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Response to Comment on "The Ocean Sink for Anthropogenic CO 2"

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By discussing the impact of feedbacks between the physical climate system and the oceanic carbon cycle, Keeling's comment (*1*) addresses a crucial issue in the determination of the air-sea balance of CO_2 beyond the direct oceanic uptake of anthropogenic CO_2. These feedbacks were already recognized by Sabine *et al*. (*2*) and identified as needing further research. However, based on the available evidence, we concluded that the impact of these effects on the air-sea CO_2 balance were small for the study period (1800 to 1994) in comparison with the uncertainties in the anthropogenic CO_2 reconstruction method itself. Keeling challenges this conclusion by making an attempt to quantify two of the potential feedbacks: ocean warming and increased stratification. He also suggests that Sabine *et al*. underestimated the uncertainty in their anthropogenic CO_2 estimate because the ΔC^* technique (*3*) neglects ocean warming and potential changes in ocean circulation.

Changes in the total oceanic carbon inventory represent the sum of the oceanic uptake of anthropogenic CO_2 from the atmosphere and changes in the carbon inventory caused by climate change. Therefore, the two feedbacks identified by Keeling address the latter component, whereas his challenge to the ΔC^* method addresses the former. The correct determination of the magnitude and uncertainty of the oceanic uptake of anthropogenic CO_2 and of the climate change feedbacks is of prime relevance to constrain the net balance of the terrestrial biosphere over the past 200 years (*2*). If Keeling's estimates were correct, the conclusion by Sabine *et al*. that the terrestrial biosphere was a net source of CO_2 to the atmosphere between 1800 and 1994 would be less compelling. Although we agree that these feedbacks exist, we believe that the uncertainty is too large and the estimated magnitude of these terms is too small to warrant corrections to the budget at this time.

To derive a proposed correction to the oceanic carbon uptake, Keeling (*1*) uses two different approaches. The changes due to increased sea surface temperature (SST) were estimated to be –13 Pg C from a box-diffusion model and estimated changes in SST between 1865 and 1994 from the literature. Keeling acknowledges that there is no simple way to estimate the stratification effect but, based on results from two models, he gives an estimate of +6 Pg C, resulting in a net climate feedback–induced correction of –7 Pg C. This net effect is not entirely negligible, but is highly uncertain. Even the two primary model references cited by Keeling do not agree on the sign, much less the magnitude of the net effect.

Keeling is correct in pointing out that the ΔC^* calculation is not a direct observation of the oceanic accumulation of carbon over time. Unfortunately, there are no direct measurements or proxies that give us accurate oceanic carbon distributions before the industrial revolution. Therefore, we must rely on a back-calculation approach that has a number of assumptions. The limitations of the technique, including the potential impacts of global warming, have been thoroughly discussed in the literature and are an area of active research (*3*–*6*). A recent review by Matsumoto and Gruber (*6*) concluded that the most substantial bias (perhaps –7%) assumes a constant air-sea disequilibrium, but not ocean circulation changes and warming. They found that most changes in the interior ocean are compensated in the method by referencing all properties back to the surface ocean.

Keeling's estimates of the sensitivity of ΔC^* to changes in oxygen and heat of about 0.8 mol mol^{-1} and 13 μmol kg^{-1} $°C^{-1}$ are not correct. These sensitivities apply only to a quantity referred to as C^* (*3*), whereas ΔC^* is the difference of C^* from its preformed concentration, C^{*0}. Because the input of heat into the ocean occurs primarily at the surface and calculations are made relative to the actual measured temperatures, both terms are affected equally and the net impact on ΔC^* ($C^* - C^{*0}$) is minimal. Similarly, a change in ocean interior circulation and mixing will affect both terms, resulting in a minimal effect on the ΔC^* term used to estimate the anthropogenic CO_2. Because the current uncertainty estimate already considers the known random uncertainties and biases, which have been well vetted in the literature, we see little justification for revising our conclusions.

In summary, we believe that our estimate of the ocean inventory of anthropogenic CO_2 is robust within the published error limits and that our conclusion about the role of the ocean in the global carbon budget remains justified. We need to emphasize, however, that our assessment of the impact of climate change on the ocean carbon inventory applies only to the past 200 years. We are as concerned as Keeling that climate change–induced feedbacks are starting to become substantial and may alter this balance substantially in the future (*7*, *8*). In addition to the feedbacks mentioned by Keeling, several other feedbacks may have an equal or even larger potential impact on carbon inventories in the future (e.g., changes on ocean productivity). One of the few approaches that will permit us to detect and quantify such changes is the continuation of the observational efforts to measure the distribution of carbon in the ocean and how that distribution is changing over time.

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References and Notes

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