Response to reviews on ‘Characteristics of Surface Physical and Biogeochemical Parameters within Mesoscale Eddies in the Southern Ocean’

We thank the editor and both reviewers for their professional comments and constructive suggestions to improve the manuscript. We have addressed all comments and revised the manuscript accordingly. In the following, we address the editor and reviewer’s comments point by point. Our response is given in the blue text below.

Yours sincerely,

Qian Liu, on behalf of the co-authors

Response to Editor

General comments

1. Please include all of the reviewers' suggestions into your revised version. Especially reviewer 1 raised the issues of the introduction not guiding well enough to your study.

Response: We have addressed each comment from the reviewers one by one and incorporated their suggestions into the revised version of the manuscript. The main modifications are shown as follows.

1） **Introduction**
In response to the comments from reviewer 1, the introduction section has been restructured to provide a clear overview of the research objectives and emphasize the novelty of the study. Additionally, we have explicitly stated that eddy-induced Ekman pumping may contribute to the occurrence of “abnormal” eddies in the introduction.

2） **Data and Methodology**
We provided more detailed information regarding the data sources and the methodology for deriving pCO_2, identifying “abnormal” eddies, and compositing eddy-induced anomalies.

3） **Discussion**
Compared to the previous response to the reviewers' comments, we have made

significant improvements to the discussion. Specifically, we revealed that in addition to the variation of the same parameter within different eddies, the dominant eddy-driven mechanisms for different parameters within the same kind of eddies also differ. The strength of the eddy stirring effect on different parameters is the major cause due to the different magnitudes of the horizontal parameter gradients.

Additionally, we have revised the abstract and conclusion sections to incorporate more details from the discussion and reflect the significance of our findings.

2. The discussion lacking some depth. My own concerns are in line with this reviewer's and I also would like to see more of a discussion on your findings in comparison with those of McGillicuddy, Gaube and colleagues on eddy induced Ekman pumping.

Response: We have deepened the discussion section and compared our findings with Gaube et al. (2014) regarding eddy-induced Ekman pumping in Section 6, Lines 396–439 (revised manuscript). We added a table, presented below, to illustrate the significance magnitudes of effects for different eddy-driven mechanisms on various parameters.

Table 1. Significance magnitudes of effects for eddy-driven mechanisms on SST, Chl-*a*, and DIC. A indicates a dominant effect. B represents an effect that contributes to the eddy-induced anomalies but is not the dominant effect. C denotes an effect that is not significant.

	SST		Chl-*a*		DIC	
	Normal	"Abnormal"	Normal	"Abnormal"	Normal	"Abnormal"
Eddy trapping	C	C	C	C	C	C
Eddy stirring	B	C	A	A	A	A
Eddy pumping	A	B	A	A	A	B
Eddy-induced Ekman pumping	B	A	B	B	B	A

In Section 6, Lines 396–439 (revised manuscript), the deepened discussion reads as follows:

“Section 5 reveals distinct influence mechanisms of eddies on SST, Chl-*a*, DIC, and *p*CO_2, which vary based on the inherent properties of each parameter and the complex interactions between eddies and the biogeochemical processes in the SO. As shown in Table 1, we compare the significance magnitudes of different effects, including eddy trapping, stirring, pumping, and eddy-induced Ekman pumping, on SST, Chl-*a*, and DIC. It should be noted that the seasonal modulation of the mixed layer is not discussed in our study due to the absence of significant seasonal variations in eddy-induced SST, Chl-*a*, and DIC anomalies (Figure S5). Additionally, the variability of *p*CO_2 anomalies within eddies is controlled by the effects of SST, Chl-*a*, and DIC, therefore, the eddy-driven mechanisms on *p*CO_2 can be demonstrated by exploring the effects of eddies on SST, Chl-*a*, and DIC.

Compared to SST, eddy stirring plays a more significant role in Chl-*a* and DIC anomalies within eddies. As eddy stirring redistributes physical and biogeochemical parameters spatially through horizontal advection, the larger the horizontal parameter gradient, the stronger the eddy stirring effect (Mcgillicuddy, 2016). We calculate the average gradients of normalized SST, Chl-*a*, and DIC in the SO from 1996 to 2015 and find their values are 0.05, 0.11, and 0.20, respectively. The specific method to obtain the gradients is demonstrated in Text S1 (Quarteroni et al., 2006). The small gradient of SST leads to a negligible effect of eddy stirring and results in more pronounced monopole patterns within eddies than other variables (Figs. 5a1–a4 and e1–e4).

By contrast, the average gradient of Chl-*a* is nearly two times higher than that of SST, thus, eddy stirring can cause a stronger effect on Chl-*a*. Both eddy stirring and eddy pumping contribute to the generation of negative/positive Chl-*a* anomalies within AEs/CEs. The combined effects of eddy stirring and eddy pumping dominate the similar patterns of Chl-*a* anomalies in normal and “abnormal” eddies. However, the effect of eddy-induced Ekman pumping on Chl-*a* is relatively small and contributes to attenuating the magnitudes of Chl-*a* anomalies within “abnormal” eddies (Figs. 5b1–b4 and f1–f4).

Such limited influence of eddy-induced Ekman pumping on Chl-*a* in the SO was also reported by Gaube et al. (2014), who plotted global maps of the cross correlation of Chl-*a* anomalies and SSH, as well as eddy-induced Ekman pumping, revealing a negative correlation between Chl-*a* anomalies and SSH and a negative correlation between Chl-*a* anomalies and eddy-induce Ekman pumping in most areas of the SO. These results indicate that AEs have negative Chl-*a* anomalies and CEs have positive Chl-*a* anomalies, and eddy-induced Ekman pumping does not dominate the variation of Chl-*a* anomalies within eddies. In addition, we obtain the composite averages for Chl-*a* anomalies in the BMC, defined by Gaube et al. (2014) as 305°–330°E and 34°–50°S (Figure S4). The patterns are similar to those obtained by Gaube et al. (2014), with dominant monopole negative Chl-*a* anomalies within AEs and positive Chl-*a* anomalies within CEs. However, we find the magnitudes of Chl-*a* anomalies within “abnormal” eddies are smaller than normal eddies, which associates with the effect of eddy-induce Ekman pumping.

The average gradient of DIC is four times higher than that of SST, indicating that eddy stirring will have a more pronounced impact on DIC than on SST. As a result, the composite DIC anomalies within eddies show dipole patterns (Figs. 5c1–c4 and g1–g4). In addition to the different impacts of eddy stirring on SST and DIC, both eddy pumping and eddy-induced Ekman pumping contribute to the variations in these parameters (Table 1). In normal eddies, eddy pumping dominates the vertical distribution of SST and DIC. Within CCEs, the upwelling of cold, DIC-rich deep water induces negative SST anomalies and positive DIC anomalies, whereas the reverse is true for WAEs. However, the influence of eddy-induced Ekman pumping becomes more prominent within "abnormal" eddies. Within WCEs, the downwelling of warm, low-DIC surface waters induces positive SST anomalies and negative DIC anomalies, whereas the reverse is true for CAEs.

The impact of eddies on pCO_2 anomalies varies by season and region, which arises from the combined effects of SST, Chl-*a*, and DIC. In winter, the dominant DIC-driven effect leads to negative pCO_2 anomalies in WAEs and WCEs, and positive anomalies in CAEs and CCEs. However, in summer, the pCO_2 anomalies are dominated by the combined effects of SST, Chl-*a*, and DIC. Notably, the pCO_2 anomalies within eddies are dominated by DIC anomalies in the ARC, with larger magnitudes of DIC anomalies in summer. In contrast, the pCO_2 anomalies within eddies are dominated by SST anomalies in the SWA, with smaller magnitudes of DIC anomalies."

3. In addition, every figure needs a thorough explanation in the text.

Response: We have thoroughly reviewed each figure and made revisions according to the suggestions provided by the reviewers and the editor. Additionally, we have ensured that every figure is accompanied by a detailed caption that provides essential information.

1) In response to the comments of reviewer 1, we removed Figs. 1, 3, and 5 and Tables 1 and 2 to the Supporting Information.

2) In Fig. 2, we used a sequential colormap, revised the figure legends to specify where the latitude 65°S is, and removed the currents and topographic features that are not mentioned in the manuscript.

3) We added captions explaining what the magenta boxes represent to Figs. 4, 6, 7, 10.

4) The caption of Fig. 4 has been revised to ensure that the blue and red colors are clearly associated with the right column only.

5) The font size in Figs. 5, 7, and 11 has been appropriately reduced.

Furthermore, in the Results section, we have provided thorough explanations for each figure, making it easier for readers to comprehend the key findings and their relevance to the study.

Response to Reviewer #1

Overall impression

The paper investigates the physical and biogeochemical characteristics of mesoscale eddies at the surface of the Southern Ocean – a region of global importance for heat and carbon exchange and biogeochemical cycles, concurrently a region dominated by eddies. This study involves many novel aspects compared to previous studies and tackles relevant topics for the community. It distinguishes between warm-core anticyclonic eddies (AEs), cold-core AEs, cold-core cyclonic eddies (CEs), and warm-core CEs (termed here as 'normal' and 'abnormal' AEs and CEs). At the same time, the discussion lacks some depth and many aspects of the methods and results/discussion remain unclear. There are also many figures which are only discussed very briefly and could be moved to the Supporting Information. These issues should be addressed before publication.

Response: We would like to thank reviewer 1 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.

General comments

1. From the introduction, it's not entirely clear what's new about this study (one finds the information eventually, but it's quite hidden and only becomes apparent later). What's new about this study compared to previous work should really be the focus of the introduction. E.g., L86: Mention that the Frenger et al. studies investigated the vertical structure, while this study is only considering the surface. The same paragraph (from L86) also reads as if the only difference between the Frenger studies and this study is that this study differentiates between 'normal' and 'abnormal' eddies. However, there are many other differences (surface vs. interior; which parameters are considered; method of eddy detection…).

Response: Thanks for the suggestion. We have restructured the Introduction section to provide a clear overview of the research objectives and emphasize the novelty of the study. The key differences between our work and previous studies were explicitly stated from several perspectives, including

1) The specific impact of "abnormal" eddies on physical and biogeochemical parameters in the SO remains unclear (Lines 70–73 in the revised manuscript).

2) Previous studies have primarily focused on the basin-wide effects of eddies on Chl-*a*, while investigations into the basin-scale effects of SO eddies on DIC and pCO_2

are lacking (Lines 73–75 in the revised manuscript).

3) It is necessary to systematically study the influence of eddies on SST, Chl-*a*, DIC, and pCO_2 in the SO (Lines 75–77 in the revised manuscript).

4) Compared to traditional eddy detection methods, the deep learning model can simultaneously detect eddy locations and distinguish between normal and "abnormal" eddies with great accuracy and efficiency (Lines 79–86 in the revised manuscript).

5) Our study focuses solely on the surface (Lines 1, 10, 78, 91, and 448 in the revised manuscript).

2. My biggest concern: McGillicuddy, Gaube, and others have pointed out that eddy-induced Ekman pumping results in the opposite signal compared to regular eddy pumping and that eddy-induced Ekman pumping is usually weaker, but can be significant, especially in regions with large wind stress. Thus, when seeing cold core AEs or warm core CEs, I would assume that there, eddy-induced Ekman pumping dominates. However, in this paper it is framed like a mystery that some AEs have cold cores, and some CEs have warm cores (termed 'abnormal eddies'). Later, the study exactly finds this, at least in the analysis with SST (Section 5.1, esp. L278). Thus, I recommend rephrasing the storyline that cold-core AEs and warm-core CEs are likely to be dominated by eddy-induced Ekman pumping.

Response: Thanks for the suggestion. We agree that eddy-induced Ekman pumping is a primary generation mechanism of "abnormal" eddies. In addition, other mechanisms are also proposed to induce the formation of "abnormal" eddies. Therefore, we added a review about the generation mechanisms of "abnormal" eddies in the Introduction section, Lines 67–70 (revised manuscript):

"Previous literature proposed that "abnormal" eddies may be induced by eddy-induced Ekman pumping (Gaube et al., 2013; Mcgillicuddy, 2015), instability during the eddy decay stage, eddy horizontal entrainment (Sun et al., 2019), and warm/cold background water (Leyba et al., 2017)."

After rephrasing the introduction, we proved that the formation of "abnormal" eddies is dominated by eddy-induced Ekman pumping in the Results section, making the study storyline more reasonable.

3. The discussion should be deepened. Currently, Sections 4 and 5 mostly show the results with a lot of figures, and Section 6 (Conclusions) is mostly a summary of these findings. I'm missing a more in-depth discussion of what this now all means and how it matters. One thing to focus on especially is the surprising finding that when considering SST anomalies, eddy-induced Ekman pumping dominates in certain eddies,

while for the other variables, different processes dominate. How can the same eddies pump DIC-rich water upwards without pumping cold water up? Once the discussion has been deepened, the abstract and conclusions can then also mention some more from the discussion. Right now, the abstract and conclusion sections are quite descriptive of the results but don't tell us much about their significance.

Response: Thanks for your valuable suggestions. We have deepened the discussion section in Section 6, Lines 396–439 (revised manuscript). The major improvements to the discussion include the following:

1) Comparing the significance magnitudes of effects for eddy trapping, stirring, pumping, and eddy-induced Ekman pumping on SST, Chl-*a*, and DIC (Table 1 in the revised manuscript), we found distinct influence mechanisms of the same kind of eddies on various parameters.

2) Calculating the average horizontal gradients of SST, Chl-*a*, and DIC, we revealed that the different dominant eddy-driven mechanisms for various parameters within the same kind of eddies are the results of the distinct strength of the eddy stirring effect on different parameters due to the different magnitudes of the horizontal parameter gradients.

3) The negligible impact of eddy stirring on SST due to small gradient values results in pronounced monopole patterns within eddies. By contrast, eddy stirring has a stronger impact on Chl-*a* and DIC, resulting in dipole patterns within eddies.

4) Both eddy stirring and eddy pumping contribute to the generation of negative/positive Chl-*a* anomalies within AEs/CEs. The combined effects of eddy stirring and eddy pumping dominate the similar patterns of Chl-*a* anomalies in normal and "abnormal" eddies.

5) Compared with the findings reported by Gaube et al. (2014), we further proved that the effect of eddy-induced Ekman pumping on Chl-*a* is relatively small and contributes to attenuating magnitudes of Chl-*a* anomalies within "abnormal" eddies.

6) Both eddy pumping and eddy-induced Ekman pumping contribute to the variations of SST and DIC. For normal eddies, eddy pumping dominates the vertical distribution of SST and DIC. Within CCEs, the upwelling of cold, DIC-rich deep water induces negative SST anomalies and positive DIC anomalies, whereas the reverse is true for WAEs. However, the influence of eddy-induced Ekman pumping becomes more prominent within "abnormal" eddies. Within WCEs, the downwelling of warm, low-DIC surface waters induces positive SST anomalies and negative DIC anomalies, whereas the reverse is true for CAEs.

Furthermore, the abstract and conclusion sections have also been revised to include more information from the discussion and reflect the significance of our results.

4. Consider moving Fig.1 and 3 and Table 1 and 2 to the Supporting Information, they don't add much new information. Fig. 5 is only discussed with one sentence (L192) and could also move to the SI or be discussed in more depth. Similarly, Fig. 7 is only very briefly touched upon and can move to the SI.

Response: Thanks for the suggestion. In the revised manuscript, Figs. 1, 3, and 5, and Tables 1–2 have been moved to the Supporting Information. Besides, Fig. 7 is retained in the manuscript since it describes the directions of horizontal parameter gradients which are used to evaluate the effects of eddy trapping and stirring on parameters, and a more detailed description and discussion about Fig. 7 are added in Section 5.

Specific comments

1. It is not immediately clear that the study only focuses on surface properties. This could be added to the title and should be clearer in the abstract and introduction.

Response: We have revised the title, abstract, and introduction to make it clearer that our study solely examines surface properties.

2. L10: add 'horizontal surface' before 'composite'

Response: "horizontal surface" has been added.

3. L73: Are the signals also different when the seasonal signal has been removed? I.e., are the anomalies computed based on mean annual reference values, or on a monthly climatology? I have a feeling that if a monthly climatology is used as a reference, the eddy anomalies might not differ so much anymore by season. This should be mentioned/discussed.

Response: We have modified the method section and added a figure (as shown below) in the Supporting Information to show that we have removed the seasonal signals. The SST and Chl-*a* anomalies are computed using a 7–90 days band-pass filter to remove the seasonal signal. For DIC and pCO_2 datasets with monthly temporal resolution, we have subtracted their climatological averages.

Since we removed the seasonal signals, there are no significant seasonal variations in eddy-induced SST, Chl-*a*, and DIC anomalies, as shown in Fig. 1 below. Moreover, Fig. 8 also shows little variation in composite averages of SST, Chl-*a*, and DIC anomalies within eddies between summer and winter.

Only pCO_2 anomalies with monthly temporal resolution show remarkable seasonal variations caused by the different dominant effects of SST, Chl-*a*, and DIC, which has been discussed in the revised manuscript (Lines 364–394).

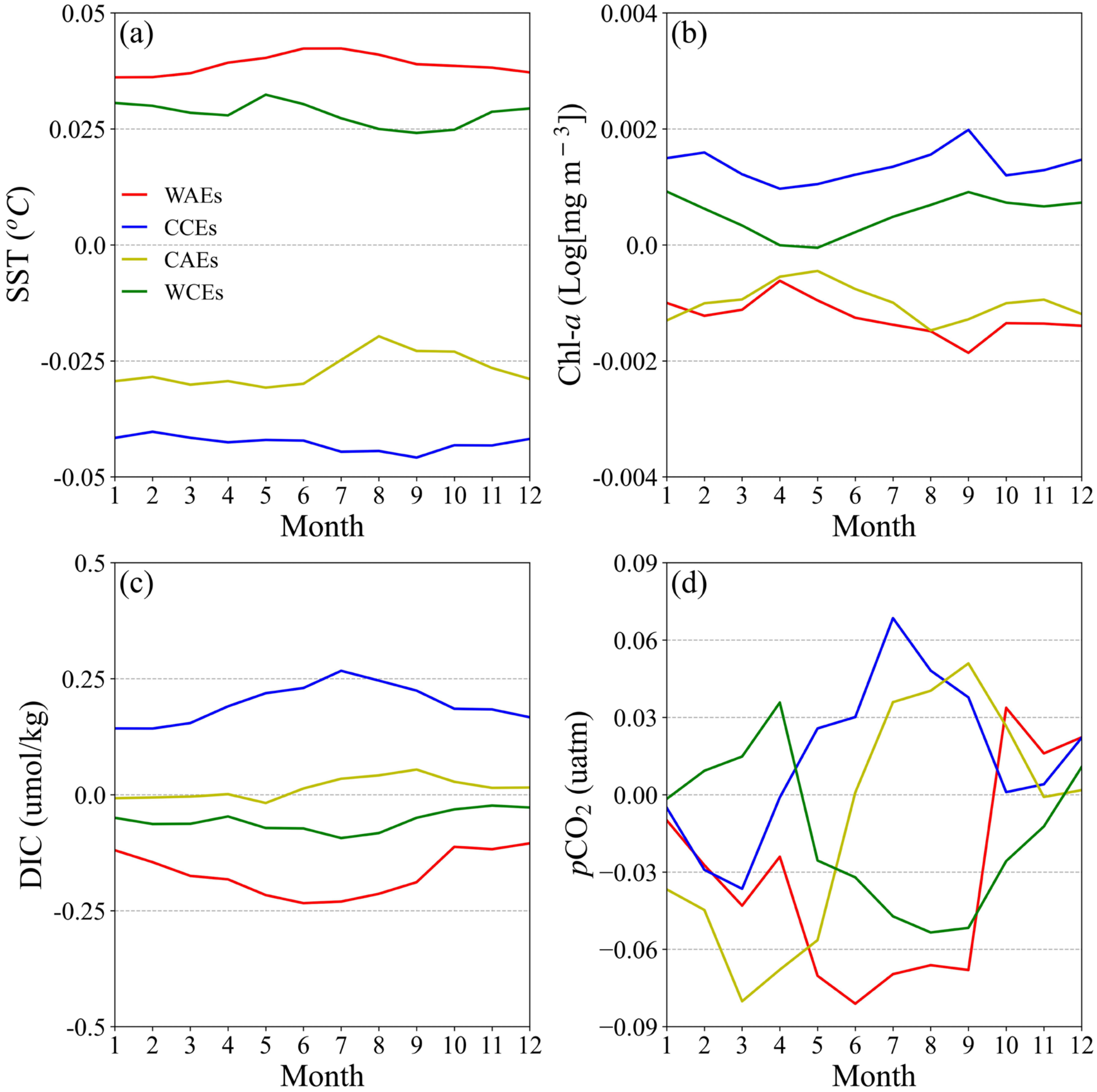

Figure 1. Variations in monthly mean eddy-induced anomalies, including (a) SST, (b) Chl-*a*, (c) DIC, and (d) pCO_2 in the SO from 1996 to 2015. Solid lines in different colors denote four kinds of eddies.

4. L119: Be specific that the DIC is gap-filled in this step.

Response: Thanks for your suggestion. We have explicitly mentioned in the manuscript that the DIC field is gap-filled during this process.

5. Section 2.2 and 2.3: be clearer that those datasets used were created by previous studies. It currently reads ambiguously if this was done during this study or if the data is from previous work.

Response: We have revised the manuscript to make it clear that these datasets were created by previous studies.

6. L127: Is 'This dataset' referring to Landschuezter et al. 2014, or to the Liu et al. 2021 product that is used in this study? If it's referring to Landschuezter: as that product has been used so widely, why did you not use that product? What's the benefit of using Liu et al? If it's referring to Liu et al: rephrase the sentence so that it's clearer (but then some of the references are wrong as they were published before 2021…)

Response: We appreciate the reviewer's comment and apologize for the confusion caused by the ambiguous reference in the manuscript. To clarify, in Line 127, "This dataset" refers to the dataset used in our study, which is from the JMA Ocean CO_2 Map dataset, established by Iida et al. (2021). The sentence in the revised manuscript (Lines 113–114) is as follows: "The pCO_2 and DIC datasets are from the Japan Meteorological Agency (JMA) Ocean CO_2 Map dataset with monthly 1° × 1° gridded values on the global ocean from 1990 to 2020 (Iida et al., 2021)."

Besides, the reason for citing references published before 2021 is that the initial version of this database was published in 2015 (Iida et al., 2015). These two versions of the pCO_2 dataset use the same approach, multiple linear regression (MLR) method. The difference is that the initial one uses sea SST, sea surface salinity (SSS), and Chl-*a* as independent variables (Iida et al., 2015). By contrast, the new version of the pCO_2 dataset is reconstructed from the fields of total alkalinity (TA), DIC, SST, and SSS (Iida et al., 2021).

To address the issue of the data source and references, we have emphasized that the dataset is provided by Iida et al. (2021) and cited accurate references related to this dataset.

7. Section 2.3: Mention how the eddy detection method differs from other, more commonly used approaches, such as the AVISO eddy database (newest version: Pegliasco et al. 2021), and why it was preferred. One could have used the AVISO eddies and classified the eddies into normal and abnormal based on their SST signature (e.g., AE with cold SST anomaly is CAE...).

Response: We have added a paragraph in Section 2.3 to highlight the differences between our eddy detection method and the AVISO eddy database, as well as why we choose this eddy dataset. Compared to the AVISO eddy database (Pegliasco et al., 2022), our study utilizes a different eddy detection method (Liu et al., 2021), which uses a deep learning model to fuse satellite SSH and SST data. The reason why we use this method is that deep learning technology has unparalleled learning ability and the capability to model complex nonlinear relationships compared to traditional statistics and machine learning methods (Reichstein et al., 2019). Besides, the method can simultaneously extract SSH features for determining eddy locations and extract SST information to help distinguish between normal and "abnormal" eddies. As a result, our method achieves great accuracy and much higher efficiency than the traditional method that first detects the eddies and then uses the SST signature to classify them into normal and “abnormal” eddies. In addition, the method is able to detect eddies in regions where traditional methods may not be effective, such as in regions with weak eddies or regions with complex oceanic dynamics (Liu et al., 2021). Given its high accuracy and comprehensive information on eddy characteristics, we find this dataset particularly useful for our study.

8. L144-149: I think this part of the paragraph still belongs to section 2.3.

Response: Thanks for the suggestion. This paragraph describes the methodology for obtaining the distribution of various sea surface variables within the eddy, so it should be included in the methodology section 3.1 rather than the data section 2.3. To address this concern, we revised the methodology section title to “Composite Eddy-induced Anomalies” and enhanced the methodology section to provide a more explicit explanation of this point in the paper.

9. L149-153: Needs a more in-depth description of how the composite eddies were made.

Response: We have added a schematic in the Supporting Information (as shown in Fig. 2 below) and revised the section to provide additional details on the methodology used to create the composite eddies in Section 3.1, Lines 168–178 (revised manuscript). The revised section reads as follows:

“Finally, we use the eddy-centric composite method to estimate the spatial pattern of the eddy-induced anomalies in sea surface variables. The positions of co-located SST, Chl-*a*, DIC, and pCO_2 observations are normalized by R, which defines the edge of an eddy as ±1 and the eddy core as 0. This allowed us to construct composite averages from eddies of varying sizes. We then extract data from −2R to 2R to include the interactions between eddies and the surrounding waters and interpolate them onto an evenly spaced 17 by 17 grid to create the surface composite patterns. For daily SST and Chl-*a*, we perform the eddy-centric composite method matching eddies and variables on the same day and calculate the mean value. By contrast, for monthly DIC and pCO_2, we calculate the eddy-centric composite maps, using all eddies of the same month with DIC and pCO_2 of that month and calculate the mean value. The composites are not rotated with the background variables gradient, as the large-scale background variables gradients in the SO are oriented north-south. Previous studies have shown that rotating eddies to the large-scale variables gradient in the SO has a negligible impact on the results (Frenger et al., 2015). Therefore, the axes in each figure point north and east.”

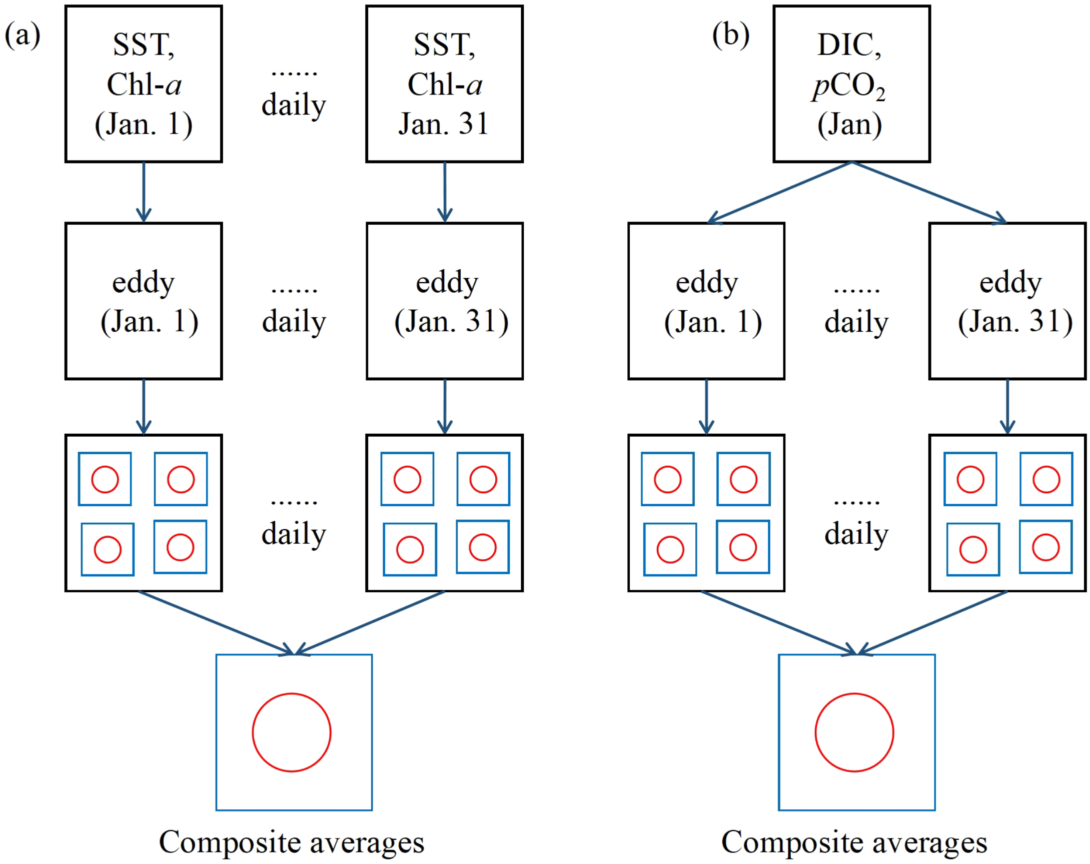

Figure 2. Schematic of eddy-centric composite method for daily (a) SST and Chl-*a* and monthly (b) DIC and pCO_2, taking January as an example.

10. L171: Be explicit about how it differs from the method by Gaube et al. 2015.

Response: We have revised the section to clarify that we use the same formula to calculate the total eddy-induced Ekman pumping and the same spatiotemporal filtering method as Gaube et al. (2015). However, we only calculate the total eddy-induced Ekman pumping and do not calculate the individual components such as SST-induced Ekman pumping and current-induced Ekman pumping. Besides, the SSH dataset we use is constructed at a daily temporal resolution, whereas the SSH data used by Gaube et al. (2015) is constructed at 7-day intervals.

11. Section 3.2: Add a reference for the methods to obtain the eddy-induced Ekman pumping.

Response: A reference (Gaube et al., 2015) has been added.

12. L239: Discuss why we want to know how the pattern differs from the pCO_2 pattern. I would have found it more interesting to see the pattern differences between normal and abnormal eddies, but there could be a reason why you chose this.

Response: We revised this section to explain why we discuss the pattern differences between pCO_2 and other variables. While SST, Chl-*a*, and DIC anomalies within eddies are found to be similar in summer and winter, pCO_2 anomalies are significantly different between the two seasons. This is because, in winter, the pCO_2 anomalies are dominated by the dominant DIC-driven effect. By contrast, in summer, the pCO_2 anomalies are dominated by SST and DIC anomalies in some regions with smaller and larger magnitudes of DIC anomalies, respectively. Due to the opposite anomalies of DIC and SST within the same kind of eddies, the basin-scale effects of SO normal and "abnormal" eddies on pCO_2 have little significant pattern differences in summer. Since we already discussed SST and DIC pattern differences between normal and "abnormal" eddies, understanding the relationship between pCO_2 and other anomalies within the eddies can explain the differences in pCO_2 patterns within normal and "abnormal" eddies.

13. L255: Mention why stirring is not a process (we can see it in the plot, but it needs to be discussed).

Response: In Section 5.1, Lines 300–304 (revised manuscript), we proposed that the meridional and zonal phase shifts in normal eddies are induced by the large-scale background SST gradient and eddy stirring. However, the SST anomalies within abnormal eddies show purely monopoly patterns, which do not reflect the stirring impact. In contrast, processes such as eddy pumping and eddy-induced Ekman pumping have a more significant impact on SST anomalies. Therefore, we did not regard it as a major process regulating the SST anomalies in eddies.

14. Generally: Personally, I would not use the terms 'normal' and 'abnormal', as everything is normal and within the expected physics (when considering eddy-induced Ekman pumping), but this may be a personal choice. Maybe 'regular' and 'unusual' fits better, as warm-core AEs and cold-core CEs are a lot more common than cold-core AEs and warm-core CEs, but I'm nit-picking now.

Response: We understand that everything can be considered normal within the expected physics, therefore, we have chosen to use the term "abnormal" in quotes to indicate that it is a relative term and not an absolute one, and we are referring specifically to departures from the expected behavior. The terms "normal" and "abnormal" are commonly used in the scientific community to describe expected and unexpected phenomena, and using them consistently throughout the paper helps maintain clarity and coherence.

15. Fig. 2: Consider using a sequential colormap. Specify the latitude where the white region starts (65S?). Most of the currents and topographic features are not referred to in the text and can be removed.

Response: A sequential colormap has been used in Fig. 2. The figure legends have been revised to specify where the latitude 65°S is. The currents and topographic features that are not mentioned in the manuscript have been removed.

16. Fig. 4 (and the following figures): Add in the caption what the magenta boxes are.

6) Response: We added captions explaining what the magenta boxes represent to Figs. 4, 6, 7, 10.

17. Fig. 6: Why are there some warm spots in cold eddies, and cold spots in warm eddies? By definition, the SST anomalies should be cold in cold eddies, and warm in warm eddies.

Response: Thanks for the comment. We apologize for the confusion caused by our carelessness in using outdated SST anomaly data for CAEs and WCEs in Fig. 6. We have revised the figure using the correct data. We assure that all other results involving SST anomaly data within eddies are based on the correct data.

18. Fig. 8: Ensure all SSIMs have the same number of decimals.

Response: All SSIMs have been corrected using the same number of decimals.

Technical corrections

1. Throughout the document: change biochemical to biogeochemical.

Response: The word biochemical has been changed to biogeochemical.

2. It’s a good habit to discuss the findings of this paper in the present tense and refer to previous studies in the past tense. E.g., L9: change to ‘we analyze’ (instead of ‘we analyzed’); same throughout the whole document.

Response: Thanks for pointing it out. We have checked the entire document and made corrections accordingly.

3. L12. I know many studies do this and it is a personal choice, but I dislike sentences with brackets for multiple things. Consider writing it out for each, e.g., ‘dominated by DIC anomalies in regions with larger magnitudes of DIC anomalies and dominated by SST anomalies in regions with smaller magnitudes. Same throughout the whole document.

Response: We have made corrections accordingly.

4. L22: existing (not exiting)

Response: The word exiting has been changed to existing.

5. The font in some figures is very large.

Response: The font size in Figs. 5, 7, and 11 has been appropriately reduced.

Response to Reviewer #2

Overall impression

The manuscript analyzed the biochemical influences of mesoscale eddies (including normal and abnormal eddies) in the Southern Ocean, by using machine learning and multi-source marine dataset. The manuscript estimated chlorophyll (Chl) and dissolved inorganic carbon (DIC) contributions to pCO_2, and found their seasonal variations. These results are interesting and are of vital importance on global biogeochemical cycles and the climate change. However, some description about methods/data are ambiguous and few conclusions need to be further discussed.

Response: We would like to thank reviewer 2 for taking the time to review the manuscript and for its valuable feedback. We acknowledge that the suggestions provided have really helped to improve the quality of this work. We hope the answers and information provided here would respond to what was demanded.

Major questions:

1. There are some other methods to identify abnormal eddies, such as using potential density and directions of geostrophic current. They are supposed to be introduced in the introduction, and point out why authors choose the method of SSTA.

Response: We acknowledge that there are other methods to identify abnormal eddies, such as using potential density and geostrophic current direction (Mcgillicuddy, 2015). We added this information in the introduction section and clarified why we used SSTA to distinguish between normal and abnormal eddies (Lines 82–86 in the revised manuscript).

Recent studies have found that abnormal eddies show opposite SSTA signals to normal eddies (Leyba et al., 2017; Liu et al., 2020; Liu et al., 2021; Ni et al., 2021). Compared to potential density, SSTA data can be obtained from satellite remote sensing with higher spatial and temporal resolutions, making it a convenient and reliable data source for identifying eddies (Castellani, 2006; Liu et al., 2021).

Moreover, detecting eddies using directions of geostrophic current is essentially based on SSH features. Our study utilizes the abnormal eddy dataset that Liu et al. (2021) developed, which uses a deep learning model to fuse satellite SSH and SST data. The method can simultaneously extract SSH features for determining eddy locations and extract SST information to help distinguish between normal and abnormal eddies with great accuracy and efficiency. In addition, the method is able to detect eddies in regions where traditional methods may not be effective, such as in regions with weak eddies or regions with complex oceanic dynamics (Liu et al., 2021). Given its high accuracy and comprehensive information on eddy characteristics, we find this dataset particularly useful for our study.

2. The methods to derive pCO_2 from Chl, SST, DIC and other variables are supposed to be introduced with more descriptions or equations.

Response: We have added the following details to explicitly describe the methods to derive pCO_2 in Lines 123–126:

“The pCO_2 field is calculated from TA, DIC, SST, and SSS based on seawater CO_2 chemistry (Iida et al., 2021). Firstly, the mean rates of regional pCO_2 and multiple regressions are used to derive the algorithms of pCO_2 expressed empirically as a function of in situ TA, DIC, SST, SSS, and the year. Then, the pCO_2 fields that filled both in space (1° × 1°) and time (monthly) are drawn by applying global data sets of TA, DIC, SST, and SSS to the variables in these empirical equations.”

3. The method to define and identify abnormal eddies should be introduced in detail even if the authors cited the paper of Liu et al., 2021. Did they identify abnormal eddies according to SSTA>0/SSTA<0 within eddy boundaries/cores? How did they distinguish AEs and CEs just according to SSTA?

Response: We have updated the manuscript to include more detailed information on our methodology for identifying abnormal eddies (Lines 133–141 in the revised manuscript).

We distinguished between normal and abnormal eddies based on the mean SSTA within eddy boundaries. Besides, we distinguished between AEs and CEs based on the SSHA, as AEs (CEs) are usually accompanied by local convergence (divergence), leading to positive (negative) SSHA. Specifically, WAEs are identified according to SSHA >0 and SSTA >0, CAEs are identified according to SSHA >0 and SSTA <0, CCEs are identified according to SSHA <0 and SSTA <0, and WCEs are identified according to SSHA <0 and SSTA >0.

4. The descriptions about eddy dataset and identification are very poor. In line 139, the authors mentioned “the ground truth data set”. What’s the ground truth data set of eddies? Is it produced by the authors or a public dataset? That’s important to the verification.

Response: Thanks for the suggestions. We have verified in the manuscript that the ground truth dataset of mesoscale eddies used in our study was generated automatically using the SSH-based method proposed by Haller (2005), and the eddy dataset was produced by Liu et al. (2021).

5. How did authors match daily eddy dataset with monthly DIC and pCO_2 temporally

and spatially when doing composite analyses? Temporally, is eddy at JAN. 31st matched with DIC of JAN. or Feb. data? is DIC data used within eddy boundaries or eddy cores?

Response: We have added a schematic in the Supporting Information and revised the section to provide additional details on the methodology used to create the composite eddies (Lines 161–178 in the revised manuscript). The positions of co-located SST, Chl-*a*, DIC, and pCO_2 observations were normalized by R, which defines the edge of an eddy as ±1 and the eddy core as 0. This allowed us to construct composite averages from eddies of varying sizes. We then extracted data from −2R to 2R to include the interactions between eddies and the surrounding waters and interpolated them onto an evenly spaced 17 by 17 grid to create the surface composite patterns. Therefore, the mean anomalies of SST, Chl-*a*, DIC, and pCO_2 are used within eddy boundaries.

For daily SST and Chl-*a*, we performed the eddy-centric composite method matching eddies and variables on the same day and calculated the mean value, as shown in the Fig. S2a. By contrast, for monthly DIC and pCO_2, we calculated the eddy-centric composite maps, using all eddies of the same month with DIC and pCO_2 of that month and calculate the mean value (Fig. S2b in the revised manuscript).

6. Taking CEs for example, commonly, upwellings are thought to transport cold water to the sea surface, as well as richer nutrients at the same time. Therefore, CEs often show lower SST and higher chlorophyll. The conclusions from Figure 8 show SSTA within abnormal eddies are dominant by Ekman pumping. However, the chlorophyll anomalies of abnormal eddies are attributed to eddy pumping. The conclusions are contradictory to each other. If they are reliable, what's the mechanism leading to contrasting vertical process on SST and chlorophyll respectively? Therefore, discussions of lines 279-280 and 295-296 need more explanations. Besides, line 279 should be "eddy-induced Ekman pumping".

Response: We have revised the Results section accordingly and deepened the discussion.

In response to the question, we further calculated the mean gradient of SST and Chl-*a* and revealed that the different dominant eddy-driven mechanisms for SST and Chl-*a* within the same kind of eddies are the results of the distinct strength of the eddy stirring effect due to the different magnitudes of the horizontal parameter gradients.

The average gradients of SST and Chl-*a* are found to be 0.03 and 0.08, respectively. The north-south gradients (north is the positive direction) of SST and Chl-*a* are 0.04 and −0.02, respectively. The east-west gradients (east is the positive direction) of SST and Chl-*a* are 0.00 and −0.04, respectively. As eddy stirring redistribute physical and biogeochemical parameters spatially through horizontal advection, the larger the horizontal parameter gradient, the stronger the eddy stirring effect (Mcgillicuddy, 2016).

The small gradient of SST leads to a negligible effect of eddy stirring. Within normal eddies, eddy pumping dominates the vertical heat advection, resulting in positive and negative SST anomalies in WAEs and CCEs, respectively. However, within "abnormal" eddies, the effect of eddy-induced Ekman pumping becomes more prominent, resulting in negative and positive SST anomalies in CAEs and WCEs, respectively.

Compared to SST, Chl-*a* has a higher gradient, resulting in a stronger effect of eddy stirring. The gradients of Chl-*a* suggest that the climatological Chl-*a* increases southward and westward. Counterclockwise rotation of AEs in the SO would advect low Chl-*a* from the northeast to the west and high Chl-*a* from the southwest to the east. The reverse is true for CEs. Previous works found that the dipole shapes arising from stirring tend to be asymmetric, with larger anomalies at the leading compared to the trailing side of eddies (Chelton et al., 2011; Frenger et al., 2015; Dawson et al., 2018; Frenger et al., 2018). As the major propagation direction of eddies is westward, the composite Chl-*a* anomalies in AEs/CEs show dominant negative/positive signals due to eddy stirring. Besides, eddy pumping tends to produce Chl-*a* anomalies of the same sign. The common effects of eddy stirring and eddy pumping overcome the effect of eddy-induced Ekman pumping, resulting in similar patterns of Chl-*a* anomalies in normal and "abnormal" eddies.

However, from Figs. 8b1–b4 and f1–f4 in the manuscript, we can see that the magnitudes of Chl-*a* anomalies within normal eddies are higher than "abnormal" eddies, which reflects the effect of eddy-induced Ekman pumping. Besides, in some regions with small amplitude, such as the south of ACC and the South Pacific Ocean, we find Chl-*a* anomalies in AEs/CEs are positive/negative (Figs. 6e–h in the manuscript). Such a result may be caused by a more dominant effect of eddy-induced Ekman pumping on Chl-*a*. Overall, eddy stirring and eddy pumping are mainly responsible for the patterns of Chl-*a* anomalies within eddies in the SO, and eddy-induced Ekman pumping attenuates the magnitudes of Chl-*a* anomalies within "abnormal" eddies.

7. The manuscript is supposed to evaluate the accuracies of abnormal eddy identification method, which can combine with Argo profiles via temperature and potential density. At the same time, it should point out the method improvement in future

Response: We have updated the manuscript to address these points. The experiments showed that the model could accurately identify "abnormal" eddies in the South China Sea (SCS) and Kuroshio Extension (KE) region (Liu et al., 2021). In addition, Argo floats data also verified the accuracy and validity of the model (Liu et al., 2021).

However, we also acknowledge that there is room for improvement in our method. Considering that the changes in SSH, SST, Chl-*a*, and roughness caused by eddies can be recorded by altimeter, infrared, ocean color, and synthetic aperture radar (SAR) remote sensing, respectively, and potential density and temperature recorded by Argo floats can also identify "abnormal" eddies, in future work, we will combine multiple remote sensing data with Argo profiles to evaluate the accuracies of "abnormal" eddy identification method.

Minor questions:

1. Lines 31-32: Authors point out that eddies have influences on "biochemical parameters". While, the listed references are both about chlorophyll, which is a biological parameter. References about chemical parameters should be introduced.

Response: References about chemical parameters have been added.

2. Lines 37-39: Rotations of eddies are related to the hemisphere. It should illustrate which hemisphere is talked about.

Response: When mentioning the rotations of the eddies, we emphasized that the eddies is in the Southern Hemisphere.

3. Line 56: How about eddy influence on chlorophyll during wintertime with deeper mixing?

Response: Thanks for your suggestions. We added information and references about the influence of eddies on Chl-*a* during wintertime with deeper mixing in AEs in the introduction.

Both mixing and eddy-induced Ekman pumping tend to produce Chl-*a* anomalies of the same sign in the nutrient-limited SO. For instance, shallower mixed layers in cyclonic eddies could result in lower Chl-*a*, while deeper mixed layers in anticyclonic eddies could lead to higher Chl-*a*. Dufois et al. (2014) suggested that in the South Indian Ocean between 20°S and 30°S, deeper mixing in winter AEs can elevate nutrient supply, while shallower mixing in CEs can reduce it, which could explain stronger positive Chl-*a* anomalies in AEs than in CEs. Dawson et al. (2018) indicated that the deepening of winter and early spring mixed layers in anticyclones and shallowing of mixed layers in cyclones are the main drivers of the positive Chl-*a* anomalies in AEs and negative Chl-*a* anomalies in CEs in summer and autumn between the Subtropical Front and the Polar Front. Such seasonal lag effect is due to deeper mixed layers in winter and spring that enhance light limitation, reducing the biological effect in AEs (Song et al., 2016). The remained nutrients in the mixed layer of AEs could sustain higher phytoplankton levels in summer when light limitation is alleviated, leading to positive Chl-*a* anomalies in summer and autumn. By contrast, the shallow mixing in CEs makes phytoplankton communities begin to consume nutrients earlier, leading to negative Chl-*a* anomalies in summer and autumn. Therefore, the influence of mixing within eddies on Chl-*a* is seasonal.

In our study, the Chl-*a* anomalies within eddies show litter seasonal variation, which contradicts the seasonal effect of mixing. Therefore, the seasonal modulation of the mixed layer is not discussed in our study. Instead, eddy stirring and eddy pumping are the main modulation processes of normal and “abnormal” eddies to Chl-*a* in the SO. Composite Chl-*a* anomalies display negative signatures in both WAEs and CAEs and positive signatures in CCEs and WCEs. However, we find the magnitudes of Chl-a anomalies within “abnormal” eddies are smaller than normal eddies, which associates with the effect of eddy-induce Ekman pumping.

4. Lines 107-108: The expression of OI-SST should be in agreement.

Response: We have corrected the expression of OI-SST.

5. Line 166: JMA is suggested to be introduced as Japan Meteorological Agency.

Response: We have introduced JMA as “Japan Meteorological Agency” upon its first mention in the manuscript.

6. Line 178: What are the denominators when calculating eddy frequencies? It should be expressed more clearly.

Response: We have added the definition of eddy frequency. The eddy frequency is the ratio of the number of days eddies appeared to the total number of observation days.

7. Lines 186-187: The conclusion is true in South America, but not evident in the south of Australia.

Response: We have revised the manuscript to demonstrate the findings explicitly. Based on Figs. 4c and 4f in the manuscript, it can be observed that “abnormal” eddies have a polarity distribution opposite to that of normal eddies in the continental boundary currents where more CCEs and CAEs occur. However, it should be noted that more WAEs and WCEs occur in the south of Australia.

8. Line 285: How to understand “eddy trapping has little influence on Chl-*a*”? Please give more descriptions to explain it.

Response: We have added more descriptions to explain why eddy trapping has little influence on Chl-*a*. Nonlinear eddies tend to trap the fluid contained in their interiors (Provenzale, 1999; Mcgillicuddy, 2016). The composition of the trapped fluid is dependent on various factors, including the eddy propagation and the local gradients in physical and biochemical properties. The tracks of long-lived eddies with lifetimes longer than 1 year show that the major propagation direction of eddies is westward, with AEs propagating north and CEs propagating south. Due to the climatological Chl-*a* increasing southward, AEs propagating northward tend to trap high Chl-*a* into northern areas with low Chl-*a*, as shown in Fig. 3 below. On the other hand, CEs propagating southward tend to trap low Chl-*a* into southern areas with high Chl-*a*. Such effect of eddy trapping on Chl-*a* contradicts the actual composite Chl-*a* anomalies over eddies with negative Chl-*a* anomalies in AEs and positive Chl-*a* anomalies in CEs. As a result, we conclude that eddy trapping has little influence on Chl-*a*.

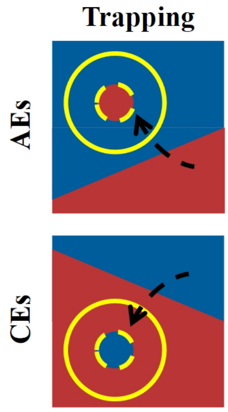

Figure 3. Schematic illustrating the eddy trapping of how AEs and CEs affect Chl-*a*. Red and blue colors represent high and low Chl-*a*, respectively.

9. Lines 303-314: Are those conclusions for summertime still "dominant"? The magnitudes seem similar for summertime.

Response: Yes, there are no significant seasonal variations in eddy-induced SST, Chl-*a*, and DIC anomalies. Therefore, the dominant mechanisms of eddies affecting these variables do not alter by season.

10. Figure 11 is suggested to be shown in wintertime and summer time respectively, based on which Figure 8, Figure 12, and Figure 13 can be better discussed.

Response: We appreciate the suggestion, but given the nature of our findings, presenting the annual mean is more appropriate for our study. In the original manuscript, we did not discuss the SST, Chl-*a*, and DIC anomalies within the eddies seasonally, as their variations did not exhibit significant seasonal patterns. Therefore, we opted to present the annual mean eddy-induced Ekman pumping in Figure 11, as it provides a comprehensive representation of the differences in variable anomalies between normal and "abnormal" eddies. We believe that this approach allows for a more convenient and meaningful comparison of the variable anomalies within the eddies.

11. In Figure 4, lines 558-599, the authors mean blue and red colors in the right column. However, blue and red colors are shown in each sub-figure, which is misleading.

Response: We have revised the manuscript to ensure that the blue and red colors are clearly associated with the right column only.

12. Figures 4d and 4e show that abnormal eddies occur along fronts, where eddies are active, and along offshore areas where accuracies of altimeters are low. It is suggested to show ratios of abnormal eddies to normal eddies (WAEs/CAEs, CCEs/WCEs). Will the abnormal eddy signals offshore be amplified offshore? What are the mean depths of clustered abnormal eddies? It should be cautious with eddies shallower than 1000 m.

Response: We appreciate the reviewer's insightful suggestions, and we calculated the ratios of "abnormal" eddies to normal eddies, as shown in Fig. 4 below. We find more CAEs in the Western Boundary Current (WBC) regions and significant dominance of WCEs in southern Australia. In the southeast of America and Campbell Plateau, with depths shallower than 1000 m (Fig. 5 below), "abnormal" eddy signals offshore may be amplified offshore due to the low accuracies of altimeters along offshore areas. We further calculate the mean depths of clustered eddies. The mean depths of WAEs, CAEs, CCEs, and WCEs are 4086 m, 3969 m, 4044 m, and 4014 m. All of them are deeper than 1000m. As mentioned in the manuscript, eddies disappear in regions shallower than 2000m because the bottom topography constrains the generation of eddies. Therefore, the amplified "abnormal" eddy signals in the southeast of America and Campbell Plateau have little influence on the results.

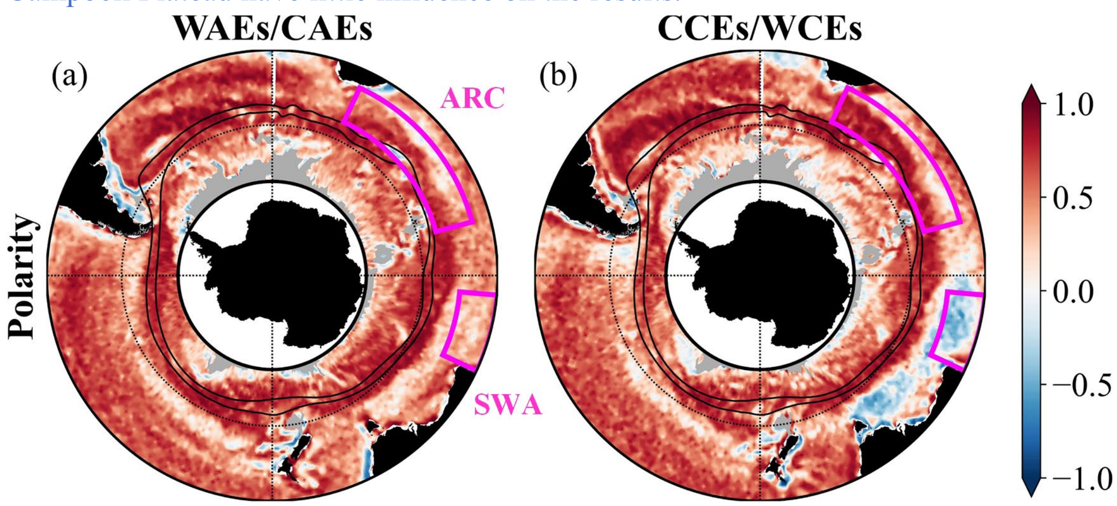

Figure 4. Spatial distribution of eddy polarity dominance in the SO from 1996 to 2015. (a) Ratio of the area occupied by WAEs over the area covered by CAEs. (b) Ratio of the area occupied by CCEs over WCEs. Values >0 in red and <0 in blue mark the dominance of normal and "abnormal" eddies, respectively. Black solid lines show the mean northern and southern positions of the ACC major fronts. The black dotted circle is 50° S. The magenta boxes represent ARC and SWA regions.

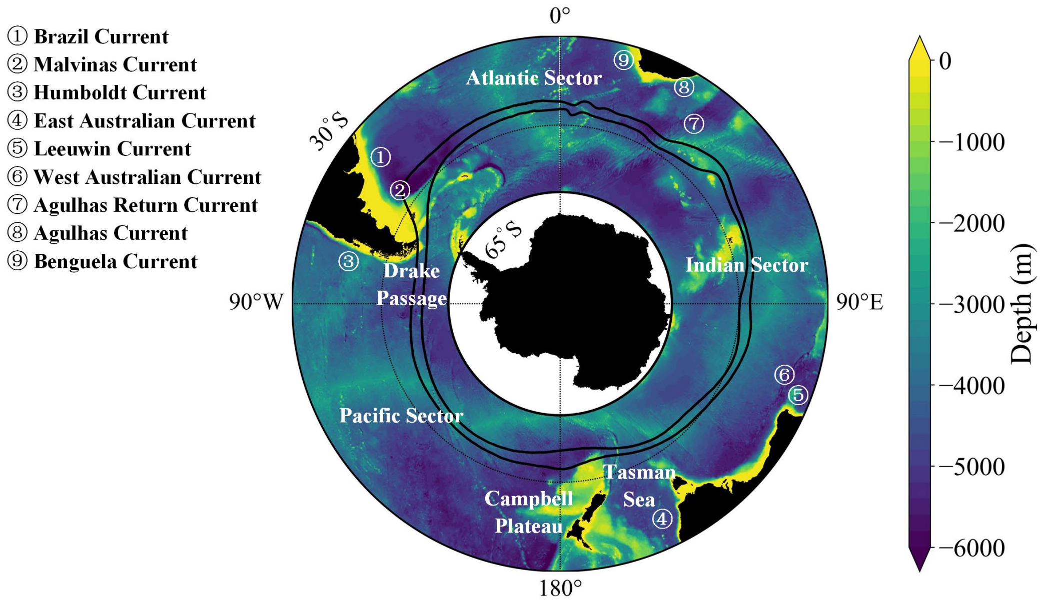

Figure 5. Southern Ocean topography and current. Black solid lines show the mean northern and southern positions of the ACC major fronts. The black dotted circle is 50° S.

13. Figure 6. The abnormal eddies are identified from SST so the SSTA of Figure 6 is regular. The other three parameters are very noisy. The magnitudes of chlorophyll and pCO$_2$ signals induced by abnormal eddies are even higher than normal eddies, which are contrasting with eddy amplitude comparisons. Why?

Response: We have added some explanations to the manuscript to address the reviewer's concern. The distributions of Chl-*a* anomalies over both normal and "abnormal" eddies are similar to the eddy amplitude distributions, with stronger negative/positive anomalies within AEs/CEs in regions of higher amplitude. This result indicates the dominant effect of eddy pumping on Chl-*a*. However, in regions of lower amplitude, we find the patterns of Chl-*a* anomalies are spotty, with average positive/negative Chl-*a* anomalies in AEs/CEs. Such a result may be caused by a more dominant effect of eddy-induced Ekman pumping on Chl-*a*.

The magnitudes of Chl-*a* anomalies induced by "abnormal" eddies are even higher than normal eddies in these regions due to the smaller amplitude and eddy pumping of "abnormal" eddies than normal eddies. Furthermore, in some regions, such as SWA, the magnitudes of pCO$_2$ anomalies induced by "abnormal" eddies are higher than normal eddies, which are related to the stronger eddy-induced Ekman pumping of "abnormal" eddies.

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