-*a* during the spring to summer for the entire study area ranges between 0.15 and 0.25 mg m^{-3} (Fig. 5). The average Chl-*a* concentration in the marginal ice zone and the heavy pack ice zone (0.27–0.40 mg m^{-3} and 0.22–0.34 mg m^{-3}, respectively) was higher than those in the open ocean (0.11–0.19 mg m^{-3}).

    The 8-day averaged concentrations for Chl-*a* in the marginal ice zone, in the heavy pack ice zone and the open ocean were 0.16–0.57 mg m^{-3}, 0.11–0.46 mg m^{-3} and 0.06–0.42 mg m^{-3}, respectively (Fig. 6). The largest variability of the 8-day averaged Chl-*a* concentration was observed in the marginal ice zone in 1998, with the maximum concentration (0.57 mg m^{-3})

Fig. 5. Time series variability of seasonal mean (January to March) Chl-*a* concentrations in open ocean, marginal ice zone, heavy pack ice zone, and whole area from 1998 to 2002.
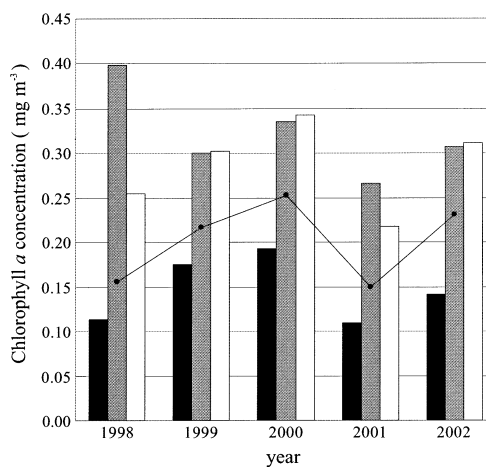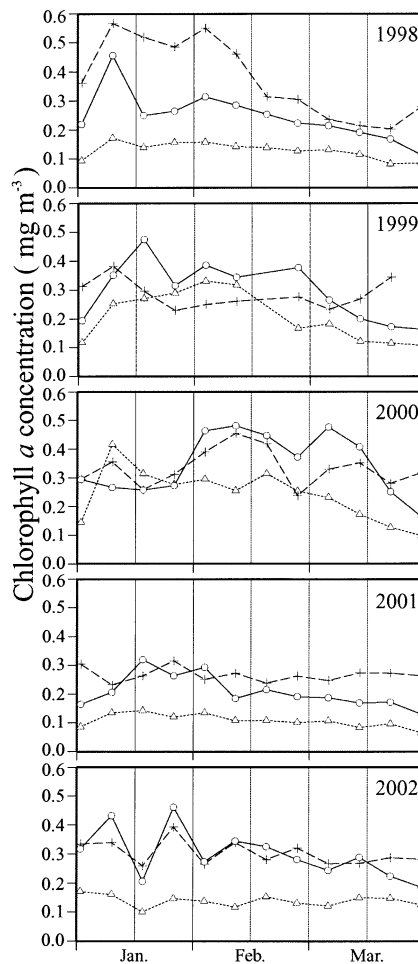
Fig. 6. Time series variability of 8-day averaged Chl-*a* concentrations in open ocean, marginal ice zone and heavy pack ice zone from 1998 to 2002.
··· △ ··· Open ocean
― + ― Marginal ice zone
― ○ ― Heavy pack ice zone

and minimum concentration (0.20 mg m^{-3}) observed in January and in March, respectively. High concentrations of Chl-*a*, and large changes in the Chl-*a* concentrations, were observed in the marginal ice zone. The variability of Chl-*a* concentration in the marginal ice zone showed little change in 1999, 2001 and 2002. High concentrations of Chl-*a* in heavy pack ice were observed during January to February and during February to March in 1999 and 2000, respectively. Chl-*a* concentrations in the heavy pack ice zone in 1998 were high in January and decreased until March, while Chl-*a* variability in the heavy pack ice zone was stable in 2001 and 2002. Chl-*a* concentrations in the open ocean area hardly changed and were generally lower than those in other areas in 1998, 2001 and 2002, while some variability of Chl-*a* concentration in the open ocean was observed in 1999 and 2000 (0.11–0.33 mg m^{-3} and 0.10–0.42 mg m^{-3}, respectively). The concentrment of Chl-*a* in the open ocean in 1999 and 2000 was often observed to exceed those in marginal ice zone and heavy pack ice zone during January and February.

Discussion

As sea ice retreats, meltwater is produced and the water condition near the ice edge is affected by meltwater. Meltwater provides vertical stability in the water column and the water condition affects phytoplankton growth. However, the high Chl-*a* concentrations distributed to large zone when the recession of sea ice was small (Fig. 2 and Fig. 4). In addition, the 8-day averaged Chl-*a* concentrations in the open ocean were often higher than those in the marginal ice zone (Fig. 6). These results suggest that the meltwater volume may not be a key factor in the occurrence of spring bloom in the marginal ice zone.

Wakatsuchi *et al*. (1984) observed two water types at the depth of 50–400 m in this study area. The first type, which was low salinity, oxygen-rich and at nearly freezing temperature, was present over the continental shelf and was locally produced through convection in winter. The second type of water, which was warm, saline and oxygen-poor, is distributed broadly offshore of the first type, affected by North Indian Deep Water and eastern South Pacific Deep Water. In additon, in the eddy regions within the Antarctic Divergence (AD), warm, saline Circumpolar Deep Water (CDW) is upwelled into the shallow layers and leads to the formation of polynyas within the ice cover (Enomoto and Ohmura, 1990; Wakatsuchi *et al*., 1994). The AD had the same properties as the second type of Wakatsuchi *et al*. (1984), while the SST distribution observed in 1998, 2001 and 2002 was similar to the result of Wakatsuchi *et al*. (1984). Figure 2 shows that a polynya was located in the same position as the Cosmonaut Polynya and to the east of the Weddell Polynya (Wakatsuchi *et al*., 1984). If the region where these polynyas appeared was in the CDW, it can be inferred that the AD was at around 65–66°S in 1998, 2001 and 2002.

Based on previous observations (Wakatsuchi *et al*., 1984), SST at 1°C is indicative of the ACC. The ACC was located closer to the coast in 1998, 2001 and 2002 than in 1999 and 2000 (Fig. 3). Past the eastern ends of the subpolar cyclones, near 30°E, the ACC shifts southward, bringing CDW close to the Antarctic Shelf Waters (Orsi *et al*., 1995). These results show that the southern shift of the ACC and appearance of the CDW is associated with narrower cold water along the coast in this study region.

The retreat of sea ice appears to provide an input of significant volumes of meltwater, which creates vertical stability for the period necessary to permit growth and accumulation of
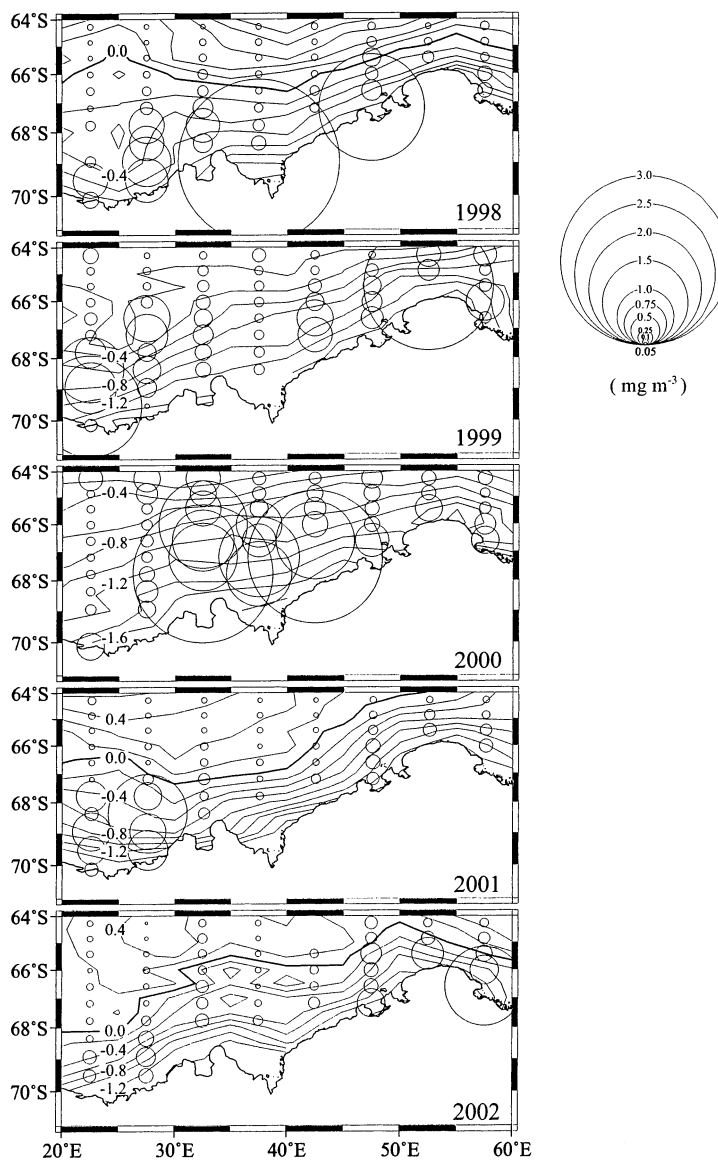
Fig. 7. Abundance of average Chl-*a* and distribution of average SST during austral summer (January to March) in each year. Circle size indicates Chl-*a* concentration.

phytoplankton within the Antarctic ice edge (Sullivan *et al*., 1988). When the upper water is produced from meltwater, the cold water mixed with meltwater creates a vertically stable water column above the depth of 400 m, while the warm water does not create a similar column. The abundance of averaged Chl-*a* concentration and SST during austral summer in each year are shown in Fig. 7. The distribution of SST was not observed to correlate directly with the distribution of Chl-*a*, even though high Chl-*a* concentrations were observed in

regions with temperatures below 0°C. When the ACC comes close to the coast, the Antarctic coastal current is narrower and meltwater is transported to the coast, the phytoplankton bloom occurs in a narrower band along the coast. Conversely, when the ACC is located further offshore, the Antarctic coastal current becomes broader and is mixed with meltwater. Then cold water provides vertical stability for the growth and accumulation of phytoplankton.

High Chl-*a* concentration is often observed in the region where the depth of the sea floor is less than 2000 m (Fig. 1 and Fig. 4). This is consistent with resuspension of micronutrients by wind-induced mixing (Comiso *et al.*, 1993).

These results suggest that the phytoplankton blooms in this study area during austral summer can be attributed to water condition affected by melting sea ice, warm and cold waters associated with movement of the ACC and sea floor topography.

Acknowledgments

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