



RESEARCH LETTER

10.1002/2016GL067937

Key Points:

- Synchronicity between spring bloom and ice retreat shows west-east asymmetry in polynyas
- Synchronicity is inversely correlated to the sea ice production in circum-Antarctic polynyas
- Local physical processes greatly differ yet are important to polynya ecosystem dynamics

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

Correspondence to:

Y. Li,
yli@whoi.edu

Citation:

Li, Y., R. Ji, S. Jenouvrier, M. Jin, and J. Stroeve (2016), Synchronicity between ice retreat and phytoplankton bloom in circum-Antarctic polynyas, *Geophys. Res. Lett.*, 43, 2086–2093, doi:10.1002/2016GL067937.

Received 25 JAN 2016

Accepted 15 FEB 2016

Accepted article online 22 FEB 2016

Published online 5 MAR 2016

Synchronicity between ice retreat and phytoplankton bloom in circum-Antarctic polynyas

Yun Li^{1,2}, Rubao Ji², Stephanie Jenouvrier^{2,3}, Meibing Jin⁴, and Julienne Stroeve^{5,6}

¹University of South Florida, College of Marine Science, Saint Petersburg, Florida, USA, ²Biology Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA, ³Centre d'Etudes Biologiques de Chizé, UMR 7372 CNRS / Univ La Rochelle-79360 Villiers en Bois, France, ⁴International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA, ⁵National Snow and Ice Data Center, University of Colorado Boulder, Boulder, Colorado, USA, ⁶Centre for Polar Observation and Modelling, University College London, London, UK

Abstract Phytoplankton in Antarctic coastal polynyas has a temporally short yet spatially variant growth window constrained by ice cover and day length. Using 18-year satellite measurements (1997–2015) of sea ice and chlorophyll concentrations, we assessed the synchronicity between the spring phytoplankton bloom and light availability, taking into account the ice cover and the incident solar irradiance, for 50 circum-Antarctic coastal polynyas. The synchronicity was strong (i.e., earlier ice-adjusted light onset leads to earlier bloom and vice versa) in most of the western Antarctic polynyas but weak in a majority of the eastern Antarctic polynyas. The west-east asymmetry is related to sea ice production rate: the formation of many eastern Antarctic polynyas is associated with strong katabatic wind and high sea ice production rate, leading to stronger water column mixing that could damp phytoplankton blooms and weaken the synchronicity.

1. Introduction

The Antarctic Ocean has experienced significant interannual and spatial variability of sea ice coverage [Parkinson and Cavalieri, 2012] and ice retreat timing [Stammerjohn *et al.*, 2008, 2012], especially in dozens of circum-Antarctic coastal polynyas [Arrigo and van Dijken, 2003; Kern, 2009]. The Antarctic polynyas play a critical role in biogeochemical cycles [Smith and Barber, 2007] and primary production [Arrigo and van Dijken, 2003] that propagate up toward higher-trophic level marine predators [e.g., Ainley *et al.*, 2010]. Phytoplankton blooms associated with Antarctic polynyas develop in a narrow growth window which is strongly associated with the seasonality of sea ice cover and solar irradiance. For polar organisms that depend on the pulsed planktonic production at their specific life stage, phytoplankton phenology, such as bloom timing, is the key to recruitment success [e.g., Schmidt *et al.*, 2012; Ji *et al.*, 2013]. Small timing mismatches between biotic and abiotic conditions (e.g., phytoplankton bloom and sea ice retreat) can have disproportionately large effects on food web structure [e.g., Edwards and Richardson, 2004; Atkinson *et al.*, 2008; Forcada and Trathan, 2009; Montes-Hugo *et al.*, 2009]. A better understanding of phytoplankton phenology is therefore needed to untangle complex trophic interactions and ecosystem response to external disturbances such as climate variability.

Ice retreat and phytoplankton bloom initiation are closely related in many places [e.g., Montes-Hugo and Yuan, 2012; Ji *et al.*, 2013]. The timing of phytoplankton bloom initiation may be “synchronized” with the timing of ice retreat (here “synchronization” denotes for two successive events that are dynamically coupled and occur in close proximity, but not necessarily in a simultaneous manner). A previous study [Arrigo and van Dijken, 2003] suggested that phytoplankton blooms occurred soon after the end of the polar night as the sea ice melts in Antarctic coastal polynyas. However, there are few quantitative studies of bloom phenology in relation to the timing of sea ice retreat, especially in the Antarctic polynyas. A common explanation for the synchronization between ice retreat and bloom initiation is adopted from ice-edge bloom dynamics [Smith and Nelson, 1986] based on Sverdrup's hypothesis [Sverdrup, 1953], where ice melt/retreat increases light availability and water column stability, causing the shoaling of mixed layer above critical depth. However, recent studies in the temperate and subpolar oceans have found a number of other environmental factors that could affect bloom initiation, such as wind forcing [Chiswell, 2011], thermal convection [Ferrari *et al.*, 2015], and photoperiod [Mignot *et al.*, 2015]. All these factors can potentially play some roles in the Antarctic polynyas, leading to exceptions to the traditional theory of synchronization.

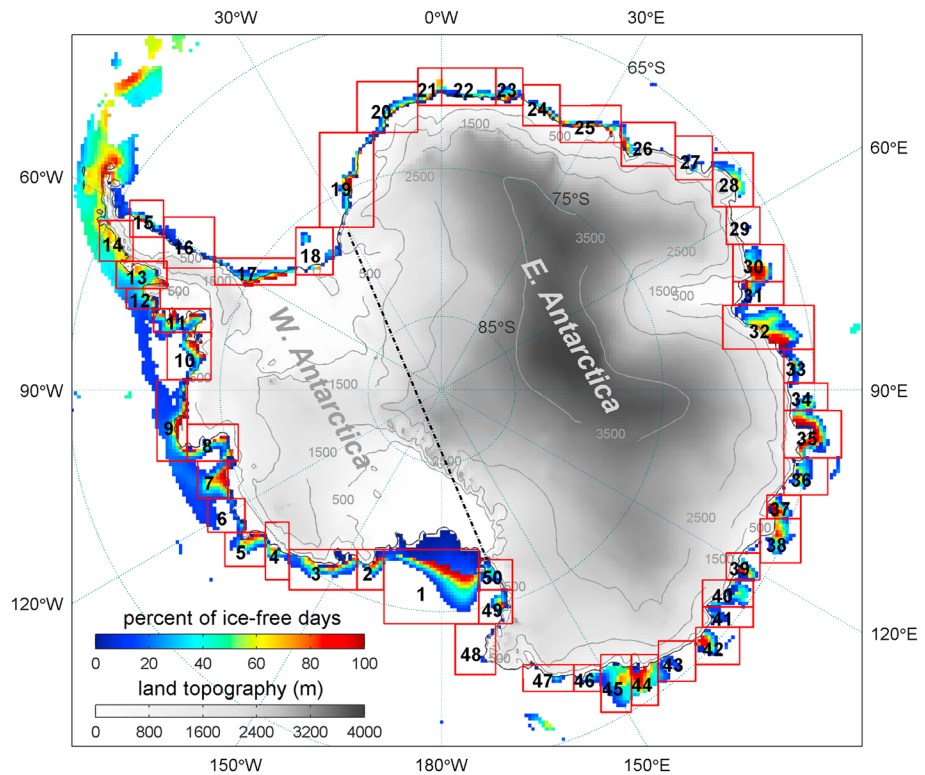


Figure 1. Spatial locations of 50 coastal polynyas around the Antarctic continental shelf. Sea ice concentration (SIC) is derived from the NASA Team algorithm (<http://nsidc.org/data/nsidc-0051> and <http://nsidc.org/data/nsidc-0081>). Jet colors represent the percentage of ice-free days (SIC < 75%) from June to October within the period of 6 September 1997 to 28 August 2015. Contours and gray color represent the land topography. The dashed line divides the western and eastern Antarctica based on the contrast in land topography. Numbered red boxes denote subregions used to estimate polynya area.

On the basis of a system-wide investigation of biological production [Arrigo and van Dijken, 2003], open water areal extent [Kern, 2009], and sea ice production [Nihashi and Ohshima, 2015] for the circum-Antarctic coastal polynyas, we examined phytoplankton phenology and its relation to ice retreat over a wide spectrum of polynyas. Here long-term satellite measurements were used to characterize the synchronicity between phytoplankton bloom and ice-modulated light availability, with the latter being predominantly modulated by ice retreat. Additionally, we explored the mechanisms linking the spatial variations of synchronicity and the heterogeneity of polynya physics.

2. Data and Methods

We conducted the analysis based on satellite data sets of sea ice and chlorophyll concentrations. Daily sea ice concentrations (SIC) derived from the NASA Team algorithm [Gloersen *et al.*, 1992; Cavalieri *et al.*, 1995] were obtained from the National Snow and Ice Data Center (<http://nsidc.org/data/nsidc-0051> and <http://nsidc.org/data/nsidc-0081>), with a spatial resolution of 25 km in the polar stereographic projection [Cavalieri *et al.*, 1996]. Ocean surface chlorophyll data were from the GlobColour Project (<http://www.globcolour.info/>), which merged data from three sensors (i.e., Sea-viewing Wide Field-of-view Sensor, Moderate Resolution Imaging Spectroradiometer, and Medium-Resolution Imaging Spectrometer), producing 8-day global ocean color maps (level 3) on a 4.63 km resolution Integerized Sinusoidal grid. The overlapped period between the two data sets spanned about 18 years from 6 September 1997 to 28 August 2015.

We used the number of ice-free days to determine the locations of Antarctic coastal polynyas, following Arrigo and van Dijken [2003]. Specifically, based on the NASA Team product, ice-free grids were defined as the SIC falling below 75% [e.g., Massom *et al.*, 1998], and the number of ice-free days was accumulated from June to October. The calculation yielded 50 polynyas along the Antarctic coast associated with different

subregions (Figure 1). The spatial distribution is in good agreement with those reported in previous studies [Massom *et al.*, 1998; Arrigo and van Dijken, 2003; Tamura *et al.*, 2008; Kern, 2009; Nihashi and Ohshima, 2015; Arrigo *et al.*, 2015], though the total count of polynyas could differ due to sea ice product resolution, time period of interest, or polynya criteria [e.g., Arrigo and van Dijken, 2003; Arrigo *et al.*, 2015]. In this study, we focused on the initial stage of polynya development (before adjacent polynyas coalesce into a larger one), and high spatial contrast of ice-free days in this specific period allows us to separate any nearby climatological open areas by an ice-covered region between them. The same polynya pattern also can be derived using the Bootstrap SIC product (<http://nsidc.org/data/nsidc-0079>) [Comiso, 2000] yet with a slightly higher SIC threshold of 85% (Figure S1 in the Supporting Information). The consistency between different SIC products allowed us to use the NASA Team SIC for further examination without causing a difference in conclusions. We defined a time-dependent polynya mask for each subregions indicated by the boxes in Figure 1. A parameter α was used at each time instant (daily for ice-adjusted light or 8 days for chlorophyll; see details in the following paragraph) to identify ice-free grids ($SIC < 75\%$) on the continental shelf (depth < 2000 m),

$$\alpha = \begin{cases} 1 & \text{if } \text{SIC} < 75\% \text{ and } h < 2000 \text{ m} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where the SIC SIC was estimated using daily NASA Team product and the bathymetry h was interpolated from ETOPO1 Global Relief (<http://www.ngdc.noaa.gov/mgg/global/global.html>).

In order to consider the effect of sea ice retreat on adjusting available light for phytoplankton in winter-spring time, we introduced the ice-adjusted day length (I_s) as an overall proxy for light availability at sea surface. Particularly, during winter-spring period, the solar irradiance increases as the sea ice cover decreases. Considering their joint effects on light availability, we estimated the incident light that reaches sea surface via ice-free area (equation (2)), assuming that light penetration through sea ice cover is of secondary importance.

$$I_s = I_0(1 - \text{SIC}) \quad (2)$$

where I_0 is the day length or photoperiod (hours) at a given time and latitude following the equation derived by Forsythe *et al.* [1995] (not shown but linearly related to satellite measurement of photosynthetically available radiation) and $(1 - \text{SIC})$ represents the fraction of ice-free area in each grid. I_s was further averaged within each polynya mask (equation (1)) to derive a polynya-wide mean I on daily basis

$$I = \frac{\sum(\alpha I_s)}{\sum \alpha} \quad (3)$$

A 15-day moving average filter was then applied to remove short-term fluctuations of I (Figure S2). Similarly, chlorophyll pixels ($\text{chl } a$) were averaged within the polynya water ($\alpha = 1$). However, if $\text{chl } a$ only covered less than 10% of the instant polynya area, it was considered missing and filled by values interpolated temporally between the previous and following time instants. The net phytoplankton growth rate was calculated as $r = \frac{d\ln(\text{chl } a)}{dt}$.

In order to detect the timing of phytoplankton bloom initiation and ice-adjusted light onset from year to year, an annual search window was selected to begin from the winter solstice at 21 June, and the time axis was defined starting from 1 January of the given year (e.g., annual search window from day -192 to 173). Within this window, the day of ice-adjusted light onset (D_I) was defined as the time when I first exceeds 8 h (Figure S3), and the day of bloom initiation ($D_{\text{chl } a}$) was taken as the first day when r is positive and increases from the previous day ($r > 0$ and $dr/dt > 0$) [e.g., Llort *et al.*, 2015]. In very few cases when r never exceeds the previous day value prior to the $\text{chl } a$ peak, we chose the second record available to be the start date.

Sea ice production in polynya can affect turbulent mixing and thus phytoplankton bloom. To understand its effects on the synchronicity, we retrieved climatological monthly integral of sea ice production (6.25 km resolution) from Nihashi and Ohshima [2015]. Spatial average was conducted for each polynya (Figure 1) during October, excluding pixels of weak ice production (< 0.1 cm) or out of continental shelf ($h > 2000$ m).

3. Results and Discussion

The timing of ice-adjusted light onset D_I displays considerable latitudinal variations, instead of a simple monotonic pattern that follows the increase of sunlight with latitude (Figure 2a). The geographic locations

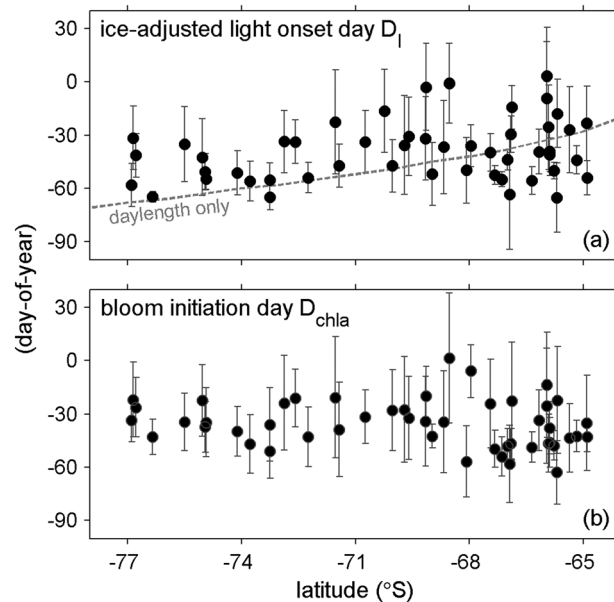


Figure 2. Changes of (a) ice-adjusted light onset day D_l and (b) bloom initiation day D_{chla} with latitude in circum-Antarctic polynyas. The black dots denote the mean, and the bars denote one standard deviation over the period of 1998–2015 for each polynya. In Figure 2a, the dashed line represents the time when the same day length l_0 is reached at different latitudes (for easy comparison within the range of D_l , l_0 is set as 20 h). The time based on l_0 alone does not include any effect of sea ice and is a monotonic function of latitude.

to a large degree (Figure 2b). Specifically, mean D_{chla} starts as early as late October yet can be postponed until late December in some polynyas, but 50% of the spatial variability of mean D_{chla} can be explained by mean D_l alone ($p < 0.001$), indicating that polynyas with earlier ice-adjusted light onset tend to develop earlier spring phytoplankton bloom. The results also suggest that ice retreat and solar irradiance were the dominant drivers among a variety of other environmental factors (e.g., wind stirring and deep convective mixing) to determine the spatial gradients of bloom timing in Antarctic polynyas.

Both D_l and D_{chla} display considerable interannual variations that are nonuniform across 50 coastal polynyas. Interannual variations of D_l (standard deviation bars on Figure 2a) range from 3 days in the Ross Sea polynya (Figure 1, subregion 37) to 32 days on the West Ice Shelf (Figure 1, subregion 33), suggesting strong spatial heterogeneity in the interannual variability of ice retreat timing for circum-Antarctic polynya systems. Our results support distinct regional patterns of ice retreat timing reported by *Stammerjohn et al.* [2012] in terms of the coastal shelf waters for different Antarctic sectors (e.g., the Antarctic Peninsula and Bellingshausen Sea versus the western Ross Sea). D_{chla} varies interannually over a range of 7 to 36 days (Figure 2b), with the largest variations mostly found in the East Antarctica.

Given the strong interannual variations, we statistically test whether the widely accepted synchronicity between bloom onset and sea ice retreat holds true in each polynya over the study period. Hypothetically, sea ice retreat can trigger ice-edge bloom by increasing light availability and water stability [*Smith and Nelson, 1986*] if no other factors (e.g., turbulent mixing or photoperiod) limit phytoplankton growth, and the synchronicity between ice retreat and bloom onset shall hold true. However, considering the narrow growth window of phytoplankton in the Antarctic polynyas, an early ice retreat in austral winter may expose phytoplankton to insufficient photoperiod or strong turbulent mixing, leading to an asynchrony between the bloom initiation and ice retreat timing. In some cases, even if sea ice retreat time is relatively unchanged, changes in the timing of adverse conditions (e.g., prolonged stormy season) are also likely to disrupt the synchronicity. By combining ice retreat and photoperiod as an overall measure of light availability, the effects of factors other than the ice-adjusted light can lead to two possibilities: First, D_{chla} follows D_l as long as D_l changes within a time window when other factors are favorable for phytoplankton growth. Second, if factors

of 50 polynyas span more than 10° in latitude. Particularly, a number of western Antarctic polynyas form to the south of 75°S , whereas most polynyas in the eastern Antarctic lie between 65°S and 70°S (Due to strong contrast in land topography, the eastern and western Antarctica are roughly divided by the Transantarctic Mountains [*Bindschadler, 2006*] instead of by the east and west hemispheres.) As a result of the wide latitudinal spread, the time scale for the sunlight progression from the northernmost polynyas in the Davis Sea and Shackleton Ice Shelf region (Figure 1, subregions 35–36) to the southernmost polynyas near the Sulzberger Bay (Figure 1, subregions 2–3) is about one month. However, the variability of mean D_l spans more than two months (late October to December), and the weak correlation ($R = 0.28$, $p = 0.05$) between the mean D_l and the latitudes suggests that it is the joint effect of local ice retreat and sunlight progression that determines the spatial pattern of D_l .

The latitudinal variation of bloom initiation time D_{chla} resembles that of mean D_l

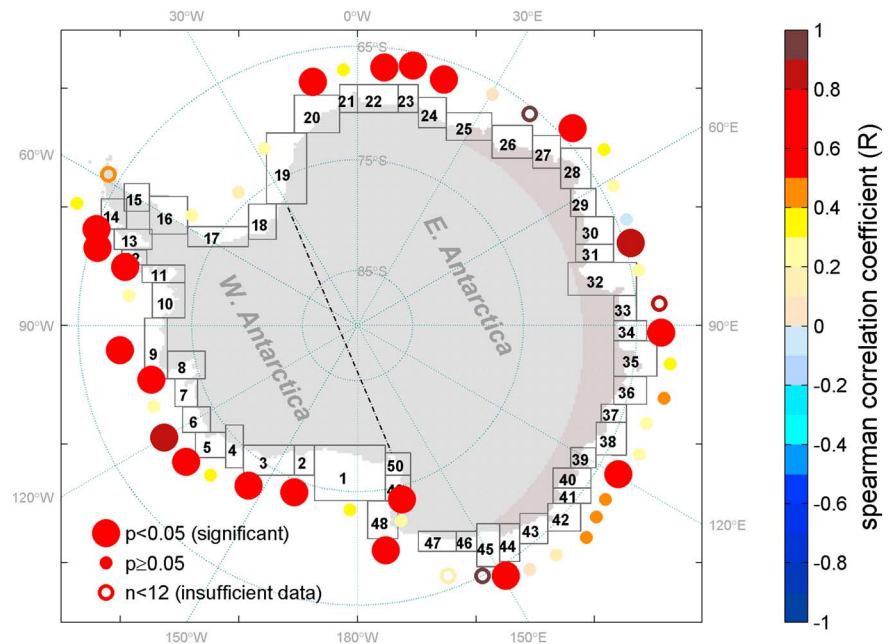


Figure 3. Spatial patterns of synchronicity between bloom initiation day (D_{chla}) and ice-adjusted light onset day (D_i). Synchronicity is calculated as Spearman's correlation over the period 1998–2015. Colors represent the correlation coefficients, with significant (insignificant) correlation in large (small) filled circles. Polynyas of less than 12 years data are marked in open circles. The dashed line divides the western and eastern Antarctica. The shaded coastal regions represent polynyas in the sector of 30°E–145°E.

other than the ice-adjusted light are limiting, D_{chla} may not respond to D_i in a timely manner. To discern those effects, a correlation analysis between D_{chla} and D_i over the 18-year period is useful to determine the synchronicity for each individual polynyas.

The synchronicity over the period of 1997–2015 is marked by a strong west-east asymmetry for polynyas across the coastal Antarctic, with weaker synchronicity in the eastern Antarctic polynyas (Figure 3). In the western Antarctic, over 56% (9 out of 16) of polynyas (polynyas with data less than 12 years are excluded) exhibit statistically significant and strong correlation ($R > 0.52$, $p < 0.05$) between D_i and D_{chla} , suggesting that in those polynyas, despite earlier or later D_i from year to year, the changes are likely within a time window that allows D_{chla} to respond in the same way. Conversely, in the eastern Antarctic, only a small percentage of polynyas (11 out of 28) at a glacier tongue or near fast ice massifs show synchronicity, while 61% (17 out of 28) of polynyas yield no significant correlation ($p \geq 0.05$) between D_i and D_{chla} . Especially in the sector between 30°E and 145°E where the slope of nearby land topography is steep (subregions 25–44, Figure 1), two timings are not significantly synchronized in 78% (14 out of total 18) of polynyas. Similar contrast is also true when using Bootstrap SIC for the analysis (Figure S4).

We argue that the west-east asymmetry of synchronicity is related to local forcings and processes, which are affected by the land topography of the Antarctica (Figure 1). In particular, the East Antarctica is marked by high-elevated mountains, sites known for strong downslope winds (i.e., katabatic winds), which are less pronounced on the West Antarctica [van Lipzig *et al.*, 2004]. The meteorological conditions then lead to quite different oceanic conditions, in which katabatic winds drive strong sea ice production [Tamura *et al.*, 2008; Nihashi and Ohshima, 2015] and brine water excretion [Maqueda *et al.*, 2004], leading to deep convection and deep mixed layer. These differences can then weaken the water column stability and damp phytoplankton bloom development in the eastern Antarctic.

To quantitatively test our hypothesis, the synchronicity is compared against the sea ice production within polynyas. Sea ice production is integrated in October prior to D_{chla} to represent the strength of deep convection in preconditioning the water column stability. The analyses reveal negative correlations between the synchronicity and the sea ice production (Figure 4, $R^2 = 0.22$, $p = 0.001$). As expected, strong synchronicity

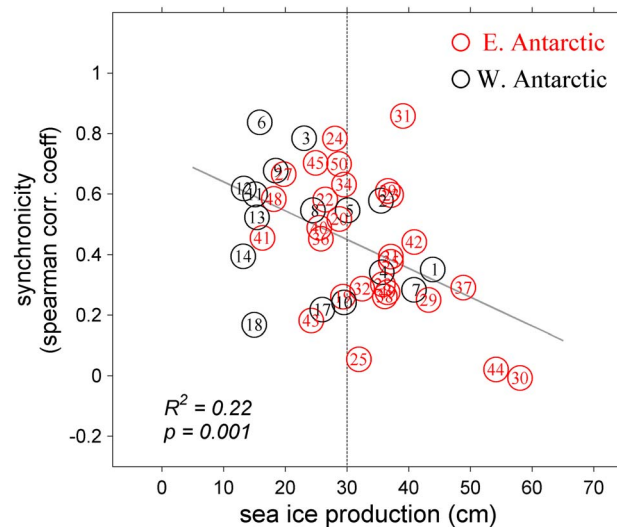


Figure 4. Relation between synchronicity and sea ice production (shown as October integral and indicative of convective mixing) in circum-Antarctica coastal polynyas. Black and red circles denote the western and eastern Antarctic polynyas, respectively. Only polynyas of more than 12 year data are plotted. Numbers correspond to the subregions in Figure 1. Synchronicity is measured by the Spearman correlation coefficient shown in Figure 3 and generally stronger in the western Antarctic.

emerges when monthly sea ice production is less than 30 cm. In contrast, the synchronicity is mostly disrupted under high sea ice production conditions. Between the two extremes are polynyas of moderate synchronicity at intermediate forcing conditions. The results are supportive of our hypothesis that in the eastern Antarctic polynyas, greater mixing prior to or during the ice retreat could weaken the meltwater-induced stratification and increase mixing layer depth, lowering the chance of phytoplankton bloom in a well-illuminated environment and thus disrupting the synchronicity. Besides, the suspended particulate matter brought by glacier meltwaters could also limit light availability for phytoplankton growth [Schloss *et al.*, 2014]. However, aside from a number of regional evidences around major islands or glaciers, turbidity data that allow for a pan-Antarctic comparison are absent [Gutt *et al.*, 2015], with their relative impacts on the synchronicity to be determined.

4. Summary and Implications

We quantitatively assessed the synchronicity between spring phytoplankton bloom and ice-adjusted light onset in 50 circum-Antarctic coastal polynyas during the period of 1997–2015. The results reveal considerable heterogeneity among Antarctic polynyas, with a general west-east asymmetry: most western (eastern) polynyas display strong (weak) synchronicity. The results suggest that due to large variations of local forcings, the synchronicity in polynyas may respond differently to the climate variability (e.g., Southern Annular Mode). Antarctic polynyas can play a disproportionately large role (relative to the total area they occupy) in global heat/salt fluxes and biogeochemical cycles [e.g., Arrigo and van Dijken, 2003; Tamura *et al.*, 2008]; however, due to the spatial dimension, they are generally underrepresented in large-scale climate models, limiting our capability of simulating and projecting polynya-related physical or biological changes under future climate scenarios. Systematic understanding of polynya dynamics is needed to improve our ability to comprehend and predict the climate impacts in the Antarctic.

Owing to the topographic settings of the Antarctica, wind stress and sea ice production during winter-spring transition time are the likely important drivers of the disruption of synchronicity. Despite a seemingly well-accepted synchronicity between phytoplankton bloom and ice retreat [e.g., Smith and Nelson, 1986; Vernet *et al.*, 2008; Taylor *et al.*, 2013], contrasting responses of phytoplankton bloom to ice retreat coexist in circum-Antarctic polynyas. For coastal polynyas with strong synchronicity, D_I provides a good proxy for bloom initiation. Since SIC records stretch much longer than the chlorophyll data, using it to infer the long-term bloom phenology provides valuable information for linking environmental forcing to primary production to higher-trophic level predators (e.g., seabirds, seals, and whales). For instance, the timing of phytoplankton bloom can affect the duration and peak of the productivity and thus the recruitment success of predators [Arrigo and van Dijken, 2003; Atkinson *et al.*, 2008; Montes-Hugo *et al.*, 2009]. A timing shift could potentially result in a phenological mismatch between successive trophic levels [Edwards and Richardson, 2004]. For the polynyas with low synchronicity, additional environmental factors besides SIC would need to be considered for better understanding of the local phytoplankton bloom dynamics. In fact, either strong sea ice production or strong wind stress could result in enhanced turbulent mixing in the upper water column to disrupt synchronicity. Future observational and numerical

investigations are warranted to address the complex interactions between physical settings and timing of phytoplankton bloom in the Antarctic polynyas.

Acknowledgments

The sea ice data derived from the NASA Team algorithm are available at <http://nsidc.org/data/nsidc-0051> and <http://nsidc.org/data/nsidc-0081>, and the sea ice data derived from the Bootstrap algorithm are available at <http://nsidc.org/data/nsidc-0079>. Ocean surface chlorophyll data were from the GlobColour Project (<http://www.glob-colour.info/>). Land topography and ocean bathymetry were interpolated from ETOPO1 Global Relief (<http://www.ngdc.noaa.gov/mgg/global/global.html>). Monthly climatology of sea ice production was published by Nihashi and Ohshima [2015]. This research was funded by NASA (grant NNX14AH74G) and U.S. National Science Foundation (grant PLR-1341558). The authors thank Nihashi and Ohshima for willing to share the sea ice production data. This work was motivated by a group discussion with all the coauthors, Marika Holland and Heather Lynch.

References

- Ainley, D., J. Russell, S. Jenouvrier, E. Woehler, P. O. B. Lyver, W. R. Fraser, and G. L. Kooyman (2010), Antarctic penguin response to habitat change as Earth's troposphere reaches 2°C above preindustrial levels, *Ecol. Monogr.*, *80*(1), 49–66, doi:10.1890/08-2289.1.
- Arrigo, K., G. L. van Dijken, and A. Strong (2015), Environmental controls of marine productivity hot spots around Antarctica, *J. Geophys. Res. Oceans*, *120*, 5545–5565, doi:10.1002/2015JC010888.
- Arrigo, K. R., and G. L. van Dijken (2003), Phytoplankton dynamics within 37 Antarctic coastal polynya systems, *J. Geophys. Res.*, *108*(C8), 3271, doi:10.1029/2002JC001739.
- Atkinson, A., et al. (2008), Oceanic circumpolar habitats of Antarctic krill, *Mar. Ecol. Prog. Ser.*, *362*, 1–23, doi:10.3354/meps07498.
- Bindschadler, R. (2006), The environment and evolution of the West Antarctic ice sheet: Setting the stage, *Philos. Trans. R. Soc. London A: Math. Phys. Eng. Sci.*, *364*(1844), 1583–1605, doi:10.1098/rsta.2006.1790.
- Cavalieri, D., C. Parkinson, P. Gloersen, and H. Zwally (1996), *Sea Ice Concentrations From Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Years 1990–2011*, NASA DAAC at the Natl. Snow and Ice Data Center, Boulder, Colo. [Updated yearly.]
- Cavalieri, D. J., K. S. Germain, and C. T. Swift (1995), Reduction of weather effects in the calculation of sea-ice concentration with the DMSP SSM/I, *J. Glaciol.*, *41*(139), 455–464.
- Chiswell, S. M. (2011), Annual cycles and spring blooms in phytoplankton: Don't abandon Sverdrup completely, *Mar. Ecol. Prog. Ser.*, *443*, 39–50, doi:10.3354/meps09453.
- Comiso, J. (2000), *Bootstrap Sea Ice Concentrations From Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 2*, NASA DAAC at the National Snow and Ice Data Center, Boulder, Colo., doi:10.5067/J6JQLS9EJ5HU.
- Edwards, M., and A. J. Richardson (2004), Impact of climate change on marine pelagic phenology and trophic mismatch, *Nature*, *430*(7002), 881–884, doi:10.1038/nature02808.
- Ferrari, R., S. T. Merrifield, and J. R. Taylor (2015), Shutdown of convection triggers increase of surface chlorophyll, *J. Mar. Syst.*, *147*, 116–122, doi:10.1016/j.jmarsys.2014.02.009.
- Forcada, J., and P. N. Trathan (2009), Penguin responses to climate change in the Southern Ocean, *Global Change Biol.*, *15*(7), 1618–1630, doi:10.1111/j.1365-2486.2009.01909.x.
- Forsythe, W. C., E. J. Rykiel, R. S. Stahl, H.-i. Wu, and R. M. Schoolfield (1995), A model comparison for daylength as a function of latitude and day of year, *Ecol. Modell.*, *80*(1), 87–95, doi:10.1016/0304-3800(94)00034-F.
- Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally (1992), *Arctic and Antarctic Sea Ice, 1978–1987: Satellite Passive-Microwave Observations and Analysis*, 290 pp., National Aeronautics and Space Administration, Washington, D. C.
- Gutt, J., N. Bertler, T. J. Bracegirdle, A. Buschmann, J. Comiso, G. Hosie, E. Isla, I. R. Schloss, C. R. Smith, and J. Tournadre (2015), The Southern Ocean ecosystem under multiple climate change stresses—An integrated circumpolar assessment, *Global Change Biol.*, *21*(4), 1434–1453, doi:10.1111/gcb.12794.
- Ji, R., M. Jin, and Ø. Varpe (2013), Sea ice phenology and timing of primary production pulses in the Arctic Ocean, *Global Change Biol.*, *19*(3), 734–741, doi:10.1111/gcb.12074.
- Kern, S. (2009), Wintertime Antarctic coastal polynya area: 1992–2008, *Geophys. Res. Lett.*, *36*, L14501, doi:10.1029/2009GL038062.
- Llort, J., M. Lévy, J.-B. Sallée, and A. Tagliabue (2015), Onset, intensification, and decline of phytoplankton blooms in the Southern Ocean, *ICES J. Mar. Sci.*, *72*(6), 1971–1984, doi:10.1093/icesjms/fsv053.
- Maqueda, M., A. Willmott, and N. Biggs (2004), Polynya dynamics: A review of observations and modeling, *Rev. Geophys.*, *42*, RG1004, doi:10.1029/2002RG000116.
- Massom, R., P. Harris, K. J. Michael, and M. Potter (1998), The distribution and formative processes of latent-heat polynyas in East Antarctica, *Ann. Glaciol.*, *27*, 420–426.
- Mignot, A., R. Ferrari, and K. Mork (2015), Spring bloom onset in the Nordic Seas, *Biogeosci. Discuss.*, *12*, 13,631–13,673, doi:10.5194/bgd-12-13631-2015.
- Montes-Hugo, M., S. C. Doney, H. W. Ducklow, W. Fraser, D. Martinson, S. E. Stammerjohn, and O. Schofield (2009), Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic Peninsula, *Science*, *323*(5920), 1470–1473, doi:10.1126/science.1164533.
- Montes-Hugo, M. A., and X. Yuan (2012), Climate patterns and phytoplankton dynamics in Antarctic latent heat polynyas, *J. Geophys. Res.*, *117*, C05031, doi:10.1029/2010JC006597.
- Nihashi, S., and K. I. Ohshima (2015), Circumpolar mapping of Antarctic coastal polynyas and landfast sea ice: Relationship and variability, *J. Clim.*, *28*(9), 3650–3670, doi:10.1175/JCLI-D-14-00369.1.
- Parkinson, C., and D. Cavalieri (2012), Antarctic sea ice variability and trends, 1979–2010, *Cryosphere*, *6*(4), 871–880, doi:10.5194/tc-6-871-2012.
- Schloss, I., A. Wasilowska, D. Dumont, G. Almandoz, M. Hernando, C.-A. Michaud-Tremblay, L. Saravia, M. Rzepecki, P. Monien, and D. Monien (2014), On the phytoplankton bloom in coastal waters of southern King George Island (Antarctica) in January 2010: An exceptional feature?, *Limnol. Oceanogr.*, *59*(1), 195–210, doi:10.4319/lo.2014.59.1.0195.
- Schmidt, K., A. Atkinson, H. J. Venables, and D. W. Pond (2012), Early spawning of Antarctic krill in the Scotia Sea is fuelled by "superfluous" feeding on non-ice associated phytoplankton blooms, *Deep Sea Res. Part II: Topical Stud. Oceanogr.*, *59*, 159–172, doi:10.1016/j.dsr2.2011.05.002.
- Smith, W. O., Jr., and D. Barber (2007), *Polynyas—Windows to the World: Windows to the World*, Elsevier Oceanogr. Ser., vol. 74, Elsevier, Amsterdam.
- Smith, W. O., and D. M. Nelson (1986), Importance of ice edge phytoplankton production in the Southern Ocean, *BioScience*, *36*, 251–257, doi:10.2307/1310215.
- Stammerjohn, S., D. Martinson, R. Smith, X. Yuan, and D. Rind (2008), Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability, *J. Geophys. Res.*, *113*, C03S90, doi:10.1029/2007JC004269.
- Stammerjohn, S., R. Massom, D. Rind, and D. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, *Geophys. Res. Lett.*, *39*, L06501, doi:10.1029/2012GL050874.
- Sverdrup, H. (1953), On conditions for the vernal blooming of phytoplankton, *J. Cons.*, *18*(3), 287–295, doi:10.1093/icesjms/18.3.287.
- Tamura, T., K. I. Ohshima, and S. Nihashi (2008), Mapping of sea ice production for Antarctic coastal polynyas, *Geophys. Res. Lett.*, *35*, L07606, doi:10.1029/2007GL032903.

- Taylor, M. H., M. Losch, and A. Bracher (2013), On the drivers of phytoplankton blooms in the Antarctic marginal ice zone: A modeling approach, *J. Geophys. Res. Oceans*, *118*, 63–75, doi:10.1029/2012JC008418.
- van Lipzig, N., J. Turner, S. Colwell, and M. van Den Broeke (2004), The near-surface wind field over the Antarctic continent, *Int. J. Climatol.*, *24*(15), 1973–1982, doi:10.1002/joc.1090.
- Vernet, M., D. Martinson, R. Iannuzzi, S. Stammerjohn, W. Kozlowski, K. Sines, R. Smith, and I. Garibotti (2008), Primary production within the sea-ice zone west of the Antarctic Peninsula: I—Sea ice, summer mixed layer, and irradiance, *Deep Sea Res. Part II: Topical Stud. Oceanogr.*, *55*(18), 2068–2085, doi:10.1016/j.dsr2.2008.05.021.