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COMMENTARY
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Key Points:

- Nowicki et al. (2022, https://doi.org/10.1029/2021GB007083) asserted "that ocean carbon storage will weaken as the oceans stratify and the subtropical gyres expand"
- The physical changes in ocean stratification, ventilation, and carbon sequestration under climate warming are described
- Assuming only changes in subtropical areas without the associated changes in ventilation leads to opposite conclusion

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Physical Mechanisms Driving Enhanced Carbon Sequestration by the Biological Pump Under Climate Warming

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Abstract As ocean Carbon Dioxide Removal techniques are being considered, it is critical that they be evaluated against our scientific understanding of the global biological carbon pump. In a recent paper Nowicki et al. (2022, https://doi.org/10.1029/2021GB007083) provide an innovative and comprehensive breakdown of the different mechanistic pathways of carbon sequestration through the present-day biological pump but then speculate that "These results suggest that ocean carbon storage will weaken as the oceans stratify and the subtropical gyres expand due to anthropogenic climate change." Essentially, the authors combine their steady state result that oligotrophic subtropical gyres have lower residence times than other areas with the climate change result of these areas increasing under climate warming and extrapolate—assuming "all else is equal"—that the overall ocean will suffer a reduction in carbon sequestration efficiency. Expressing global changes in carbon sequestered by the ocean's biological pump as the summation of local changes in the sequestered carbon, timescale of return to the surface, and biogeographical area, I discuss how all three terms are tightly coupled, and summarize decades of climate change modeling consistently indicating that the global scale physical sequestration response is an increase - in opposition of what one would infer from changes in subtropical area alone.

1. Commentary

As ocean Carbon Dioxide Removal (CDR) techniques are being considered, it is critical they be evaluated against our scientific understanding of the global biological carbon pump. In a recent paper in Global Biogeochemical Cycles entitled, "Quantifying the Carbon Export and Sequestration Pathways of the Ocean's Biological Carbon Pump," Nowicki et al. (2022) provide an innovative and comprehensive breakdown of the different mechanistic pathways of carbon sequestration through the present-day biological pump by combining constraints from a suite of satellite, in situ, and process level observations, an inverse estimate ocean circulation and associated biogeochemistry. This synthesis provides a highly valuable, observationally informed target for next generation coupled carbon-climate Earth system model development. One of the major conclusions is that the subtropical thermocline sequesters less carbon than higher latitudes. However, the paper continues with unsupported speculation that "These results suggest that ocean carbon storage will weaken as the oceans stratify and the subtropical gyres expand due to anthropogenic climate change." The implicit assumption to arrive at this conclusion is that the subtropical region's sequestration/ventilation timescale remains the same low value as in present day while its area and stratification increase. Similarly implicit to arrive at this conclusion is the assumption that tropical and high latitude areas with higher present-day sequestration/ventilation times do not increase their sequestration/ventilation times as they correspondingly decrease in area while they stratify. Essentially, the authors combine their steady state result that oligotrophic subtropical gyres have lower residence times than other areas and the climate change result of these areas increasing under climate warming and extrapolate—assuming "all else is equal"—that the overall ocean will reduce in carbon sequestration efficiency. Mathematically, we can express changes in the total global amount of carbon sequestered by the ocean's biological pump (δC; PgC) as the summation of local changes in the sequestered carbon flux (F_i; PgC m^{-2} yr^{-1}), timescale of return to the surface (T_i; yr), and area (A_i; m^2): $\delta C = \Sigma_i\ \delta(F_i\ T_i\ A_i)$. Within this framework, Nowicki et al. suggest the net effect can be approximated considering changes in area alone: $\delta C \sim \Sigma_i\ F_i\ T_i\ \delta A_i$. As I describe below, these three terms are tightly coupled, and decades of climate change science have consistently indicated that the global scale physical response is in opposition of what one would infer from changes in subtropical Ai alone.

In the mean state, tropical stratification is balanced between air-sea heat flux and wind forcing while deep ocean ventilation is balanced by buoyancy forcing. The ocean response to climate change, however, involves several "unbalanced" mechanisms of coupled atmosphere and ocean interactions (Figure 1). As increases in CO_2 and

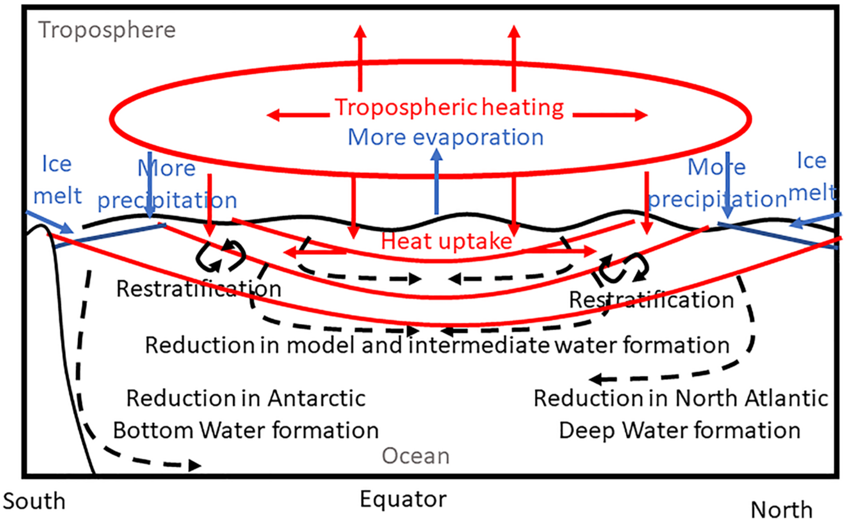

Figure 1. Schematic of the coupled atmosphere-ocean response to greenhouse gas forcing with heating in red, freshening in blue, and restratification by mesoscale eddies in black. Also shown in dashed black lines are pathways of ocean ventilation that are reduced.

other greenhouse gases trap more infrared radiation in the troposphere, temperature increases throughout the troposphere which allows it to hold more water vapor, expands the Hadley cell upward and poleward (Lu et al., 2007; Vecchi & Soden, 2007), increases sea surface temperature, and evaporates more water. Because seawater density is driven by temperature at low and mid-latitudes, as the surface ocean warms, the entire thermocline stratifies and expands. As the wind driven circulation penetrates heating into the upper thermocline, eddy restratification is critical in spreading that heat further poleward as another stratification feedback (Griffies et al., 2015; Winton et al., 2013). At higher latitudes where salinity has a more active control on seawater density, intensification of the hydrological cycle has a rectifying effect as enhanced poleward transfer of moisture from lower latitudes freshens the surface and reduces wintertime convection. This freshening stratification effect is further enhanced by the melting of land and sea ice in both the north (Swingedouw et al., 2007) and south (Bronselaer et al., 2020). As shown in the Sarmiento et al. (2004a) multi-model analysis of physical climate models and subsequent multi-model analyses of coupled carbon-climate models (e.g., Bopp et al., 2013; Kwiatkowski et al., 2020) and Intergovernmental Panel on Climate Change (IPCC) assessments, this buoyancy forcing by anomalous heating in the tropics and subtropics is complemented by enhanced freshwater to the subpolar and polar regions such that the buoyancy forcing is everywhere stratifying. These changes are well documented in both models and observations in both low (Durack & Wijffels, 2010; Durack et al., 2012; Levitus et al., 2000, 2012; Winton et al., 2013) and higher latitudes in both the Northern (Caesar et al., 2018; Manabe et al., 1991; Stouffer et al., 1989) and more recently Southern (Bronselaer et al., 2020; Purkey & Johnson, 2012) oceans with the northern mechanism analyzed as part of the IPCC 2nd assessment (Kattenberg et al., 1996). As such, these pervasive increases in low latitude thermal stratification (which dominates over counterbalancing salinity destratification) and high latitude thermal and salinity stratification (which act together to both stratify) combine for nearly ubiquitous reduction in ocean ventilation.

The biogeochemical consequences of this near ubiquitous reduction in ventilation are a combination of reduction in nutrient and associated remineralized carbon supply to the surface, enhancement of the sequestration timescale for both the solubility and biological pumps, and enhanced accumulation of remineralized nutrients and carbon through the biological pump, particularly in the subtropical gyres (e.g., Resplandy et al., 2013). While additional complicating factors such as the enhancement of Southern Ocean Westerly winds (Russell et al., 2006) and low latitude salinity forcing in a few regions such as off the coast of Chile (Gnanadesikan et al., 2012) are not necessarily well represented in models and provide diversity in model response, the overall global model response is fundamentally well grounded in geophysical fluid dynamics and thermodynamics. As described in the multi-model analyses of coupled carbon-climate models (e.g., Bopp et al., 2013; Kwiatkowski et al., 2020), the downward flux (F) in many models decreases as nutrient supply to the surface diminishes—a direct effect of the increased sequestration time of nutrients and overall decrease in surface nutrient concentration (Bopp et al., 2001; Liu et al., 2023; Sarmiento et al., 2004a). A more expansive discussion of this distinction between the rate and efficiency of carbon and nutrient sequestration by the biological pump is provided in Sarmiento et al. (2004b).

Past modeling of climate demonstrates that intensification of the ocean energy and water cycles cannot increase both overall stratification and subtropical gyre area without also increasing the residence time within the ocean interior with the assumption of Nowicki et al. (2022) having been consistently contradicted by over two decades of climate and earth system modeling (Arora et al., 2020; Sarmiento et al., 1998) and incorporated in the 4th (Solomon et al., 2007), 5th (Collins et al., 2013) and 6th (Canadell et al., 2021; Fox-Kemper et al., 2021; Lee et al., 2021) IPCC Assessments. The increase in sequestration of carbon through enhancement of biological pump efficiency was described long ago as a consequence of thermohaline circulation shutdown (Sarmiento et al., 1998) and later expanded as a consequence of generally increased stratification and reduced nutrient supply to the surface ocean (Sarmiento et al., 2004a). Multi-model analyses have confirmed these finding though each generation of coupled carbon-climate models (Arora et al., 2013; Friedlingstein et al., 2006). Most recently these effects were quantified by Arora et al. (2020; see their Figure 13) who show that biological carbon sequestration increases by about 50 PgC in CMIP6 models under strong greenhouse gas forcing (as part of 600 PgC total ocean uptake, see their Figure 3), as "The regenerated carbon pool enhances the carbon stored below the surface waters, typically providing an additional 0.2 mol C m^{-3} within the Southern Ocean and older waters spreading from the Southern Ocean into the Atlantic and below the thermocline in the Pacific."

Beyond its implications for carbon, the combination of assumptions implicitly made by Nowicki et al. (2022) is also contradicted by available reports/studies relating other elemental cycles. While the mechanisms underlying the biogeochemical response can be complex among models (Laufkötter et al., 2016), the overall regional responses have shown strong consistency (Cabré, Marinov, & Leung, 2015). On the regional scale, consequences of meridional overturning slowdown are not only the reduction indeep water formation, but also the reduction of supply of oldest water through the thermocline on the return toward the surface. This leads to some areas of increases in oxygen in areas of lowest oxygen (Cabré, Marinov, Bernardello, & Bianchi, 2015) and a general source of uncertainty with respect to regional patterns in interior ocean oxygen. On the global scale, however, multimodel studies have consistently illustrated overall deoxygenation through the combination of decreased solubility and increased sequestration time (Bopp et al., 2013; Oschlies et al., 2018).

As with all modeling studies, limitations of the models leave several aspects of uncertainty. On the physical side, it is easy to argue that the current suite of the climate models do not represent the full spectrum of structural uncertainty. All rely on the parameterizations of unresolved processes to achieve radiatively and hydrologically stable "Preindustrial controls" while at the same time representing response to radiative forcing through various direct and indirect means of "tuning" or "calibration" (Hourdin et al., 2017; Schmidt et al., 2017). On the biogeochemistry side, models commonly "tune" the major and micronutrient intensity to get the right surface nutrient distribution and carry fixed assumptions independent of temperature, acidification, or other environmental changes that may not continue to apply under environmental change or biodiversity change. While the central point of this communication is that the physical residence times increase independent of the uncertainties in biogeochemical interactions, there are also many aspects of biogeochemistry that may change, particularly sinking speeds and efficiencies (e.g., Luo et al., 2022) under increased temperature and stratification which are important areas of ongoing study. While Nowicki et al. (2022) are right to point out that when analyzing global carbon uptake or sequestration, one cannot just consider the changes in the area of each region—as changes in any of Area (A_i), Flux (F_i), and sequestration/residence time (T_i) in one region may be compensated by changes in another. One need only to look at Arora et al. (2020) for the meridional and depth dependence of the different terms in CO_2 sequestration separately to refute their argument (see Figure 11 in Arora et al., 2020).

While new insights from ever more comprehensive observations and models continue to advance our understanding of the magnitude and implications of climate change, the fundamental sign and magnitude of global climate system response to greenhouse gas forcing has remained similar over the last decades (Meehl, 2023; Stouffer et al., 1989) and consistent with historical observations (Stouffer & Manabe, 2017). One of these mechanisms is the slowing ocean ventilation. As the Earth system science community continues to grapple with the consequences of human-induced climate change and its implications for humanity, ocean biogeochemical research plays a key role in building on these advances and narrowing the uncertainties in the future carbon cycle. This understanding is fundamental to assessing the viability of ocean CDR methods in the context of our evolving coupled carbon-climate system.

Data Availability Statement

Data were not used, nor created for this research.

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