The E3SM Biogeochemistry Group: Progress and Plans

Kate Calvin and Susannah Burrows
(on behalf the whole E3SM BGC team)

The BGC Team

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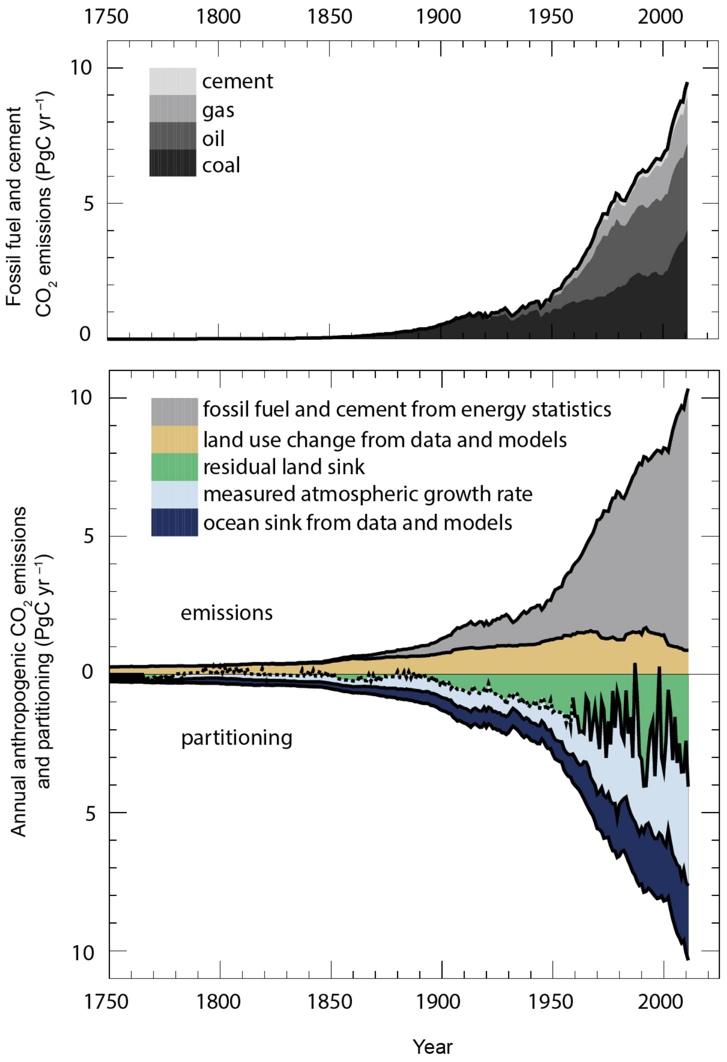
Future changes in the Earth system have consequences for biogeochemistry

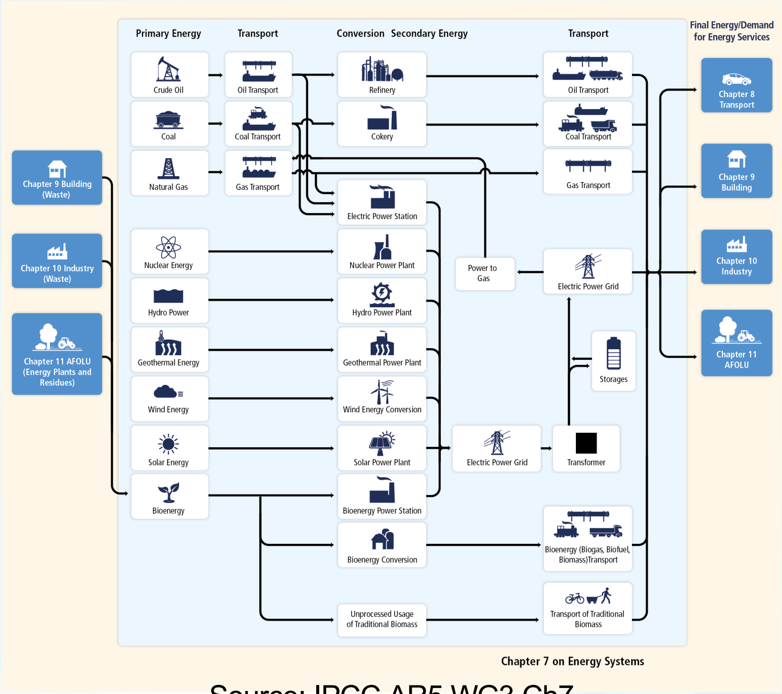
- The RCP8.5 results in:
  - Increased air temperature,
  - Soil drying in North America,
  - Increased forest fires in the US, and
  - Permafrost thaw.
- These changes could reduce terrestrial carbon storage and ocean carbon uptake.
  - **Nutrient availability** limits biological CO_2 uptake in both land and ocean.
  - The land sink is substantially modified by human-driven land use change (e.g., conversion of forests to crops).



Future changes in the Earth system also have consequences for the energy system.

- Earth system changes have implications for energy and land, including:
  - Increases in energy use for air conditioning,
  - Changes in electricity generation (thermoelectric, hydropower, wind, and solar),
  - Changes in crop yields and bioenergy potential,
  - Energy system disruptions (e.g., power outages).

The Energy System



Source: IPCC AR5 WG3 Ch7

Science Questions

- Overarching Question:
  - How do the biogeochemical cycles interact with other Earth system components to influence energy-sector decisions?

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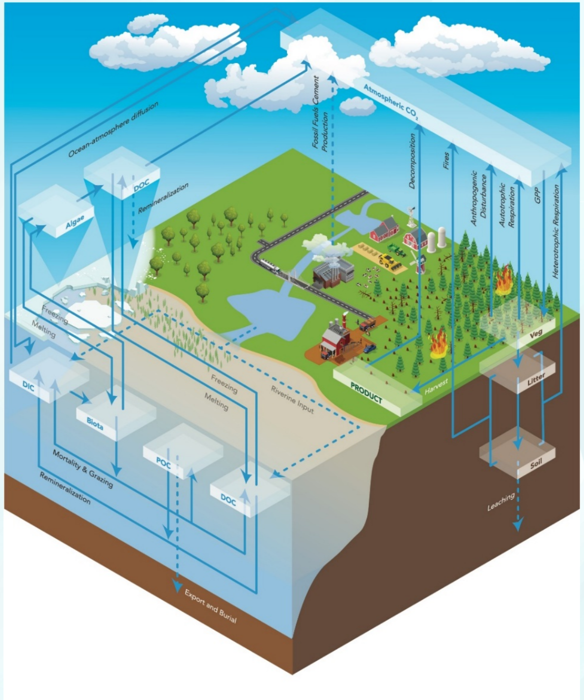
  - How do the biogeochemical cycles interact with other Earth system components to influence energy-sector decisions?
- V1 Question:
  - What are the effects of nitrogen and phosphorous on climate-biogeochemistry interactions, and how sensitive are these interactions to model structural uncertainty?

Carbon and nutrient cycles in the DOE's Earth System Model

- **Objective:**
  - Introduce, describe and evaluate the introduction of carbon and nutrient cycle simulations into U.S. DOE's Energy Exascale Earth System Model (E3SMv1.1-BGC).
- **Approach:**
  - Characterize ecosystem-climate responses in a standard set of simulations.
  - Evaluate the model using observational benchmarks, such as measurements of atmospheric carbon dioxide concentrations and surface exchange.
  - Explore the impact and structural uncertainties of terrestrial nitrogen and phosphorus limitations.
- **Impact:**
  - The evaluation showed significant improvements to the land-based carbon cycle compared to previous models. Important biases were identified in the ocean carbon cycle, which will be improved in future versions of E3SM.
  - E3SMv1.1-BGC provides a platform for future studies of coupled Earth systems. It represents an important step towards the development of an emission-driven model in E3SMv2, which will enable studies of the Earth System response to a range of future energy scenarios.



E3SMv1.1-BGC allows researchers to model the Earth's carbon cycle and how it interacts with land use and energy systems.

Burrows, et al., 2020. "The DOE E3SM v1.1 biogeochemistry configuration: description and simulated ecosystem-climate responses to historical changes in forcing," *Journal of Advances in Modelling Earth Systems, 12, e2019MS001766. https://doi.org/10.1029/2019MS001766 .*

Estimating future ecosystem-climate feedbacks using the E3SM v1.1 BGC model

Objective

- Quantify the land, atmosphere, and ocean components of coupled biogeochemistry-climate system feedbacks under a high forcing future scenario.

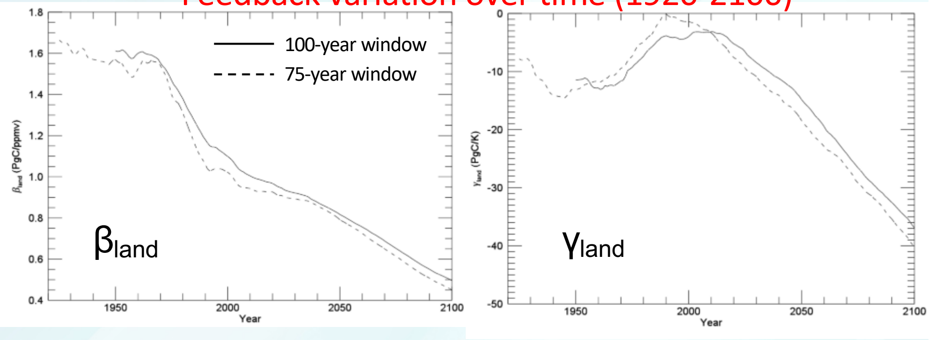
Approach

- Use a moving-window multi-year regression approach to estimate spatial and temporal variation in feedback metrics from a series of E3SM v1.1 BGC simulations.

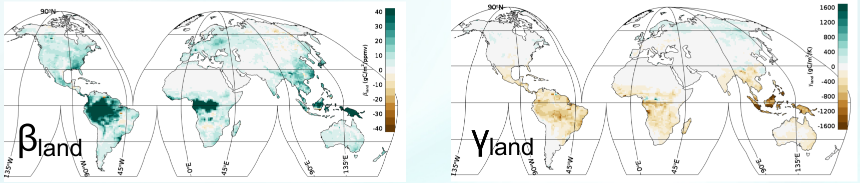
Results

- CO_2 fertilization feedback (β_{land}) weakens over time due to increasing nutrient limitation, resulting in less C uptake. Climate feedback (γ_{land}) strengthens over time as increased respiration overtakes additional nutrient mineralization, resulting in more C release.

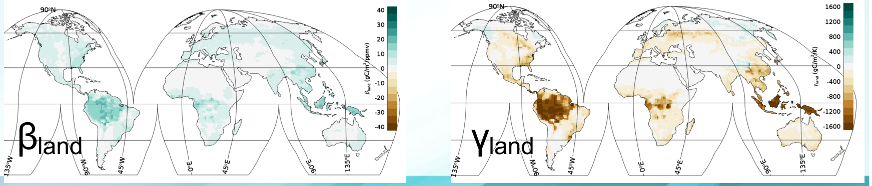
Feedback variation over time (1920-2100)



Feedbacks assessed at 2015



Feedbacks assessed at 2100



Progress: v1 Papers

Title (or topic)	Lead Author	Status
Investigating controls on sea ice algal production using E3SMv1.1-BGC	Nicole Jeffery	Published
The DOE E3SM coupled model v1.1 biogeochemistry configuration: overview and evaluation of coupled carbon-climate experiments	Susannah Burrows	Published
Implications of Phosphorous on the carbon cycle	Peter Thornton	Analyzing simulation results
Nutrient limitations on the carbon cycle	Qing Zhu	Analyzing simulation results
Observationally-inferred nutrient limitations and perturbation responses	Bill Riley	Planning/Scoping
Analysis of BGC impacts on atmospheric dynamics	Bryce Harrop	Analyzing simulation results
The implications of structural uncertainty on carbon cycle dynamics	Ben Bond-Lamberty	Not Started

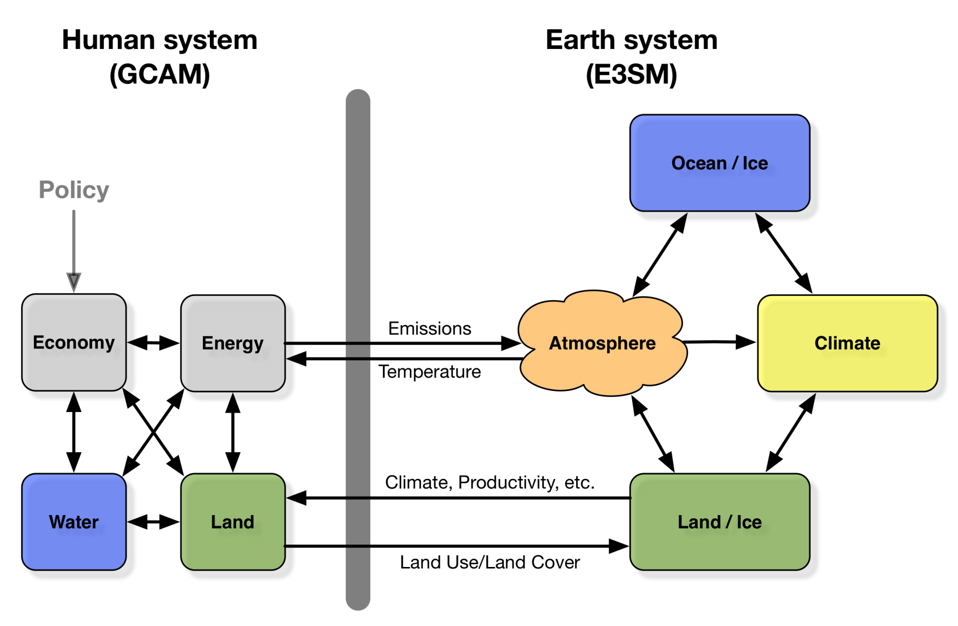
Science Questions

- Overarching Question:
  - How do the biogeochemical cycles interact with other Earth system components to influence energy-sector decisions?
- V2 Question:
  - What are the implications of different energy futures for the biogeochemical cycle through changes in land use land cover, water availability, and extreme events?

Energy Developments for v2

- 🟡 Couple the Global Change Analysis Model (GCAM) with the E3SM
  - GCAM to E3SM: LULCC, CO_2 emissions, Non-CO_2 emissions/concentrations
  - E3SM to GCAM: changes in land productivity

Enhanced E3SM-GCAM



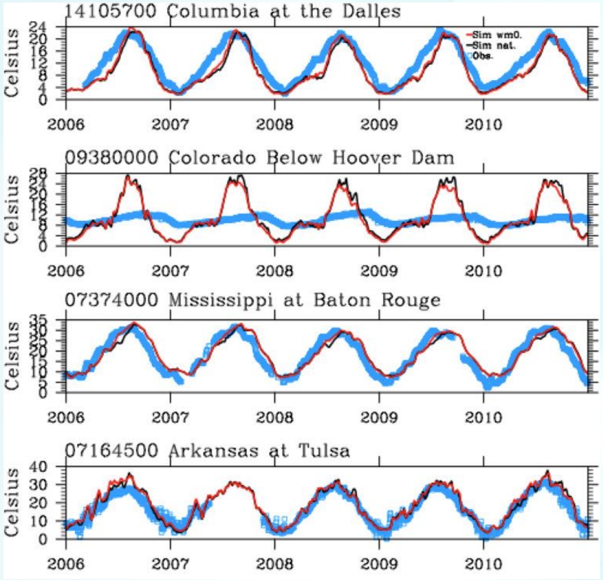
🟢 = Complete, 🟡 = In Progress

Land/River Model Developments for v2

- Developments for the core simulations:
  - 🟢 Soil erosion
  - 🟢 Stream temperature
  - 🟢 Vegetation scheme
  - 🟡 Variable soil thickness

- Developments for sensitivity simulations:
  - 🟢 Vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES)
  - 🟢 Crop model, with explicit representations of maize, wheat, and soybean

Stream Temperature



Simulated (red, black) and observed (blue) stream temperature for different river basins. Simulated temperatures are with (red) and without (black) water management.

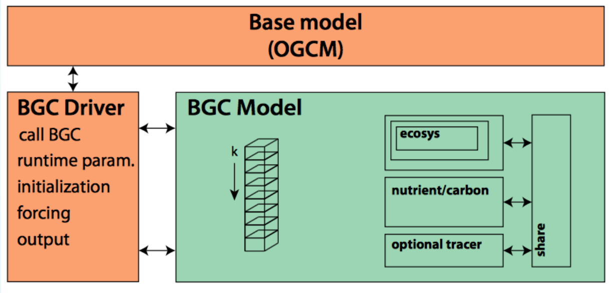
🟢 = Complete, 🟡 = In Progress

Li, H.-Y., et al. (2015), Modeling stream temperature in the Anthropocene: An earth system modeling approach, JAMES.

Ocean, Ice, and Atmosphere Developments for V2

- Ocean & Ice:
  - Incorporate MARBL, a modular framework for representing biogeochemistry, into MPAS-O
  - Improvements to ocean physics, including Redi mixing
  - Improved river nutrient inputs
  - Black carbon and dust deposition on sea ice
  - Super cycling of tracer advection

Marine Biogeochemistry Library (MARBL) Schematic



- Atmosphere:
  - Fixes to conserve carbon

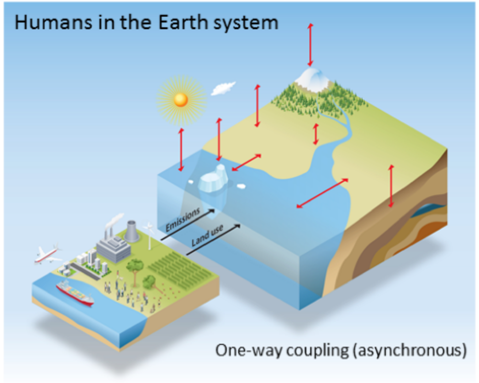
= Complete, = In Progress

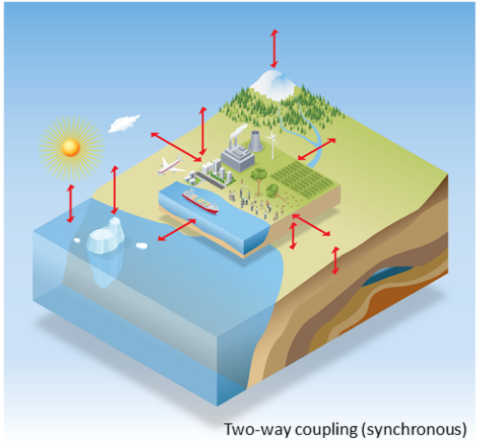
Simulation Plan

- Model configuration:
  – Regionally-refined model, branching from water cycle
  – Active biogeochemistry in the atmosphere, land, ocean, and sea ice

- Simulation modes:
  – One-way coupling (CMIP-like)
  – Two-way coupling, with human-Earth system interactions

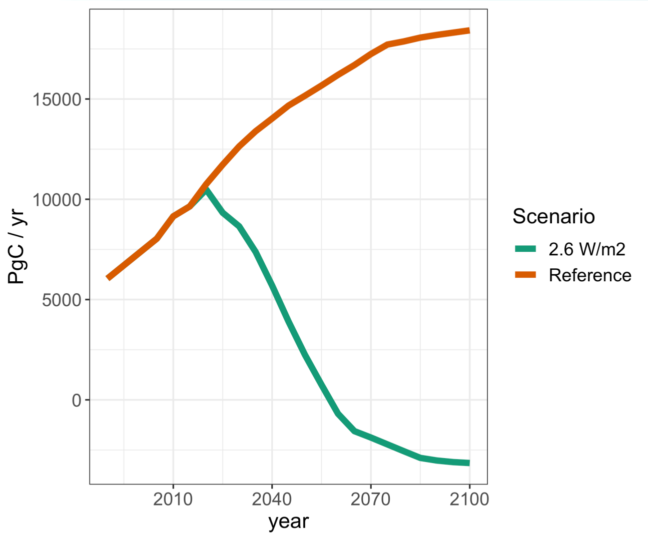
BGC Simulation Modes



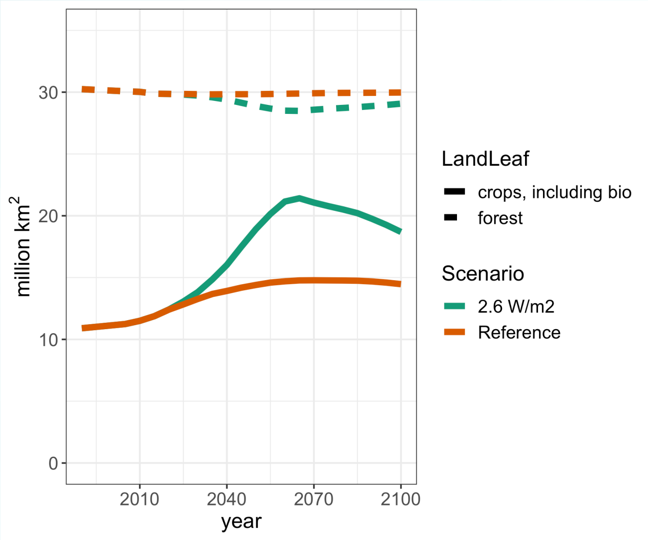


Simulation Plan

Fossil Fuel CO_2 Emissions



Cropland and Forest Cover



Simulation Plan

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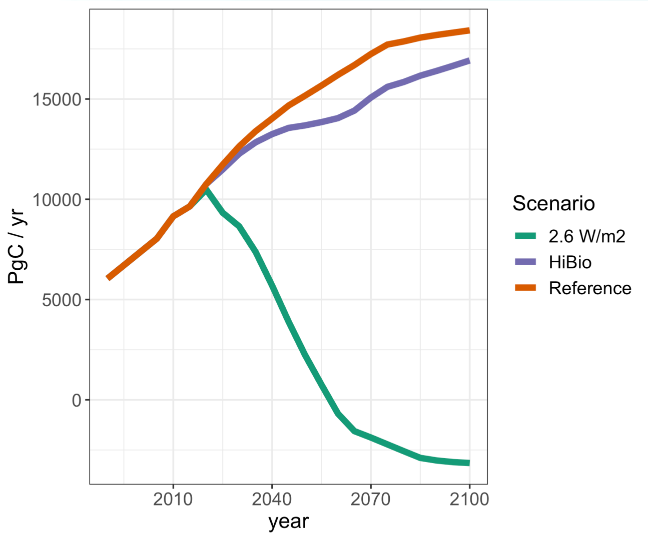
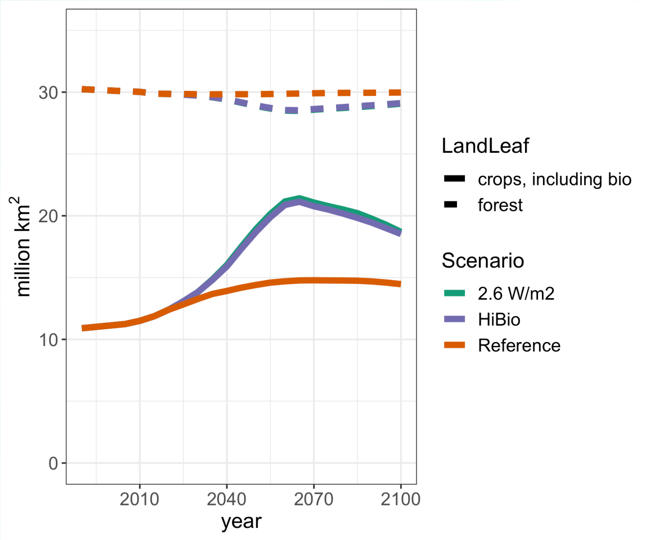


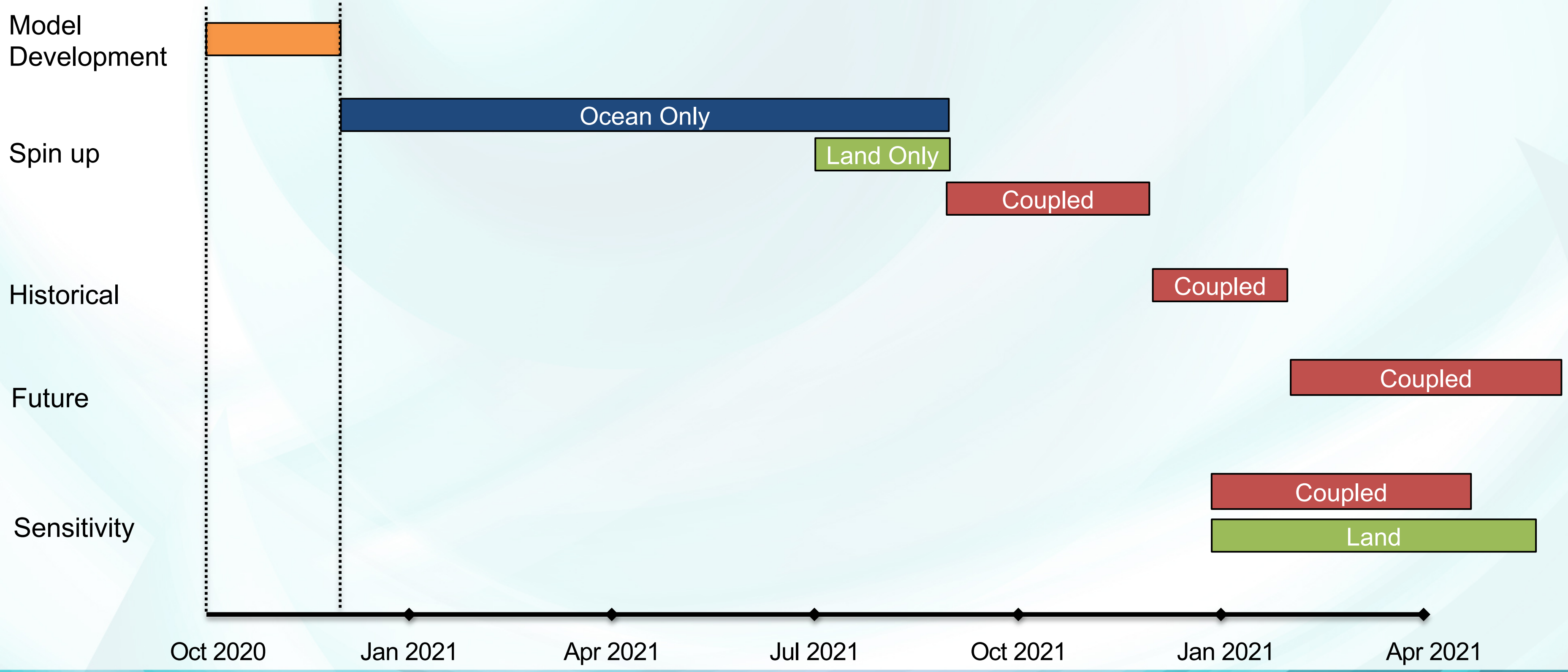
Cropland and Forest Cover



Simulation Plan

- To understand the effect of model features and forcing factors, we will perform a series of land-only, ocean-only, and coupled model sensitivity experiments, including simulations:
  - With different initial conditions,
  - With and without FATES (offline land model only),
  - With and without explicit crops, and
  - With and without RRM.

Timeline


Model Development
Spin up
Ocean Only
Land Only
Coupled
Historical
Coupled
Future
Coupled
Sensitivity
Coupled
Land
Oct 2020
Jan 2021
Apr 2021
Jul 2021
Oct 2021
Jan 2021
Apr 2021

Thank you!