Response to the reviewers' comments on "*racing the contributions of dust sources on deposition and phytoplankton carbon uptake in global oceans*"

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Dear Editors and Reviewers:

Thanks for your letter and for the valuable comments. We carefully studied all comments and revised the manuscript accordingly. The updates in the manuscript are marked in red, which is quoted in *blue italics* in this response letter. The main revisions in the paper and replies to comments point by point are as following.

In response to the reviewers' comments, we have made the following key revisions: 1. We incorporated model-based dissolved iron data from CMIP6 to complement sparse observations, enabling a more robust spatial and seasonal assessment of dust-driven marine phytoplankton carbon uptake. 2. We carefully re-examined the relationship between our study and previous research, and substantially revised the relevant discussion to improve accuracy and avoid potential confusion for readers. 3. We refined several expressions related to carbon uptake to enhance consistency and scientific precision, and reorganized the presentation of figures by moving several to the supplementary materials to streamline the main text and improve overall readability.

Response to the comments from reviewer 1

General comments:

The article presents modeling results of global iron emissions from natural dust simulated with an ESM (CLM). These simulations take into account various dust source regions, which lead to varying Fe solubility. This approach is original since most, if not all previous global studies of Fe dust deposition used a global average for Fe solubility in dust. These Fe dust estimates are then translated into dissolved Fe (dFe) fluxes at the surface ocean, and extrapolated as C uptake according to Equation 4.

The authors underline the importance of Fe deposition for surface ocean carbon cycling, in particular in HNLC areas such as the Southern Ocean.

The original idea of simulating Fe dust deposition while considering spatial variability in the sources is interesting and novel. Estimating the potential implications for carbon uptake by phytoplankton is also interesting. However, the authors maintain (maybe involuntarily) a huge confusion with carbon uptake estimates. As a result, it may seem like the authors are estimating total ocean carbon uptake (i.e. air-sea carbon fluxes). They even compare their results with such estimates in the discussion. But this is not what the authors are calculating in this study. What is estimated here, is phytoplankton uptake of carbon, driven by the Fe supply from natural dust. I want to trust that this confusion is not a voluntary one by the authors. However, this must be corrected before the article can be published.

The use of the term 'carbon uptake' leads to some confusion. It is stated in the abstract that the authors refer to "phytoplankton carbon uptake". But later in the text, it is termed "marine carbon uptake" (e.g. lines, 101, 103, 110, 132, 271). A good definition of the term 'carbon uptake' is central to the understanding of this manuscript. I recommend the authors clarify the term throughout the manuscript and refer to "phytoplankton carbon uptake". Marine carbon uptake

is very different from phytoplankton carbon uptake. In this study, the authors quantify phytoplankton carbon uptake, and not marine carbon uptake (which is mostly driven by physical factors).

Response: Thank you for your thoughtful and constructive comments, as well as your appreciation of our work. We sincerely apologize for any confusion caused by our previous wording regarding 'carbon uptake', it was never our intention to mislead. We fully agree that our study focuses on carbon uptake by phytoplankton driven by iron (Fe) supplied from dust. In response, we added a clear definition of the term 'carbon uptake' in our study in Line 131-134: "*In this study, marine phytoplankton carbon uptake specifically refers to the amount of carbon uptake by phytoplankton as a result of dust-derived dFe input, estimated using the Fe: C ratio in phytoplankton cells under the assumption of Fe-limited marine conditions.*", and we have revised the term "marine carbon uptake" to "marine phytoplankton carbon uptake" throughout the manuscript to improve clarity. We have retained the term "marine" to emphasize that our study specifically concerns oceanic phytoplankton, rather than freshwater systems such as lakes.

Abstract:

The authors claim that their results show that iron dust deposition promotes "5.6 Pg C yr^{-1} of carbon uptake by marine phytoplankton." This value should be compared with the global uptake estimated without iron dust. Is this additional uptake significant?

Response: Thank you for your comment. We fully agree that comparing the marine phytoplankton carbon uptake driven by dust-borne Fe we estimated with global marine phytoplankton carbon uptake in the absence of dust-borne Fe would provide a clearer context for evaluating the significance of our results. However, to the best of our knowledge, it is regret that there is currently no publicly available global estimate of marine phytoplankton carbon uptake, nor those that do not include contributions from

Fe dust deposition. In our study, we attempt to isolate the contribution of dust-borne Fe by developing a dust-Fe-induced marine phytoplankton uptake estimate based on observational data and comparing it with results calculated by dissolved Fe data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) model simulations.

We used dFe concentration data from the CMIP6 to estimate marine phytoplankton carbon uptake driven by dust deposition. Based on dFe concentration data from CESM2 (2000-2014) historical simulations, the estimated marine phytoplankton carbon uptake driven by dust deposition was 2.2 Pg C yr^{-1}, while that from Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) (2010-2014) was 3.2 Pg C yr^{-1} (Fig. R1). Compared to the estimates derived from observational data, the spatial distributions of marine phytoplankton carbon uptake from CMIP6 models (CESM2 and GFDL-ESM4) show similar global patterns, with high uptake mainly observed in the Equatorial Atlantic Ocean and Equatorial Indian Ocean, particularly in the northwestern EI. The use of CESM2 and GFDL-ESM4 dFe data resulted in approximately 61% and 43% reductions, respectively, in estimated marine phytoplankton carbon uptake relative to observation-based estimates. For CESM2-based results, the reduction was particularly pronounced in the southern RS, where uptake decreased from 0.4 to 0.1 Pg C yr^{-1}; the western Arabian Sea (in the Equatorial Indian Ocean), from 1.8 to 0.5 Pg C yr^{-1}; and the north-central EA, from 2.2 to 0.7 Pg C yr^{-1} (Fig. R1). For GFDL-ESM4-based results, notable reductions were also observed in the north-central Equatorial Atlantic Ocean (from 2.2 to 0.9 Pg C yr^{-1}) and the western Arabian Sea (from 1.8 to 0.7 Pg C yr^{-1}), whereas an evident increase occurred in the Equatorial Pacific Ocean, from 0.3 to 0.7 Pg C yr^{-1} (Fig. R1).

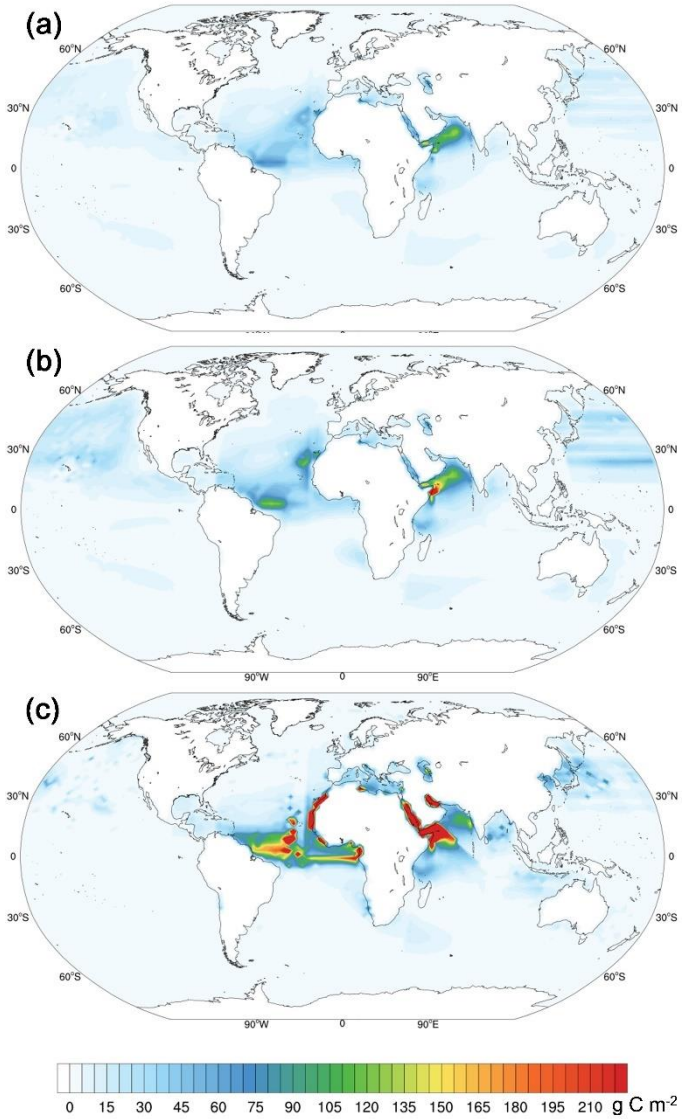

Fig. R1 The spatial distribution of annually marine phytoplankton carbon uptake driven by dust-borne iron by using (a) CESM2 and (b) GFDL-ESM4, (c) and observed dissolved iron data

Introduction:

Lines 113-122: I'm not certain that the paragraph on satellite observation is necessary here.

Response: Thanks for your suggestion. We have deleted the paragraph on satellite observation in Line 113-122 of previous version.

Methods:

2.1. Community Earth System Model

Some details are lacking. What is the time step of the model for emissions and depositions? What is the spatial resolution of the model? How many vertical levels are represented in the model? Did you run simulations? Which forcings did you use? Which environmental conditions?

Response: Thanks for the comments on supplying the detailed information about the simulation. Yes, we did run simulations, the time step in our simulation is 30min, the spatial resolution we used is 1.9°×2.5°, and there are 30 vertical levels in the model. We used prescribed, annually repeating aerosol emissions corresponding to the year 2000 as well as prescribed climatological sea ice and sea surface temperature from Hadley Centre. The environmental conditions were derived from the Community Earth System Model (CESM) default surface dataset for the year 2000, which provides land cover, soil properties, vegetation distribution, and dust source regions. Atmospheric initial conditions were prescribed using a standard initial file for the Community Atmosphere Model.

We have added these information in Lines 153-156"*In the model, atmospheric dust is emitted from the land by wind in the Community Land Model (CLM) (Mahowald et al., 2006) and then transported and processed in the atmosphere by the Community Atmosphere Model (CAM) (Neale et al., 2010).*", Lines 159-161 "*More details could be found in Technical Description of CLM v4.0 (Oleson et al., 2010) and CAM5 Scientific Guide (Neale et al., 2012)*", Lines 197-199 "*We conducted five-year simulations with a spatial resolution of 1.9° × 2.5°, a 30-min time step, and monthly output frequency to investigate the characteristics of global dust emission and deposition.*", and Lines 204-212 "*The model configuration included 30 vertical layers. We employed prescribed aerosol emissions that repeat annually, based on emission inventories representative of the year 2000. The configuration imposes a climatological forcing by applying an identical annual emission cycle throughout the simulation*

period. Prescribed climatological sea ice and sea surface temperature from Hadley Centre were used to drive the climate. Environmental boundary conditions were derived from the default CESM surface dataset for the year 2000, which includes land cover, soil properties, vegetation distribution, and dust source regions. Atmospheric initial conditions were specified using the standard initialization file provided for CAM."

Reference

Neale, R. B., Gettelman, A., Park, S., Chen, C.-C., Lauritzen, P. H., Williamson, D. L., Conley, A. J., Kinnison, D., Marsh, D., Smith, A. K., Vitt, F. M., Garcia, R., Lamarque, J.-F., Mills, M. J., Tilmes, S., Morrison, H., Cameron-Smith, P., Collins, W. D., Iacono, M. J., Easter, R. C., Liu, X., Ghan, S. J., Rasch, P. J., and Taylor, M. A.: Description of the NCAR Community Atmosphere Model (CAM 5.0), UCAR/NCAR – Library, https://n2t.net/ark:/85065/d7s46whd, 2012.

Oleson, W., Lawrence, M., Bonan, B., Flanner, G., Kluzek, E., Lawrence, J., Levis, S., Swenson, C., Thornton, E., Dai, A., Decker, M., Dickinson, R., Feddema, J., Heald, L., Hoffman, F., Lamarque, J., Mahowald, N., Niu, G., Qian, T. T., Randerson, J., Running, S., Sakaguchi, K., Slater, A., Stöckli, R., Wang, A. H., Yang, Z. L., Zeng, X., Zeng, X.. Technical Description of version 4.0 of the Community Land Model (CLM) (No. NCAR/TN-478+STR). University Corporation for Atmospheric Research, 10.5065/D6FB50WZ, 2010.

In Equation 1, the different factors should be properly defined: how do you define the tuning factor? What values does it take? Give the values and units of all variables.

Response: Thanks for the comments. T is a tuning factor that compensates for the Dust Entrainment and Deposition (DEAD) model's sensitivity to horizontal and temporal resolution and equals 5 x 10^{-4} in the Community Land Model (CLM) instead of 7 x 10^{-4} in Zender et al. (2003). We have given the values and added units for variables:

"*In dust model, the total vertical dust mass flux (F_j, kg m^{-2} s^{-1}), from the ground into transport bin j is calculated by the following function:*

$$F_j = TSf_m\alpha Q_S \sum_{i=1}^{I} M_{i,j} \qquad (1)$$

Where T is a tuning factor that compensates for the DEAD model's sensitivity to horizontal and temporal resolution and equals 5 × 10^{-4}, S is the source erodibility

factor set to 1 and serves as a place holder, f_m is a dimensionless fraction representing the exposed bare soil, α is the sandblasting mass efficiency (m^{-1}), Q_S is the total horizontally saltating mass flux (kg m^{-1} s^{-1}), and $M_{i,j}$ is the dimensionless mass fraction of each source mode i carried in different bin j."

Line 193: Replace "marine carbon uptake" by "phytoplankton carbon uptake". This sentence should be moved to section 2.5.

Response: Thanks for your suggestion. We have replaced "marine carbon uptake" with "marine phytoplankton carbon uptake", and relocated the sentence in Section 2.5, Lines 293-298: "*In this study, we used a broad Fe: C ratio range in phytoplankton cells (3-90 μmol Fe mol^{-1} C) and an FeOpt of 1.75 nM for all phytoplankton groups, as proposed by Wiseman et al (2023), to estimate phytoplankton carbon uptake driven by Fe from dust. Given that Fe is the primary limiting nutrient in HNLC regions, we also calculated phytoplankton carbon uptake attributable to dust deposition in these regions.*"

Reference

Wiseman, N. A., Moore, J. K., Twining, B. S., Hamilton, D. S., and Mahowald, N. M.: Acclimation of phytoplankton Fe:C ratios dampens the biogeochemical response to varying atmospheric deposition of soluble iron, Global Biogeochem. Cycles, 37, 10.1029/2022GB007491, 2023.

Paragraph lines 198-203: What's the time resolution of you simulations?

Response: Thank you for your question. A monthly output frequency was specified in our simulations, and the relevant information has been provided in Lines 197-199 "*We conducted five-year simulations with a spatial resolution of 1.9° × 2.5°, a 30-min time step, and monthly output frequency to investigate the characteristics of global dust emission and deposition.*"

Line 239: "The dFe concentration data is a necessary factor for calculating the Fe: C ratio *in phytoplankton cells*".

Response: Thank you for the suggestion. We have revised the expression 'Fe: C ratio' to '*Fe: C ratio in phytoplankton cells*' throughout the manuscript.

2.5 Calculation of Carbon Uptake

This section lacks details and precision, from which stem a lot of confusion. Dfe is concentration data taken from the GEOTRACES database (according to section 2.3), but on line 280, it is described as "dFe is the local concentration of soluble Fe". Soluble and dissolved Fe are different things.

Response: We agree with your observation and apologize for the unintended confusion. We have revised the sentence in Lines 291-292 to read: "*dFe is the local concentration of dissolved Fe*".

The definition of FeOpt should be detailed: is it the optimal Fe concentration in the water or in phytoplankton cells?

Response: Thank you for your comments. FeOpt refers to the iron concentration at which the Fe: C ratio reaches its maximum value. We have updated our expression in Lines 292-293 "*FeOpt refers to the Fe concentration at which Fe: C ratio in phytoplankton cells reaches its maximum value*".

Finally, in order to avoid any confusion, the Fe:C ratio should be referred to Fe:C ratio in phytoplankton cells.

Response: We appreciate your suggestion. We have revised the expression 'Fe: C ratio' to '*Fe: C ratio in phytoplankton cells*' throughout the manuscript.

Line 275: "ambient soluble Fe" should be replaced by "dissolved Fe in seawater".

Response: Thank you for your suggestion. We have replaced the sentence "Phytoplankton Fe: C ratio for new growth (gQfe) is defined to be a linear function of the ambient soluble Fe concentration in specific marine area" by "*Fe: C ratio in phytoplankton cells (gQfe) is defined to be a linear function of the dFe concentration in seawater*" in Lines 285-286.

Line 276: marine carbon uptake should be replaced by phytoplankton carbon uptake

Response: We appreciate your recommendations about the expression about 'carbon uptake' in this manuscript. We have updated the 'marine carbon uptake' by '*marine phytoplankton carbon uptake*' in the manuscript.

The units of each term in Equation 4 should be described.

Response: Thanks for your suggestion and we have supplied the units of each term in Equation 4.

"*Fe: C ratios are employed to calculate carbon uptake caused by dust deposition with the function as follows:*

$$C = \frac{D * Fe_{con} * Fe_{sol}}{gQfe} \qquad (4)$$

where C *is the amount of marine carbon uptake driven by dust deposition,* D *(Tg) is the amount of dust from source regions and deposit to oceans,* Fe_{con} *(%) is the Fe content for different dust source region, and* Fe_{sol} *(%) is the solubility of Fe over various oceans.*"

Results:

The results are presented with great details. However, most figures could be reworked to be simplified and easier to read.

The paragraph and associated figures on wet/dry deposition may be removed since you don't discuss these results. Maybe they can remain in supplement, but I don't find these results central to the study.

Response: We are grateful for your recommendation. We agree that the wet and dry deposition results are not the central focus of this study. Therefore, we deleted the figures related to wet and dry deposition from the manuscript. However, we have retained the sentence "*Wet deposition dominates the dust deposition, accounting for 77.4% of the total dust deposition to the ocean*.".

Figure 1: the names of the regions are difficult to read

Response: We appreciate your valuable feedback. We have added a table that lists the full names and corresponding abbreviations of the dust source regions and oceans, to help readers more easily distinguish among the different regions.

Table 1 List of abbreviations and full terms for dust source regions and oceans

Dust source regions/ oceans	Full terms	Abbreviations
Dust source regions	Northwest Africa	NWAf
	Northeast Africa	NEAf
	Middle Africa	MAf
	South Africa	SAf
	North America	NAm
	South America	SAm
	West Asia	WAs
	Middle-North Asia	MNAs
	East Asia	EAs
	South Asia	SAs
	Australia	AU
Oceans	North Pacific Ocean	NP
	North Atlantic Ocean	NA
	Mediterranean Sea	MS
	Southern Ocean	SO
	Equatorial Pacific Ocean	EP
	Equatorial Atlantic Ocean	EA
	Equatorial Indian Ocean	EI
	Red Sea	RS
	high nutrient, low chlorophyll regions in Equatorial Pacific Ocean	HNLC_EP
	high nutrient, low chlorophyll regions in North Pacific Ocean	HNLC_NP

Figure 2: The pie charts are almost impossible to see on the figure. The percentage already appears, so, maybe they can be removed.

Response: Thanks for your suggestion, we have removed the pie charts in Figure 2 and retained the percentage.

Figures 3 and 7 could be grouped in 1 figure with 2 panels.

Response: We appreciate your suggestion and we think maybe you refer to combine Figures 3 and 6 into a single figure with two panels, and we have combined them.

Figure 4: remove the pie charts. Describe the percentages either in the text or in the legend.

Response: Thank you for your suggestion. We have processed Figure 4 in the same manner as Figure 2: the pie chart was removed, while the percentages were retained.

Figure 7 and 8 are very interesting, but I do not understand what the longitudinal columns with percentages represent. Maybe this could be simplified. Figure 8 can go in supplement.

Response: Thank you very much for your constructive suggestion. Each column on the left represents the fraction of dust emitted from a given source region that is ultimately deposited in individual oceans, with different colors indicating the respective oceans. For example, 75% of the dust emitted from East Asia that is deposited over the ocean ultimately settles in the North Pacific. Each column on the right shows the contributions of various dust source regions to dust deposition over each ocean, with different colors corresponding to different dust source regions. For instance, 39% of the dust deposited in the North Pacific originates from East Asia.

While we understand the intention to simplify the figure, we have chosen to retain the percentage values in the columns. This decision was made because identifying the detailed contributions of individual dust source regions to specific oceans is a key aspect of our study. The inclusion of these values enhances the interpretability of the spatial distribution patterns, which we believe is important for conveying the novelty and significance of our results. To improve clarity, we have revised the legend in the manuscript accordingly. "*Each column on the left represents the fraction of dust emitted*

from a given source region that is ultimately deposited in individual oceans, with different colors indicating the respective oceans. Each column on the right shows the contributions of various dust source regions to dust deposition over each ocean, with different colors corresponding to different dust source regions.".

We have moved Figure 8 to the supplement material.

Figure 9: Remove the pie charts and change the legend to indicate that this is phytoplankton carbon uptake.

Response: Thank you for your suggestion. We have removed the pie chart, while the percentages were retained in the figure. The legend related to "carbon uptake for new growth" is revised by "phytoplankton carbon uptake": "*The annual phytoplankton carbon uptake induced by dust deposition. The percentages represent the proportion of annual dust-driven phytoplankton carbon uptake in each ocean to global ocean*".

Figure 10 can go in supplement

Response: Thanks for your suggestion, Figure 10 has been moved to the supplementary material.

Figure 11: change the legend to indicate that this is phytoplankton carbon uptake. Figure 11 and 12 could be merged into 1 figure with 2 panels.

Response: We appreciate your suggestion, the legend related to "carbon uptake for new growth" in Figure 11 is revised by "phytoplankton carbon uptake": "*Seasonal variations of phytoplankton carbon uptake for new growth caused by Fe supply from dust deposition over each ocean area*", and have combined Figures 11 and 12 into a single figure with two panels.

Figure 13: I do not understand the longitudinal columns. They can be removed to simplify the figure. Correct the legend to "phytoplankton carbon uptake".

Response: Thank you for your constructive suggestion. Each column on the left represents the fraction of dust emitted from a given source region that ultimately induces phytoplankton carbon uptake in individual oceans, with different colors indicating the corresponding oceans. For example, 15% of the phytoplankton carbon uptake induced by dust emissions from East Asia affects the Equatorial Pacific. Each column on the right shows the contributions of various dust source regions to phytoplankton carbon uptake driven by dust deposition over each ocean, with different colors representing the respective dust sources. For instance, 37% of the phytoplankton carbon uptake caused by dust deposition in the North Pacific originates from South Asia.

We understand your intention to remove the longitudinal columns to simplify the figure, as a complex layout may confuse readers; however, the percentage values provide detailed information on the contributions of individual dust source regions to phytoplankton carbon uptake in specific oceans, which is a distinctive feature of our study. To enhance clarity, we have revised the figure legend in the manuscript accordingly: "*Each column on the left represents the fraction of dust emitted from a given source region that ultimately induces phytoplankton carbon uptake in individual oceans, with different colors indicating the corresponding oceans. Each column on the right shows the contributions of various dust source regions to phytoplankton carbon uptake driven by dust deposition over each ocean, with different colors representing the respective dust sources.*".

Lines 425-433: there is a lot of information that has already been described in the Methods. Some sentences can be removed (e.g. lines 431-433). Here specifically, the authors introduce a lot of confusion by writing "marine carbon uptake"

instead of "phytoplankton carbon uptake". Please change all occurrences to "phytoplankton carbon uptake".

Response: We appreciate your suggestion and have removed the sentences in Line 431-433: "*Thus, we incorporate varying Fe contents for each dust source and utilize a dataset of Fe solubility to the same grid based on observations (Zhang et al., 2015; Ito et al., 2019).*". The term "marine carbon uptake" has been replaced with "phytoplankton carbon uptake" throughout the manuscript.

Lines 436-445: This seems to be discussion more than results.

Response: Thanks for your comment. We have moved Lines 436-440 to the discussion section (Line 626-629), and relocated Lines 441- 445 to the section discussing uncertainty (Lines 747-752).

Lines 441-445: "We estimated the global marine carbon uptake associated with new growth resulting from dust deposition, using the Fe:C ratio, since, regardless of whether in HNLC or LNLC regions, phytoplankton can respond to dust deposition. However, Fe is not the sole primary limiting nutrient in LNLC regions; therefore, we also quantified the marine carbon uptake resulting from new growth driven by dust deposition exclusively in HNLC regions.". I don't understand these statements.

Response: Thank you for highlighting this point and providing the opportunity to clarify our explanation. In high-nutrient, low-chlorophyll (HNLC) regions, Fe is widely recognized as the primary limiting nutrient, thus, its addition has traditionally been proposed to stimulate phytoplankton blooms. However, in low-nutrient, low-chlorophyll (LNLC) regions, Fe is not the sole primary limiting nutrient; nitrogen and phosphorus can also directly or indirectly influence phytoplankton growth (i.e. phosphorus and Fe can stimulate nitrogen fixation in certain oceanic regions). Our study

investigates phytoplankton carbon uptake driven by Fe supply from dust. We estimated the global phytoplankton carbon uptake resulting from dust deposition, as phytoplankton in both HNLC and LNLC regions can respond to Fe addition. Given that Fe is the sole major limiting nutrient in HNLC regions, whereas LNLC regions are limited by multiple nutrients, we have presented a separate result focusing specifically on the HNLC regions.

We updated the related expression in Lines 449-454 "*We estimated global phytoplankton carbon uptake resulting from dust deposition using the Fe: C ratio in phytoplankton cells, as phytoplankton in both HNLC and LNLC regions can respond to Fe addition. However, because Fe is not the sole primary limiting nutrient in LNLC regions, which are limited by multiple nutrients, we also quantified phytoplankton carbon uptake driven by dust deposition exclusively in HNLC regions.*".

Later (lines 499-501) it is stated: "Since Fe is the most primary limiting factor in HNLC regions, we estimated the result of marine carbon uptake for new growth induced by dust deposition only over HNLC regions." Did you or did you not look at LNLC regions and why?

Response: Thank you for your comments. We estimated global marine phytoplankton carbon uptake resulting from dust deposition across both HNLC and LNLC regions and separately calculated the uptake driven exclusively by dust deposition in HNLC regions. The HNLC regions were assessed separately because phytoplankton growth in these areas is predominantly limited by Fe availability, which allows for a more accurate estimation of dust-driven carbon uptake. We did not present a result focused solely on LNLC regions, as these areas are limited by multiple nutrients.

Discussion:

The discussion lacks some quantitative comparison of the author's results with previous works. For instance, the authors found that the Equatorial Indian and Atlantic oceans receive most of the global dust, and this dust is coming from the main emission sources. How did the author's work bring novelty to these observations? As currently written, the discussion repeats the results instead of putting the study results into perspective.

Response: Thank you for your thoughtful comments. At present, few studies have quantified the large-scale response of marine phytoplankton carbon uptake to dust-borne iron inputs; therefore, there are limited previous results for direct comparison. This is one of the reasons we aim to provide an observation-based quantification of these contributions, which we hope may serve as a valuable reference for future studies. Our finding that the Equatorial Indian and Atlantic Oceans receive most of the global dust input, primarily originating from major emission sources, is supported by the quantified contributions of dust from various source regions to different oceans. This represents a central focus and key innovation of our study relative to previous work.

To enrich the discussion, we conducted additional analyses using simulated data to estimate marine phytoplankton carbon uptake driven by dust-borne Fe. Specifically, we used both annual and monthly dissolved Fe concentrations from CESM2 and the Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) historical simulations for the period 2000-2014 and 2010-2014, respectively, provided by the Coupled Model Intercomparison Project Phase 6 (CMIP6). We compared the estimates of marine phytoplankton carbon uptake induced by dust-borne Fe based on observed and simulated dissolved Fe data, highlighting differences in spatial distributions and regional values, and further quantified the uncertainty between observed and modeled dissolved Fe concentrations. Additionally, the monthly dissolved Fe data from CESM2 and GFDL-ESM4 were used to investigate the seasonal variability of marine phytoplankton carbon uptake caused by dust-borne Fe. The relevant details have been added in Lines 691-697 "*We also utilized dFe concentration*

data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to estimate marine phytoplankton carbon uptake driven by dust deposition. Based on dFe concentration data from CESM2 (2000-2014) historical simulations, the estimated marine phytoplankton carbon uptake driven by dust deposition was 2.2 Pg C yr^{-1}, while that from Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) (2010-2014) was 3.2 Pg C yr^{-1} (Fig. S13).", Lines 702-715 "*Compared to the estimates derived from observational data, the spatial distributions of marine phytoplankton carbon uptake from CMIP6 models (CESM2 and GFDL-ESM4) show similar global patterns, with high uptake mainly observed in the EA and EI, particularly in the northwestern EI. The use of CESM2 and GFDL-ESM4 dFe data resulted in approximately 61% and 43% reductions, respectively, in estimated marine phytoplankton carbon uptake relative to observation-based estimates. For CESM2-based results, the reduction was particularly pronounced in the southern RS, where uptake decreased from 0.4 to 0.1 Pg C yr^{-1}; the western Arabian Sea (in the EI), from 1.8 to 0.5 Pg C yr^{-1}; and the north-central EA, from 2.2 to 0.7 Pg C yr^{-1} (compare Fig. 6 and Fig. S13). For GFDL-ESM4-based results, notable reductions were also observed in the north-central EA (from 2.2 to 0.9 Pg C yr^{-1}) and the western Arabian Sea (from 1.8 to 0.7 Pg C yr^{-1}), whereas an evident increase occurred in the EP, from 0.3 to 0.7 Pg C yr^{-1}(compare Fig. 6 and Fig. S13).*" and Lines 757-768 "*We incorporated monthly dFe concentration data from CESM2 (2000-2014) and GFDL-ESM4 (2010-2014) historical simulations provided by CMIP6 to complement the sparse observational data, thereby attempting to better capture seasonal variations in marine phytoplankton carbon uptake. The monthly dFe data from CESM2 indicate that marine phytoplankton carbon uptake driven by dust deposition is 0.7 Pg C in summer, followed by 0.6 Pg C in spring, and 0.4 Pg C in both autumn and winter. The monthly dFe data from GFDL-ESM4 show that marine phytoplankton carbon uptake driven by dust deposition is 1.0 Pg C in both spring and summer, and 0.6 Pg C in both autumn and winter. Although the carbon uptake by marine phytoplankton due to dust deposition assessed using CESM2 and GFDL-ESM4 dFe data differed in value across four*

seasons, the spatial distribution remained relatively consistent. (compare Fig. S15 and Fig. S16).".

Lines 613-620: The comparison of the results with Mahowald's results is very confusing and I think, false. This study quantifies carbon uptake by phytoplankton, it is in no way a translation of total carbon uptake by the ocean. The difference between this study and Mahowald's results does not just stem from different methods, but on different objectives. This entire paragraph of discussion should be removed as these are not comparable results.

Response: Thank you for your insightful comments. We agree that our carbon uptake estimates, derived from Fe: C ratios in phytoplankton cells stimulated by dust-borne iron, are not directly comparable to the air-sea CO_2 flux estimates presented by Mahowald et al. (2010), which were generated using a coupled biogeochemical ocean model including carbonate chemistry. Nevertheless, we believe their findings offer a valuable point of reference, as both studies address the influence of dust deposition on oceanic carbon cycling from complementary perspectives. Dust deposition delivers iron to the ocean, supporting the broader framework of the Fe hypothesis; the resulting carbon dynamics ultimately stem from phytoplankton uptake and utilization of this Fe. While Mahowald et al. (2010) focused on net carbon sequestration at the air-sea interface, our study elucidates the physiological responses of marine phytoplankton to iron enrichment-responses that constitute a critical mechanistic step in carbon fixation. Including this reference provides broader context for understanding the full cascade of processes linking dust deposition to changes in oceanic carbon cycling. In the revised manuscript, we have de-emphasized direct comparisons involving specific parameters of their study (e.g., dust Fe content and Fe), and have clarified both the differences and the conceptual links between our approaches.

We have updated the expression about Mahowald et al. (2010) in Lines 636-655 "*Mahowald et al (2010) demonstrated that dust deposition trends increase ocean*

productivity by 6% over the 20th century, leading to marine carbon uptake of 8 Pg C (equivalent to 4ppm in atmospheric CO_2). They combined the ecosystem component of the Biogeochemical Elemental Cycling (BEC) ocean model and a carbonate chemistry module to calculate pCO_2 and air-sea CO_2 flux to estimate the variation of carbon. Although their carbon uptake estimate differs in magnitude and approach from ours, it offers a valuable point of reference. The air-sea CO_2 flux reflects the net oceanic uptake of atmospheric CO_2, which is determined by the ultimate fate of fixed carbon (e.g., export, remineralization, or trophic transfer). In contrast, the Fe: C ratio in phytoplankton cells reflects their physiological response to iron enrichment, directly influencing their capacity for photosynthetic carbon fixation. As a portion of the fixed carbon is later released through respiration, remineralization, or physical mixing, estimates based on Fe: C ratios in phytoplankton cells generally exceed the amount of carbon that is ultimately sequestered and captured in net air-sea CO_2 fluxes. Although our carbon uptake estimates, based on Fe: C ratios in phytoplankton, may not be directly comparable to the air-sea CO_2 flux estimates presented by Mahowald et al. (2010), the two approaches represent different yet complementary stages of the oceanic carbon cycle. Our study focuses on the initial carbon fixation response triggered by dust-borne Fe inputs, while Mahowald et al. (2010) evaluated the net carbon sequestration resulting from ocean-atmosphere CO_2 exchange.".

Reference

Mahowald, N. M., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, J. R., Albani, S., Doney, S. C., Bhattacharya, A., Curran, M. A. J., Flanner, M. G., Hoffman, F. M., Lawrence, D. M., Lindsay, K., Mayewski, P. A., Neff, J., Rothenberg, D., Thomas, E., Thornton, P. E., and Zender, C. S.: Observed 20th century desert dust variability: impact on climate and biogeochemistry, Atmos. Chem. Phys., 10, 10875-10893, 10.5194/acp-10-10875-2010, 2010.

Lines 643-646: "Moreover, ecological models, such as the BEC model, incorporate various potentially growth-limiting nutrients and have ability to simulate different phytoplankton functional groups, which could be compared to our evaluation." In this study, only Fe is considered a limiting nutrient for phytoplankton. You

could discuss the implications of this assumption since, as stated here, other nutrients may limit or co-limit phytoplankton growth and carbon uptake.

Response: We appreciate your comments. We have removed this expression and clarified that the marine phytoplankton carbon uptake estimated in our study is not directly comparable to the marine carbon uptake reported by Mahowald et al. (2010). We also elaborated on the conceptual differences and methodological connections between the two studies. Furthermore, we clarified that their estimates of marine biogeochemical changes were based on increases in anthropogenic inorganic nitrogen and soluble iron from atmospheric processing of dust and combustion sources, rather than from dust alone. Moreover, our study focused solely on the role of iron in dust in promoting carbon uptake by marine phytoplankton, without accounting for regions such as low-nutrient, low-chlorophyll (LNLC) areas, where Fe is not the only primary limiting nutrient and nitrogen and phosphorus may also affect phytoplankton growth. we noted the uncertainty in LNLC regions due to multiple nutrient limitations and therefore reported separate results specifically for HNLC regions, please see Lines 776-781 "*We assumed that phytoplankton in both HNLC and LNLC regions might respond to dust deposition as a maximum estimate, considering Fe is particularly important for nitrogen fixing phytoplankton in LNLC regions. However, the phytoplankton growth by dust addition in LNLC regions relies not only on Fe, but also on phosphorus. Therefore, future estimations in LNLC regions should account for other nutrients to achieve more accurate results.*" and Lines 513-526 "*We estimated global phytoplankton carbon uptake resulting from dust deposition using the Fe: C ratio in phytoplankton cells, as phytoplankton in both HNLC and LNLC regions can respond to Fe addition. However, because Fe is not the sole primary limiting nutrient in LNLC regions, which are limited by multiple nutrients, we also quantified phytoplankton carbon uptake driven by dust deposition exclusively in HNLC regions. The results show that annual dust deposition provides 0.8 Tg Fe to HNLC regions, of which 2.2 ×10^{-2} Tg is dFe, causing a marine phytoplankton carbon uptake of 0.2 Pg C yr^{-1}. The results show that annual dust deposition provides 0.8 Tg Fe to HNLC regions, of which 2.2 ×10^{-2} Tg is dFe, causing*

a marine phytoplankton carbon uptake of 0.2 Pg C yr^{-1}. The marine phytoplankton carbon uptake driven by dust deposition occurred in the HNLC region over NP, SO and EP is 1.6×10^{-1}, 7.2×10^{-2} and 9.3 ×10^{-3} Pg C yr^{-1}, respectively. The estimation of global marine phytoplankton carbon uptake attributed to dust deposition is 5.6 Pg C yr^{-1}, which may be overestimated due to the assumption that every grid where dust deposition occurs over the ocean responds to its Fe supply. Therefore, the actual annual marine phytoplankton carbon uptake due to dust deposition worldwide is likely between 0.2 Pg C yr^{-1} and 5.6 Pg C yr^{-1}.".

Reference

Mahowald, N. M., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, J. R., Albani, S., Doney, S. C., Bhattacharya, A., Curran, M. A. J., Flanner, M. G., Hoffman, F. M., Lawrence, D. M., Lindsay, K., Mayewski, P. A., Neff, J., Rothenberg, D., Thomas, E., Thornton, P. E., and Zender, C. S.: Observed 20th century desert dust variability: impact on climate and biogeochemistry, Atmos. Chem. Phys., 10, 10875-10893, 10.5194/acp-10-10875-2010, 2010.

Lines 646-648: The comparison with Westberry is also complicated here, primary production and phytoplankton carbon uptake are not strictly similar processes and may not be directly comparable. The following discussion on satellite data seems unnecessary to the article.

Response: We sincerely appreciate your insightful comments. Phytoplankton are responsible for majority of oceanic primary production through photosynthesis, and their carbon uptake efficiency directly influences the overall productivity of the marine ecosystem. Under optimal conditions, such as sufficient nutrients and appropriate light availability, the carbon uptake by phytoplankton closely approximates the total primary production. Therefore, while our study addresses different aspects, we believe that the findings of Westberry et al. (2023) are not entirely unrelated and have therefore been retained for reference and discussion. Due to the absence of comparable methodologies for estimating global phytoplankton carbon uptake, we referenced alternative ocean carbon cycle studies. While differing in approach and focus, these studies offer complementary perspectives for understanding marine carbon dynamics. We have also

clarified the distinctions between the two studies. We also apologize for the lack of clarity in our previous wording. The following discussion of satellite data is intended to highlight the potential underestimation in their results, and we have refined the relevant description accordingly. Please see Lines 661-680 "*Westberry et al. (2023) employed an observation-based empirical approach, utilizing the Carbon-based Production Model (CbPM) to estimate the net primary production response to dust deposition by comparing ocean color properties during 4-day periods before and after dust events. In contrast, our study aimed to quantify phytoplankton carbon uptake by identifying the contributions of dFe from various dust source regions to the ocean and applying Fe: C ratios in phytoplankton cells. Additionally, the approach used by Westberry et al. (2023) primarily captures short-term biological responses through changes in chlorophyll and phytoplankton carbon biomass, but it does not account for delayed ecosystem feedbacks. As a result, CbPM-based analyses may underestimate longer-term or region-specific productivity enhancements driven by dFe, particularly in HNLC regions where phytoplankton growth is strongly Fe-limited. In such regions, the biological response to atmospheric Fe deposition may be delayed or only weakly evident in short-term changes in ocean color properties. Consequently, empirical models such as CbPM, which rely on brief pre- and post-event comparisons of satellite-derived chlorophyll and phytoplankton carbon, may difficult to fully capture the longer-term or more subtle productivity enhancements induced by dust-borne Fe inputs. Moreover, satellite data are susceptible to atmospheric conditions and cloud cover, and satellite-derived ocean color products often rely on empirical inversion models, which may also contribute to the underestimation of their results.*".

The comparison with CMIP6 data should be more clearly explicited. Which models did you use? What variables did you compare your results to? Do all CMIP models use a variable Fe: C ratio for phytoplankton? How does that affect your comparison? Which years of CMIP simulations did you use? Which scenario?

Response: We are grateful for your recommendation to provide more detailed information regarding the data used from the Coupled Model Intercomparison Project Phase 6 (CMIP6). We used annually and monthly dFe concentrations from the CESM2 and Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) historical simulation for the period 2000-2014 and 2010-2014, respectively.

Based on dissolved Fe concentration data from CESM2 (2000-2014) historical simulations, the estimated marine phytoplankton carbon uptake driven by dust deposition was 2.2 Pg C yr^{-1}, whereas the estimate from the GFDL-ESM4 (2010-2014) was 3.2 Pg C yr^{-1}. Compared to estimates derived from observational data, the spatial distributions of marine phytoplankton carbon uptake simulated by the CMIP6 models (CESM2 and GFDL-ESM4) exhibit similar global patterns, with high uptake primarily occurring in the equatorial Atlantic and the equatorial Indian Ocean, especially in the northwestern equatorial Indian Ocean (Fig. R1). Using dissolved Fe data from CESM2 and GFDL-ESM4 resulted in approximately 61% and 43% reductions, respectively, in estimated marine phytoplankton carbon uptake relative to our observation-based estimates. For CESM2-based results, reductions were particularly pronounced in the southern Red Sea, where uptake decreased from 0.4 to 0.1 Pg C yr^{-1}; the western Arabian Sea (within the equatorial Indian Ocean), from 1.8 to 0.5 Pg C yr^{-1}; and the north-central equatorial Atlantic, from 2.2 to 0.7 Pg C yr^{-1}. For GFDL-ESM4-based results, notable reductions were also observed in the north-central equatorial Atlantic (from 2.2 to 0.9 Pg C yr^{-1}) and the western Arabian Sea (from 1.8 to 0.7 Pg C yr^{-1}), whereas a marked increase was observed in the equatorial Pacific, from 0.3 to 0.7 Pg C yr^{-1}.

Additionally, we incorporated monthly dissolved Fe concentration data from CESM2 (2000-2014) and GFDL-ESM4 (2010-2014) historical simulations provided by CMIP6 to complement the sparse observational data, thereby attempting to better capture seasonal variations in marine phytoplankton carbon uptake. The monthly dissolved Fe data from CESM2 indicate that marine phytoplankton carbon uptake driven by dust deposition is 0.7 Pg C in summer, followed by 0.6 Pg C in spring, and

0.4 Pg C in both autumn and winter. The monthly dissolved Fe data from GFDL-ESM4 show that marine phytoplankton carbon uptake driven by dust deposition is 1.0 Pg C in both spring and summer, and 0.6 Pg C in both autumn and winter. Although the carbon uptake by marine phytoplankton due to dust deposition assessed using CESM2 and GFDL-ESM4 dissolved Fe data differed in value across the four seasons, the spatial distribution remained relatively consistent (compare Fig. R2 and Fig. R3).

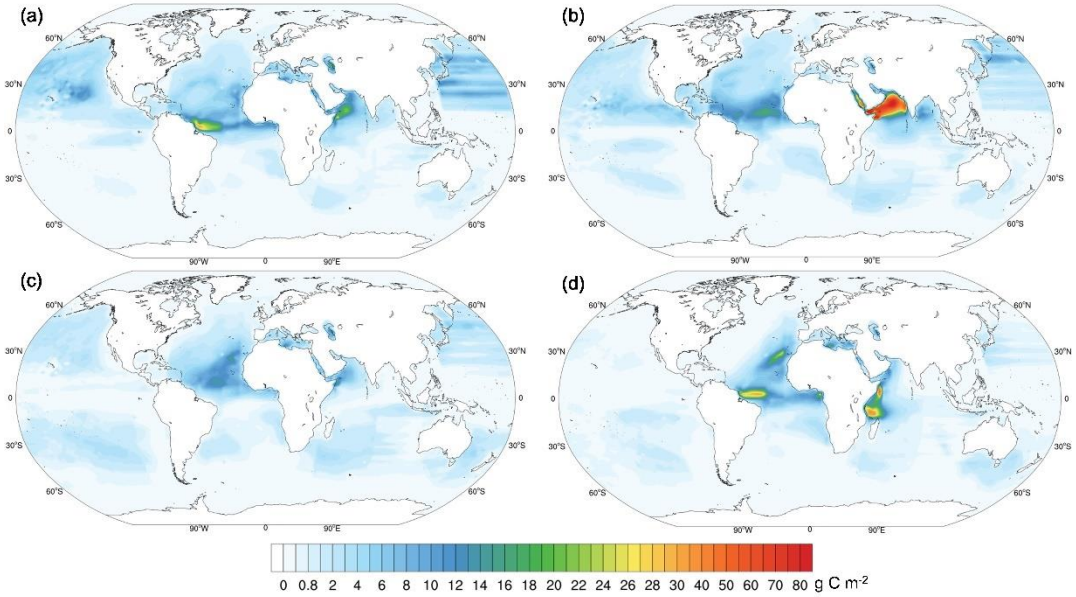

Fig. R2 Seasonal distribution of marine phytoplankton carbon uptake driven by dust-borne iron by using CESM2 dissolved iron data
(a) spring; (b) summer; (c)autumn; (d) winter

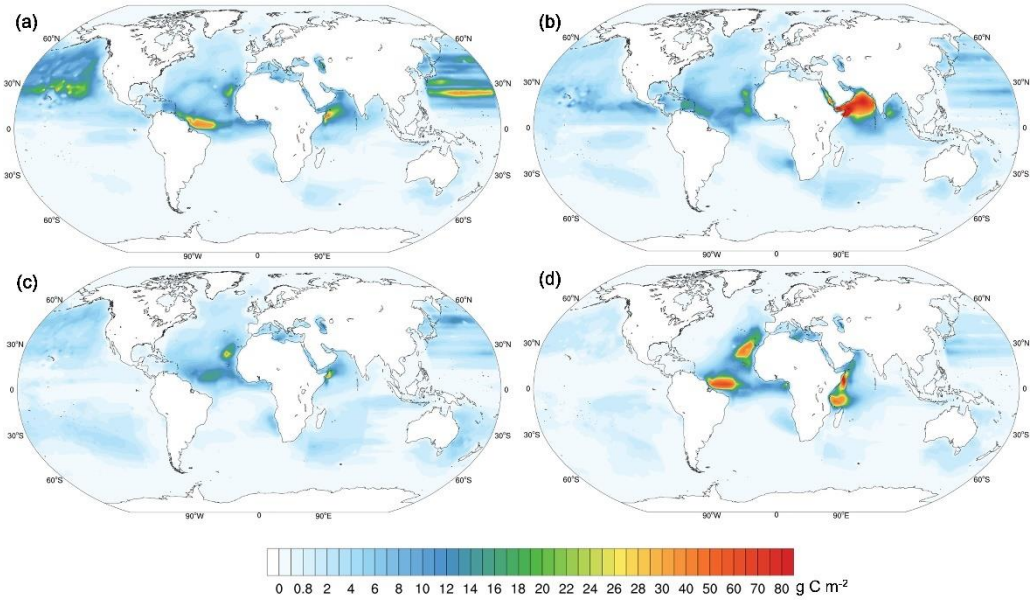

Fig. R3 Seasonal distribution of marine phytoplankton carbon uptake driven by dust-borne iron by using GFDL-ESM4 dissolved iron data
(a) spring; (b) summer; (c)autumn; (d) winter

We have mentioned this in the manuscript with Lines 691-697 "*We also utilized dFe concentration data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to estimate marine phytoplankton carbon uptake driven by dust deposition. Based on dFe concentration data from CESM2 (2000-2014) historical simulations, the estimated marine phytoplankton carbon uptake driven by dust deposition was 2.2 Pg C* yr^{-1}*, while that from Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) (2010-2014) was 3.2 Pg C* yr^{-1} *(Fig. S13).*", Lines 702-715 "*Compared to the estimates derived from observational data, the spatial distributions of marine phytoplankton carbon uptake from CMIP6 models (CESM2 and GFDL-ESM4) show similar global patterns, with high uptake mainly observed in the EA and EI, particularly in the northwestern EI. The use of CESM2 and GFDL-ESM4 dFe data resulted in approximately 61% and 43% reductions, respectively, in estimated marine phytoplankton carbon uptake relative to observation-based estimates. For CESM2-based results, the reduction was particularly pronounced in the southern RS, where uptake decreased from 0.4 to 0.1 Pg C* yr^{-1}*; the western Arabian Sea (in the EI), from 1.8 to 0.5 Pg C* yr^{-1}*; and the north-central EA, from 2.2 to 0.7 Pg C* yr^{-1} *(compare Fig. 6 and Fig. S13). For GFDL-ESM4-based results, notable reductions were also*

observed in the north-central EA (from 2.2 to 0.9 Pg C yr^{-1}) and the western Arabian Sea (from 1.8 to 0.7 Pg C yr^{-1}), whereas an evident increase occurred in the EP, from 0.3 to 0.7 Pg C yr^{-1} (compare Fig. 6 and Fig. S13)." and "*We incorporated monthly dFe concentration data from CESM2 (2000-2014) and GFDL-ESM4 (2010-2014) historical simulations provided by CMIP6 to complement the sparse observational data, thereby attempting to better capture seasonal variations in marine phytoplankton carbon uptake. The monthly dFe data from CESM2 indicate that marine phytoplankton carbon uptake driven by dust deposition is 0.7 Pg C in summer, followed by 0.6 Pg C in spring, and 0.4 Pg C in both autumn and winter. The monthly dFe data from GFDL-ESM4 show that marine phytoplankton carbon uptake driven by dust deposition is 1.0 Pg C in both spring and summer, and 0.6 Pg C in both autumn and winter. Although the carbon uptake by marine phytoplankton due to dust deposition assessed using CESM2 and GFDL-ESM4 dFe data differed in value across the four seasons, the spatial distribution remained relatively consistent. (compare Fig. S15 and Fig. S16).*" in Lines 757-768.

Minor comments:

Abstract line 30: " Dust provides iron, *which is an* essential for marine phytoplankton growth,"

Response: Thanks for the suggestion. The sentence in Line 30 is revised by "*Dust provides iron, which is an essential for marine phytoplankton growth, altering their carbon uptake capacity and affecting the global carbon cycle.*".

Line 36: "...based on *a* series of simulations…"

Response: Thanks for the suggestion and we have added "a" before "series of simulations".

Line 47: replace "carrying' by "carries" and add "be" before "deposited".

Response: Thanks for your suggestion and we have revised the sentence in Line 47 "*Dust carries various micronutrients can be transported thousands of kilometers and be deposited in remote ocean regions, ultimately resulting in the redistribution of nutrient elements.*".

Line 101: Rephrase to avoid the repetition of "carbon uptake" and clarify that you are talking about phytoplankton carbon uptake.

Response: Thanks for the suggestion. We have revised the term "carbon uptake" to "marine phytoplankton carbon uptake" throughout the manuscript.

Line 136-137: "Fe:C ratios *in phytoplankton cells* […] to estimate the global *carbon uptake by phytoplankton*"

Response: Thanks for your suggestion. The sentence is revised in Line – "*Fe is a significant limiting nutrient over global oceans, and Fe: C ratios* ***in phytoplankton cells*** *could be considered as a bridge to estimate the global* ***carbon uptake by phytoplankton*** *to dust deposition.*".

Line 140: replace "marine carbon uptake" by "phytoplankton carbon uptake".

Response: Thanks for the suggestion. We have revised the term "marine carbon uptake" to "marine phytoplankton carbon uptake" throughout the manuscript.

Line 211: "Fe solubility is also a key factor to estimate the carbon uptake of ocean to dust deposition" replace carbon uptake of ocean, by "carbon uptake of phytoplankton".

Response: We appreciate your suggestion. The sentence is revised as "*Fe solubility is also a key factor to estimate the carbon uptake of phytoplankton to dust deposition.*" In Line 220-221.

Line 239: "The dFe concentration data is a necessary factor for calculating the Fe: C ratio." Do you mean the Fe:C ratio of phytoplankton?

Response: Thank you for your comment. The sentence has been revised to: "*The dFe concentration data is a necessary factor for calculating the Fe: C ratio in phytoplankton cells.*" (Lines 248-249).

Special thanks to you for the very constructive comments!

Response to the comments from reviewer #2

Summary

The manuscript by Liu et al. (2025) presents a comprehensive modeling study investigating the contribution of atmospheric dust deposition to marine phytoplankton carbon uptake across global oceans. The research provides a quantitative evaluation of the dust source (land) and sinks (ocean) and estimates its potential fertilisation effect. These results are achieved by firstly refining the iron solubility in the model Community Earth System Model (CESM). Secondly, authors estimate the phytoplankton carbon uptake associated with dust deposition employing the iron to carbon stochiometric relationships (Fe: C ratios) based on the approach by Wiseman et al, 2023.

The main estimates for dust and soluble iron (global dust deposition supplies 11.1 Tg yr^{-1} of total iron and 0.4 Tg yr^{-1} of dissolved iron to oceans) are in line with previous research while the estimates of dust-induced carbon uptake (5.6 Pg C yr^{-1}) shows some discrepancies with recent literature (Westberry et al, 2023).

The manuscript provides interesting and relevant new insights into the regional and seasonal distribution of dust emissions and deposition. However, the results on phytoplankton carbon uptake linked to dust are less convincing and require some additional work to accept the manuscript for publication.

General comments

The main general comment I have is the need for an accurate estimation of uncertainties associated with interpolating limited observational databases to the global ocean. Interpolated maps of dFe and solubility are impacted by mathematical artefacts (e.g., longitudinal lines in the North Pacific or latitudinal band in the Indian Ocean in Fig. S1 and S2) with spatial patterns that do not follow regional biomes (Henson et al, 2010) nor major dust transport pathways. Applying a flexible Fe: C ratio on top of these

heavily interpolated observations results in an overlap of uncertainties and potential error propagation that strongly weakens conclusions. In the current approach, the accuracy improvement associated with observational databases might be lost due to interpolation. In the way the manuscript is currently presented, this issue is critical because it directly impacts the dust-induced carbon uptake estimates.

Two potential alternative amendments to the manuscript:

1. **Simply focus on the dust distribution from land sources to oceanic regions. This part of the manuscript holds interest on its own, although it will require additional content and some minor improvements to ease readability (see Other Comments section)**

Response: We sincerely thank you for your appreciation of our research topic and for your constructive comments. Quantifying the specific contributions of dust and iron (Fe) from various source regions to different ocean basins represents a key focus and innovation of our study relative to previous work. For this reason, we aim to make effective use of the detailed source-receptor relationships identified in our study. At present, few studies have quantified the large-scale response of marine phytoplankton carbon uptake to dust-borne Fe inputs. Therefore, we aim to provide an observation-based quantification of these contributions, which we hope may serve as a useful reference for future studies. While we have complemented our findings with model-based estimates to broaden the range of possible outcomes, we acknowledge that uncertainties remain, and we hope that future research will continue to refine and build upon these results.

2. **In order to include dust-induced carbon uptake estimates, authors need to rethink the observational approach. The estimates could, for instance, be focused on the bioregions where observations are abundant. Or apply a more sophisticated interpolation method that takes into account the oceanic biogeochemical regions and their seasonal dynamics. The results of this hypothetical approach would need**

to be validated against subsampled observations not used in the interpolation or/against modelling estimates of solubility and dissolved Fe (Hamilton, Moore et al, 2020, Bergas-Massó et al, 2023). Based on these analyses, maps should always include spatially variable uncertainty estimates or at least mark where results are statistically uncertain.

Response: We appreciate your constructive suggestion. We concur that incorporating oceanic biogeochemical regions and their seasonal dynamics into the interpolation method would improve the accuracy of the results. However, only 514 data points for Fe solubility and 3304 sites for dissolved Fe concentration are available. Considering that the ocean covers approximately 71% of the Earth's surface, these data are insufficient, and additional observational studies are required to improve data coverage in the future. Moreover, due to the limited and uneven spatial distribution of observations, incorporating biogeochemical regional divisions during interpolation may result in a lack of data points in many regions. Under such circumstances, obtaining seasonal data for each observation site to support interpolation that accounts for seasonal dynamics is challenging. In our interpolation approach, we select the five nearest data points to the target location for inverse distance weighted interpolation, ensuring that interpolation points are not separated by land, thereby preventing influence from crossing terrestrial barriers. We also tested other interpolation techniques, including kriging and nearest-neighbor methods; however, these approaches produced less satisfactory results. Although the sparse and uneven distribution of observational sites occasionally leads to banding patterns along certain latitudes or longitudes, the current method the most reliable performance achievable given the existing data constraints.

To mitigate the limitation of interpolated observational data in capturing seasonal variations in marine phytoplankton carbon uptake, we incorporated monthly dissolved Fe concentration data from Community Earth System Model version 2 (CESM2) (2000-2014) and Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) (2010-2014) historical simulations provided by CMIP6 in the revised

manuscript. The monthly dissolved Fe data from CESM2 indicate that marine phytoplankton carbon uptake driven by dust deposition is 0.7 Pg C in summer, followed by 0.6 Pg C in spring, and 0.4 Pg C in both autumn and winter. The monthly dissolved Fe data from GFDL-ESM4 show that marine phytoplankton carbon uptake driven by dust deposition is 1.0 Pg C in both spring and summer, and 0.6 Pg C in both autumn and winter. Although the carbon uptake by marine phytoplankton due to dust deposition assessed using CESM2 and GFDL-ESM4 dFe data differed in value across four seasons, the spatial distribution remained relatively consistent. (compare Fig. R4 and Fig. R5).

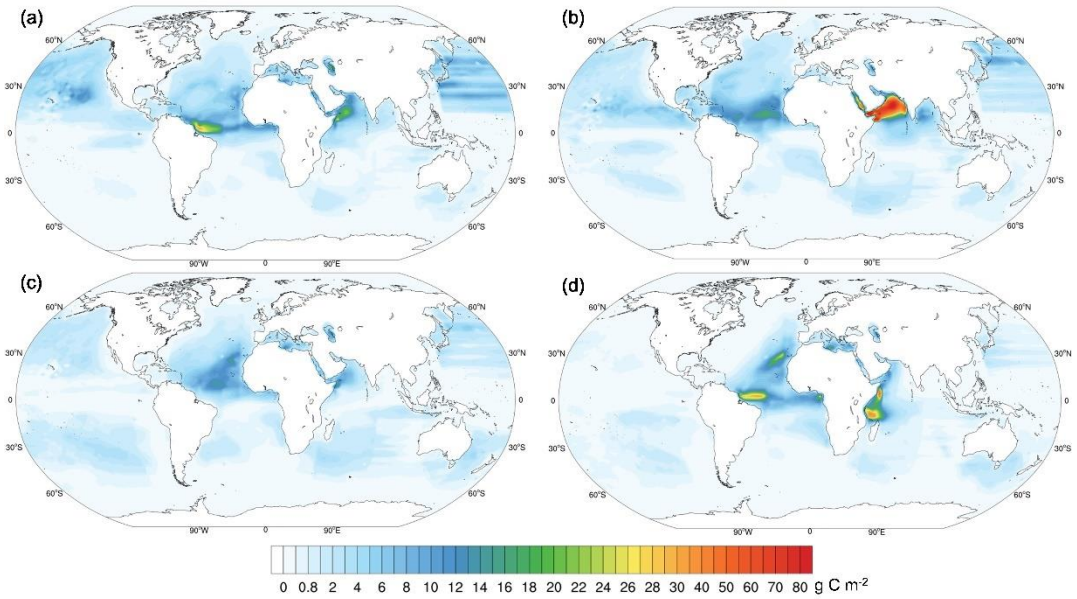

Fig. R4 Seasonal distribution of marine phytoplankton carbon uptake driven by dust-borne iron by using CESM2 dissolved iron data
(a) spring; (b) summer; (c)autumn; (d) winter

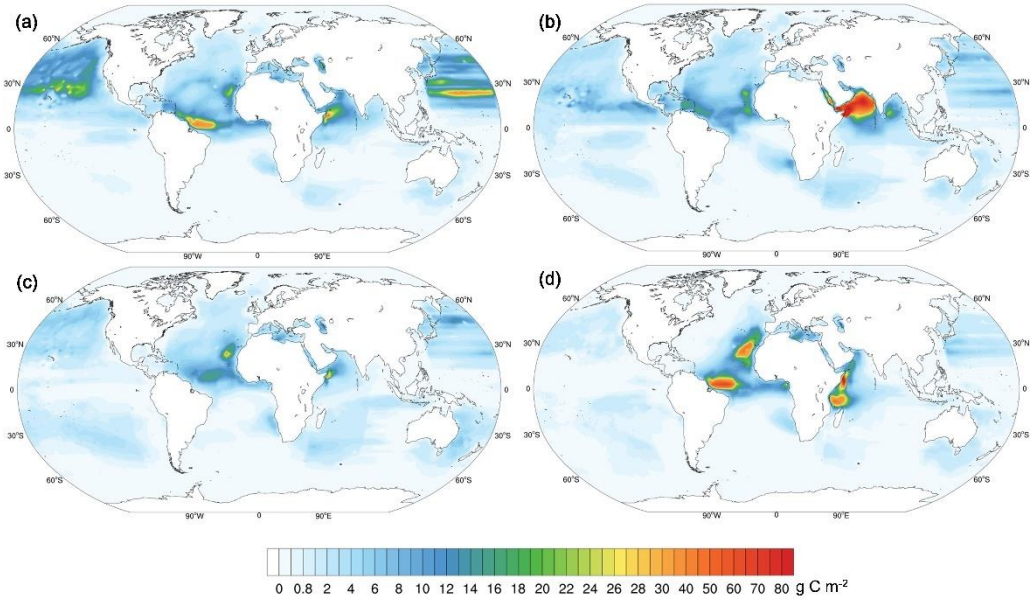

Fig. R5 Seasonal distribution of marine phytoplankton carbon uptake driven by dust-borne iron by using GFDL-ESM4 dissolved iron data
(a) spring; (b) summer; (c)autumn; (d) winter

We have carefully revisited the references you suggested. The data provided by Hamilton et al. (2020) are expressed as a flux of soluble iron in units of kg m^{-2} s^{-1}, while the data from Bergas-Massó et al. (2023) represent the total mass of soluble iron in units of Tg yr^{-1}. We sincerely apologize for any confusion that may have been caused by the wording in the original manuscript:

"*The following is the function to calculate Fe: C ratio used in this study (Wiseman et al., 2023):*

$$gQf = min\,(gQfe\_max,\ max(gQfe\_min, gQfe\_max \times \frac{dFe}{FeOpt})) \qquad (5)$$

where gQfe is the Fe: C ratio for new growth, gQfe_max is the prescribed maximum Fe: C, gQfe_min is the prescribed minimum Fe: C, dFe is the local concentration of ***soluble Fe*** *(nmol/L), and FeOpt is the iron concentration where Fe: C ratio reaches its maximum value. In this study, we used a broad Fe: C ratio range for new growth (3-90 µmol Fe* mol^{-1} *C) and an FeOpt of 1.75 nM for all phytoplankton groups which are proposed by Wiseman et al (2023).*"

In the original manuscript, we mistakenly described dissolved Fe as the local concentration of soluble Fe, whereas it actually refers to dissolved Fe. We sincerely

apologize for any confusion caused by our wording, which may have inadvertently given the impression that we used soluble Fe data. This has been corrected to "dissolved Fe" in the revised manuscript. Dissolved Fe generally refers to Fe species that pass through a 0.2 µm filter, encompassing both truly dissolved and colloidal fractions, whereas soluble iron typically denotes the more bioavailable fraction that passes through a 0.02 µm filter. The difference between these definitions can be substantial, especially in regions affected by dust deposition, where colloidal Fe may comprise a large fraction of the total dissolved Fe pool. Given this distinction, we excluded data from two studies (Hamilton et al., 2020; Bergas-Massó et al., 2023) that specifically focused on soluble Fe concentration. We have mentioned this discrepancy in the manuscript, please see Lines 697-702 "*It is important to note that Equation (4) is based on dissolved iron (dFe) concentrations. Some studies, such as Hamilton et al. (2020) and Bergas-Massó et al. (2023), report data for soluble Fe, which differs substantially from dFe. Specifically, colloidal Fe and complexing capacity—ranging from >200 kDa to <0.2 µm—are inferred from the difference between the dissolved and soluble fractions (Boye et al., 2010).*".

The uncertainties of the observed dissolved Fe data were assessed by comparing the observations with model data from CESM2 and GFDL-ESM4, extracted at the specific grid cells corresponding to the geographic locations of the observations. The results indicate that the model-simulated values are frequently lower than the observed data. Approximately 7% of the CESM2-simulated dissolved Fe data are at least ten times lower than the observed values, and approximately 1% are more than one hundred times lower. Similarly, about 4% of the GFDL-ESM4 dissolved Fe data are at least ten times lower than the observed values. On average, the dissolved Fe concentrations simulated by CESM2 and GFDL-ESM4 are ~ 4-5 times lower than the observed values. The comparison between the observed and modeled values shows that the discrepancy can reach up to two orders of magnitude when using modeled dissolved Fe data to validate the values interpolated from observations. As an inverse distance weighted interpolation method is used to estimate both Fe solubility and dissolved Fe

concentrations, the spatial distribution and density of observational sites exert a significant influence on the interpolation results. For Fe solubility, observational data are dense in the equatorial Atlantic Ocean, which may result in low interpolation uncertainty. In contrast, the central and southern equatorial Indian Ocean are characterized by sparse observations, potentially leading to high interpolation uncertainty. For dissolved Fe, observational data are dense in both the equatorial and North Atlantic Ocean, supporting relatively accurate interpolation in these regions. In contrast, data scarcity in the southern equatorial Indian Ocean may contribute to increased uncertainty. However, in the equatorial Atlantic Ocean, where interpolation uncertainty is low due to dense observational coverage, the modeled dissolved Fe concentrations significantly underestimate the dust-driven carbon uptake by marine phytoplankton compared to estimates based on observations. Specifically, the estimates based on CESM2 and GFDL-ESM4 are approximately 68% and 59% lower, respectively, than those derived from observed dissolved Fe data. This further highlights the importance of incorporating observational data in this study.

We have added "*We also utilized dFe concentration data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to estimate marine phytoplankton carbon uptake driven by dust deposition. Based on dFe concentration data from CESM2 (2000-2014) historical simulations, the estimated marine phytoplankton carbon uptake driven by dust deposition was 2.2 Pg C* yr^{-1}*, while that from Geophysical Fluid Dynamics Laboratory Earth System Model version 4 (GFDL-ESM4) (2010-2014) was 3.2 Pg C* yr^{-1} *(Fig. S13).*" In Lines 691-697, "*Compared to the estimates derived from observational data, the spatial distributions of marine phytoplankton carbon uptake from CMIP6 models (CESM2 and GFDL-ESM4) show similar global patterns, with high uptake mainly observed in the EA and EI, particularly in the northwestern EI. The use of CESM2 and GFDL-ESM4 dFe data resulted in approximately 61% and 43% reductions, respectively, in estimated marine phytoplankton carbon uptake relative to observation-based estimates. For CESM2-based results, the reduction was particularly pronounced in the southern RS, where uptake decreased from 0.4 to 0.1 Pg C* yr^{-1}*; the*

western Arabian Sea (in the EI), from 1.8 to 0.5 Pg C yr^{-1}; and the north-central EA, from 2.2 to 0.7 Pg C yr^{-1} (compare Fig. 6 and Fig. S13). For GFDL-ESM4-based results, notable reductions were also observed in the north-central EA (from 2.2 to 0.9 Pg C yr^{-1}) and the western Arabian Sea (from 1.8 to 0.7 Pg C yr^{-1}), whereas an evident increase occurred in the EP, from 0.3 to 0.7 Pg C yr^{-1} (compare Fig. 6 and Fig. S13). Additionally, the uncertainties of the observed dissolved Fe data were assessed by comparing the observations with model data from CESM2 and GFDL-ESM4, extracted at the specific grid cells corresponding to the geographic locations of the observations. The results indicate that simulated values are often substantially lower than the observed data. Approximately 7% of the CESM2-simulated dissolved Fe data are at least ten times lower than the observed values, and about 1% are more than one hundred times lower. Similarly, about 4% of the GFDL-ESM4-simulated dFe data are at least ten times lower than the observed values. On average, the dissolved Fe concentrations simulated by CESM2 and GFDL-ESM4 are ~ 4-5 times lower than the observed values. The discrepancies between observed and simulated dFe can reach up to two orders of magnitude. As an inverse distance weighted interpolation method is used to estimate both Fe solubility and dFe concentrations, the spatial distribution and density of observational sites exert a significant influence on the interpolation results. For Fe solubility, observational data are dense in the EA, which may result in low interpolation uncertainty. In contrast, the central and southern EI are characterized by sparse observations, potentially leading to high interpolation uncertainty. For dFe, observational data are dense in both the EA and NA, supporting relatively accurate interpolation in these regions. In contrast, data scarcity in the southern EI may contribute to increased uncertainty. However, in the EA, where interpolation uncertainty is relatively low due to dense observational coverage, the modeled dFe concentrations significantly underestimate the dust-driven carbon uptake by marine phytoplankton compared to estimates based on observations. Specifically, the estimates based on CESM2 and GFDL-ESM4 are approximately 68% and 59% lower, respectively, than those derived from observed dFe data. These findings further underscore the importance of incorporating observational data in the estimation of the

contribution of iron deposition to marine phytoplankton carbon uptake. Despite data scarcity and interpolation uncertainties, observation-based constraints substantially correct the underestimation of totally simulations, demonstrably lowering uncertainties in data-rich areas—with critical implications for optimizing future observing systems and observation-based methodologies." in Lines 702-744 and added "*We incorporated monthly dFe concentration data from CESM2 (2000-2014) and GFDL-ESM4 (2010-2014) historical simulations provided by CMIP6 to complement the sparse observational data, thereby attempting to better capture seasonal variations in marine phytoplankton carbon uptake. The monthly dFe data from CESM2 indicate that marine phytoplankton carbon uptake driven by dust deposition is 0.7 Pg C in summer, followed by 0.6 Pg C in spring, and 0.4 Pg C in both autumn and winter. The monthly dFe data from GFDL-ESM4 show that marine phytoplankton carbon uptake driven by dust deposition is 1.0 Pg C in both spring and summer, and 0.6 Pg C in both autumn and winter. Although the carbon uptake by marine phytoplankton due to dust deposition assessed using CESM2 and GFDL-ESM4 dFe data differed in value across the four seasons, the spatial distribution remained relatively consistent. (compare Fig. S15 and Fig. S16).*" in Lines 757-768.

Reference

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A last general comment is that this study focuses only on dust but uses a flexible Fe: C approach developed in a model including other aerosols, from pyrogenic or anthropogenic sources, which are known to contain Fe in highly soluble forms (Hamilton, Moore et al, 2020). These non-dust contributions are also naturally included in observations, where differentiating between aerosol sources is very challenging. If the inclusion of non-dust aerosols is not possible, authors need to acknowledge this limitation and propose hypotheses on how their results might be affected by it.

Response: Thanks for your suggestion. We agree that the approach of estimating Fe: C ratios in phytoplankton cells is do developed not only consider the dust-borne Fe, including other aerosols, from pyrogenic or anthropogenic sources, which are known to contain highly Fe solubility. It is difficult to estimate Fe: C ratios in phytoplankton cells with only dust sources in the observation dataset. As a result, applying these ratios to estimate marine phytoplankton carbon uptake driven solely by dust-derived Fe may lead to an overestimation, particularly in remote ocean regions where dust is the dominant or sole source of iron. We have added this limitation in Lines 781-787 "*The approach used to estimate Fe: C ratios in phytoplankton cells considers not only dust-borne Fe, but also other aerosol sources, such as pyrogenic and anthropogenic emissions, which often contain Fe with high solubility. As a result, applying such ratios to estimate marine phytoplankton carbon uptake driven solely by dust-derived Fe may lead to some degree of overestimation, particularly in remote ocean regions where dust is the predominant or only Fe source.*".

Other comments

Dust transport and deposition

- The regional division of dust sources is very useful and provides interesting results when linked with the oceanic regions. However, this regionalisation generates 20 different acronyms that make the reading arduous. I'm unsure how

this could be solved, but maybe using more explicit acronyms, reducing the number of them (or focusing on the most relevant ones).

Response: We appreciate your valuable comments. We have added a table that lists the full names and corresponding abbreviations of the dust source regions and oceans, hoping it could help readers more easily distinguish among the different regions.

Table 1 List of abbreviations and full terms for dust source regions and oceans

Dust source regions/ oceans	Full terms	Abbreviations
Dust source regions	Northwest Africa	NWAf
	Northeast Africa	NEAf
	Middle Africa	MAf
	South Africa	SAf
	North America	NAm
	South America	SAm
	West Asia	WAs
	Middle-North Asia	MNAs
	East Asia	EAs
	South Asia	SAs
	Australia	AU
Oceans	North Pacific Ocean	NP
	North Atlantic Ocean	NA
	Mediterranean Sea	MS
	Southern Ocean	SO
	Equatorial Pacific Ocean	EP
	Equatorial Atlantic Ocean	EA
	Equatorial Indian Ocean	EI
	Red Sea	RS
	high nutrient, low chlorophyll regions in Equatorial Pacific Ocean	HNLC_EP
	high nutrient, low chlorophyll regions in North Pacific Ocean	HNLC_NP

- Figure 7 is for me one of the most interesting results of the manuscript. However, its repetition for each season (Fig 8) is excessive and very hard to follow. I'd suggest moving Fig 8 to Supplementary Material. Additionally, it would be very interesting to capture the most important seasonal dynamics and show them

in a figure or the text, to understand where and why sources-to-sink links change from one season to another.

Response: We thank your appreciation to our work and your helpful comments. Figure 8 has been moved to the supplementary material. In addition, we focused on oceanic regions with the most pronounced seasonal variations in dust deposition, namely the Red Sea, Equatorial Indian Ocean, North Pacific Ocean, and Equatorial Pacific Ocean, which exhibit seasonal amplitudes of 626.3%, 600.4%, 550.0%, and 424.9%, respectively. Dust deposition over the Red Sea, Equatorial Indian Ocean, North Pacific Ocean, and Equatorial Pacific Ocean exhibits the most pronounced seasonal variations among oceanic regions, with seasonal amplitudes of 626.3%, 600.4%, 550.0%, and 424.9%, respectively. The Red Sea region is consistently dominated by dust contributions from North East Africa and West Asia, jointly accounting for over 90% of the total deposition. However, their relative contributions vary seasonally. In summer, enhanced eastward transport from North East Africa increases its contribution by 15-21% relative to other seasons, significantly widening the deposition gap between summer and winter, and serving as the primary driver of the 626.3% summer-to-winter increase. The North Pacific Ocean is primarily influenced by dust emissions from East Asia and South Asia, which together contribute over 80% of the deposition, with a distinct emission peak in spring. This leads to springtime dust deposition levels 550.0% higher than those in winter. For Equatorial Pacific Ocean, Asian dust sources dominate throughout the year except in summer, during which North West Africa and North East Africa become the principal contributors, together accounting for 73.0% of the total (41.6% from North West Africa and 31.4% from North East Africa). Their contributions in summer are 2 to 26 times greater than in other seasons, driving the 424.9% increase in summer deposition relative to winter.

The related expression could be found in Lines 414-435 "*Dust deposition over RS, EI, NP and EP exhibits the largest seasonal variations among ocean areas, with variations of 626.3%, 600.4%, 550.0% and 424.9%, respectively. NEAf and WAs have consistently been the primary sources of dust deposition in the RS region, contributing*

over 90% of the total, though their respective contributions show noticeable seasonal variations (Fig. S8). During the summer, the eastward transport of dust from NEAf increases, leading to a 15-21% rise in its contribution to dust deposition in the RS region compared to other seasons (Fig. S8). The contribution of dust from NEAf shows a significant increase only in summer, further widening the gap with seasons of lower dust deposition. This is a key factor in the 626.3% increase in dust deposition over the RS in summer compared to winter (Fig. 3). The seasonal variation in dust deposition over the NP region is driven by the large seasonal variations in Asian dust emissions as its primary source (Fig. S8). Dust from EAs and SAs consistently contributing over 80% of the dust deposition over the NP area with emission peak in spring (Fig. S8). As a result, dust deposition over NP is much higher in spring than in other seasons, with an increase of 550.0% compared to winter. The primary sources of dust deposition over EP are also dust sources in Asian, except during summer (Fig. S8). The primary contributors to dust deposition over EP in summer are NWAf and NEAf, accounting for 73.0% (41.6% for NWAf and 31.4% for NEAf). Dust from NWAf and NEAf leads to 2 to 26 times more dust deposition over the EP during the summer compared to other seasons, resulting in a large seasonal disparity in dust deposition. Therefore, dust deposition over EP in summer is 424.9% higher than that in winter.".

- Related to the previous comment, is it possible to also analyse interannual variability?

Response: We sincerely appreciate your valuable suggestion. However, our current simulation is designed to represent a climatological mean state under fixed boundary conditions. Specifically, we employed annually recurring aerosol emissions based on the year 2000 as well as prescribed climatological sea ice and sea surface temperature from Hadley Centre. Given this setup, we respectfully consider that an analysis of interannual variability may not be particularly meaningful within the context of our study.

We have added detailed information regarding our simulation in Lines 204-212: "*The model configuration included 30 vertical layers. We employed prescribed aerosol emissions that repeat annually, based on emission inventories representative of the year 2000. The configuration imposes a climatological forcing by applying an identical annual emission cycle throughout the simulation period. Prescribed climatological sea ice and sea surface temperature from Hadley Centre were used to drive the climate. Environmental boundary conditions were derived from the default CESM surface dataset for the year 2000, which includes land cover, soil properties, vegetation distribution, and dust source regions. Atmospheric initial conditions were specified using the standard initialization file provided for CAM.*".

Biological response

- The study could strongly increase its relevance by including some additional diagnostics related to the use of a flexible Fe: C or non-constant Fe solubility values. For instance, how does carbon uptake change when using a constant Fe: C or Fe solubility?

Response: Thank you for your constructive suggestion regarding the calculation of a new result using constant variables for comparison with our original findings. Based on previous studies (Jickells et al., 2005; Hamilton et al., 2022; Mahowald et al., 2005; Mahowald et al., 2017), we assumed that 3.5% of dust consists of Fe with an average solubility of 2%, and we adopted a mean Fe:C ratio of 19.4 μmol Fe mol^{-1} C in phytoplankton cells to estimate marine phytoplankton carbon uptake driven by dust-borne Fe. The results indicated that the iron supplied through dust deposition could support 4.4 Pg C yr^{-1} of marine phytoplankton carbon uptake, which is approximately 21% lower than the estimate derived using spatially variable parameters. Using constant values to estimate marine phytoplankton carbon uptake weakens the spatial variability of the results, leading to a distribution pattern that closely resembles the spatial pattern of dust deposition intensity (Fig. R6). This finding underscores the importance of incorporating spatially distributed variables in such estimations.

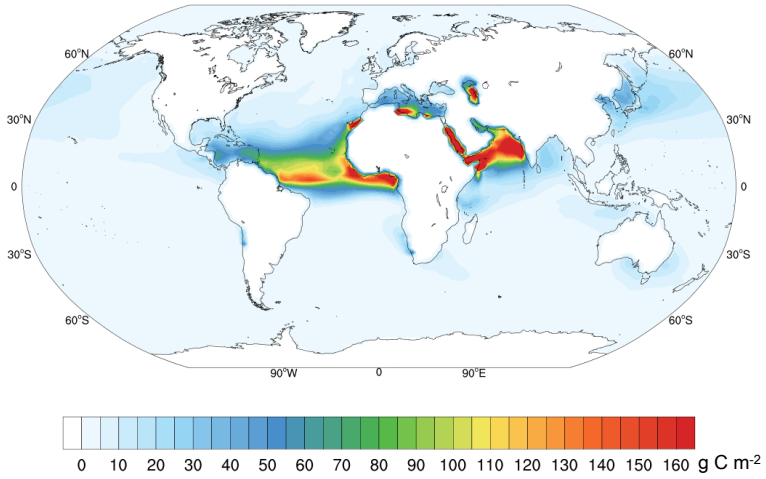

Fig. R6. Spatial distribution of annual marine phytoplankton carbon uptake driven by dust-borne Fe, estimated using constant values for Fe content, iron solubility, and the Fe: C ratio in phytoplankton cells.

We have added the results of marine phytoplankton carbon uptake driven by dust-borne Fe, estimated using constant values for Fe content, Fe solubility, and the Fe: C ratio in phytoplankton cells in the revised manuscript. Please see Lines 744-750 "*Compared with the results obtained using spatially variable parameters, the estimate of marine phytoplankton carbon uptake based on constant values for Fe content in dust (3.5%), Fe solubility (2%), and a mean Fe:C ratio of 19.4 μmol Fe mol^{-1} C in phytoplankton cells is approximately 21% lower. Using constant values also reduces the spatial variability of the results, leading to a distribution pattern that largely reflects the spatial intensity of dust deposition (Fig. S14).*".

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Prospero, J. M., and Tegen, I.: Atmospheric global dust cycle and iron inputs to the ocean, Global Biogeochem. Cycles, 19, 10.1029/2004GB002402, 2005.

- L646 The discrepancies with Westberry et al, 2023 should be explicitly addressed, providing hypotheses on the sources of such discrepancies.

Response: We appreciate your suggestion to explicitly explain the reasons for the discrepancies between our results and those of Westberry et al. (2023). The primary reason for these discrepancies lies in the differing methodologies employed. Westberry et al. (2023) employed an observation-based empirical approach, utilizing the Carbon-based Production Model (CbPM) to estimate the net primary production (NPP) response to dust deposition by comparing ocean color properties during 4-day periods before and after dust events. In contrast, our study aimed to quantify phytoplankton carbon uptake by identifying the contributions of dissolved iron (dFe) from various dust source regions to the ocean and applying Fe: C ratios in phytoplankton cells. Additionally, the approach used by Westberry et al. (2023) primarily captures short-term biological responses through changes in chlorophyll and phytoplankton carbon biomass, but it does not account for delayed ecosystem feedbacks. As a result, CbPM-based analyses may underestimate longer-term or region-specific productivity enhancements driven by dFe, particularly in high-nutrient, low-chlorophyll (HNLC) regions where phytoplankton growth is strongly iron-limited. In such regions, the biological response to atmospheric iron deposition may be delayed or only weakly evident in short-term changes in ocean color properties. Consequently, empirical models such as CbPM, which rely on brief pre- and post-event comparisons of satellite-derived chlorophyll and phytoplankton carbon, may difficult to fully capture the longer-term or more subtle productivity enhancements induced by dust-borne iron inputs. Furthermore, satellite data are susceptible to atmospheric conditions and cloud cover, and satellite-derived ocean color products often rely on empirical inversion models, which may also contribute to the underestimation of their results.

We have added the related expression in Lines 660-680: "*The primary reason for the discrepancies between their results and us depends on the differing methodologies employed. Westberry et al. (2023) employed an observation-based empirical approach, utilizing the Carbon-based Production Model (CbPM) to estimate the net primary production response to dust deposition by comparing ocean color properties during 4-day periods before and after dust events. In contrast, our study aimed to quantify phytoplankton carbon uptake by identifying the contributions of dFe from various dust source regions to the ocean and applying Fe: C ratios in phytoplankton cells. Additionally, the approach used by Westberry et al. (2023) primarily captures short-term biological responses through changes in chlorophyll and phytoplankton carbon biomass, but it does not account for delayed ecosystem feedbacks. As a result, CbPM-based analyses may underestimate longer-term or region-specific productivity enhancements driven by dFe, particularly in HNLC regions where phytoplankton growth is strongly Fe-limited. In such regions, the biological response to atmospheric Fe deposition may be delayed or only weakly evident in short-term changes in ocean color properties. Consequently, empirical models such as CbPM, which rely on brief pre- and post-event comparisons of satellite-derived chlorophyll and phytoplankton carbon, may difficult to fully capture the longer-term or more subtle productivity enhancements induced by dust-borne Fe inputs. Moreover, satellite data are susceptible to atmospheric conditions and cloud cover, and satellite-derived ocean color products often rely on empirical inversion models, which may also contribute to the underestimation of their results.*".

Reference

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Once again, thank you very much for all the comments and suggestions.