Three-Compartment, Two Parameter, Concentration-Driven Model for Uptake of Excess Atmospheric CO2 by the Global Ocean

By Stephen Schwartz

As the title suggests, this paper describes a diagnostic, three-compartment, two-parameter, concentration-driven global model of the ocean CO_2 sink. The paper is well written and contributes to understanding of the processes governing the ocean's uptake of anthropogenic CO_2 since the beginning of the industrial age. It should be published after addressing a few small issues listed below.

The primary advantages of the model describe here are its relative simplicity and associated mechanistic transparency. This model divides the Earth system into atmospheric, mixed-layer ocean (ML) and deep ocean (DO) reservoirs. A third critical carbon reservoir, the terrestrial biosphere (TB) is not modeled explicitly, but is estimated from the difference between the anthropogenic CO_2 emissions and the anthropogenic contributions to the other reservoirs. The exchange of carbon between these global reservoirs is determined by diffusion coefficients, directly traceable to available, time-dependent observations of the atmospheric CO_2 concentration and ocean heat transport.

The exchange of carbon from the atmosphere to ML is determined by the transfer coefficient, k_{am}, and that between the ML and atmosphere is given by k_{ma}, which are governed by turbulent mixing and (to a lesser extent) concentration gradients across the interface. The transfer of carbon between the ML and DO reservoirs, k_{md}, is parameterized by a piston velocity, v_p, such that $k_{md} = v_p / z_m$, where z_m is the depth of the mixed layer. Because measurements of stocks and fluxes of carbon between the ML and DO are not adequate, the piston velocity is derived from the rate of heat uptake by the global ocean over the past 50 years.

With these definitions, the exchange of anthropogenic carbon between the atmosphere, ML and DO is described by a pair of differential equations (Equations 5.6). The deposition of anthropogenic carbon from the atmosphere into ML and DO is then described by solving these equations, with appropriate initial conditions, for the period extending from 1750 to the present. Changes in carbon stocks predicted by this model are then validated against global totals derived from global ocean biogeochemistry models (GOBMs) by the Global Carbon Project (c.f., Fig 3).

As noted above, a key asset of this simple model is its ability to identify the relationship between key transport processes and their changes over time. For example, the results presented in Figure 4 indicate that while the gross carbon transport coefficient between the ML and DO is assumed to be constant over the industrial era, the net transport coefficient has actually decreased, slightly, largely due presumably to the turnover of the DO and associated return flux to the ML during this period. However, as acknowledged here, the model cannot explicitly identify the root cause of this change.

More importantly, this simple model clearly shows that the rate of uptake of anthropogenic CO_2 by the global ocean is governed largely by the rate of exchange of carbon between the ML and DO, parameterized by the piston velocity, v_p, in this model. In contrast, the ML stock is insensitive to the value of v_p, such that the transfer coefficient between the atmosphere and ML can be approximated by assuming that the atmosphere and ML are in equilibrium without introducing large errors (lines 580-582). This result is not a surprise to those most familiar with existing measurements and models of the ocean carbon sink, but it is not generally recognized across the larger carbon cycle community, and is not as obvious from results of GOBMs or Earth System Models.

This result has two critical implications for existing carbon cycle models. First, as noted in Section 7, because the efficiency of the ocean CO_2 sink depends strongly the exchange of anthropogenic carbon between the ML and DO, uncertainties in this transport (parameterized as v_p in this model) drive uncertainties in the ocean sink. More importantly, and NOT mentioned here, any CHANGE in ocean dynamics associated with climate change that alters the net ML to DO transport of carbon could have significant consequences for the efficiency of the ocean sink. The author is strongly encouraged to reinforce this point.

Minor points:

Line 12: "This piston velocity is determined from the measured the rate of uptake of heat …'

➔ This piston velocity is determined from the measured rate of uptake of heat …

Line 140: "… the net land-use–change (LUC) emission, represents the net annual carbon flux from the TB into the atmosphere from net deforestation, i.e., the flux from deforestation minus that from afforestation."

Land use change also affects soil carbon, grasslands, etc. Is that ignored here, or just rolled into this term?

Line 145: This paragraph suggests that the only significant changes in the TB are LUC from deforestation/afforestation. These are the primary processes, but other processes should be acknowledged. For example, the TB also exchanges carbon with the ocean through river runoff. This is mentioned in the next paragraph and discussed in sections 4.2 and 5, and 6. However, at this point, the reader does not know whether this process is ultimately ignored (as acknowledged in section 4.2, line 422, section 6, line 785) or incorporated into the ocean or TB reservoirs. In addition, on longer time scales, atmospheric CO_2 is lost through weathering and sedimentation. These terms are all small on annual to centennial time scales, but should be acknowledged.

Line 153: "The PI ML and the DO are in steady state."

Do you mean "In in the PI, ML and DO are assumed to be in steady state."

Line 180: "…the TB is not actively modeled but is evaluated, mainly for reference, as the residual between time-dependent integrated anthropogenic emissions and the anthropogenic stocks in the other three compartments."

The author might note that this assumption is partially justified by the fact that over the industrial era, stock changes associated the TB sink roughly equal those from land use change, such that the these two processes largely cancel out, leaving the ocean as the only net sink of anthropogenic carbon during this period.

Lines 689 – 700 '… Where is this ^{14}C coming from? It must be coming from the terrestrial biosphere, …

That is at least one source. Another possibility is that it is coming from land use change (LUC) that disturbs soil that was exposed to ^{14}C during the atmospheric test period.

Line 904-905: " …there is no confident measure of the amount of CO_2 that has been (or is being) taken up by the terrestrial biosphere"

This statement is slightly dated. The amount of CO_2 that is being taken up by the terrestrial biosphere is now being monitored at increasing spatial resolution by a growing fleet of space-based sensors. While the CO_2 fluxes estimated from these measurements still have significant uncertainties (~0.3 to 1 PgC/yr when integrated over the globe), there is growing confidence in their results.

Line 902: The focus on prognostic CO_2 models in the opening paragraph of the Discussion seemed a little strange, given that the model described here is a diagnostic model that "cannot be used prognostically" as acknowledged on line 25. Later in this (long) paragraph, it states "As a means of assessing their accuracy, these models are run in emissions-driven mode over time historically over the Anthropocene to obtain the integrated net uptake of emitted CO2 into the global ocean and the terrestrial biosphere; the difference between emissions and uptake is the anthropogenic increase of atmospheric stock, which can then be compared to atmospheric measurements. Such comparisons, together with comparison of results of multiple models serve as a measure of the confidence that can be placed in the models and their predictive capability." Only then can we make this connection. You might consider reorganizing this paragraph to introduced the value of the diagnostic approach before documenting the challenges of Earth System Models.

Lines 954-959: "The largest contribution …"

These two sentences state what is perhaps the most profound scientific conclusion presented in this paper. While not entirely new, these points are often obscured by the complexity of GOBMs and Earth System Models. You might consider moving these points the beginning or end of a paragraph. You might also consider rewording this conclusion to emphasize its implications beyond the details of the model described here. For example,

"The largest contribution to uncertainty in the rate and extent of uptake of anthropogenic CO2 by the global ocean is due to uncertainties in the transport between the ML and DO, simulated here as v_p, which is uncertain by ~20% 1-sigma. As DIC in the ML ocean is in near equilibrium with atmospheric CO_2, uncertainty in the transfer coefficient (deposition velocity) governing the gross rate of uptake of atmospheric CO_2 by the ML, (simulated here by k_{am}), makes only a minor contribution to the overall uncertainty in the rate of uptake of atmospheric CO_2 by the global ocean."

Then start a new paragraph with "There is some indication in the model results …"

Finally, throughout the paper, a few dozen commas are needed to improve readability. Whenever a sentence starts with a preposition, (line 40: "About 250 years ago humankind …" → "About 250 years ago, humankind …"), it should be followed by a comma. This is currently done about half the tiem. Variables introduced as appositives should also be offset by commas (line 217, "The rate of volume exchange F_V may" → "The rate of volume exchange, F_V, may …" (line 218, "denoted piston velocity v_p." → "denoted piston velocity, v_p."