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Key Points:

- Subregions of the West Antarctic Peninsula marine system show varying amplitudes of seasonal cycles of air-sea CO_2 flux and Chlorophyll-a
- Seasonal cycles of both air-sea CO_2 flux and Chlorophyll-a increase in amplitude moving poleward
- Massive biological drawdown of CO_2 occurs over the Southern Shelf in summer

Supporting Information:

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

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Seasonal Variability of Surface Ocean Carbon Uptake and Chlorophyll-a Concentration in the West Antarctic Peninsula Over Two Decades

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Abstract The Southern Ocean plays a vital role in global CO_2 uptake, but the magnitude and even the sign of the flux remain uncertain, and the influence of phytoplankton phenology is underexplored. This study focuses on the West Antarctic Peninsula, a region experiencing rapid climate change, to examine shifts in seasonal carbon uptake. Using 20 years of in situ air-sea CO_2 flux and satellite-derived Chlorophyll-a, we observe that the seasonal cycles of both air-sea CO_2 flux and Chlorophyll-a intensify poleward. The amplitude of the seasonal cycle of the non-thermal component of surface ocean pCO_2 increases with increasing latitude, while the amplitude of the thermal component remains relatively stable. Pronounced biological uptake occurs over the shelf in austral summer despite reduced CO_2 solubility in warmer waters, which typically limits carbon uptake through physical processes. These findings underscore the prominence of biological mechanisms in regulating carbon fluxes in this rapidly changing region.

Plain Language Summary The Southern Ocean plays a key role in absorbing carbon dioxide from the atmosphere, but we are still trying to understand exactly how much carbon dioxide the Southern Ocean absorbs and what factors influence this process. The West Antarctic Peninsula is an important area for studying these changes because it is experiencing rapid warming. We looked at changes in the amount of carbon dioxide in the surface ocean water and the amount of microscopic drifting plants (phytoplankton) based on the amount of the pigment Chlorophyll-a over the past 20 years. Seasonal cycles of both carbon dioxide and Chlorophyll-a increase from north to south in their amplitude, or their range between the minimum and the maximum each year. In summer, contrary to the effect of warm temperatures which would usually limit carbon uptake by way of physics, strong biological drawdown by phytoplankton dominates the signal.

1. Introduction

Despite the Southern Ocean playing a major role in the global carbon budget, many questions remain about the role of phytoplankton as a mechanism for carbon uptake. The Southern Ocean acts as a central hub for the world's oceans, where waters from all the world's water masses converge and mix. It is a region of deep water formation and represents an important region in regulating pre-industrial and anthropogenic ocean carbon levels, thus also impacting atmospheric CO_2 levels (Caldeira & Duffy, 2000; Marinov et al., 2006; Sarmiento & Orr, 1991). Debate remains about whether the Southern Ocean is a net sink or source for atmospheric CO_2. Models and airborne observations suggest that the Southern Ocean is a CO_2 net sink (Long et al., 2021), but early results from profiling floats suggest that it is a net source (Bushinsky et al., 2019; Gray et al., 2018). The magnitude of the difference between those two estimates is ~0.9 Gt C yr^{-1} (Long et al., 2021), approximately one third of the total global air-sea CO_2 flux (ΔpCO_2) (2.8 Gt C yr^{-1}) (Friedlingstein et al., 2023). Limited observations due to its remote location and rough conditions are the main reason for this uncertainty.

The role of phytoplankton processes is often underemphasized despite its contribution to ΔpCO_2, specifically in the Southern Ocean. Instead, physical mechanisms are more commonly emphasized, such as isopycnal transport, diapycnal eddy diffusion, transfer from the continental shelf to the deep ocean, entrainment/detrainment, and air-sea gas exchange (Arroyo et al., 2020; Bernardello et al., 2014; Caldeira & Duffy, 2000; Yang et al., 2021). However, in many regions of the Southern Ocean, strong summer season primary production is a key contributor to the seasonal oceanic CO_2 sink (Carrillo et al., 2004; Legge et al., 2015, 2017; Schultz et al., 2021; Tortell et al., 2015). Compared with other oceans, the Southern Ocean is unique in that biology plays a dominant role in the surface ocean carbon cycle on all timescales (Fay & McKinley, 2017). The biological contribution of phytoplankton production, while partially balanced by physical mechanisms at annual timescales (Munro, Lovenduski, Stephens, et al., 2015), is a principal factor, especially within the seasonal sea ice zone.

Regions vary widely and the Southern Ocean cannot be considered as a single ecosystem. Phytoplankton from different zones respond differently to environmental forcings over time (Turner et al., 2024) with polynyas and coastal zones often acting as substantial carbon sinks despite their small size (Monteiro, Kerr, & Machado, 2020; St-Laurent et al., 2019). The Drake Passage and continental shelf west of the Antarctic Peninsula (Figure 1) serve as a representative case study of spatial variability in phytoplankton biomass, phenology, and air-sea carbon exchange. The Drake Passage is a highly variable region in terms of carbon uptake, with multiple zones of CO_2 sinks and sources delimited by marine fronts (Arbilla et al., 2024). Drake Passage Chlorophyll-a concentration (Chl-a) is relatively low compared to coastal Antarctic waters, representative of conditions in the broader subpolar Southern Ocean (Fay et al., 2018).

In contrast, over the continental shelf, the seasonal cycle of air-sea carbon exchange is larger in amplitude, with surface ocean Chl-a and carbon uptake generally increasing moving poleward due to biological processes (Eveleth et al., 2017; Kim et al., 2018; Turner et al., 2024). Within the West Antarctic Peninsula (WAP) region, ocean biogeochemistry and physics are highly regionalized (Testa et al., 2021), and there is high spatial variability in carbonate system parameters in the Mid Shelf subregion (Hauri et al., 2015). Mooring data from the WAP continental shelf show that this area is an annual atmospheric CO_2 sink, with substantial biological drawdown in spring and summer only partially replenished by physical processes since seasonal sea ice suppresses winter outgassing (Shadwick et al., 2021; Yang et al., 2021). The WAP region is a sentinel region for polar ecosystem change with regionally relevant sinks for anthropogenic CO_2 (Arrigo et al., 2008; Henley et al., 2019; Schofield et al., 2018). The WAP region is losing sea ice more rapidly than other parts of Antarctica (Reid et al., 2024; Stammerjohn & Scambos, 2020), and that loss impacts water column stability, primary production and surface ocean carbon uptake (Brown et al., 2019; Ducklow et al., 2013; Schofield et al., 2017).

When considering the contribution of primary production to the seasonal CO_2 sink, the seasonal timing or phenology is often ignored. Shifts in the timing of the occurrence of the phytoplankton growing season have the potential to alter carbon cycling. Most observations in Antarctica are made in summer, thus seasonal dynamics are understudied and longer-term fluctuations in the rest of the seasonal cycle are mostly unknown. Phenological analysis is especially crucial in this region (Cimino et al., 2023) because most of the WAP shows high interannual variability in the seasonal cycle of Chl-a via satellite observations, with interannual variability increasing over time (Thomalla et al., 2011, 2023). Ship-based observations of the entire WAP marine ecosystem are available during summer and there are year-round mooring observations of pCO_2 for some isolated years; however, satellite Chl-a and ship-based pCO_2 observations specifically enable analysis of the seasonal cycle of the surface ocean carbon cycle and its biological component. The consequences of seasonality need to be considered.

This paper documents strong north-to-south gradients in the amplitude of seasonal cycles of ΔpCO_2 and Chl-a and demonstrates tight coupling between ΔpCO_2 and Chl-a seasonal cycles indicating the strong seasonal biological drawdown in this region. These findings contribute to resolving the ongoing debate about whether the Southern Ocean is a net sink or source of atmospheric CO_2, a question with significant implications for global carbon budget estimates.

2. Methods

2.1. Data Sources

2.1.1. In Situ ΔpCO_2, pCO_{2atm}, and pCO_{2sur} Observations

ΔpCO_2 was calculated using the observed partial pressure of CO_2 in the atmosphere (pCO_{2atm}) and partial pressure of CO_2 in the surface ocean (pCO_{2sur}) as the difference pCO_{2sur}–pCO_{2atm}. pCO_{2atm} is the dry air mixing ratio of atmospheric CO_2 from the Global Monitoring Laboratory surface marine boundary layer CO_2 (Lan

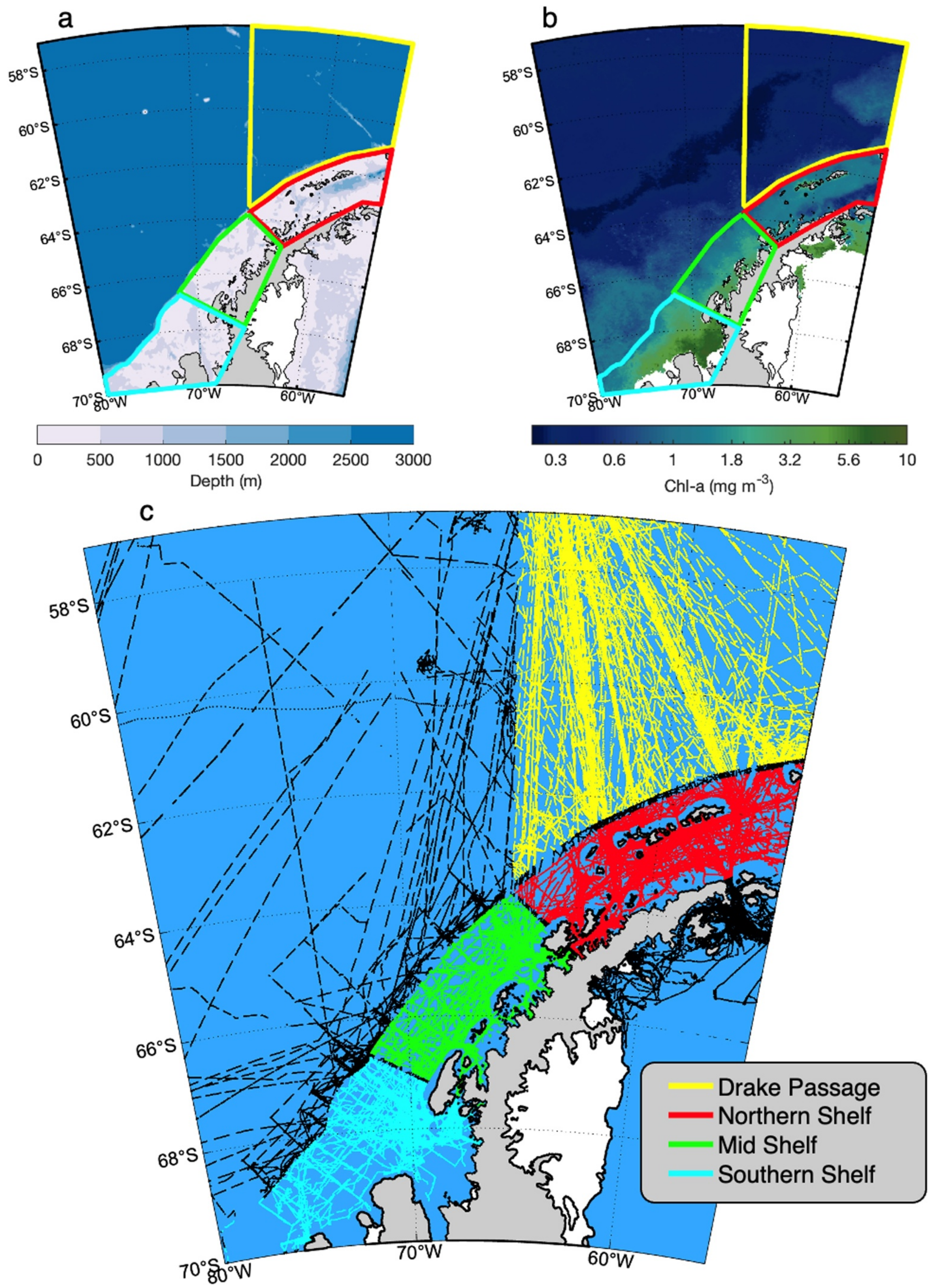

Figure 1. Map of the study area (55–80°W, 57–70°S) with subregions Drake Passage (yellow), Northern Shelf (red), Mid Shelf (green), and Southern Shelf (cyan), showing (a) bathymetry, (b) mean satellite-derived Chl-a 1997–2022, and (c) ship track locations for underway pCO_2 data 2000–2020.

et al., 2023) multiplied by NCEP sea level pressure (Kalnay et al., 1996) at monthly resolution and applying the water vapor correction according to Dickson et al. (2007). Underway pCO_{2sur} data were collected on research vessels (ship tracks) from 2000 to 2020 (Figure 1a). pCO_{2sur} was collected mainly from ships using underway and discrete sampling. More detailed methods for the collection of data in the Drake Passage Time-series and Surface Ocean CO_2 Atlas (SOCAT) v2023 (Bakker et al., 2016) are described in detail by Munro, Lovenduski, Stephens et al. (2015), Munro, Lovenduski, Takahashi et al. (2015). Many of the in situ pCO_{2sur} observations were collected as part of the Palmer Long Term Ecological Research (Pal-LTER) program. pCO_{2sur} observations are collected in nearly every month of the year, which is uncommon in the Southern Ocean region, and the high sampling frequency makes this seasonal analysis possible.

2.1.2. Satellite Chl-a Observations

Satellite-derived Chl-a data (Turner, 2025) were sourced from OC-CCI v6.0 (Sathyendranath et al., 2019), a merged multi-sensor, 4 km spatial resolution, monthly level-3 product using a global Chl-a algorithm estimated using a blended combination of OCI, OCI2, OC2, and OCX algorithms depending on optical water class membership (Gohin et al., 2002; Hu et al., 2012; O'Reilly & Werdell, 2019). Satellite-derived surface Chl-a is useful in polar regions despite inherent limitations (e.g., imperfect metric for biomass, high solar zenith angle, surface-only, limited winter data) because satellite data availability enables analysis over austral spring, summer, and early fall in the WAP (e.g., Turner et al., 2024). Ocean color data were used where >15% of monthly observations were present to avoid analyzing locations covered by sea ice for most of the record. Since global algorithms underestimate in situ WAP Chl-a by a factor of 2–2.5 (Dierssen & Smith, 2000; Kahru & Mitchell, 2010; Mitchell, 1992; Mitchell & Holm-Hansen, 1991), a correction was applied to better reflect the spatial range of in situ Chl-a for the WAP region as in Dierssen and Smith (2000), which had minimal effects at low Chl-a concentrations representative of offshore waters where the global algorithm generally performs well (Dierssen, 2000; Haëntjens et al., 2017) (Figure S1 in Supporting Information S1).

2.2. Data Analysis

Spatially, four subregions of the WAP were analyzed (Figure 1). The Drake Passage region encompasses the narrow ocean region which includes the Drake Passage Time-series ship tracks. The shelf regions are bounded by the edge of the shelf (1,000 m isobath) and sub-divided into Northern, Mid, and Southern Shelf subregions based on long-term mean Chl-a concentrations. The Drake Passage subregion here corresponds to zones from Gray et al. (2018), Haëntjens et al. (2017), and Fay and McKinley (2014) which have similar characteristics in terms of temperature, Chl-a, and seasonality. The Northern Shelf subregion corresponds to an area north of the traditional area sampled every austral summer by the Pal-LTER program, whereas the Mid Shelf subregion used here corresponds to main area sampled by the Pal-LTER program. The Southern Shelf subregion includes Marguerite Bay and comprises the southernmost portion of the Pal-LTER sampling area.

Temporally, monthly means were used to mitigate data sparsity especially of in situ pCO_{2sur} observations (Figure S2, Table S1 in Supporting Information S1). Satellite Chl-a data are unavailable over the shelf from April to September due to low light and the presence of sea ice. Ship-based pCO_{2sur} observations are limited for the winter season in the Mid Shelf and slightly biased toward summer for all subregions. Data were analyzed for austral years 2000–2020 that is, 1 July 2000 to 30 June 2020. Seasons used for the Southern Hemisphere are delimited by the months December to February (summer), March to May (fall), June to August (winter), and September to November (spring).

Sea surface temperature (SST) values from concurrent underway ship track data were used to calculate thermally driven (pCO_{2sur}-T) and non-thermally-driven (pCO_{2sur}-non-T) components of the pCO_{2sur} seasonal cycles. pCO_{2sur}-T and pCO_{2sur}-non-T components were calculated following the approach of Takahashi et al. (1993) using equations from Wanninkhof et al. (2022).

Correlations between seasonal cycles of Chl-a and pCO_2 seasonal cycles (ΔpCO_2, pCO_{2sur}, pCO_{2sur}-T, and pCO_{2sur}-non-T) were calculated over all months per year when data were present. We determined the Pearson correlation coefficient (R) between variables and computed the significance (p) by testing the null hypothesis that the correlation is zero using a Student's t-distribution via MATLAB function "corrcoef". Amplitudes of seasonal cycles were calculated via the difference between the maximum and minimum monthly values over the year for each decadal mean seasonal cycle (i.e., for 2000–2010, Chl-a seasonal cycle amplitude = maximum in January–minimum in September).

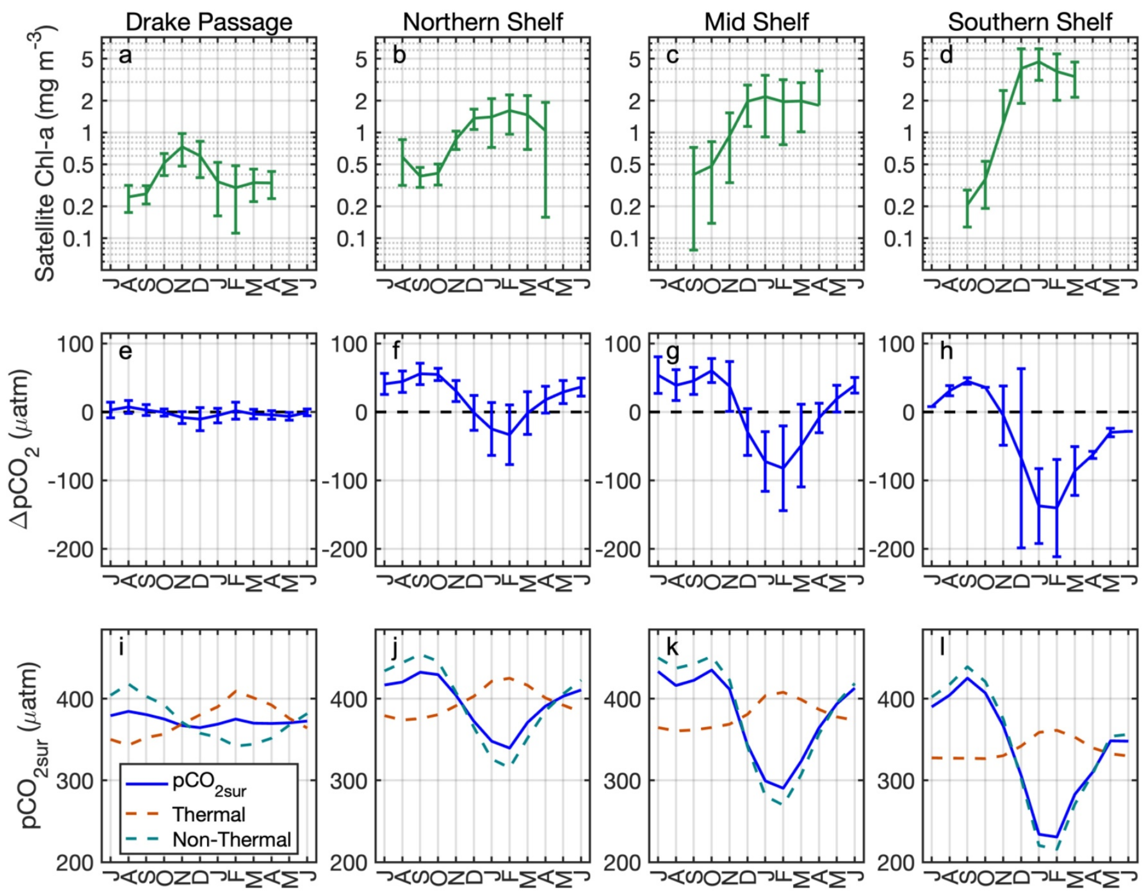

Figure 2. Seasonal cycles of Chl-a, ΔpCO_2, and pCO_{2sur} with thermal and non-thermal components 2000–2020 showing Chl-a (a–d), ΔpCO_2 (e–h), and pCO_{2sur} (i–l) for the Drake Passage (a, e and i), Northern Shelf (b, f and j), Mid Shelf (c, g and k), and Southern Shelf (d,h,l) subregions. (See Figure S3 in Supporting Information S1 for ΔpCO_2 as in e-h with regionally scaled *y*-axes). Error bars represent ±1 standard deviation.

3. Results

3.1. Seasonal Patterns and Amplitudes of Seasonal Cycles

Seasonal cycles in Chl-a and ΔpCO_2 increase in amplitude moving poleward (Figure 2, Table 1). In the Drake Passage, Chl-a is generally low (<1 mg m^{-3}) with a small amplitude seasonal cycle (0.5 mg m^{-3}) (Figure 2a). The ΔpCO_2 seasonal cycle in the Drake Passage is similarly relatively small in amplitude (18 μatm) (Figure 2e, Figure S3 in Supporting Information S1). In the Northern Shelf, the Chl-a seasonal cycle amplitude of 1.2 mg m^{-3} (Figure 2b) and the ΔpCO_2 seasonal cycle amplitude of 89 μatm (Figure 2f) are larger than those of the Drake Passage but not as substantial as those in subregions farther to the south. In the Mid Shelf, Chl-a shows a greater seasonal cycle amplitude of 1.8 mg m^{-3} (Figure 2c) and a similarly large ΔpCO_2 seasonal cycle amplitude (143 μatm) (Figure 2g). The Southern Shelf has the highest amplitude seasonal cycles of any subregion for both Chl-a (4.5 mg m^{-3}) (Figure 2d) and ΔpCO_2 (186 μatm) (Figure 2h).

The thermal and non-thermal components of the pCO_{2sur} seasonal cycle are balanced in the Drake Passage, but non-thermal drivers including biology overpower the seasonal cycle over the shelf, particularly in the Southern Shelf subregion. The small amplitudes of the pCO_{2sur} and ΔpCO_2 seasonal cycles in the Drake Passage result from the opposing effects of temperature and non-temperature related factors including biology (Figure 2i). Winter cooling decreases pCO_{2sur} concurrent with deep mixing increasing pCO_{2sur}. Summer warming increases pCO_{2sur} while biological carbon uptake lowers pCO_{2sur}. In the Drake Passage, these components balance one another to result in a small-amplitude seasonal cycle. In the Northern Shelf and Mid Shelf, the thermal component is only partially balanced by the non-thermal component, with the non-thermal component showing strong

Table 1
Amplitudes and Correlations of Chl-a, ΔpCO_2, pCO_{2sur} and the Thermal and Non-Thermal Components of pCO_{2sur} Seasonal Cycles

	Drake passage		Northern shelf		Mid shelf		Southern shelf	
Seasonal Cycle Amplitudes								
Chl-a	0.5 mg m^{-3}		1.2 mg m^{-3}		1.8 mg m^{-3}		4.5 mg m^{-3}	
ΔpCO_2	18 µatm		89 µatm		143 µatm		186 µatm	
pCO_{2sur}	20 µatm		93 µatm		145 µatm		195 µatm	
pCO_{2sur}-T	66 µatm		51 µatm		47 µatm		35 µatm	
pCO_{2sur}-non-T	76 µatm		139 µatm		182 µatm		224 µatm	
Seasonal Cycle Correlations[a]								
	R[a]	p	R	p	R	p	R	p
Chl-a versus ΔpCO_2	*−0.76*	*0.018*	*−0.97*	*< 0.001*	*−0.93*	*0.001*	*−0.95*	*0.001*
Chl-a versus pCO_{2sur}	−0.66	0.055	*−0.97*	*< 0.001*	*−0.93*	*0.001*	*−0.95*	*0.001*
Chl-a versus pCO_{2sur}-T	−0.07	0.854	*0.96*	*< 0.001*	*0.90*	*0.002*	*0.90*	*0.006*
Chl-a versus pCO_{2sur}-non-T	−0.13	0.740	*−0.98*	*< 0.001*	*−0.94*	*0.000*	*−0.95*	*0.001*

Note. Italicized values indicate significant correlations ($p < 0.05$). [a]Pearson correlation coefficient.

negative correlations with the Chl-a seasonal cycle (Table 1). In the Southern Shelf, the non-thermal component dominates the seasonal cycle (Figure 2l). This far south, biological production is strong enough to substantially overbalance the thermal component.

3.2. Coupling Between Seasonal Cycles of Chl-a and ΔpCO_2

Seasonal cycles of phytoplankton biomass and carbon uptake are generally the inverse of one another in subpolar and polar regions (Körtzinger et al., 2008; Lüger et al., 2004; Takahashi et al., 1993, 2002). In this analysis, Chl-a and ΔpCO_2 seasonal cycles are strongly and significantly negatively correlated to one another ($p < 0.05$) in every subregion (Figure 2, Table 1). The strongest Chl-a–ΔpCO_2 correlations occur in the three shelf subregions ($R = -0.97$, -0.93, and -0.95). Slightly less strong Chl-a–ΔpCO_2 correlations are found in the Drake Passage ($R = -0.76$) where the seasonal cycle of ΔpCO_2 is less distinct. Chl-a and pCO_{2sur} seasonal cycles are strongly negatively correlated over the shelf, but not significantly in the Drake Passage. Over the shelf, correlations between Chl-a and the thermal and non-thermal components of pCO_{2sur} are strongly correlated, with positive correlations ($R = 0.9$ to 0.96) between the Chl-a and the thermal component and negative correlations ($R = -0.94$ to -0.98) between Chl-a and the non-thermal component (which includes biology). In the Drake Passage, no correlation was found between Chl-a and the thermal and non-thermal components of pCO_{2sur} (Table 1).

4. Discussion

4.1. Biologically Mediated ΔpCO_2 Seasonal Cycles

The seasonal cycle of pCO_{2sur} in the subregions is driven by a combination of thermal and non-thermal factors, with non-thermal components (including biological processes) showing larger amplitudes than thermal components and stronger correlations with Chl-a (Table 1, Figure 2). Sea ice formation, meltwater, and vertical mixing likely regulate pCO_2 seasonal cycles in addition to temperature and biological influences; however, the strong correlations between Chl-a and the non-thermal component of the pCO_2 seasonal cycles support the idea that biological production is a strong driver over the shelf. In the Drake Passage, the opposing influences of temperature and biology result in a small-amplitude seasonal cycle and a modest CO_2 sink. Conversely, in the Northern and Mid Shelves, the non-thermal component is only partially balanced by thermal effects. The Southern Shelf is dominated by non-thermal factors, including biological production, producing a large seasonal cycle amplitude and functioning as a noteworthy CO_2 sink.

These results suggest that biology dominates the seasonal cycle of surface ocean carbon uptake, especially over the Southern Shelf. Correlations between the seasonal cycles of ΔpCO_2 and Chl-a are strongly negative in all subregions (Figure 2, Table 1). The amplitudes of the non-thermally-driven component of the seasonal cycle of pCO_{2sur} (which includes biology) are larger in all subregions than those of the thermally driven component (Figures 2i–2l). pCO_{2sur}-non-T amplitudes reach 224 µatm (Southern Shelf), while pCO_{2sur}-T seasonal cycle amplitudes range from 35 to 66 µatm (Table 1). The thermal component of the seasonal cycle is mirrored in SST seasonal cycles, which show warm temperatures in summer months with the highest temperatures occurring in summer in all subregions. Contrary to the effect of summer warming which would typically limit carbon uptake via low solubility in other ocean regions, strong biological drawdown dominates the ΔpCO_2 seasonal signal during these warm months in the shelf subregions. The Southern Ocean is the only global ocean region where biology controls the surface ocean carbon cycle at all timescales (Fay & McKinley, 2017); the WAP continental shelf is a prime example of this phenomenon. Biology-driven control of pCO_2 has been observed in the WAP more so than in other subregions of the Pacific Southern Ocean (Mo et al., 2023), and in the Northern Shelf biological activity was a dominant surface ocean carbon removal mechanism (Ito et al., 2018). The Drake Passage, with its open ocean characteristics, allows physical mechanisms to partially balance out biological uptake, acting to dampen the seasonal cycle in this region (Munro, Lovenduski, Stephens et al., 2015). Conversely, over the WAP continental shelf, the seasonal cycles of ΔpCO_2 and Chl-a are tightly coupled (Figure 2, Table 1) and large in amplitude, suggesting that biology governs the surface ocean carbon cycle over the shelf.

4.2. Strong North–South Gradient in Biological Carbon Drawdown

The amplitudes of the seasonal cycles of ΔpCO_2 and Chl-a increase moving poleward (Figure 2). The Drake Passage ΔpCO_2 seasonal cycle amplitude of 18 µatm compares well with that of the Southern Ocean Time Series just south of Australia (Yang et al., 2024) and is representative of open-ocean Southern Ocean waters. Over the continental shelf, moving from north to south, the amplitudes increase, with approximately an order of magnitude difference between the Drake Passage and the Southern Shelf subregion amplitudes (from 18–186 µatm to 0.5–4.5 mg m^{-3}) (Figure 2, Table 1). While the Northern Shelf and Mid Shelf show strong relationships between Chl-a and the non-thermal component of pCO_{2sur}, the seasonal cycles of carbon uptake there are not as strongly biologically driven nor as strong a sink as in the Southern Shelf. During austral summer the Northern Shelf acts as a CO_2 sink, but at the annual timescale operates as a net source (Ito et al., 2018; Monteiro, Kerr, Orselli, & Lencina-Avila, 2020). The Southern Shelf amplitudes are considerably large, demonstrating highly productive waters with some of the highest seasonal biologically driven inorganic carbon drawdown anywhere in the global ocean (Legge et al., 2015; Roobaert et al., 2019). The biological contribution of phytoplankton production is more substantial near the seasonal sea ice zone, possibly due to sea ice's effects to enhance the stability of the upper water column, shielding from wind mixing, or ice edge upwelling, or gradients in nutrient availability (Smith, 1987), drivers which require future research.

4.3. Ecosystem Implications

Changes in carbon uptake are intricately associated with shifts in the overall carbonate chemistry of the system, occurring simultaneously and influencing each other through various feedback mechanisms. There may be a shift in pH and saturation state of aragonite especially in summer and fall over the shelf. In the Australian sector of Southern Ocean, the seasonal cycle of pCO_2 increased in amplitude from 2011 to 2020 with a corresponding decrease in pH (Shadwick et al., 2023). In the WAP, large biological carbon drawdown in summer generally increases aragonite saturation state in surface waters nearshore despite meltwater inputs, thus there are unlikely to be negative consequences in terms of acidified conditions for calcifying organisms in this system in the near term. In terms of phytoplankton community composition, diatoms are particularly important for the efficiency of the biological pump over the shelf in this region (Brown et al., 2019; Costa et al., 2020), and the seasonal succession of different groups and top-down grazing pressure likely moderate the biological contribution to ΔpCO_2 (Costa et al., 2023); these factors merit further study. Overall, our results highlight the need for a broader understanding of seasonal variability and long-term trends in the WAP marine ecosystem, including continued monitoring and research efforts to assess the impacts of climate change on coastal Antarctic environments.

5. Conclusions

In summary, the seasonality of surface ocean carbon uptake varies with latitude in the WAP region, and seasonal cycles show strong biologically driven uptake moving poleward. Seasonal cycles of both ΔpCO_2 and Chl-a increase in amplitude moving poleward, from small-amplitude seasonal cycles (18 µatm and 0.5 mg m^{-3}) in the Drake Passage to high-amplitude seasonal cycles (186 μatm and 4.5 mg m^{-3}) over the southern continental shelf region. Massive biological drawdown of CO_2 occurs over the continental shelf in summer, with biological utilization driving pCO_{2sur} substantially lower, overshadowing the tendency for summer warming and low solubility to concurrently raise pCO_{2sur}. These findings help answer whether the Southern Ocean acts as a net sink or source of CO_2 in the context of the global carbon budget.

Appendix A: Notation

Abbreviation Definition
Amplitude
Maximum minus minimum monthly values over the seasonal cycle
Chl-a
Chlorophyll-a pigment concentration (mg m^{-3})
OC-CCI
Ocean color climate change initiative
OC2
Ocean Color-2 Chl-a algorithm using two wavelengths (O'Reilly et al., 2000)
OCI
Ocean Color Index Chl-a algorithm (Hu et al., 2019)
OCI2
Chl-a algorithm adjusted as a hybrid between one version of OCI and OCX (Hu et al., 2019).
OCX
Ocean Color-3 to −6 series of Chl-a algorithms using 3 to 6 wavelengths (O'Reilly & Werdell, 2019).
ΔpCO_2
Air-sea CO_2 flux, the difference pCO_{2sur}–pCO_{2atm} (μatm)
pCO_{2atm}
Partial pressure of carbon dioxide in the atmosphere (μatm)
pCO_{2sur}
Partial pressure of carbon dioxide in the surface ocean (μatm)
pCO_{2sur}-T
Thermal component of the pCO_{2sur} seasonal cycle (μatm)
pCO_{2sur}-non-T
Non-thermal component of the pCO_{2sur} seasonal cycle (μatm)
Pal-LTER
Palmer Long-term ecological research program
SOCAT
Surface Ocean CO_2 Atlas
SST
Sea surface temperature
WAP
West Antarctic Peninsula

Data Availability Statement

Ocean color data used in satellite-derived Chl-a analysis are available from the Ocean Colour Climate Change Initiative (OC-CCI) (Sathyendranath et al., 2019) and are accessible at https://www.oceancolour.org/thredds/catalog-cci.html?dataset=CCI_ALL-v6.0-MONTHLY. Surface ocean pCO_2 data are available from the Surface Ocean CO_2 Atlas (SOCAT) v2023 (Bakker et al., 2016) and are accessible at https://socat.info/index.php/data-access/. For this study SOCAT V2023 was used which is available at https://socat.info/index.php/previous-versions/. pCO_{2atm} is the dry air mixing ratio of atmospheric CO_2 (xCO_2) from the Global Monitoring Laboratory surface marine boundary layer CO_2 product available at https://gml.noaa.gov/ccgg/mbl/mbl.html (last access: 19 November 2024) (Lan et al., 2023). Code to make figures in this paper is available at https://doi.org/10.5281/zenodo.14608738 (Turner, 2025).

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