Overall impression

The manuscript aims at biochemical influences of normal and abnormal eddies in the Southern Ocean (SO), discussing influences of different eddy mechanism on sea surface temperature (SST), chlorophyll-a (Chl-*a*), dissolved inorganic carbon (DIC) and their contributions to $p\mathrm{CO}_2$. The topic is of vital importance on eddy contributions in the global biogeochemical cycles. Many results are interesting and the figures are displayed very clearly. While, some conclusions still should be rethinking and the writing could be improved. The manuscript would be more suitable for publication after a major revision.

Response: We would like to thank the reviewer for the professional comments and valuable suggestions to improve the manuscript. We hope the answers and information presented here would respond to what was demanded.

Major questions:

1. The manuscript needs to highlight its innovation and scientific meanings. Although the authors stress eddy's importance on the biogeochemical cycle, what are the contributions to future scientific studies and what are the scientific meanings?

Response: Thanks for your suggestion. In the manuscript, we stated four significant scientific meanings, including

1) Considering the distinct role of “abnormal” eddies in modulating physical and biogeochemical parameters enhances the precision of estimating mesoscale eddy impacts.

2) The spatial distribution of eddy-induced Chl-*a* anomalies indicates the potential for localized hotspots of productivity and nutrient supply within eddies (Figs. 3e–h in the manuscript).

3) Eddy impacts on DIC distributions highlight their role in transporting carbon-rich waters, notably affecting regional carbon budgets and oceanic carbon uptake.

4) Understanding the complexity of eddy-driven processes in the SO is vital for accurately simulating and predicting the biogeochemical dynamics of the SO.

For future scientific studies, we acknowledge two key limitations that warrant consideration.

1) First, our study focuses solely on the surface ocean, potentially overlooking subsurface Chl-*a* maxima (Cornec et al., 2021). Eddy-induced effects on phytoplankton growth are likely more prominent in the lower euphotic zone and could manifest less prominently at the surface (Mcgillicuddy et al., 2007; Siegel et al., 2011). The development of oceanic autonomous observation platforms,

especially biogeochemical Argo (BGC-Argo) floats, can help characterize the vertical structure of Chl-*a* and nutrients, improving our understanding of the physical-biological interactions.

2) Furthermore, we may underestimate the overall impact of SO eddies on physical and biogeochemical parameters due to unaccounted effects of smaller mesoscale features and submesoscale processes near eddy boundaries, such as submesoscale secondary circulations and small-scale turbulent mixing (Ning et al., 2021; Wang et al., 2021). Submesoscale processes support vertical velocities of up to 10–100 m day^{-1}, an order of magnitude larger than those induced by mesoscale eddies (Klein and Lapeyre, 2009). Expanding our investigation to smaller scales can enrich our understanding of eddy-driven processes.

2. Many expressions and conclusions need solid support.

(1) The most concern, the authors state that the eddies in the SO is mainly westward. Considering the large number of eastward eddies in ACC, statistics about westward/eastward and northward/southward eddy propagation should be clarified in the whole SO, rather than just focusing on eddies with lifetimes longer than 1 year (Figure 7).

Response: Thanks for your valuable feedback. In response to your suggestion, we have incorporated statistics that encompass a broader range of eddy lifetimes, including both short-lived and long-lived eddies, to represent eddy propagation directions accurately. Table 1, presented below, illustrates that regardless of the lifespan, both AEs and CEs propagate primarily westward and northward. By contrast, AEs and CEs living longer than 1 year propagate primarily northward and southward, respectively, corresponding with the intrinsic meridional propagation of eddies (Cushman-Roisin and Beckers, 2011). Frenger et al. (2015) reported that only partial eddies follow this intrinsic meridional propagation in the SO, owing to the strong overcompensation by the background meridional deflections of the mean current. Figure 7 in the manuscript shows that between 30°S and the ACC, the major propagation direction of eddies is westward, with AEs propagating north and CEs propagating south. However, most eddies in the ACC influence area propagate eastward, with AEs propagating south and CEs propagating north. These results are similar to those reported by Dawson et al. (2018).

According to the fact that more AEs and CEs propagate westward and northward, we added a paragraph in Section 4.1 to illustrate the eddy propagation directions. We also revised the descriptions in Section 5 regarding the influence of eddy trapping on SST, Chl-*a*, and DIC anomalies as follows:

1) We revised the sentences in lines 294–299 as follows:
"Table S3 shows that the predominant propagation direction of eddies is westward and northward (Fig. 3). According to the southward decreasing SST, northward propagating eddies would trap cold water and result in negative SST anomalies. However, this process contradicts the positive SST anomalies within WAEs and WCEs, indicating the weak effect of eddy trapping on SST."

2) We revised the sentences in lines 324–328 as follows:

“Due to the climatological Chl-*a* increasing southward (Figs. 5b1–b3), eddies propagating northward tend to trap high Chl-*a* into northern areas with low Chl-*a*. Likewise, due to the climatological Chl-*a* increasing westward, eddies propagating westward tend to trap low Chl-*a* into western areas with high Chl-*a*. However, the effect of eddy trapping on Chl-*a* cannot explain the opposite Chl-*a* anomalies between AEs and CEs (Figs. 6b1, b2, f1, and f2). Consequently, it can be inferred that the role of eddy trapping in influencing Chl-*a* distributions is limited.”

3) We revised the sentences in lines 350–352 as follows:
“Under the condition of southward increasing DIC (Figs. 5c1–c3), eddies propagating northward tend to trap high DIC. Thus, the effect of eddy trapping may contribute to the positive signals of DIC anomalies within eddies.”

Table 1. Number of AEs and CEs moving westward/eastward and northward/southward, including the overall eddies and eddies with lifetimes longer than 1 year.

	Eastward	Westward	Northward	Southward
AEs	7,924,626	9,261,954	9,266,102	7,920,478
CEs	8,387,806	9,300,955	9,824,357	7,864,404
AEs (>1 year)	44,184	323,242	294,536	72,890
CEs (>1 year)	97,955	294,167	140,362	251,760

(2) The authors use a number of averages to illustrate positive/negative signals induced by normal/abnormal eddies. Accounting for many noises (as shown in Figure 5), the standard error is suggested to be added to prove the reliability of the averages.

Response: Thank you for your insightful feedback. We calculated the averages and standard error of SST, Chl-*a*, DIC, and $p\mathrm{CO_2}$ anomalies within WAEs, CAEs, CCEs, and WCEs, as shown in Table 2 and Fig. 1 below. The averages are consistent with the dominant signals of the anomaly patterns within eddies (Fig. 5 in the manuscript). The small standard error proves the reliability of the averages. These results strengthen the robustness of our conclusions and ensure a more accurate representation of the uncertainties associated with our results. We have added Table 2 and Fig. 1 (presented below) in supplementary.

Table 2. Averages and standard error (in parentheses) of SST, Chl-*a*, DIC, and pCO_2 anomalies within WAEs, CAEs, CCEs, and WCEs.

	WAEs	CAEs	CCEs	WCEs
SST	0.03898 (0.00007)	-0.02697 (0.00011)	-0.04284 (0.00007)	0.02828 (0.00010)
Chl-*a*	-0.00125 (0.00001)	-0.00101 (0.00002)	0.00136 (0.00001)	0.00054 (0.00002)
DIC	-0.18258 (0.00062)	0.02228 (0.00120)	0.21712 (0.00066)	-0.07598 (0.00106)
pCO_2	-0.0323 (0.00061)	-0.01046 (0.00098)	0.01498 (0.00060)	-0.01383 (0.00090)

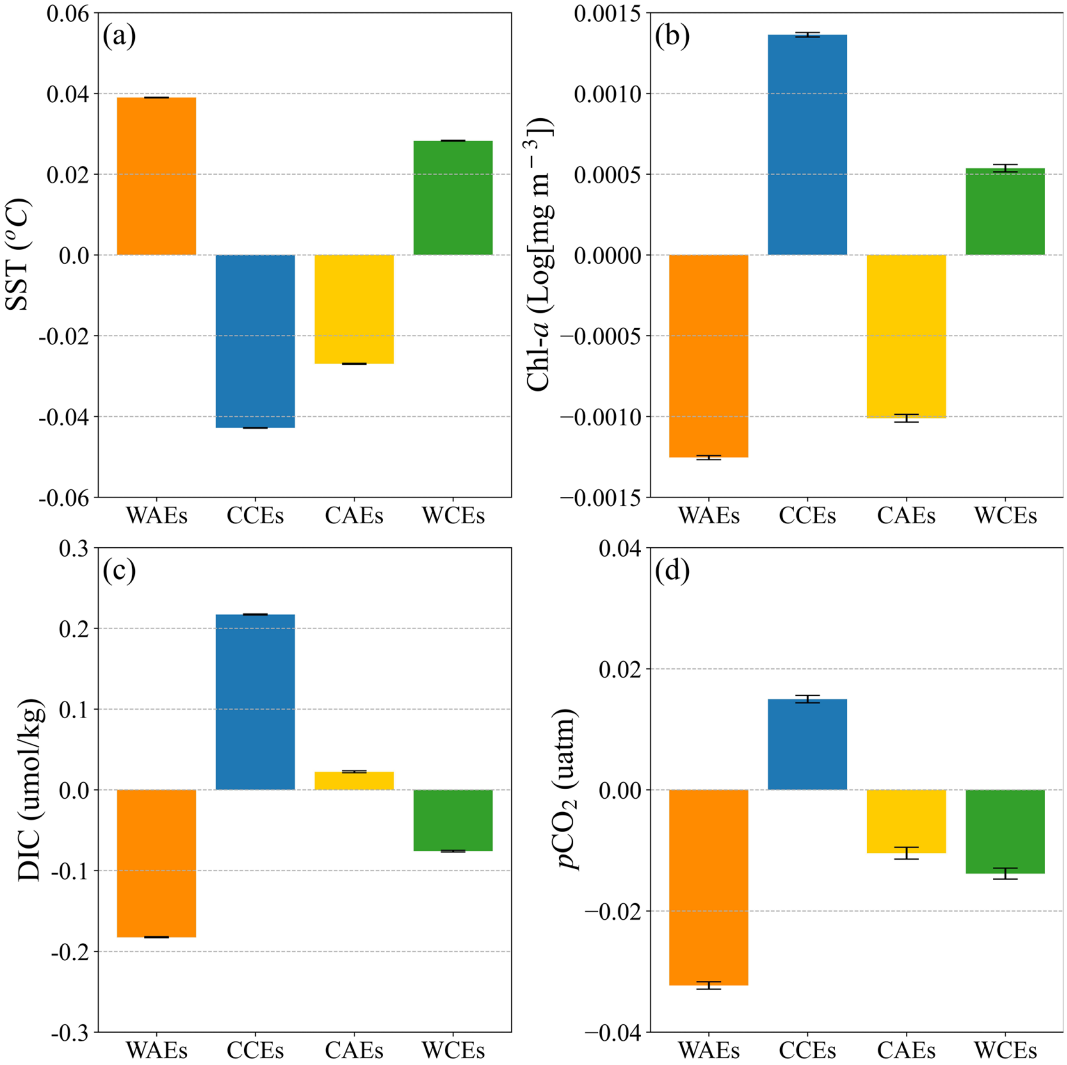

Figure 1. Averages (bars) and standard error (error bars) of SST, Chl-*a*, DIC, and pCO_2 anomalies within WAEs, CCEs, CAEs, and WCEs.

(3) For some results, the authors should cite references or give figures or significance to support the statement. For example, lines 236-237, “The amplitude and Chl-*a* anomalies are negatively correlated in subtropical waters north of the ACC and positively correlated along the ACC”, needs evidence. Please revise the similar problems in the whole manuscript.

Response: Thank you for your suggestions. We have conducted a comprehensive review of the manuscript, ensuring that each result is adequately supported through appropriate citations or relevant figures or significance. We have undertaken the following revisions:

1) Lines 236–237: We calculated the correlation coefficient between Chl-*a* anomalies and eddy amplitude along latitudes. According to Fig. 2 below, we revised the sentences in lines 236–237 as follows:
   “As shown in Fig. S4, the correlation coefficients between amplitude and Chl-*a* anomalies have larger magnitudes in subtropical waters, with negative values in WAEs and CAEs and positive values in CCEs and WCEs. This result illustrates that in subtropical regions with higher amplitudes, such as BMC, ARC, and Tasman Sea, WAEs and CAEs induced stronger negative Chl-*a* anomalies, while CCEs and WCEs induced stronger positive Chl-*a* anomalies.”

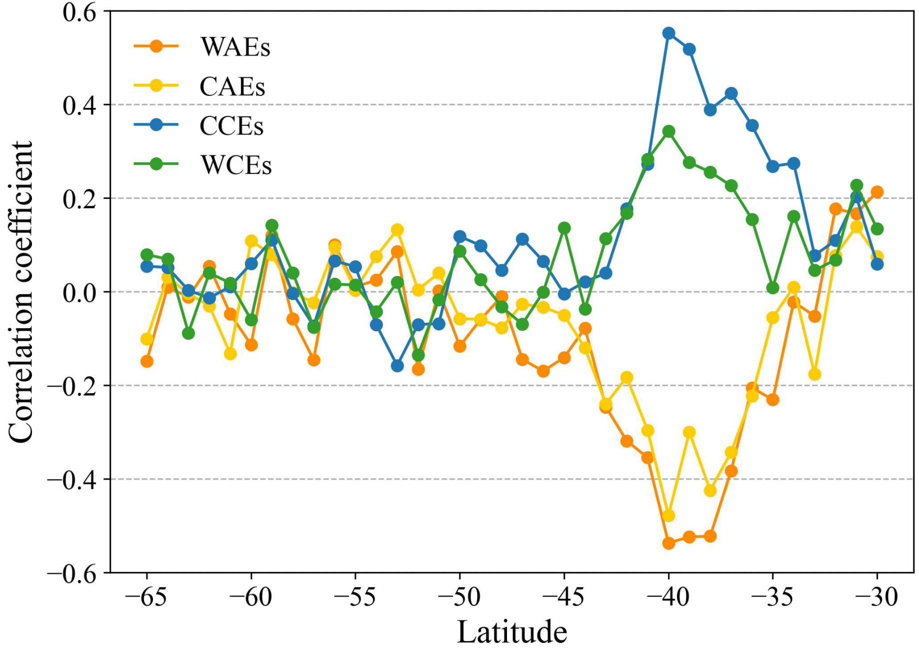

Figure 2. Correlation coefficients between Chl-*a* anomalies and eddy amplitudes along latitudes. The correlation coefficients range from -1 to 1, where -1 and 1 indicate perfect negative and positive linear correlations, respectively, and 0 signifies no linear correlation. Solid lines in different colors denote four kinds of eddies.

2) Lines 301–303: We added figures and revised the sentences as follows:
   “Specifically, WAEs rotating counterclockwise through the SST gradient would advect warmer water from the north to the southeast, leading to positive extremums slightly shifting westward and poleward relative to the cores (Figs. 6a1, e1). Conversely, CCEs rotating clockwise through the SST gradient would advect cooler water from the south to the northwest, leading to negative extremums slightly shifting westward and equatorward relative to the cores (Figs. 6a3, e3).”

3) Lines 333–334: We added a table and figures to support the statement:
   "As the major propagation direction of eddies is westward (Table S3), the composite Chl-*a* anomalies in AEs/CEs show dominant negative/positive signals due to eddy stirring (Figs. 6b1–b4 and f1–f4)."

4) Lines 380–382: We added figures to support the statement:
   "Likewise, the $p\mathrm{CO}_2$ anomalies over eddies are determined by the DIC anomalies in winter, which is also associated with the higher magnitudes of DIC anomalies in winter compared to summer (Figs. 6c1–c4 and g1–g4)."

5) Lines 443–444: We added a table to support the statement:
   "Specifically, in the SWA dominated by "abnormal" eddies, the contributions of "abnormal" eddies to $p\mathrm{CO}_2$ are opposite to normal eddies and are about twice as high as normal eddies (Table S5)."

3. The eddy mechanisms for SST/Chl-*a*/DIC analyzes need more thinking.

The authors try to explain the SST, Chl-*a*, and DIC anomalies affected by normal and abnormal eddies via eddy pumping/Ekman pumping/eddy tripping/eddy stirring. I got lost in section 5 and many times feel hard to understand how the authors obtained the conclusion. Some times their figures don't support their conclusions, and sometimes the conclusions are not solid.

Response: Thanks for your valuable suggestions. To clarity of our analysis on the eddy mechanisms influencing on SST, Chl-*a*, and DIC anomalies, we added a schematic diagram showcasing the results and conclusions in Section 5, as shown below.

Furthermore, we have thoroughly assessed the alignment between our figures and the corresponding explanations to ensure that they consistently support our conclusions.

We also conducted more in-depth analyses to validate our findings and conclusions.

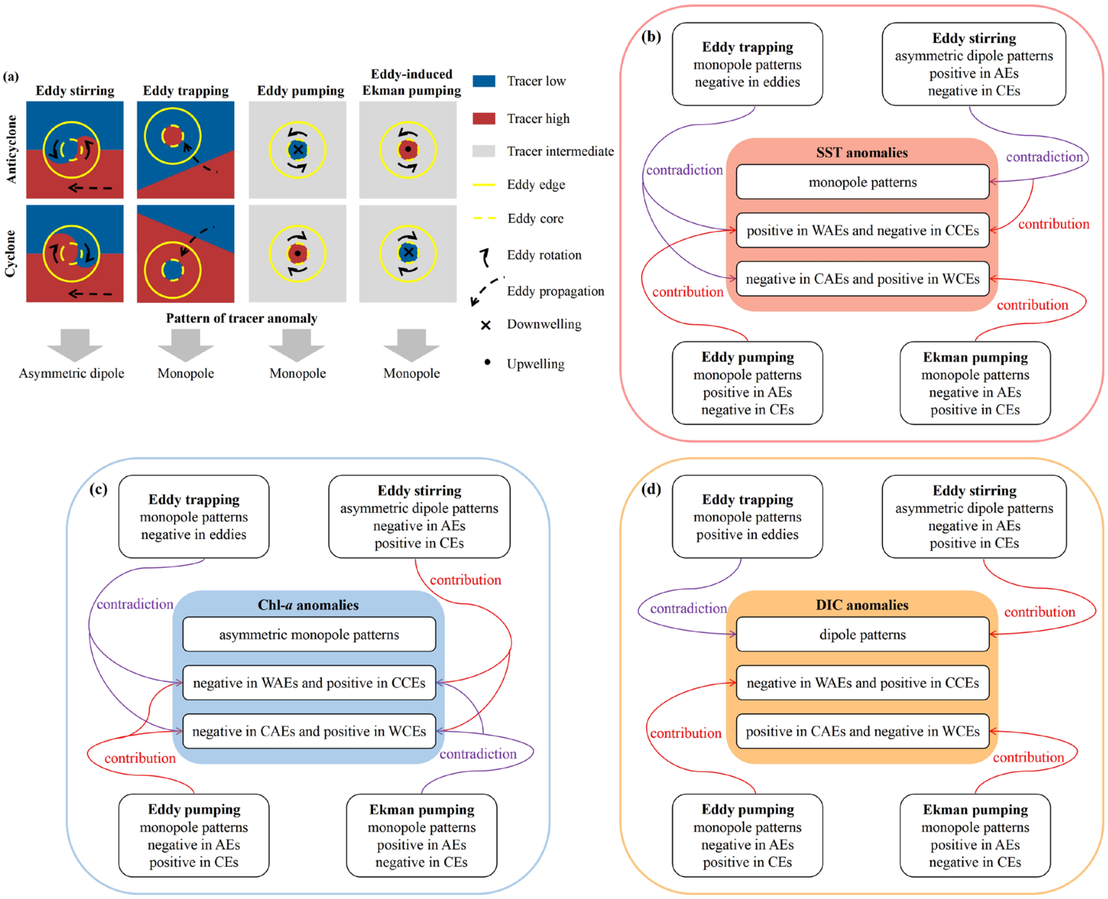

Figure 3. (a) Schematic illustrating the mechanisms of how eddies affect physical and biogeochemical parameters in the SO, including eddy stirring, eddy trapping, eddy pumping, and eddy-induced Ekman pumping. The patterns of SST anomalies induced by vertical pumping are opposite to the corresponding patterns shown in this schematic. The figure is inspired by Frenger et al. (2018), Fig. 1. Schematic diagram of the eddy mechanisms influencing (a) SST, (b) Chl-*a*, and (c) DIC anomalies.

Minor questions:

1. The authors point out that amplitudes of abnormal eddies are smaller than normal eddies, so that the eddy pumping of abnormal eddies are weaker. While looking at table S1, is the difference of amplitude significant enough to induce opposite results of normal and abnormal eddies?

Response: Thanks for your feedback. Figures. 3a–d in the manuscript illustrate that in the regions with larger amplitude, the magnitudes of SST anomalies within normal eddies are higher and those within “abnormal” eddies are lower. We further compared the quantitative relationship between SST anomalies and amplitudes over normal and “abnormal” eddies, as shown in Fig. 4 below. The SST anomalies in WAEs and CAEs are positively correlated with amplitudes, while the SST anomalies in CCEs and WCEs are negatively correlated with amplitudes. These findings indicate a positive correlation between amplitude and eddy pumping, as eddy pumping within AEs/CEs corresponds to downwelling/upwelling, inducing positive/negative SST anomalies. The smaller the amplitude of "abnormal" eddies, the weaker the eddy pumping, making them more susceptible to the influence of eddy-induced Ekman pumping. This results in opposite SST anomalies within "abnormal" eddies compared to normal eddies. Therefore, the negative/positive SST anomalies with high magnitudes in CAEs/WCEs in the low-amplitude regions characterize the final composite maps of SST anomalies within "abnormal" eddies (Figs. 5a2, a4, e2, and e4 in the manuscript).

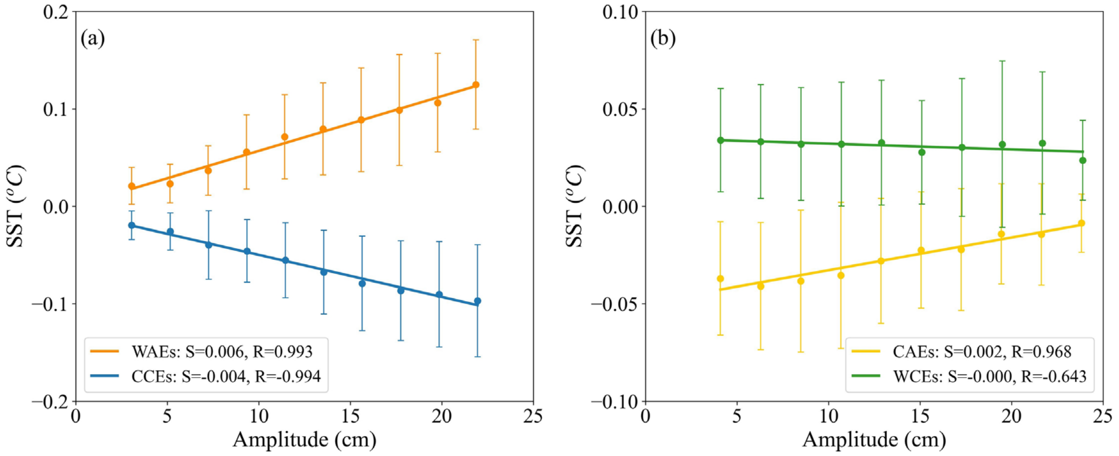

Figure 4. The mean SST anomaly within (a) normal eddies and (b) "abnormal" eddies as a function of eddy amplitude in the SO. Dots denote the values averaged at the binned amplitude intervals of 2 cm. Solid lines denote the regression lines obtained from least squares fitting with S being the slope and R the correlation coefficient. Solid lines in different colors denote four kinds of eddies.

2. Some descriptions about data processing are very detailed in the manuscript, such as lines 171 to 175. It is suggested to be moved in supplementary.

Response: Thanks for your suggestion. The descriptions you mentioned have been moved in supplementary.

3. A table could be added to supplementary to better show information of spatial/temporal resolution and filtering methods.

Response: Thanks for your suggestion. We have added a table (as shown below) in supplementary to presents information about spatial and temporal resolutions and filtering methods employed.

Table 3. Spatial and temporal resolutions and filtering methods of SST, Chl-*a*, DIC, and $p\mathrm{CO}_2$.

	Temporal resolution	Spatial resolution	Temporal filter	Spatial filter
SST	daily	0.25° × 0.25°	7-90 days band-pass filter	spatial high-pass filtering with 6° × 6°
Chl-*a*	daily	4 km × 4 km		
DIC	monthly	1° × 1°	subtracting the climatological averages	
$p\mathrm{CO}_2$	monthly	1° × 1°		

4. As for mechanisms for sea surface temperature and chlorophyll anomalies induced by abnormal eddies, the authors conclude that negative SST anomalies within CAEs are caused by eddy-induced Ekman pumping, while their negative Chl-*a* anomalies are due to eddy pumping. How can eddies modulate sea waters via two different vertical mechanisms? Although the authors explain that Chl-*a* is also affected by eddy stirring and show gradients of Chl-*a* background, the results shown in Figure 5 are not in agreement with their conclusions. Eddy stirring is supposed to induce dipole patterns, while Figure 5 shows monopoles (such as 5b2, 5f2). As a result, the authors should think more about the mechanisms.

Response: Thank you for your insightful questions and comments regarding our paper. Firstly, to address your concerns about the monopole Chl-*a* anomalies within winter eddies, as shown in Figs. 5b1–b4 in the manuscript, we calculated the seasonal average gradients of Chl-*a* in the SO. In winter, the north-south gradient of Chl-*a* is −0.01 (north is the positive direction), and the east-west gradient of Chl-*a* is −0.01 (east is the positive direction). However, in summer, the north-south gradient of Chl-*a* is −0.02, and the east-west gradient of Chl-*a* is −0.05. Compared to the summer Chl-*a* anomalies (Figs. 5f1–f4 in the manuscript), the smaller gradients of winter Chl-*a* weaken the impacts of eddy stirring, diminishing the dipole patterns of Chl-*a* anomalies within winter eddies (Figs. 5b1–b4 in the manuscript).

Although the dipole patterns of winter Chl-*a* anomalies are not obvious, we can still find the impacts of eddy stirring on Chl-*a*, that is, the meridional and zonal shifts of Chl-*a* anomalies extremums (Figs. 5b2–b4 and f1–f4 in the manuscript), which are proposed to be induced by the large-scale background Chl-*a* gradient and eddy stirring (Hausmann and Czaja, 2012; Villas Bôas et al., 2015). For meridional shifts, AEs rotating counterclockwise through the southward increasing Chl-*a* gradient would induce negative extremums slightly shifting poleward relative to the cores (Figs. 5b2, f1, and f2 in the manuscript). The reverse is true for CEs (Figs. 5b3, b4, f3, and f4 in the manuscript). For zonal shifts, AEs rotating counterclockwise through the westward increasing Chl-*a* gradient would induce negative extremums slightly shifting westward relative to the cores (Figs. 5b2, f1, and f2 in the manuscript). The reverse is true for CEs (Figs. 5b3, b4, f3, and f4 in the manuscript).

Furthermore, Frenger et al. (2018) have demonstrated that eddy-induced Chl-*a* anomalies in the SO primarily stem from stirring, but they did not account for the impacts of vertical pumping induced by eddies. They proposed that lateral entrainment diminishes the dipole component of the Chl-*a* anomalies, resulting in predominantly monopole Chl-*a* anomaly patterns rather than dipole patterns.

In addition to the horizontal redistribution of Chl-*a* anomalies, the major limitation of marine Chl-*a* is the insufficient supplement of nutrients from depth into the euphotic zone (Mahadevan, 2016). The transport of nutrients enriched in deep seawater is mainly controlled by eddy pumping. By contrast, the variations of SST and DIC anomalies are prone to be influenced by heat and carbon exchange at the ocean-atmosphere interface (Gaube et al., 2015; Song et al., 2016), making them susceptible to eddy-induced Ekman pumping. Consequently, Chl-*a* anomalies in normal and "abnormal" eddies show similar patterns and signals, whereas SST and DIC anomalies in normal and "abnormal" eddies show opposite signals.

We have revised the eddy influencing mechanisms on Chl-*a* anomalies and deepened the discussion.

5. Line 339-341, it's a little hard for the readers to follow the authors' thinking. Please make the expression clearer, such as "the more evident Ekman pumping mechanism of abnormal eddies resisting eddy pumping and leads to lower Chl-*a* magnitude within abnormal eddies than normal eddies". Other similar problems in the manuscript could be also improved.

Response: Thanks for your suggestions. We have reviewed the entire manuscript to revise these problems. The specific modifications are shown below:

1) We revised the sentences in lines 339–341 as follows:
   "However, the more evident Ekman pumping mechanism of "abnormal" eddies resists eddy pumping and leads to lower Chl-*a* magnitude within "abnormal" eddies than normal eddies (Figs. 6b1–b4 and f1–f4)."

2) We revised the sentences in lines 423–425 as follows:
   "However, the magnitudes of Chl-*a* anomalies within "abnormal" eddies are lower than normal eddies, which is related to the more pronounced impact of "abnormal" eddies in counteracting eddy pumping through the mechanism of Ekman pumping."

6. Line 358-361. How did the authors get the conclusion? Please add references or show their own results. A similar problem also occurs in other expressions. Please read the manuscript seriously and improve them.

Response: Thanks for your advice. We have thoroughly reviewed the manuscript to address these problems. The specific modifications are shown below:

1) Lines 358–361: We added figures to show the results. The revised sentences are shown as follows:

"Moreover, the Ekman pumping caused by WAEs is stronger than that caused by CAEs (Figs. 8a1, a2), resulting in stronger positive DIC anomalies within WAEs than CAEs (Figs. 6c1, c2, g1, and g2). Similarly, the Ekman pumping caused by WCEs is stronger than that caused by CCEs (Figs. 8a3, a4), resulting in stronger negative DIC anomalies within WCEs than CCEs (Figs. 6c3, c4, g3, and g4)."

2) Lines 435–439: We added figures and revised the sentences as follows:
"In winter, the dominant DIC-driven effect leads to negative $p\mathrm{CO}_2$ anomalies in WAEs and WCEs and positive anomalies in CAEs and CCEs (Figs. 6d1–d4). However, in summer, the $p\mathrm{CO}_2$ anomalies are dominated by the combined effects of SST, Chl-*a*, and DIC (Figs. 6h1–h4). Notably, the $p\mathrm{CO}_2$ anomalies within eddies are dominated by SST anomalies in the summer SWA, with smaller magnitudes of DIC anomalies (Fig. 9). In contrast, the $p\mathrm{CO}_2$ anomalies within eddies are dominated by DIC anomalies in the ARC, with larger magnitudes of DIC anomalies (Fig. 10)."

7. Line 364, missing space.

Response: Revised.

8. Line 398-399, how did the authors evaluate the significance of different mechanisms? Are there any quantitative criteria?

Response: Thanks for your feedback. Regarding the evaluation of the significance of different mechanisms, our analysis focused on qualitative rather than quantitative assessment. By comparing the patterns and signals of SST, Chl-*a*, and DIC with the effects of eddy trapping, stirring, pumping, and eddy-induced Ekman pumping, we were able to identify the relative importance of each mechanism. While we acknowledge the value of quantitative criteria, our study aimed to provide insights into the dominant mechanisms through a qualitative analysis of the observed patterns and signals.

9. The writing in Figure 4a1 is suggested in Figure 4a1.

Response: Revised.

Reference

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