Remote Sensing Letters

Taylor & Francis
Taylor & Francis Group

ISSN: 2150-704X (Print) 2150-7058 (Online) Journal homepage: https://www.tandfonline.com/loi/trsl20

Atmospheric factors influencing biological productivity in the Antarctic polynyas, derived from satellite and reanalysis data

Jisoo Park, Edward K. Shin, Eunho Ko & Taewook Park

REMOTE SENSING LETTERS
2019, VOL. 10, NO. 11, 1113–1122
https://doi.org/10.1080/2150704X.2019.1650983

Atmospheric factors influencing biological productivity in the Antarctic polynyas, derived from satellite and reanalysis data

Jisoo Park[a,b], Edward K. Shin[a,c], Eunho Ko[a,b] and Taewook Park[a]

[a]Division of Polar Ocean Sciences, Korea Polar Research Institute, Incheon, South Korea; [b]University of Science and Technology, Daejeon, South Korea; [c]ESSEC Business School, Cergy, France

ABSTRACT

Antarctic coastal polynyas are the most productive area in the Southern Ocean, playing a significant role in a polar ecosystem. Understanding polynya properties is important because changes in polynya's environment can alter, or even disrupt, the polar food web. Nevertheless, there are still many unknown aspects of polynyas and its subsequent effects in the ecosystem. Based on satellite and atmospheric reanalysis data for 1998–2016, roles of atmospheric forcing on phytoplankton dynamics are examined. We find that chlorophyll-*a* (chl-*a*) has a noticeable year-to-year variability and its responses to atmospheric forcing differ regionally. That is, winds have a strong correlation with chl-*a* in the west Antarctic polynyas since strong winds tend to increase nutrient entrainment from subsurface water. A cloud cover is suggested to influence chl-*a* variability with a strong inverse correlation in the Weddell Sea and a moderate inverse correlation in the Amundsen Sea. We also find that chl-*a* decreases for 1998–2016 in the Amundsen Sea and Weddell Sea, which implies that a large amount of glacier meltwater is likely to decrease chl-*a* by enhancing oceanic stratification, whereas iron supply from recent higher ice melt would not directly affect such a long-term chl-*a* change.

ARTICLE HISTORY
Received 3 April 2019
Accepted 24 July 2019

1. Introduction

Polynyas, where its open water is surrounded by sea ice, are unique areas of a polar ecosystem and are crucial to enrich the Antarctic marine ecosystem. Even small environmental changes in polynyas can have a significant impact on various marine organisms (both in lower and upper trophic levels) that reside in this ecosystem. Antarctic coastal polynyas are the most productive region in the Southern Ocean (Arrigo and van Dijken 2003; Arrigo, van Dijken, and Strong 2015) and are important in global ocean circulation through dense water formation as well as global biogeochemical cycles and CO_2 uptake. Observational studies have shown that the Terra Nova Bay polynya plays a key role in the formation of salty shelf water in the Ross Sea (Rusciano et al. 2013) and in carbonate system properties from *in situ* and satellite data in the western Ross Sea (Rivaro et al. 2019). Therefore, it is imperative to know how the recent environmental changes can affect this ecosystem.

CONTACT Taewook Park twpark@kopri.re.kr Korea Polar Research Institute, Incheon, South Korea

West Antarctica has been profoundly affected by the global warming and has undergone rapid loss of ice shelves in recent years (Rignot et al. 2008, 2013; Paolo, Fricker, and Padman 2015). Glacier meltwater considerably affects oceanic stratification, thereby controlling nutrient entrainment from subsurface water or phytoplankton exposure to light. Moreover, meltwater affects facilitating of iron supply, which is one of the main limiting factors of phytoplankton growth in the Southern Ocean (Alderkamp et al. 2012; Gerringa et al. 2012) and in the Antarctic polynyas (Arrigo, van Dijken, and Strong 2015). The importance of iron supply for phytoplankton growth (de Baar et al. 1995, 2005; Boyd et al. 2007), as well as the relationship between ice melting and iron supply (McGillicuddy Jr. et al. 2015), has been argued. Under the assumption that the primary limiting factor of phytoplankton growth in the Antarctic coastal waters is Fe, we hypothesize that the West Antarctic biomass/productivity increases due to the iron supply that has been favoured by the recent increase in ice melting.

We defined Antarctic coastal polynyas using satellite-derived sea ice data and investigated the causes and the implications of the biomass/productivity change of phytoplankton in polynyas. Furthermore, we examined atmospheric forcing terms that influences chlorophyll-*a* (chl-*a)* concentrations.

2. Data and methods

2.1. Satellite and atmospheric reanalysis data

We retrieved daily sea ice concentration data from National Snow & Ice Data Center (Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data; http://nsidc.org), and daily chl-*a* concentration data from GlobColour (http://hermes.acri.fr). The spatial resolution of data was approximately 25 km per pixel for sea ice concentration data and 9 km per pixel for chl-*a* data. We used sea ice concentration and chl-*a* data spanned from 1 October 1997 to 30 April 2016. For atmospheric variables, monthly winds and total cloud coverage for 1997–2016 are extracted from European Centre for Medium-Range Weather Forecast (ECMWF) climatic reanalysis interim (ERA-Interim).

The winds and cloud cover influences oceanic state dynamically and thermodynamically, thereby potentially driving chl-*a* variability. Strong winds tend to deepen mixed layer depth through turbulent mixing, increasing phytoplankton growth by bringing nutrient-rich water to the surface (Abbott et al. 2000; Deppeler and Davidson 2017). Also, we evaluate the impact of cloud cover on phytoplankton booms since cloud cover is one of the factors that can influence light intensity.

In the Southern Ocean, satellite-derived estimates of chl-*a* is largely affected by cloud cover, low sun angles, and sea ice in the high latitudes. In particular, cloud contamination is a problematic issue to obtain reliable ocean colour data. Thus, monthly averaged chl-*a* estimates are also used to compare a relationship with cloud cover because this averaging scheme reduces the number of missing data points.

2.2. Polynya definition and chlorophyll-a phenology

Sea ice concentration was set at 15%, meaning that sea ice below 15% was classified as open water. Polynya area for each time frame was calculated by multiplying 625 km^2 (size of each pixel) by a number of open water pixels connected to the reference points within the polynya boundary. To first identify and determine commonly accepted polynya locations, we referred to previous research such as Arrigo and van Dijken (2003) that listed 37 polynyas and Li (2016) that contained 50 polynyas. After mapping daily and monthly sea ice concentration and extent maps, and their frequency of occurrence over the study duration, we inspected each polynya and ultimately narrowed down to 15 polynyas that are bigger than 10,000 km^2 in size and forms every season (Figure 1). Here, polynya #1 ~ #7 are classified as West Antarctic polynyas, whereas polynya #8 ~ #15 are classified as East Antarctic polynyas. Once daily polynya area for all polynyas from 1978 to 2016 has been calculated, we solved for 7-day running average to suppress short-term variability of less than 2 weeks. Using time-series data from these daily polynya areas, morphological variables (i.e., polynya maximum area, polynya opening days, polynya duration, etc.) were calculated for each polynya. To calculate bloom metrics, the 13-day running average has been applied to daily chl-*a* outputs to minimize short-term variability and remove missing data. Considering the distribution characteristics of chl-*a* in the ocean (Campbell 1995), the natural logarithm of chl-*a* was used for statistical analyses as following the method used by Thomalla et al. (2011).

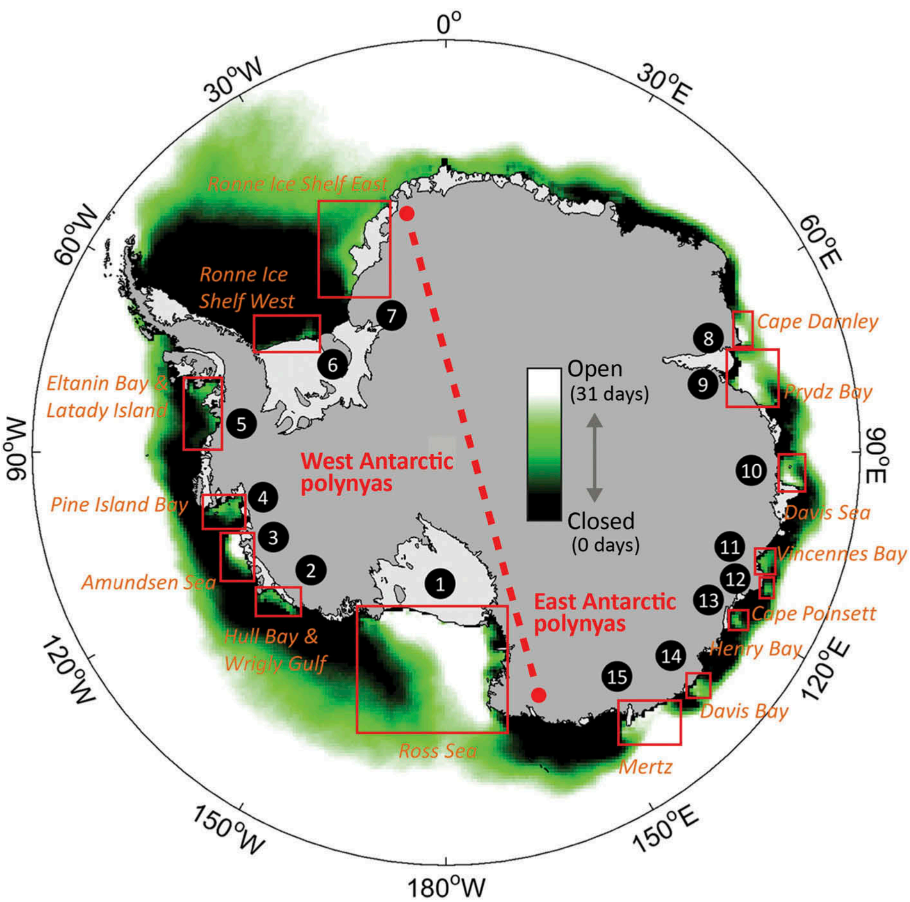

Figure 1. Fifteen distinct Antarctic coastal polynyas. Colour represents the number of open (<15% sea ice concentration) days in January 1978–2016.

3. Results and discussion

3.1. General features of 15 polynyas

The size of 15 representative Antarctic coastal polynyas varied greatly from one another, of which Ross Sea was the largest. As the sea ice melts in the austral summer, the polynya size generally reached its maximum in February. The average values during the study (1978–2016) ranged from 10,091 km^2 (Cape Poinsett Polynya) to 249,703 km^2 (Ross Sea Polynya), with a mean value was 54,027 km^2 (Figure 2a). The average duration of summer polynya formation was approximately four and a half months (137 days) and ranged from 104 to 156 days (Figure 2b). Meanwhile, phytoplankton bloom duration was quite different from one another, ranging from 37 to 83 days (with a mean of 64 days), indicating that biological features have considerable variability that does not depend on physical aspects (Figure 2c). Chl-*a* concentration per unit area at the peak of phytoplankton bloom was lowest in Davis Bay polynya (1.20 mg m^{-3}) and highest in Amundsen Sea polynya (5.88 mg m^{-3}) with an overall mean of 2.83 mg m^{-3} (Figure 2d). Distinct biological trends between the two sides of Antarctica, particularly the bloom duration and peak time chl-*a* concentrations, could result in non-trivial changes in their respective ecosystems.

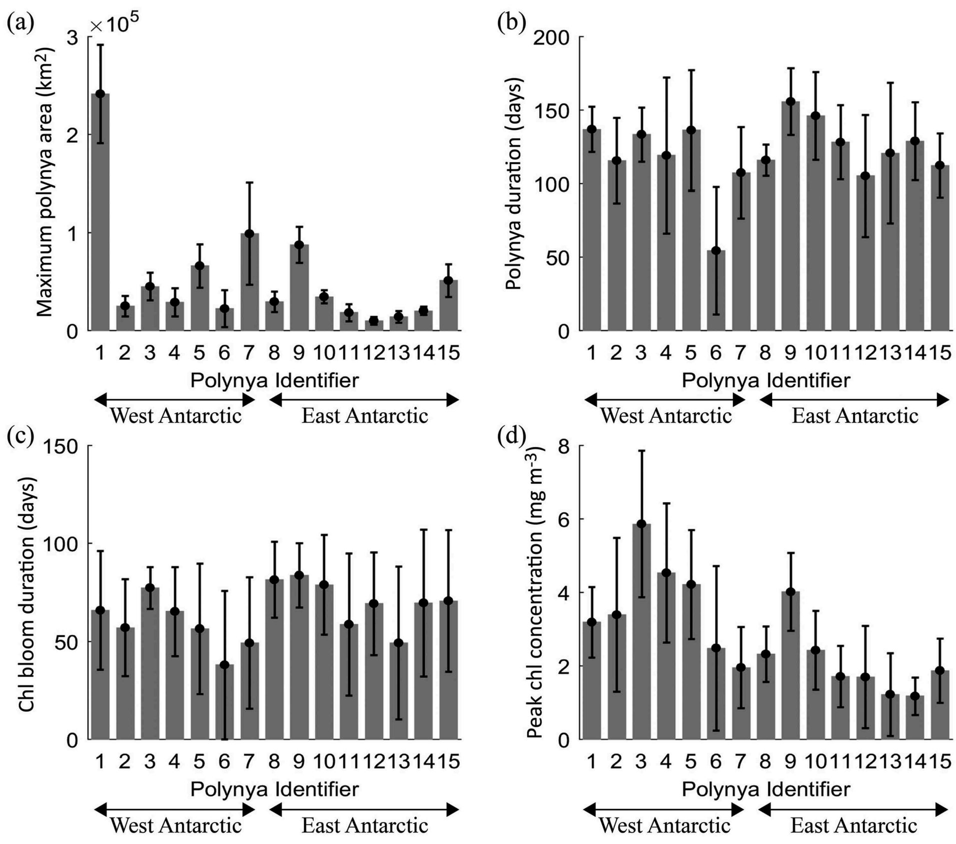

Figure 2. Mean characteristics in each 15 polynyas. Each error bar is constructed using one standard deviation from the mean. (a) Maximum polynya area (km^2), (b) polynya duration (days), (c) chlorophyll bloom duration (days), and (d) peak chl-*a* concentration (mg m^{-3}) at each polynya.

3.2. Relationships between chlorophyll-a and physical factors in coastal polynyas

The interannual variability of chl-*a* differs greatly from region to region, showing stronger variability in the west Antarctic marginal seas (Figure 3). We grouped polynyas into five areas: Ross Sea (polynya #1), Amundsen Sea (polynyas #2–4), Bellingshausen Sea (polynya #5), Weddell Sea (polynyas #6–7), and Eastern Antarctica (polynyas #8–15). We calculated Pearson's correlation coefficients (*r*) between chl-*a* and atmospheric forcing terms after extracting the long-term linear trend.

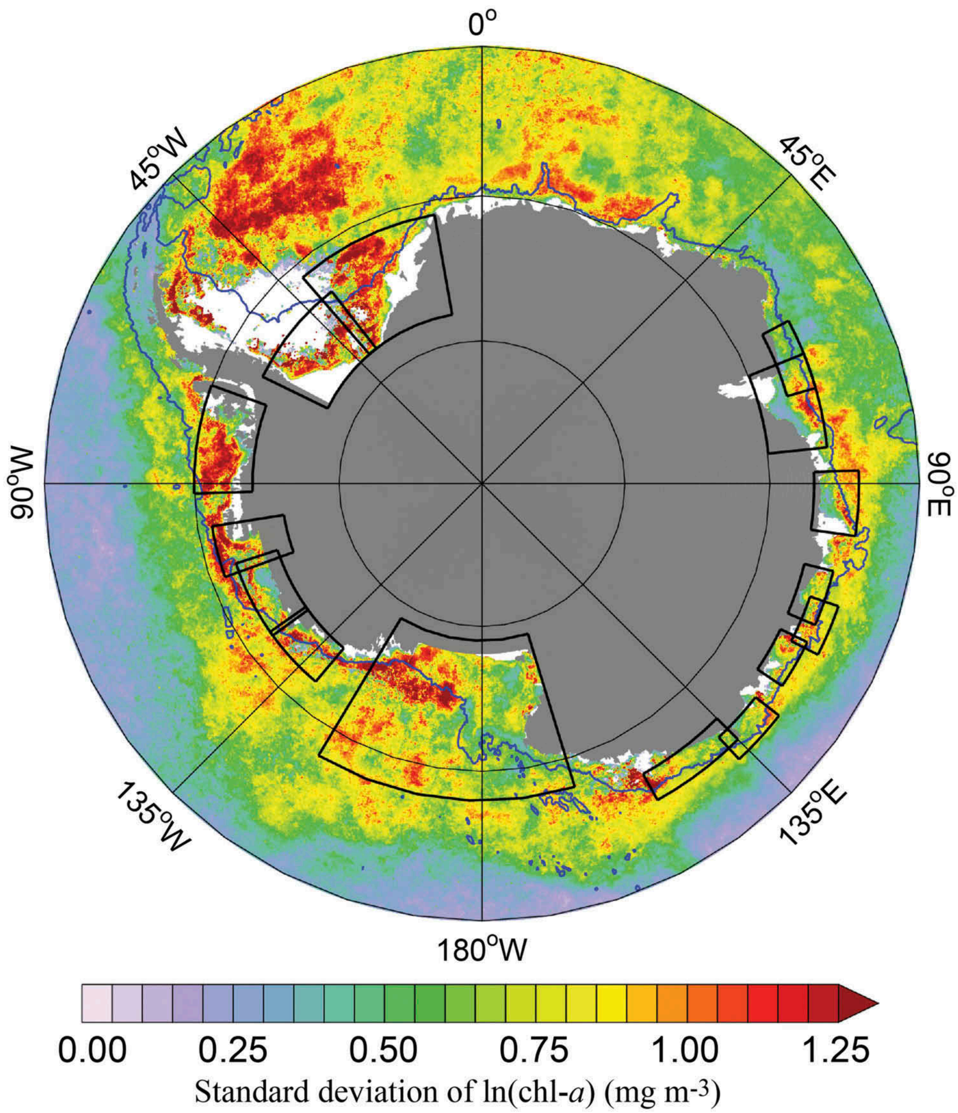

Figure 3. A map of standard deviations from 1 October 1997 to 30 April 2016 using the annual mean value from October to April of daily chl-*a* (mg m^{-3}) data in a log unit. A blue contour indicates the 2000-m isobath. Data are re-gridded onto 0.1°×0.1° grid.

The correlation coefficients between chl-*a* and cloud cover were negatively high in the Amundsen Sea (r = – 0.36, p-value < 0.15) and the Weddell Sea (r = – 0.50, p-value < 0.05) (left panel in Figure 4). In fact, light condition, along with iron, is a well-known parameter as a major limiting factor for phytoplankton growth in the Southern Ocean (Mitchell et al. 1991; Sunda and Huntsman 1997; Park et al. 2017). In a comparison with using monthly composite chl-*a* data as described in Section 2, there is strong relationship in the Amundsen (r = – 0.31, p < 0.20) and the Weddell Sea (r = – 0.46, p < 0.05) supporting our argument from the result of using daily chl-*a* data.

We also investigated roles of wind speeds (right panel in Figure 4). The chl-*a* and wind speed were tightly correlated in the west Antarctic polynyas, such as Ross Sea (r = 0.50, p-value < 0.05), Amundsen Sea (r = 0.36, p-value < 0.15), and Bellingshausen Sea (r = 0.40, p-value < 0.10). On the other hand, there is a weakly negative relationship in the east Antarctic polynyas where wind speed is stronger than 4 ms^{-1} (not shown). Such distinct responses to wind speed are consistent with a study of Fitch and Moore (2007) that shows largely suppressed blooms at high wind speeds stronger than 5 ms^{-1}.

The correlation analysis finds that wind speed is a dominant factor for chl-*a* variability in the west Antarctic polynyas (Ross Sea, Amundsen Sea, and Bellingshausen Sea). Cloud cover is suggested to be a parameter for chl-*a* variability in the Weddell Sea and the Amundsen Sea. By contrast, the relationship between chl-*a* and both cloud cover and winds in the East Antarctic polynyas are negligibly weak. Another factor not addressed in the study is upper ocean temperature and salinity structure that defines a mixed layer depth. Also, light intensity in the mixed layer depth would need to be assessed using observational data. Because of lack of long-term *in situ* observations in Antarctic marginal seas, we leave understanding oceanic mixed layer processes controlling chl-*a* for a future study.

3.3. Observed long-term trends (1998–2016) of chlorophyll-a concentration

A long-term trend of chl-*a* in polynyas has not been much documented. Schine, van Dijken, and Arrigo (2016) investigated chl-*a* trend in the Ross Sea for 1997–2013 and showed only several patches of the Ross Sea exhibited a significant decrease in peak chl-*a*, but did not focus on the trend in the polynya. We calculated Sens' slopes (S) and p-values for evaluating linear trends of West Antarctica (Ross, Amundsen, Bellingshausen, and Weddell Seas) and East Antarctica (Figure 5(b,d)). Statistically significant decreasing trends were found in the Amundsen Sea (S = – 0.1181 mg m^{-3} $year^{-1}$, p-value < 0.05) and Weddell Sea (S = – 0.0925 mg m^{-3} $year^{-1}$, p-value <0.1). On the other hand, a trend was not statistically significant in the Ross Sea, Bellingshausen Sea, and East Antarctica (Figure 5(a,c,e)). It is hard to demonstrate which forcing mainly causes such a long-term change because of the short period of available data. Other factors, such as cloud cover and winds do not have statistically significant trends during the same period (not shown). The chl-*a* decrease in the Amundsen Sea for nearly two decades implies that a recent large amount of meltwater (Mouginot, Rignot, and Scheuchl 2014) is likely to decrease chl-*a* by enhancing oceanic stratification, while iron supply from the higher ice melt rate could not be directly responsible for a long-term chl-*a* change.

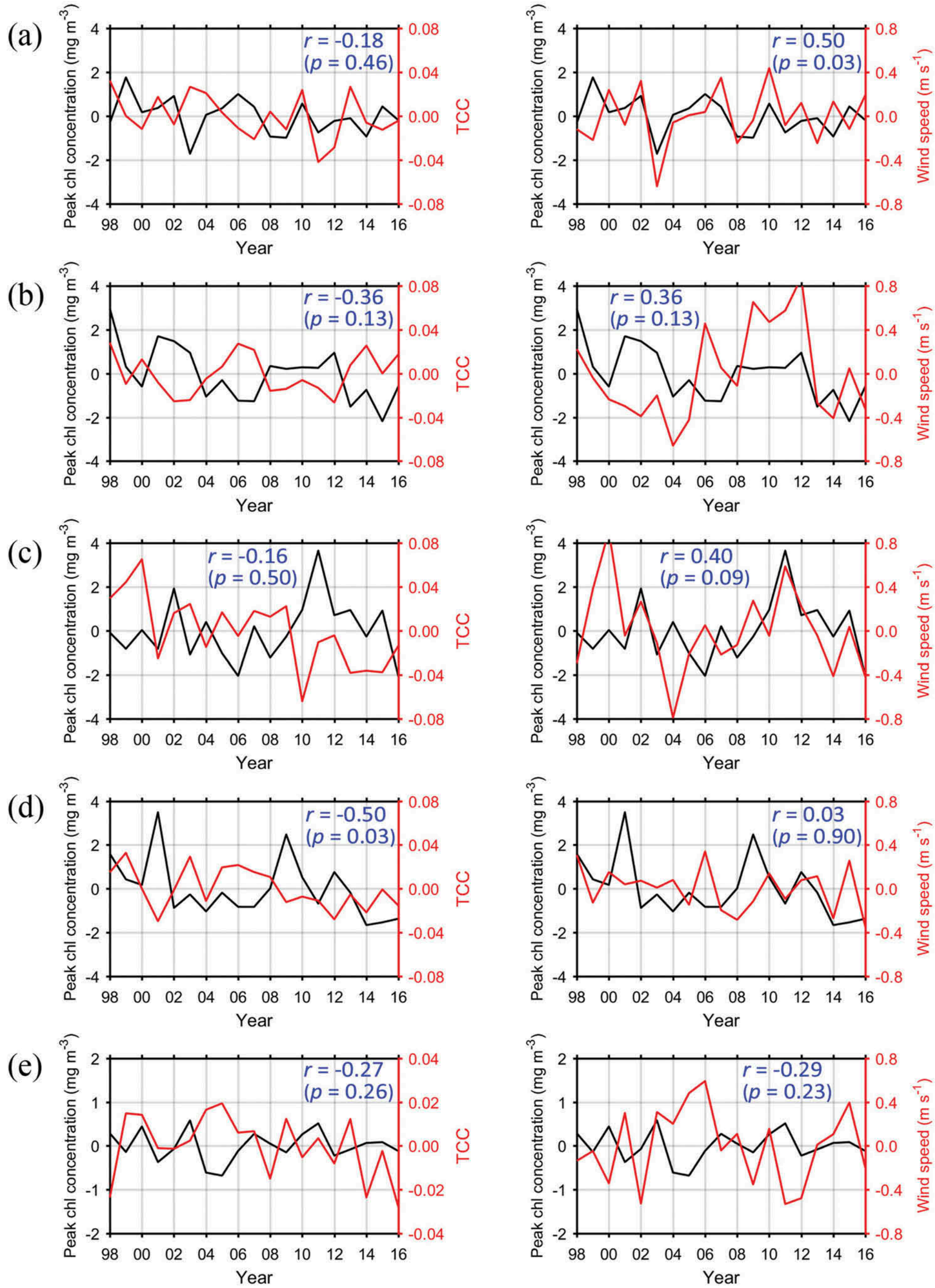

Figure 4. Comparisons of total cloud coverage (left panel, TCC; 0–1) and wind speed (right panel, m s^{-1}) against peak chl-*a* (mg m^{-3}), across five polynya groups for the years 1998–2016. The three variables are anomalies obtained by subtracting 1998–2016 long-term average from the original timeseries. (a) Ross Sea (no. 1), (b) Amundsen Sea (no. 2–4), (c) Bellingshausen Sea (no. 5), (d) Weddell Sea (no. 6–7), and (e) East Antarctica (no. 8–15). Panels (a)–(d) correspond to West Antarctica.

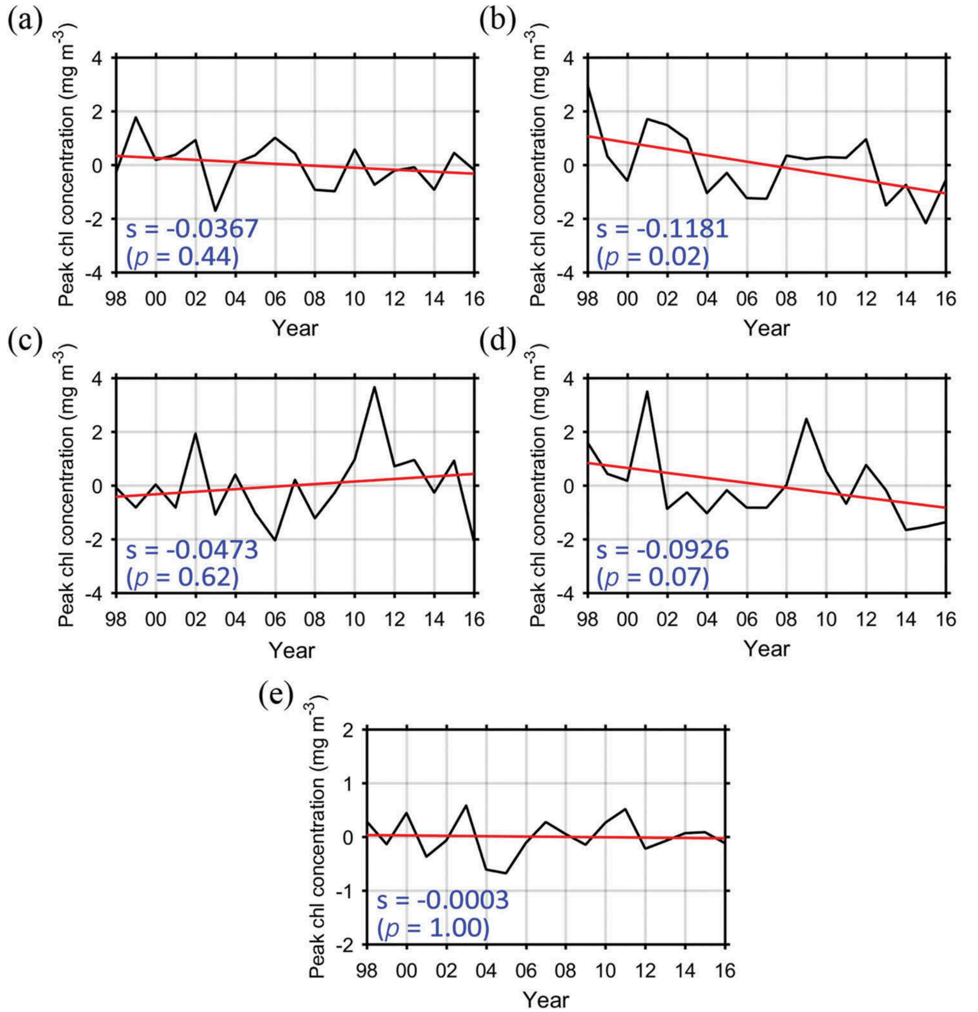

Figure 5. A time series of peak chl-*a* concentration (mg m^{-3}) (black line) and a linear trend (red line) averaged for the polynyas in (a) Ross Sea, (b) Amundsen Sea, (c) Bellingshausen Sea, (d) Weddell Sea, and (e) East Antarctica. Panels (a)–(d) correspond to West Antarctica.

4. Conclusions

We defined 15 polynyas in the Antarctic marginal seas using satellite-derived sea ice concentration data. Based on 1998–2016 chl-*a* concentration and atmospheric reanalysis, we examined contributions of atmospheric condition, such as cloud cover and winds, to the chl-*a* variability. This study finds that interannual variability of chl-*a* in the West Antarctica is tightly related with winds that induce entrainment of nutrient-rich subsurface water. In particular, cloud cover also plays a key factor in chl-*a* variability in the Amundsen Sea, implying a potential role of light condition on primary productivity. We argue that a recent long-term decrease of the chl-*a* in the Amundsen Sea for 1998–2016 is unlikely to attribute to direct iron supply, whereas enhanced oceanic stratification could be responsible for the recent chl-*a* decrease. Further explorations based on comprehensive *in situ* observations and climate modellings are necessary to identify the detailed physical processes associated with climate variability, such as Southern Annular Mode and El Niño–Southern Oscillation on the biological productivity in the Antarctic polynyas.

Funding

This work was supported by the Korea Polar Research Institute [PE19060].

ORCID

Taewook Park http://orcid.org/0000-0002-7787-0042

References

Abbott, M. R., J. G. Richman, R. M. Letelier, and J. S. Bartlett. 2000. "The Spring Bloom in the Antarctic Polar Frontal Zone as Observed from a Mesoscale Array of Bio-optical Sensors." *Deep Sea Research Part II: Topical Studies in Oceanography* 47 (15–16): 3285–3314. doi:10.1016/S0967-0645(00)00069-2.

Alderkamp, A.-C., M. M. Mills, G. L. van Dijken, P. Laan, C.-E. Thuróczy, L. J. A. Gerringa, H. J. W. de Baar, et al. 2012. "Iron from Melting Glaciers Fuels Phytoplankton Blooms in the Amundsen Sea (southern Ocean): Phytoplankton Characteristics and Productivity." *Deep Sea Research Part II: Topical Studies in Oceanography* 71–76: 32–48. doi:10.1016/j.dsr2.2012.03.005.

Arrigo, K. R., and G. L. van Dijken. 2003. "Phytoplankton Dynamics within 37 Antarctic Coastal Polynya Systems." *Journal of Geophysical Research* 108 (C8): 3271. doi:10.1029/2002jc001739.

Arrigo, K. R., G. L. van Dijken, and A. L. Strong. 2015. "Environmental Controls of Marine Productivity Hot Spots around Antarctica." *Journal of Geophysical Research: Oceans* 120 (8): 5545–5565. doi:10.1002/2015jc010888.

Boyd, P. W., T. Jickells, C. S. Law, S. Blain, E. A. Boyle, K. O. Buesseler, K. H. Coale, et al. 2007. "Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions." *Science* 315 (5812): 612–617. doi:10.1126/science.1131669.

Campbell, J. W. 1995. "The Lognormal Distribution as a Model for Bio-optical Variability in the Sea." *Journal of Geophysical Research* 100 (C7): 13237–13254. doi:10.1029/95jc00458.

de Baar, H. J. W., P. W. Boyd, K. H. Coale, M. R. Landry, A. Tsuda, P. Assmy, D. C. E. Bakker, et al. 2005. "Synthesis of Iron Fertilization Experiments: From the Iron Age in the Age of Enlightenment." *Journal of Geophysical Research* 110 (C9): C09S16. doi:10.1029/2004jc002601.

de Baar, H. J. W., J. T. M. de Jong, D. C. E. Bakker, B. M. Loscher, C. Veth, U. Bathmann, and V. Smetacek. 1995. "Importance of Iron for Plankton Blooms and Carbon Dioxide Drawdown in the Southern Ocean." *Nature* 373 (6513): 412–415. doi:10.1038/373412a0.

Deppeler, S. L., and A. T. Davidson. 2017. "Southern Ocean Phytoplankton in a Changing Climate." *Frontiers in Marine Science* 4. doi:10.3389/fmars.2017.00040.

Fitch, D. T., and J. Keith Moore. 2007. "Wind Speed Influence on Phytoplankton Bloom Dynamics in the Southern Ocean Marginal Ice Zone." *Journal of Geophysical Research: Oceans* 112 (C8). doi:10.1029/2006jc004061.

Gerringa, L. J. A., A.-C. Alderkamp, P. Laan, C.-E. Thuróczy, H. J. W. De Baar, M. M. Mills, G. L. van Dijken, H. van Haren, and K. R. Arrigo. 2012. "Iron from Melting Glaciers Fuels the Phytoplankton Blooms in Amundsen Sea (southern Ocean): Iron Biogeochemistry." *Deep Sea Research Part II: Topical Studies in Oceanography* 71–76: 16–31. doi:10.1016/j.dsr2.2012.03.007.

Li, Y., R. Ji, S. Jenouvrier, M. Jin, and J. Stroeve. 2016. "Synchronicity between Ice Retreat and Phytoplankton Bloom in circum-Antarctic Polynyas." *Geophysical Research Letters* 43 (5): 2086–2093. doi:10.1002/2016gl067937.

McGillicuddy, D. J., Jr., P. N. Sedwick, M. S. Dinniman, K. R. Arrigo, T. S. Bibby, B. J. W. Greenan, E. E. Hofmann, et al. 2015. "Iron Supply and Demand in an Antarctic Shelf Ecosystem." *Geophysical Research Letters* 42 (19): 8088–8097. doi:10.1002/2015GL065727.

Mitchell, B. G., E. A. Brody, O. Holm-Hansen, C. McClain, and J. Bishop. 1991. "Light Limitation of Phytoplankton Biomass and Macronutrient Utilization in the Southern Ocean." *Limnology and Oceanography* 36 (8): 1662–1677. doi:10.4319/lo.1991.36.8.1662.

Mouginot, J., E. Rignot, and B. Scheuchl. 2014. "Sustained Increase in Ice Discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013." *Geophysical Research Letters* 41 (5): 1576–1584. doi:10.1002/2013gl059069.

Paolo, F. S., H. A. Fricker, and L. Padman. 2015. "Volume Loss from Antarctic Ice Shelves Is Accelerating." *Science* 348: 327–331. doi:10.1126/science.aaa0940.

Park, J., F. I. Kuzminov, B. Bailleul, E. J. Yang, S. Lee, P. G. Falkowski, and M. Y. Gorbunov. 2017. "Light Availability Rather than Fe Controls the Magnitude of Massive Phytoplankton Bloom in the Amundsen Sea Polynyas, Antarctica." *Limnology and Oceanography* 62 (5): 2260–2276. doi:10.1002/lno.10565.

Rignot, E., S. Jacobs, J. Mouginot, and B. Scheuchl. 2013. "Ice-Shelf Melting Around Antarctica." *Science* 341 (6143): 266–270. doi:10.1126/science.1235798.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard. 2008. "Recent Antarctic Ice Mass Loss from Radar Interferometry and Regional Climate Modelling." *Nature Geoscience* 1 (2): 106–110. doi:10.1038/ngeo102.

Rivaro, P., C. Ianni, L. Raimondi, C. Manno, S. Sandrini, P. Castagno, Y. Cotroneo, and P. Falco. 2019. "Analysis of Physical and Biogeochemical Control Mechanisms on Summertime Surface Carbonate System Variability in the Western Ross Sea (antarctica) Using in Situ and Satellite Data." *Remote Sensing* 11: 238. doi:10.3390/rs11030238.

Rusciano, E., G. Budillon, G. Fusco, and G. Spezie. 2013. "Evidence of Atmosphere–Sea Ice–Ocean Coupling in the Terra Nova Bay Polynya (ross Sea-Antarctica)." *Continental Shelf Research* 61: 112–124. doi:10.1016/j.csr.2013.04.002.

Schine, C. M. S., G. van Dijken, and K. R. Arrigo. 2016. "Spatial Analysis of Trends in Primary Production and Relationship with Large-scale Climate Variability in the Ross Sea, Antarctica (1997–2013)." *Journal of Geophysical Research: Oceans* 121 (1): 368–386. doi:10.1002/2015jc011014.

Sunda, W. G., and S. A. Huntsman. 1997. "Interrelated Influence of Iron, Light and Cell Size on Marine Phytoplankton Growth." *Nature* 390 (6658): 389–392. doi:10.1038/37093.

Thomalla, S. J., N. Fauchereau, S. Swart, and P. M. S. Monteiro. 2011. "Regional Scale Characteristics of the Seasonal Cycle of Chlorophyll in the Southern Ocean." *Biogeosciences* 8 (10): 2849–2866. doi:10.5194/bg-8-2849-2011.