Oceans can capture more carbon dioxide than previously thought

The strength of the biological carbon pump was estimated using direct measurements of nutrients collected over decades. The findings indicate that ocean waters can capture and store larger amounts of carbon dioxide than previously estimated. This might have implications for climate-change models.

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The problem

Marine algae in the sunlit zone (within 200 metres of the sea surface) produce organic matter from carbon dioxide — a process known as primary production. The resulting matter is then transferred to deep waters through several pathways. The combination of these processes is called the biological carbon pump, which removes CO_2 from the atmosphere, captures it in organic matter and stores it in the ocean, where it can remain sequestered anywhere from days to thousands of years. The pump is therefore an important regulator of Earth's climate (Fig. 1). Because it is impossible to directly measure this carbon transfer at global scales, the strength of the biological carbon pump remains uncertain, with model estimates ranging from 5 to 12 petagrams (10^{15} grams) of carbon a year[1].

The solution

The biological carbon pump can be inferred from the concentrations of several tracers (such as nutrients, oxygen and carbon) for which direct measurements collected by ship expeditions are available, spanning multiple decades. Respiration — the breakdown of organic matter — in deep waters leaves subsurface waters enriched in dissolved inorganic carbon and depleted in dissolved oxygen. From these observations, the rate of carbon export, or transfer, to deep waters can be quantified by inverse models (which estimate a variable from the observable changes that it induces). We developed an inverse model that provides an excellent fit to the available observations. It can be used to estimate the strength of the biological carbon pump without having to measure the individual carbon fluxes.

The estimated flux of the biological carbon pump is 15 petagrams of carbon a year at a depth of 73 metres. This quantity of carbon is consistent with the estimated oxygen consumption at depth and is therefore sufficient to meet the carbon demand of mesopelagic organisms — those living below the sunlit zone. This result contrasts with some estimates obtained using *in situ* measurements[2]. Those models sometimes had difficulties balancing the metabolic energy needs of mesopelagic communities with the supply of energy-rich organic matter, possibly because some organic carbon export pathways might be missing because it is difficult to do observations year-round[2,3].

Our model's estimate of the strength of the biological carbon pump captures the annually averaged export of all organic carbon transfer pathways. Thus, it provides a helpful baseline with which to calibrate models used to predict climate change. As such, it is much more robust than satellite-observation-based estimates that rely on noisy measurements and potentially biased algorithms for calculating the net primary production and carbon export.

Future directions

Our model finds that the transfer efficiency of organic carbon from the sunlit zone to the subsurface ocean is lower in regions with higher sea surface temperatures than in cold ones. We therefore speculate that the efficiency of the biological carbon pump will decline in response to global warming. However, our model cannot establish whether the correlation is causative, nor can it provide a definitive explanation for the inferred correlation[4]. More research into the temperature dependence of the individual processes responsible for the carbon export is needed.

Another important limitation is that our model is built on the assumption that the processes do not change over time. If the pump is changing in response to global warming and other perturbations, our model would average these changes without detecting them. To detect changes in the ocean's biological carbon pump, further measurements obtained by ship expeditions, such as those that made our research possible, and a careful analysis of the differences between measurements and predictions will be essential.

Future developments of our inverse model should include the effects of seasonality, to estimate the amplitude and phase of the pump's seasonal cycle. We are working on improving our model with this goal in mind[5]. We are also including more nutrients and carbon isotopes to further improve its robustness.

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EXPERT OPINION

“A ground-breaking merit of this work is solving a long-standing caveat that has persisted in previous models and explicitly integrating distinct carbon-export pathways. The authors report an increased strength of the biological carbon pump, which has a far-reaching effect on the reconciliation of the classical conundrum regarding the carbon imbalance between upper layer supply and demand at depth. This is an extremely timely work for the community.” (CC BY 4.0)

A reviewer

FIGURE

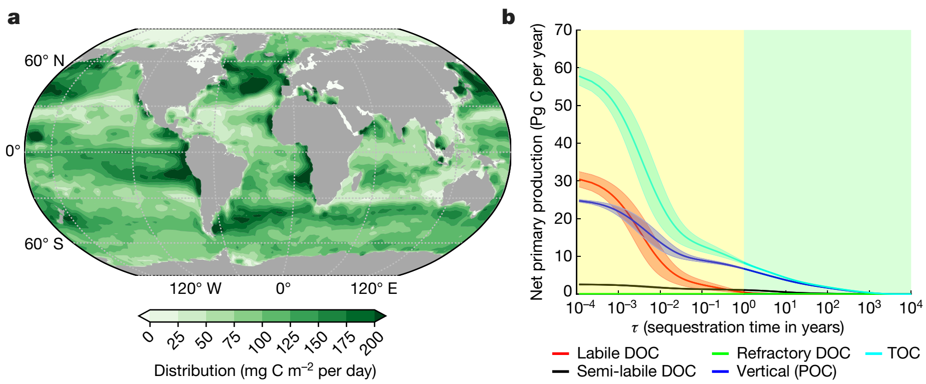

Figure 1 | Distribution of the flow of organic carbon. a, Distribution of the total organic carbon flux (in milligrams of carbon per square metre per day) at the depth (73.4 metres) used in our model. The carbon flux is highest where a large net primary production is combined with an efficient transfer to deeper waters. **b**, The sequestration time (τ) of produced organic carbon. The net primary production fluxes (in petagrams of carbon) of total organic carbon (TOC) are shown with the sequestration times. TOC contributions are separated into those of particulate organic carbon (POC) and several fractions of dissolved organic carbon (DOC), which have decay times ranging from hours to millennia. The sequestration times are measured from the time point at which the organic carbon is respired into dissolved inorganic carbon to when the regenerated dissolved inorganic carbon is transported back to the top layer of the model. The lines and shaded areas show the mean and standard deviation, respectively. The background colours indicate values shorter (yellow) and longer (green) than one year. Wang, W.-L. *et al.*/*Nature* (CC BY 4.0).

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BEHIND THE PAPER

This paper marks a milestone in our long-term goal of creating a marine biogeochemical inverse model that encompasses the cycling of key nutrients (such as phosphorus, nitrogen, carbon, oxygen, silicon and iron). One of the most appealing features of the inverse model is its ability to calibrate parameters objectively and automatically using observations, bypassing the need to manually tune the model. However, the development of this capability presented a formidable coding challenge. Specifically, we needed to encode and test 21 first-order derivative equations and 231 second-order partial-derivative ones. Notably, a substantial portion of this painstaking coding work took place during the COVID-19 pandemic, highlighting the importance of keeping an optimistic mind during difficult times.

W.-L.W.

FROM THE EDITOR

This work provides insights into the strength of the ocean’s biological carbon pump, which drives carbon storage in the deep ocean. This is important for our understanding of the carbon cycle and potential strategies for mitigating climate change in the oceans.

Juliane Mössinger, Senior Editor, *Nature*