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: We appreciate the reviewer's comments regarding the clarity of the introduction and the need to highlight the novelty of our study better. We carefully reviewed the introduction and added a paragraph that explicitly states the key differences between our work and previous studies. The added paragraph reads as follows:

"The role of eddies in modulating surface physical and biogeochemical parameters in the SO is still unclear. Previous studies only focused on the basin-wide impact of eddies on Chl-*a* (Frenger et al., 2015; Dawson et al., 2018; Frenger et al., 2018). To our knowledge, no research yet investigates the basin-scale effects of SO eddies on DIC and pCO_2. Given the potential interactions between different physical and biogeochemical parameters and the importance of the SO in global climate change, biological productivity, and carbon cycling, it is necessary to systematically study the influence of eddies on SST, Chl-*a*, DIC, and pCO_2 in the SO. Most importantly, previous research did not distinguish between normal and "abnormal" eddies (Frenger et al., 2015; Dawson et al., 2018; Frenger et al., 2018). "Abnormal" eddies have SST anomalies opposite to normal eddies, which can potentially affect the biogeochemical parameters within eddies. Therefore, when investigating the regulation of air-sea variables induced by mesoscale eddies, it is important to consider the role of "abnormal" eddies, as this can lead to a more accurate estimation of mesoscale eddies' overall impact. In addition, previous work used traditional eddy detection methods based on satellite sea surface height (SSH) data (Chelton et al., 2011; Faghmous et al., 2015). In contrast, the eddy dataset we used is developed by a deep learning (DL) model based on the fusion of SSH and SST data (Liu et al., 2021), which can simultaneously detect eddy locations and distinguish between normal and "abnormal" eddies with great accuracy and efficiency."

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: We agree and we added a paragraph when mentioning abnormal eddies in the introduction to explain why we need to discuss how the abnormal eddies. The added paragraph reads as follows:

" "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). However, there is still a gap regarding the cause of "abnormal" eddies in the SO."

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: We deepened the discussion and revised the manuscript. To address the question that the influence mechanisms of eddies on SST, Chl-*a*, DIC, and pCO_2 are different, we calculated the average gradient of these variables in the SO from 1996 to 2015. The gradients of SST, Chl-*a*, DIC, and pCO_2 are 0.05, 0.11, 0.20, and 0.31, which are normalized prior to calculation. 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 gradient of DIC is four times higher than that of SST, which indicates that eddy stirring will have a stronger effect on DIC than on SST. Thus, the composite DIC anomalies within eddies show dipole patterns, whereas the composite SST anomalies within eddies show monopole patterns. In addition to the different effects of eddy stirring on SST and DIC, both eddy pumping and eddy-induced Ekman pumping have an effect on SST and DIC. For normal eddies, eddy pumping dominates the vertical distribution of variables. Within CCEs, the upwelling with cold, DIC-rich deep water induces negative SST anomalies and positive DIC anomalies, and the reverse is true for WAEs. However, for abnormal eddies, eddy-induced Ekman pumping dominates the vertical distribution of variables. Within WCEs, the downwelling of warm, low-DIC surface waters induces positive SST anomalies and negative DIC anomalies, and the reverse is true for CAEs. Therefore, the influence mechanism of eddies on different variables is not universal, and it varies depending on the inherent properties of each variable and the complex interactions between them and the eddies.

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: Figs. 1, 3, and 5 and Tables 1 and 2 have been moved to the Supporting Information. We added the description and discussion related to Fig. 7 so that Fig. 7 is not moved.

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 the monthly temporal resolution, we subtracted their climatology averages. As shown in Fig. 1 below, there are no significant seasonal variations in eddy-induced SST, Chl-*a*, and DIC anomalies. By contrast, pCO_2 anomalies were remarkably different between the two seasons, caused by the different dominant effects of SST, Chl-*a*, and DIC, as we discuss in the manuscript.

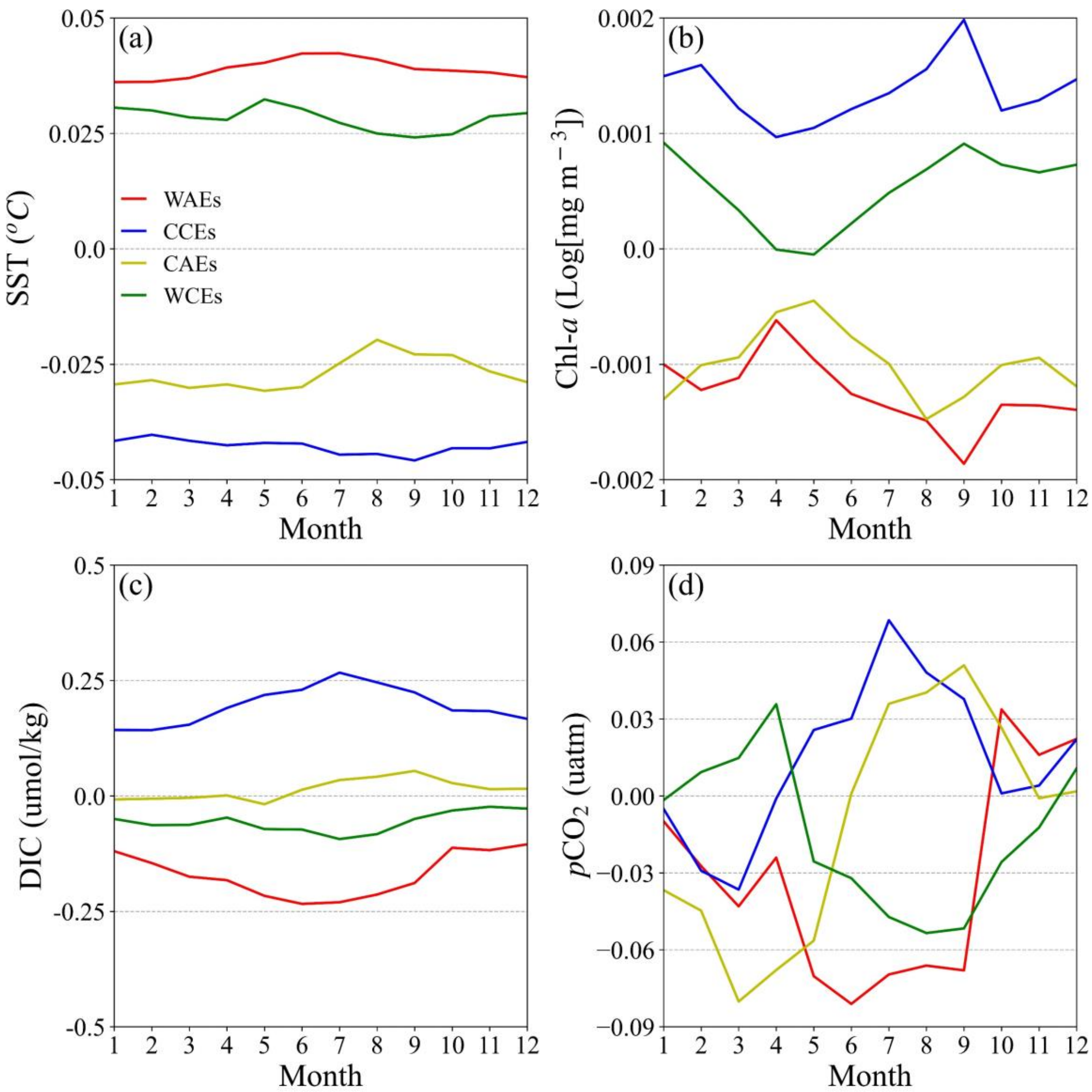

Figure 1. Variations in monthly mean eddy-induced anomalies, including (a) SST, (b) Chl-*a*, (c) DIC, and (d) pCO_2 in the SO from 1996 to 2015. Solid lines in different colors denote four kinds of eddies.

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

Response: 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 manuscript is as follows: " The pCO_2 and DIC datasets are from the 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 both 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 feedback. 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. 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."

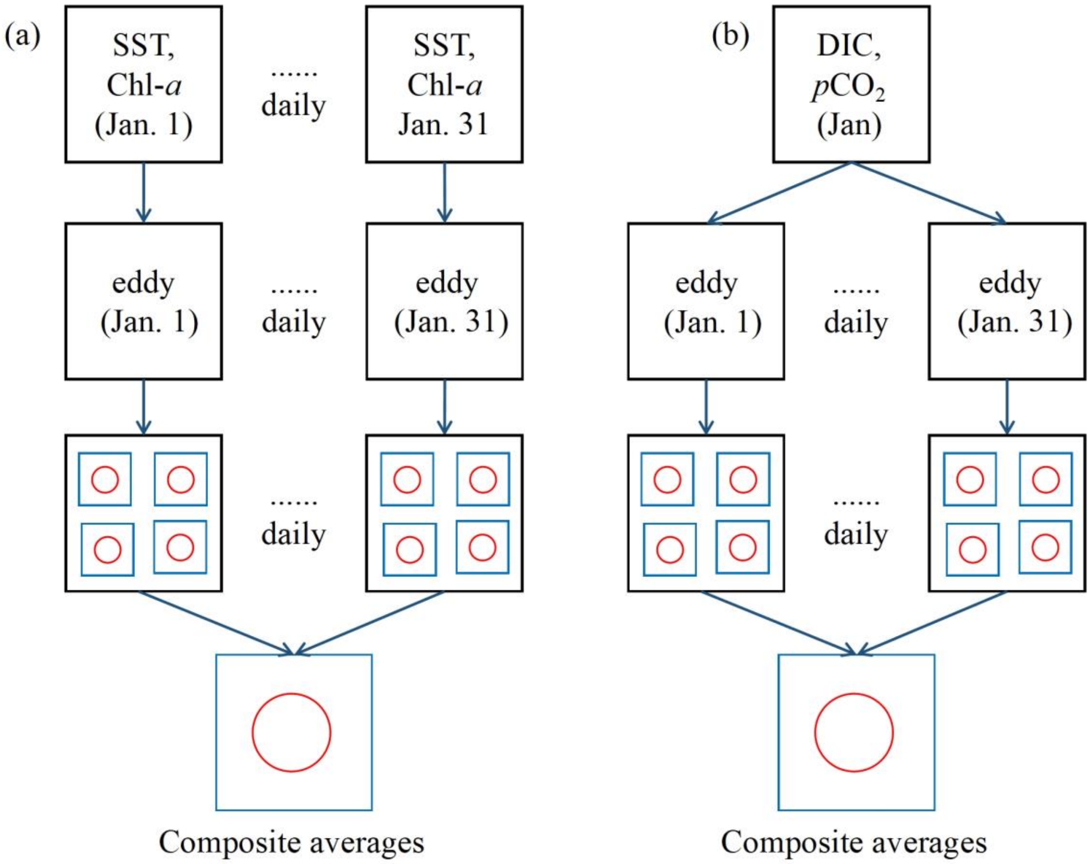

Figure 2. Schematic of eddy-centric composite method for daily (a) SST and Chl-*a* and monthly (b) DIC and pCO_2, taking January as an example.

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 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 our study, we propose 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 do 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. 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.

Response: Captions have been added to all relevant figures.

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 by 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 in some figures has been reduced appropriately.

Reference

Frenger, I., Münnich, M., Gruber, N., and Knutti, R.: Southern Ocean eddy phenomenology, J. Geophys. Res.-Oceans, 120, 7413-7449, https://doi.org/10.1002/2015jc011047, 2015.

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