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Key Points:

- Southern Ocean surface chlorophyll variability is predominantly driven by small scale processes
- Multi-annual processes, such as the Southern Annular Mode, only explain ~10% of chlorophyll variability in the Southern Ocean
- Analyses that average chlorophyll should account for relevant spatio-temporal scales to meaningfully interpret chlorophyll variability

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
H. L. Joy-Warren,
hjoyw@uw.edu

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The Importance of Spatial and Temporal Scales in Understanding Chlorophyll Variability in the Southern Ocean

Hannah L. Joy-Warren[1,2,3]

[1]Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle, WA, USA, [2]School of Oceanography, University of Washington, Seattle, WA, USA, [3]Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA, USA

Abstract Polar regions are undergoing dramatic, rapid, and possibly irreversible changes. Substantial shifts in patterns of sea ice extent and thickness have cascading effects on polar ecosystems (including phytoplankton), with implications for carbon cycling and global climate. Phytoplankton growth is closely tied to environmental variables such as light and nutrient availability, which are sensitive to climate-induced changes in upper ocean circulation, stratification, and sea ice cover. Recently, Prend et al. (2022, https://doi.org/10.1029/2022GB007329) investigated temporal and spatial scales of chlorophyll (a proxy for phytoplankton biomass) variability in the Southern Ocean. They demonstrated that the dominant temporal scale of variability is sub-seasonal (~0.5–3 months). The implications of this are two-fold: first, climate oscillations (such as the Southern Annular Mode) are not major drivers of year-to-year variation in chlorophyll; second, intermittent bursts of chlorophyll, generated by small-scale processes such as storms and eddies, dictate the annual mean chlorophyll concentration. Additionally, spatial autocorrelation for chlorophyll concentration varied by time scale: seasonal chlorophyll variability was correlated over much larger areas than were variations in year-to-year chlorophyll concentration. Based on Prend et al. (2022, https://doi.org/10.1029/2022GB007329), future work should be cognizant of (a) the spatio-temporal scales over which chlorophyll is averaged and (b) the need to focus on small-scale, sub-seasonal events (rather than large-scale climate oscillations) to mechanistically explain chlorophyll variability.

Plain Language Summary The distribution of carbon between the atmosphere and ocean, in part, regulates global climate. The amount of carbon transferred between the atmosphere and ocean is affected by both marine biological growth (through photosynthesis) and physical processes (such as storms and mixing). The Southern Ocean, around Antarctica, is one of the most important oceanic systems in determining how much natural carbon is transferred from the atmosphere to the ocean, but it is experiencing adverse impacts of climate change that affect both biological growth and physical processes. To predict future distributions of carbon, and thus future climate, we must first understand how and why these processes change. Prend et al. (2022, https://doi.org/10.1029/2022GB007329) tackle part of this challenge by investigating variability in biological growth over space and time. Despite common thinking that multi-year climatic patterns (like El Niño) are large drivers of variability, the authors show that shorter processes (over ~0.5–3 months) are the most important drivers of both average growth and variability. Variations in biological growth from year-to-year were only correlated over small areas (~100–300 km). These findings signify that future work should be aware of the spatial and temporal scales relevant to the questions the study seek.

1. Introduction

Polar ecosystems are currently undergoing increasingly rapid changes in atmospheric and ocean circulation, temperature, sea ice cover, and stratification (Doney et al., 2012) that potentially impact light and nutrient availability. These changes alter the duration and magnitude of primary production as well as the phenology of the phytoplankton community. Shifts in primary production can significantly alter regional and global nutrient cycling (Assmy et al., 2013; Sarmiento et al., 2004), carbon drawdown (Hoppe et al., 2013; Moreau et al., 2012), organic carbon and biogenic silica export (Assmy et al., 2013; Salter et al., 2007), grazing communities and higher trophic levels (Montes-Hugo et al., 2009; Saba et al., 2014), and benthic-pelagic coupling (energy and nutrient transfer from the pelagic to the benthos) (Assmy et al., 2009).

The impact of climate change is highly regional across the Southern Ocean. Sea ice extent, for example, is not changing uniformly around Antarctica. Because regional changes compensate for one another, there is no clear overall trend (Ludescher et al., 2019). Rising global air and sea surface temperatures impact productivity through elevated water temperatures and decreased sea ice extent, thickness, and duration. Over the last century, warmer periods in the Southern Ocean have been less productive (Gutt et al., 2015). Historically, increased productivity has been linked to cooler air temperatures that contributed to increased upwelling of nutrient-rich circumpolar deep water, enabling elevated primary production (Gutt et al., 2015). However, warmer conditions also decrease the extent of sea ice, lengthening the growing season and increasing total annual primary production (Arrigo et al., 2008).

Due to its vastness, remoteness, and harsh conditions, the Southern Ocean has been historically undersampled. Remote observing techniques provide the possibility of measuring proxies for phytoplankton growth over larger spatiotemporal scales than in situ measurements. Satellite remote sensing, in particular, has been used to observe spatial and temporal trends in chlorophyll concentration (Sullivan et al., 1993, and many others) and net primary production (Arrigo et al., 2008). More recently, autonomous platforms, including profiling floats (Mohrmann et al., 2022) such as Biogeochemical-Argo floats (Briggs et al., 2018; Claustre et al., 2020; Johnson et al., 2017), unmanned surface vehicles such as Saildrones (Sutton et al., 2021), and gliders (du Plessis et al., 2022; Giddy et al., 2021; Nicholson et al., 2022), have opened a window into monitoring biogeochemical and phytoplankton dynamics in the Southern Ocean. In order to capture changes, we need to make measurements at high spatial and temporal resolution. Despite their still fairly limited spatial scales, autonomous platforms expand our ability to capture high resolution temporal variability and the data can be used to validate satellite measurements. Still, satellite ocean color measurements remain our only tool to observe the ocean ecosystem at high temporal resolution (capturing sub-seasonal variability) and across the global ocean (Bindoff et al., 2019), despite only measuring the surface layer of the ocean.

The impact of climate change on the oceans is felt locally and manifests in varied regional trends (Bindoff et al., 2019). However, climate change-induced oceanic changes are overlain on natural fluctuations at temporal scales that vary from minutes to centuries and across spatial scales that vary from subregional to ocean basins (Fox-Kemper et al., 2021). In order to identify climate change trends, it is necessary to disentangle scales of variability from sub-seasonal (~0.5–3 months) to multi-annual (>12 months) and to investigate these trends regionally.

Prend et al. (2022) rise to this challenge by employing a statistical approach from Keerthi et al. (2020) to identify the temporal scales (sub-seasonal to multi-annual) over which Southern Ocean phytoplankton production varies. To quantify the variability along various time scales, the authors employed a statistical decomposition method to separate chlorophyll variability into the following frequency bands: sub-seasonal (0.5–3 months), seasonal (3–12 months), and multi-annual (>12 months). This approach illuminated the relative importance of different spatio-temporal scales of chlorophyll variability in the Southern Ocean. The authors quantify chlorophyll concentration using satellite data, and therefore their results are specific to surface chlorophyll. However, they demonstrate a strong relationship between surface chlorophyll concentration and vertically integrated chlorophyll measured from autonomous biogeochemical profiling floats and thus their results likely apply broadly to chlorophyll patterns.

2. Spatial Scales of Importance

A key finding of Prend et al. (2022) is that the relevant timescales over which chlorophyll concentration varies differ by region. The subtropics (generally taken to be south of 30°S and north of the Subtropical Front) are characterized by a repeating sinusoidal cycle with low overall magnitudes and little change in amplitude from year-to-year. Chlorophyll variability was correlated across areas >600 km in the subtropics. In this region, the seasonal component dominated the variability in chlorophyll concentration, indicating that the annual mean is closely tied to the seasonal bloom magnitude (see Figure 1, top panel, as an example).

In contrast, in the Antarctic Circumpolar Current (ACC), even though the seasonal component still represented the mean chlorophyll concentration, the largest fluctuations were associated with the sub-seasonal component (see Figure 1, bottom panel, as an example). This difference indicates that the annual mean chlorophyll concentration in the ACC reflects the sum of ephemeral spikes in growth. Additionally, sub-seasonal variability was

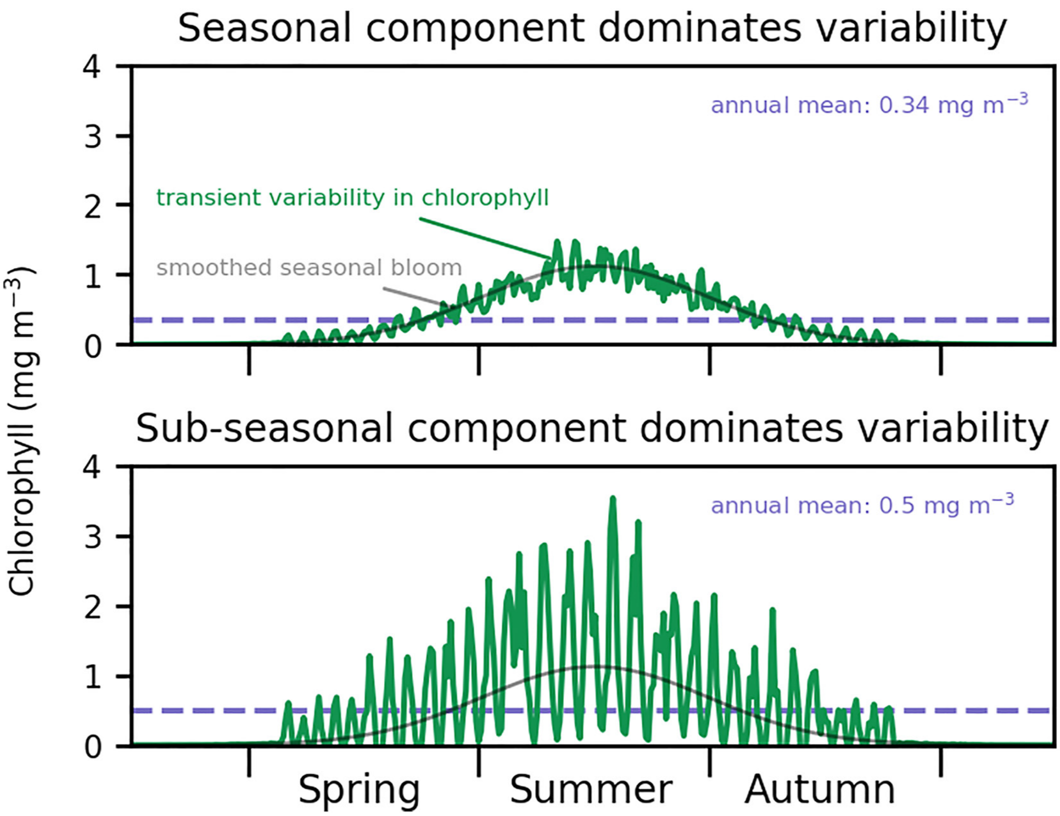

Figure 1. Schematic representing different time scales of chlorophyll variability (synthetic data). When the seasonal component dominates the variability in chlorophyll, the annual mean is closely tied to the seasonal bloom magnitude, as demonstrated in the top panel. The subtropics are an example of a region characterized by seasonal variability. In other regions, such as the Antarctic Circumpolar Current, sub-seasonal spikes in chlorophyll determine the annual mean chlorophyll concentration, as demonstrated in the bottom panel. Note that there is also a multi-year component in chlorophyll concentration, but as it only explains ~10% of chlorophyll variability, it is not represented here (see Prend et al. (2022) for real data).

correlated across much smaller spatial scales (~50–100 km) than seasonal variability. Events on ~weekly timescales are likely mechanisms for the short term variability observed in chlorophyll concentration in the ACC, such as mixing events (e.g., storms, eddies, and variability in submesoscale physical dynamics) or biological variability (resulting from nutrient and/or light limitation or grazing). Prend et al. (2022) demonstrate that, in the ACC, variations in the annual mean chlorophyll concentration occur over small spatial scales (~100–300 km; shown with an autocorrelation analysis).

3. Temporal Scales of Importance

Previous work has regressed satellite chlorophyll concentration in the Southern Ocean against climate oscillation indices, such as the Southern Annular Mode (SAM), but found limited explanatory power for chlorophyll variability (Prend et al., 2022; see, e.g., Lovenduski & Gruber, 2005). Overall, Prend et al. (2022) found that the multi-annual component explained very little of the total chlorophyll variability across most of the Southern Ocean. To investigate why the SAM index has little explanatory power of chlorophyll variability, the authors correlated the SAM index with chlorophyll variability within each temporal component (sub-seasonal, seasonal, and multi-annual). While the multi-annual component was strongly correlated with the SAM index, over the Southern Ocean this component explained only ~10% of chlorophyll variability. Because the multi-annual component explained such a small amount of the chlorophyll variability, it is hard to extract a relationship between chlorophyll variability and SAM. Instead, the authors found that phytoplankton biomass variability is better correlated with the sub-seasonal than with the multi-annual time scale (i.e., climate oscillations).

4. Suggestions for Future Work

By identifying the relevant temporal and spatial scales of chlorophyll variability, Prend et al. (2022) take an important step toward understanding future changes in the Southern Ocean and possible impacts to carbon cycling and global climate. Future analyses that average chlorophyll measurements should heed the authors' demonstration of variance in scales of autocorrelation by region and appropriately account for relevant spatio-temporal scales to meaningfully interpret chlorophyll variability.

The next steps include discerning the mechanisms driving chlorophyll variability over a range of temporal and spatial scales. Prend et al. (2022) attempted to attribute observed chlorophyll variability to mechanisms, but found only modest relationships, likely due to the current lack of sufficiently accurate and high resolution measurements (see their Supporting Information S1 (https://agupubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1029/2022GB007329%26file=2022GB007329-sup-0001-Supporting+Information+SI-S01.pdf)). Prend et al. (2022) also raise an important point in identifying mechanisms driving chlorophyll variability: the same forcing (such as a storm or eddy) could have an opposite effect on chlorophyll depending on whether light or nutrients are limiting phytoplankton growth. When light is limiting, a senescence of mixing can enable surface layer stratification that concentrates phytoplankton in the well-lit surface layer, lifting light limitation. However, when nutrients are limiting, increased mixing can entrain nutrients from deeper layers, releasing nutrient limitation.

Given that the largest variability is observed on shorter time scales, this would be a prudent place to focus future efforts through local studies that resolve sub-seasonal and small-scale processes. At the same time, because the impact of episodic events differs based on what factor is limiting phytoplankton growth, the key to determining driving mechanisms will include monitoring mechanistic relationships over the annual cycle. To do so, we need to fill in the spatial and temporal observational gaps that we have not previously been able to resolve. More and more, autonomous platforms are filling these gaps and hold significant promise for the future. For example, Biogeochemical-Argo profiling floats will allow us to tackle similar questions deeper than the surface layer of the ocean that satellites can measure.

Combining tools that cover a wide range of spatial and temporal scales (including observations from satellites, autonomous platforms, and ships) with climate models will be imperative to fully quantify the different mechanisms contributing to chlorophyll variability. Calls for the need to understand oceanic mechanisms at a higher resolution than we are presently resolving are also coming from the modeling community (Hewitt et al., 2022). Understanding the temporal and spatial scales of variability in both chlorophyll and other biogeochemical as well as physical parameters will allow us to connect drivers at different scales to the variability we can now observe with higher resolution measurements.

Acronyms

ACC	Antarctic Circumpolar Current
SAM	Southern Annular Mode

Data Availability Statement

Data were neither used nor created for this work.

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