Reviewer 2 comments for the manuscript "Simulating vertical phytoplankton dynamics in a stratified ocean using a two-layered ecosystem model" by Zheng et al.

We would like to thank the reviewer 2 for their thoughtful and constructive comments, which have helped us improve the quality and clarity of our manuscript. Below, we address each comment in detail and outline the revisions made to the text. The referee's comment is shown in black, and our response is beneath in blue. In addition, to improve the manuscript, we have corrected grammatical errors and rewritten the summary section to improve the flow.

The authors developed a novel two-layered NPZ model to simulate the dynamics of surface and subsurface phytoplankton. Using BATS as the research object and adopting reasonable two-layered different parameter settings, they found opposite trends in surface and subsurface phytoplankton after 2011, and analyzed the reasons for this difference. The characteristics of phytoplankton are very consistent with observations in both seasonal changes and long-term trends, further enhancing the credibility of the research results. By establishing and validating this model, the authors provide support for studying the changing characteristics of ecosystems under current conditions. The design and results of this model may also have great applicability and can be further used to predict ecosystem changes under continued warming conditions in the future.

The manuscript is clearly structured and well written. The authors present a compelling study and vividly illustrate their hypotheses and conclusions using well-designed figures and clear explanations. I have some comments and suggestions that I hope will be helpful.

We really appreciate your constructive comments. Your suggestions have helped us to improve our manuscript. Below we carefully address each question you raised and have improved the content accordingly in the revised manuscript. We provide a detailed response to each comment and outline the corresponding changes made to the text. In the tracked-change manuscript, we highlighted all the changes in blue expect for the appendix.

(Text directly from the article is enclosed in "quotation marks".)

1. Questions

(1) The two layers of ecosystems are interconnected by dynamic transport of nutrients and light attenuation. The authors used a fixed mixing coefficient (μm) in this study. In equations (5, 17), there is a linear relationship between the nutrients interacting between the two layers and the depth of the mixed layer. But in the real ocean, this relationship is influenced by wind-driven, temperature gradients, and ocean circulation, and is not necessarily linear. I suggest that the authors further explain the effects of the dynamic transport of nutrients in the model on the change of phytoplankton in the two layers in the discussion section. This not only helps to understand the applicability of the two-layered model under real-world conditions, but also provides a reference for future improvements in the model to better simulate actual ocean processes.

Thank you for this valuable suggestion. We agree that explicitly addressing this point will provide a useful reference for future users. In traditional NPZ modelling, it is common to apply a fixed mixing coefficient to represent simply the mixing processes. To improve upon this, we approximated the interaction between the two layers using a linear relationship that includes the dynamic impacts from mixed layer depth (MLD). However, we acknowledge that, in reality, this relationship is neither strictly linear nor fixed. The extent of nutrient transport from the subsurface layer can influence surface phytoplankton growth and the nutrient cycle. Future improvements in the approximation of mixing processes could enhance the model's ability to simulate phytoplankton and nutrient dynamics more realistically.

In response to your comment, and to potentially add some nonlinearity to the exchange of nutrients between layers, we have explored including an entrainment term explicitly, driven by variations in the MLD, to increase the complexity and realism of nutrient exchanges. Initially, our model did not account for interactions between particulate material across the two layers, driven by MLD variability. However, if the MLD oscillates, particulate material (in the form of phytoplankton, as zooplankton are considered

motile) from different layers could transfer between layers, through entrainment. To include this interaction, we first assumed that at each layer, the dominant phytoplankton is the superior competitor, which means intrusion of phytoplankton into the other layer will result in death (and consequent conversion to nutrient). As our model does not explicitly include a detrital variable, the death of phytoplankton adds to the nutrient pools in each layer. This interaction driven by the MLD was explicitly included in the model (see Appendix B), but did not significantly alter our main findings, confirming the robustness of our simpler, original mixing scheme. A more detailed description and corresponding results can be found in Appendix B (see pages 32-35). The blue colour in Appendix B highlighted the modifications we made to the equations in Sec. 2 in the manuscript.

Considering the comment raised, we have emphasised in the discussion that our model assumes a linear relationship between nutrients interacting between the two layers and the depth of the mixed layer, and that in cases where this relationship is not linear, our model may not be appropriate to use. We have also directed the reader to the additional experiments we did in Appendix B. See lines 543-549 on page 26 of the tracked-change manuscript.

(2) The time series of surface Ns observed in Figure 4(c) has many abrupt changes, while the model seems to follow some kind of seasonal cycle. Besides, in Figure 4(d), the standard deviation of the observed results appears to be much larger than the model, although the time-averaged results (Figure 4h) don't show this (You also mentioned this in the article). Why the observation and models are so different on these? What are the potential consequences of this. (Is it related to the daily time resolution?)

The primary reason why the observations and model differ in terms of nutrients, particularly at the subsurface layer, is that simple NPZ models generally struggle to accurately simulate the nutrient cycle, especially in deeper layers. Unlike more complex 3D ecosystem models, this type of simplified model omits many processes necessary for accurately representing the nitrogen cycle, such as nitrogen fixation. However, these processes may not be essential for addressing the main research questions of our study (simulate phytoplankton dynamics in two layers). At the subsurface layer, phytoplankton growth is only limited by light rather than nutrients, which is the main reason we did not employ a more complex nutrient modelling approach. Additionally, as you mentioned, achieving a precise point-to-point match at high temporal resolution (daily) is particularly challenging.

Regarding surface nutrients, the figure shows that nutrient measurements are very sparse, make it theoretically impossible to achieve a day-to-day match. Nevertheless, our model successfully captures the general seasonal patterns and reasonable magnitudes of subsurface nutrients, indicating that our simplified approach remains appropriate for addressing our primary research objectives. However, we acknowledge your concern and have noted this limitation in the discussion section (lines 536-537), emphasising that incorporating more complex processes in the model may be necessary for addressing scientific questions related to nitrogen cycling.

(3) For the model results, the seasonal cycles in Figure 4(e) and Figure 4(g) looks highly correlated. In contrast, the seasonal cycles in Figure 4(f) and Figure 4(h) looks anti-correlated. While, for the subsurface, there seem to be other processes affecting their relationship in winter and spring (Jan-May). Can you explain these further?

Yes, the strong correlation between surface phytoplankton (Figure 4e) and surface nutrients (Figure 4g) in the model occurs primarily because phytoplankton growth at the surface is nutrient limited. In this layer, light is typically abundant, while nutrients are depleted, thus directly controlling phytoplankton productivity. As surface phytoplankton die, they replenish surface nutrients, further reinforcing this close coupling and positive correlation.

In contrast to the surface layer, the modelled seasonality of phytoplankton (Figure 4f) and nutrients in the subsurface (Figure 4h) exhibit an anti-correlation because subsurface phytoplankton growth is limited by light rather than nutrients. In the subsurface layer, nutrients are abundant, but light is depleted, which means phytoplankton growth is not nutrient-limited, but the phytoplankton uptake of nutrients still reduces nutrient concentrations, creating an inverse relationship. Furthermore, subsurface nutrients are influenced not only by local phytoplankton death but also significantly by remineralisation of surface phytoplankton and zooplankton. During winter and spring (January–May), surface phytoplankton blooms further complicate this relationship: blooms at the surface greatly reduce the subsurface light

availability, limiting subsurface phytoplankton growth. However, these same blooms simultaneously enhance nutrient replenishment in the subsurface through increased remineralisation, making the relationship between subsurface phytoplankton and nutrients particularly complex during this period.

(4) Line 397 "This correlation becomes strong over 2011–2022, reflected by an increase in Corr. to 0.75 (Table 4)": The cause of the improved correlation isn't explored. Why does the correlation improve after 2011?

One possible reason for the improved correlation after 2011 is that the impact of ocean warming became more pronounced during the period 2011–2022. Recent research by Viljoen et al. (2024) (see Figure 2 from https://www.nature.com/articles/s41558-024-02136-6) demonstrates that the surface ocean temperature trend intensified notably from 2011 onward compared to earlier decades (1990–2010), which aligns with our findings for subsurface phytoplankton variability. Indeed, a comparison of variance in de-seasonalised subsurface phytoplankton time series reveals a marked shift. The variance of the de-seasonalised subsurface phytoplankton after 2010. For 1990-2010, it is 19.4 (mg m^{-2})^2 in the model and 14.9 (mg m^{-2})^2 in the observations, whereas it increased significantly over 2011–2022, reaching 31.2 (mg m^{-2})^2 in model and 32.7 (mg m^{-2})^2 in observations. This reduces the discrepancy in variance between model and observations from 4.5 over 1990-2010 to 1.5 (mg m^{-2})^2 over 2011-2022, highlighting that the model captures the observed increase in interannual variability associated with intensified ocean warming.

2. Suggestions for improving the content description

Abstract

(1) "reproducing trends post 2011 caused by ocean warming": I suggest going straight to the specific main trends observed at the surface and in the subsurface.

Thank you for your suggestion. We agree that this modification will make abstract more straightforward to readers. This sentence has been revised (see lines 12-15 in page 1).

(2) "simulating the ecosystem in the subsurface layer was more challenging than the ecosystem in the surface mixed-layer": I would suggest briefly mentioning why simulating the subsurface is more challenging, or specifically stating which aspects (e.g. nutrient dynamics) are not accurate.

Thank you for your suggestions and we have now added a brief explanation to this sentence as suggested (see lines 17-18 in page 1).

Introduction

In the fourth paragraph of the introduction section "A wide range of ecosystem models are available…": This part seems a bit information-dense, which may make it difficult for readers to grasp the main points. I propose to categorize the models listed and describe the ecological problems that each type can solve.

We really appreciate the suggestions and agree this paragraph needed to be improved for a broad audience to understand. We have revised the paragraph to highlight the main points, providing a general background to ecosystem modelling (see lines 54-59 in pages 2-3). However, we have not included detailed information about categorising the models and describing the ecological problems that each type can solve. We think such a task would require a more comprehensive review appropriate to a review paper, which was not the goal of our paper.

Results

Page 18: For this paragraph "To understand the drivers of the decreasing trend in $Chla_s$ over 2011–2022, we first show…", the authors explain that the vertical-average result is also decreasing, indicating that the decreasing trend is not purely caused by the decrease in surface layer water volume. This

explanation is very good. However, at the beginning of this paragraph, authors mentioned “we first show the interannual variability of observational mixed layer depth…”, readers would therefore expect this paragraph to describe the relationship between mixed layer depth and chlorophyll, and/or whether the trend of mixed layer depth affects the trend of chlorophyll. It is recommended to adjust/add appropriate content to make the content complete.

Thank you for this suggestion. We agree and have now modified this paragraph to guide the readers through the key findings (lines 417-418 in page 20). However, the relationship between mixed layer depth and chlorophyll stocks at surface layer is quite complex and we cannot explain them within one paragraph. To help readers link back to the previous paragraph to understand the full story, we also added a note in the following paragraph (lines 429-430 in page 20).

Discussion

Line 515-517: It was mentioned that “The processes designed in this model do not incorporate all the key biogeochemical processes in stratified systems, such as nitrogen fixation and iron limitation”. Could you further explain how the lack of this part will affect this study?

Yes, this model could benefit from including nitrogen fixation processes by improving the agreement between model and observations that you highlighted in your comments Question (2). Diazotrophs can fix atmospheric nitrogen and introduce them into inorganic format in oceans, which could increase the agreement between observational and modelled nitrogen at the surface layer. Given that the BATS site in the Sargasso Sea is characterised by oligotrophic surface waters often limited by nitrogen availability, including nitrogen fixation could relieve nitrogen limitation, thus influencing phytoplankton growth at the surface. Enhanced surface phytoplankton productivity would subsequently affect subsurface nutrient cycling through increased remineralisation, likely improving the agreement between modelled and observed nitrogen in both layers.

The lack of a process describing iron limitation will not significantly affect this study because BATS site is not a high-nutrient, low-chlorophyll (HNLC) zone. Typically, HNLC regions are defined by higher nitrate availability but low phytoplankton biomass due to iron limitation. Although including an iron limitation process will not impact this study, it would likely be essential for simulating phytoplankton dynamics in known HNLC areas, such as the Southern Ocean, North Pacific, or Equatorial Pacific.

3. Minor error

Informal expressions like “our ocean” and “less is known about it” should be replaced.

Thank you for pointing this out. This text has now been revised (see lines 2 and 5 in page 1).

Figure 3 caption: “The integration of chlorophyll and nutrients from model and observation, and their relationship" can be revised to: The integration of chlorophyll and nutrients from model and observation, and their relationships.

Thank you for your suggestion. We think you meant Table 3. This text has now been revised (see page 17).

Figure 4 caption: “(d) Daily nitrogen stocks at the surface layer”: This should be from subsurface.

We really appreciate you pointing this out. The text has now been corrected (see page 16).

Line 499: “Integration between 2011 to 2022” can be revised to: Integration between 2011 and 2022

Thank you for your suggestion. The text has now been revised (see line 518 in page 25).