Bathymetical influences on spatial and temporal characteristics of chlorophyll-a concentrations in the Southern Ocean from 2002 to 2012 (October to March) using MODIS

Chao SONG and Ling KE*

School of Remote Sensing and Information Engineering, Wuhan University, 129 Luoyu Road, Wuhan 430079, China

(Received 9 September 2015; accepted 27 October 2015)

Phytoplankton blooms, particularly in the Southern Ocean, can have significant impact on global biogeochemistry cycling. To investigate the accuracy of chlorophyll-a distribution, and to better understand the spatial and temporal dynamics of phytoplankton biomass, we examine chlorophyll-a estimates (October–March from 2002 to 2012) derived from Moderate Resolution Imaging Spectrometer (MODIS) data following the ocean chlorophyll-a 3 model (OC3M) algorithm. Noticeable seasonality occurs in the temporal distribution of chlorophyll-a concentrations, which shows the highest value in December and January and an increasing tendency during the 2002–2012 period. The spatial distribution of chlorophyll-a varies greatly with latitude, as higher latitudes experience more phytoplankton blooms (chlorophyll-a concentration larger than 1 mg/m³) and marginal seas (Ross Sea and Amundsen Sea) show different bloom anomalies caused by two dominant algae species. Areas at higher latitudes and shallow water (<500 m) experience the shorter ice-free periods with greater seasonality. A noticeable bathymetry gradient exists at 2500-m isobaths, while water at the 500–2500-m depth experiences quite long ice-free periods with a stable water environment. Blooms generally occur near topographic features where currents have strong interactions when the water depth is more than 2500 m. Based on these findings, we can classify the Southern Ocean into two bloom subregions, 0–500 m as an enhanced bloom zone (EBZ), and 500–2500 m as a moderate bloom zone (MBZ). The EBZ has a quite high-bloom probability of about 30%, while the MBZ has only 10%.

keywords: chlorophyll-a distribution; Moderate Resolution Imaging Spectrometer (MODIS); bathymetry; spatial and temporal characteristics; the Southern Ocean

1. Introduction

Chlorophyll-a dynamics in the Southern Ocean plays a critical role in modulating climate change and global biogeochemical cycling (1). Physical geographic factors, such as topography, geographic region, and latitude, influence the spatial and temporal distribution of chlorophyll-a (2–6). When coupled with physical oceanographic mechanisms, distinct “bloom zones” can form, which can cause chlorophyll-a concentrations to exceed 1.0 mg/m³ (7, 8).

Since it has been observed that chlorophyll-a is distributed asymmetrically throughout the Southern Ocean water column, many researchers argue that phytoplankton blooms are triggered by the interaction between the currents and topographic features. Such phytoplankton blooms can occur in deep mixed waters, coastal areas, or along ocean fronts (e.g. the Antarctic Circumpolar Current and Polar Front which interacts with the North Scotia Ridge and Kerguelen Plateau) (9). In some cases, blooms are associated with large bathymetric features (10). The elevated water irradiance, caused by the reduced ice cover (11), a result of the offshore katabatic winds and seasonal ice melt, can favor the formation and growth of phytoplankton (12–15). Moreover, the factors that affect phytoplankton biomass can also include the availability of iron (16), which increases with melting sea ice (17, 18), floating ice packs (19–21), upwelling circumpolar deep water (22), and melting glaciers (23).

However, studies based on in situ data typically focus on biologically productive marginal ice zones in selective parts of the Southern Ocean. This leaves gaps in our understanding of the spatial and temporal dynamics of chlorophyll distribution and bloom events across the entire region (7). Because current studies bias toward regions with in situ samples/data, a large gap in long-term observations and large-scale monitoring of the influence of physical geographic features on chlorophyll-a distribution in the Southern Ocean exists. Stumpf and Tomlinson (24) and Shen et al. (25) have pointed out that spatial–temporal exploration of the complicated interaction between physical oceanographic mechanisms and geographic features needs to be addressed for improved management of the Southern Ocean resources.

Recently, researchers have paid more attention to satellite data, providing an opportunity for greater spatial coverage of the Southern Ocean due to the multiple spatial, temporal, and spectral resolutions of satellite imagery (13–15). Studies using satellite data are dedicated to finding the relationships between chlorophyll-a and other physical processes from ocean color measurements at broad scales (14, 24). Satellite data cover larger, basin-scale areas including those areas poorly sampled by
in situ efforts, and can be used to discern spatial temporal dynamics without the bias of unevenly distributed in situ data. The use of satellite data in ocean process studies of the Southern Ocean has an accuracy of 60% for the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (26) and up to 51% for Moderate Resolution Imaging Spectrometer (MODIS) (27).

To seek a better understanding of bloom distribution, as well as the physical oceanographic mechanisms and geographic features responsible for this bloom distribution, satellite remote sensing of continuously monitored chlorophyll-a concentration at large scales is needed (9). In this study, we assess a long-term MODIS data-set to explore the impact of water depth, topographical features, and sea ice concentrations on the chlorophyll-a bloom distribution patterns by geographic region. It should be noted that we focus on the latitudinal zones rather than the longitudinal zones/regions by previous studies. Examining latitudinal zones can be helpful in understanding regional phytoplankton dynamics, as symmetrical distributions of phytoplankton, zooplankton, and biotopes are caused by similar macro circulation patterns at different latitudinal zones (28). Validation experiments between the MODIS chlorophyll-a algorithm and in situ measurements, as well as between sea ice cover and MODIS ice flag data were carried out to validate and justify the applicability of satellite imagery from MODIS for use in understanding the spatial–temporal chlorophyll-a bloom dynamics in the Southern Ocean.

2. Methodology
2.1. Study area

The Southern Ocean consists of the southern portions of the Atlantic, Indian, and Pacific Oceans, and covers the region from the South Pole to the 60°S latitude (Figure 1). As the fourth largest ocean in the world, the Southern Ocean has sea surface temperatures ranging from 10 °C to −2 °C. The temperature contrast between ice and open ocean water in the Southern Ocean creates strong winds which travel eastward (29) and are responsible for generating the Antarctic Circumpolar Current. The depth of the Southern Ocean is approximately 4000 to 5000 m throughout most of its extent, with small portions of water (451.572 km²) shallower than 200 m and 1394.29 km² shallower than 400 m, as computed from ETOPO1 (30).

2.2. Data acquisition and preparation

The surface chlorophyll-a concentrations (Chla) were derived from the MODIS water leaving radiance following the OC3M algorithm, which is developed by the Ocean Biology Processing Group, using the default atmospheric correction algorithm (31). The formula is expressed as

\[ Chla = 10^\left(\frac{\log 10(R_{rs}(443)) + \log 10(R_{rs}(489))}{\log 10(R_{rs}(547))}\right) \]

\[ x = \log 10\left(\frac{\max(R_{rs}(443), R_{rs}(489))}{R_{rs}(547)}\right) \]

where the coefficients \( a_0, a_1, a_2, a_3, \) and \( a_4 \) are 0.2424, −2.7423, 1.8017, 0.0015, and −1.2280, respectively. \( R_{rs} \) means MODIS remote sensing reflectance and the number behind it means the wavelength value (in unit nm).

We obtained three MODIS-derived daily level standard gridded images (\( n = 1823 \)) of surface chlorophyll-a concentration (4.25 km × 4.25 km) during the period October 2002 to March 2012 from the Ocean Color Website (http://oceancolor.gsfc.nasa.gov). Since half of the year in the Southern Ocean is dark due to low solar elevation, the available ocean color data cover only six months of the year, from October to March. The data were averaged across months to fully take into account the accumulation of algal biomass and data loss from quality control flags (7, 14). Several attributes, including chlorophyll-a, sea ice cover, and QA/QC flags were computed for latitudinal zones 60–65°S, 65–70°S, and >70°S for each month from October to March.

The in situ data, high-performance liquid chromatography samples (\( n = 1664 \)) between October 2002 and March 2012, were compiled from the SeaBASS bio-optical data archive (http://seabass.gsfc.nasa.gov/) and the Palmer Long-Term Ecological Research program (http://pal.lternet.edu/data). All the chlorophyll-a in situ data were filtered by the geographic extent of 180°E–180°W, 60°S–90°S, and to waters shallower than the first optical depth (1.9–21 m when \( \lambda = 490 \) nm) for further statistical analysis. After constraining the matchups to within a ±24 h window and averaging to a 3 × 3 pixel grid, 282 pairs of in situ and MODIS-derived chlorophyll-a were obtained. The matchups show a good relationship between in situ and MODIS data (Figure 2).

ETOPO1 bathymetry data were downloaded from National Geophysical Data Center. ETOPO1 is a 1 arc-minute global relief model of Earth’s surface that integrates
land topography and ocean bathymetry from numerous global and regional data-sets (30).

The sea ice extent around Antarctica was downloaded (25 km × 25 km) from the National Snow and Ice Data Center for the same period and geographic extent (http://nsidc.org/data/docs/daac/nsidc0051_gsc_seaice.gd.html). These data were generated from brightness temperature data derived from several sensors: the Nimbus-7 Scanning Multichannel Microwave Radiometer, the Defense Meteorological Satellite Program (DMSP)-F8, -F11 and -F13 Special Sensor Microwave/Imagers (SSM/Is), and the DMSP-F17 Special Sensor Microwave Imager/Sounder (SSMIS).

2.3. Statistical analyses

To understand the influence of water depth on surface chlorophyll-a concentration, average chlorophyll-a concentrations were computed at 50-m intervals from 0 to −5500 m. Bloom (>1.0 mg/m³) probability (bloom event divided by the total number of bloom events for each pixel) was also plotted for the respective water depth to show the bloom distribution and occurrence. Annual (October–March) anomalies (annual minus decadal average) of chlorophyll-a concentrations were calculated to visualize the relationship between bathymetry and bloom activity.

A bathymetrical gradient index was calculated, showing submarine topography. This allows for better visualization of the influence of water depth variation on bloom probability. The topographic gradient index was calculated as follows:

\[ G(x, y) = \Delta x(i, j) + \Delta y(i, j) \]  
\[ \Delta x(i, j) = I(i + 1, j) - I(i, j) \]  
\[ \Delta y(i, j) = I(i, j + 1) - I(i, j) \]

where \( G \) is the gradient index, \( I \) is the water depth, and \((i, j)\) is the image pixel coordinate.

3. Results

3.1. Monthly and annual variation across latitudinal zones

Latitudinal distribution of chlorophyll-a concentration in the Southern Ocean for six months from 2002 and 2012 was shown in Figure 3. Monthly variation of MODIS-derived chlorophyll-a followed a parabolic curve from October to March, with peak values occurred in January (Figure 3(a)–(c)). The average, minimum, and maximum values for the lowest latitudinal range 60°–65°S

![Figure 2. Regression of chlorophyll-a measured in situ against chlorophyll-a derived from MODIS data.](image)

![Figure 3. Latitudinal distribution of chlorophyll-a concentration in the Southern Ocean for six months from 2002 to 2012. The upper short line represents maximum chlorophyll concentration, and the lower is minimum. A dashed line connects the average monthly concentrations latitudinal range in (a) 60°–65°S; (b) 65°–70°S; (c) >70°S; (d) 60°–90°S. (No computations included invalid data.)](image)
Figure 3(a) showed little seasonal variation during the 6 months. Higher latitudinal zones >70°S (Figure 3(c)) exhibited more significant seasonal difference. The monthly average of the entire study area (Figure 3(d)) was 0.337 mg/m³ in chlorophyll-a concentration at its peak. The lowest chlorophyll-a average value occurred in October at about 0.085 mg/m³. The gap between the chlorophyll-a concentration in January and that in October was large (0.252 mg/m³). A relatively unusual situation occurred in March; when almost all minimum values were lower in the 65°–70°S rather than in the 60°–65°S area. This is contrary to the prevailing notion that higher chlorophyll-a concentration values would be found in higher latitudes near ice. This will be discussed in Section 4.2, and the influence of high-sea ice concentration (>50%) on chlorophyll-a distribution was analyzed by calculating the flag rate (Figure 4).

Monthly average variation of chlorophyll-a concentrations over the past decade (2002–2012) was shown in Figure 5. Chlorophyll-a concentrations continue to increase from October, to a peak value, in January, occasionally December (2007 and 2011), and then decreases again through March. Chlorophyll-a concentrations in October fall into the range of 0.1–0.2 mg/m³, whereas the peaks of chlorophyll-a in December or January range from 0.4 to 0.7 mg/m³. Figure 5 also showed that there was a significant increase in chlorophyll-a concentration from 2002 to 2006, followed by a decline in 2007. Another increase occurred between 2008 and 2010 followed by a depression in the average value that occurred in 2011 and 2012. In general, there was an overall upward trend of chlorophyll concentration (solid line). Although variation in chlorophyll-a concentration during the six-month period shows a single peak distribution in some years (e.g. 2004, 2005, 2008, and 2009); high-chlorophyll-a values appear in both December and January.

### 3.2. Chlorophyll-a distribution and topographic influence

To investigate the relationship between monthly average value of chlorophyll-a concentration and its corresponding bathymetrical conditions, we overlaid annually average value of chlorophyll-a concentration on bathymetric contour data (Figure 6). Chlorophyll-a blooms (>1.0 mg/m³) tend to occur in marginal seas such as the Ross, Amundsen, and Weddell Seas (Figure 6(a)). The Ross Sea appeared to generate phytoplankton blooms in November (Figure 6(b)), whereas deep-water areas, with depth over 4000 m, retain low concentrations of chlorophyll-a, around 0.1 mg/m³ (blue pixels). Figure 6(c) demonstrated that in December, the bloom extent in Prydz Bay grows, and significant blooms occurred largely in the Ross Sea. The Amundsen Sea appears to have the largest spatial extent of blooms. The chlorophyll-a concentrations in most areas at latitudes higher than 60°S reach up to 1.0 mg/m³ (green pixels) with an exception of the northwest part of Antarctic Peninsula. Though at lower concentrations chlorophyll-a in the Ross Sea and Prydz Bay surface waters, at depths from 0 to 2000 m, tend to increase in January (Figure 6(d)). Phytoplankton blooms in Prydz Bay occur later in the season in comparison to the Ross Sea. From February to March, the chlorophyll-a concentrations continue to decline throughout the entire research area (Figure 6(e) and (f)).

Two bathymetry influences are located outside the Antarctic continental shelf area at 3000–4000-m depth.

![Figure 4. Rate of flag data in latitudinal zones over October–March.](image)

![Figure 5. Monthly average variation of chlorophyll-a concentrations for October (O), November (N), December (D), January (J), February (F), and March (M) from 2002 to 2012 (The averages cover an area from 180°E–180°W and 60°–90°S).](image)
The North Scotia and Pacific Antarctica Ridges (Figure 6(a)) appeared to have significant chlorophyll-a blooms. High concentrations of phytoplankton emerged near the North Scotia Ridge surface water in November (Figure 6(b)) and continued to February (Figure 6(e)) to a great extent, and remains through March (Figure 6(f)). Although no extensive blooms occurred near the Pacific Antarctica Ridge surface waters, notable high values (green pixels, 1.0 mg/m³) are visible on the 4000-m isobath area when compared to the surrounding region (blue pixels, 0.1 mg/m³) (Figure 6(e) and (f)). In addition, relatively small chlorophyll-a blooms were found near the Pacific Antarctica Ridge in December, January, and February (Figure 6(c)–(e)).

Relationship of water depth and MODIS-derived chlorophyll-a concentrations of various months was shown in Figure 7(a). It showed the low-chlorophyll-a concentrations in October with little variation (about 0.10–0.25 mg/m³). During November, the largest increase in chlorophyll-a was observed at the 500–2500-m contour with an average range between 0.5 and 2.0 mg/m³. Moreover, it showed no obvious increase in chlorophyll-a concentrations in the deep-water region (>2500 m) during October. December was the month where the value of chlorophyll-a concentration is the highest especially in the 500–2500-m water depth range. The average value of chlorophyll-a concentration increased in the shallow water region (<500 m), with a high value in 500–2500-m water depth, and suddenly decreasing in deep water (>2500 m) with an unexpected peak at about the 3800-m depth. The same relationship between the chlorophyll-a concentration and water depth existed in January and December, but the interval range of the concentration shrinks to 0–1.2 mg/m³. Chlorophyll-a concentration decreased in February with no large difference between three water depth ranges (<500 m, 500–2500 m, and >2500 m). It showed significant decrease in shallow water (<2500 m) and kept its quite high value (slightly increasing and reaching more than 1.0 mg/m³ in 3800 m water depth) in water deeper than 2500 m in March.

The relationship of water depth and MODIS-derived chlorophyll-a concentrations of different depths was shown in Figure 7(b). Three major colors were used to represent three water depth internals, red for <500 m (shallow), blue for 500–2500 m (intermediate), and yellow for >2500 m (deep). Red lines increased from October to January and then decreased again up through March. The region with water shallower than 500 m has quite a long period over which chlorophyll-a concentration increases. Chlorophyll-a concentration values seemed to be higher in the shallower (red) and intermediate (blue) depth zones than in the deeper water zones. The highest values across the shallow and intermediate zones occurred in December and January. All of the monthly time series of chlorophyll-a concentrations at 500–2500-m depth (blue lines) increased from October to December, remained relatively constant from December to January, and then declined until March. Chlorophyll-a concentration generally showed an increase between October and December across all depths except >4000 m. Chlorophyll-a concentrations at depth zones from 2500 m to >4000 m (yellow lines) represent deeper waters and increased more gradually, and at lower concentrations, than the zones shallower than 2500 m. The peak of chlorophyll-a concentration across the deeper zones peaked in January, declined less rapidly, and retained higher in March.

3.3. Annual anomalies

There were no significant anomalous trends throughout the decade with no consistent spatial anomalies
Compared to the high-peak years in Figure 5 (2005–2006, 2008–2009, 2009–2010, and 2010–2011), the areas of the Ross Sea, Prydz Bay, and the Amundsen Sea were associated with large positive anomalies (Figure 8). The most apparent anomalous points occurred in shallow coastal waters. In shallow waters, the strength of the anomaly remained relatively low between the austral summer of 2002–2003 and 2007–2008, while retaining a relatively large negative anomaly. High peaks in anomalous values occurred in the years 2005–2006, 2008–2009, 2009–2010, and 2010–2011. Large areas of negative anomalies occurred in the Ross Sea during the years 2002–2003, 2003–2004, 2007–2008, and 2009–2010; in Prydz Bay during the years 2004–2005, 2006–2007, and 2007–2008; and in the Amundsen Sea during the years 2002–2003, 2003–2004, 2004–2005, and 2011–2012. Positive anomalies also appeared in the Amundsen Sea during 2002–2003, 2006–2007, and 2008–2009; and in the Ross Sea during 2005–2006, 2006–2007, 2008–2009, 2009–2010, and 2011–2012. All three regions had a plate terrain and shallow water that provide optimal conditions for phytoplankton growth. Both positive and negative anomalies often occurred in the same region, illustrating the influence of the highly dynamic marginal ice zone on the ecology of the coastal seas.

3.4. Bloom probability and water depth gradient index
Chlorophyll-a bloom probability distribution across the decades was shown in Figure 9. Considering areas that have a greater than 30% high-bloom probability (yellow and red points), the Ross Sea, Prydz Bay, and Amundsen Sea seemed to experience more bloom events than other regions. Bloom probabilities decreased at lower latitudes, except for the outer edge of the Ross Sea, where blooms occurred far away from the continent, at 150°W–180°W and 60°–65°S. All relatively high-bloom areas (green points with a 10% bloom probability) were adjacent to productive regions near the Antarctica continent.
Areas of high-depth gradients (Figure 10) were mainly found in two regions, the North Scotia Ridge and Pacific Antarctica Ridge (labeled in Figure 6(a)). A significant gradient occurred around the Antarctic continent (Figure 10, red arrow) and matched the 2500-m water depth line seen in Figure 9 (yellow line). The Weddell and Ross Seas were low-gradient marginal seas. The Ross Sea was quite special, because of its low-bathymetrical gradient and high-bloom probability (Figure 9). Other bloom areas appeared to be correlated with areas of rapid change and fluctuation in the depth gradient (red and yellow pixels in Figure 10). However, not all high-chlorophyll-a bloom events were associated with the high-gradient variations in water depth.

4. Discussion

4.1. Annual cycles and temporal chlorophyll-a distribution

Our study illustrates the annual cycles of chlorophyll-a concentration in the Southern Ocean with an increase from October to December (or January), decreasing through March (Figures 6–8). Phytoplankton biomass responds positively to solar elevation, a critical limitation for phytoplankton growth (32). Moore found that seasonal chlorophyll-a concentration peaks in December can be mostly attributed to the seasonal solar radiation cycle (7). Increasing solar irradiance leads to a warming atmospheric temperature and results in severe sea ice melting. This provides more space and nutrients for phytoplankton growth. In addition, light can also contribute
significantly to Antarctic phytoplankton abundance and productivity (32). Melting sea ice generates fresh water for stratification, which plays an important role in facilitating phytoplankton accumulation and a stable living environment (33).

From November to January, increasing phytoplankton concentrations create bloom conditions. Large concentrations of biomass deplete the limited nutrients supplied by sea ice, especially iron (16). An increase in melting ice provides more nutrient supplements for phytoplankton growth, especially at higher latitudes (directly related by the flag rate in Figure 4). A reduction in sea ice coverage also contributes to phytoplankton growth and accumulation.

Though the sea ice coverage appears to be smallest in February (Figure 4), the peak in the annual value of chlorophyll-a concentration (Figures 3, 5, and 6) occurs in January. Sufficient ice-free areas in January guarantee adequate space for phytoplankton growth, so the seasonal declines in blooms that begin in February are likely due to the shortage of nutrients (16, 34), and the lack of optimal conditions such as vertical mixing induced by winds or decreased irradiance (35, 36). The acceleration of global warming has enhanced the melting of thin ice shelves in the Southern Ocean. This also enhances algal blooms (37).

4.2. Spatial anomaly and latitudinal chlorophyll-a distribution

There were significant inter-annual patterns in bloom activity with two months of high-chlorophyll-a concentration, and chlorophyll-a anomalies also emphasized the simultaneous positive and negative chlorophyll-a values located in the Ross and Amundsen Sea (Figures 5 and 8). The blooms in those productive regions are reported to be a mix of diatoms and *Phaeocystis Antarctica* (13, 38). Two dominant phytoplankton species cause algal blooms in various prime months (December or January) due to the availability of solar irradiance (39, 40) and nutrients (33). It has been found that *Phaeocystis antarctica* is well adapted to those large fluctuations of sea surface temperature, currents, and nutrient supply and has a major influence on phytoplankton productivity, and the spatial and temporal diversities of bloom events (39, 40). Latitudinal chlorophyll-a distribution is affected by sea ice coverage, for ice coverage occupies parts of the surface of the water, and restrains phytoplankton growth. More sea ice coverage and shorter ice-free periods in high latitudes are revealed in the seasonal curves shown in Figure 3(c). The slight curve shown in Figure 3(a) demonstrates that the lower latitudes have less seasonality in chlorophyll-a variation due to the decreased presence of sea ice. Decreased complexity in sea ice–phytoplankton interactions at lower latitudes (60°–65°S) illustrates the stability of the open ocean environment when compared to the highly dynamic, marginal sea ice zone.

There are great gaps in seasonal sea ice flag rates affecting MODIS flag data. The difference (gap between maximum and minimum values) is about 17% in >70°S, 10% in 65°–70°S, and 8% in 60°–65°S, respectively (Figure 4). This illustrates a positive relationship between sea ice nutrient supplement and the phytoplankton growth. Nonetheless, chlorophyll-a concentration peaks at 60°–65°S and >70°S occurring in January as opposed to February, while chlorophyll-a concentration values remain constant in January and February at 65°–70°S. Because more phytoplankton and more nutrient supplement in the latitudinal zone of >70°S occur in January, there is more nutrient demand in this region when compared to the 65°–70°S region. As a result, phytoplankton typically experiences nutrient shortages more quickly in February at high latitudes (>70°S).
4.3. Topographical influences on chlorophyll-a variation

Previous studies support a strong negative relationship between water depth and chlorophyll-a concentration distribution in the Southern Ocean (41). Our results also show that phytoplankton favors relatively shallow water (<500 m). As sea ice gradually melts, the melting processes mainly occur in shallow continental shelves characterized by thin ice sheets. The ocean area, with little ice coverage, can provide more space and light to supplement phytoplankton growth (9, 11). Flat offshore shelves stimulate the sea ice to rapidly melt, providing greater accumulation of organic matter and nutrients for chlorophyll-a bloom generation. In addition, a shallow mixing layer, due to fresh water from ice melt, serves as a stable environment, lessens nutrient deposition, and increases the supplements for phytoplankton growth. Intense phytoplankton blooms have been observed in offshore areas likely due to the elevated iron availability (42). However, not all phytoplankton blooms occur in areas along the shelf, which is due to the localized impact of wind-induced mixing.

A decrease in nutrient replenishment and light penetration due to the lack of sea ice melt reduces the likelihood of phytoplankton growth in deep-water regions (>2500 m) (14). Other factors influencing large-scale blooms in the deep ocean include current convergence zones, winds, and eddy-driven upwelling (35, 43). Therefore, deep-water regions have a lower probability of bloom occurrence when compared with shallower waters (Figure 9).

Two places in the deep ocean receive special notice because of their persistent low-chlorophyll-a concentrations even in December. Wind-driven upwelling occurs across 60°–65°S between 20° and 70°E and marks the location of the Antarctic Divergence. The mixing of the water column here disturbs the stable environment and can restrain phytoplankton growth (12, 41). Another low-chlorophyll-a concentration area is found in the 100°–130°E at similar latitudes and is characterized by high-speed winds and strong upwelling during the austral summer (41). Arrigo et al. (12) point out that in December, the regions of lower phytoplankton concentration are generally associated with abyssal waters north of the Antarctic Divergence. This can be attributed to a variety of factors including the deep mixing layer and iron limitation (43–45).

A large bloom is evident at 4000-m depth and is associated with the Pacific Antarctic and North Scotia Ridges (Figure 6(c)). The interaction between current fronts and large bathymetrical features, which can lead to upwelling and an increased flux of nutrients to surface waters (46), is the major reason for the presence of deep water blooms (9). The Pacific Antarctic Ridge is along the Weddell Gyre (22) and can cause a strong upwelling of nutrient-rich water (47). The North Scotia Ridge, near the coastal islands of Antarctic Peninsula, where divergence accelerates nutrient flux to surface waters (48–50) and the spring–autumn phenomenon of chlorophyll-a accumulation caused by a combination of ice retreat and divergence (51, 52), leads to high concentrations of chlorophyll in this area. Additionally, physical processes of vertical mixing can be attributed to meso-scale eddies, which can also result in the flux of nutrients to the surface (53).

4.4. Classification of MODIS chlorophyll-a zones in the Southern Ocean

Our results do not illustrate a clear negative relationship between water depth and chlorophyll-a concentration. However, chlorophyll-a blooms tend to occur in areas shallower than the 500-m isobaths (Figure 9), and areas with a low-gradient seafloor, especially in the Ross Sea (Figure 10). In addition, chlorophyll-a concentration increases with depth in <500-m isobath areas (Figure 7), indicating that the optimal conditions (stratification and nutrient supply) are present and promote algal growth. An appropriate water layer is important to provide a stable environment for phytoplankton growth. Water, which is too shallow, can encounter mixing from high winds while the interaction of decaying sea ice disturbs stratification, thus limiting the phytoplankton growth.

The value of chlorophyll-a concentration in the region of 500–2500-m water depth is higher than it is in deep water (>2500 m). This area (500–2500-m water depths) experiences significant sea ice melt and has long periods that are ice free (Figures 4 and 6). A Chlorophyll-a bloom probability at 10% (Figure 9) is mostly located along the 2500-m isobaths except for in a small part of the northeastern Weddell Sea. The bathymetric gradient line at 2500 m shows that water depth suddenly falls (red arrow in Figure 10) and that the seafloor environment changes significantly.

The deep water region (>2500 m) experiences little sea ice cover in lower latitude and chlorophyll-a concentration has little variation with no significant seasonal diversity during the year. However, interactions with large topographic features and currents can supply nutrients in deep ocean areas and supplement surface phytoplankton growth.

We classified the 0–500-m water depth region as enhanced bloom zone (EBZ), and 500–2500-m water depth region as a moderate bloom zone (MBZ). EBZ and MBZ, experience chlorophyll-a bloom probabilities of 30 and 10%, respectively, and share the similar hydrological features caused by ice dynamics. Significant seasonal ice retreat causes the EBZ to be more productive than the MBZ (54). The melting sea ice or floating glaciers precipitates a stratified layer that enhances phytoplankton growth (55).

The two subregions, EBZ, and MBZ, both have adequate nutrients in early spring, corresponding to high-chlorophyll-a concentrations and phytoplankton biomass.
peaks. As water depth decreases, the presence of more sea ice decay influenced by atmospheric temperature, results in the greater phytoplankton growth and higher chlorophyll-a concentration values. However, the depletion of nutrients, which occurs in the EBZ and MBZ during the summer along the ice edge, may limit phytoplankton growth (44). A lack of macronutrients can also hinder biomass production. Nitrate, phosphate, and silicate were observed to decrease in coastal waters and in the EBZ in late summer. The EBZ only has a short ice-free period owning strong seasonal variation when compared to an ice-free period of at least six months for in MBZ (56). Therefore, the MBZ begins to be productive in November, December, and January, while EBZ has its own phytoplankton boom in December and January.

5. Conclusions

This paper examined the temporal and spatial characteristics of a ten-year MODIS chlorophyll-a time series in the Southern Ocean. Chlorophyll-a concentration varies with latitude, a result of the symmetrical annual cycle of solar radiance and the distribution of melting sea ice. Water depth is another important factor for environmental conditions. We classified the two subregions, the <500 m as the EBZ and the area between 500–2500 m as MBZ. The EBZ has quite a high-chlorophyll-a bloom probability (>30%), and a relatively low-water depth gradient. Chlorophyll-a concentration increased with depth; this region is productive in December and January. In MBZ, the chlorophyll-a bloom probability is 10%, a longer ice-free period and experiences a phytoplankton bloom between November and January. A sudden change in depth along the 2500-m isobaths forms a highly visible depth gradient line around Antarctica continent. This abrupt change along with gigantic seafloor features (Antarctica Ridge, and the North Scotia Ridge) promotes upwelling that can nurture algal growth in deep water (>2500 m).

Since 2002, MODIS has been providing a synoptic view of chlorophyll-a distribution in the Southern Ocean. This research improves the accuracy of identifying chlorophyll-a distribution here and contributes to a better understanding of the spatial and temporal dynamics of phytoplankton.

Acknowledgments

We would like to thank the products from Making Earth Science Data Records for Use in Research Environments (MEaSUREs) initiative of NASA and data from the Palmer LTER data repository. We also would like to appreciate the hard work of the anonymous reviewers.

Notes on contributors

Chao Song is a PhD candidate in Wuhan University. His research focuses on the applications of remote sensing in the ecological environment.

Ling Ke is a lecturer of Wuchang Shouyi University, and a PhD candidate in Wuhan University. Her research interest includes remote sensing image classification and analysis.

References

(1) Wang, S.; Moore, J.K. Variability of Primary Production and Air-Sea CO2 Flux in the Southern Ocean. Global Biogeochem. Cycles. 2012, 26 (1), GB1008
(2) Constable, A.J.; Nicol, S.; Strutton, P.G. Southern Ocean Productivity in Relation to Spatial and Temporal Variation in the Physical Environment. J. Geophys. Res. 2003, 108 (C4), 8079.
(3) Park, J.; Oh, I.S.; Kim, H.C.; Yoo, S. Variability of Sea-WiFs Chlorophyll-a in the Southwest Atlantic Sector of the Southern Ocean: Strong Topographic Effects and Weak Seasonality. Deep Sea Res. Part I Oceanogr. Res. Papers. 2010, 57 (4), 604–620.
(4) Sarmiento, J.L.; Le Quere, C. Oceanic Carbon Dioxide Uptake in a Model of Century-scale Global Warming. Science. 1996, 274 (5291), 1346–1350.
(5) Caldeira, K.; Duffy, P.B. The Role of the Southern Ocean in Uptake and Storage of Anthropogenic Carbon Dioxide. Science. 2000, 287 (5453), 620–622.
(6) Sarmiento, J.L.; Hughes, T.M.; Stouffer, R.J.; Manabe, S. Simulated Response of the Ocean Carbon Cycle to Anthropogenic Climate Warming. Nature. 1998, 393 (6682), 245–249.
(7) Moore, J.K.; Abbott, M.R. Phytoplankton Chlorophyll Distributions and Primary Production in the Southern Ocean. J. Geophys. Res. 2000, 105 (C12), 28709–28722.
(8) Shen, L.; Xu, H.; Guo, X. Satellite Remote Sensing of Harmful Algal Blooms (HABs) and a Potential Synthesized Framework. Sensors. 2012, 12 (6), 7778–7803.
(9) Moore, J.K.; Abbott, M.R. Surface Chlorophyll Concentrations in Relation to the Antarctic Polar Front: Seasonal and Spatial Patterns from Satellite Observations. J. Mar. Syst. 2002, 37 (1-3), 69–86.
(10) Sokolov, S.; Rintoul, S.R. Multiple Jets of the Antarctic Circumpolar Current South of Australia. J. Phys. Oceanogr. 2007, 37 (5), 1394–1412.
(11) Meiners, K.M.; Vancoppenolle, M.; Thanassekos, S.; Dieckmann, G.S.; Thomas, D.N.; Tison, J.-L.; Arrigo, K.R.; Garrison, D.L.; McMinn, A.; Lannuze, D.; van der Merwe, P.; Swadling, K. M.; Smith, W.O. Jr.; Melnikov, I.; Raymond, B. Chlorophyll-a in Antarctic Sea Ice from Historical Ice Core Data. Geophys. Res. Lett. 2012, 39 (21), L21602.
(12) Arrigo, K.R.; Robinson, D.H.; Worthen, D.L.; Dunbar, R.B.; DiTullio, G.R.; VanWoert, M.; Lizotte, M.P. Phytoplankton Community Structure and the Drawdown of Nutrients and CO2 in the Southern Ocean. Science. 1999, 283 (5400), 365–367.
(13) Arrigo, K.R.; van Dijken, G.L. Phytoplankton Dynamics within 37 Antarctic Coastal Polynya Systems. J. Geophys. Res. 2003, 108 (C8), 3271.
(14) Arrigo, K.R.; van Dijken, G.L.; Bushinsky, S. Primary Production in the Southern Ocean, 1997–2006. J. Geophys. Res. Oceans. 2008, 113 (C8), C08004.
(15) Arrigo, K.R.; van Dijken, G.; Long, M. Coastal Southern Ocean: A Strong Anthropogenic CO2 Sink. Geophys. Res. Lett. 2008, 35 (21), L21602.
(16) Boyd, P.W.; Jickells, T.; Law, C.S.; Blain, S.; Boyle, E.A.; Buesseler, K.O.; Coale, K.H.; Cullen, J.J.; de Baar, H.J.W.; Follows, M.; Harvey, M.; Lancelot, C.; Levasseur, M.; Owens, N.P.J.; Pollard, R.; Rivkin, R.B.; Sarmiento, J.; Schoemann, V.; Smetacek, V.; Takeda, S.; Tsuda, A.; Turner, S.; Watson, A.J. Mesoscale Iron Enrichment
Experiments 1993–2005: Synthesis and Future Directions. Science. 2007, 315 (5812), 612–617.

(17) Sedwick, P.N.; DiTullio, G.R. Regulation of Algal Blooms in Antarctic Shelf Waters by the Release of Iron from Melting Sea Ice. Geophys. Res. Lett. 1997, 24 (20), 2515–2518.

(18) Lannuzel, D.; Schoemann, V.; de Jong, J.; Pasquer, B.; Van der Merwe, P.; Masson, F.; Tison, J.-L.; Bowie, A. Distribution of Dissolved Iron in Antarctic Sea Ice: Spatial, Seasonal, and Inter-annual Variability. J. Geophys. Res. Biogeosci. 2010, 115 (G3), G03022.

(19) Raiswell, R.; Benning, L.G.; Tranter, M.; Tulaczyk, S. Bioavailable Iron in the Southern Ocean: The Significance of the Iceberg Conveyor Belt. Geochim. Trans. 2008, 9 (1), 7.

(20) Raiswell, R. Iceberg-hosted Nanoparticulate Fe in the Southern Ocean: Mineralogy, Origin, Dissolution Kinetics and Source of Bioavailable Fe. Deep Sea Res. Part II Top. Stud. Oceanogr. 2011, 58 (11–12), 1364–1375.

(21) Raiswell, R.; Benning, R.; Hekx, C.R.; Vu, H.P.; Moore, W.S.; Dudgeon, R.; Smith, K.L. Jr. Input, Composition, and Potential Impact of Terrigenous Material from Free-drifting Icebergs in the Weddell Sea. Deep Sea Res. Part II Top. Stud. Oceanogr. 2011, 58 (11–12), 1376–1383.

(22) Klunder, M.B.; Laan, P.; Middag, R.; De Baar, H.J.W.; Twining, B.S.; Johnson, Z.I. Southern Ocean Iron Enrichment Experiment: Carbon Cycling in High-and Low-Si Waters. Science. 2004, 304 (5669), 408–414.

(23) DiTullio, G.R.; Grébmeier, J.M.; Arrigo, K.R.; Lizotte, M.P.; Robinson, D.H.; Leverentz, A.; Barry, J.P.; VanWoert, M.L.; Dunbar, R.B. Rapid and Early Export of Phaeocystis antarctica Blooms in the Ross Sea. Nature. 2000, 404 (6778), 595–598.

(24) Gerringa, L.J.; Alderkamp, A.C.; Laan, P.; Thuróczy, C.E.; De Baar, H.J.; Mills, M.M.; van Dijken, G.L.; van Haren, H.; Arrigo, K.R. Iron from Melting Glaciers Fuels the Phytoplankton Blooms in Amundsen Sea (Southern Ocean): Iron Biogeochemistry. Deep Sea Res. Part II Top. Stud. Oceanogr. 2012, 71–76, 16–31.

(25) Fragos, G.M.; Smith, W.O. Jr Influence of Hydrography on Phytoplankton Distribution in the Amundsen and Ross Seas, Antarctica. J. Mar. Syst. 2012, 89 (1), 19–29.

(26) Kropuenske, L.R.; Mills, M.M.; van Dijken, G.L.; Bailey, S.; Robinson, D.H.; Welschmeyer, N.A.; Arrigo, K.R. Pho physiology in Two Major Southern Ocean Phytoplankton Taxa: Photoprotection in Phaeocystis antarctica and Fragilariopsis cylindrus. Limnol. Oceanogr. 2009, 54 (4), 1176–1196.

(27) Mills, M.M.; Kropuenske, L.R.; van Dijken, G.L.; Alderkamp, A.C.; Berg, G.M.; Robinson, D.H.; Welschmeyer, N.A.; Arrigo, K.R. Photophysiology in Two Southern Ocean Phytoplankton Taxa: Photosynthesis of Phaeocystis antarctica (Prymnesiophyceae) and Fragilariopsis cylindrus (Bacillariophyceae) under Simulated in situ Mixed-layer Irradiance. J. Phycol. 2010, 46 (6), 1114–1127.

(28) Comiso, J.C.; McClain, C.R.; Sullivan, C.W.; Ryan, J.P.; Leonard, C.L. Coastal Zone Color Scanner Pigment Concentrations in the Southern Ocean and Relationships to Geophysical Surface Features. J. Geophys. Res. 1993, 98 (C2), 2419–2451.

(29) Sullivan, C.W.; Arrigo, K.R.; McClain, C.R.; Comiso, J.C.; Firestone, J. Distributions of Phytoplankton Blooms in the Southern Ocean. Science. 1993, 262 (5141), 1832–1837.

(30) Mitchell, B.G.; Brody, E.A.; Holm-Hansen, O.; McClain, C.; Bishop, J. Light Limitation of Phytoplankton Biomass and Macronutrient Utilization in the Southern Ocean. Limnol. Oceanogr. 1991, 36 (8), 1662–1677.

(31) Martin, J.H.; Gordon, R.M.; Fitzwater, S.E. Iron in Antarctic waters. Nature. 1990, 345 (6271), 156–158.

(32) Boyd, P.W.; Watson, A.J.; Law, C.S.; Abraham, E.R.; Trull, T.; Murdoch, R.; Bakker, D.C.E.; Bowie, A.R.; Buesseler, K.O.; Chang, H.; Charette, M.; Crook, P.; Downing, K.; Frew, R.; Gall, M.; Hadfield, M.; Hall, J.; Harvey, M.; Jameson, G.; Lacroche, J.; Liddicoat, M.; Ling, R.; Muldonado, M.T.; McKay, R.M.; Nodder, S;
Pickmere, S.; Pridmore, R.; Rintoul, S.; Safi, K.; Sutton, P.; Strzepek, R.; Tanneberger, K.; Turner, S.; Waite, A.; Zeldis, J. A Mesoscale Phytoplankton Bloom in the Polar Southern Ocean Stimulated by Iron Fertilization. *Nature*. **2000**, *407* (6805), 695–702.

(46) Sokolov, S.; Rintoul, S.R. On the Relationship between Fronts of the Antarctic Circumpolar Current and Surface Chlorophyll Concentrations in the Southern Ocean. *J. Geophys. Res. Oceans*. **2007**, *112* (C7), C07030.

(47) Hansen, J.; Sato, M.; Ruedy, R.; Lacis, A.; Oinas, V. Global Warming in the Twenty-first Century: An Alternative Scenario. *Proc. Nat. Acad. Sci.* **2000**, *97* (18), 9875–9880.

(48) Korb, R.E.; Whitehouse, M. Contrasting Primary Production Regimes around South Georgia, Southern Ocean: Large Blooms versus High Nutrient, Low Chlorophyll Waters. *Deep Sea Res. Part I Oceanogr. Res. Papers*. **2004**, *51* (5), 721–738.

(49) Daniault, N.; Menard, Y.; Gonella, J. Eddy Kinetic Energy Distribution in the Southern Ocean from Seasat Altimeter and FGGE Drifting Buoys. In *Large-scale Oceanographic Experiments and Satellites*; Gautier, C., Fieux, C.M., Eds.; Springer: Berlin Heidelberg, 1984; pp 41–56.

(50) Park, Y.H.; Gambéroni, L.; Charriaud, E. Frontal Structure and Transport of the Antarctic Circumpolar Current in the South Indian Ocean Sector, 40–80°E. *Mar. Chem.* **1991**, *35* (1–4), 45–62.

(51) Comiso, J.C.; Maynard, N.G.; Smith, W.O.; Sullivan, C.W. Satellite Ocean Color Studies of Antarctic Ice Edges in Summer and Autumn. *J. Geophys. Res.* **1990**, *95* (C6), 9481–9496.

(52) Jones, E.P.J.; Nelson, D.M.; Treguer, P. Chemical Oceanography. In *Polar Oceanography*; Smith, W.O. Jr., Ed.; Academic Press: New York, 1990; pp 407–476.

(53) Moore, J.K.; Abbott, M.R.; Richman, J.G.; Smith, W.O.; Cowles, T.J.; Coale, K.H.; Gardner, W.D.; Barber, R.T. SeaWiFS Satellite Ocean Color Data from the Southern Ocean. *Geophys. Res. Lett.* **1999**, *26* (10), 1465–1468.

(54) Tréguer, P.; Van Bennekom, A.J. The Annual Production of Biogenic Silica in the Antarctic Ocean. *Mar. Chem.* **1991**, *35* (1–4), 477–487.

(55) Allison, L.C.; Johnson, H.L.; Marshall, D.P.; Munday, D.R. Where Do Winds Drive the Antarctic Circumpolar Current? *Geophys. Res. Lett.* **2010**, *37* (12), L12605.

(56) Zwally, H.J.; Comiso, J.C.; Parkinson, C.L. Variability of Antarctic Sea Ice 1979–1998. *J. Geophys. Res.* **2002**, *107* (C5), 3041.