Response to Reviewer #2

Overall Assessment and Recommendation

I appreciate the overall topic of this study, which addresses an important and timely question: the multi-centennial response of ocean biogeochemistry and marine ecosystems to anthropogenic CO2 forcing. Long-term projections beyond 2100 remain relatively scarce, and the results presented here have the potential to provide valuable insights into both the future evolution of the ocean carbon sink and the persistence of ecosystem stressors. These are important issues that deserve attention and publication.

However, I find that the current manuscript suffers from significant organizational and conceptual weaknesses. First, the scientific objectives are not clearly defined or sufficiently justified. The Introduction combines several distinct themes—including ocean carbon uptake, low-latitude productivity, nutrient cycling, ocean acidification, and ecosystem stress—without developing a coherent argument that explains why the long-term response (2100–2500) should be investigated and which specific scientific questions are being addressed. As a result, the narrative lacks focus and the reader is left uncertain about the primary goals of the study.

The Results section reflects this lack of focus. It concentrates disproportionately on the evolution of DIC and NPP, while other potentially more impactful aspects of the simulations receive limited attention. More generally, the manuscript attempts to address two major questions—long-term *carbon uptake and long-term ecosystem stressors—without clearly separating them or establishing strong links between them.*

In its current form, I do not believe that the manuscript is ready for publication in Biogeosciences. I strongly recommend a major reorganization of the paper. The authors should either clearly separate the carbon uptake and ecosystem stress components into distinct parts of the manuscript, each with dedicated objectives and analyses, or alternatively choose to focus on only one of these themes. Such a restructuring would require a substantial rewriting of the Introduction, a clearer formulation of the scientific objectives, and a reconsideration of the results presented in the central sections of the paper. I believe that these changes would significantly improve the clarity, impact, and overall scientific value of the study.

We thank the reviewer for the thoughtful and constructive assessment of our manuscript. We appreciate the recognition that multi-centennial projections of ocean biogeochemistry remain scarce and that such simulations have the potential to provide important insights into the long-term evolution of the ocean carbon sink and marine ecosystems.

We agree that the original manuscript did not sufficiently articulate its central scientific objectives or clearly explain the common scientific question linking the different components of the study. Our objective is to understand how the long-term adjustment of the ocean to anthropogenic CO_2 forcing differs among emission pathways, and how these differences shape the evolution of ocean carbon uptake, carbonate chemistry, biological productivity, and ecosystem stress over multi-centennial timescales. Rather than examining each of these processes in isolation, this study ai

ms to understand how these components co-evolve and interact during t
he long-term adjustment of the ocean to anthropogenic CO2 forcing. We
respectfully consider that ocean carbon uptake and ecosystem stress are
not independent themes, but complementary aspects of the long-term re
sponse of the ocean to anthropogenic CO2 forcing.

In response to the reviewer's comments, we will substantially revise the
manuscript. We will reorganize the Introduction to better motivate the sc
ientific importance of simulations extending beyond 2100, explicitly stat
e the scientific questions addressed in this study, and clarify the rational
e for investigating long-term ocean biogeochemical responses across m
ultiple emission scenarios. We will also strengthen the motivation for inv
estigating ecosystem stress by introducing recent studies that use Earth
system model projections to assess impacts on higher trophic levels (e.
g., FISHMIP), thereby clarifying how long-term changes in ocean biogeoc
hemistry provide an important foundation for understanding future mar
ine ecosystem responses. In addition, we will expand the discussion of pr
evious long-term Earth system simulations and more clearly position the
present study within this broader context.

We will also reorganize parts of the Results section to better distinguish
responses established during the 21st century from slower multi-centen
nial adjustment processes while emphasizing their common physical and
biogeochemical drivers. To strengthen the mechanistic interpretation, w
e will expand the analyses of biological productivity and ocean carbon st
orage. In particular, we will distinguish the contributions of preformed a
nd regenerated carbon to long-term carbon sequestration, further exami
ne the transient evolution of net primary production and export product

ion in relation to atmospheric CO2 and changes in the Atlantic Meridional Overturning Circulation, and clarify the regional characteristics of these responses. We will also add new figures, where appropriate, and promote selected supplementary figures to the main text to better illustrate these relationships.

These additional analyses will clarify that many key ocean biogeochemical responses are established primarily during the 21st century, whereas their adjustment continues over subsequent centuries. By comparing multiple emission scenarios, the revised manuscript will more clearly demonstrate how both the magnitude and persistence of these long-term responses depend on the trajectory of anthropogenic forcing, highlighting an aspect that cannot be inferred from conventional end-of-century analyses alone.

Finally, we will expand the Discussion to clarify the physical and biogeochemical mechanisms responsible for the simulated changes, compare our results more comprehensively with previous studies, and explicitly discuss important model limitations and uncertainties, including alkalinity feedbacks, sediment processes, freshwater forcing from ice-sheet melt, and uncertainties in carbonate-system buffering.

We believe that these planned revisions will substantially improve the clarity, organization, and scientific focus of the manuscript while more clearly communicating its central scientific objective of understanding how long-term ocean adjustment differs among emission pathways and the implications of these differences for ocean carbon uptake and marine ecosystems.

Specific Comments

(1) Introduction

The Introduction requires substantial reorganization. As it stands, it interweaves results and concepts related to the evolution of the ocean carbon sink, primary productivity, and ecosystem stressors (e.g., acidification), without clearly distinguishing these components or explaining why they should be considered together, nor how they potentially interact or feed back on one another. Some statements appear overly general and insufficiently supported by the literature; for instance, the claim that "low-latitude productivity is crucial for the global carbon cycle" is too simplistic and would benefit from a more explicit and better substantiated discussion.

In addition, the paragraph starting at line 59 ("Analyses using CMIP models have also advanced understanding of present-day oceanic uptake of anthropogenic CO2") transitions abruptly from present-day understanding to long-term projections without a clear logical bridge. Given the relatively limited number of studies addressing multi-centennial ocean biogeochemistry, the motivation for focusing on long-term responses needs to be strengthened. In particular, the authors should better justify why centennial-to-millennial timescales are relevant, explicitly discussing ocean adjustment timescales, (ir)reversibility of carbon-cycle changes, and the relevance for net-zero or overshoot scenarios.

We thank the reviewer for this important and constructive comment. We agree that the original Introduction did not sufficiently articulate the ov erarching motivation of the study or clearly define the scientific questions addressed. We also agree that the connections among long-term ocean carbon uptake, carbonate chemistry, biological productivity, and ecosystem stress were not adequately explained, and that the motivation for extending the analysis beyond 2100 required a stronger justification.

To address these concerns, we will substantially revise the Introduction. We will reorganize the Introduction to more clearly motivate the need for simulations extending beyond 2100 and explicitly state the scientific questions addressed in this study. We will strengthen the motivation by discussing the long adjustment timescales of the ocean and their relevance to future mitigation pathways. We will also clarify why ocean carbon uptake, carbonate chemistry, biological productivity, and ecosystem stress are investigated together by emphasizing that they represent complementary components of the long-term ocean biogeochemical response within a common Earth system framework. Furthermore, we will strengthen the Introduction by incorporating recent studies that link Earth system model projections to higher trophic-level ecosystem impacts (e.g., FISHMIP), thereby providing a clearer motivation for examining long-term ecosystem stress. We will also revise several overly general statements, including the discussion of low-latitude productivity, to provide a more balanced description supported by the relevant literature.

The revised Introduction will conclude with the following paragraph:

"Despite growing understanding of 21st-century ocean change, the long-term evolution of ocean biogeochemistry after atmospheric CO2 stabilization remains poorly constrained. Because ocean circulation, carbon stora

ge, nutrient redistribution, and ecosystem responses operate on timescales ranging from decades to centuries, substantial adjustments may continue long after atmospheric CO2 concentrations cease increasing. Understanding these delayed responses is particularly relevant for evaluating the long-term consequences of mitigation pathways. In this study, we use extended SSP simulations with MIROC-ES2L through the year 2500 to address three questions: (1) How does ocean carbon uptake evolve after atmospheric CO2 stabilization? (2) What processes control the long-term evolution of ocean carbonate chemistry and buffering capacity? (3) How do biological productivity and ecosystem stress evolve on multi-centennial timescales? By addressing these questions within a single Earth system model framework and across multiple emission scenarios, we identify how long-term ocean adjustment depends on the trajectory of anthropogenic forcing and distinguish responses established during the 21st century from slower adjustment processes that continue for centuries thereafter."

(2) Results structure and metrics

The first results section is relatively short and focuses primarily on dissolved inorganic carbon (DIC) and net primary production (NPP)/export production. This choice is not sufficiently justified. In particular, it is unclear why the evolution of ocean carbon uptake itself is not treated as a central diagnostic, given that it is arguably one of the key variables of the study.

We thank the reviewer for this helpful comment. We agree that the central role of ocean carbon uptake was not sufficiently emphasized in the original presentation of the Results. Our intention was to first describe the large-scale redistribution of dissolved inorganic carbon, which provides the physical and biogeochemical context for the subsequent analyses of ocean carbon uptake, carbonate chemistry, and deep-ocean carbon storage.

To make this progression clearer, we will revise the first Results section to more explicitly highlight the evolution of ocean carbon uptake. In particular, we will add the time evolution of the accumulated ocean carbon inventory for each scenario, thereby providing a more direct diagnostic of long-term ocean carbon uptake and complementing the redistribution of dissolved inorganic carbon. We will also revise the subsection title to better reflect that this section describes both the redistribution of dissolved inorganic carbon and the evolution of ocean carbon uptake.

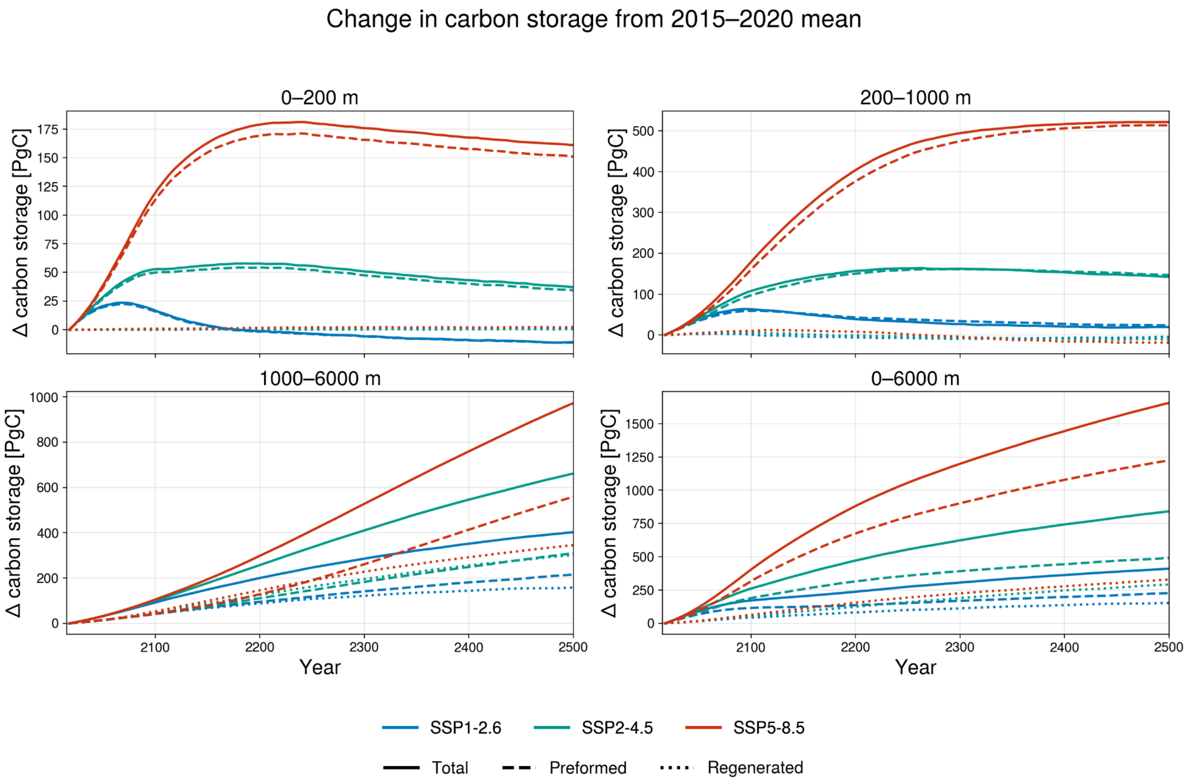

Figure R1. Time evolution of changes in ocean carbon storage (PgC) unde r the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios for the (a) 0–200 m, (b) 2 00–1000 m, (c) 1000–6000 m, and (d) 0–6000 m depth ranges. Solid lines denote total carbon storage, dashed lines denote preformed carbon stora ge, and dotted lines denote regenerated carbon storage. Regenerated car bon was estimated from apparent oxygen utilization, and preformed carb on was obtained as the residual.

(3) NPP response under contrasting scenarios

The evolution of NPP differs markedly between scenarios, with a decreas e under high-emission conditions and an increase under low-emission co nditions. This is a striking and potentially highly significant result. Howe *ver, it is not discussed or explained in any depth, which represents a mis sed opportunity given its implications.*

We thank the reviewer for highlighting the importance of this result. We agree that the contrasting responses of net primary production under lo w- and high-emission scenarios are one of the key findings of this study and deserve further discussion.

In response to this comment, we will substantially expand the correspon ding Results and Discussion sections. In particular, we will examine the t emporal evolution of net primary production in relation to atmospheric CO2 and changes in the Atlantic Meridional Overturning Circulation, hig hlighting that much of the divergence among emission scenarios is estab lished during the 21st century and subsequently evolves more gradually over multi-centennial timescales. We will also clarify the regional charac teristics of the simulated responses and discuss their consistency with p revious studies.

At the same time, we recognize that a complete attribution of the underly ing mechanisms would require additional process-oriented diagnostics a nd dedicated sensitivity experiments to separate the respective roles of physical circulation, nutrient redistribution, and biological feedbacks. Su ch analyses would require dedicated sensitivity experiments and additio nal diagnostic calculations to isolate the relative contributions of physic al circulation, nutrient redistribution, and biological feedbacks, and are t herefore beyond the scope of the present study.

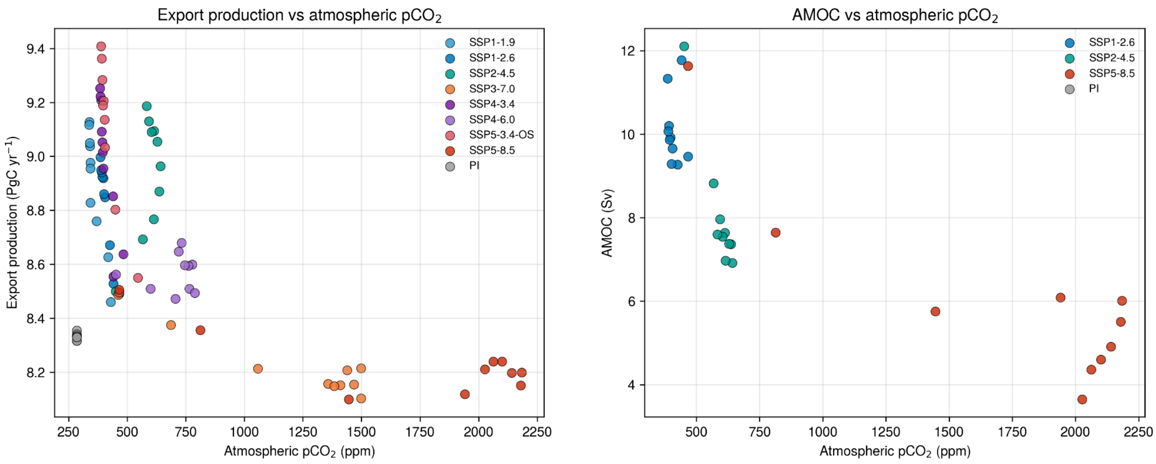

Figure R2. Scatter plots showing the relationships between atmospheric CO2 concentration and (a) global export production (Pg C yr^{-1}) for all emi ssion scenarios analyzed in this study, and (b) Atlantic Meridional Overt urning Circulation (AMOC) strength (Sv) under the SSP1–2.6, SSP2–4.5, an d SSP5–8.5 scenarios.

(4) Carbon uptake drivers and biological pump

The section describing the drivers of carbon uptake is generally well dev eloped and clearly presented. However, it would be particularly interesti ng to further explore the role of the biological pump across these long ti mescales, especially in comparison with the physical pump. In particular, the manuscript could attempt to assess whether biological processes bec ome increasingly important in controlling carbon uptake over centennial to millennial scales.

We thank the reviewer for this valuable suggestion. We agree that the rel ative roles of the biological and physical pumps in regulating long-term ocean carbon uptake deserve further discussion.

In response to this comment, we will expand the Discussion by explicitly considering the complementary roles of physical circulation and biological processes over multi-centennial timescales. Building on the newly added analysis of preformed and regenerated carbon storage, we will discuss how these diagnostics provide additional insight into the mechanisms controlling long-term carbon sequestration. In particular, we will emphasize that regenerated carbon storage continues to increase even as export production declines under the high-emission scenarios, whereas preformed carbon remains the dominant contributor to the long-term increase in deep-ocean carbon storage. These contrasting responses suggest that long-term regenerated carbon storage is influenced not only by biological export but also by changes in ocean circulation and water-mass residence time.

Accordingly, we will add the following discussion to Section 4.1.3 “Deep-ocean carbon sequestration, circulation pathways, and potential CO_2 outgassing”:

"Separating deep-ocean carbon storage into preformed and regenerated components further illustrates the complementary roles of the physical and biological pumps in long-term carbon sequestration. Although export production declines under the high-emission scenarios, regenerated carbon storage continues to increase. This contrasting behavior suggests that long-term regenerated carbon storage is influenced not only by biological export but also by changes in ocean circulation and water-mass residence time. Nevertheless, preformed carbon remains the dominant contributor to the long-term increase in deep-ocean carbon storage. These results suggest that changes in ocean circulation remain a primary control on long-term carbon sequestration, while biological processes continue to influence the redistribution and storage of carbon within the ocean interior."

A complete quantitative attribution of the respective contributions of the physical and biological pumps would require additional process-oriented diagnostics and dedicated sensitivity experiments, and is therefore beyond the scope of the present study.

(5) Ecosystem focus

The analysis of specific ecosystems (e.g., kelp forests, coral reefs) appears underdeveloped and only marginally integrated into the overall narrative. It is not entirely clear that this level of ecosystem-specific detail is essential for the scope of the manuscript, and reconsideration of this section may help improve focus and coherence.

We thank the reviewer for this helpful suggestion. We agree that the role of the ecosystem-specific examples was not sufficiently clear in the original manuscript.

Our intention is not to provide detailed assessments of individual ecosystems, but rather to illustrate how long-term changes in ocean biogeochemistry may translate into persistent ecosystem stress under different emission pathways. To clarify this objective, we will revise both the Introduction and the Results. In the Introduction, we will strengthen the motivation for including ecosystem stress by discussing recent studies that use Earth system model projections to assess impacts on higher trophic leve ls (e.g., FISHMIP), thereby placing the ecosystem analyses within a broader Earth system context. In the Results, we will reduce descriptive details associated with individual ecosystem types and instead emphasize that coral reefs, kelp forests, and other examples are intended to illustrate broader patterns of long-term ecosystem vulnerability rather than to provide ecosystem-specific assessments.

These revisions will strengthen the connection between the ecosystem analyses and the central objective of the manuscript, namely understanding how long-term ocean biogeochemical adjustment differs among emission pathways and how these differences influence future marine ecosystem stress.