nature portfolio

Peer Review File

Marine heatwaves in a shifting Southern Ocean induce dynamical changes in primary production

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

Decision letter and referee reports: first round

24th Jan 24

Dear Mr Fernández-Barba,

Your manuscript titled "Marine heatwaves-induced changes in primary production in the Southern Ocean" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a thoroughly revised version that fully addresses these serious concerns. Specifically, the revised manuscript must
(1) perform robust analysis for the drivers behind the Southern Ocean MHWs; (2) clearly explain the underlying physical processes for the MHWs to affect NPP; and (3) provide convincing evidence to support the explanation in (2). If however the authors wish to focus on the "impacts of SO MHWs on NPP", the paper must thoroughly address (2) and (3).

We hope you will find the reviewers' comments useful as you decide how to proceed. If you can address these criticisms by doing additional work, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

[redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

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EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review of “Marine heatwaves-induced changes in primary production in the Southern Ocean” by Fernández-Barba et al.

This study investigates the characteristics of marine heatwaves (MHWs) in the Southern Ocean and its impact on primary production in the region. This is an interesting study that covers an important topic. The structure is overall good and easy to follow. However, I found that the discussions on the physical linkage between MHWs and primary production somewhat descriptive, without providing many insights or new evidence for the underlying physical processes. Based on my evaluation, I would like to recommend a “major revision”. I have listed my specific comments below.

Major comments:
While this study has some merits, I found that the sections on the physical processes through which the MHWs affect the primary production inadequate. In particular, the impact of MHWs on primary production is explained mainly through the shallowing of the mixed layer and more exposed to the sunlight associated with sea ice melting. However, the SST warming, sea ice reduction, and shallowing of mixed layer are all closely linked to each other. For instance, it has been suggested that the shallower mixed layer is important for driving the MHWs (e.g., Amaya et al., 2021). On the other hand, it remains elusive whether the MHWs can indeed affect the mixed layer depth (or by how much). Furthermore, the sea ice reduction may be the cause for MHWs through reduced surface albedo as well. These processes could also lead to a high correlation between MHWs and primary production variability, even though the SST warming may not be a direct cause (or play a minor role). I would suggest the authors to more carefully investigate and/or provide more evidence for the physical processes associated with MHWs that directly contribute to primary production changes.

Minor comments:
1. L35: “but also to” => “but also on”

2. L93: “standardized definition” => “conventional definition”
3. L141: “a manifest MHW hotspot” seems an awkward expression.
4. L150, L370 and L504: The format of references in these sentences are different from others in the manuscript.
5. L161: “notably” => “evident”
6. Figure 3a: By construction, the average of SSTA during 1982–2015 should be the same as average during 2013–2015, since the climatology is defined based on 1982–2012.
7. The stippling in Figures 5a–d is not discernible. Please revise the figure to enhance readability.

References:
Amaya, D. J., M. A. Alexander, A. Capotondi, C. Deser, K. B. Karnauskas, A. J. Miller, and N. J. Mantua, 2021: Are Long-Term Changes in Mixed Layer Depth Influencing North Pacific Marine Heatwaves? Bull. Am. Meteorol. Soc., 102, S59–S66, https://doi.org/10.1175/BAMS-D-20-0144.1.

Reviewer #2 (Remarks to the Author):

The article describes temporal and spatial trends in Southern Ocean marine heatwaves, and attempts to link these extreme events to changes in marine productivity through the use of an Net Primary Productivity product (CbPM).

This is now the third time I’ve reviewed this manuscript and I certainly appreciate the topic that the authors have taken on. Both marine heatwaves, and the links between the physical and biogeochemistry of the Southern Ocean (outside of CO2 export) are understudied, and a giagantic black hole in the literature. As such, on topic alone, this paper has merit.

Unfortunately, however, this paper tries to do too much, given the constraints of a short form journal. The link between ocean temperature extremes and changes in marine producicivity are, in my opinion, not well supported by the analysis undertaken (see major comment below) and while the discussion of the potential drivers oftrends in Southern Ocean marine heatwaves is contains a detailed discussion of the literature, limited new results are presented. As such, I don’t really think that the paper manages to do what it sets out to do.

I would strongly encourage the authors to take a step back and develop a strong foundation for each of the components they discuss here. For example:
- What are the drivers of Southern Ocean marine heatwaves?
- What are the drivers of NPP trends in the Southern Ocean?
- How does marine productivity respond to ocean extremes?

Each of the above questions, treated separately and in sufficient detail, could make exceedingly valuable contributions to the literature. However, but jumbling all these questions together, the authors don’t do justice to the topics they’ve picked. A series of detailed, well motived case studies, analysis base on heat and nutrient budgets, ect... could easily provide the foundations an excellent paper (or series of papers).

As stated, I don’t want to be discouraging. The topics above are in vital need of being addressed.

Major comments

Drivers of Southern Ocean marine heatwave trends

In the section Potential drivers behind the SO MHWs the authors include a detailed discussion of the literature, but barely a single new result. New information is limited to a single figure, showing regional and seasonal trends. The link between sea-ice concentration and temperatures in regions so far from the sea-ice zone is speculative (at best) and after reading the section, I can't say that I've learned much above Southern Ocean marine heatwaves.

I feel that this discussion requires a lot more detail. For instance, what is the role played by fronts and eddies (if any)? How about changing winds? Heat bugets and/or water mass analysis could tackle these questions, but the analysis is missing to support it.

Linking Marine Heatwaves to changes in primary productivity

In section Changing Temporal Trends of Biogeochemistry and Marine Producitivity, the authors attempt to link marine heatwave trends with estimates of marine productivity from the CbPM. I believe that the analysis in the section does not support the authors' conclusions.

As I mentioned in a previous review of this manuscript, marine heatwaves are distinct "events" with a beginning, peak, and an end. The standard statistics of these events, such as mean intensity or duration, when using a fixed "baseline" period, almost guaranteed to show strong temporal trends as the global warming signal comes to dominate natural variability. As such, it is very difficult, if not impossible, to disentangle long term trends in temperatures from long term trends in marine heatwave metrics.

As such, I struggle to place much faith in the analysis presented in (for example) Fig. 5, where the authors correlate spatially averaged marine heatwave metrics with NPP, I would argue that it's impossible to know if these correlations are not simply driven by the background warming signal, particularly when some of the highest trends in NPP are found in regions with the largest post-2015 temperature trends. The authors make no attempt to control for the background global warming signature. Other than two relatively brief case studies, there is no real attempt to look into "events" as they occur.

MInor comment

Figure 6: This figure would be much, much clearer if the results were plotted as anomalies with respect to the seasonal climatology.

Reviewer #3 (Remarks to the Author):

I have seen an earlier version of the manuscript and appreciate that some of my comments have been addressed. However, major concerns remain.

General comment:
This marine heatwave (MHW) study focuses on the Southern Ocean and is therefore a valuable addition to previous MHW studies conducted at the global scale or over other ocean basins. The distribution and evolution of Southern Ocean MHWs are characterized over the satellite period, using commonly defined MHW metrics. You show increasing MHW activity over the satellite period, which has been described and related to climate change by previous MHW studies (e.g., Oliver et al. 2018). You further relate the rise in MHW activity to the sudden sea-ice loss in 2015, which was associated with increased radiative surface warming. The study then investigates the link between Southern

Ocean marine heatwaves and changes in primary productivity. You use the CbPM NPP product, which is highly uncertain in the Southern Ocean close to sea-ice. Annual mean NPP is compared to annual mean MHW metrics. Note that a positive correlation between annual mean NPP and MHW metrics does not prove that marine heatwaves lead to high NPP, nor that they co-occur with high NPP. Throughout the manuscript, you could better distinguish between hypotheses and actual conclusions that can be drawn from your analysis.

Detailed comments:

L. 18-20. "A rapid but not long-lasting warming of the sea surface was found to trigger phytoplankton activity through stabilization of the water column." This study does not address the stability of the water column. It simply shows that this warming was associated with enhanced phytoplankton activity. Which warming do you exactly refer to here? As far as I understand, this is a decadal warming, which is longer-lasting than discrete marine heatwave events.

L. 31-32: "defined as discrete persistent extreme events where sea surface temperature (SST) exceeds certain criteria based on a seasonally varying climatological threshold and variability (8–10)." Maybe specify "commonly defined", as although this is the common marine heatwave definition by Hobday et al. 2016, marine heatwaves can also be defined using an absolute, non-seasonally varying threshold, depending on the biological impact to be quantified (e.g. Gruber et al. 2021, https://doi.org/10.1038/s41586-021-03981-7).

L. 34-36: "This thermal tolerance is not only dependent on the intensity of the underlying SST anomalies (SSTAs), but also to the frequency and duration of MHWs." Provide references.

L.140 and in the rest of the paper: Consider replacing "intensity" by "magnitude". Intensity commonly refers to the exceedance above a percentile threshold, whereas the magnitude is the exceedance above the climatology (Gruber et al. 2021, https://doi.org/10.1038/s41586-021-03981-7).

L.182-184: "However, maximum intensities (SSTAs) are greater in the Atlantic sector, while longest–lasting events occur in the Pacific area. This heterogeneity highlights SO climate regionality." This is an interesting result, which could be further discussed. Do you have an explanation for this heterogeneity?

L. 197 Does the "correlation" refer to a correlation between annual mean MHW metrics and climate variables? Maybe specify here.

L.237 "Changing temporal trends of biogeochemistry and marine productivity" This section covers aspects not yet addressed by previous marine heatwave studies carried out at the global scale. Using biogeochemical trends before and after the rapid sea-ice melting in 2015, you hypothesize that marine heatwaves trigger sea-ice melting in the Southern Ocean, which releases iron and favors phytoplankton growth. However, the rapid sea-ice melting in 2015 may have been driven by long-term changes in the Southern Ocean instead of by marine heatwaves. Why not rather focus on marine heatwave events and compute the mean sea-ice extent, nutrient levels, and chlorophyll anomalies during these events?

L. 255 You should mention that there are large uncertainties in NPP estimates, especially in the Southern Ocean (Le Grix et al. 2022, https://doi.org/10.5194/bg-19-5807-2022). It is especially uncertain how NPP reacts to Southern Ocean marine heatwaves. The CbPM is one of a number of models deriving NPP from satellite observations; all give very different estimates.

L. 275-289. Interesting discussion on how marine heatwaves may change phytoplankton growth, biomass, and community structure, but where do your results contribute to this discussion? You may want to move this paragraph to the Discussion. Moreover, many of the cited papers are not specific to marine heatwaves. This study could have contributed to the discussion by proving some of the hypotheses in the specific case of marine heatwaves.

L. 276-277. "playing a key role the physiological": Rephrase.

L. 281. There is no reason for the CbPM to include grazing since it calculates NPP as the product of the growth rate and carbon biomass, with the carbon biomass directly derived from the particulate backscattering coefficient.

Fig. 5: Specify that the correlation is computed between "annually averaged" MHW metrics and NPP. Maybe explain in the discussion why you compute the correlation between annual averages. Isn't the MHW period (austral summer) interrupted? You could also have averaged NPP over each MHW event or over each austral summer season.

Note that a high correlation between annual mean MHW metrics and NPP does not prove that marine heatwaves lead to high NPP, nor that they co-occur with high NPP. For example, the long-term warming may have increased the MHW frequency, intensity, and duration as well NPP over the years, resulting in a positive correlation, which doesn't mean NPP is directly related to MHW activity.

Fig. 6. How would you explain the compound MHW-HNPP event in winter 2015 in the Davis Sea under high sea-ice?
Consider adding the seasonal cycle of the sea-ice extent in Fig. 6, so the readers know whether in a given year, sea-ice extent is unusually high or low compared to the climatology.
Why are there heatwaves in winter on Fig. 6? The methods state that temperatures must exceed the long-term mean summer temperature. Is this criterion dropped?

L. 440-441 "Phytoplankton responses to MHWs have shown to be zonally asymmetric, as previously suggested by refs." The references do not specifically refer to MHWs. Here, and at other times in the manuscript, generalizations are made on the phytoplankton response to MHWs based on studies that consider moderate or long-term warming. Phytoplankton may, however, respond differently under discrete and extreme warming events.

L. 441-442. "It should be highlighted that MHWs are not the sole direct cause of increased NPP in the vast SO." This study does not prove that MHWs generally drive increased NPP. It shows that there is a positive correlation between annual mean MHW metrics and NPP, and that an increase in MHW frequency over recent years has been associated with an increase in NPP.

L. 501. Note that all regions covered by some sea-ice will give misleading results for CbPM NPP. The CbPM NPP estimates are derived from observations that are highly uncertain close to sea-ice.

L. 538. The use of the LMST criterion is a nice addition from previous marine heatwaves studies at the global scale and allows to focus on heatwaves that are potentially harmful for Southern Ocean species. The criterion implies that marine heatwaves usually occur in austral summer. You may want to clarify earlier in the manuscript that this study focuses on summer marine heatwaves. On Fig. 6, it seems that MHWs occur also when the temperature is less than the LMST. Have you not applied the LMST criterion?

L. 555. MHW metrics are annually averaged although each austral summer spans across two calendar years. Consider averaging over summer, or spring to autumn, instead of a calendar year.

L. 566-568. “Nevertheless, the austral warm season lasts from December to May, thus an event can occur within two different years in high Southern latitudes. When this occurs, the event is counted in the year in which it begins.” How does that impact the calculation of the correlation calculation of MHW metrics with annual mean NPP?

Fig. S5. Specify what the red shading indicates. Do MHWs occur when the SSTA is lower than the LMST, contrary to what is stated in the Methods?

Revised Responses to Reviewers' Questions for 'Marine heatwaves in a changing Southern Ocean: Drivers and impacts on net primary production'

This document includes cited references, which can be seen grouped together at the end of the response addressed to each reviewer. Please note that they do not match the order of those in the manuscript.

The authors would like to express their sincere gratitude to the editor for the esteemed consideration of our manuscript, as well as the three anonymous reviewers for their useful and constructive comments and appreciate their acknowledgments of the novelty of this work and its contribution to the field. We have carefully considered all the suggestions and present a revised version of the manuscript, which includes additional robust analysis, figures, and details aimed at addressing the points raised by the reviewers and improving the quality and clarity of our work.

Reviewer #1

Major comments:

Reviewer #1: While this study has some merits, I found that the sections on the physical processes through which the MHWs affect the primary production inadequate. In particular, the impact of MHWs on primary production is explained mainly through the shallowing of the mixed layer and more exposed to the sunlight associated with sea ice melting. However, the SST warming, sea ice reduction, and shallowing of mixed layer are all closely linked to each other. For instance, it has been suggested that the shallower mixed layer is important for driving the MHWs (e.g., Amaya et al., 2021). On the other hand, it remains elusive whether the MHWs can indeed affect the mixed layer depth (or by how much). Furthermore, the sea ice reduction may be the cause for MHWs through reduced surface albedo as well. These processes could also lead to a high correlation between MHWs and primary production variability, even though the SST warming may not be a direct cause (or play a minor role). I would suggest the authors to more carefully investigate and/or provide more evidence for the physical processes associated with MHWs that directly contribute to primary production changes.

Response: Firstly, we would like to thank the Anonymous Reviewer #1 for their encouraging comments and for recognizing the importance of our work. We also appreciate their feedback on the manuscript's structure and readability.
We understand your concern about the physical processes through which Marine Heatwaves (MHWs) influence Net Primary Production (NPP), and we recognize the importance of clearly elucidating these mechanisms.
We have substantially revised our manuscript. Among the changes made, we assessed the local physical drivers of MHWs in the Southern Ocean (SO) by examining heat term budget anomalies available in MOM4p1 (Griffies, 2015) during the onset and decline phases of MHWs (Fig. 3). The methodology we followed is detailed in Methods section (L. 640-698):

"[…] **Analysis of local drivers of marine heatwaves in the Southern Ocean**

To assess the local physical drivers of MHWs, we made use of a global, fully coupled carbon-climate Earth System Model (ESM) developed at the National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory (GFDL)[86]. The GFDL ESM2M couples an oceanic circulation model (MOM4p1) to an atmospheric circulation model (AM2), and incorporates a land model (LM3.0), representations of sea ice and iceberg dynamics, as well as interactions within biogeochemical cycles. Specifically, we used temperature tendency heat budgets available in MOM4p1[51] (https://github.com/mom-ocean/MOM4p1). This ocean model uses a tripolar horizontal grid of 1ºx1º, increasing meridionally to up to 1/3º towards the Equator, and with 50 depth levels. We analysed daily-mean outputs of all tendency terms that change the SST (over the upper 10 m) from a 500-yr preindustrial control simulation (with atmospheric CO_2, along with all other agents that influence radiation fixed at their preindustrial levels) and confirmed with an eight-member ensemble simulation of the GFDL ESM2M driven by historical data and the Representative Concentration Pathway 8.5 (RCP8.5) scenario from 1982 to 2021, following ref.[52,87].

For each grid cell, the model dissects the total heat change (ΔQ_{total}) across time intervals into various heat budget components. These components signify temperature changes due to distinct processes modeled. The total tendency of heat at the ocean surface, in W m^{-2}, is determined by equation(4)[51]:

$$\Delta Q_{total} = \Delta Q_{adv} + \Delta Q_{a\text{-}s} + \Delta Q_{vmix} + \Delta Q_{vdiff} + \Delta Q_{res}; \quad (4)$$

where ΔQ_{adv} represent the change in heat resulting from both horizontal and vertical advective heat fluxes, both explicitly resolved and approximated on subgrid scales through parameterization. $\Delta Q_{a\text{-}s}$ is the air-sea exchange of heat, including the balance of shortwave radiation (the net incoming surface shortwave radiation reduced by the fraction of shortwave radiation that goes beyond the surface layer) along with the net incoming longwave radiation, in addition to the net fluxes of latent and sensible heat[86]. ΔQ_{vmix} refers to the heat flux generated by the non-local segment of the K-profile parameterization (KPP)[51], representing convective vertical mixing within the ocean boundary layer in response to negative buoyancy forcing. ΔQ_{vdiff} accounts for heat fluxes caused by vertical diffusion, encompassing vertical mixing within the ocean boundary layer attributed to the local component of the KPP, as well as tidal mixing. Furthermore, the residual term (ΔQ_{res}) includes other smaller processes such as heat exchange due to river runoff, solid runoff from iceberg calving, neutral diffusion, or the heat flux exchange resulting from interactions of surface water masses due to precipitation and evaporation. A detailed description of each term can be found in Extended Data equations(S2–6) and in ref.[51].

We then computed anomalies of all these heat budget terms relative to their seasonal cycles for each ocean grid cell, to ultimately average them separately over the days of the onset (build-up of heat) and decay (dissipation of heat) phases of the MHWs (see Extended Data Fig. S1). Moreover, based on the change in heat content, the change in potential temperature ($\Delta\theta$), in ºC d^{-1}, can be approximated using equation(5)[51]:

$$\Delta\theta = \frac{\Delta Q_{\text{total}}}{C_p^0 \rho_0 dz}, \quad (5)$$

where C_p^0 is a fixed value for heat capacity, set at 3992.1 J kg^{-1} K^{-1} in MOM4p1; ρ_0 is the constant Boussinesq density of 1.035 kg m^{-3}, and dz is the changing thickness of vertical grid cells over time, measured in m, as described by ref.[51]. In our analysis, we assumed a thickness of dz = 10m, which led to a conversion factor of 0.00209 ºC m^2 s^{-1} W^{-1}. This inference is justified because the real fluctuations in the thickness of grid cells differ minimally (with the largest changes being around $1 \cdot 10^{-2}$ in the open ocean), resulting in negligible adjustments to the conversion factor. Despite the fact that these errors can accumulate over time, for time scales of MHW durations (days to few months), these are significantly reduced, as demonstrated by ref.[52].

The motivation for using the GFDL ESM2M (MOM4p1) model for the assessment of local physical drivers of MHWs in the Southern Ocean was due to the good agreement between the climatological characteristics and the trends of modelled and observation-based MHWs globally[26,52,87], as a result of the model's fidelity in simulating the mean state and interannual variations in SST. Moreover, in the SO outside the sea ice area, the model fits good with observational data[26,52]. […]".

Results (Fig. 3; Extended Data Figs. S1 and S5) are described in L. 194-229 of the revised manuscript:

"[…] Local physical drivers of MHWs over the SO were assessed by examining heat term budgets available in the Modular Ocean Model (MOM4p1)[51] (Figs. 3a–i). Additionally, the correlation between MHWs and several essential climate variables from 1982 to 2021 was also explored (Figs. 3j–m and Extended Data Table S3). The annual mean heat flux anomalies in the surface ocean layer averaged during the MHW onset (i.e., build-up of heat) and decay (i.e., dissipation of heat) phases (Extended Data Fig. S1) are listed in Extended Data Fig. S5. Results from the heat budget analysis showed that temperature changes during MHWs were mainly explained by four most important counteracting processes (Figs. 3a–i). While ocean advection, sea-air heat fluxes, and vertical diffusion positively contributed to the formation of MHWs in the SO, as well as to the subsequent heat loss, convective vertical mixing (from the non-local part, see Methods) inherently acted in a contrasting mode. This arises from the intrinsic characteristics of this non-local term, which was incorporated in the MOM4p1 to mitigate air-sea heat fluxes when faced with negative buoyancy forcing conditions[51]. During the onset phase of MHWs, the averaged circumpolar surface ocean heat gain reported in the preindustrial control simulation was 20 W m^{-2}, with air-sea heat fluxes being the dominant MHW driver (Extended Data Fig. S5a). Nevertheless, in the eight-member ensemble simulation for the 1982–2021 period, the circumpolar heat gain during the onset phase amounted to 39.8 W m^{-2}. This was explained by the increased contribution of vertical diffusion (26 W m^{-2} or 65.2 %; Extended Data Fig. S5b and Fig. 3g). Despite the major role of the surface heat fluxes (Figs. 3c–d), which was especially important in the Atlantic sector, vertical diffusion emerged as the dominant process both in driving MHWs in the SO and as an overarching cooling contributor to their decline (Figs. 3g–h). This was particularly relevant across much of the areas connecting the sea ice zone (defined by averaged SIC > 20%; Extended Data Fig. S2) and the southernmost subantarctic belt along the Atlantic and Indian sectors. This finding highlighted the significant feedback between sea ice variability and surface ocean temperature extremes in these regions (as also demonstrated in Extended Data Figs. S6a–b). Horizontal advective heat fluxes followed the ACC pathways, though they appeared to play a secondary role, affecting the development of MHWs in the SO only locally (Figs. 3a–b). However, it is important to note that the MOM4p1 model may underestimate the impact of advection, as its relatively low horizontal resolution cannot resolve mesoscale processes[51]. Furthermore, the contribution of drivers did not necessarily depend on the strength of the MHWs (as measured by the cumulative intensity) in the SO (Fig. 3i), and various combinations of driving mechanisms were possible; being consistent with ref.[52]. That is to say, the strongest and weakest MHW events were primarily driven by the same leading processes –positive ocean heat uptake anomalies and vertical diffusion– and were dampened by convective vertical mixing during their onset phases. While both air-sea heat fluxes and vertical diffusive processes led to the dissipation of heat, advection and contrasting vertical mixing played minor roles during the decay phases (Fig. 3i). […]".

Moreover, to more clearly illustrate the changes in the SO surface layer during MHW events, we averaged the distributions of NPP, Sea Ice Concentration (SIC), and Mixed Layer Depth (MLD) over the months (from November to March, owing to methodological reasons in applying the long-term mean summer temperature) with and without MHWs (Figs. 4b-d). The changes are readily apparent, even considering the conservative nature of the violin plots. Furthermore, we applied Empirical Dynamic Modelling (EDM) through Convergent Cross Mapping (CCM; Sugihara et al., 2012) to reveal nonlinear causal relationships between changes induced in the SO surface layer (Max SSTA, SIC, and MLD) and dynamical alterations in NPP. This cutting-edge analysis showed the predictive capacity of changes in the SO surface layer for NPP dynamics (Figs. 4e-f). Specifically, it allowed to analyse the spatio-temporal influence of different physical variables (Max SSTA, SIC, and MLD) on the dynamic changes in phytoplankton communities. For instance, through CCM, we empirically evidenced the extent of the influence that sea ice melting exerts on NPP in the open waters of the SO (Fig. 4f). The methodology applied for causal inference through EDM is described in the Methods section (L. 718-777) of the revised manuscript:

"[…] **Causal interactions through empirical dynamic modeling**
In an effort to investigate the causal interactions among the key variables in our study (Max. SSTA, NPP, SIC, and MLD), we applied Empirical Dynamic Modeling (EDM). This cutting-edge framework is based on Takens' theorem, which provides tools for attractor reconstruction[92] and allows for the modeling of causal relationships in nonlinear dynamic systems in the absence of governing dynamic equations[66]. In dynamical systems, two state variables *X* and *Y* are considered to be causally linked if they contain shared information that allows reconstructing the observed dynamics from one state variable, say X, from the dynamics of the other variable, Y. This shared information can allow for a unidirectional reconstruction (e.g., X causes Y), or a bidirectional reconstruction (both variables cause each other) of the dynamics[66]. In essence, Takens' theorem shows that the dynamics of a state variable Y caused by another variable X is encoded in the delayed-coordinates embedding[66] of the causing variable, X in this case. This is provided by the so-called attractor manifold *M* which, in the absence of a governing dynamics equation, contains all the information needed to encode the dynamic system: it is the region of the state space that contains all the possible states of the system in the long-term. The essential assumption of EDM is that causality within a dynamic system is more strongly dependent on the proximity of the values of the variables in the state space that in their proximity in time[66,92]. In our analysis, we applied Convergent Cross Mapping (CCM), introduced by ref.[66], to perform the nonlinear state space reconstruction. CCM assesses causality by evaluating how accurately the historical data of *Y* can predict the state of *X*, or viceversa. This prediction is feasible only if *X* has a causal impact on *Y*. To delve deeper, CCM seeks evidence of *X*'s influence within *Y*'s time series by examining if the 'library' of points (*L*) in the attractor constructed from *Y*, denoted as M_Y, matches with the points in *X*'s attractor, M_X. Both manifolds, M_Y and M_X, are formed from the time-delayed coordinates of the variables *Y* and *X*, respectively[66].

Considering two time series of length l, $\{X\} = \{X(1), X(2), \ldots, X(l)\}$ and $\{Y\} = \{Y(1), Y(2), \ldots, Y(l)\}$, we created delay embedding vectors from a time series following equation (6):

$$x(t) = [X(t), X(t\text{-}\tau), X(t\text{-}2\tau), \ldots, X(t\text{-}(E\text{-}1)\tau)] \text{ for } t = 1+(E\text{-}1)\tau \text{ to } t = l \; ; \quad (6)$$

where τ is the time delay (i.e., lag), E is the embedding dimension, and t is time. These vectors form the 'reconstructed manifold' or 'shadow manifold' (M_X). To create a cross-mapped prediction of $Y(t)$, expressed as $\hat{Y}(t)|M_X$, we started by locating the corresponding lagged-coordinate vector on M_X, $x(t)$, and then identifying its E+1 nearest neighbors. We then labeled the time indices of these E+1 nearest neighbors of $x(t)$, in order from nearest to farthest, as $t_1, \ldots, t_{E+1}$ (equation(7)). These specific time indices, which were closest to $x(t)$ on M_X, were utilised to locate corresponding points (neighbors) in Y (considered a prospective neighborhood) to approximate $Y(t)$ through a locally weighted average of the E+1 values of $Y(t_i)$.

$$\hat{Y}(t) \mid M_X = \Sigma \, w_i \, Y(t_i), \quad i = 1 \ldots E+1; \quad (7)$$

where w_i is a weighting that is determined by the Euclidean distance between $x(t)$ and its i^{th} closest neighbor within M_X and $Y(t_i)$ are the concurrent values of Y. The strength of this cross-mapping and its convergence as the l increases serve as evidence of causality[66].

We applied CCM on monthly time series of Max. SSTA, NPP, SIC, and MLD from 1998 to 2021 (288 values) corresponding to each ocean grid cell. Although CCM is regarded as a non-parametric method, the selection of the τ and E parameters must indeed be conducted with care to ensure that the phase space reconstruction accurately reflects the true dynamics of the system. Therefore, in our analysis, we performed a sensitivity test via mutual information to identify the τ value that maximizes the shared information between $X(t)$ and $X(t\text{-}\tau)$, thereby indicating the most effective delay, following ref.[93]. Furthermore, we also determined the minimum embedding dimension required for the reconstructed phase space to unfold the system's dynamics (Extended Data Fig. S10). From this, we obtained an optimal τ of 3 (which is coherent with seasonal time scales) and an E = 6. To quantify the prediction skill, CCM uses the Pearson's correlation coefficient between the actual states of the system (e.g., the true values of Y) and the predicted states (using the reconstructed dynamics from X). High correlation suggested a strong causal link, where the ability to predict Y from X suggested that X has a causal influence on Y.

Given their minimal assumptions, EDM and concretely CCM, is especially robust for analysing systems that exhibit strongly non-equilibrium dynamics and nonlinear behaviour, where interactions vary over time and depend on the system's current state[66]. That is to say, these approaches are particularly suitable for studying NPP dynamics under a changing SO. […]".

Results of the new analysis of NPP responses to changing SO conditions (Fig. 4, Extended Data Figs. S6, S8, and S10) are described in L. 300-343 of the revised manuscript:

"[…] Distinctive distributions of NPP were observed when rates were averaged over the months (from November to March) under MHW conditions, and over months without MHWs from 1998 to 2021 (Fig. 4b). The average NPP rates manifested an elevation during MHWs, with a difference of approximately 100 mgC m^{-2} day^{-1} compared to the NPP in the same months where the SST remained within its climatological standards.

Additionally, the average minimum NPP increased from 1 to 74 mgC m^{-2} day^{-1} under MHW influence. These results were consistent with the relatively lower SIC (greater density at lower values) and shallower mixed-layer depths (MLD) during the MHW conditions (Figs. 4c–d). Such conditions are conducive to retaining meltwater-induced nutrients and trace elements within the euphotic layer, thus promoting phytoplankton proliferation[38]. Furthermore, causal analysis through convergent cross mapping (CCM)[66] highlighted the intricate interdependencies within the complex SO system (Figs. 4e–g). The predictive skill for NPP based on the time series of Max SSTA (NPP xmap Max SSTA; Fig. 4e) exhibited spatial heterogeneity, with high cross-map skills in subantarctic regions and the weakest skills obtained in the most dynamic areas (between ACC and the subantarctic front). However, the generally moderate skill of cross map estimates suggested that extremes of temperature alone were not the sole determinant of primary production variability. Additionally, the influence of sea ice melting on NPP could be appreciated in the southernmost subantarctic band (Fig. 4f), where moderate causal linkages emphasised the important role of ice dynamics within these areas. Nonetheless, the variable that best identified the state of NPP was the MLD, with the highest and generally homogeneous values of cross-map skills (Fig. 4g). This underscored the critical role of shallower MLDs in concentrating light and nutrients in the upper layers of the SO, facilitating the thriving of phytoplankton[60]. It is imperative to highlight that these three physical variables (Max SSTA, SIC, and MLD) were closely interlinked, with a significantly higher forcing impact of Max SSTA on SIC and a close causal bidirectional relationship between MLD and temperature extremes (Extended Data Fig. S6), as previously demonstrated by ref.[20]. […] Thus, causation is transitive (eg., if Max SSTA leads to shallower MLD –and vice versa–, and shallower MLD enhances NPP in the SO, then Max SSTA and NPP are also indirectly causally linked). Conversely, prediction skills of the reconstructions of Max SSTA, SIC, or MLD from the true values of NPP, as expected, were lower (Extended Data Fig. S8). Therefore, despite the bidirectionality in the system, results from the empirical dynamic modeling (EDM) showed the measurable non-linear causal coupling between the changing upper-layer physical conditions of the SO and the spatiotemporal dynamics of the primary producers' communities (Figs. 4e–g). […]".

Finally, we revised the two case studies by including the variable MLD and reducing the study areas to ensure consistency between them (Fig. 5). There, we illustrated how sustained high air (N-SAT) and sea (MHW) temperatures, along with associated sea ice melting and a shallower MLD, led to the occurrence of high net primary production (HNPP) events in subantarctic regions.

In response to Reviewer #1's comments, we agree that the interconnections between temperature extremes, (also sea ice reduction in the SO) and the shallowing of the mixed layer are complex and significant. As you rightly pointed out, changes in the thickness of the mixed layer have been shown to lead to MHWs, for example, through vertical advection (Amaya et al., 2021; Oliver et al., 2021). Nevertheless, it has also been evidenced that MHW events, such as those induced by atmospheric warming, naturally result in shallower mixed layer thicknesses (Oliver et al., 2021; Schlegel et al., 2021). In our study, applying CCM analysis, we have also empirically shown the close causal bidirectional linkages between MLD and temperature extremes north to the sea ice zone. Furthermore, we have also revealed that the impact of Max SSTA on SIC is significantly greater than the forcing of SIC on Max SSTA, which also existed (Extended Data Fig.

S6). This underscored the complex and interconnected dynamics of these three physical variables in the SO, as mentioned in the revised manuscript (L. 321-324, and 337-343).

"[…] It is imperative to highlight that these three physical variables (Max SSTA, SIC, and MLD) were closely interlinked, with a significantly higher forcing impact of Max SSTA on SIC and a close causal bidirectional relationship between MLD and temperature extremes (Extended Data Fig. S6), as previously demonstrated by ref.[19]. […] Thus, causation is transitive (eg., if Max SSTA leads to shallower MLD –and vice versa–, and shallower MLD enhances NPP in the SO, then Max SSTA and NPP are also indirectly causally linked). Conversely, prediction skills of the reconstructions of Max SSTA, SIC, or MLD from the true values of NPP, as expected, were lower (Extended Data Fig. S8). Therefore, despite the bidirectionality in the system, results from the empirical dynamic modeling (EDM) demonstrated the measurable nonlinear causal coupling between the changing upper-layer physical conditions of the SO and the spatio-temporal dynamics of the primary producers' communities (Figs. 4e–g). […]".

To address these complexities, our discussion of the physical processes through which MHWs alter NPP were conducted following recent studies that analysed phytoplankton responses to MHWs both globally (Noh et al., 2022; Smith et al., 2023) and regionally (Gomes et al., 2024; Hayashida et al., 2020). These studies emphasised that the stabilization of the water column, primarily through thermal stratification, plays a pivotal role in modulating nutrient availability, which is crucial for NPP. Moreover, they (Gomes et al., 2024; Smith et al., 2023) showed that MHWs alter the structure and functioning of ecosystems by modifying food webs and energy fluxes. In other words, MHWs also impact grazer communities, which ultimately modulates a significant part of the phytoplankton responses, as we discussed in L. 381-383 and 460-463:

"[…] Moreover, it is also necessary to consider that extreme temperatures affect grazer communities, such as Antarctic krill (*Euphausia superba*), which control phytoplankton biomass[69], ultimately modulating their regional responses. […]".

"[…] Many processes can be involved in the dynamic response of the extensive SO phytoplankton communities to a changing climate. Among them, species-specific responses to environmental stress, competition for resources, and trophic interactions (e.g., grazing)[69] would explain a significant part of the NPP response in the SO. […]".

Focusing on the SO, significant work has been done on the dynamic shifts in phytoplankton communities as a consequence of water column stabilization (Noh et al., 2021; Oh et al., 2022; Thomalla et al., 2023). Additionally, the major role of meltwater in driving macro- and micronutrients to the surface layer has also been documented (Bronselaer et al., 2020; Deppeler & Davidson, 2017; Pinkerton et al., 2021), enhancing our understanding of nutrient dynamics in the SO. Notably, the most recent review article on the role of phytoplankton in the SO's carbon cycle underscored the unexpectedly high carbon export flux, despite the iron limitation commonly observed in this region (Boyd et al., 2024). This article pointed out the significant role of iron contributions from sea ice melting in driving magnified ice-edge phytoplankton blooms. Moreover, Noh et al. (2022) examined the responses of chlorophyll to MHWs on a global scale, observing positive responses at high latitudes in the 40-50ºS band. They demonstrated that the latitudinal change in the responses from negative to positive was closely related to the latitudinal contrast of the climatological nitrate concentrations. Furthermore, they

highlighted the distinctive positive responses in the warm season, as a consequence of shallower mixed layers.
All of this led us to formulate the hypothesis that the increasing activity of MHWs is stimulating NPP rates south of 40ºS. It is challenging to provide a singular detailed biogeochemical response of SO phytoplankton communities to MHW events. Among other reasons, this is because the vast SO harbours different phytoplankton functional types (PFT), and each group responds differently to the various limiting factors, as discussed in L. 366-375:

"[…] It should be, however, pointed out here that predicting a single response of phytoplankton to extreme temperature conditions in the SO is challenging. There are many different phytoplankton groups in the Antarctic waters, each responding differently to environmental changes[16,60,67]. Additionally, due to its vast expanse, ocean physics are not uniform everywhere in the SO (as seen in Figs. 1–3). Therefore, an interesting asymmetry was observed not only meridionally but also zonally in the response of primary producers to temperature extremes (Figs. 4a and 4e). As previously suggested by ref.[49], this zonal asymmetry around the higher subantarctic region was closely linked to the variability of the limiting factors for phytoplankton growth in each area, where both sea-ice melting and ocean surface warming played a critical role in stabilizing and transporting micronutrients to the surface layer. […]".

In this context, as mentioned in L. 473-474, "[…] Future analyses based on SO MHW–induced plankton phenology changes would be required to properly assess the impacts of these extreme events over particular PFTs. […]".

However, in our study, we have empirically evidenced nonlinear causal relationships between the changing physical conditions of the SO's upper layer and the spatio-temporal dynamics of primary producers' communities (Figs. 4 and 5). These findings are crucial because they suggest that climate change-related impacts, with MHWs being an important component, are significantly altering the partitioning of basin-scale NPP in the SO, which is critical for grasping key processes in the SO carbon cycle.

Minor comments:
Reviewer #1: 1. L35: "but also to" => "but also on"

Response: Done (L. 34).

Reviewer #1: 2. L93: "standardized definition" => "conventional definition"

Response: Changed (L. 90).

Reviewer #1: 3. L141: "a manifest MHW hotspot" seems an awkward expression.

Response: The authors apologise for any confusion that this expression may have caused and replace it (L. 138-139):

"[…] was also identified as a pronounced MHW area. […]".

Reviewer #1: 4. L150, L370 and L504: The format of references in these sentences are different from others in the manuscript.

Response: We thank Reviewer #1 for this observation and have accordingly modified these citations (L. 147, 372, and 537).

Reviewer #1: 5. L161: “notably” => “evident”

Response: Done (L. 158).

Reviewer #1: 6. Figure 3a: By construction, the average of SSTA during 1982–2015 should be the same as average during 2013–2015, since the climatology is defined based on 1982–2012.

Response: We apologise for any confusion that this figure may have caused and are grateful for the valuable insights provided by Reviewer #1. In the revised Fig. 3 of local physical drivers of SO MHWs, we have included only the SSTA averaged for the period 2009-2015 (seven years prior to the abrupt decline in sea ice) and for the period 2015-2021 (seven years thereafter) (Figs. 3l-m). (L. 261).

Reviewer #1: 7. The stippling in Figures 5a–d is not discernible. Please revise the figure to enhance readability.

Response: Once again, we apologise for any confusion caused. We have replaced previous Fig. 5 with our new Fig. 4, because “correlation does not necessarily imply causation”. In this context, we then investigated causal relationships between physical variables and NPP through Empirical Dynamical Modelling (EDM). Specifically, we applied Convergent Cross Mapping (CCM; Sugihara et al., 2012) to detect nonlinear causal interactions between these variables (Figs. 4e-g).

References

Amaya, D.J., Alexander, M.A., Capotondi, A., Deser, C., Karnauskas, K.B., Miller, A.J., Mantua, N.J., 2021. Are Long-Term Changes in Mixed Layer Depth Influencing North Pacific Marine Heatwaves? Bulletin of the American Meteorological Society 102, S59–S66. https://doi.org/10.1175/BAMS-D-20-0144.1

Boyd, P.W., Arrigo, K.R., Ardyna, M., Halfter, S., Huckstadt, L., Kuhn, A.M., Lannuzel, D., Neukermans, G., Novaglio, C., Shadwick, E.H., Swart, S., Thomalla, S.J., 2024. The role of biota in the Southern Ocean carbon cycle. Nat Rev Earth Environ. https://doi.org/10.1038/s43017-024-00531-3

Bronselaer, B., Russell, J.L., Winton, M., Williams, N.L., Key, R.M., Dunne, J.P., Feely, R.A., Johnson, K.S., Sarmiento, J.L., 2020. Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean. Nat. Geosci. 13, 35–42. https://doi.org/10.1038/s41561-019-0502-8

Deppeler, S.L., Davidson, A.T., 2017. Southern Ocean Phytoplankton in a Changing Climate. Front. Mar. Sci. 4. https://doi.org/10.3389/fmars.2017.00040

Gomes, D.G.E., Ruzicka, J.J., Crozier, L.G., Huff, D.D., Brodeur, R.D., Stewart, J.D., 2024. Marine heatwaves disrupt ecosystem structure and function via altered food

webs and energy flux. Nat Commun 15, 1988. https://doi.org/10.1038/s41467-024-46263-2
Griffies, S.M., 2015. Working notes on the ocean heat budget in GFDL-ESM2M. https://mom-ocean.github.io/assets/pdfs/ESM2M_heat_budget.pdf [Accessed February 8, 2024].
Hayashida, H., Matear, R.J., Strutton, P.G., 2020. Background nutrient concentration determines phytoplankton bloom response to marine heatwaves. Glob Change Biol 26, 4800–4811. https://doi.org/10.1111/gcb.15255
Noh, K.M., Lim, H.-G., Kug, J.-S., 2022. Global chlorophyll responses to marine heatwaves in satellite ocean color. Environ. Res. Lett. 17, 064034. https://doi.org/10.1088/1748-9326/ac70ec
Noh, K.M., Lim, H.-G., Kug, J.-S., 2021. Zonally asymmetric phytoplankton response to the Southern annular mode in the marginal sea of the Southern ocean. Sci Rep 11, 10266. https://doi.org/10.1038/s41598-021-89720-4
Oh, J.-H., Noh, K.M., Lim, H.-G., Jin, E.K., Jun, S.-Y., Kug, J.-S., 2022. Antarctic meltwater-induced dynamical changes in phytoplankton in the Southern Ocean. Environ. Res. Lett. 17, 024022. https://doi.org/10.1088/1748-9326/ac444e
Oliver, E.C.J., Benthuysen, J.A., Darmaraki, S., Donat, M.G., Hobday, A.J., Holbrook, N.J., Schlegel, R.W., Sen Gupta, A., 2021. Marine Heatwaves. Annu. Rev. Mar. Sci. 13, 313–342. https://doi.org/10.1146/annurev-marine-032720-095144
Pinkerton, M.H., Boyd, P.W., Deppeler, S., Hayward, A., Höfer, J., Moreau, S., 2021. Evidence for the Impact of Climate Change on Primary Producers in the Southern Ocean. Front. Ecol. Evol. 9, 592027. https://doi.org/10.3389/fevo.2021.592027
Schlegel, R.W., Oliver, E.C.J., Chen, K., 2021. Drivers of Marine Heatwaves in the Northwest Atlantic: The Role of Air–Sea Interaction During Onset and Decline. Front. Mar. Sci. 8, 627970. https://doi.org/10.3389/fmars.2021.627970
Smith, K.E., Burrows, M.T., Hobday, A.J., King, N.G., Moore, P.J., Sen Gupta, A., Thomsen, M.S., Wernberg, T., Smale, D.A., 2023. Biological Impacts of Marine Heatwaves. Annu. Rev. Mar. Sci. 15, 119–145. https://doi.org/10.1146/annurev-marine-032122-121437
Sugihara, G., May, R., Ye, H., Hsieh, C., Deyle, E., Fogarty, M., Munch, S., 2012. Detecting Causality in Complex Ecosystems. Science 338, 496–500. https://doi.org/10.1126/science.1227079
Thomalla, S.J., Nicholson, S.-A., Ryan-Keogh, T.J., Smith, M.E., 2023. Widespread changes in Southern Ocean phytoplankton blooms linked to climate drivers. Nat. Clim. Chang. 13, 975–984. https://doi.org/10.1038/s41558-023-01768-4

Reviewer #2

Major comments

Reviewer #2: Drivers of Southern Ocean marine heatwave trends

In the section Potential drivers behind the SO MHWs the authors include a detailed discussion of the literature, but barely a single new result. New information is limited to a single figure, showing regional and seasonal trends. The link between sea-ice concentration and temperatures in regions so far from the sea-ice zone is speculative (at best) and after reading the section, I can't say that I've learned much above Southern Ocean marine heatwaves.

I feel that this discussion requires a lot more detail. For instance, what is the role played by fronts and eddies (if any)? How about changing winds? Heat bugets and/or water mass analysis could tackle these questions, but the analysis is missing to support it.

Response: First of all, we would like to thank the Anonymous Reviewer #2 for their continued engagement and detailed feedbacks on our manuscript. We are particularly grateful for their insights highlighting the complexity and interconnectivity of the topics we have considered to address. Their comments have been instrumental in guiding our revisions, prompting us to thoroughly reconsider the focus and structure of our paper.
In response to their valuable suggestions, we have reassessed and strengthen the foundational aspects of our research. We have now provided a clearer and more detailed exploration of the core questions that Reviewer #2 proposed. These approaches have allowed us to better address the local physical drivers of Southern Ocean (SO) marine heatwaves (MHWs), and then to more clearly examine the response of net primary production (NPP) to a changing upper-layer physical conditions in the SO, with the depth and precision required to achieve the objectives of our work.
We have thoroughly revised our manuscript. To better analyse the local physical drivers of MHWs in the SO, we have examined heat term budgets available in the Modular Ocean Model (MOM4p1; Griffies, 2015), following your guidance. We also followed the methodologies of Burger et al. (2022) and Vogt et al. (2022). It has been detailed in the Methods section (L. 640-698) of the revised manuscript:

"[…] **Analysis of local drivers of marine heatwaves in the Southern Ocean**
To assess the local physical drivers of MHWs, we made use of a global, fully coupled carbon-climate Earth System Model (ESM) developed at the National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory (GFDL)[86]. The GFDL ESM2M couples an oceanic circulation model (MOM4p1) to an atmospheric circulation model (AM2), and incorporates a land model (LM3.0), representations of sea ice and iceberg dynamics, as well as interactions within biogeochemical cycles. Specifically, we used temperature tendency heat budgets available in MOM4p1[51] (https://github.com/mom-ocean/MOM4p1). This ocean model uses a tripolar horizontal grid of 1°x1°, increasing meridionally to up to 1/3° towards the Equator, and with 50 depth levels. We analysed daily-mean outputs of all tendency terms that change the SST (over the upper 10 m) from a 500-yr preindustrial control simulation (with atmospheric CO_2, along with all other agents that influence radiation fixed at their preindustrial levels) and confirmed with an eight-member ensemble simulation of the

GFDL ESM2M driven by historical data and the Representative Concentration Pathway 8.5 (RCP8.5) scenario from 1982 to 2021, following ref.[52,87].

For each grid cell, the model dissects the total heat change (ΔQ_{total}) across time intervals into various heat budget components. These components signify temperature changes due to distinct processes modeled. The total tendency of heat at the ocean surface, in W m^{-2}, is determined by equation(4)[51]:

$$\Delta Q_{total} = \Delta Q_{adv} + \Delta Q_{a\text{-}s} + \Delta Q_{vmix} + \Delta Q_{vdiff} + \Delta Q_{res}; \tag{4}$$

where ΔQ_{adv} represent the change in heat resulting from both horizontal and vertical advective heat fluxes, both explicitly resolved and approximated on subgrid scales through parameterization. $\Delta Q_{a\text{-}s}$ is the air-sea exchange of heat, including the balance of shortwave radiation (the net incoming surface shortwave radiation reduced by the fraction of shortwave radiation that goes beyond the surface layer) along with the net incoming longwave radiation, in addition to the net fluxes of latent and sensible heat[86]. ΔQ_{vmix} refers to the heat flux generated by the non-local segment of the K-profile parameterization (KPP)[51], representing convective vertical mixing within the ocean boundary layer in response to negative buoyancy forcing. ΔQ_{vdiff} accounts for heat fluxes caused by vertical diffusion, encompassing vertical mixing within the ocean boundary layer attributed to the local component of the KPP, as well as tidal mixing. Furthermore, the residual term (ΔQ_{res}) includes other smaller processes such as heat exchange due to river runoff, solid runoff from iceberg calving, neutral diffusion, or the heat flux exchange resulting from interactions of surface water masses due to precipitation and evaporation. A detailed description of each term can be found in Extended Data equations(S2–6) and in ref.[51].

We then computed anomalies of all these heat budget terms relative to their seasonal cycles for each ocean grid cell, to ultimately average them separately over the days of the onset (build-up of heat) and decay (dissipation of heat) phases of the MHWs (see Extended Data Fig. S1). Moreover, based on the change in heat content, the change in potential temperature ($\Delta\theta$), in ºC d^{-1}, can be approximated using equation(5)[51]:

$$\Delta\theta = \frac{\Delta Q_{\text{total}}}{C_p^0 \rho_0 dz}, \tag{5}$$

where C_p^0 is a fixed value for heat capacity, set at 3992.1 J kg^{-1} K^{-1} in MOM4p1; ρ_0 is the constant Boussinesq density of 1.035 kg m^{-3}, and dz is the changing thickness of vertical grid cells over time, measured in m, as described by ref.[51]. In our analysis, we assumed a thickness of dz = 10m, which led to a conversion factor of 0.00209 ºC m^2 s^{-1} W^{-1}. This inference is justified because the real fluctuations in the thickness of grid cells differ minimally (with the largest changes being around $1\cdot10^{-2}$ in the open ocean), resulting in negligible adjustments to the conversion factor. Despite the fact that these errors can accumulate over time, for time scales of MHW durations (days to few months), these are significantly reduced, as demonstrated by ref.[52].

The motivation for using the GFDL ESM2M (MOM4p1) model for the assessment of local physical drivers of MHWs in the Southern Ocean was due to the good agreement between the climatological characteristics and the trends of modelled and observation-based MHWs globally[26,52,87], as a result of the model's fidelity in simulating the mean state and interannual variations in SST. Moreover, in the SO outside the sea ice area, the model fits good with observational data[26,52]. […]".

The results are presented in the new Fig. 3 and Extended Data Fig. S5. Additionally, the discussion of our findings can be found on L. 194-229 of the revised version of the manuscript:

"[…] Local physical drivers of MHWs over the SO were assessed by examining heat term budgets available in the Modular Ocean Model (MOM4p1)[51] (Figs. 3a–i). Additionally, the correlation between MHWs and several essential climate variables from 1982 to 2021 was also explored (Figs. 3j–m and Extended Data Table S3). The annual mean heat flux anomalies in the surface ocean layer averaged during the MHW onset (i.e., build-up of heat) and decay (i.e., dissipation of heat) phases (Extended Data Fig. S1) are listed in Extended Data Fig. S5. Results from the heat budget analysis showed that temperature changes during MHWs were mainly explained by four most important counteracting processes (Figs. 3a–i). While ocean advection, sea-air heat fluxes, and vertical diffusion positively contributed to the formation of MHWs in the SO, as well as to the subsequent heat loss, convective vertical mixing (from the non-local part, see Methods) inherently acted in a contrasting mode. This arises from the intrinsic characteristics of this non-local term, which was incorporated in the MOM4p1 to mitigate air-sea heat fluxes when faced with negative buoyancy forcing conditions[51]. During the onset phase of MHWs, the averaged circumpolar surface ocean heat gain reported in the preindustrial control simulation was 20 W m^{-2}, with air-sea heat fluxes being the dominant MHW driver (Extended Data Fig. S5a). Nevertheless, in the eight-member ensemble simulation for the 1982–2021 period, the circumpolar heat gain during the onset phase amounted to 39.8 W m^{-2}. This was explained by the increased contribution of vertical diffusion (26 W m^{-2} or 65.2 %; Extended Data Fig. S5b and Fig. 3g). Despite the major role of the surface heat fluxes (Figs. 3c–d), which was especially important in the Atlantic sector, vertical diffusion emerged as the dominant process both in driving MHWs in the SO and as an overarching cooling contributor to their decline (Figs. 3g–h). This was particularly relevant across much of the areas connecting the sea ice zone (defined by averaged SIC > 20%; Extended Data Fig. S2) and the southernmost subantarctic belt along the Atlantic and Indian sectors. This finding highlighted the significant feedback between sea ice variability and surface ocean temperature extremes in these regions (as also demonstrated in Extended Data Figs. S6a–b). Horizontal advective heat fluxes followed the ACC pathways, though they appeared to play a secondary role, affecting the development of MHWs in the SO only locally (Figs. 3a–b). However, it is important to note that the MOM4p1 model may underestimate the impact of advection, as its relatively low horizontal resolution cannot resolve mesoscale processes[51]. Furthermore, the contribution of drivers did not necessarily depend on the strength of the MHWs (as measured by the cumulative intensity) in the SO (Fig. 3i), and various combinations of driving mechanisms were possible; being consistent with ref.[52]. That is to say, the strongest and weakest MHW events were primarily driven by the same leading processes –positive ocean heat uptake anomalies and vertical diffusion– and were dampened by convective vertical mixing during their onset phases. While both air-sea heat fluxes and vertical diffusive processes led to the dissipation of heat, advection and contrasting vertical mixing played minor roles during the decay phases (Fig. 3i). […]".

Reviewer #2: Linking Marine Heatwaves to changes in primary productivity

In section Changing Temporal Trends of Biogeochemistry and Marine Producitivity, the authors attempt to link marine heatwave trends with estimates of marine productivity from the CbPM. I believe that the analysis in the section does not support the authors' conclusions.

As I mentioned in a previous review of this manuscript, marine heatwaves are distinct "events" with a beginning, peak, and an end. The standard statistics of these events, such as mean intensity or duration, when using a fixed "baseline" period, almost guaranteed to show strong temporal trends as the global warming signal comes to dominate natural variability. As such, it is very difficult, if not impossible, to disentangle long term trends in temperatures from long term trends in marine heatwave metrics.

As such, I struggle to place much faith in the analysis presented in (for example) Fig. 5, where the authors correlate spatially averaged marine heatwave metrics with NPP, I would argue that it's impossible to know if these correlations are not simply driven by the background warming signal, particularly when some of the highest trends in NPP are found in regions with the largest post-2015 temperature trends. The authors make no attempt to control for the background global warming signature. Other than two relatively brief case studies, there is no real attempt to look into "events" as they occur.

Response: The authors would like to once again express our gratitude for the constructive comments provided by Reviewer #2. These comments clearly demonstrate a keen interest in the subject matter and a desire to contribute to the literature on this topic.
First, we fully concur with the difficulty of distinguishing long-term warming from climate variability (trends in MHW metrics) using a fixed baseline period. Consequently, throughout the manuscript, we discussed that the increasing activity of MHWs was associated with global warming, which in turn increased the probability of SST surpassing the MHW threshold. Additionally, we agree with Reviewer #2 that the previous Fig. 5 did not support the main hypotheses posited in our work. The positive annual correlations could have been due to simple long-term warming. Furthermore, we acknowledge that correlation does not necessarily imply causation. Consequently, we have reassessed and strengthened the analysis (revised Fig. 4). We averaged the distributions of NPP, Sea Ice Concentration (SIC), and Mixed Layer Depth (MLD) over the months (from November to March, owing to methodological reasons in applying the long-term mean summer temperature) with and without MHWs (Figs. 4b-d), to more clearly illustrate the changes in the SO surface layer during MHW events. The changes are readily apparent, even considering the conservative nature of the violin plots. Furthermore, we applied Empirical Dynamic Modelling (EDM) through Convergent Cross Mapping (CCM; Sugihara et al., 2012) to reveal the nonlinear causal relationships between changes induced in the SO surface layer (Max SSTA, SIC, and MLD) and dynamical alterations in NPP. This cutting-edge analysis showed the predictive capacity of changes in the SO surface layer for NPP dynamics (Figs. 4e-f). Specifically, it allowed to analyse the spatio-temporal influence of different physical variables (Max SSTA, SIC, and MLD) on the dynamic changes in phytoplankton communities. For instance, through CCM, we empirically evidenced the extent of the influence that sea ice melting exerts on NPP in the open waters of the SO (Fig. 4f). The discussion of the obtained results is presented on L. 300-343 of the revised manuscript:

"[…] Distinctive distributions of NPP were observed when rates were averaged over the months (from November to March) under MHW conditions, and over months without MHWs from 1998 to 2021 (Fig. 4b). The average NPP rates manifested an elevation during MHWs, with a difference of approximately 100 mgC m^{-2} day^{-1} compared to the

NPP in the same months where the SST remained within its climatological standards. Additionally, the average minimum NPP increased from 1 to 74 mgC m^{-2} day^{-1} under MHW influence. These results were consistent with the relatively lower SIC (greater density at lower values) and shallower mixed-layer depths (MLD) during the MHW conditions (Figs. 4c–d). Such conditions are conducive to retaining meltwater-induced nutrients and trace elements within the euphotic layer, thus promoting phytoplankton proliferation[38]. Furthermore, causal analysis through convergent cross mapping (CCM)[65] highlighted the intricate interdependencies within the complex SO system (Figs. 4e–g). The predictive skill for NPP based on the time series of Max SSTA (NPP xmap Max SSTA; Fig. 4e) exhibited spatial heterogeneity, with high cross-map skills in subantarctic regions and the weakest skills obtained in the most dynamic areas (between ACC and the subantarctic front). However, the generally moderate skill of cross map estimates suggested that extremes of temperature alone were not the sole determinant of primary production variability. Additionally, the influence of sea ice melting on NPP could be appreciated in the southernmost subantarctic band (Fig. 4f), where moderate causal linkages emphasised the important role of ice dynamics within these areas. Nonetheless, the variable that best identified the state of NPP was the MLD, with the highest and generally homogeneous values of cross-map skills (Fig. 4g). This underscored the critical role of shallower MLDs in concentrating light and nutrients in the upper layers of the SO, facilitating the thriving of phytoplankton[60]. It is imperative to highlight that these three physical variables (Max SSTA, SIC, and MLD) were closely interlinked, with a significantly higher forcing impact of Max SSTA on SIC and a close causal bidirectional relationship between MLD and temperature extremes (Extended Data Fig. S6), as previously demonstrated by ref.[19]. […] Thus, causation is transitive (eg., if Max SSTA leads to shallower MLD –and vice versa–, and shallower MLD enhances NPP in the SO, then Max SSTA and NPP are also indirectly causally linked). Conversely, prediction skills of the reconstructions of Max SSTA, SIC, or MLD from the true values of NPP, as expected, were lower (Extended Data Fig. S8). Therefore, despite the bidirectionality in the system, results from the empirical dynamic modeling (EDM) showed the measurable nonlinear causal coupling between the changing upper-layer physical conditions of the SO and the spatiotemporal dynamics of the primary producers' communities (Figs. 4e–g). […]".

The methodology applied for causal inference through EDM is described in the Methods section (L. 718-777):

"[…]**Causal interactions through empirical dynamic modeling**
In an effort to investigate the causal interactions among the key variables in our study (Max. SSTA, NPP, SIC, and MLD), we applied Empirical Dynamic Modeling (EDM). This cutting-edge framework is based on Takens' theorem, which provides tools for attractor reconstruction[92] and allows for the modeling of causal relationships in nonlinear dynamic systems in the absence of governing dynamic equations[66]. In dynamical systems, two state variables *X* and *Y* are considered to be causally linked if they contain shared information that allows reconstructing the observed dynamics from one state variable, say X, from the dynamics of the other variable, Y. This shared information can allow for a unidirectional reconstruction (e.g., X causes Y), or a bidirectional reconstruction (both variables cause each other) of the dynamics[66]. In essence, Takens' theorem shows that the dynamics of a state variable Y caused by another variable X is encoded in the delayed-coordinates embedding[66] of the causing variable, X in this case. This is provided by the so-called attractor manifold *M* which, in the absence of a governing dynamics equation,

contains all the information needed to encode the dynamic system: it is the region of the state space that contains all the possible states of the system in the long-term. The essential assumption of EDM is that causality within a dynamic system is more strongly dependent on the proximity of the values of the variables in the state space that in their proximity in time[66,92]. In our analysis, we applied Convergent Cross Mapping (CCM), introduced by ref.[66], to perform the nonlinear state space reconstruction. CCM assesses causality by evaluating how accurately the historical data of *Y* can predict the state of *X*, or viceversa. This prediction is feasible only if *X* has a causal impact on *Y*. To delve deeper, CCM seeks evidence of *X*'s influence within *Y*'s time series by examining if the 'library' of points (*L*) in the attractor constructed from *Y*, denoted as M_Y, matches with the points in *X*'s attractor, M_X. Both manifolds, M_Y and M_X, are formed from the time-delayed coordinates of the variables *Y* and *X*, respectively[66].

Considering two time series of length l, $\{X\} = \{X(1), X(2), \ldots, X(l)\}$ and $\{Y\} = \{Y(1), Y(2), \ldots, Y(l)\}$, we created delay embedding vectors from a time series following equation (6):

$$x(t) = [X(t), X(t\text{-}\tau), X(t\text{-}2\tau), \ldots, X(t\text{-}(E\text{-}1)\tau)] \text{ for } t = 1+(E\text{-}1)\tau \text{ to } t = l \; ; \quad (6)$$

where τ is the time delay (i.e., lag), E is the embedding dimension, and t is time. These vectors form the 'reconstructed manifold' or 'shadow manifold' (M_X). To create a cross-mapped prediction of $Y(t)$, expressed as $\hat{Y}(t)|M_X$, we started by locating the corresponding lagged-coordinate vector on M_X, $x(t)$, and then identifying its E+1 nearest neighbors. We then labeled the time indices of these E+1 nearest neighbors of $x(t)$, in order from nearest to farthest, as $t_1, \ldots, t_{E+1}$ (equation(7)). These specific time indices, which were closest to $x(t)$ on M_X, were utilised to locate corresponding points (neighbors) in *Y* (considered a prospective neighborhood) to approximate $Y(t)$ through a locally weighted average of the E+1 values of $Y(t_i)$.

$$\hat{Y}(t) \mid M_X = \Sigma\, w_i\, Y(t_i), \quad i = 1 \ldots E+1; \quad (7)$$

where w_i is a weighting that is determined by the Euclidean distance between $x(t)$ and its i^{th} closest neighbor within M_X and $Y(t_i)$ are the concurrent values of *Y*. The strength of this cross-mapping and its convergence as the l increases serve as evidence of causality[66].

We applied CCM on monthly time series of Max. SSTA, NPP, SIC, and MLD from 1998 to 2021 (288 values) corresponding to each ocean grid cell. Although CCM is regarded as a non-parametric method, the selection of the τ and E parameters must indeed be conducted with care to ensure that the phase space reconstruction accurately reflects the true dynamics of the system. Therefore, in our analysis, we performed a sensitivity test via mutual information to identify the τ value that maximizes the shared information between $X(t)$ and $X(t\text{-}\ \tau)$, thereby indicating the most effective delay, following ref.[93]. Furthermore, we also determined the minimum embedding dimension required for the reconstructed phase space to unfold the system's dynamics (Extended Data Fig. S10). From this, we obtained an optimal τ of 3 (which is coherent with seasonal time scales) and an E = 6. To quantify the prediction skill, CCM uses the Pearson's correlation coefficient between the actual states of the system (e.g., the true values of *Y*) and the predicted states (using the reconstructed dynamics from *X*). High correlation suggested a strong causal link, where the ability to predict *Y* from *X* suggested that *X* has a causal influence on *Y*.

Given their minimal assumptions, EDM and concretely CCM, is especially robust for analysing systems that exhibit strongly non-equilibrium dynamics and nonlinear behaviour, where interactions vary over time and depend on the system's current state[66]. That is to say, these approaches are particularly suitable for studying NPP dynamics under a changing SO. […]".

In our study, applying CCM analysis, we have also evidenced the close causal bidirectional linkages between MLD and temperature extremes north to the sea ice zone. Furthermore, we have also shown that the impact of Max SSTA on SIC is significantly greater than the forcing of SIC on Max SSTA, which also exists (Extended Data Fig. S6). This underscored the complex and interconnected dynamics of these three physical variables in the SO (L. 321-343).

"[…] It is imperative to highlight that these three physical variables (Max SSTA, SIC, and MLD) were closely interlinked, with a significantly higher forcing impact of Max SSTA on SIC and a close causal bidirectional relationship between MLD and temperature extremes (Extended Data Fig. S6), as previously demonstrated by ref.[20]. […] Thus, causation is transitive (eg., if Max SSTA leads to shallower MLD –and vice versa–, and shallower MLD enhances NPP in the SO, then Max SSTA and NPP are also indirectly causally linked). Conversely, prediction skills of the reconstructions of Max SSTA, SIC, or MLD from the true values of NPP, as expected, were lower (Extended Data Fig. S8). Therefore, despite the bidirectionality in the system, results from the empirical dynamic modeling (EDM) showed the measurable non-linear causal coupling between the changing upper-layer physical conditions of the SO and the spatiotemporal dynamics of the primary producers' communities (Figs. 4e–g). […]".

Significant work has been conducted on the dynamic shifts in SO phytoplankton communities as a consequence of water column stabilization (Noh et al., 2021; Oh et al., 2022; Thomalla et al., 2023). Additionally, the major role of meltwater in driving macro- and micronutrients to the surface layer has also been documented (Bronselaer et al., 2020; Deppeler & Davidson, 2017; Pinkerton et al., 2021), enhancing our understanding of nutrient dynamics in the SO. Notably, the most recent review article on the role of phytoplankton in the SO's carbon cycle underscored the unexpectedly high carbon export flux, despite the iron limitation commonly observed in this region (Boyd et al., 2024). This article pointed out the significant role of iron contributions from sea ice melting in driving magnified ice-edge phytoplankton blooms. Moreover, Noh et al. (2022) examined the responses of chlorophyll to MHWs on a global scale, observing positive responses at high latitudes in the 40-50ºS band. They demonstrated that the latitudinal change in the responses from negative to positive was closely related to the latitudinal contrast of the climatological nitrate concentrations. Furthermore, they highlighted the distinctive positive responses in the warm season, as a consequence of shallower mixed layers.
All of this led us to formulate the hypothesis that the increasing activity of MHWs is stimulating NPP rates south of 40ºS. It is challenging to provide a singular detailed biogeochemical response of SO phytoplankton communities to MHW events. Among other reasons, this is because the vast SO harbours different phytoplankton functional types (PFT), and each group responds differently to the various limiting factors, as discussed in L. 366-375:

"[…] It should be, however, pointed out here that predicting a single response of phytoplankton to extreme temperature conditions in the SO is challenging. There are many different phytoplankton groups in the Antarctic waters, each responding differently to environmental changes[16,60,67]. Additionally, due to its vast expanse, ocean physics are not uniform everywhere in the SO (as seen in Figs. 1–3). Therefore, an interesting asymmetry was observed not only meridionally but also zonally in the response of primary producers to temperature extremes (Figs. 4a and 4e). As previously suggested by ref.[49], this zonal asymmetry around the higher subantarctic region was closely linked to the variability of the limiting factors for phytoplankton growth in each area, where both sea-ice melting and ocean surface warming played a critical role in stabilizing and transporting micronutrients to the surface layer. […]".

In this context, as mentioned in L. 473-474, "[…] Future analyses based on SO MHW–induced plankton phenology changes would be required to properly assess the impacts of these extreme events over particular PFTs. […]".

However, in our study, we have empirically evidenced nonlinear causal relationships between the changing physical conditions of the SO's upper layer and the spatio-temporal dynamics of primary producers' communities (Figs. 4 and 5). These findings are crucial because they suggest that climate change-related impacts, with MHWs being an important component, are significantly altering the partitioning of basin-scale NPP in the SO, which is critical for grasping key processes in the SO carbon cycle.

Minor comment

Reviewer #2: Figure 6: This figure would be much, much clearer if the results were plotted as anomalies with respect to the seasonal climatology.

Response: The authors concur with Reviewer #2 that the case studies would be clearer if the events of MHW and HNPP were plotted as anomalies. However, to maintain consistency with the methodology applied in our work, which was based on the conventional definition of MHWs (Hobday et al., 2016; Holbrook et al., 2020; Oliver et al., 2021), the case studies of compound MHW and HNPP events were represented as intensities, that is, relative to the seasonally varying threshold (95^{th} percentile).
We revised the two case studies by including the variable MLD and reducing the study areas to ensure consistency between them. We then illustrated how sustained high air (N-SAT) and sea (MHW) temperatures, along with associated sea ice melting and a shallower MLD, led to the occurrence of high net primary production (HNPP) events in subantarctic regions (Fig. 5).

References

Boyd, P.W., Arrigo, K.R., Ardyna, M., Halfter, S., Huckstadt, L., Kuhn, A.M., Lannuzel, D., Neukermans, G., Novaglio, C., Shadwick, E.H., Swart, S., Thomalla, S.J., 2024. The role of biota in the Southern Ocean carbon cycle. Nat Rev Earth Environ. https://doi.org/10.1038/s43017-024-00531-3

Bronselaer, B., Russell, J.L., Winton, M., Williams, N.L., Key, R.M., Dunne, J.P., Feely, R.A., Johnson, K.S., Sarmiento, J.L., 2020. Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean. Nat. Geosci. 13, 35–42. https://doi.org/10.1038/s41561-019-0502-8

Burger, F.A., Terhaar, J., Frölicher, T.L., 2022. Compound marine heatwaves and ocean acidity extremes. Nat Commun 13, 4722. https://doi.org/10.1038/s41467-022-32120-7

Deppeler, S.L., Davidson, A.T., 2017. Southern Ocean Phytoplankton in a Changing Climate. Front. Mar. Sci. 4. https://doi.org/10.3389/fmars.2017.00040

Griffies, S.M., 2015. Working notes on the ocean heat budget in GFDL-ESM2M. https://mom-ocean.github.io/assets/pdfs/ESM2M_heat_budget.pdf [Accessed February 8, 2024].

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M., Holbrook, N.J., Moore, P.J., Scannell, H.A., Sen Gupta, A., Wernberg, T., 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography 141, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

Holbrook, N.J., Sen Gupta, A., Oliver, E.C.J., Hobday, A.J., Benthuysen, J.A., Scannell, H.A., Smale, D.A., Wernberg, T., 2020. Keeping pace with marine heatwaves. Nat Rev Earth Environ 1, 482–493. https://doi.org/10.1038/s43017-020-0068-4

Noh, K.M., Lim, H.-G., Kug, J.-S., 2022. Global chlorophyll responses to marine heatwaves in satellite ocean color. Environ. Res. Lett. 17, 064034. https://doi.org/10.1088/1748-9326/ac70ec

Noh, K.M., Lim, H.-G., Kug, J.-S., 2021. Zonally asymmetric phytoplankton response to the Southern annular mode in the marginal sea of the Southern ocean. Sci Rep 11, 10266. https://doi.org/10.1038/s41598-021-89720-4

Oh, J.-H., Noh, K.M., Lim, H.-G., Jin, E.K., Jun, S.-Y., Kug, J.-S., 2022. Antarctic meltwater-induced dynamical changes in phytoplankton in the Southern Ocean. Environ. Res. Lett. 17, 024022. https://doi.org/10.1088/1748-9326/ac444e

Oliver, E.C.J., Benthuysen, J.A., Darmaraki, S., Donat, M.G., Hobday, A.J., Holbrook, N.J., Schlegel, R.W., Sen Gupta, A., 2021. Marine Heatwaves. Annu. Rev. Mar. Sci. 13, 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

Pinkerton, M.H., Boyd, P.W., Deppeler, S., Hayward, A., Höfer, J., Moreau, S., 2021. Evidence for the Impact of Climate Change on Primary Producers in the Southern Ocean. Front. Ecol. Evol. 9, 592027. https://doi.org/10.3389/fevo.2021.592027

Sugihara, G., May, R., Ye, H., Hsieh, C., Deyle, E., Fogarty, M., Munch, S., 2012. Detecting Causality in Complex Ecosystems. Science 338, 496–500. https://doi.org/10.1126/science.1227079

Thomalla, S.J., Nicholson, S.-A., Ryan-Keogh, T.J., Smith, M.E., 2023. Widespread changes in Southern Ocean phytoplankton blooms linked to climate drivers. Nat. Clim. Chang. 13, 975–984. https://doi.org/10.1038/s41558-023-01768-4

Vogt, L., Burger, F.A., Griffies, S.M., Frölicher, T.L., 2022. Local Drivers of Marine Heatwaves: A Global Analysis With an Earth System Model. Front. Clim. 4, 847995. https://doi.org/10.3389/fclim.2022.847995

Reviewer #3

General comment:
Reviewer #3: This marine heatwave (MHW) study focuses on the Southern Ocean and is therefore a valuable addition to previous MHW studies conducted at the global scale or over other ocean basins. The distribution and evolution of Southern Ocean MHWs are characterized over the satellite period, using commonly defined MHW metrics. You show increasing MHW activity over the satellite period, which has been described and related to climate change by previous MHW studies (e.g., Oliver et al. 2018). You further relate the rise in MHW activity to the sudden sea-ice loss in 2015, which was associated with increased radiative surface warming. The study then investigates the link between Southern Ocean marine heatwaves and changes in primary productivity. You use the CbPM NPP product, which is highly uncertain in the Southern Ocean close to sea-ice. Annual mean NPP is compared to annual mean MHW metrics. Note that a positive correlation between annual mean NPP and MHW metrics does not prove that marine heatwaves lead to high NPP, nor that they co-occur with high NPP. Throughout the manuscript, you could better distinguish between hypotheses and actual conclusions that can be drawn from your analysis.

Response: We sincerely appreciate Anonymous Reviewer #3's continued engagement with our manuscript and their insightful comments on our study. Their feedback has been essential in guiding the refinement of our research and enhancing the clarity of our findings.
Firstly, as Reviewer #3 may notice, we have substantially revised our manuscript. Among the changes made, we have introduced a new, more comprehensive and robust characterisation of the local physical drivers of MHWs in the SO (Fig. 3), through an analysis of heat budget terms available in MOM4p1 (Griffies, 2015). The discussion of the results can be found on L. 194-229:

"[…]Local physical drivers of MHWs over the SO were assessed by examining heat term budgets available in the Modular Ocean Model (MOM4p1)[51] (Figs. 3a–i). Additionally, the correlation between MHWs and several essential climate variables from 1982 to 2021 was also explored (Figs. 3j–m). The annual mean heat flux anomalies in the surface ocean layer averaged during the MHW onset (i.e., build-up of heat) and decay (i.e., dissipation of heat) phases (Extended Data Fig. S1) are listed in Extended Data Fig. S5. Results from the heat budget analysis showed that temperature changes during MHWs were mainly explained by four most important counteracting processes (Figs. 3a–i). While ocean advection, sea-air heat fluxes, and vertical diffusion positively contributed to the formation of MHWs in the SO, as well as to the subsequent heat loss, convective vertical mixing (from the non-local part, see Methods) inherently acted in a contrasting mode. This arises from the intrinsic characteristics of this non-local term, which was incorporated in the MOM4p1 to mitigate air-sea heat fluxes when faced with negative buoyancy forcing conditions[51]. During the onset phase of MHWs, the averaged circumpolar surface ocean heat gain reported in the preindustrial control simulation was 20 W m^{-2}, with air-sea heat fluxes being the dominant MHW driver (Extended Data Fig. S5a). Nevertheless, in the eight-member ensemble simulation for the 1982–2021 period, the circumpolar heat gain during the onset phase amounted to 39.8 W m^{-2}. This was explained by the increased contribution of vertical diffusion (26 W m^{-2} or 65.2 %; Extended Data Fig. S5b and Fig. 3g). Despite the major role of the surface heat fluxes (Figs. 3c–d), which was especially important in the Atlantic sector, vertical diffusion emerged as the dominant process both in driving MHWs in the SO and as an overarching cooling contributor to their decline (Figs. 3g–h). This was particularly relevant across much of the areas connecting the sea ice zone (defined by averaged SIC > 20%; Extended Data Fig. S2) and the southernmost subantarctic belt along the Atlantic and Indian sectors. This finding highlighted the significant feedback between sea ice variability and surface ocean temperature extremes in these regions (as also demonstrated in Extended Data Figs. S6a–b). Horizontal advective heat fluxes followed the ACC pathways, though they appeared to play a secondary role, affecting the development of MHWs in the SO only locally (Figs. 3a–b). However, it is important to note that the MOM4p1 model may underestimate the impact of advection, as its relatively low horizontal resolution cannot resolve mesoscale processes[51]. Furthermore, the contribution of drivers did not necessarily depend on the strength of the MHWs (as measured by the cumulative intensity) in the SO (Fig. 3i), and various combinations of driving mechanisms were possible; being consistent with ref.[52]. That is to say, the strongest and weakest MHW events were primarily driven by the same leading processes –positive ocean heat uptake anomalies and vertical diffusion– and were dampened by convective vertical mixing during their onset phases. While both air-sea heat fluxes and vertical diffusive processes led to the dissipation of heat, advection and contrasting vertical mixing played minor roles during the decay phases (Fig. 3i). […]".

Furthermore, the methodology followed is described in the Methods section (L. 640-698):

"[…] **Analysis of local drivers of marine heatwaves in the Southern Ocean**
To assess the local physical drivers of MHWs, we made use of a global, fully coupled carbon-climate Earth System Model (ESM) developed at the National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory (GFDL)[86]. The GFDL ESM2M couples an oceanic circulation model (MOM4p1) to an atmospheric circulation model (AM2), and incorporates a land model (LM3.0), representations of sea ice and iceberg dynamics, as well as interactions within biogeochemical cycles. Specifically, we used temperature tendency heat budgets available in MOM4p1[51] (https://github.com/mom-ocean/MOM4p1). This ocean model uses a tripolar horizontal grid of 1ºx1º, increasing meridionally to up to 1/3º towards the Equator, and with 50 depth levels. We analysed daily-mean outputs of all tendency terms that change the SST (over the upper 10 m) from a 500-yr preindustrial control simulation (with atmospheric CO_2, along with all other agents that influence radiation fixed at their preindustrial levels) and confirmed with an eight-member ensemble simulation of the GFDL ESM2M driven by historical data and the Representative Concentration Pathway 8.5 (RCP8.5) scenario from 1982 to 2021, following ref.[52,87].

For each grid cell, the model dissects the total heat change (ΔQ_{total}) across time intervals into various heat budget components. These components signify temperature changes due to distinct processes modeled. The total tendency of heat at the ocean surface, in W m^{-2}, is determined by equation(4)[51]:

$$\Delta Q_{total} = \Delta Q_{adv} + \Delta Q_{a\text{-}s} + \Delta Q_{vmix} + \Delta Q_{vdiff} + \Delta Q_{res}; \quad (4)$$

where ΔQ_{adv} represent the change in heat resulting from both horizontal and vertical advective heat fluxes, both explicitly resolved and approximated on subgrid scales through parameterization. $\Delta Q_{a\text{-}s}$ is the air-sea exchange of heat, including the balance of shortwave radiation (the net incoming surface shortwave radiation reduced by the fraction of shortwave radiation that goes beyond the surface layer) along with the net incoming longwave radiation, in addition to the net fluxes of latent and sensible heat[86]. ΔQ_{vmix} refers to the heat flux generated by the non-local segment of the K-profile parameterization (KPP)[51], representing convective vertical mixing within the ocean boundary layer in response to negative buoyancy forcing. ΔQ_{vdiff} accounts for heat fluxes caused by vertical diffusion, encompassing vertical mixing within the ocean boundary layer attributed to the local component of the KPP, as well as tidal mixing. Furthermore, the residual term (ΔQ_{res}) includes other smaller processes such as heat exchange due to river runoff, solid runoff from iceberg calving, neutral diffusion, or the heat flux exchange resulting from interactions of surface water masses due to precipitation and evaporation. A detailed description of each term can be found in Extended Data equations(S2–6) and in ref.[51].

We then computed anomalies of all these heat budget terms relative to their seasonal cycles for each ocean grid cell, to ultimately average them separately over the days of the onset (build-up of heat) and decay (dissipation of heat) phases of the MHWs (see Extended Data Fig. S1). Moreover, based on the change in heat content, the change in potential temperature ($\Delta\theta$), in ºC d^{-1}, can be approximated using equation(5)[51]:

$$\Delta\theta = \frac{\Delta Q_{\mathrm{total}}}{C_p^0 \rho_0 dz}, \qquad (5)$$

where C_p^0 is a fixed value for heat capacity, set at 3992.1 J kg^{-1} K^{-1} in MOM4p1; ρ_0 is the constant Boussinesq density of 1.035 kg m^{-3}, and dz is the changing thickness of vertical grid cells over time, measured in m, as described by ref.[51]. In our analysis, we assumed a thickness of dz = 10m, which led to a conversion factor of 0.00209 ºC m^2 s^{-1} W^{-1}. This inference is justified because the real fluctuations in the thickness of grid cells differ minimally (with the largest changes being around $1 \cdot 10^{-2}$ in the open ocean), resulting in negligible adjustments to the conversion factor. Despite the fact that these errors can accumulate over time, for time scales of MHW durations (days to few months), these are significantly reduced, as demonstrated by ref.[52].

The motivation for using the GFDL ESM2M (MOM4p1) model for the assessment of local physical drivers of MHWs in the Southern Ocean was due to the good agreement between the climatological characteristics and the trends of modelled and observation-based MHWs globally[26,52,87], as a result of the model's fidelity in simulating the mean state and interannual variations in SST. Moreover, in the SO outside the sea ice area, the model fits good with observational data[26,52]. […]".

In response to Reviewer #3's concerns, we acknowledge that correlation does not necessarily imply causation. Consequently, we have reassessed and strengthened the analysis (revised Fig. 4). We averaged the distributions of NPP, Sea Ice Concentration (SIC), and Mixed Layer Depth (MLD) over the months (from November to March, owing to methodological reasons in applying the long-term mean summer temperature) with and without MHWs (Figs. 4b-d), to more clearly illustrate the changes in the SO surface layer during MHW events. The changes are readily apparent, even considering the conservative nature of the violin plots. Furthermore, we applied Empirical Dynamic Modelling (EDM) through Convergent Cross Mapping (CCM; Sugihara et al., 2012) to reveal the nonlinear causal relationships between changes induced in the SO surface layer (Max SSTA, SIC, and MLD) and dynamical alterations in NPP. This cutting-edge analysis showed the predictive capacity of changes in the SO surface layer for NPP dynamics (Figs. 4e-f). Specifically, it allowed to analyse the spatio-temporal influence of different physical variables (Max SSTA, SIC, and MLD) on the dynamic changes in phytoplankton communities. For instance, through CCM, we empirically evidenced the extent of the influence that sea ice melting exerts on NPP in the open waters of the SO (Fig. 4f). The discussion of the obtained results is presented on L. 300-343:

"[…] Distinctive distributions of NPP were observed when rates were averaged over the months (from November to March) under MHW conditions, and over months without MHWs from 1998 to 2021 (Fig. 4b). The average NPP rates manifested an elevation during MHWs, with a difference of approximately 100 mgC m^{-2} day^{-1} compared to the NPP in the same months where the SST remained within its climatological standards. Additionally, the average minimum NPP increased from 1 to 74 mgC m^{-2} day^{-1} under MHW influence. These results were consistent with the relatively lower SIC (greater density at lower values) and shallower mixed-layer depths (MLD) during the MHW conditions (Figs. 4c–d). Such conditions are conducive to retaining meltwater-induced nutrients and trace elements within the euphotic layer, thus promoting phytoplankton proliferation[38]. Furthermore, causal analysis through convergent cross mapping (CCM)[65] highlighted the intricate interdependencies within the complex SO system (Figs. 4e–g). The predictive skill for NPP based on the time series of Max SSTA (NPP xmap Max SSTA; Fig. 4e) exhibited spatial heterogeneity, with high cross-map skills in subantarctic regions and the weakest skills obtained in the most dynamic areas (between ACC and the subantarctic front). However, the generally moderate skill of cross map estimates suggested that extremes of temperature alone were not the sole determinant of primary production variability. Additionally, the influence of sea ice melting on NPP could be appreciated in the southernmost subantarctic band (Fig. 4f), where moderate causal linkages emphasised the important role of ice dynamics within these areas. Nonetheless, the variable that best identified the state of NPP was the MLD, with the highest and generally homogeneous values of cross-map skills (Fig. 4g). This underscored the critical role of shallower MLDs in concentrating light and nutrients in the upper layers of the SO, facilitating the thriving of phytoplankton[60]. It is imperative to highlight that these three physical variables (Max SSTA, SIC, and MLD) were closely interlinked, with a significantly higher forcing impact of Max SSTA on SIC and a close causal bidirectional relationship between MLD and temperature extremes (Extended Data Fig. S6), as previously demonstrated by ref.[19]. […] Thus, causation is transitive (eg., if Max SSTA leads to shallower MLD –and vice versa–, and shallower MLD enhances NPP in the SO, then Max SSTA and NPP are also indirectly causally linked). Conversely, prediction skills of the reconstructions of Max SSTA, SIC, or MLD from the true values of NPP, as expected, were lower (Extended Data Fig. S8). Therefore, despite the bidirectionality in the system, results from the empirical dynamic modeling (EDM) showed the measurable nonlinear causal coupling between the changing upper-layer physical conditions of the SO and the spatiotemporal dynamics of the primary producers' communities (Figs. 4e–g). […]".

The methodology applied for causal inference through EDM is described in the Methods section (L. 718-777):

"[…]**Causal interactions through empirical dynamic modeling**
In an effort to investigate the causal interactions among the key variables in our study (Max. SSTA, NPP, SIC, and MLD), we applied Empirical Dynamic Modeling (EDM). This cutting-edge framework is based on Takens' theorem, which provides tools for attractor reconstruction[92] and allows for the modeling of causal relationships in nonlinear dynamic systems in the absence of governing dynamic equations[66]. In dynamical systems,

two state variables X and Y are considered to be causally linked if they contain shared information that allows reconstructing the observed dynamics from one state variable, say X, from the dynamics of the other variable, Y. This shared information can allow for a unidirectional reconstruction (e.g., X causes Y), or a bidirectional reconstruction (both variables cause each other) of the dynamics[66]. In essence, Takens' theorem shows that the dynamics of a state variable Y caused by another variable X is encoded in the delayed-coordinates embedding[66] of the causing variable, X in this case. This is provided by the so-called attractor manifold M which, in the absence of a governing dynamics equation, contains all the information needed to encode the dynamic system: it is the region of the state space that contains all the possible states of the system in the long-term. The essential assumption of EDM is that causality within a dynamic system is more strongly dependent on the proximity of the values of the variables in the state space that in their proximity in time[66,92]. In our analysis, we applied Convergent Cross Mapping (CCM), introduced by ref.[66], to perform the nonlinear state space reconstruction. CCM assesses causality by evaluating how accurately the historical data of Y can predict the state of X, or viceversa. This prediction is feasible only if X has a causal impact on Y. To delve deeper, CCM seeks evidence of X's influence within Y's time series by examining if the 'library' of points (L) in the attractor constructed from Y, denoted as M_Y, matches with the points in X's attractor, M_X. Both manifolds, M_Y and M_X, are formed from the time-delayed coordinates of the variables Y and X, respectively[66].

Considering two time series of length l, $\{X\} = \{X(1), X(2), \ldots, X(l)\}$ and $\{Y\} = \{Y(1), Y(2), \ldots, Y(l)\}$, we created delay embedding vectors from a time series following equation (6):

$$x(t) = [X(t), X(t-\tau), X(t-2\tau), \ldots, X(t-(E-1)\tau)] \text{ for } t = 1+(E-1)\tau \text{ to } t = l\,; \quad (6)$$

where τ is the time delay (i.e., lag), E is the embedding dimension, and t is time. These vectors form the 'reconstructed manifold' or 'shadow manifold' (M_X). To create a cross-mapped prediction of $Y(t)$, expressed as $\hat{Y}(t)|M_X$, we started by locating the corresponding lagged-coordinate vector on M_X, $x(t)$, and then identifying its E+1 nearest neighbors. We then labeled the time indices of these E+1 nearest neighbors of $x(t)$, in order from nearest to farthest, as $t_1, \ldots, t_{E+1}$ (equation(7)). These specific time indices, which were closest to $x(t)$ on M_X, were utilised to locate corresponding points (neighbors) in Y (considered a prospective neighborhood) to approximate $Y(t)$ through a locally weighted average of the E+1 values of $Y(t_i)$.

$$\hat{Y}(t) \mid M_X = \Sigma\, w_i\, Y(t_i), \quad i = 1 \ldots E+1; \quad (7)$$

where w_i is a weighting that is determined by the Euclidean distance between $x(t)$ and its i^{th} closest neighbor within M_X and $Y(t_i)$ are the concurrent values of Y. The strength of this cross-mapping and its convergence as the l increases serve as evidence of causality[66].

We applied CCM on monthly time series of Max. SSTA, NPP, SIC, and MLD from 1998 to 2021 (288 values) corresponding to each ocean grid cell. Although CCM is regarded as a non-parametric method, the selection of the τ and E parameters must indeed be conducted with care to ensure that the phase space reconstruction accurately reflects the true dynamics of the system. Therefore, in our analysis, we performed a sensitivity test via mutual information to identify the τ value that maximizes the shared information between $X(t)$ and $X(t-\tau)$, thereby indicating the most effective delay, following ref.[93]. Furthermore, we also determined the minimum embedding dimension required for the reconstructed phase space to unfold the system's dynamics (Extended Data Fig. S10).

From this, we obtained an optimal τ of 3 (which is coherent with seasonal time scales) and an E = 6. To quantify the prediction skill, CCM uses the Pearson's correlation coefficient between the actual states of the system (e.g., the true values of *Y*) and the predicted states (using the reconstructed dynamics from *X*). High correlation suggested a strong causal link, where the ability to predict *Y* from *X* suggested that *X* has a causal influence on *Y*.

Given their minimal assumptions, EDM and concretely CCM, is especially robust for analysing systems that exhibit strongly non-equilibrium dynamics and nonlinear behaviour, where interactions vary over time and depend on the system's current state[66]. That is to say, these approaches are particularly suitable for studying NPP dynamics under a changing SO. […]".

Furthermore, we have revised the two case studies by including the variable MLD and reducing the study areas to ensure consistency between them (Fig. 5). We have also applied the long-term mean summer temperature (LMST) criterion, which was previously overlooked due to an oversight. We extent our sincere thanks to Reviewer #3 for that observation. There, we illustrated how sustained high air (N-SAT) and sea (MHW) temperatures, along with associated sea ice melting and a shallower MLD, led to the occurrence of high net primary production (HNPP) events in subantarctic regions (Fig. 5).

Finally, we acknowledge that the CbPM NPP product may exhibit uncertainties close to sea-ice, as it is a model of biomass estimates derived from satellite data. We have added a brief discussion in the Methods section (L. 541-549) regarding the selection criteria for the CbPM model, following Behrenfeld et al. (2005), Boyd et al. (2024), and Westberry et al. (2008); and acknowledged any uncertainties that may exist in the SO, following Le Grix et al. (2022):

"[…] It must be emphasised that there are uncertainties associated with the NPP rates derived from the CbPM. There are various models that derive NPP from satellite data, and each provides different estimates in the SO[83]. Nevertheless, in our study, the CbPM was chosen over alternatives, like the Vertically Generalized Production Model (VgPM), due to its superior capability to directly relate satellite-derived chlorophyll observations to carbon-based productivity. The CbPM is specifically calibrated for carbon flux estimation, making it more suitable for studies focused on carbon dynamics in marine environments[81,82]. This was crucial in our study region (SO), where carbon uptake plays a significant role in the global carbon cycle[72]. […]".

Detailed comments:

Reviewer #3: L. 18-20. "A rapid but not long-lasting warming of the sea surface was found to trigger phytoplankton activity through stabilization of the water column." This study does not address the stability of the water column. It simply shows that this warming was associated with enhanced phytoplankton activity. Which warming do you exactly refer to here? As far as I understand, this is a decadal warming, which is longer-lasting than discrete marine heatwave events.

Response: We apologise for any confusion that may have arisen from this paragraph. We have removed it, as we have conducted more robust analyses. Please note that we have rewritten the abstract (L. 17-25):

"[…] We find that increasing climate change-related MHW activity, primarily explained by sea-air heat fluxes and vertical diffusion anomalies, enhances net primary production (NPP) through stabilization of the water column. We empirically reveal causal nonlinear relationships between marine extreme temperatures and NPP, especially in the southernmost subantarctic areas where the concurrent sea ice decrease also plays a key role. Furthermore, our study shows a zonally asymmetric responses of primary producers to MHWs north of the Antarctic polar front. These results provide the first insights into the role of MHWs promoting carbon (C) assimilation (and uptake) in the SO through the biological carbon pump, which is crucial for constraining the oceanic C cycle under climate change. […]".

Reviewer #3: L. 31-32: "defined as discrete persistent extreme events where sea surface temperature (SST) exceeds certain criteria based on a seasonally varying climatological threshold and variability (8–10)." Maybe specify "commonly defined", as although this is the common marine heatwave definition by Hobday et al. 2016, marine heatwaves can also be defined using an absolute, non-seasonally varying threshold, depending on the biological impact to be quantified (e.g., Gruber et al. 2021, https://doi.org/10.1038/s41586-021-03981-7)

Response: The authors appreciate this insightful observation from Reviewer #3. We have specified it on L. 30.

Reviewer #3: L. 34-36: "This thermal tolerance is not only dependent on the intensity of the underlying SST anomalies (SSTAs), but also to the frequency and duration of MHWs." Provide references.

Response: Done (L. 35).

Reviewer #3: L.140 and in the rest of the paper: Consider replacing "intensity" by "magnitude". Intensity commonly refers to the exceedance above a percentile threshold, whereas the magnitude is the exceedance above the climatology (Gruber et al. 2021,

Response: The authors express their gratitude for this insightful observation made by Reviewer #3. It has been accordingly modified in L. 137 and throughout the revised manuscript.

Reviewer #3: L.182-184: "However, maximum intensities (SSTAs) are greater in the Atlantic sector, while longest–lasting events occur in the Pacific area. This heterogeneity highlights SO climate regionality." This is an interesting result, which could be further discussed. Do you have an explanation for this heterogeneity?

Response: We thank Reviewer #3 for this great appreciation. As we mentioned, the observed heterogeneity in the frequency, magnitudes, and the duration of events between the three sectors underscored the climate regionality of the SO. This could be attributed to several ocean-atmosphere dynamics that are region-specific, as evidenced by Holbrook et al. (2019) in the global ocean. We have included a paragraph in the Discussion section (L. 415-422):

"[…] Moreover, the prevalence of persistent atmospheric patterns over the Pacific sector, such as ENSO, could sustain anomalies over longer periods[23] (Fig. 2g). In the Atlantic and Indian sectors, surface dynamics played a significant role in amplifying thermal anomalies, as presumably observed in Figs. 2a and 2j and as evidenced in the heat budgets analysis (Fig. 3 and Extended Data Fig. S5). Furthermore, in these regions, TSA and SAM appeared to be the dominant climate modes of variability[23] (Extended Data Figs. S3d–i). This also highlighted the importance of remote forcing on surface temperature variability, which affected regional scales asymmetrically in the SO. […]".

Reviewer #3: L. 197 Does the "correlation" refer to a correlation between annual mean MHW metrics and climate variables? Maybe specify here.

Response: It refers to monthly averages from November to March. Specified in L. 232 and also in the revised Extended Data Table S3.

Reviewer #3: L.237 "Changing temporal trends of biogeochemistry and marine productivity" This section covers aspects not yet addressed by previous marine heatwave studies carried out at the global scale. Using biogeochemical trends before and after the rapid sea-ice melting in 2015, you hypothesize that marine heatwaves trigger sea-ice melting in the Southern Ocean, which releases iron and favors phytoplankton growth. However, the rapid sea-ice melting in 2015 may have been driven by long-term changes in the Southern Ocean instead of by marine heatwaves. Why not rather focus on marine heatwave events and compute the mean sea-ice extent, nutrient levels, and chlorophyll anomalies during these events?

Response: We thank Reviewer #3 for their insightful comments. As mentioned above, in our new analysis, we averaged the NPP, SIC and MLD distributions over the months (from November to March) with and without MHW conditions (Figs. 4b-d). This approach helped us differentiate between the physical and biogeochemical changes in the SO surface layer under MHW events and during standard conditions. The consideration of the same months (November to March) made the results displayed in the violin plots more conservative. However, this also made the analysis more robust, as it allows for a clear differentiation between the MHW conditions and standard SST conditions for the same months.
On the other hand, through CCM, we evidenced a close relationship between Max. SSTA, SIC, and MLD in the SO. We also showed that although SIC influenced surface variability in the southernmost subantarctic band, the effect of Max. SSTA on SIC was greater (Extended Data Fig. S6), as also mentioned in the revised manuscript (L. 321-324):

"[…] It is imperative to highlight that these three physical variables (Max SSTA, SIC, and MLD) were closely interlinked, with a significantly higher forcing impact of Max SSTA on SIC and a close causal bidirectional relationship between MLD and temperature extremes (Extended Data Fig. S6), as previously demonstrated by ref.[20]. […]".

Reviewer #3: L. 255 You should mention that there are large uncertainties in NPP estimates, especially in the Southern Ocean (Le Grix et al. 2022,
https://doi.org/10.5194/bg-19-5807-2022
). It is especially uncertain how NPP reacts to Southern Ocean marine heatwaves. The CbPM is one of a number of models deriving NPP from satellite observations; all give very different estimates.

Response: We thank Reviewer #3 for this observation. Mentioned (L. 541-549):

"[…] It must be emphasised that there are uncertainties associated with the NPP rates derived from the CbPM. There are various models that derive NPP from satellite data, and each provides different estimates in the SO[83]. Nevertheless, in our study, the CbPM was chosen over alternatives, like the Vertically Generalized Production Model (VgPM), due to its superior capability to directly relate satellite-derived chlorophyll observations to carbon-based productivity. The CbPM is specifically calibrated for carbon flux estimation, making it more suitable for studies focused on carbon dynamics in marine environments[81,82]. This was crucial in our study region (SO), where carbon uptake plays a significant role in the global carbon cycle[72]. […]".

Reviewer #3: L. 275-289. Interesting discussion on how marine heatwaves may change phytoplankton growth, biomass, and community structure, but where do your results contribute to this discussion? You may want to move this paragraph to the Discussion. Moreover, many of the cited papers are not specific to marine heatwaves. This study could have contributed to the discussion by proving some of the hypotheses in the specific case of marine heatwaves.

Response: We rephrased and moved that paragraph to the Discussion section (L. 460-472):

"[…] Many processes can be involved in the dynamic response of the extensive SO phytoplankton communities to a changing climate. Among them, species-specific responses to environmental stress, competition for resources, and trophic interactions (e.g., grazing)[69] would explain a significant part of the NPP response in the SO. Furthermore, dominant limiting factors (i.e., light availability and concentration of nutrients in sea-water), impacted by changes in SO sea ice concentrations and MHWs-induced mixed layer shoaling, would be likely affecting the growth rates of phytoplankton communities from local to regional scales along the subantarctic region (Fig. 5). These factors may also condition the composition of phytoplankton functional types (PFTs). In fact, phytoplankton diversity increases in the SO under persistent global warming[64,74]. All these considerations must be taken into account when evaluating dynamic changes in phytoplankton communities in the SO. Nevertheless, the massive variety of phytoplankton species and their differing response to environmental changes makes it challenging to predict a global and single phytoplankton response to extreme events. […]".

It is challenging to provide a singular detailed biogeochemical response of SO phytoplankton communities to MHW events. Among other reasons, this is because the vast SO harbours different phytoplankton functional types (PFT), and each group responds differently to the various limiting factors, as discussed in L. 366-375:

"[…] It should be, however, pointed out here that predicting a single response of phytoplankton to extreme temperature conditions in the SO is challenging. There are many different phytoplankton groups in the Antarctic waters, each responding differently to environmental changes[16,60,67]. Additionally, due to its vast expanse, ocean physics are not uniform everywhere in the SO (as seen in Figs. 1–3). Therefore, an interesting asymmetry was observed not only meridionally but also zonally in the response of primary producers to temperature extremes (Figs. 4a and 4e). As previously suggested by ref.[49], this zonal asymmetry around the higher subantarctic region was closely linked to the variability of the limiting factors for phytoplankton growth in each area, where both sea-ice melting and ocean surface warming played a critical role in stabilizing and transporting micronutrients to the surface layer. […]".

In this context, as mentioned in L. 473-474, "[…]Future analyses based on SO MHW–induced plankton phenology changes would be required to properly assess the impacts of these extreme events over particular PFTs.[…]".

However, in our study, we have empirically evidenced nonlinear causal relationships between the changing physical conditions of the SO's upper layer and the spatio-temporal dynamics of primary producers' communities (Figs. 4 and 5). These findings are crucial because they suggest that climate change-related impacts, with MHWs being an important component, are significantly altering the partitioning of basin-scale NPP in the SO, which is critical for grasping key processes in the SO carbon cycle.

Reviewer #3: L. 276-277. "playing a key role the physiological": Rephrase.

Response: Rephrased (L. 460-472).

Reviewer #3: L. 281. There is no reason for the CbPM to include grazing since it calculates NPP as the product of the growth rate and carbon biomass, with the carbon biomass directly derived from the particulate backscattering coefficient.

Response: We apologise for any confusion that this statement may have caused. We simply meant to indicate that we were not considering this process. We removed that phrase to avoid confusion.

Reviewer #3: Fig. 5: Specify that the correlation is computed between "annually averaged" MHW metrics and NPP. Maybe explain in the discussion why you compute the correlation between annual averages. Isn't the MHW period (austral summer) interrupted? You could also have averaged NPP over each MHW event or over each austral summer season.

Response: The Reviewer #3 is right. We have now presented a more robust and comprehensive analysis of the impact of MHWs on NPP, SIC, and MLD in the SO, following Reviewer #3's advices (Fig. 4).

Reviewer #3: Note that a high correlation between annual mean MHW metrics and NPP does not prove that marine heatwaves lead to high NPP, nor that they co-occur with high NPP. For example, the long-term warming may have increased the MHW frequency, intensity, and duration as well NPP over the years, resulting in a positive correlation, which doesn't mean NPP is directly related to MHW activity.

Response: As previously mentioned, we fully agree with Reviewer #3. Primarily for this reason that a mere annual correlation does not imply causality, we applied EDM via CCM to demonstrate the spatio-temporal influence of the physical variables (Max. SSTA, SIC, and MLD) on NPP (Fig. 4). Although it must be highlighted that long-term warming may have increased temperature extremes, our new CCM analysis of monthly series has allowed for a more robust examination of the non-linear causal relationships between the dynamics in changing upper-layer physical conditions and NPP rates in the SO.

Reviewer #3: Fig. 6. How would you explain the compound MHW-HNPP event in winter 2015 in the Davis Sea under high sea-ice?
Consider adding the seasonal cycle of the sea-ice extent in Fig. 6, so the readers know whether in a given year, sea-ice extent is unusually high or low compared to the climatology.
Why are there heatwaves in winter on Fig. 6? The methods state that temperatures must exceed the long-term mean summer temperature. Is this criterion dropped?

Response: We have modified Fig. 6 (now Fig. 5), as we have previously explained in our response to Reviewer #3's general comments. Among the revisions made, we have adjusted the study areas to ensure consistency between them. For this reason, the data series have changed slightly. Furthermore, we have included the MLD variable to enhance the coherence of the discussion of the results. Due to the extensive amount of information (time series), we have not deemed it appropriate to add another series on the seasonal cycle of sea-ice extent, as this would compromise clarity. However, should the reviewer still firmly believe that its inclusion is necessary, we are prepared to incorporate it.
On another note, we apologise once again for any confusion that may have arisen from the omission of the LMST in the case studies. We have included this criterion in the revised case studies, although it now only affects the September 2017 event in the Davis Sea (Fig. 5a).

Reviewer #3: L. 440-441 "Phytoplankton responses to MHWs have shown to be zonally asymmetric, as previously suggested by refs." The references do not specifically refer to MHWs. Here, and at other times in the manuscript, generalizations are made on the phytoplankton response to MHWs based on studies that consider moderate or long-term warming. Phytoplankton may, however, respond differently under discrete and extreme warming events.

Response: We thank Reviewer #3 for this highly constructive comment. We accordingly rephrased (L. 454-457):

"[…] However, phytoplankton responses to changing climate have been shown to be zonally asymmetric in the SO[49,60,69]. Although these organisms may respond differently under discrete and extreme warming events, our results also showed zonal heterogeneity in the NPP dynamical responses to changing physical conditions in the SO (Figs. 4e-g). […]".

Reviewer #3: L. 441-442. "It should be highlighted that MHWs are not the sole direct cause of increased NPP in the vast SO." This study does not prove that MHWs generally drive increased NPP. It shows that there is a positive correlation between annual mean MHW metrics and NPP, and that an increase in MHW frequency over recent years has been associated with an increase in NPP.

Response: In the revised Fig. 4, we have included the monthly distributions of NPP under MHW conditions and with standard SST conditions (Fig. 4b). This has allowed, in a general context, to discern the response of NPP rates to discrete and prolonged extreme

temperature events. Moreover, through the CCM analysis, we have revealed causal non-linear relationships between temperature extremes and increased NPP (Fig. 4e). We would like to emphasise that it is complicated to provide a detailed account of the biochemical response of primary producers to MHW events in the extensive SO. Nonetheless, we have showed that NPP rates respond to extreme thermal events (Fig. 4) and suggested that in the southernmost subantarctic zone (Fig. 5), the influence of sea ice melting and the stabilization of the water column played a pivotal role in the transport of micronutrients to the surface layer, where primary producers could undergo photosynthesis.
Therefore, when we stated that "MHWs alone are not the sole direct cause of increased NPP," we precisely intended to underscore that numerous processes can be involved in the responses of primary producers to changing physical conditions. Furthermore, although we generally demonstrated that NPP responded to temperature extremes, this response can be highly varied or may even prove to be insignificant in certain areas, as we have observed in the more dynamic regions of the SO (Fig. 4e).

Reviewer #3: L. 501. Note that all regions covered by some sea-ice will give misleading results for CbPM NPP. The CbPM NPP estimates are derived from observations that are highly uncertain close to sea-ice.

Response: The authors appreciate the constructive comment from Reviewer #3 and acknowledge the uncertainties that both the SST and the CbPM NPP products may have. We masked out regions where SIC were greater than 20%, since MHW metrics are less trustworthy in those areas with associated low SST standard deviation (Huang et al., 2021; Oliver et al., 2018). Nevertheless, we also advised of these uncertainties associated with the CPM NPP estimates (L. 541-549):

"[…] It must be emphasised that there are uncertainties associated with the NPP rates derived from the CbPM. There are various models that derive NPP from satellite data, and each provides different estimates in the SO[83]. Nevertheless, in our study, the CbPM was chosen over alternatives, like the Vertically Generalized Production Model (VgPM), due to its superior capability to directly relate satellite-derived chlorophyll observations to carbon-based productivity. The CbPM is specifically calibrated for carbon flux estimation, making it more suitable for studies focused on carbon dynamics in marine environments[81,82]. This was crucial in our study region (SO), where carbon uptake plays a significant role in the global carbon cycle[64]. […]".

Reviewer #3: L. 538. The use of the LMST criterion is a nice addition from previous marine heatwaves studies at the global scale and allows to focus on heatwaves that are potentially harmful for Southern Ocean species.
The criterion implies that marine heatwaves usually occur in austral summer. You may want to clarify earlier in the manuscript that this study focuses on summer marine heatwaves. On Fig. 6, it seems that MHWs occur also when the temperature is less than the LMST. Have you not applied the LMST criterion?

Response: We thank Reviewer #3 for their valuable feedback regarding our methodology.
The application of the LMST criterion entails that the average temperature of the MHW event must exceed the LMST. For a more detailed graphical explanation, please refer to the new Extended Data Fig. S1. In the first MHW event, the starting temperature is lower

than the LMST. However, during the onset phase (build-up of heat), the temperature rises to exceed the LMST at that specific location. On the other hand, you may also observe that in the days leading up to this, there are two periods where the temperature surpasses the 95th percentile for at least five days. Nevertheless, we do not count these as MHWs because they do not entirely exceed the LMST.
The reviewer rightly pointed out that MHWs typically occur in the austral summer under the LMST criterion. However, due to the inherent nature of these events, we have found that they can extend from November to March (not shown in the manuscript). Consequently, when analysing local physical drivers (Fig. 3), as well as when examining NPP, SIC, and MLD conditions under MHWs (Figs. 4b-d), we averaged over these months. Therefore, by definition, it is not strictly the austral summer, but rather warm months. We have specified earlier in the text (L. 241-244):

"[…] During the warm months, MHWs (Figs. 2c, 2f, 2i and 2l) were clearly enhanced with warmer surface air temperature (Fig. 3j) and a reduction of SIC (Fig. 3k) over the SO, particularly during 2015–2021. Conversely, the weakest events occurred in years with larger sea ice cover and associated atmospheric cooling. […]".

Regarding to the previous Fig. 6 (now Fig. 5), we once again apologise for having overlooked this criterion and extend our gratitude to Reviewer #3 for this significant observation. It has been corrected (L. 386).

Reviewer #3: L. 555. MHW metrics are annually averaged although each austral summer spans across two calendar years. Consider averaging over summer, or spring to autumn, instead of a calendar year.

Response: MHW metrics were only averaged annually in Figs. 2c, 2f, 2i, and 2l, to represent their temporal evolution. As mentioned in the Methods section (L. 605-607), when an event spans from one calendar year to the next, we account for it in the year in which it starts.
In our new analyses, both in the assessment of the local physical drivers (Fig. 3) and in the responses of the NPP to the MHWs (Fig. 4), we have utilised the actual days and months of MHWs, respectively. Consequently, that initial consideration does not influence our new results.

Reviewer #3: L. 566-568. "Nevertheless, the austral warm season lasts from December to May, thus an event can occur within two different years in high Southern latitudes. When this occurs, the event is counted in the year in which it begins." How does that impact the calculation of the correlation calculation of MHW metrics with annual mean NPP?

Response: We fully agree with Reviewer #3, as we previously discussed. On the other hand, we meant to say from December to March (L. 610).

Reviewer #3: Fig. S5. Specify what the red shading indicates. Do MHWs occur when the SSTA is lower than the LMST, contrary to what is stated in the Methods?

Response: Specified (now it is Extended Data Fig. S9). We have included a more detailed (and graphical) explanation in the new Extended Data Fig. S1.

References

Behrenfeld, M.J., Boss, E., Siegel, D.A., Shea, D.M., 2005. Carbon-based ocean productivity and phytoplankton physiology from space: PHYTOPLANKTON GROWTH RATES AND OCEAN PRODUCTIVITY. Global Biogeochem. Cycles 19. https://doi.org/10.1029/2004GB002299

Boyd, P.W., Arrigo, K.R., Ardyna, M., Halfter, S., Huckstadt, L., Kuhn, A.M., Lannuzel, D., Neukermans, G., Novaglio, C., Shadwick, E.H., Swart, S., Thomalla, S.J., 2024. The role of biota in the Southern Ocean carbon cycle. Nat Rev Earth Environ. https://doi.org/10.1038/s43017-024-00531-

Griffies, S.M., 2015. Working notes on the ocean heat budget in GFDL-ESM2M. https://mom-ocean.github.io/assets/pdfs/ESM2M_heat_budget.pdf [Accessed February 8, 2024].

Holbrook, N.J., Scannell, H.A., Sen Gupta, A., Benthuysen, J.A., Feng, M., Oliver, E.C.J., Alexander, L.V., Burrows, M.T., Donat, M.G., Hobday, A.J., Moore, P.J., Perkins-Kirkpatrick, S.E., Smale, D.A., Straub, S.C., Wernberg, T., 2019. A global assessment of marine heatwaves and their drivers. Nat Commun 10, 2624. https://doi.org/10.1038/s41467-019-10206-z

Huang, B., Wang, Z., Yin, X., Arguez, A., Graham, G., Liu, C., Smith, T., Zhang, H., 2021. Prolonged Marine Heatwaves in the Arctic: 1982−2020. Geophysical Research Letters 48. https://doi.org/10.1029/2021GL095590

Le Grix, N., Zscheischler, J., Rodgers, K.B., Yamaguchi, R., Frölicher, T.L., 2022. Hotspots and drivers of compound marine heatwaves and low net primary production extremes. Biogeosciences 19, 5807–5835. https://doi.org/10.5194/bg-19-5807-2022

Oliver, E.C.J., Donat, M.G., Burrows, M.T., Moore, P.J., Smale, D.A., Alexander, L.V., Benthuysen, J.A., Feng, M., Sen Gupta, A., Hobday, A.J., Holbrook, N.J., Perkins-Kirkpatrick, S.E., Scannell, H.A., Straub, S.C., Wernberg, T., 2018. Longer and more frequent marine heatwaves over the past century. Nat Commun 9, 1324. https://doi.org/10.1038/s41467-018-03732-9

Sugihara, G., May, R., Ye, H., Hsieh, C., Deyle, E., Fogarty, M., Munch, S., 2012. Detecting Causality in Complex Ecosystems. Science 338, 496–500. https://doi.org/10.1126/science.1227079

Westberry, T., Behrenfeld, M.J., Siegel, D.A., Boss, E., 2008. Carbon-based primary productivity modeling with vertically resolved photoacclimation: CARBON-BASED PRODUCTION MODEL. Global Biogeochem. Cycles 22, n/a-n/a. https://doi.org/10.1029/2007GB003078

Decision letter and referee reports: second round

10th Jun 24

Dear Mr Fernández-Barba,

Your revised manuscript titled "Marine heatwaves in a changing Southern Ocean: Drivers and impacts on net primary production" has now been seen by our original reviewers 1 and 3, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

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Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I appreciate the authors' efforts in addressing my previous comments. The manuscript has significantly improved over the previous version. In particular, I am glad to see that the authors have analyzed additional model simulations to investigate the formation mechanisms of marine heatwaves, and performed Convergent Cross Mapping analysis to examine the causality between MHWs, sea ice changes, MLD shallowing, and NPP anomalies.
As the authors pointed out, it is still challenging to fully unravel the complex relationships between MHWs and changes in the MLD and NPP. Additionally, some important processes such as mesoscale eddies are still missing in the model simulations. Nevertheless, I believe that the findings in this study will help advance our understanding in this matter. Hence, I would like to recommend acceptance of the manuscript for publication.

Reviewer #3 (Remarks to the Author):

I appreciate the authors' detailed answers to my review and thank them for revising the manuscript accordingly. All of my concerns have been addressed. I am satisfied with the revised manuscript.

Responses to Reviewers' Comments for 'Marine heatwaves in a shifting Southern Ocean induce dynamical changes in primary production'

The authors would like to express, once again through this document, our deep gratitude to the editorial team and the three anonymous reviewers for their valuable and constructive feedback. The final version of our manuscript is, in part, the result of their esteemed insights and their constant involvement, driven by their belief that this work significantly contributes to advancing our understanding in the field of marine heatwaves and their associated biogeochemical impacts.

Reviewer #1 (Remarks to the Author): I appreciate the authors' efforts in addressing my previous comments. The manuscript has significantly improved over the previous version. In particular, I am glad to see that the authors have analyzed additional model simulations to investigate the formation mechanisms of marine heatwaves, and performed Convergent Cross Mapping analysis to examine the causality between MHWs, sea ice changes, MLD shallowing, and NPP anomalies.
As the authors pointed out, it is still challenging to fully unravel the complex relationships between MHWs and changes in the MLD and NPP. Additionally, some important processes such as mesoscale eddies are still missing in the model simulations. Nevertheless, I believe that the findings in this study will help advance our understanding in this matter. Hence, I would like to recommend acceptance of the manuscript for publication.

Response: We greatly appreciate Reviewer #1's time and effort devoting to reviewing our manuscript. Particularly, their concerns regarding a better understanding of the local physical drivers of marine heatwaves in the Southern Ocean, as well as the interactions between long-term changes in mixed layer depth and extreme thermal events, have significantly enhanced the depth of our study in this regard. Furthermore, Reviewer #1's suggestion to carefully analyse the NPP responses to marine heatwaves prompted us to apply empirical dynamic modeling, thus providing the required consistency.
In response to Reviewer #1's concern regarding the inclusion of mesoscale eddies, we firmly agree with them that this is such a relevant process. Nevertheless, the MOM4p1 model cannot resolve mesoscale processes due to its coarse horizontal resolution and, as such, the impact of advection in our study area may be underestimated, as indicated in the main manuscript. However, for future studies, it would be highly interesting and indeed appropriate to analyse eddy kinetic energy at mesoscale and sub-mesoscale levels, which could further our understanding not only of the surface dynamics of the region but also of the associated biogeochemical impacts.
Once again, we deeply appreciate Anonymous Reviewer #1's recognition of our work and the valued consideration.

Reviewer #3 (Remarks to the Author): I appreciate the authors' detailed answers to my review and thank them for revising the manuscript accordingly. All of my concerns have been addressed. I am satisfied with the revised manuscript.

Response: We are deeply grateful for Reviewer #3's dedication in reviewing our manuscript, both in initial and subsequent evaluations. Reviewer #3's detailed and insightful comments have been invaluable in refining our work. The quality of our revised manuscript is, in large part, thanks to Reviewer #3's perseverance in addressing the key points our work undertake and, therefore, their commitment to seeing it published.