### Causes and Implications of Persistent Atmospheric Carbon Dioxide Biases in Earth System Models

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### Abstract

The strength of feedbacks between a changing climate and future CO₂ concentrations is uncertain and difficult to predict using Earth System Models (ESMs). We analyzed emission-driven simulations—in which atmospheric CO₂ levels were computed prognostically—for historical (1850–2005) and future periods (RCP 8.5 for 2006–2100) produced by 15 ESMs for the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5). Comparison of ESMs’ prognostic atmospheric CO₂ over the historical period with observations indicated that ESMs, on average, had a small positive bias in predictions of contemporary atmospheric CO₂. Weak ocean carbon uptake in many ESMs contributed to this bias based on comparisons with observations of ocean and atmospheric anthropogenic carbon inventories. We found a significant linear relationship between contemporary atmospheric CO₂ biases and future CO₂ levels for the multi-model ensemble. We used this relationship to create a contemporary CO₂ tuned model (CCTM) estimate of the atmospheric CO₂ trajectory for the 21st century. The CCTM yielded CO₂ estimates of 600 ± 14 ppm at 2060 and 947 ± 35 ppm at 2100, which were 25 ± 25 ppm below the multi-model mean during these two time periods. Using this emergent constraint approach, the likely ranges of future atmospheric CO₂, CO₂-induced radiative forcing, and CO₂-induced temperature increases for the RCP 8.5 scenario were considerably narrowed compared to estimates from the full ESM ensemble. Our analysis provided evidence that much of the model-to-model variation in projected CO₂ during the 21st century was tied to biases that existed during the observational era, and that model differences in the representation of concentration-carbon feedbacks and other slowly changing carbon cycle processes appear to be the primary driver of this variability. By improving models to more closely match the long-term time series of CO₂ from Mauna Loa, our analysis suggests uncertainties in future climate projections can be reduced.

### Observations and Calculations

- We used an observationally based estimate of anthropogenic CO₂ uptake by the ocean, produced by Khatiwala et al. (2009, 2013) using a Green’s function model for ocean tracer transport, in combination with observed atmospheric CO₂ and fossil fuel emission estimates to assess model biases in carbon accumulation in the atmosphere, ocean, and land reservoirs.

### Figures

1. **Observed Carbon Accumulation Since 1850**

2. **Causes and Implications of the Contemporary Bias**
   - A key driver of the persistent high bias was weak ocean carbon uptake exhibited by the majority of ESMs.
   - The high atmospheric CO₂ bias for the multi-model mean produced radiative forcing that was too large and, consequently, an unrealistically high temperature increase during the historical period.
   - We will see that the atmospheric CO₂ bias persists into the future, causing large and divergent model projections during the 21st century.

3. **ESM Historical Atmospheric CO₂ Mole Fraction**

4. **Contemporary Biases in Atmospheric CO₂**

5. **Persistence of Biases into the Future**

6. **Causes and Implications of the Contemporary Bias**

7. **Probability Density of Atmospheric CO₂ Mole Fraction**

### Discussion and Conclusions

- Many of the processes that contribute to contemporary carbon cycle biases persist over decadal timescales.
- Terrestrial and ocean carbon accumulation compensated for one another within individual models (R = 0.91), reducing the bias in predicted atmospheric CO₂.
- The CCTM estimates of atmospheric CO₂ were 21 ppm lower than the multi-model mean in 2060 and 32 ppm lower at 2100, suggesting that stabilization targets may be unnecessarily loose.
- Uncertainty estimates derived from this approach were almost 6 times smaller at 2060 and almost 5 times smaller at 2100 than those from the ESM ensemble.
- Community-based model benchmarking (e.g., ILAMB) and model tuning could reduce biases and decrease multi-model spread of future predictions.

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