# DETERMINING SEASONALITY OF OPEN OCEAN PHYTOPLANKTON BLOOMS IN THE SOUTHERN OCEAN USING BIOGEOCHEMICAL ARGO DATA

By


**Christina Malyshko**

*Class of 2022*


A thesis submitted to the

School of Environmental and Biological Sciences

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements of

The George H. Cook Scholars Program

Written under the direction of

Oscar Schofield

And approved by

Oscar Schofield, Project Advisor
Department of Marine and Coastal Sciences,

Joshua Kohut, Reader
Department of Marine and Coastal Sciences

New Brunswick, New Jersey

May 2022

# DETERMINING SEASONALITY OF OPEN OCEAN PHYTOPLANKTON BLOOMS IN THE SOUTHERN OCEAN USING BIOGEOCHEMICAL ARGO DATA

Christina Malyshko


## Abstract

With the rising concern of the multitude of effects that humans have created on the environment, it has become of the utmost important to truly understand key planetary processes. One of the most understudied locations on our planet is the Southern Ocean surrounding Antarctica, due to its rough seas and remote locations. Of the many unknowns is the mechanisms behind the seasonal patterns of phytoplankton blooms dynamics. These blooms provide the world's oceans with most of its food and helps to absorb excess $CO_2$ from the atmosphere, so knowing their mechanics is extremely important. Through analysis of data provided from autonomous BioGeoChemical ARGO floats in the Bellingshausen Sea, it was found that chlorophyll a concentration and backscatter measurements were correlated. Seasonal blooms export carbon to the deep sea as these blooms decompose. These blooms are occurring before the peak warm periods of the summer months and can be greatly impacted by El Niño cycles and sea ice concentration. However, as climate change continues to grow, these impacts may worsen as well.

## Introduction

The Southern Ocean is classified as the ocean region located between 35-60ºS surrounding Antarctica, uninterrupted by continental landmasses (Gruber et al, 2019). Making up only 9.6% of the world's ocean, it is home to a vast diversity of animals ranging from the Gentoo Penguins to Ice Fish to Antarctic Krill (Xavier et al, 2016). However, little is known about these animals along with the biology of the continent due to the extremely rough water surrounding the continent created by the convergence of the Atlantic, Pacific, and Indian Oceans into it as well as the remote location of the continent makes it to be very difficult to access (Arrigo et al, 1998). In hindsight, with the use of more modern technology, it has become evident that the Southern Ocean is a crucial asset and main driver for the global biological carbon pump in which it is responsible for capturing about 40% of the world's anthropogenic carbon and about 75% of the excess heat created on the Earth's surface (Gruber et al, 2019).

The Biological Carbon Pump is a combination of biological, physical, and chemical process that transfer the large amount of organic carbon that is produced near the surface by phytoplankton to depth (Buesseler et al, 2020). Phytoplankton are small photosynthetic organisms that use solar radiation to fix dissolved atmospheric carbon dioxide into dissolved oxygen in the upper 200 meters of the water column. Making up less than 1% of the Earth's plant biomass, phytoplankton are responsible for about 50% of the world's oxygen productivity and are the main energy source for the marine food web (Winder and Sommer, 2012). Phytoplankton have very short lifespans lasting about one to two weeks and once they have run their course, they will travel out of the upper layer of the water column, i.e., export flux. This export process is accomplished by the aggregation of dead phytoplankton matter, decaying organisms, and other marine debris in this area, i.e., marine snow. This marine snow sinks to the deep sea (Bishop, 2009) where it can be recirculated to the surface through upwelling or used to distribute carbon, i.e., food, throughout the water column (Taucher, 2018). The other sector of the BCP is considered the “alkalinity pump” which is the chemical process of turning the atmospheric carbon dioxide into bicarbonate ions to increase the ocean pH back to a neutral level as dissolved carbon dioxide decreases pH making the ocean more acidic (Nozaki and Yamamoto, 2001).

As has become evident by many studies in both the Antarctic and Arctic, the processes behind the BCP system in open ocean regions, like the Southern Ocean, are not well understood and much more research needs to be done to both understand the mechanisms behind them as well as how they are being altered with a changing climate (Bol, 2018 and St Laurent, 2019). An overall understanding of export flux created during phytoplankton blooms in coastal ocean regions is standard in the scientific community due to the ease of access of these locations. In the past, it was made evident that many regions display seasonal cycles of phytoplankton blooms from observations made by international satellite data, but satellite data does not provide much about the dynamics of the blooms, only that they are happening (Uchida, 2019). This data disparity has led many to turn to remote and autonomous systems, e.g., satellites, gliders, and ARGO floats, to attain the missing data and paint a picture of the ocean conditions during these events. Using remote sensing, evidence was found to support that phytoplankton blooms occur seasonally typically in the spring when the water becomes increasingly warmer post-winter (Huppert et al, 2005). It was known that these blooms helped to transfer carbon throughout the marine food chain, but how it was done was still a mystery (Taucher, 2018). Technology has continued to evolve and with new advanced remote sensing equipment, it has become recently apparent that the use of backscatter is a very important parameter to consider when determining the cycles of these blooms and has allowed for a more accurate portrayal of them. Previously, backscatter measurements, i.e., the reflection of light off particulate matter in the water column, were considered junk data and not important when analyzing biogeochemical processes, but in more recent studies, it has become clear that this backscatter can be correlated to the carbon export out of the system as a bloom is coming down from its peak (Uchida, 2019). In other words, the backscatter can be used to represent the ending of the seasonal phytoplankton blooms and the particulate matter that sinks as dead organic matter, as is seen in the Biological Carbon Pump.

Due to the immense success seen with autonomous technology in the past, ARGO floats were selected for this study. ARGO is an is an international program in partnership with 30 countries that uses a fleet of autonomous robotic floats that take vertical profiles in the water column and collect data about various oceanographic properties. The program has about 4,000 floats currently deployed worldwide. The program is broken up into a variety of subsectors that complete a myriad of missions globally. This project in particular focuses on the BioGeoChemical ARGO program that employs missions focusing on direct observations of seasonal and decadal productivity cycles, nutrient cycling, ocean acidification, hypoxia, and ocean uptake of $CO_2$. The BGC ARGO program's mission to understand the impacts of climate change and carbon uptake in the ocean, as well as the use of marine resources to learn more about the ocean to develop new strategies to combat climate change (ARGO, 1999). This subsector is again broken up into smaller ocean specific projects, the main group focused on here is the SOCCOM project. SOCCOM, Southern Ocean Carbon and Climate Observations and Modeling, is a multi-institutional BGC mission striving to unlock the mysteries of the Southern

Ocean with about 200 floats in total, currently deployed and retired. The float itself is completely self-operational on which it is employed with a variety of sensors used to measure properties like temperature, salinity, pH, dissolved oxygen, nutrient concentration, chlorophyll a concentration, suspended particle concentration, and irradiance (SOCCOM, 2020). Each float is deployed from a research vessel from which it will complete a series of 10-day data collection cycles for the entirety of its mission. The float will initially sink to its cruising depth of 1000 meters where it will reside for about 9 days. It will then rapidly sink to 2000 meters and slowly rise back up to the surface where it remains for 15 minutes to an hour communicating to a satellite via GPS sending its data back to land. Once collected, the data is available to access within 24 hours on multiple online databases (Claustre, Johnson, Takeshita, 2020). After the data transfer, it will sink back to 1000 meters and complete the same 10-day cycle for the next 4 to 5 years or until its battery dies. Over the entire 10-day cycle, the float is consistently collecting data to record any rapid changes or slight nuances that may occur over the mission (ARGO, 1999).

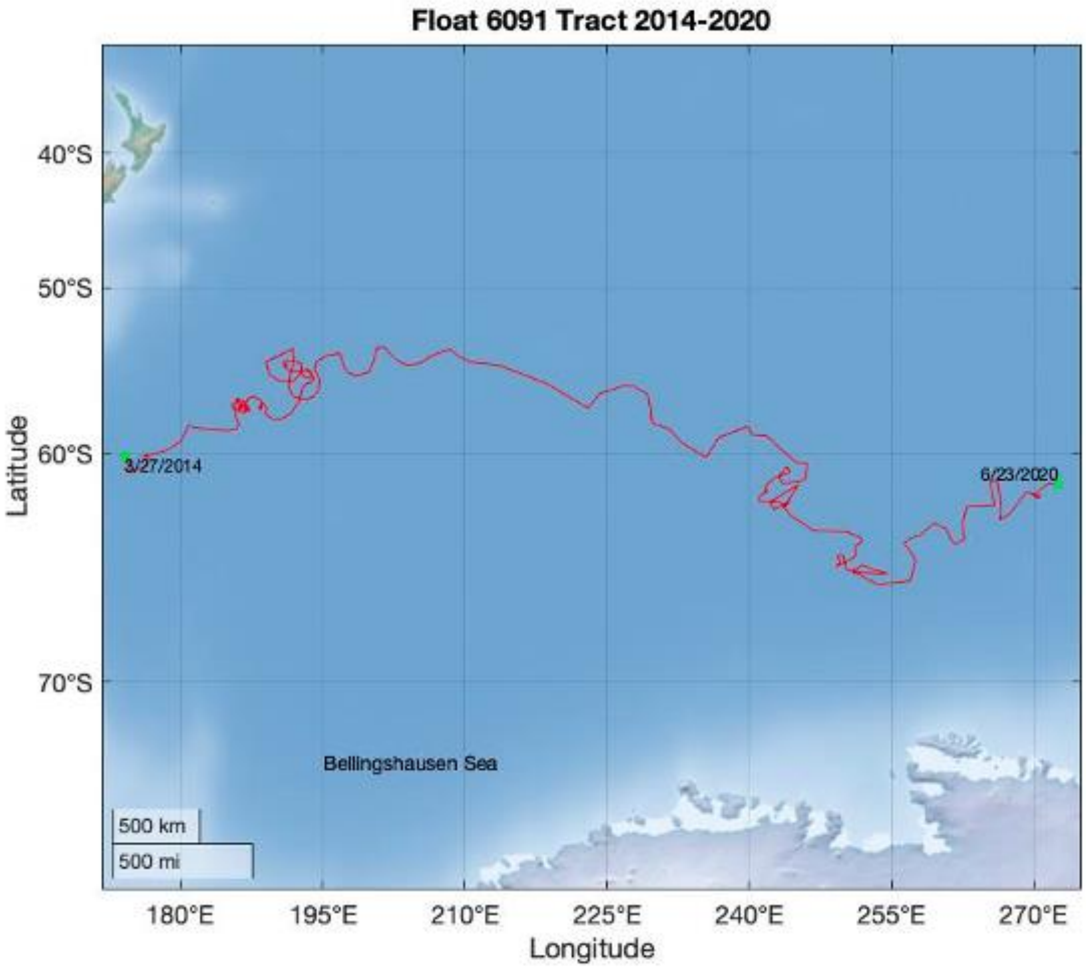



**Figure 1:** *This figure represents the total deployment track of float 6091 as it traveled through the Bellingshausen Sea. It started on March 27, 2014 at -60.053º, 174.161º ending on June 23, 2020 at -61.555º, 272.614º.*

## **Methods**

SOCCOM float 6091 was selected for this project, which traveled across the Bellingshausen Sea located to the left of the West Antarctic Peninsula for a 6 year 3 month deployment mission, as can be seen in figure 1. The West Antarctic Continental Shelf, which spans from the West Antarctic Peninsula to the Western Amundsen Sea, is a very important region of the Southern Ocean when looking at the biology of this area. This region is characterized by the shallowing of the subsurface temperature maximum in the summer months, above 200 meters, (De Boyer Montégut et al, 2007) leading to warmer, salty Circumpolar Deep Water, a derivative of the Antarctic Circumpolar Current (Prézelin et al, 200), to disperse throughout. The subsurface temperature maximum, SSTM, is the deepest of the water column where warm surface water reaches, separated by a thermocline from the deep cold water (De Boyer Montégut et al, 2007). The increase of CDW into this area allows for warmer water temperatures in comparison to other Antarctic Continental shelf regions (Schubert et al, 2021) and provides reservoirs of nutrient-rich water at about 150 meters to be upwelled (Prézelin et al, 200). The combination of warm, nutrient rich water with a shallower SSTM in the Bellingshausen Sea provides the ideal environment for the growth of phytoplankton.

For this study, the data was accessed from the Monterey Bay Aquarium Research Institute's FloatViz 6.0 database, which provides data for entire ARGO network worldwide to be downloaded and put specified variables into simple plots to analyze general trends in the region of interest. Before final float selection, three floats with similar trip trajectories and length were selected, float 6091, 9092, and 1288. From each mission, the following data was downloaded and reviewed: longitude, latitude, depth, salinity, temperature, date, time, chlorophyll a (Chl*a*), and particulate backscattering coefficient ($b_{bp}$). Within the FloatViz 6.0 website, plots of Chl*a* versus depth, Chl*a* versus time, Chl*a* versus $b_{bp}$ (each year), $b_{bp}$ versus depth, $b_{bp}$ and versus time were created to ensure the selected float showed distinct patterns of chlorophyll concentration increases at the surface, backscatter moving out of the system, and a strong correlation between chlorophyll and backscatter. The data was brought into MATLAB where higher quality, enhanced renderings of the previous plots were created to reveal the specific float that depicted the strongest evidence of Bellingshausen Sea phytoplankton bloom from its mission. It was determined that float 6091 was the best candidate for the desired representation.

Thus, began further in-depth analysis of this mission. Using the previously created plots, the patterns revealed by the temperature data were compared to the Chl*a* and $b_{bp}$ data to show any potential correlation between the increase temperatures seen with the beginning of the Antarctic summer and the spikes in productivity as well as the decrease in temperature seen with the beginning of fall and the spikes in carbon export. These same patterns were also tested using the ratio of Chl*a* to $b_{bp}$ to determine if the concentration of organic carbon entering the system is equivalent to that leaving. To consolidate the previous bloom depictions, the Chl*a* and $b_{bp}$ were integrated to represent the mean data along the time series and remove any potential outliers from the final plots. This same procedure was then applied to the ratio of Chl*a* to $b_{bp}$ as well to better characterize their relationship. To further analyze the $b_{bp}$ data, the mean and standard deviation of the dataset was taken for the points that fell below 500 meters in depth, and the values that were greater than the calculated standard deviation plus the mean were isolated. These values are considered the anomalies of backscatter data considered to be of the highest significance, thus being used as the proxy to represent carbon export from the system. This anomaly plot was further integrated into a dual y-axis plot to show the relationship between these derived extreme values and the original backscatter data. The final derivation was breaking up the anomaly plots by year to represent the export flux being transported each cycle to determine if it is significant in terms of the amount of primary productivity being created during each bloom.

Following a drastic decrease in water temperature following the end of the mission, two factors were considered when trying to determine the cause the plumet. The first method was to match the El Niño-La Niña periods experienced in the Pacific with the data collected. Typically, La Niña brings warmer water into the Bellingshausen Sea while El Niño bring cold water (Vergani et al, 2008). The second method was to analyze the sea ice concentration with respect to where the float was located at each specific point. Sea ice visualization data was acquired from the National Snow and Ice Data Center's Sea Ice Index Visualization tool to compare sea ice extent maximums in the Southern Hemisphere monthly from 2019-2020, where the major temperature decrease was displayed. Each image was then downloaded and brough into Mac Text Editor where the longitude and latitude lines where matched with the coordinates of the float location and marked with a float icon, green representing ice-float crossing and yellow representing no ice-float crossing.

## **Results**

Looking at the variations of seasonal temperature, temperatures above 500 meters ranged from about 4ºC to about 10ºC, with colder temperatures (<4ºC) between 500 meters and 1000 meters. Each year there is a warming period last only a few weeks around December and January in the upper 200 meters, and that warm period slowly mixes deeper into the water column as the year progress. From the end of 2018 to 2020, there was much less warming occurring and a large cold-water mass remained in the upper 200 meters for a large portion of 2019. Moving to the variations in seasonal productivity, like the strong increases in temperature, there is an annual spike in the chlorophyll a concentration in the upper 100 meters. Around December and January there is large peaks in chlorophyll a ranging from 2.5 μg/ liter towards the beginning of the spike falling to around 1.5 μg/ liter towards the end of the spike. Showing a similar pattern to the temperature and chlorophyll concentration, backscatter displayed annual spikes in particulate concentration, ranging from $8\text{-}10x10^{-4}$ 1/m, in the upper water column during December to January. Backscatter also revealed scatter increases in concentrated throughout the entire water column during and after the large spike near the surface. When comparing chlorophyll and backscatter using linear regression, a positive correlation was determined with a p-value of 0, reject the null hypothesis and test is statistically significant, $R^2$ of 0.7795 and line equation of $y=356.1507x + (-0.0548)$. Each variable is represented in figure 2 as a visual schematic.

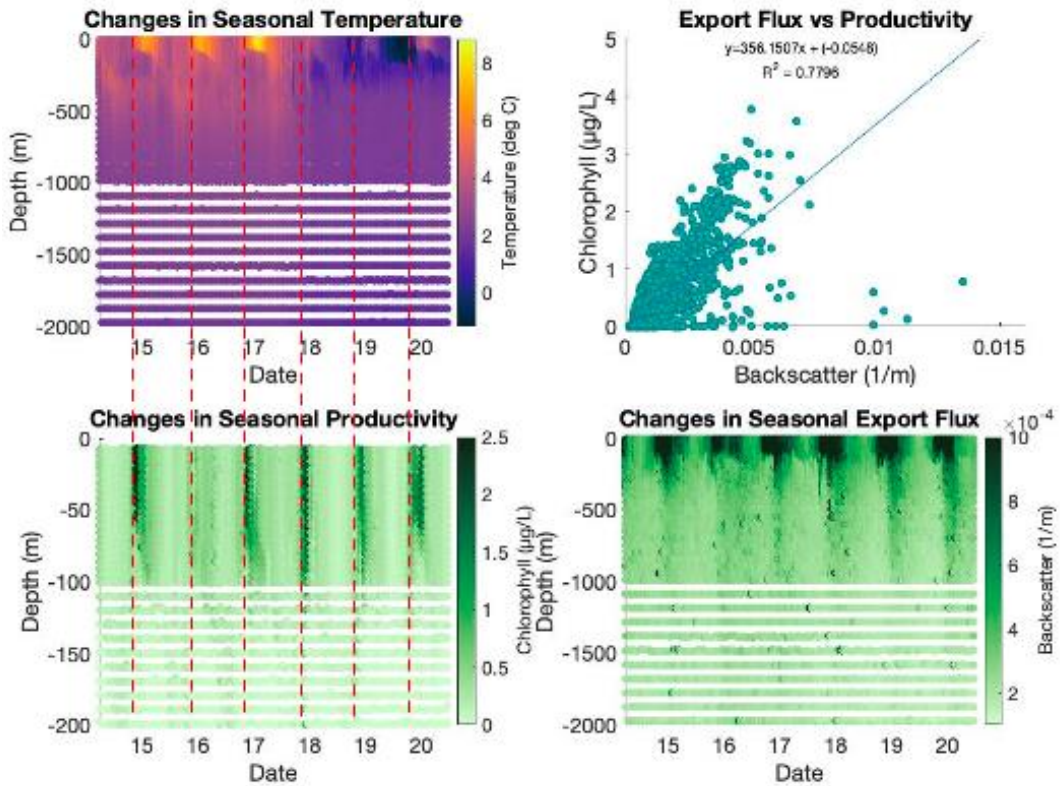
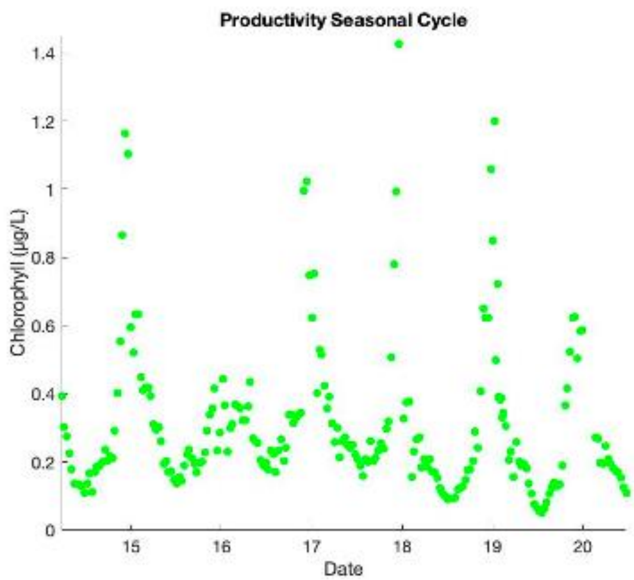
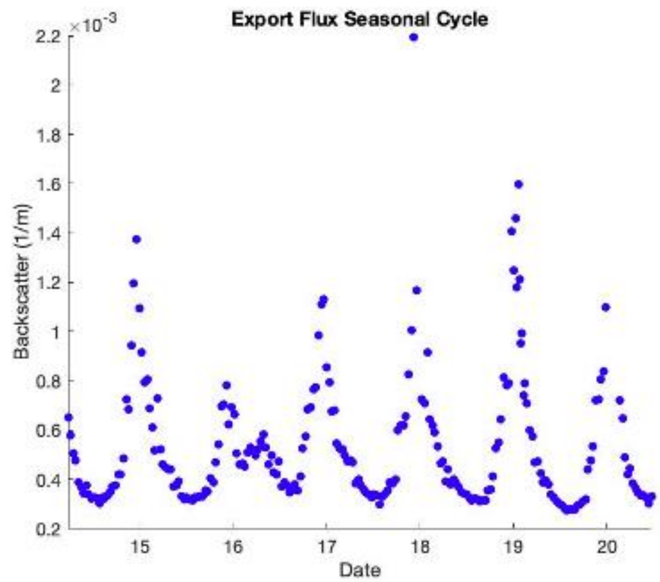



**Figure 2:** *This figure represents the seasonal variability seen annually in the biological properties: temperature, chlorophyll, backscatter all over depth. The top left plot represents the annual variability of temperature as it changes with depth and seasonally. Date by year is on the x-axis, depth starting from the surface at the top (0m) to 2000m at the bottom, and the color represents the temperature value (below 0ºC in dark blue to 10ºC in yellow). The dashed lines indicate the period right before the warming where blooms are seen to begin in the plot below. The lower left plot indicates the annual changes in productivity as it changes with depth and seasonally. Date by year is on the x-axis, depth starting from the surface at the top (0m) to 200m at the bottom (note the change in depth), and the color represents the chlorophyll concentration used to measure productivity (0µg/ liter in light green to 2.50 µg/ liter in dark green). The plot on the bottom left represents the annual changes in export flux as it changes with depth and seasonally. Date by year is on the x-axis, depth starting from the surface at the top (0m) to 2000m at the bottom, and the color represents the concentration of backscatter used to measure export flux (0 1/m in light green and $10x10^{-4}$1/m in dark green). The top right plot represents the relationship between chlorophyll and backscatter. A positive correlation is seen with a line equation of y=356.1507x + (-0.0548), a $R^2$ value of 0.7795, and p-value of 0.*

Focusing on spikes in chlorophyll a and backscatter, figure 3 depicts each over time. Each year has a sharp increase in both chlorophyll and backscatter lasting for a short period, then drastically decreasing to a lower concentration. Each of these spikes is again seen in the period between December and January. 2014 experienced a peak in chlorophyll of 3.5806μg/L occurring on December 20, 2014; 2015 peaked at 2.6244μg/L on December 16, 2015; 2016 2.7704μg/L on December 11, 2016; 2017 1.7885μg/L on December 29, 2017; 2018 1.7885μg/L on January 4, 2019, and 2020 on 3.7706μg/L on January 10, 2020. 2014 experienced a peak in backscatter of $8.867 \times 10^{-3}$ 1/m on December 20, 2014; 2015 saw $9.949 \times 10^{-3}$ 1/m on March 12, 2015; 2016 saw $5.697 \times 10^{-3}$ 1/m on June 29, 2016; 2017 saw $19.381 \times 10^{-3}$ 1/m on December 8, 2017; 2018 saw $9.93 \times 10^{-3}$ 1/m on December 25, 2018; 2019 saw $6.13 \times 10^{-3}$ 1/m on January 14, 2019, and 2020 saw $7.01 \times 10^{-3}$ 1/m on January 10, 2020.



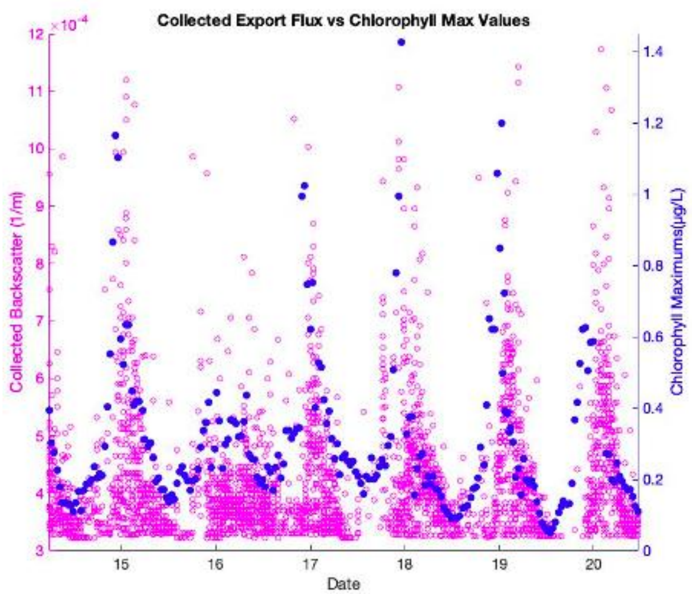




**Figure 3:** *This figure represents the revealed seasonal patterns of phytoplankton blooms in the study region. The top left plot depicts the patterns seen by the active bloom via chlorophyll. The top right depicts the export flux out of the system via backscatter. The bottom plot depicts the two patterns overlaid (note the chlorophyll data is integrated to use the maximum values) and how export follows the peak bloom.*

After analyzing the sea ice concentration, it was found that when the float drifted below 60ºS latitude there is potential for the float to cross the sea ice extent. In March 2019 the float was at 64ºS latitude, but the ice extent was small. From April to October 2019, the sea ice extended past the floats general area with a peak extent to 60ºS in August. In April 2019, the float was at 65ºS latitude, May 2019 the float was between 64-65ºS latitude, June- July 2019 the float was at 65ºS latitude, August 2019 the float was between 65-66ºS latitude, September the float was at 64ºS latitude, October 2019 the float was between 63-64ºS latitude. Past October the float still remains in the 63ºS area but the sea ice retreats back to the coast until March 2020 when it begins to extend again.

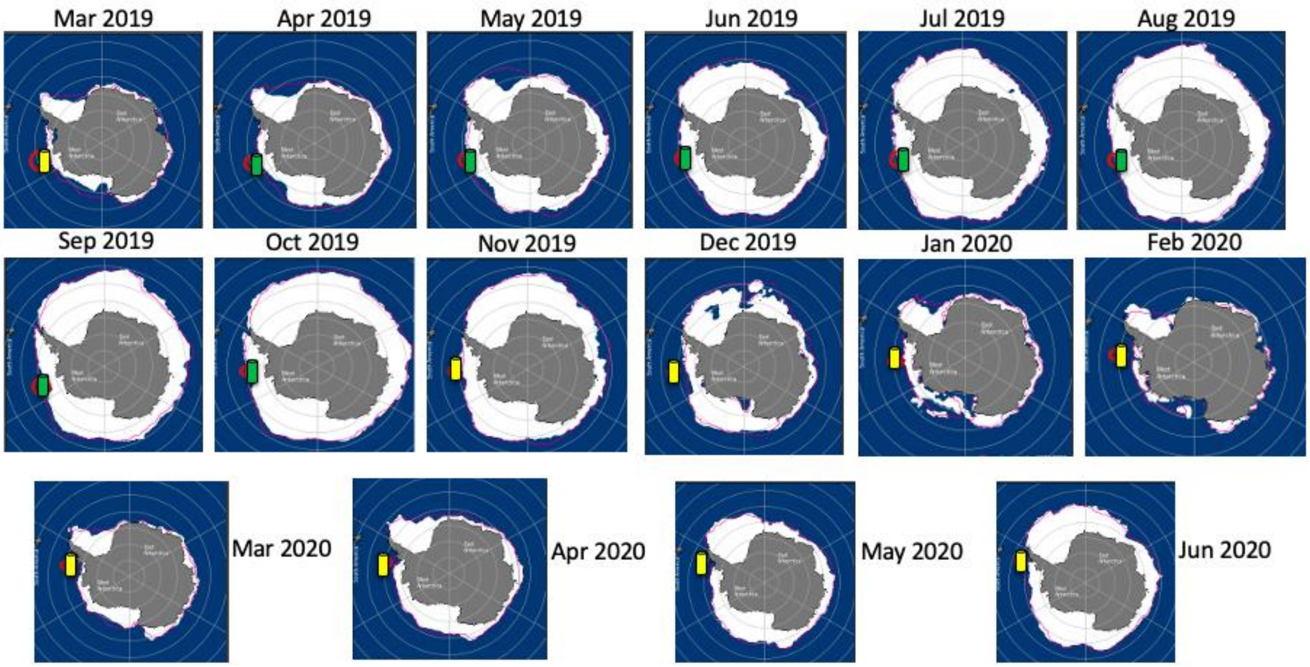



**Figure 4:** *This figure represents the monthly sea ice extents from the coast of Antarctica into the Southern Ocean. The small icon represents where the float was in that month of the deployment. Yellow depicted no float to ice contact and green depicting float to ice contact. The white represents where the sea ice reached in that period and the pink line represents the median ice edge from 1981-2010. (Modified from NSIDC Sea Ice Index)*

## Discussion

As can be seen in figure 2, the large peaks in productivity begin right before the large peaks in temperature, as highlighted by the red dashed line. This reveals that the timing of the blooms each year are occurring prior to the large warming of the upper water column, where the maximum values of chlorophyll are located. December-January is summer in the Southern Hemisphere, so the patterns seen here correlate to the peak blooms seen in the Northern Hemisphere around late spring-early summer. A period of interest during this time series was in 2016, where the peak bloom was significantly smaller than that of the rest of the years. This was discovered to be due to the Super El Niño event that occurred in the Pacific near the end of 2015 into early 2016 (Chen et al, 2017). This event led to more warm, moist area to travel over the area and an increase in storm intensity at sea (Ren, 2017), so because of this the surface water most likely became extremely rough and could not support a large abundance of phytoplankton during this period.

Comparing the productivity to export, it was seen that the two are interconnected. There was a strong correlation shown between the two and as chlorophyll increases at the surface, the more export flux leaves the system. It was also seen that in most cases, the export flux is slightly offset from the peak bloom period revealing the peak, fall, and export of the organic matter from the phytoplankton. In 2015 and 2016 however, the offset was more drastic at about 4 to 6 months between peak chlorophyll and peak backscatter. This can be due to a few things. First being influence from the El Niño. Backscatter picks up any sizable particulate in the water, it is not exclusive to dead phytoplankton matter. It can detect large aggregations of air bubbles, other decaying matter, and even large groups of animals. So those peak values occurring far after the peak bloom can be attributed to large amounts of oxygen getting pumped into the surface layer from intense storm activity or an increase in animal activity due to warmer conditions. These values were not significantly higher than the rest of the years, and one would expect to see lower amounts of export due to less productivity at the surface, once again pointing to the backscatter picking up another signal. Further analyzing the export flux plot in figure 2 shows that there is a clear depiction of small aggregates falling from the surface to the deep. The large green peaks at the surface seem to slowly trickle down as depth increases, a positive to support the idea of using backscatter as a good variable to depict export flux.

Like was seen in 2016, another anomaly that became an area of interest was in the drastic drop in surface temperature seen in 2019. At first glance, this anomaly may also be caused by El Niño/La Niña, but from further analysis of the trends in that time, the patterns did not align. With further analysis, it had become evident that due to the float's change in trajectory towards the coast, as can be clearly seen in figure 1, a drop below 60ºS latitude puts into effect the potential influence from sea ice. As shown in figure 4, this thought process was successful and not only did the float get close to sea ice, creating colder water temperatures, but it had also crossed the line of sea ice extent around the same time the extreme drop in temperature was recorded. Not only did this drop in temperature correlate to sea ice contact, but it had also shown an increase in export flux. It has been found in other studies that in areas of high sea ice concentration, there is on average more export flux leaving the system (Lavoie, 2010). One may question the validity of this data since in many cases argo floats have a history of getting trapped in thick sea ice and do not record accurate data. But from looking at the coordinates of the float, it continued moving throughout its time near and in the sea ice, so there is no evidence in this data set that at any point it did become stuck. It may also be possible that since the float only made contact with the outer most layers of ice, it was not too thick and did not pose a threat to the float's trajectory.

## Conclusion

Blooms have been found to occur in late spring-early summer in the period right before the peak warming occurs in the region. For the Bellingshausen Sea that period was mid- December to early-January when solar irradiance is increasing and causing the surface temperature to increase. This was seen throughout the entire time series except at the time when float made contact with sea ice. In this case, there was no drastic change in productivity, and the phytoplankton still acquired enough solar radiation to continue to thrive. As was seen in each of these large seasonal blooms, there was a very strong correlation between backscatter and chlorophyll as the amount of chlorophyll increased the backscatter also increased. This further supports the use of backscatter as an important variable to consider when trying to visualize export flux and to determine the role that a region has in the operation of the biological carbon pump. Along with a correlation between the two variables, on average there was very strong evidence of seasonal export flux revealing that most of the carbon that is processed in the Southern Ocean is done so during these seasonal bloom periods.

Aside from the average bloom and export cycle, there was supporting evidence found to prove that in areas of high sea ice concentration there is an increase in the amount of export flux falling from the surface. This can potentially be due to more particulate matter being trapped under the ice and will slowly descend to depth or lower levels of sunlight under the ice causes phytoplankton to have shorter life spans and die sooner. No matter the reason, this is a very important point to consider when trying to determine some future implications caused by climate change. These sea ice covered areas revealed to be large carbon providers for the global ocean carbon pump, and with decreasing sea ice concentrations as ambient temperatures of the planet increase, issues may arise. As can be seen in figure 5, up until around 2013 the relative sea ice concentration has shown strong evidence of interannual variability, whenever there was a drastic drop, it was followed by a large increase to counteract it. However, as pressures induced by anthropogenic factors increases with time, the impacts are slowly starting to reveal themselves over a shorter timeline. The Antarctic sea ice concentration has reached a threshold of no return and continues to plumet. There may be slight increases, but the planet is becoming too warm to sustain considerable sea ice cover in the region. This has potential implications on the functioning of global carbon pump a large fraction of the export is accomplished here and without it there is potential for a slowing or maybe even a shutdown of this cycle. This potential slowdown could also be induced by an unmanageable increase in both solar radiation and temperature that phytoplankton will no longer be able to bloom once again decreasing the amount of flux added to the carbon pump. Without the proper functioning of the biological carbon pump, there is potential for the entire marine ecosystem to collapse as phytoplankton and the carbon supplied from export flux are primary food sources for many small species which are food for larger species. This discrepancy continues up the food chain, concluding with no resources to sustain a diverse, prospering ocean environment.

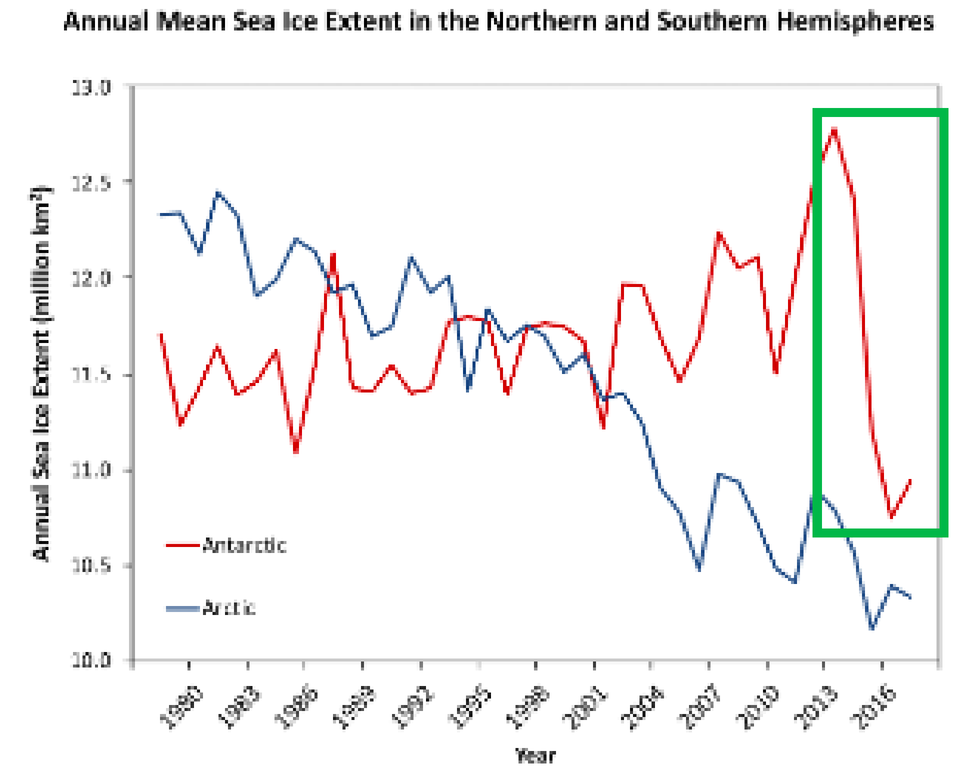



**Figure 5:** *This figure represents the average annual sea ice concentration variation in both the Arctic and Antarctic. For the study in particular, the red line of the Antarctic is highlighted for significance. There is strong evidence of interannual variability and each of the changes balanced out the following year. But as highlighted in the green box, post- 2013 Antarctic sea ice has reached a threshold and has not significantly increased since.*

## **References**

ARGO. *Scripps Institute of Oceanography, UC San Diego*, 1999, https://argo.ucsd.edu/.

Arrigo, Kevin R., et al. "Primary Production in Southern Ocean Waters." *Journal of Geophysical Research: Oceans*, vol. 103, no. C8, 1998, pp. 15587–15600., https://doi.org/10.1029/98jc00930.

Bishop, James. "Autonomous Observations of the Ocean Biological Carbon Pump." *Oceanography*, vol. 22, no. 2, 1 June 2009, pp. 182–193., https://doi.org/10.5670/oceanog.2009.48.

Buesseler, Ken O., et al. "Metrics That Matter for Assessing the Ocean Biological Carbon Pump." *Proceedings of the National Academy of Sciences*, vol. 117, no. 18, 30 Dec. 2020, pp. 9679–9687., https://doi.org/10.1073/pnas.1918114117.

Chen, Lin, et al. "Formation Mechanism for 2015/16 Super El Niño." *Scientific Reports*, vol. 7, no. 1, 7 June 2017, https://doi.org/10.1038/s41598-017-02926-3.

Claustre, Hervé, et al. "Observing the Global Ocean with Biogeochemical-Argo." *Annual Review of Marine Science*, vol. 12, no. 1, 2020, pp. 23–48., https://doi.org/10.1146/annurev-marine-010419-010956.

De Boyer Montégut, Clément, et al. "Control of Salinity on the Mixed Layer Depth in the World Ocean: 1. General Description." *Journal of Geophysical Research*, vol. 112, no. C6, 2007, https://doi.org/10.1029/2006jc003953.

Gruber, Nicolas, et al. "The Variable Southern Ocean Carbon Sink." *Annual Review of Marine Science*, vol. 11, no. 1, 3 Jan. 2019, pp. 159–186., https://doi.org/10.1146/annurev-marine-121916-063407.

Huppert, Amit, et al. "A Model for Seasonal Phytoplankton Blooms." *Journal of Theoretical Biology*, vol. 236, no. 3, 7 Oct. 2005, pp. 276–290., https://doi.org/10.1016/j.jtbi.2005.03.012.

Lavoie, Diane, et al. "Effects of Future Climate Change on Primary Productivity and Export Fluxes in the Beaufort Sea." *Journal of Geophysical Research*, vol. 115, no. C4, 23 Apr. 2010, https://doi.org/10.1029/2009jc005493.

Nozaki, Yoshiyuki, and Yoshiyuki Yamamoto. "Radium 228 Based Nitrate Fluxes in the Eastern Indian Ocean and the South China Sea and a Silicon-Induced 'Alkalinity Pump' Hypothesis." *Global Biogeochemical Cycles*, vol. 15, no. 3, 1 Sept. 2001, pp. 555–567., https://doi.org/10.1029/2000gb001309.

NSIDC. "National Snow and Ice Data Center." *BIST Compare Anomalies | National Snow and Ice Data Center*, https://nsidc.org/data/seaice_index/bist.

Prézelin, Barbara B., et al. "The Linkage between Upper Circumpolar Deep Water (UCDW) and Phytoplankton Assemblages on the West Antarctic Peninsula Continental Shelf." *Journal of Marine Research*, vol. 58, no. 2, 2000, pp. 165–202., https://doi.org/10.1357/002224000321511133.

Ren, Hong-Li, et al. “Upper-Ocean Dynamical Features and Prediction of the Super El Niño in 2015/16: A Comparison with the Cases in 1982/83 and 1997/98.” *Journal of Meteorological Research*, vol. 31, no. 2, 6 May 2017, pp. 278–294., https://doi.org/10.1007/s13351-017-6194-3.

Schubert, R., Thompson, A. F., Speer, K., Schulze Chretien, L., and Bebieva, Y.: The Antarctic Coastal Current in the Bellingshausen Sea, The Cryosphere, 15, 4179–4199, https://doi.org/10.5194/tc-15-4179-2021, 2021

“SOCCOM.” *Princeton University*, The Trustees of Princeton University, 2020, http://soccom.princeton.edu/content/overview.

Taucher, Jan, et al. “In Situ Camera Observations Reveal Major Role of Zooplankton in Modulating Marine Snow Formation during an Upwelling-Induced Plankton Bloom.” *Progress in Oceanography*, vol. 164, June 2018, pp. 75–88., https://doi.org/10.1016/j.pocean.2018.01.004.

Vergani, D. F., et al. “The Effects of El Niño/La Niña on Reproductive Parameters of Elephant Seals Feeding in the Bellingshausen Sea.” *Journal of Biogeography*, 6 Feb. 2007, https://doi.org/10.1111/j.1365-2699.2007.01780.x.

Winder, Monika, and Ulrich Sommer. “Phytoplankton Response to a Changing Climate.” *Phytoplankton Responses to Human Impacts at Different Scales*, 26 May 2012, pp. 5–16., https://doi.org/10.1007/978-94-007-5790-5_2.