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Quantifying uncertainty in future ocean carbon uptake

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Key Points:
- Partitioning uncertainty in air-sea CO_2 flux is important to understanding future carbon uptake and planning observing networks
- To meet climate stabilization targets, uncertainty in carbon uptake dominates total uncertainty in allowable emissions

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Abstract Attributing uncertainty in ocean carbon uptake between societal trajectory (scenarios), Earth System Model construction (structure), and inherent natural variation in climate (internal) is critical to make progress in identifying, understanding, and reducing those uncertainties. In the present issue of Global Biogeochemical Cycles, Lovenduski et al. (2016) disentangle these drivers of uncertainty in ocean carbon uptake over time and space and assess the resulting implications for the emergence timescales of structural and scenario uncertainty over internal variability. Such efforts are critical for establishing realizable and efficient monitoring goals and prioritizing areas of continued model development. Under recently proposed climate stabilization targets, such efforts to partition uncertainty also become increasingly critical to societal decision-making in the context of carbon stabilization.

Future climate will be largely determined by the combination of fossil fuel CO_2 emissions and mitigation, land use, and uptake of anthropogenic carbon by land and ocean. To simulate these coupled carbon-climate feedbacks, a suite of Earth System Models (ESMs) has been developed that simulate not only climate dynamics and thermodynamics but interactive biogeochemistry, ecology, and land use associated with carbon cycling through the atmosphere, land, and ocean.

The power of model intercomparison is threefold as (1) a scoping assessment of the "state of the art," (2) a "best guess" via the ensemble average of models with independent and opposing errors, and (3) a characterization model spread about the mean, or model diversity. The most recent Coupled Model Intercomparison Project Phase 5 (CMIP5) [*Taylor et al*., 2012] used in the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC AR5) [*Ciais et al*., 2013] contrasted climate projections under four scenarios of future human behavior. These Representative Concentration Pathways, or RCPs, spanned a range of assumptions from limited climate mitigation—so called "business as usual"—to rapidly and intensively adapted climate mitigation. These RCPs span global radiative forcing range of 2.6–8.5 W m^{-2} with associated emissions and concentrations of greenhouse gases and aerosols over the 21st century [*Meinshausen et al*., 2011]. A multimodel suite of ESMs were used to project the coupled carbon-climate responses under each of these RCPs. In addition, the Community Earth System Model (CESM) group conducted a 53-member ensemble with RCP4.5 and RCP8.5 to characterize the role of natural variations in climate, or model internal variability [*Kay et al*., 2015].

Analysis of climate model ensembles provides critical information toward the detection and attribution of possible climate change drivers and impacts. The challenges to detection and attribution come in three main modes of uncertainty: the fundamental chaotic nature of climate variability, the uncertainty in future scenarios associated with human behavioral choices, and the structural uncertainty associated with the many diverse approximations and parameterizations in models. Several years ago, *Hawkins and Sutton* [2009, 2011] proposed an approach to attribute uncertainty in predictions of climate variables to these modes of internal variability, scenario uncertainty, and model structural uncertainty. A schematic of factors involved in this ensembling process is shown in Figure 1. This approach has gained considerable traction and is now being applied on a suite of variables at both global and regional scales.

In the present issue of Global Biogeochemical Cycles, *Lovenduski et al*. [2016] analyze the global and regional patterns and trends of CO_2 flux into the ocean in both the CMIP5 multimodel suite and a large ensemble of one CMIP5 member. The authors demonstrate that on the global scale, internal variability initially dominates the total uncertainty before structural uncertainty takes over after approximately a decade. By midcentury, however, scenario uncertainty eventually dominates the total uncertainty. At the regional scale, they further demonstrate the dominance of structural uncertainty throughout the century with a much larger secondary role played by internal variability than at the global scale. The authors thus powerfully illustrate this high

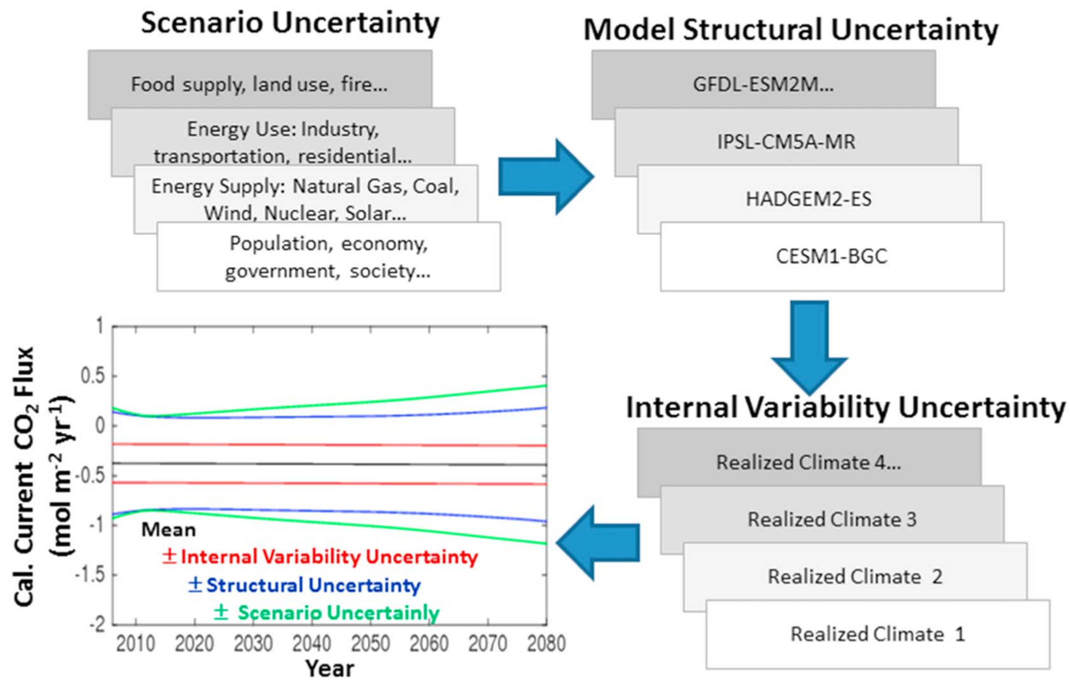

Figure 1. Schematic of the ensembling process for the set of (top left) societal decision-making scenarios for population, emissions, land use, etc., which are fed into a suite of different Earth System Models that represent (top right) coupled carbon-climate interactions in models of the global general circulation which provide a suite of (bottom right) simulations that have independent realization of climate variability within a model type (variability uncertainty) and differences due to model formulation (structural uncertainty). These results are analyzed to assess and attribute the three sources of climate variability as they evolve regionally for the (bottom left) California Current with the structural uncertainty (blue lines) more than doubling the near-term fundamental uncertainty associated with climate variability (red lines) on the absolute CO_2 flux (black line), and with scenario uncertainty (green lines) gradually increasing the total uncertainty over the century (Figure 1, bottom left; analysis and image courtesy of Nicole Lovenduski (personal communication, 2016)).

relative internal and structural uncertainty (lower signal to noise) as the key challenge to detection and attribution of air-sea carbon cycle fluxes at the regional scale. Creatively highlighting needs for future model development, *Lovenduski et al*. [2016] point out that scenario uncertainty dominates over internal variability relatively early in regions of high anthropogenic CO_2 flux across the air-sea interface (North Atlantic, North Pacific, and Southern Ocean), but that model structural uncertainty dominates over scenario uncertainty throughout the century in most other regions. This relatively large role of uncertainty at the regional scale is highlighted in Figure 1 (bottom left) which shows that total uncertainty in the air-sea CO_2 flux in the California Current (green lines) far exceeds the mean flux (black line) due to the dominant role of structural uncertainty (blue lines). Even just considering internal variability (red lines), the uncertainty in the mean flux is of order 50%. This fundamental uncertainty poses a critical challenge for the design and interpretation of potential CO_2 flux monitoring systems and demonstrates the continued need for ESM development toward decreasing structural uncertainty and harnessing potential predictability in the carbon system to make best use of initialized prediction (initial value) systems capable of reducing the uncertainty associated with internal variability.

The original analyses with this method focused on key observables of climate change, surface air temperature [*Hawkins and Sutton*, 2009], and precipitation (2011). The advantage to focusing on key observables was in affording the interpretation and attribution of change in this observable. The disadvantage is the inability to relate the attributed uncertainty to underlying processes and mechanisms. Rather than focus on the key observable parameter of carbon dissolved in the ocean, *Lovenduski et al*. [2016] focus on the process level metric of air-sea gas fluxes with an eye toward identifying the model mechanisms most sensitive to the three types of uncertainty and thus to identify key areas of future model development. One fundamental role of ocean circulation is to geographically dislocate the areas of CO_2 uptake from the areas of anthropogenic carbon accumulation. The *Lovenduski et al*. [2016] key finding that the early dominance of structural uncertainty occurs in the high air-sea CO_2 flux regions of the North Atlantic, North Pacific, and Southern Ocean points to a need for particular focus on improving model fidelity in these regions.

Meanwhile, with industry adoption of higher emission standards and growth of alternative energy economies becoming ever more widespread, the concept of "business as usual" itself is changing, with the highest emission scenarios seeming increasingly unlikely in recent years. The framework proposed last year in Paris (COP21) provides a landmark shift in focus from "climate change" to "climate stabilization." If the COP21 momentum continues to drive policy, the climate modeling community will shift projections from change under future warming to ongoing equilibrium to current climate. With the 1.5C threshold ostensibly met and 2C threshold approaching [*Rogelj et al*., 2016], the climate target becomes ever more certain and uncertainty in emissions trajectories becomes ever more dependent on assumptions concerning the land and ocean carbon cycle response. Critically, the climate warming trajectory appears to be tightly coupled to cumulative CO_2-equivalent emissions [*Matthews and Caldeira*, 2008; *Matthews et al*., 2009; *Zickfeld et al*., 2009; *Krasting et al*., 2014]. In the relatively unconstrained scenarios of climate change gross emissions and the structural uncertainty in climate sensitivity dominate the global response. In strong contrast, scenarios of climate stabilization must necessarily be relatively tightly constrained to near zero net CO_2-equivalent emissions, and uncertainty in allowable emissions is directly driven by structural uncertainty in the land and ocean carbon cycle. As such, the current scientific research focus on carbon system change under anthropogenic forcing is also evolving toward "carbon sustainability" research.

In the context of coupled climate and carbon cycle sustainability, the type of ocean carbon research and associated model development discussed in *Lovenduski et al*. [2016] will become increasingly important. To support the robust characterization of carbon system responses to societal decisions in support of climate sustainability, research should transition from rudimentary structural description focused on scenario uncertainty toward structural and internal variability uncertainty. Under "sustainable" (net zero) emissions, climate services provided by land and ocean carbon cycles reequilibrating to changed climate will largely determine allowable energy trajectories. Ocean-related challenges requiring more comprehensive Earth System Modeling include identification of climate services of carbon storage in marine environments such as "Blue Carbon," [*Nellemann et al*., 2009] assessment of potential stressors and their tipping points such as acidification and meridional overturning, characterization of biodiversity change, detection and attribution of carbon change such as the present study of *Lovenduski et al*. [2016], and primary factors determining climate carbon feedbacks and trajectories in dominant carbon pools such as the Southern Ocean.

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