

Article

Climate-Driven Decadal Trends of Particulate Organic Carbon in the Agulhas Current System

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Abstract

The Agulhas Current system, the strongest western boundary current in the Southern Hemisphere, plays a key role in regulating carbon cycling in the southwestern Indian Ocean. However, the variability of particulate organic carbon (POC) and its response to climate forcing remain poorly understood. Using multi-source satellite observations and reanalysis data from 1998–2025, we investigated the spatial, seasonal, interannual, and decadal variability of POC, chlorophyll-a (Chl-a), and POC:Chl-a in the Agulhas Current system. Our results show that Chl-a and POC concentrations are consistently higher in the Agulhas Retroflexion than in the Return Current region, reflecting enhanced mesoscale activity and nutrient supply. Seasonally, Chl-a and POC peaked during austral spring–summer and declined during autumn–winter, whereas POC:Chl-a exhibited an opposite cycle driven by variations in light availability and mixed-layer depth. At inter-annual timescales, ENSO exerted a pronounced influence on POC variability. El Niño events increased Chl-a and POC by up to 0.3 mg m⁻³ and 30 mg m⁻³, respectively, while reducing POC:Chl-a by up to 60 g g⁻¹ through enhanced eddy activity and improved light conditions; the opposing anomalies occurred during La Niña events. Positive Southern Annular Mode (SAM), phases increased Chl-a and POC in the Return Current region by strengthening vertical mixing and nutrient entrainment. On multi-decadal timescales, contrasting regional trends resulted in a persistent increase in the POC:Chl—a ratio across both regions, suggesting a structural shift in the particulate carbon pool and an increasing decoupling between particulate organic carbon and phytoplankton biomass. These results highlight the combined roles of stratification, mesoscale dynamics, and climate modes in regulating regional carbon cycling and carbon-sink variability.

Keywords: satellite observations; carbon cycling; chlorophyll-a; eddy kinetic energy; southern annular mode; El Niño–Southern Oscillation

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1. Introduction

Particulate organic carbon (POC), the carbon contained in suspended and sinking organic particles, is a major component of the marine organic carbon pool and a key carrier of the biological carbon pump [1,2]. As the primary producers in the ocean, phyto-

plankton convert dissolved inorganic carbon into organic matter through photosynthesis and represent one of the principal sources of POC [2]. By linking surface primary production with deep-ocean carbon sequestration, POC plays a critical role in regulating marine carbon cycling [1–4]. Therefore, understanding its distribution patterns and controlling mechanisms is essential for quantifying regional and global carbon cycle dynamics.

The Agulhas Current, one of the strongest western boundary currents in the global ocean, flows southwestward along the southeastern coast of Africa and transports warm, saline Indian Ocean waters into the South Atlantic through Agulhas leakage [5,6]. Its hydrographic variability has been extensively documented using shipboard observations, satellite remote sensing, and numerical modeling, providing important insights into regional circulation, water-mass properties, and mesoscale dynamics [5–7]. Long-term ocean carbon observation programs, such as the Carbon-Sakhalin observational site in the Sea of Okhotsk, further highlight the value of sustained observations for understanding regional carbon-cycle variability [8]. This process exerts an important influence on the global meridional overturning circulation and oceanic heat redistribution [7]. Variability in the Agulhas Current is strongly regulated by large-scale climate modes, including the Southern Annular Mode (SAM) and the El Niño–Southern Oscillation (ENSO) [5]. For example, El Niño events can intensify the current and promote its westward extension, often enhancing upper-ocean stratification and suppressing upwelling [9,10]. These changes reduce nutrient supply to the euphotic zone, thereby affecting phytoplankton productivity, POC production, and carbon export [11–14].

Recent advances in satellite remote sensing have enabled long-term monitoring of marine biogeochemical properties in the Agulhas Current region [11–13,15,16]. Previous studies have reported a significant increase in chlorophyll-a (Chl-a) concentrations between 1998 and 2022, particularly in the Agulhas Return Current region, suggesting enhanced phytoplankton carbon fixation potential [11]. In addition, SAM and ENSO have been shown to influence the seasonal and interannual variability of Chl-a through their regulation of mesoscale physical processes such as eddy activity [11,12]. Although the Agulhas Current system is recognized as a region of elevated productivity and carbon export potential due to its dynamic nutrient transport processes [11–18], the spatiotemporal variability of POC and its responses to environmental forcing across multiple time-scales remain poorly understood.

To address these knowledge gaps, this study employs satellite remote sensing and reanalysis datasets spanning 1998–2025 to investigate the seasonal, interannual, and long-term variability of Chl-a, POC, and the POC:Chl-a ratio in the Agulhas Current region. We further examine the influences of key environmental factors, including light availability, Sea Surface Temperature (SST), Sea Surface Wind (SSW), Mixed Layer Depth (MLD), and Eddy Kinetic Energy (EKE), on Chl-a and POC dynamics. The results provide new insights into carbon cycling processes in the Agulhas Current system and contribute to improving predictions of regional carbon-sink variability and ecosystem responses under future climate change.

2. Materials and Methods

2.1. Regional Setting

The study area is located in the northwestern Southern Ocean (15–50° S, 5–55° E; Figure 1), encompassing the Agulhas Current, the Agulhas Retroflexion, and the Agulhas Return Current, which together form the core region of the Agulhas Current system. To investigate POC variability under contrasting physical environments, two representative subregions were selected based on the long-term distributions of SST, mean geostrophic circulation, EKE, and the climatological patterns of Chl-a and POC (Figure 1). Subregion A (39–44° S, 14–20° E) is located within the Agulhas Retroflexion, where strong currents,

enhanced EKE, and sharp SST gradients indicate intense mesoscale activity and vigorous water-mass exchange. In contrast, Subregion B (39–44° S, 25–45° E) is situated in the Agulhas Return Current region, which is characterized by relatively weaker currents, lower EKE, and more homogeneous SST, representing comparatively stable open-ocean conditions.

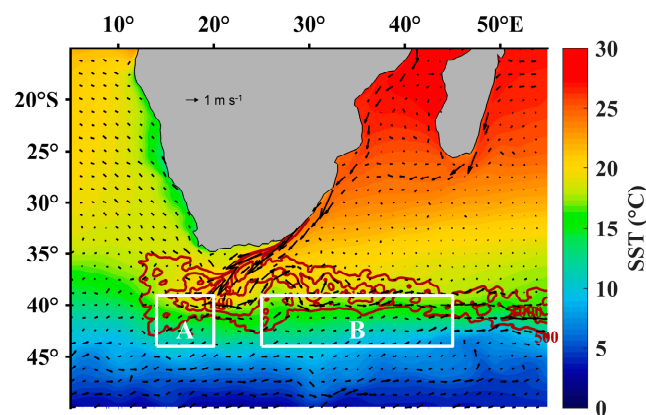


Figure 1. Climatological (1998–2025) distributions of sea surface temperature (SST, shading), surface circulation (vectors), and eddy kinetic energy (EKE, contours) in the Agulhas Current system. The black boxes indicate the two study subregions (A and B).

2.2. Data

Monthly Chl-a, POC, photosynthetically active radiation (PAR), and diffuse attenuation coefficient at 490 nm [$K_d(490)$] for the period 1998–2025 were obtained from the European Space Agency GlobColour multi-sensor merged dataset (<https://hermes.acri.fr/index.php>, accessed on 1 January 2026). This dataset integrates observations from SeaWiFS, MODIS-Aqua, MERIS, VIIRS-SNPP, and OLCI-A/B sensors and provides Level-3 products at a spatial resolution of 4 km following atmospheric correction and bio-optical processing. Monthly SSW data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) global wind and wind-stress climate product with a spatial resolution of 0.25° (https://data.marine.copernicus.eu/product/WIND_GLO_PHY_CLIMATE_L4_MY_012_003/description, accessed on 1 January 2026). Monthly geostrophic velocity anomalies (0.25° resolution) were obtained from the Archiving Validation and Interpretation of Satellite Oceanography (AVISO) database (https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_MY_008_047/description, accessed on 1 January 2026).

Monthly SST and MLD fields were derived from the CMEMS ARMOR3D Level-4 multi-observation merged product (https://data.marine.copernicus.eu/product/MULTI-OBS_GLO_PHY_TSUV_3D_MYNRT_015_012/description, accessed on 1 January 2026), which combines satellite and in situ observations through optimal interpolation to generate three-dimensional oceanographic fields at a spatial resolution of 0.25° .

To examine the influence of large-scale climate variability on POC and Chl-a, the SAM and ENSO indices were analyzed. Monthly SAM indices were obtained from the British Antarctic Survey (<https://legacy.bas.ac.uk/met/gjma/sam.html>, accessed on 1 January 2026), while ENSO variability was represented by the Multivariate ENSO Index version 2 (MEI.v2) provided by the NOAA Physical Sciences Laboratory (<https://psl.noaa.gov/enso/mei>, accessed on 1 January 2026).

2.3. Data Processing and Analysis

2.3.1. Climatological and Seasonal Analysis

Monthly climatological means were calculated using the 1998–2025 time series to characterize the seasonal variability of Chl-a, POC, POC:Chl-a, and environmental variables. Longitude–month climatological sections were constructed to illustrate seasonal evolution across the study region.

2.3.2. Interannual Variability Analysis

Monthly anomalies were calculated by removing the climatological seasonal cycle. A 13-month running mean was applied to suppress seasonal variability and emphasize interannual signals. Relationships between biological variables and the SAM and ENSO indices were examined.

2.3.3. Trend Analysis

Decadal trends during 1998–2025 were quantified using pixel-wise ordinary least-squares linear regression. The regression slope was used to represent the rate of temporal change, while statistical significance was evaluated using a two-tailed Student's *t*-test with a significance level of $p < 0.05$. This approach enables the identification of spatial patterns of change in key variables, including Chl-a and POC, and provides a quantitative basis for assessing trend variations in regional carbon cycling.

2.3.4. Environmental Indicators

To characterize the light environment experienced by phytoplankton within the mixed layer, I_m was estimated following [19]:

$$I_m = \frac{1}{K_d Z_{ml}} I_0 e^{-K_d Z_{ml}} (1 - e^{-K_d Z_{ml}}) \quad (1)$$

where I_0 is the surface PAR, K_d is the diffuse attenuation coefficient, and Z_{ml} is the mixed-layer depth.

Mesoscale dynamical activity was quantified using *EKE*, calculated from monthly geostrophic current velocity fields as [20]:

$$EKE = \frac{1}{2} \times (u'^2 + v'^2) \quad (2)$$

where u' and v' denote anomalies of the zonal and meridional current velocities, respectively.

3. Results

3.1. Climatological Spatial Distribution of Chl-a and POC

The climatological distributions of Chl-a and POC during 1998–2025 exhibit pronounced spatial heterogeneity across the Agulhas Current system (Figure 2). Elevated concentrations are primarily concentrated in Subregions A and B, indicating that these areas represent biological hotspots within the study region. Subregion A (Agulhas Retroflection) exhibits the highest values, with Chl-a ranging from 0.25 to 0.40 mg m^{−3} and POC from 80 to 100 mg m^{−3} (Figure 2a,b). Subregion B (Agulhas Return Current) also shows relatively high concentrations, although both Chl-a (0.25–0.35 mg m^{−3}) and POC (80–90 mg m^{−3}) are slightly lower than those in Subregion A (Figure 2a,b). The POC:Chl-a ratio remains generally below 300 g:g in both regions (Figure 2c), suggesting a strong coupling between particulate organic carbon and phytoplankton biomass. Overall, the spatial coincidence of elevated Chl-a and POC highlights the importance of the Agulhas Retroflection and Return Current regions as areas of enhanced biological production and carbon accumulation.

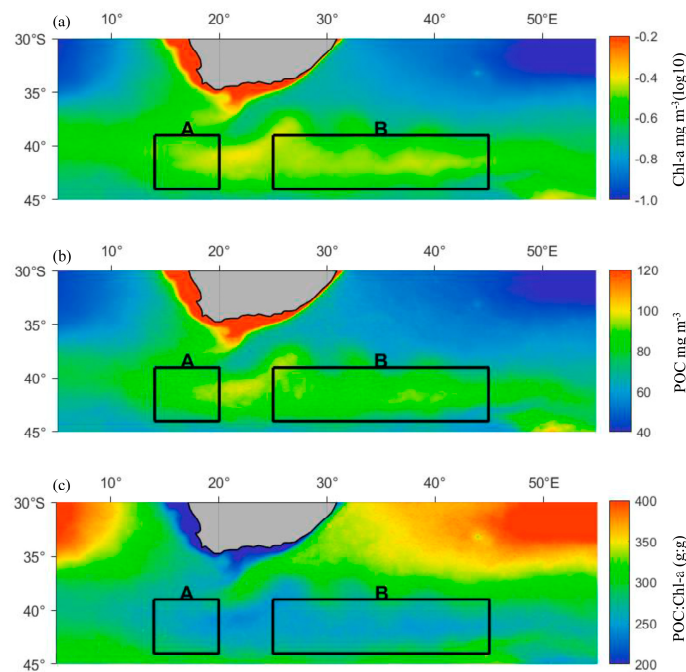


Figure 2. Climatological (1998–2025) spatial distributions of (a) chlorophyll-a (Chl-a), (b) particulate organic carbon (POC), and (c) POC:Chl-a in the Agulhas Current system.

3.2. Seasonal Variability of Chl-a and POC

Both subregions display a pronounced seasonal cycle characteristic of mid-to-high latitude regions of the Southern Hemisphere, with maximum values occurring during austral spring–summer and minima during autumn–winter (Figure 3). Biological production peaks between September and February, when Chl-a reaches 0.36–0.48 mg m^{-3} in Subregion A and 0.32–0.44 mg m^{-3} in Subregion B (Figure 3a,b). During the same period, POC concentrations remain high, ranging from approximately 90–100 mg m^{-3} in Subregion A and 85–100 mg m^{-3} in Subregion B (Figure 3a,b). The POC:Chl-a ratio remains relatively stable (240–295 g:g; Figure 3c), indicating that newly produced phytoplankton biomass is the dominant contributor to the POC pool.

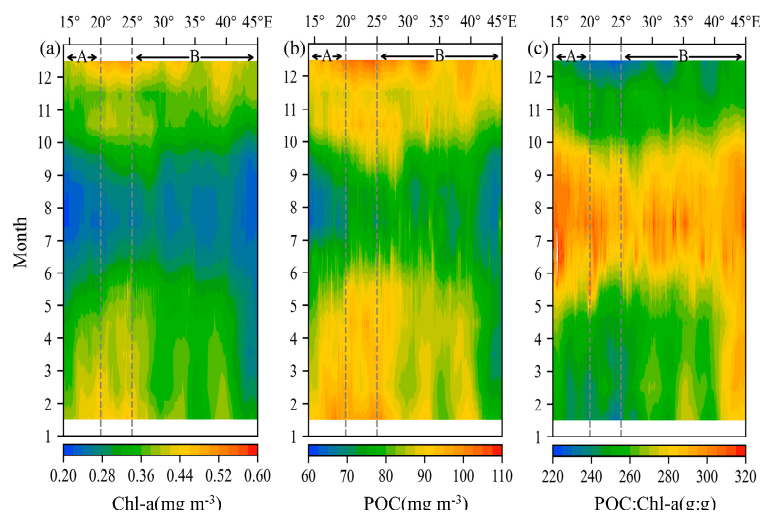


Figure 3. Longitude–month climatological distributions of monthly mean (a) chlorophyll-a (Chl-a), (b) particulate organic carbon (POC), and (c) POC:Chl-a in the study region for 1998–2025. The

dashed vertical lines indicate the boundary between Subregion A (Retroflexion region) and Subregion B (Return Current region).

During austral autumn and winter (March–August), Chl-*a* decreases markedly in both regions, reaching values near 0.20 mg m^{-3} (Figure 3a). POC also declines, particularly in Subregion A, where concentrations decrease to $65\text{--}75 \text{ mg m}^{-3}$ (Figure 3b). In contrast, Subregion B maintains comparatively higher POC levels ($70\text{--}95 \text{ mg m}^{-3}$; Figure 3b). Accompanying these changes, the POC:Chl-*a* ratio increases to $270\text{--}310 \text{ g:g}$ and is consistently higher in Subregion B (Figure 3c). This seasonal decoupling between POC and Chl-*a* suggests an increasing contribution of detrital material and/or enhanced cellular carbon accumulation under unfavorable growth conditions.

3.3. Interannual Variability of Chl-*a* and POC

Substantial interannual variability is observed in Chl-*a*, POC, and the POC:Chl-*a* ratio throughout the study period (Figure 4), reflecting the influence of large-scale climate modes. In Subregion A, variability is closely associated with ENSO (Figure 4b–e). El Niño events generally correspond to positive anomalies in both Chl-*a* and POC, whereas La Niña events are accompanied by negative anomalies (Figure 4b–e). During the strong El Niño event of 1998, Chl-*a* and POC anomalies reached approximately 0.3 mg m^{-3} and 30 mg m^{-3} , respectively (Figure 4b–d), while the POC:Chl-*a* ratio decreased by nearly 60 g:g (Figure 4e). Conversely, during the 2020–2022 La Niña event, Chl-*a* and POC exhibited negative anomalies of approximately -0.1 mg m^{-3} and -10 mg m^{-3} , accompanied by a positive POC:Chl-*a* anomaly of about 60 g:g (Figure 4b–e). Notably, the response to El Niño events is not uniform. Despite the 2015–2016 El Niño being one of the strongest on record, the POC anomaly in 2015 was considerably weaker than that observed during the 1998 and 2009 El Niño events (Figure 4c,d). This discrepancy suggests that additional factors modulate the biological response to ENSO forcing in this region, which will be further examined in the discussion.

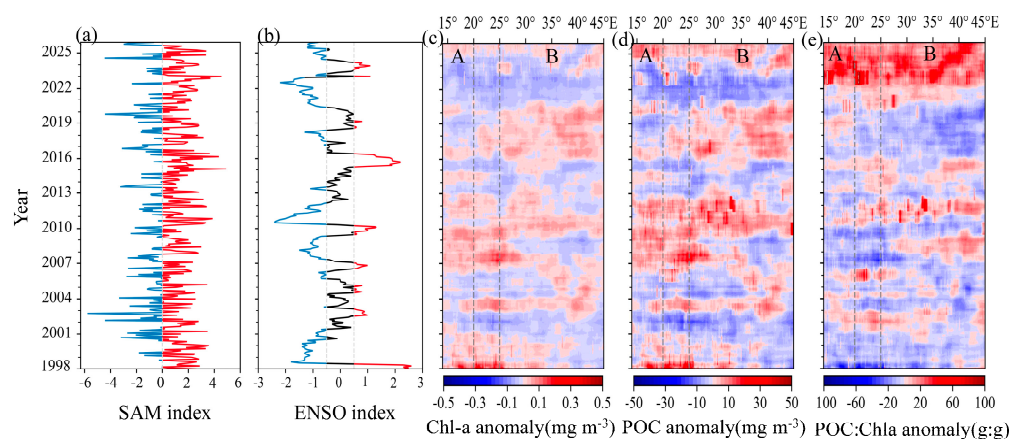


Figure 4. Temporal variations of the (a) Southern Annular Mode (SAM) index and (b) ENSO index during 1998–2025, together with longitude–year distributions of anomalies in (c) chlorophyll-*a* (Chl-*a*), (d) particulate organic carbon (POC), and (e) POC:Chl-*a* across the study region. The time-series in (c–e) are smoothed with a 13-month running mean.

In contrast, biological variability in Subregion B appears to be more strongly linked to SAM. Positive SAM phases, particularly during 2010–2013 and 2016–2019, are associated with positive Chl-*a* and POC anomalies ($\sim 0.1 \text{ mg m}^{-3}$ and $\sim 10 \text{ mg m}^{-3}$, respectively) and reduced POC:Chl-*a* ratios (Figure 4). Negative SAM phases produce the

opposite pattern, characterized by lower Chl-a and POC concentrations and elevated POC:Chl-a values (Figure 4). These results indicate that different climate modes dominate interannual variability in the two subregions.

3.4. Decadal Trends in Chl-a and POC

Long-term trend analysis reveals contrasting trajectories between Subregions A and B over the period 1998–2025 (Figure 5). In Subregion A, both Chl-a and POC exhibit widespread declining trends (Figure 5a,b), with regional mean decreases of $0.017 \text{ mg m}^{-3} \text{ decade}^{-1}$ and $1.019 \text{ mg m}^{-3} \text{ decade}^{-1}$, respectively (Figure 5d,e). Despite these declines, the POC:Chl-a ratio increases significantly at a rate of $10.15 \text{ g:g decade}^{-1}$ (Figure 5f), indicating a progressive shift toward higher carbon content relative to phytoplankton biomass.

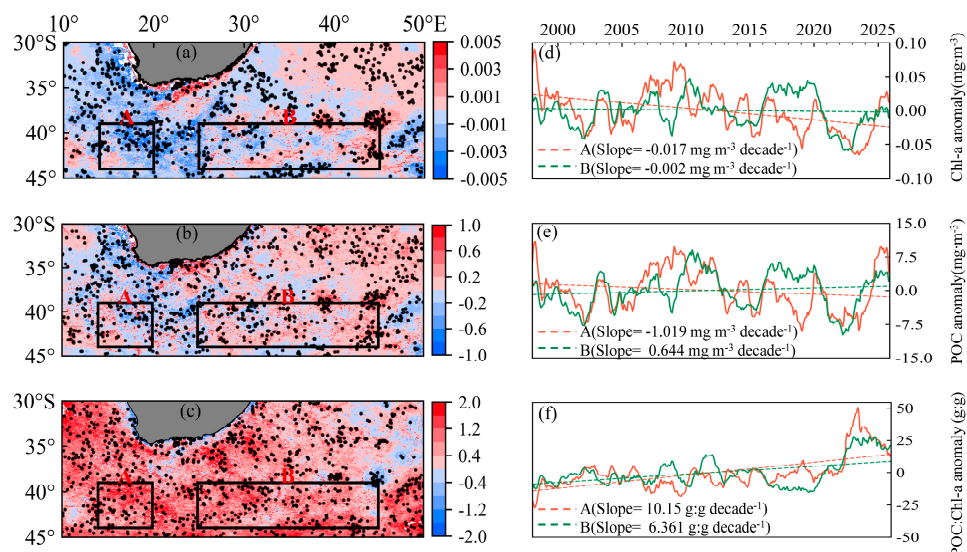


Figure 5. Spatial linear trends in (a) chlorophyll-a (Chl-a), (b) particulate organic carbon (POC), and (c) POC:Chl-a during 1998–2025. Panels (d–f) present the area-averaged time series and corresponding linear trends of Chl-a, POC, and POC:Chl-a for the Agulhas Retroflection region (A) and Agulhas Return Current region (B). The black dots indicate grid cells where the trend is statistically significant at the 95% confidence level ($p < 0.05$).

By contrast, Subregion B shows a weak declining trend in Chl-a but a persistent increase in POC (Figure 5a,b), with regional trends of $-0.002 \text{ mg m}^{-3} \text{ decade}^{-1}$ and $0.644 \text{ mg m}^{-3} \text{ decade}^{-1}$, respectively (Figure 5d,e). The POC:Chl-a ratio also increases, at a rate of $6.361 \text{ g:g decade}^{-1}$ (Figure 5f). The divergence between the declining Chl-a and increasing POC suggests that POC in this region is influenced not only by local phytoplankton production but also by additional processes such as detrital accumulation and lateral transport. Collectively, these contrasting trends highlight substantial regional differences in the mechanisms controlling biological production and carbon cycling within the Agulhas Current system.

4. Discussion

4.1. Seasonal Controls on POC Variability

Seasonal variability in POC within the Agulhas Current system is primarily regulated by light availability and upper-ocean mixing processes [11,12]. Because nutrient concentrations are generally sufficient in this high-latitude region, variations in phytoplankton production are largely controlled by changes in irradiance and mixed-layer dynamics.

During austral spring and summer, increased PAR and reduced wind-driven mixing promote surface warming and mixed-layer shoaling (Figure 6). The resulting increase in mixed-layer mean irradiance enhances phytoplankton photosynthesis and carbon fixation (Figures 6e and 7), leading to concurrent increases in Chl-a and POC. The lower POC:Chl-a ratios observed during this period suggest that newly produced phytoplankton biomass constitutes the dominant fraction of the particulate carbon pool. Thus, seasonal increases in POC are primarily driven by enhanced biological production under favorable light conditions.

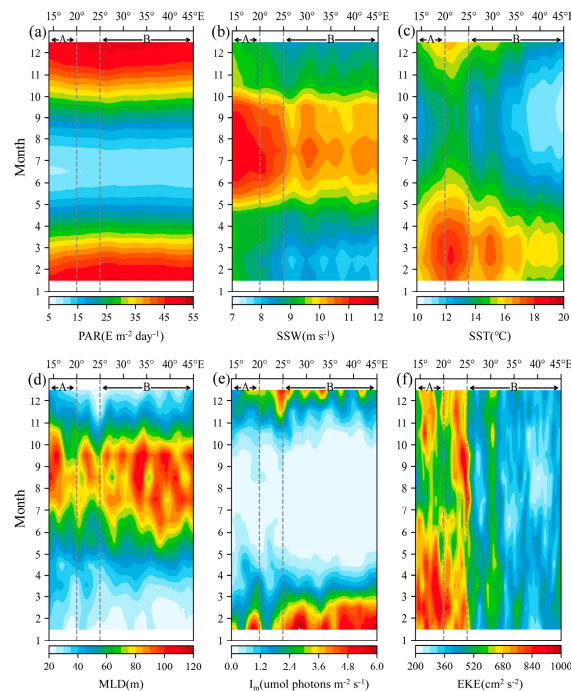


Figure 6. Longitude–month climatological sections of (a) photosynthetically available radiation (PAR), (b) wind speed, (c) sea surface temperature (SST), (d) mixed-layer depth (MLD), (e) mixed-layer mean irradiance (I_m), and (f) eddy kinetic energy (EKE) in the study region for 1998–2025.

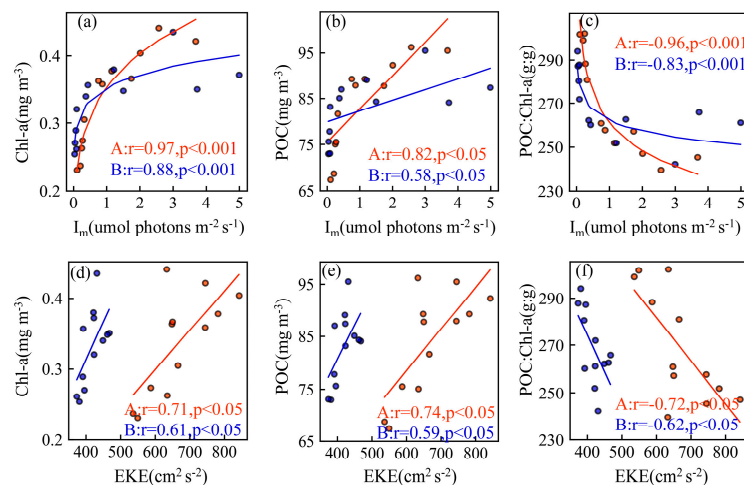


Figure 7. Scatterplots of climatological monthly mean chlorophyll-a (Chl-a), particulate organic carbon (POC), and POC:Chl-a versus mixed-layer mean irradiance (I_m) (a–c) and eddy kinetic

energy (EKE) (d–f) for Subregions A and B during 1998–2025. Solid lines indicate the linear and power regression fits.

Despite exhibiting similar seasonal cycles, Subregions A and B differ substantially in productivity levels. Subregion A, located within the Agulhas Retroflection, is characterized by persistently elevated EKE (Figures 6f and 7), reflecting intense mesoscale activity associated with current retroflection and eddy shedding. Enhanced eddy-induced vertical and horizontal exchanges facilitate nutrient transport into the euphotic zone, sustaining higher phytoplankton biomass and POC concentrations than those observed in Subregion B. These results suggest that mesoscale dynamics amplify the biological response to favorable seasonal light conditions and contribute to the elevated productivity of the retroflection region.

During austral autumn and winter, declining PAR and enhanced wind forcing deepen the mixed layer and reduce average light exposure within the upper ocean (Figures 6 and 7). Consequently, phytoplankton growth is suppressed, leading to lower Chl-a and POC concentrations throughout the study area. The simultaneous increase in POC:Chl-a indicates that seasonal changes in particulate carbon are not solely controlled by phytoplankton biomass. Under low-light conditions, phytoplankton may increase intracellular chlorophyll content as a photoacclimation strategy [19,21], while the relative contribution of detrital organic matter to total POC may also increase. Therefore, the elevated POC:Chl-a ratio during autumn and winter likely reflects a combination of physiological adaptation and changes in particle composition. These findings highlight that seasonal variations in POC composition can be as important as changes in total biomass when evaluating regional carbon dynamics.

4.2. Contrasting Impacts of SAM and ENSO on Interannual POC Variability

Large-scale climate modes exert a strong influence on biological production and carbon cycling in the Agulhas Current system [11,12,22]. However, the responses of Chl-a and POC to climate forcing exhibit pronounced regional heterogeneity, indicating that local oceanographic conditions modulate the propagation of climate signals into marine ecosystems. The SAM primarily influences the Southern Ocean through changes in the intensity and latitudinal position of the westerly winds [22]. Positive SAM phases generally strengthen wind-driven mixing and enhance nutrient supply from deeper waters (Figure 8a,c). However, the biological response to SAM differs markedly between the two subregions. In Subregion A, the intrusion of warm, nutrient-poor Indian Ocean waters strengthens upper-ocean stratification and counteracts the potential enhancement of nutrient supply associated with positive SAM conditions [5,10,11]. Consequently, no consistent relationship is observed between SAM and biological variability in this region.

In contrast, Subregion B is more directly exposed to atmospheric forcing associated with SAM and is less affected by warm-water intrusions [11,22]. Variations in wind strength during positive SAM phases enhance vertical mixing and nutrient entrainment, promoting phytoplankton growth and increasing POC concentrations (Figure 8a–c). The accompanying decrease in POC:Chl-a suggests that additional particulate carbon is primarily derived from newly produced phytoplankton biomass rather than detrital sources. These results indicate that SAM-induced changes in upper-ocean mixing constitute an important driver of biological variability in the Agulhas Return Current region.

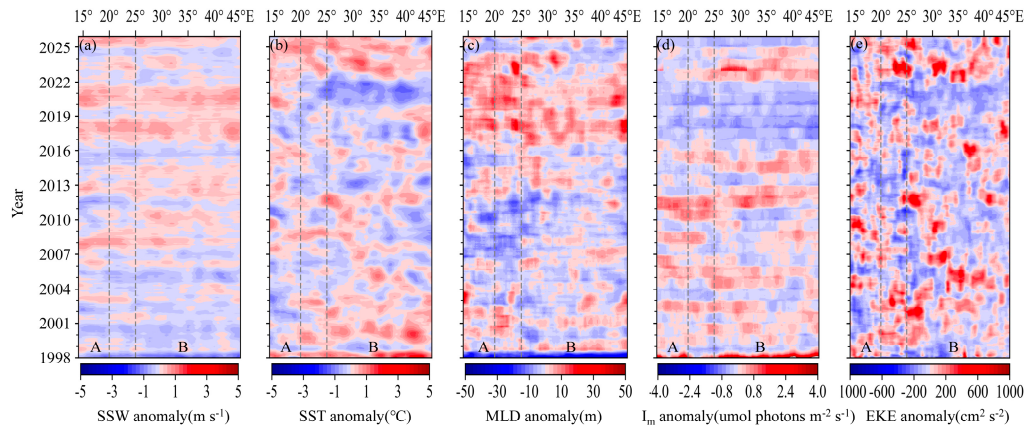


Figure 8. Longitude–year distributions of anomalies in (a) sea surface wind (SSW), (b) sea surface temperature (SST), (c) mixed-layer depth (MLD), (d) mixed-layer mean irradiance (I_m), and (e) eddy kinetic energy (EKE) in the study region during 1998–2025. The time-series are smoothed with a 13-month running mean.

ENSO affects the study area through a different pathway. In Subregion A, interannual variability is closely linked to ENSO-related changes in stratification and mesoscale dynamics [23–25]. During El Niño events, weakened winds and elevated SST lead to a shallower mixed layer and improved light conditions within the euphotic zone (Figure 8b–d). Simultaneously, enhanced EKE promotes nutrient injection through mesoscale eddy activity (Figure 8e). The simultaneous enhancement of light availability and nutrient supply stimulates phytoplankton growth, resulting in elevated Chl-a and POC concentrations and reduced POC:Chl-a ratios. Conversely, during La Niña events, reduced EKE weakens nutrient replenishment and particle transport, leading to lower Chl-a and POC concentrations and higher POC:Chl-a ratios. The stronger ENSO response observed in Subregion A likely reflects its inherently energetic circulation regime. Because mesoscale eddy activity is already intense in the Agulhas Retroflexion region [23–25], relatively small ENSO-induced perturbations can produce substantial ecological responses. By contrast, biological variability in Subregion B is more strongly linked to SAM-induced changes in wind forcing and upper-ocean mixing. This spatial contrast reveals an “ENSO-sensitive” regime in the retroflexion region and a “SAM-sensitive” regime in the return current region.

However, the weak POC anomaly during the 2015–2016 El Niño, compared with the 1998 and 2009 events (Figure 4), suggests that ENSO–biogeochemical linkages are strongly modulated by the background physical environment. During 2015–2016, a deepened mixed layer in Subregion A and B led to reduced mean light availability (I_m , Figure 8), which likely imposed strong light limitation on phytoplankton growth and carbon production, offsetting potential nutrient-driven enhancement. In contrast, earlier El Niño events occurred under more favorable light conditions, allowing nutrient enrichment to more effectively translate into increased biomass and POC. In addition, the 2015–2016 event coincided with a strong positive SAM (Figure 4a), which likely intensified wind-driven mixing and further deepened the mixed layer, reinforcing light limitation. The combined influence of ENSO and SAM therefore weakened the expected biological response, highlighting the need to consider both light–nutrient balance and the interaction of multiple climate modes when interpreting carbon-cycle variability in the Agulhas Current system. Overall, these results suggest that climate-driven biological variability in the Agulhas Current system cannot be explained solely by large-scale atmospheric forcing.

Instead, regional oceanographic conditions determine how climate signals are translated into ecosystem and carbon-cycle responses.

4.3. Trend Response of POC to Climate Change

Unlike seasonal and interannual variability, long-term changes in POC appear to be controlled by persistent modifications of upper-ocean stratification and mesoscale circulation under climate change. The contrasting trends observed between Subregions A and B highlight the importance of regional physical processes in regulating carbon cycling on decadal timescales.

In Subregion A, SST exhibits a significant warming trend throughout the study period (Figure 9a,d). Enhanced upper-ocean stratification associated with surface warming suppresses vertical nutrient transport and reduces nutrient supply to the euphotic zone. Meanwhile, mixed-layer mean irradiance (I_m) shows a persistent declining trend (Figure 9b,e), indicating increasingly unfavorable light conditions for phytoplankton growth. The combined effects of reduced nutrient availability and declining light availability likely contributed to the long-term decreases in both Chl-a and POC. Although both variables declined, the POC:Chl-a ratio increased substantially, suggesting that particulate organic carbon decreased less rapidly than phytoplankton biomass and that the composition of the particulate carbon pool gradually shifted over time. Meanwhile, EKE exhibited a weak declining trend (Figure 9c,f), indicating that enhanced mesoscale activity was unlikely to be the primary driver of the increasing POC:Chl-a ratio. Instead, the observed increase is more likely associated with long-term changes in carbon sources and particle composition under increasingly stratified and light-limited conditions.

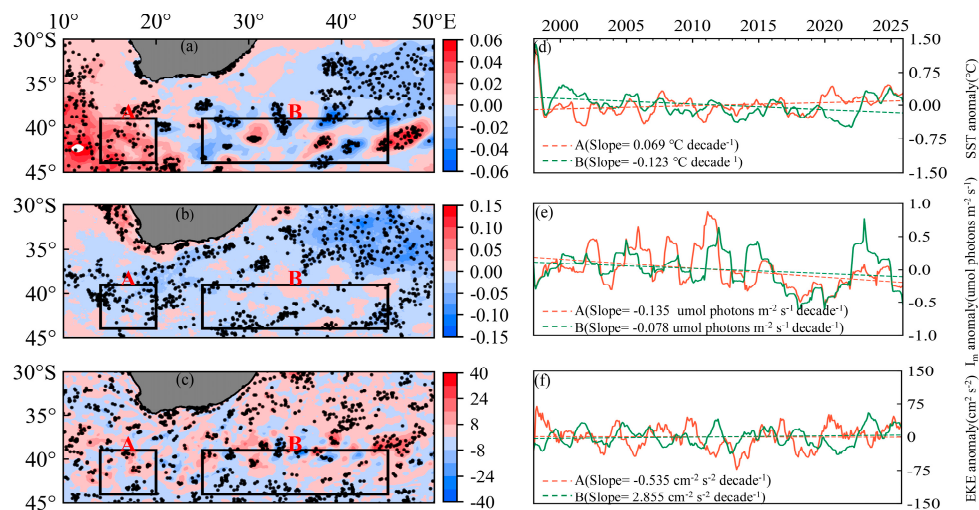


Figure 9. Spatial linear trends in (a) sea surface temperature (SST), (b) mixed-layer mean irradiance (I_m), and (c) eddy kinetic energy (EKE) during 1998–2025. Panels (d–f) present the area-averaged time series and corresponding linear trends of SST, I_m , and EKE for the Agulhas Retroflection region (A) and Agulhas Return Current region (B). The black dots indicate grid cells where the trend is statistically significant at the 95% confidence level ($p < 0.05$). The climatological fields were calculated as monthly climatologies from the 1998–2025 monthly mean datasets.

A contrasting pattern is observed in Subregion B. Here, long-term cooling weakens upper-ocean stratification and favors deeper mixing, thereby enhancing nutrient supply to surface waters (Figure 9a,d). However, mixed-layer mean irradiance also declined slightly during the study period (Figure 9b,e), suggesting that improved nutrient availa-

bility may have been partly offset by reduced light availability. Consequently, Chl-a exhibited a weak declining trend, whereas POC continued to increase. At the same time, EKE increased markedly (Figure 9c,f), implying enhanced mesoscale activity. Stronger eddy activity may promote the lateral transport, aggregation, and retention of particulate organic matter, thereby contributing to POC accumulation despite the absence of increasing phytoplankton biomass. The contrasting long-term trends of increasing POC but slightly decreasing Chl-a resulted in a pronounced increase in the POC:Chl-a ratio, indicating an increasing decoupling between particulate carbon accumulation and phytoplankton biomass. This pattern suggests that processes beyond local phytoplankton production, including physical transport and particle redistribution, play an increasingly important role in regulating the particulate carbon pool in the Agulhas Return Current region [25,26].

Taken together, previous studies in the Agulhas Current system have primarily focused on chlorophyll-a variability and the responses of phytoplankton to climate modes such as ENSO and SAM [11,12]. These studies demonstrated that mesoscale dynamics and climate forcing regulate nutrient availability and phytoplankton productivity, particularly in the Agulhas Return Current region. The present study is broadly consistent with these findings, showing that long-term biological variability is jointly regulated by nutrient availability, light conditions, and mesoscale circulation. However, by incorporating long-term satellite-derived POC observations, this study extends previous work beyond phytoplankton biomass. Our results demonstrate that POC and Chl-a exhibit contrasting long-term responses in the two subregions, with the most pronounced decoupling occurring in the Agulhas Return Current region, where POC increased despite a slight decline in Chl-a. These findings suggest that climate change influences not only phytoplankton biomass but also the production, transport, and accumulation of particulate organic carbon, highlighting the importance of considering changes in carbon pool composition when assessing long-term ecosystem and biogeochemical responses in the Agulhas Current system.

5. Conclusions

Using multi-source satellite and reanalysis data from 1998–2025, we show that POC, Chl-a, and POC:Chl-a in the Agulhas Current system exhibit distinct spatial, seasonal, interannual, and long-term patterns. Strong mesoscale dynamics drive higher productivity in the Retroflexion region than in the Return Current region. Seasonally, spring–summer POC is dominated by phytoplankton production, while detrital contributions rise in autumn–winter, producing an inverse POC:Chl-a seasonal signal. Interannually, ENSO regulates carbon dynamics via coupled wind–mixed layer–eddy processes, whereas SAM primarily impacts the Return Current region, with the Retroflexion region buffered by warm Indian Ocean intrusions. On decadal timescales, the two subregions exhibit contrasting carbon-cycle responses, with a persistent increase in the POC:Chl-a ratio in both regions and a pronounced decoupling between POC and Chl-a in the Return Current region. These findings suggest that long-term climate change alters not only phytoplankton biomass but also the accumulation and redistribution of particulate organic carbon.

This study is based primarily on satellite observations and reanalysis products, which characterize surface biogeochemical variability but cannot directly resolve subsurface carbon transport or biological carbon export. The relationships among climate variability, mesoscale dynamics, and POC are therefore inferred from observational evidence. Moreover, the present analysis is confined to the Agulhas Current system, and whether similar climate-driven responses occur in other western boundary current systems remains to be investigated through dedicated comparative studies. Integrating satellite observations with Biogeochemical-Argo measurements, field observations, and coupled

physical–biogeochemical models will provide a more comprehensive understanding of three-dimensional carbon cycling and improve predictions of ecosystem and carbon-sink responses under future climate change.

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Data Availability Statement: The original data presented in the study are openly available as follows: monthly ocean-color products, including chlorophyll-a (Chl-a), particulate organic carbon (POC), diffuse attenuation coefficient at 490 nm (Kd490), and photosynthetically available radiation (PAR), were obtained from the GlobColour project (<https://hermes.acri.fr/>). Monthly sea surface wind speed data were acquired from the Copernicus Marine Environment Monitoring Service (CMEMS; WIND_GLO_PHY_CLIMATE_L4_MY_012_003, https://data.marine.copernicus.eu/product/WIND_GLO_PHY_CLIMATE_L4_MY_012_003/description, accessed on 1 January 2026). Sea surface temperature (SST) and mixed-layer depth (MLD) fields were derived from the CMEMS AR-MOR3D product (MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012, https://data.marine.copernicus.eu/product/MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012/description, accessed on 1 January 2026). Geostrophic currents data were obtained from https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_MY_008_047/description, accessed on 1 January 2026. The Southern Annular Mode (SAM) index was obtained from the British Antarctic Survey (<https://legacy.bas.ac.uk/met/gjma/sam.html>, accessed on 1 January 2026), while the Multivariate ENSO Index (MEI) was obtained from the NOAA Physical Sciences Laboratory (<https://psl.noaa.gov/enso/mei>, accessed on 1 January 2026).

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