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Carbon futures: a valiant attempt to bring scientific order from modeling chaos

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The global carbon cycle, the continual exchange of carbon between the oceans, terrestrial ecosystems and the atmosphere, provides a massive subsidy to the human enterprise, absorbing roughly half of fossil fuel and land use emissions of CO$_2$ and thus reducing the climate impact of the human enterprise by half (Le Quéré et al 2015). The uptake of CO$_2$ by the oceans and land plants is due to feedbacks between atmospheric CO$_2$, climate and the terrestrial and marine reservoirs of carbon. The net effect of these Earth system feedbacks is to translate emissions of CO$_2$ into atmospheric concentrations that are about half of what they would be otherwise (figure 1). If the strength of these feedbacks were to change, that the impact on climate of human emissions will change.

Earth system models simulate the interaction of the carbon cycle and the physical climate system. They include the physical, chemical and biological processes that control the oceanic storage of carbon, and are calibrated against geochemical and isotopic constraints on how ocean carbon storage has changed over the decades and carbon storage in terrestrial vegetation and soils, and how it responds to increasing CO$_2$, temperature, rainfall and other factors. These models build on decades of work in the oceanographic and ecological communities, but their inclusion in models of the Earth’s climate system is relatively recent (Fisher et al 2014).

When models of the coupled carbon cycle–climate system are used to simulate the next century, they diverge wildly (Friedlingstein 2015). While ocean models disagree about future carbon uptake rates, terrestrial models do not even agree about the sign of future carbon exchange, with some showing continued uptake, and others indicating weakening uptake or even transitioning to sources. These lead to plots, sometimes called spaghetti plots, because lines showing future carbon uptake trajectories are so confusing.

In a recent paper, Lovenduski and Bonan (2017) asked whether the confusion of future carbon and climate could be simplified to a single strand by assigning weights to models based on their ability to simulate key carbon cycle observations. This general approach has been used before, for other aspects of climate system models, and has often significantly reduced overall uncertainty. However, this case, they found that applying even a very strict constraint, requiring models to almost perfectly match the observational record, still resulted in a wide range of future carbon scenarios.

That is, models which simulated the past century or so equally well, disagreed wildly when simulating future conditions, and the bulk of this disagreement came from the land model components. They differed in their sensitivity to changing future concentrations of CO$_2$ and climate implying they matched the past record for different reasons. This may reflect the nature of the carbon cycle, where changes in storage reflect small difference between large and opposing flows of uptake and release, allowing models considerable freedom as to how to capture that small difference.

They identify three sources of uncertainty in carbon cycle–climate model projections, the assumed human emission trajectory itself, the simulated natural variability of the system itself, and model-to-model differences. To make a long story short, for terrestrial carbon models, the latter dominates, despite the wide range of emission scenarios included. Lovenduski and Bonan then use weighted model averaging to demonstrate the impact this model-to-model variation has on the prediction from a set of models. They do this by weighting the model results in the average, based on the model’s ability to reproduce observations of the past. Even applying very strict weighting, emphasizing the small number of models closest to the observations, scarcely reduced the overall spread of results.

This highlights a problem with weighted averaging of carbon cycle–climate models. Model averaging implicitly assumes the same parameters and processes exist across the models, so averaging makes sense.
Figure 1. Earth system feedbacks translate human emissions from fossil fuel burning and deforestation into atmospheric concentrations. The current operation of the Earth system removes nearly half of human emissions, but if this changes in the future, far more stringent mitigation might be required to achieve climate targets. The Earth system sinks on land and the oceans (right-hand arrows) depend on atmospheric CO$_2$ itself, climate and other factors that are imperfectly understood! Values shown are consistent with Le Quéré et al (2015), for the year 2014.

(Banner and Higgs 2017). However, today’s carbon cycle models, especially the land models, vary greatly in the processes and level of detail they include, and so averaging may not be appropriate. As Lovenduski and Bonan note, the models differ even in the net sign of their results, and so their weighted central tendency may not be very informative. A better approach would be to evaluate specific regions and processes within models, but global data currently available aren’t resolved enough to allow this.

This is an important study that quantifies and illustrates with clear measures the persistent disagreements between carbon cycle–climate models. There are a wide range of hypotheses about the dominant controls and key parameter values governing land carbon storage, and a parallel range of ways in which these hypotheses are implemented in the codes of land models. While the historical performance of ocean models can be benchmarked against global inventories of ocean carbon, only recently have equivalently robust global estimates been developed for some components of land carbon storage (Saatchi et al 2011) and soils, the largest reservoir, remains very sparsely sampled. This leads to inadequate data for both model falsification and improvement, as Lovenduski and Bonan show so dramatically.

In fact, the ecosystems with the largest reservoirs of carbon, and the most vigorous exchange, are the least sampled, and so it may be no surprise that these poorly-understood systems are not simulated well (Schimel et al 2015). The largest reservoirs of carbon on land are in the forests of the tropics and the soils of northern high latitudes, which are paradoxically, the least studied of terrestrial ecosystems, with the bulk of research effort made where most ecologists live, in the mid-latitudes.

Lovenduski and Bonan show that terrestrial models that fit historical data roughly equally well predict very different futures. This is not new but, they have done a service by illustrating this issue with incisive clarity. They provide motivation for a new round of model development conducted in close concert with observational studies. New approaches to gathering data, and far closer coordination between observational and modeling studies are required to identify and quantify correctly the critical processes that have governed and will control the carbon cycle in the future.

Attempts to mitigate future climate change are based on climate targets, reflecting atmospheric greenhouse gas concentrations. These concentrations are used to set targets for emission reduction assuming an emission-concentration relationship. If relationships between emissions and concentrations change in the future, assumptions that global emission mitigation regimes depend on could fall apart. Key climate targets might not be met if future land and ocean sinks...
weaken in ways we cannot now predict. Lovenduski and Bonan’s work illustrates how far away we are from confident prediction of future emission-concentration relationships.

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