Characterizing Carbon Sink Responses to Decarbonization across Model Structures

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Biogeochemical feedbacks dictate the net land and ocean carbon sinks

The global carbon cycle

Anthropogenic fluxes 2013-2022 average GtC per year

- Fossil CO$_2$ $F_{fossil}$
- Land-use change $F_{landuse}$
- Ocean uptake $F_{ocean}$
- Stock flux $F_{stocks}$
- Atmospheric increase $F_{atm}$
- Budget imbalance $F_{imbalance}$

Friedlingstein et al. 2022
Biogeochemical feedbacks dictate the net land and ocean carbon sinks

The global carbon cycle

Structure of FaIR (Simple Climate Model)

Friedlingstein et al. 2022

Adapted from Leach et al. 2021
Biogeochemical feedbacks dictate the net land and ocean carbon sinks

Structure of FaIR (Simple Climate Model)

- Timescale adjustment, \( a(t) \)
- Emissions of \( \text{CO}_2 \)
- Concentrations of \( \text{CO}_2 \)
- Effective radiative forcing
- Temperature

Gas pools (Carbon Cycle model)

- \( \tau_1 \)
- \( \tau_2 \)
- \( \tau_3 \)
- \( \tau_4 \)

Anthropogenic fluxes 2013-2022 average GtC per year

- Fossil \( \text{CO}_2 \), \( E_{\text{Fossil}} \)
- Land use change, \( E_{\text{LUC}} \)
- CDR not included in \( E_{\text{LUC}} \)
- Ocean uptake, \( S_{\text{trans}} \)
- Land uptake, \( S_{\text{land}} \)
- Atmospheric increase, \( G_{\text{atm}} \)
- Budget Imbalance, \( B_{\text{budget}} \)

Friedlingstein et al. 2022

Adapted from Leach et al. 2021
Biogeochemical feedbacks dictate the net land and ocean carbon sinks

Structure of FaIR (Simple Climate Model)

Friedlingstein et al. 2022

Adapted from Leach et al. 2021
SCMs are tuned to observations and ESMs, only ESMs in the future

ESM process representation

SCMS parameters are tuned to reproduce the ESM output (using CMIP scenarios for future)
SCMs increasingly used to assess and interpret climate mitigation
Structure of the carbon cycle inside these SCMs varies a lot.
Models reproduce historical emissions to concentration

- Out of the box, models can reproduce observed record of CO$_2$ concentrations since pre-industrial
  - FF and LUC emissions data from Global Carbon Budget 2021 (Friedlingstein et al., 2022)
- Demonstrates their ability to capture carbon cycle in an emissions regime.
SCMs vary by ~100 Pg C in remaining carbon budget

• Using each model’s TCRE and ZEC, we can compute remaining carbon budgets for a temperature change limit of 1.5°C.
SCMs show spread in remaining carbon budget and net-zero date

- Using each model’s TCRE and ZEC, we can compute remaining carbon budgets for a temperature change limit of 1.5°C.
- From these budgets, we can project simplified linear ramp-down trajectories to estimate time-to-net-zero emissions.
- RCBs vary by ~100 Pg C and 20 years in net-zero date.
Replaced timescales in FaIR with a 9-box land and 7-box ocean model.

FaIR

FaIR_bgc

Parton et al. 1987, 1988 (CENTURY), Potter et al. 1993 (CASA), Swann 2010, Toggweiler 1999
Sampled biogeochemical feedbacks by perturbing parameters

FaIР:

- 3 parameters that influence the carbon cycle
- 11 parameters → energy balance model
- Concentrations of CH₄ and N₂O are held constant

- $r_0$, preindustrial uptake from atmos.
- $r_U$, lifetime adjustment to cumulative uptake
- $r_T$, lifetime adjustment to atmos. temperature
Sampled biogeochemical feedbacks by perturbing parameters

**FaIR:**
- **3 parameters that influence the carbon cycle**
  - 11 parameters $\rightarrow$ energy balance model
  - Concentrations of CH$_4$ and N$_2$O are held constant

**FaIR$_{bgc}$:**
- **5 parameters that influence the carbon cycle**
  - 11 parameters $\rightarrow$ energy balance model
  - Concentrations of CH$_4$ and N$_2$O are held constant

$r_0$, preindustrial uptake from atmosphere
$r_U$, lifetime adjustment to cumulative uptake
$r_T$, lifetime adjustment to atmosphere temperature

$\beta$, fertilization factor
$Q_{10}$, respiration rate ratio
$S_{kw}$, gas exchange scaling
$S_\Psi$, circulation scaling
$S_{dbh}$, circ. response to climate

Parton et al. 1987, 1988 (CENTURY), Potter et al. 1993 (CASA), Swann 2010, Toggweiler 1999
Compare atmospheric CO$_2$ and carbon sinks to observations

Friedlingstein et al. 2022
We see minimal changes to TCRE (calculated using the esm-flat10-zec emissions trajectory)
Small shift in ZEC with different carbon cycle structures
Use 3xp to diagnose emergent timescales of carbon removal
FaIR_bgc carbon cycle parameters connect timescales with processes

Variance explained ($R^2$) by FaIR_bgc parameter

- $\beta$, fertilization factor
- $Q_{20}$, respiration rate ratio
- $S_{b_0}$, gas exchange scaling
- $S_{q}$, circulation scaling
- $S_{ag}$, circ. response to climate

Land

Ocean
Variance explained ($R^2$) by FaIR_bgc timescales

$\tau_1$

$\tau_2$

$\tau_3$
FaIR\_bgc timescales cannot explain variance in temperature response

For comparison:
Contributions to TCRE in C4MIP ESMs:
FaIR_bgc energy balance model parameters explain variance in temperature response.

Variance explained ($R^2$) by FaIR_bgc timescales:
- $\tau_1$
- $\tau_2$
- $\tau_3$

Variance explained ($R^2$) by EBM parameters:
- $\lambda$, climate feedback
- $\kappa_2$, heat transfer coefficient
- $\kappa_3$, heat transfer coefficient
EBM parameters the control energy fluxes and evolution of temperature

\[ \begin{align*}
C_1 T_1 & \\
\kappa_2 (T_1 - T_2) & \\
C_2 T_2 & \\
\varepsilon \kappa_3 (T_2 - T_3) & \\
C_3 T_3 & \\
\lambda & T_1
\end{align*} \]

Variance explained (R²) by EBM parameters

- \( TCRE1000 \)
- \( ZEC50 \)
- \( ZEC500 \)

\( \lambda \), climate feedback

\( \kappa_2 \), heat transfer coefficient

\( \kappa_3 \), heat transfer coefficient

Cummins et al. 2020
Why do carbon sink timescales influence ZEC so little?

Timescale adjustment, $\alpha(t)$

Emissions of CO$_2$

Concentrations of CO$_2$

Effective radiative forcing

Temperature

Gas pools (Carbon Cycle model)

Thermal layers (EBM model)
Why do carbon sink timescales influence ZEC so little?

No structural link between processes that govern carbon and energy fluxes!
Ocean carbon uptake and heat uptake are both impacted by circulation.
Hypothesis: if we correlate ocean circulation with ocean heat uptake, the influence of carbon uptake on ZEC may change.

Does the influence of carbon cycle timescales increase when thermal boxes are connected through correlation to carbon cycle boxes?

• Created a new Latin Hypercube ensemble with correlated parameter values for $S_\psi$ and heat transport, $\kappa_3$. 

![Diagram showing relationships between various parameters and ocean circulation scalars.]

Heat transport to deep ocean
Can adding correlation between circulation rate and thermal transfer shift TCRE?
TCRE gets stronger!
Can adding correlation between circulation rate and thermal transfer shift ZEC?
ZEC gets weakly more negative
Uncorrelated: circulation affects CO₂ and climate through atmos. CO₂

Historical emission of CO₂ →

In constraining to observed CO₂ and ΔT,

We select other parameters that compensate for these circulation-driven outcomes.

Sluggish circulation
- slow ocean sink → higher atmos. CO₂ → Stronger atmos. warming

Fast circulation
- rapid ocean sink → lower atmos. CO₂ → Weaker atmos. warming
Historical emission of CO₂ →

Sluggish circulation:
- Slow ocean sink → Higher atmos. CO₂ → Stronger atmos. warming

Fast circulation:
- Rapid ocean sink → Lower atmos. CO₂ → Weaker atmos. warming

In constraining to observed CO₂ and ΔT

We select other parameters that compensate for these circulation-driven outcomes.
Historical emission of CO₂ →

**Sluggish circulation**
- Weak ocean heat uptake → Warmer atmos. temperature → Stronger atmos. warming
- Slow ocean sink

**Fast circulation**
- Rapid ocean sink → Lower atmos. CO₂ → Weaker atmos. warming
- Strong ocean heat uptake

In constraining to observed CO₂ and ΔT:
We select other parameters that compensate for these circulation-driven outcomes.

lower atmos. CO₂ → $G(k_{T1} + k_{T3})$
Compensating shift in EBM parameters when constrained to CO$_2$ & T

In constraining to observed CO$_2$ and ΔT, we select other parameters that compensate for these circulation-driven outcomes.
Compensating shift in CC parameters when constrained to CO$_2$ & T

In constraining to observed CO$_2$ and $\Delta T$

We select other parameters that compensate for these circulation-driven outcomes.
Implications for remaining carbon budget?
Drop in RCB in correlated ensemble $\rightarrow$ different emissions necessary to meet mitigation goals.
Drop in RCB in correlated ensemble $\rightarrow$ different emissions necessary to meet mitigation goals.

![Graph showing remaining carbon budget by model and implied linear ramp-down in emissions.](image-url)
Connecting carbon and climate dramatically changes the decarbonization rate needed for mitigation.
Implications for CESM Community

Need for ESM-driven constraints on connections between processes that influence carbon and climate:

→ e.g. ESM carbon fluxes and heat fluxes as outputs from emissions-driven runs

→ Carbon cycle PPEs would allow us to sample across realizations of the carbon-climate system