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Eddy-induced chlorophyll profile characteristics and underlying dynamic mechanisms in the South Pacific Ocean

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Abstract. Many studies have consistently demonstrated that the near-surface phytoplankton chlorophyll (Chl) levels in anticyclonic eddies (AEs) are higher than in cyclonic eddies (CEs) in the South Pacific Ocean (SPO) using remote sensing data, which is attributed to higher phytoplankton biomass or physiological adjustments in AEs. However, the characteristics of the Chl profile induced by mesoscale eddies and their underlying dynamic mechanism have not been comprehensively studied by means of field measurement. In this study, we mainly utilized BGC-Argo data to investigate the relationships between Chl levels and environmental factors (C_{Phyto}, Nitrate, Temperature and Light) and the underlying dynamic mechanisms of mesoscale eddies in SPO. Our findings showed that, the elevated Chl levels in AEs primarily result from increased phytoplankton biomass within the Mixed Layer Depth (MLD), which is induced by enhanced nutrient availability due to the deepening MLD in AEs. At depths ranging from 50m to 110m (the depth between the bottom of the mixed layer and pycnocline), the dominant factor affecting higher Chl levels in CEs is the physiological adaptation of phytoplankton, driven by reduced temperature and light availability. Between 110m and 150m（near the depth of pycnocline or bottom of the euphotic zone）, both phytoplankton biomass induced by eddy pumping and physiological adjustments for lower light and temperature contributed to higher Chl levels in CEs. At depths exceeding 150m (beyond the euphotic zone), higher Chl in AEs is primarily influenced by phytoplankton biomass as a result of the downwelling by eddy pumping. To a certain extent, this work would advance our comprehensive understanding of the physical-biological interactions of mesoscale eddies and their impacts on primary productivity throughout the water column, which has important implications for accurately assessing the biogeochemical processes and ocean carbon cycle.

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1 Introduction

Marine phytoplankton accounts for nearly 50% of global primary productivity and provides a huge fishery resource (Field et al., 1998; Chassot et al., 2010; Feng et al., 2015). As one of the important components of phytoplankton cells, Chl is the main carrier for photosynthesis. The concentration of Chl which can reflect the phytoplankton biomass to a certain extent is an important effective indicator of marine primary productivity (Zhao et al., 2021), also reflects physiological adaptations in cellular pigmentation that occur in response to alterations in light, temperature and nutrient conditions in the upper ocean (Behrenfeld et al., 2016; Halsey and Jones, 2015). Therefore, to enhance the assessment of oceanic primary productivity and carbon cycling, it is imperative to investigate the correlation between CHL and its growth-influencing factors that be usually regulated by ocean dynamic processes.

Mesoscale eddies are rotating bodies of water that occupy 25–30% of the global ocean surface, and persist for weeks to years in the global ocean, with horizontal scales of O(100) km and vertical scales of thousands of meters into the ocean interior (Chelton et al., 2011a; He et al., 2018; Wang et al., 2023). Cyclonic (anticyclonic) eddies induce divergence (convergence) of the ocean's inner subsurface water under the action of Coriolis forces, and form an upwelling (downwelling) at the center of eddies, transporting substances (nutrients, etc.) to the surface (bottom) of the sea. The eddies facilitate the horizontal and vertical transportation of nutrients from the seawater under the combination of Coriolis force and ocean currents, which affect the growth of marine phytoplankton and play a crucial role in regulating marine ecosystems and carbon cycles (Batten and Crawford, 2005; Chelton et al., 2011b; Conway et al., 2018; Xu et al., 2019; Liu et al., 2020).

Generally speaking, AEs induce a negative anomaly in the sea surface chlorophyll concentration indicating that the chlorophyll levels in CEs are higher than that in AEs. The standard hypothesis for this paradigm states that CEs and AEs have the effect of increasing and decreasing the accumulation of phytoplankton biomass, respectively (Mcgillicuddy Jr, 2016). However, in oligotrophic oceans such as the South Pacific Ocean (SPO), mesoscale eddies induce sea surface chlorophyll characteristics that contradict the traditional paradigm, with higher near-surface Chl in AEs than in CEs (Gaube et al., 2013). Several controversial mechanisms for explaining the anomalous phenomenon have been proposed. Some research claimed that winter mixing enhances the productivity of AEs over CEs in subtropical gyres (Dufois et al., 2016). Another explanation is the physiological regulation of pigment changes in

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phytoplankton cells caused by eddy-induced changes in the upper ocean physical environment, such as the reduced illumination caused by deepened Mixed Layer Depth (MLD), which increased the chlorophyll concentration in AEs but the biomass (Arteaga et al., 2016; He et al., 2021).

Currently, the investigation of chlorophyll anomalies in SPO primarily relies on satellite remote sensing data. However, remote sensing measurements are limited to the near-surface sea, and no measured data has been available to further study and verify the distribution of Chl in the ocean interior (Gordon and Mccluney, 1975; Cornec et al., 2021b). The quantitative assessment and clarifying hidden driving mechanism of Chl levels between surface and subsurface layers or even the entire water column induced by eddies, which are of great significance for the open sea with stable stratified structures, such as subequatorial and subtropical waters, and mesoscale eddies may be the main environmental factor to driver these stable regions (Cullen, 2015; Letelier et al., 2000; Cornec et al., 2021a).

To fill this gap, this paper compared and analyzed the sea surface and profile characteristics of Chl in parts of the SPO (16°S~24°S, 160°W~144°W) based on remote sensing and BGC-Argo data. The influence of mesoscale eddies and environmental factors is also investigated. Each eddy was matched with the Chl data from satellite remote sensing, and the distribution of sea surface Chl concentration in different polar eddies was investigated. Furthermore, the Chl vertical profile characteristics in AEs/CEs were analyzed using BGC-Argo data, and we studied the effects of light, nutrients and temperature variations driven by eddies (AEs/CEs) on Chl concentration at different depths, as well as their roles in changing the intensity and depth of Subsurface Chlorophyll Maximum (SCM). The findings indicate that the characteristics of Chl profiles and their influencing factors vary across different depths in seawater. For example, the Chl concentration in AEs is higher than that in CEs within the mixed layer, primarily due to the elevated nutrient concentration in AEs, which resulted in an increase of phytoplankton biomass. And from the bottom of MLD to the depth of Subsurface Chlorophyll Maximum (SCMD), Chl concentration in CEs is higher than that in AEs due to physiological adaptations, the lower temperature and light conditions in CEs stimulate an increased production of Chl by phytoplankton cells. Therefore, the concentration of sea surface Chl observed by satellite remote sensing induced by eddies does not accurately reflect the primary productivity and even leads to an opposite conclusion. This study will have significant implications for enhancing our understanding of the biogeochemical processes and carbon cycle associated with eddies.

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2 Materials and Methods

2.1 Eddy Datasets

In this study, a delayed time daily dataset of mesoscale eddy designed by AVISO and distributed by CMEMS (Copernicus Marine and Environment Monitoring Services) was used, with a spatial resolution of 0.25°×0.25° from January 2000 to August 2021 (Schlax and Chelton, 2016). The eddy data were detected from multimission altimetry datasets, and the location, length of life, radius(R), amplitude, speed and polarity (CEs/AEs) of eddies were contained in this dataset (Chelton et al., 2011a). The method of eddy identification is based on the characteristics of closed contour lines and single-core eddy center displayed by eddies in sea-level height anomalies (Chen and Han, 2019; Peng et al., 2021). This method is representative in eddy identification and tracking research and has been proven to be effective through several studies.

2.2 Multi-satellite merged ocean color products

A variety of remote sensing products (CHL/ZEU/BBP et al.) at different temporal and spatial scales were contained in Multi-satellite merged ocean color products produced by the GlobColour project. The merged data can improve the spatial and temporal resolution of remote sensing data, and reduce the impact of data noise caused by single sensor. The CHL product was used in this study, with a spatial resolution of 0.25° and a temporal resolution of one day between January 2000 and August 2021.

2.3 Argo and BGC-Argo Datasets

Argo is an international program that provides vertical profiles of temperature, pressure and salinity using a fleet of robotic instruments that drift with the ocean currents in the upper 2000m (Wong et al., 2020). BGC-Argo program is a continuation of the Argo program, in addition to measuring temperature, salinity and pressure values of the three parameters, also include chlorophyll-a, suspended particles, irradiance, oxygen (O2), nitrate (NO3) and pH (Johnson and Claustre, 2016; Bittig et al., 2019). These data freely available by users and without any restriction, can be used to assess the marine hydrological environment (Bittig et al., 2019; Chai et al., 2020; Xing et al., 2014). The delayed mode data of Chl, BBP (particulate backscattering coefficients), Temperature, PAR (Photosynthetic Available Radiation) and Nitrate produced by BGC-Argo are used in this study.

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2.4 Data Processing

Eddies with an amplitude exceeding 1cm and a lifetime surpassing 10 days identification and tracking dataset distributed by AVISO from January 2000 to August 2021 have been chosen and excluded the eddies obtained by the interpolation algorithm to reduce the error. The boundary of every eddy consists of 20 points connected, each with a corresponding latitude and longitude. We matched the remote sensing data and BGC-Argo profile data with eddies according to the latitude and longitude, and judged that the data was in AEs, CEs or OE (outside the eddy).

Quality control and pre-processing are performed on BGC-Argo data before being used. We performed spatial interpolation of these data using both linear and non-linear methods, and after interpolation, the profile data has a vertical spatial resolution of 1 meter, which improved the vertical resolution of the profile. Quality control was performed on these data and some outliers were removed, and the median filtering and mean filtering are carried out on the profile data to improve the accuracy of the data.

The MLD was determined based on the temperature differential threshold criterion of 0.5°C, with reference to the temperature at a depth of 10 m under sea level, and is widely used for areas of subtropical gyres (De Boyer Montégut et al., 2004; Cornec et al., 2021a). The euphotic zone (ZEU) is the maximum depth at which plants can photosynthesize, approximately 95% of photosynthesis takes place here, and ZEU was defined as PAR down to the depth of the sea surface value of 1%. C_{Phyto} was calculated from BBP which is defined as: $C_{Phyto} = 13000 \times (BBP-0.00035)$ (Westberry et al., 2008), and C_{Phyto} represents the quantity of biomass. θ was defined as the ratio between Chl and C_{Phyto}, $\theta = Chl/C_{Phyto}$, it signifies the capacity of physiological adaptations in cellular pigmentation. A higher value of θ indicates a greater concentration of Chl within an individual cell.

For remote sensing data, at each 1°×1° grid in the selected area, we computed mean relative differences of Chl between AEs and CEs. The relative difference of Chl is defined as Chl anomaly (Chl'), which is computed as Eq (1) (Dufois et al., 2016; He et al., 2021).

$$Chl' = \frac{\overline{Chl_{AE}} - \overline{Chl_{CE}}}{\overline{Chl_{OE}}} \quad (1)$$

OE means Chl values outside eddies, and overbars represent mean values. The same method was used to calculate the anomaly of Chl, C_{Phyto} and θ ($Chl', C_{Phyto}', \theta'$) in SPO using BGC-Argo data.

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3 Results

3.1 Chlorophyll characteristics of sea-surface

We first derived the distribution of global sea-surface Chl anomalies through analysis of remote sensing data (Figure 1a). The concentration of Chl in AEs was higher than that in CEs in subtropical gyres, such as SPO and South Indian Ocean (SIO), which was opposite with mid-latitude oceans and areas of boundary currents. To study this anomaly in sea-surface and subsurface of Chl characteristics, a specific area (16°S-24°S, 160°W-144°W) was selected and used to represent the SPO. In this region, the Chl'>0 at each 1°×1° grid, ensured the stability of Chl anomalies in this region, and the mean value peaked to 11.6%. There were hundreds of biochemical profiles containing Chl, BBP, Nitrate, Temperature and Light data in the selected area (Figure 1b), providing a possibility for the study of Chl profile characteristics and environmental factors in this area.

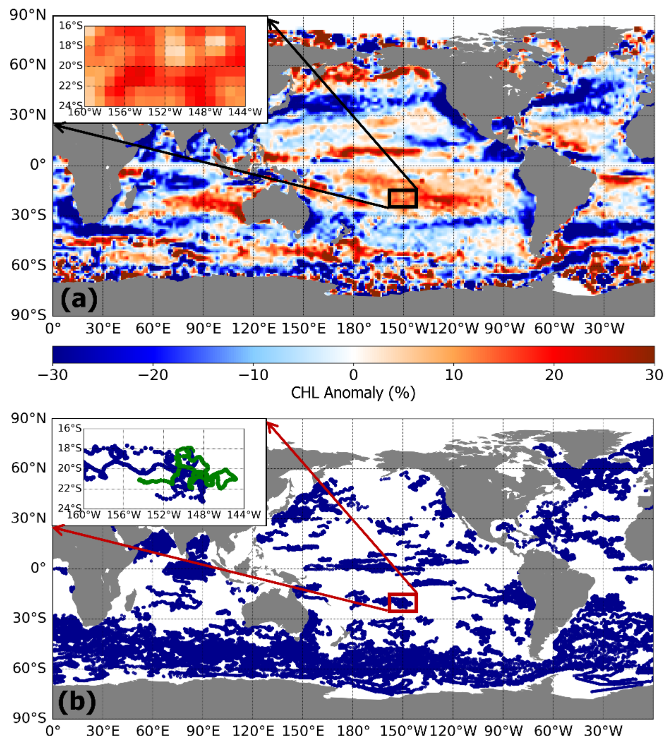

Figure 1. (a) Geographic distributions of eddy-induced Chl′ between January 2000 and August 2021, the upper left subplot displays the distribution of Chl′ in the selected area. (b) Map of profiles containing Chl data. In the upper left subplot, each profile of BGC-Argo floats contained Chl, BBP, Temperature, and PAR data, the green dots indicate that the profile contained Nitrate data.

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3.2 Subsurface chlorophyll structure in eddies

After quality control, we retained 883 biochemical profiles in the selected area, 120 profiles were located in CEs and 139 AEs. All these profiles contained Chl, BBP, Temperature and PAR data, and the Nitrate data is slightly less. In this study, we categorized the Chl profile into three distinct layers: the MLD, the intermediate layer spanning from 50m to 150m (the middle layer is further divided into two sub-layers, one ranging from 50m to 110m and the other from 110m to 150m near the pycnocline, which encompasses the SCM), and the deep layer situated below 150m. Then we calculated $Chl', Cphyto', \theta'$ and SCM' within the corresponding layer (Table 1), and the depth of MLD, ZEU and SCMD (Table 2).

In MLD, the Chl concentration in AEs was slightly higher than that in CEs (Figure 2), and the $Chl' = 5.5\%$, was lower than the result of remote sensing data. At the depth of 50-150m in the middle layer, the Chl concentration increased rapidly with depth, and the Chl concentration of CEs was significantly higher than that of AEs, which was inconsistent with the results of MLD and remote sensing. At the bottom of the middle layer (110-150m), SCM features appeared, and the relative ratio of Chl within AEs and CEs reached the maximum ($SCM' = -27.5\%$). Furthermore, the application of AEs resulted in a deepening of SCMD, while CEs shallowed it ($SCMD_{AE}$=137m, $SCMD_{CE}$=130m, $SCMD_{OE}$=135m). Below 150m of the sea surface, there was a rapid decline in Chl concentration. Meanwhile, the Chl concentration within AEs was higher than that in CEs. It is worth mentioning that the depth of 150m underwater is deeper than ZEU, rendering it essentially in a state of “almost complete darkness” and unsuitable for plant growth. Therefore, the Chl synthesis signal was gradually attenuated, leading to a decline in biomass and a rapid reduction in Chl concentration.

In general, both phytoplankton biomass and physiological adaptations in cellular pigmentation can affect Chl concentrations (Kerimoglu et al., 2017). Therefore, to gain a comprehensive understanding of Chl profile characteristics, C_{Phyto} data and θ data need to be studied.

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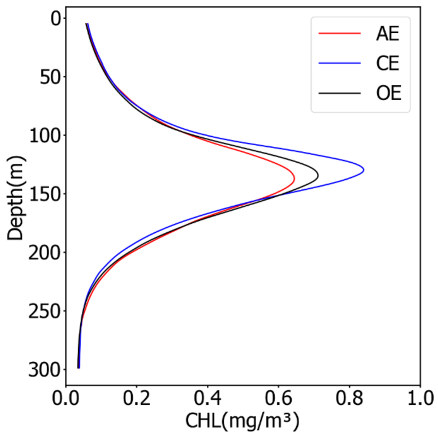

Figure 2. Mean profiles of Chl in eddies of different polarity, red blue and black lines indicate that the profile is in AEs, CEs and OE, respectively.

Table 1 Anomaly of Chl, Cphyto and θ in different levels calculated by BGC-Argo data.

	CHL′	**Cphyto′**	**θ′**
0-MLD	5.5%	12.3%	-7.2%
50-110m	-7.2%	3.7%	-10.9%
110-150m	-24%	-2.4%	-21.8%
150-300m	7.5%	18.3%	-
0-300m	-8.03%	7.1%	-
SCM	-27.5%	-	-

Table 2 Depth of MLD, ZEU and SCMD, and the value of SCM in eddies of different polarity.

	AE	**CE**	**OE**
MLD (m)	51	40	44
ZEU (m)	126.39	125.06	126.59
SCMD (m)	137	130	135

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3.3 C_{Phyto} and θ

To quantify the relationship between phytoplankton biomass, physiological adjustment and Chl, C_{Phyto} and θ profiles were examined using BGC-Argo data (Figure 3). The C_{Phyto} profile data depicts the biomass distribution influenced by AEs/CEs within the ocean's interior (Figure 3a). θ means the concentration of pigment in phytoplankton cells (Figure 3b), it reflects the strength of the physiological adjustment ability of phytoplankton. The increase of θ indicates a proportional rise in the concentration of Chl within the phytoplankton cell. Similar to the Chl profile, C_{Phyto} and θ also showed a trend of first increasing and then decreasing with increasing depth. It reflected that Chl concentration was influenced by both physiological adjustment and biomass of phytoplankton.

In MLD, the concentration of C_{Phyto} in AEs was found to be higher compared to CEs, which was consistent with the Chl results. The Chl' =5.5% and the $Cphyto'$=12.3% in MLD, this suggests that although the biomass in AEs was much higher than in CEs, while the Chl was not significantly higher. The θ profile precisely explains this phenomenon, θ'=-7.6% in this layer, indicating that the pigment concentration per individual phytoplankton cell in CEs is higher than in AEs. That is, in MLD, the higher Chl concentration in AEs compared to CEs is primarily driven by biomass, while the physiological adjustment of phytoplankton plays a contrasting role, and induced the lower of Chl' than $Cphyto'$.

Within the middle layer of 50-110m, the concentration of C_{Phyto} in AEs is higher than that in CEs ($C_{Phyto}{}'$=3.7%), whereas the Chl concentration in AEs is lower (Chl' =-7.2%). This observation suggests that the increased C_{Phyto} concentration in AEs does not lead to a higher Chl concentration compared to CEs at this layer. Whereas the physiological adjustment of phytoplankton is the primary factor contributing to the lower Chl concentration in AEs compared to CEs (θ'=-10.9%), and the biomass hindered this process. In 110-150m, the C_{Phyto} concentration and θ in CEs were higher than those in AEs ($C_{Phyto}{}'$=-2.4%, θ'=-21.8%). Biomass and capacity for physiological adaptation have also reached its peak in this layer. The higher Chl within CEs compared to AEs can be attributed to the synergistic effect of enhanced biomass and physiological regulation in CEs.

At depths of 150m and deeper, the C_{Phyto} content was higher in AEs than in CEs, which was consistent with the Chl results ($C_{Phyto}{}'$=18.3%, Chl'=7.5%). Below the depth of 150m of sea-surface, the light is extremely weak or absent, it’s unsuitable for photosynthesis in phytoplankton. Therefore, the

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physiological adjustment of phytoplankton is not within the scope of discussion in this study at this layer, the higher Chl concentration within AEs than CEs is determined by biomass.

In conclusion, the Chl concentration is influenced by biomass and physiological adjustment of phytoplankton, and cannot be simply lumped together. At different depths, the extent that the biomass and the capacity of phytoplankton physiological adjustment affect in Chl concentration is different.

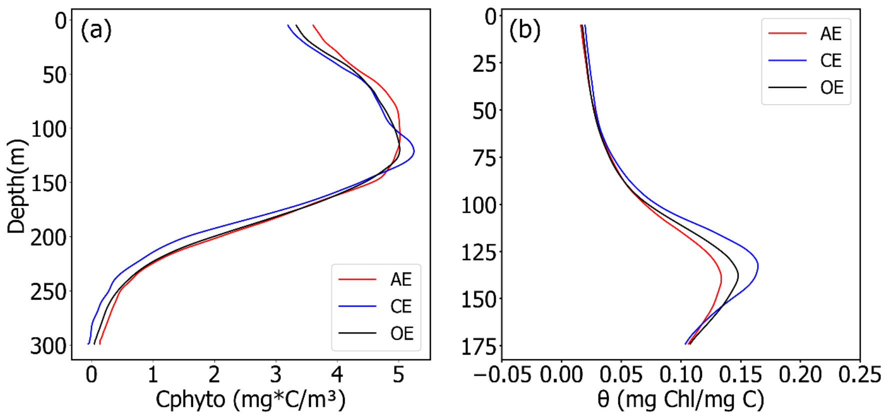

Figure 3. (a and b) Mean profiles of CPhyto and θ in eddies of different polarity, red blue and black lines indicate that the profile is in AEs, CEs and OE, respectively.

4 Discussion

To further understand the mechanism of Chl anomaly, we analyzed how eddies modulate biomass and physiological adjustment through regulating nutrients, temperature and light, and ultimately influence the Chl concentration using biochemical data. By and large, nutrients play a greater role in influencing phytoplankton biomass (Sukigara, 2022). This is also illustrated by the fact that the nitrate and C_{Phyto} profiles exhibited high correlations, the nutrient concentration decreased with the increase of biomass due to the consumption of phytoplankton growth (Figure 3a, Figure 4c). Temperature and light tend to affect the physiological regulation of phytoplankton, the lower temperature and light can promote Chl synthesis in phytoplankton cells (Graff et al., 2016).

In MLD, it is already known that the higher Chl concentration in AEs than in CEs is due mainly to the higher biomass concentration, while the physiological adjustment of phytoplankton played the opposite role. In fact, whether biomass or pigment concentration is responsible for the difference in Chl concentration between AEs and CEs, is ultimately relies on the influence of eddies on nutrients,

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temperature and light (Poppeschi et al., 2022). Due to the modulation mechanism of the eddies on the MLD (AEs deepen the MLD and CEs make it shallower), AEs can contact deeper nutrient lines, the mixing of turbulent flow enables AEs to have higher nutrient concentrations and promotes phytoplankton growth(Figure 4c). Meanwhile, because of the function of the eddy pump, AEs have a higher temperature relative to the CEs (Figure 4a). On the one hand, the higher temperature promotes the metabolic capacity of phytoplankton, promoted the growth of phytoplankton, and increased the biomass. On the other hand, higher temperature will also reduce the concentration of pigment in phytoplankton cells, and finally weakened the Chl concentration within AEs, making the Chl' lower than C_{Phyto}'. It is worth mentioning that for the results of satellite remote sensing, some scholars believed that the higher Chl concentration of AEs than CEs is caused by physiological adaptations in cellular pigmentation of phytoplankton, rather than the increase of biomass. And suggested that this adaptation is primarily due to the deepening of the MLD in AEs, resulting in reduced illumination and consequently contributing to an increase in cellular pigment. Actually, the reduced light in AEs will make the Chl concentration higher and result in Chl' greater than C_{Phyto}', however, the opposite situation has emerged currently, which indicates that within the well-illuminated MLD, the physiological adjustment of phytoplankton is more influenced by temperature rather than light induced by eddies.

At the depth of 50-110m in the middle layer, the Chl concentration in CEs was higher than that in AEs mainly due to the higher physiological adjustment ability of phytoplankton in CEs compared to AEs. Although the higher nutrient concentration in AEs resulted in increased biomass and chlorophyll concentration of phytoplankton, indicating a positive response to nutrient enrichment (Figure 3a, Figure 4c), however, the light is weakened as the depth deepens, the physiological adjustment ability of phytoplankton is also gradually increased, and finally becomes the main factor to dominate the Chl concentration (Figure 3b, Figure 4b). At the same time, the lower temperature in CEs promoted the higher Chl in CEs compared to AEs.

In the vicinity of the pycnocline at 110 to 150m in the middle layer, the Chl concentration, physiological adjustment and biomass in AEs were significantly lower than in CEs. And in comparison to AEs, CEs have a stronger SCM and a shallower SCMD. Possible explanation lies in the convergence and subsidence of AEs and the divergence and uplift of CEs near SCMs, which resulted in phytoplankton in AEs being transported to deeper layers, leading to a dilution effect on biomass. Conversely, phytoplankton in CEs was enriched due to the uplifting, resulting in higher biomass and Chl

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concentration compared with AEs. Furthermore, the Chl' is greater than C_{Phyto}' in CEs and θ>0, indicating that the increase in Chl concentration in CEs is due to both an increase in biomass and higher pigment concentrations within phytoplankton cells resulted by physiological adjustment. This physiological adjustment may due to the lower temperature induced by the pumping of CEs and illumination at this depth.

Below 150m depth and deeper, the Chl and biomass concentration within AEs/CEs/OE decreased sharply, whereas the concentration of nutrients, in contrast, exhibited a significant increase (Figure 4c). A possible mechanism may be that, below the depth of ZEU and SCM (SCM generally occurs under the ZEU), the light was too weak or no light to allow phytoplankton to photosynthesize, which means that Chl synthesis is 'off' and caused a sharp reduction in biomass (Behrenfeld et al., 2016). And the nitrate concentration dramatically increased in the absence of phytoplankton depletion. Meanwhile, the downwelling sank down the phytoplankton in AEs, and the upwelling in CEs uplifted it, which resulted in Chl concentration and biomass higher in AEs compared to CEs.

On the whole, the biomass of phytoplankton in AEs is higher than that in CEs in SPO (Table 1), which is consistent with previous research (Dufois et al., 2016). The latest research showing that, anticyclonic eddies aggregate pelagic predators in subtropical gyres (Arostegui et al., 2022). This may be due to the fact that the increased phytoplankton volume in the AEs feed more zooplankton and then attract more predators. This also attests to the validity of this study from another perspective.

Additionally, the eddy pump enables CEs to transport substances such as nutrients from the deep to the shallow of the ocean, thereby facilitating phytoplankton growth. Conversely, AEs have an opposite effect. However, it has been observed that the Chl concentration, biomass and nutrient in AEs exceed those found in CEs within the MLD in this region, which contradict to the traditional assumption based on the eddy pump. The reason may be that, in the subtropical gyres region, the eddy kinetic energy is weak (Chen and Han, 2019), and the capacity of marine stratification is stronger than in other regions. Therefore, it's difficult for CEs to carry the eutrophic water to the surface layer of marine under the barrier of the pycnocline, however, AEs can contact more nutrients because of the deepening MLD. This may be one of the reasons for the higher Chl concentration in AEs compared to CEs in the subtropical gyres such as SPO and SIO, presented by current satellite remote sensing results.

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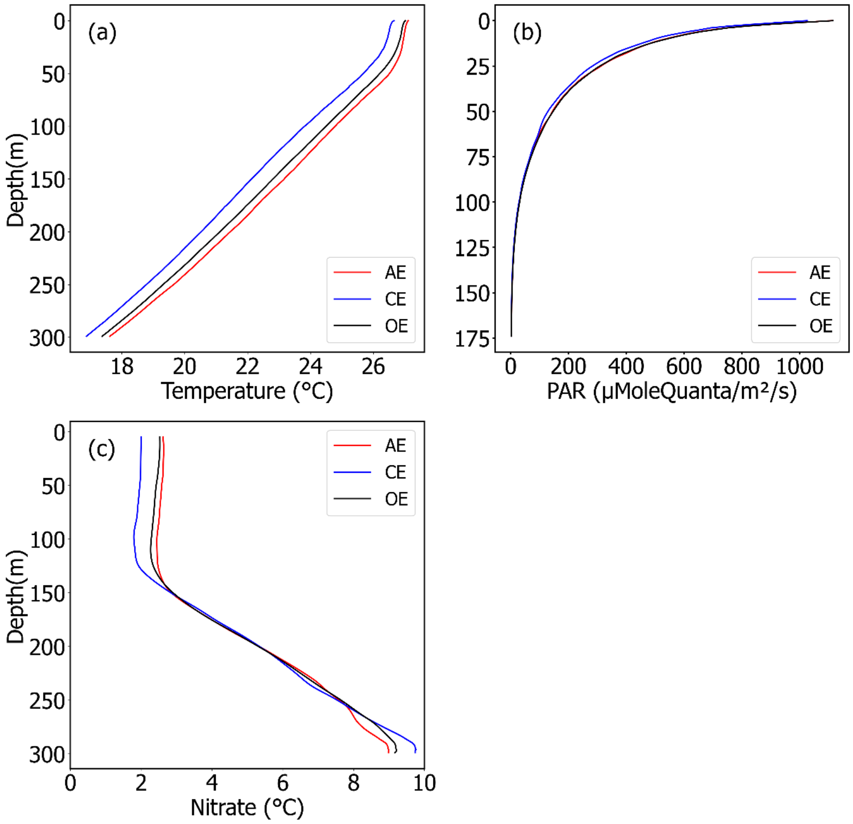

305 **Figure 4. (a, b and c) Profiles of Temperature, PAR and Nitrate in eddies of different polarity, red blue and black lines indicate that the profile is in AEs, CEs and OE, respectively.**

5 Conclusion

In this study, we addressed the effect of mesoscale eddies as well as the environments on Chl profile characteristics in parts of SPO (16°S~24°S, 160°W~140°W), and explained the mechanism of Chl anomaly of previous study mainly using remote sensing data. Firstly, whether Chl concentration was influenced dominantly by biomass or by physiological adjustment was analyzed in conjunction with the profile characteristics of C_{Phyto} and θ in the region. Then we further analyzed how mesoscale eddies have an impact on biomass, regulating physiological processes, and thus Chl distribution by affecting nutrients, temperature and light using Nitrate, Temperature and PAR data. The results showed that although nutrients, temperature and light all had an effect on phytoplankton biomass and physiological adjustment, they each had their own focus among different depths of water column.

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The findings were as follows:

(1) In MLD, AEs have a higher Chl concentration than CEs, mainly from the contribution of phytoplankton biomass, and the physiological regulation caused by temperature plays a small negative contribution. As a result of the convergent subsidence, AEs deepened MLD and can contact deeper nutrient lines, the mixing of turbulent flow enables AEs to have higher nutrient concentrations and promotes phytoplankton growth. The higher temperature induced by downwelling reduced the Chl concentration in AEs by lowing the intracellular pigment level.

(2) At the depth of 50-110m, the Chl concentration in CEs was higher than that in AEs mainly because the light was weakened with the increase of depth, which enhanced the physiological adjustment ability of phytoplankton, and then became the dominant factor affecting Chl concentration. The lower temperature and light in CEs promoted the increase of pigment in phytoplankton cells.

(3) Near the SCM at 110-150 m, CEs have higher Chl concentration than AEs, due to an increase in biomass on the one hand, and physiological effects on the other. The lower temperature and light in CEs increased pigmentation in phytoplankton cells, and the upwelling in the CEs caused phytoplankton to rise and accumulated there, both of them promoted a higher Chl concentration in CEs at this layer, and resulted in a stronger SCM and a shallower SCMD in CEs.

(4) Below 150m depth and deeper, the light is too weak to allow phytoplankton to photosynthesize, and both the pigment concentration in phytoplankton and biomass are decreased sharply. The higher concentration of Chl in AEs compared to CEs is due mainly to the sedimentation (rising) of phytoplankton in AEs (CEs) caused by the downwelling (upwelling).

In the future, with the increasing of BGC-Argo profiles numbers, we will conduct seasonal and quantitative analyses of environmental factors affecting Chl concentrations and biomass. The contribution of nutrients, temperature and PAR in this region will also be evaluated respectively. Eddy-induced biochemical cycle is a complex process, the Chl and biomass of phytoplankton interact with various environmental factors and adapt to each other. A single model cannot perfectly explain the characteristics of Chl and biomass distribution and the capability of primary productivity at different depths in the ocean. Stratifying the ecological effects induced by eddies according to different depths provided a new idea for the assessment of marine primary productivity and carbon cycling under the influence of eddies.

Data Availability. BGC-Argo data used in this study are available at http://doi.org/10.17882/42182#98126 or at ftp://ftp.ifremer.fr/ifremer/argo/dac/. GlobColour data are available at http://globcolour.info (accessed on 2 June 2022). Mesoscale Eddy data can be downloaded at https://www.aviso.altimetry.fr/en/data/products/value-added-products/global-mesoscale-eddy-trajectory-product.html (doi: 10.24400/527896/a01-2022.005.220209).

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Competing interests. The authors declare no conflict of interest.

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