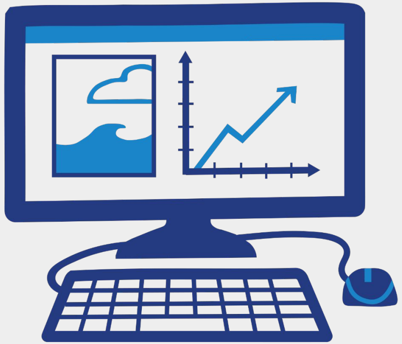


Innovations in Coupled System Modeling
Air-sea, ice-ocean and land-ocean interactions

Theresa Morrison

Q1: Concerning GFDL's core strength of building and improving models of the weather, oceans, and climate for societal benefits, how can GFDL leverage advances in science and computational capabilities to improve its key models? What are the strengths, gaps, and new frontiers?

Coupled System Modeling at GFDL

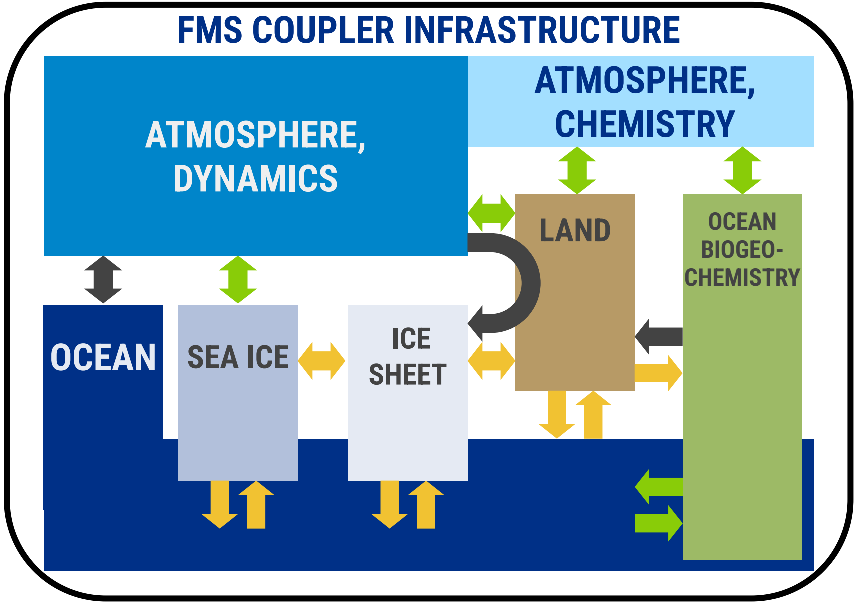


Diagram showing the connection between the different components of the Earth System developed at GFDL and the FMS framework that connects them.

Often, coupled model components are developed by independent groups connected in a “hub-and-spoke” framework. At GFDL, by working across disciplines and with the Flexible Modeling System (FMS) coupler, components can be coupled implicitly.

This implicit coupling is made possible by the exchange grid inherent to the FMS coupler. First demonstrated in the land-atmosphere coupling, implicit coupling is being applied to the ice-ocean coupling, and will be used in land-ocean coupling. Implicit coupling reduces lag between component states which can cause instabilities or make representing some parts of the Earth system impossible.

In these slides, achievements of coupling of the land, ocean, and atmosphere are highlighted. Then gaps in land-ocean coupling and on going development to address them are shown. Finally, the status ice-ocean coupling is discussed.

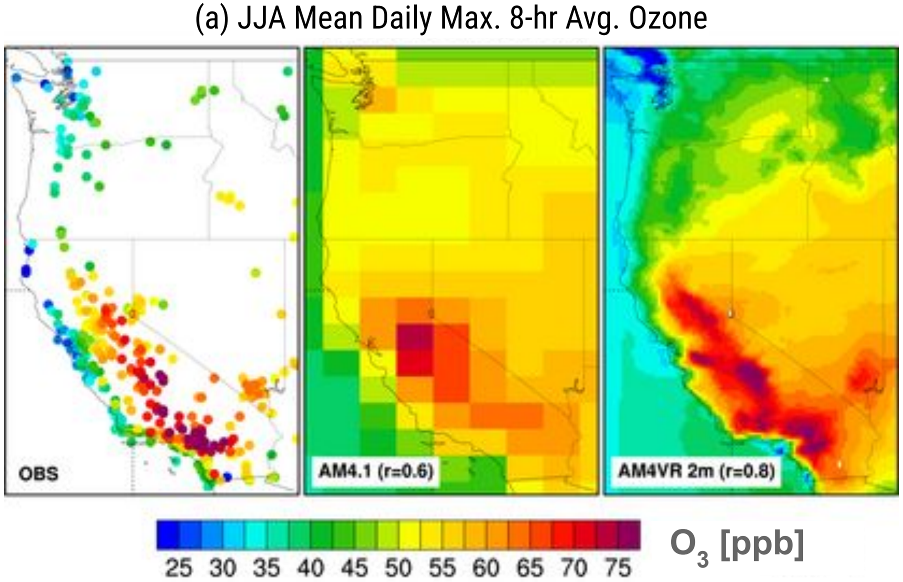
Land-Atmosphere Coupling Represents Earth System Feedbacks

Implicit coupling of the land and atmosphere coupling has been successful and motivated expanding this tight coupling to other components.

Interactions between the atmosphere and biosphere, included in the land component, are important for representing the Earth system feedbacks that are needed to better represent air pollution, drought, and extreme heat.

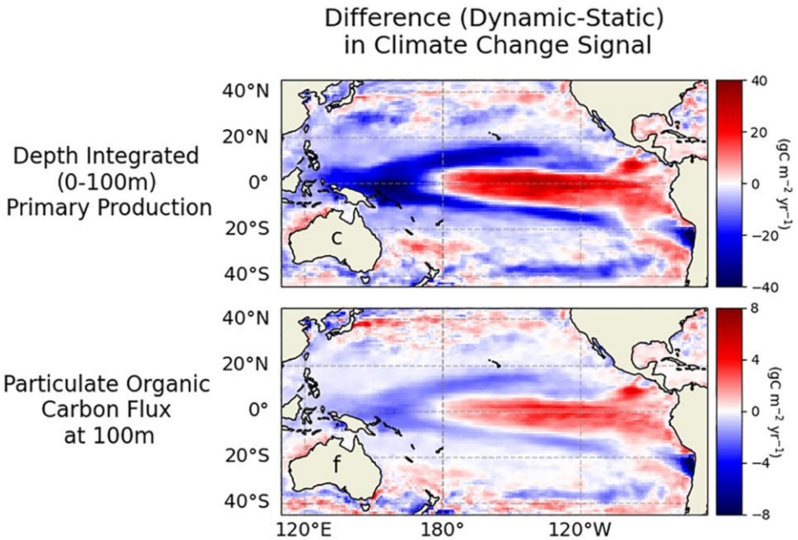
By using the sub-grid decomposition of Paulot et al 2018 to account for surface heterogeneity and implicit land-atmosphere coupling, Lin M. et al 2024 was able to investigate of how improved representation of precipitation and drought impact air quality.

Meiyun Lin will discuss AM4VR in more detail in Question 2.



From Lin M. et al 2024 (Figure 26), near surface ozone concentrations in a simulations with (AM4VR) and without (AM4.1) dynamic vegetation. The improvement in ozone pollution over CA reflects many changes; including biosphere-atmosphere coupling through which better representation of summer droughts leads to a reduction in ozone removal by vegetation.

Land-Atmosphere-Ocean Coupling



From Figure 3 of [Drenkard et al 2023](), difference in the multi-decadal mean changes (future—historical) in integrated upper-ocean primary production and particulate organic carbon flux from simulations with dynamic and static iron deposition. Simulations with dynamic deposition show an increase in productivity in the central and eastern equatorial Pacific, and decrease in westward and poleward waters relative to simulations with static deposition.

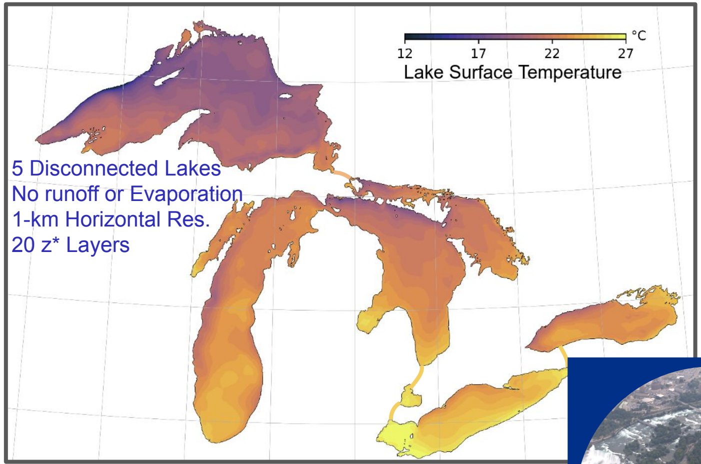
Similarly, coupling of the land, atmosphere, ocean, and biogeochemistry models is important for representing the nitrogen cycle and nutrient limitation in the ocean.

An interactive representation of nitrogen exchange between the ocean and atmosphere was used to show the compensating effects of increasing atmospheric CO_2 and marine nitrogen enrichment. ([Paulot et al 2020]())

Bringing together the coupling of the land-air-sea for the dynamic deposition of dust is important to future projections of tropical Pacific nutrient limitation. [Drenkard et al 2023]() showed key shifts in primary productivity and nutrient limitation climate change signals with and without dynamic dust.

These studies are able to explore changes to ocean biochemistry that result from combined changes in land and ocean properties because of the coupling of these components.

Using MOM6 for Large Lakes



August 2023 Lake Surface Temperatures from a regional Great Lakes configuration being developed by He Wang using MOM6.

Niagara Falls, C. M. Highsmith 2018

Niagara Falls is represented using a hydraulic jump, where the velocity is capped at a value proportional to the upstream supercritical flow. Porous barriers represent the subgrid scale channels and rivers that connect the Great Lakes to each other and the ocean.

The Great Lakes influence regional climate through heat and moisture fluxes. The MOM6 is being developed to be suitable to simulate the Great Lakes which were previously represented using a one-dimensional lake model in the land model. This requires new two-way coupling of land and oceans where properties are passed from land to ocean and back to land.

In CM4 and ESM4, without lake circulation, there are biases in the lake surface temperature and lake ice that can be addressed by using the ocean model to simulate the lake circulation.

Improvements to MOM6 including porous barriers ([Wang et al 2024]) and hydraulic jumps will allow simulation of Great Lakes and connecting waterways in the next generation of global models (CM5) and regional models, as shown on the left.

Future work includes expanding the set of represented lakes to include the Caspian Sea, large Canadian Lakes, Lake Baikal, and the African Great Lakes.

Connecting Rivers and Oceans

Other innovations in land-ocean coupling are focused on the connection between rivers and the ocean. These connections will improve GFDL model's ability to simulate coastal zones.

Tidal forcing

The stream flow is changed by tidal forcing far upstream, which can contribute flooding.

Salt inundation

Both rivers and groundwater, sources of freshwater for coastal cities, are vulnerable to salt intrusions as sea levels rise.

Nutrients from rivers

The vertical distribution of river nutrients is important for the biogeochemical response, especially in higher resolution models where shelf and estuaries are resolved.

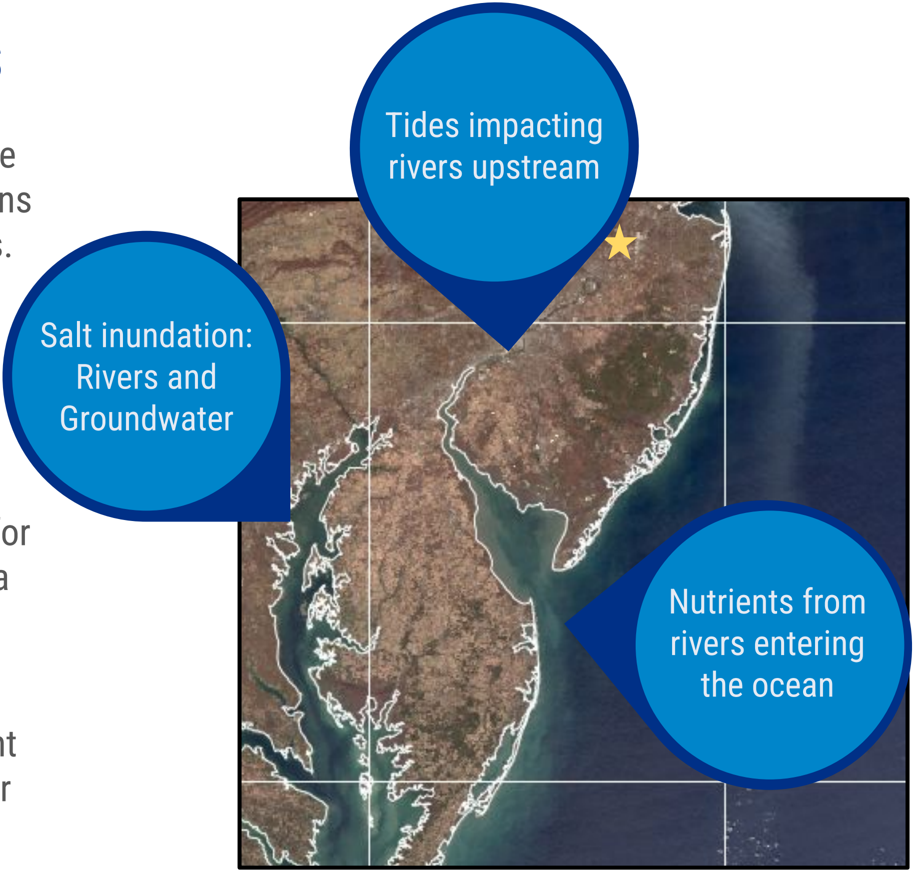


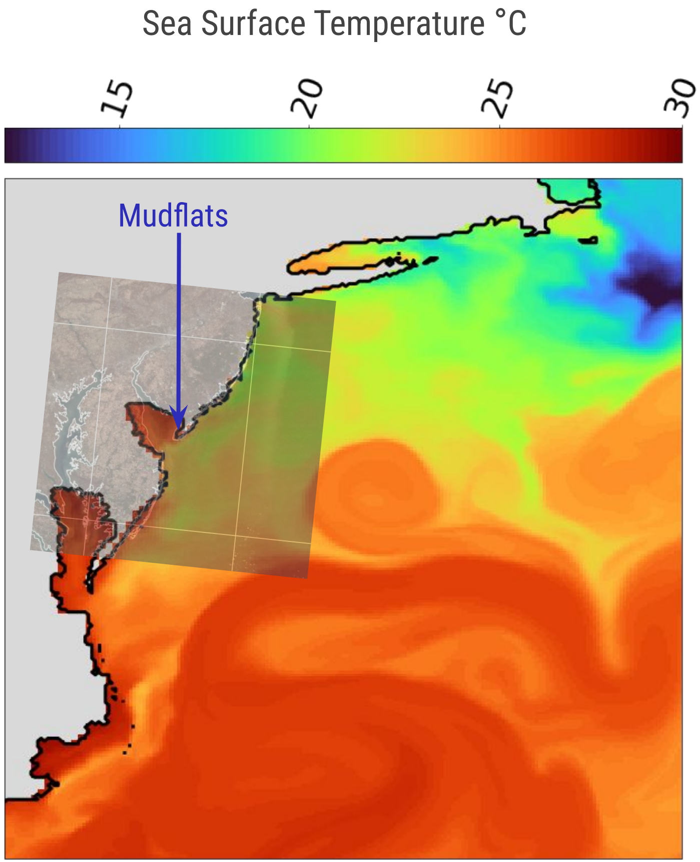
Image from NOAA CoastWatch

Changing Coastlines

In the high resolution regional configurations being run at GFDL, explicit tides can cause changes in sea level on short timescales in mudflats, mangroves, and estuaries. These areas at the land-ocean interface are important for biological productivity and dissipating wave energy, among other reasons.

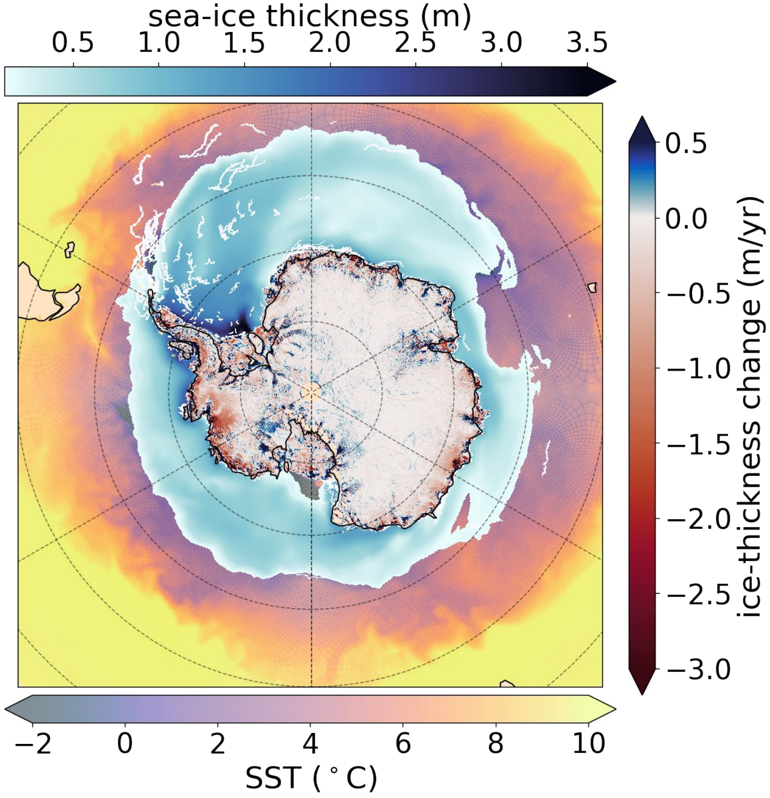
The dynamic contribution to grid scale changes in land-ocean interface can be represented by wetting and drying in MOM6 (Wang et al 2024). However, work remains to address the differences in the thermodynamic fluxes with the atmosphere and land in dry areas or the ocean in wet areas.

For long term projections of sea level change, more complex coupling between land and ocean to account for large changes and the recategorization of grid cells and the rerouting of rivers is required.



Sea Surface Temperature in a 1/25th degree regional Northwest Atlantic simulation. The resolution is approaching the scale needed to resolve the New Jersey Mudflats (~1km). Simulation results from A. Ross, configuration developed in collaboration with M. Ilıcak and E. Curchitser (Rutgers U.)

Migrating Grounding Lines and Calving Icebergs



A coupled ocean-cryosphere model, called iOM, simulates self-consistent ocean-cryosphere interactions. Olga Sergienko will discuss iOM in more detail; an example of the southern hemisphere ocean cryosphere from this configuration is shown on the left.

iOM is able to directly represent ice-sheet ocean feedbacks and the contribution of ice sheets to sea level rise. The coupling of ocean and ice sheet simulates evolution of the grounding line position. Similarly, there is calving of ice shelves and production of icebergs which are transported by the ocean (white lines in figure). Currently these icebergs are point particles, but ongoing work will allow submerged icebergs to calve from ice shelves.

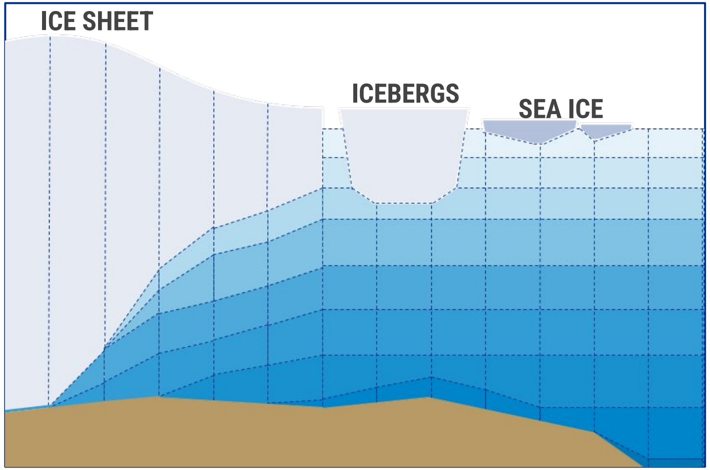
The ocean and cryosphere in iOM, including SST, sea ice, icebergs, ice shelves, and land ice. Figure from O. Sergienko.

Coupling Ice-Ocean Dynamics to Submerge Ice

To simulate interactions of tabular and other kinds of icebergs and sea ice with the ocean, these forms of floating ice must be submerged into the ocean. Currently, models levitate them, meaning they do not exert pressure on nor deform the ocean surface. This is an unphysical solution to the difficulty of coupling sea ice, icebergs and ocean models on the timescale of submerged ice and water moving together.

To link these separate components the dynamics of floating ice must be incorporated into the barotropic dynamical core of MOM6. This will allow the ocean model free surface to evolve with the movement of floating ice. This fundamental change to the coupling involves restructuring the interface and dynamical solvers of both components.

Coupling of the sea ice and ocean velocities separate from the thermodynamics is the first of many steps in the process of embedding floating ice in the ocean. This implicit coupling of the sea ice and ocean velocities can also be shown to prevent surface stress instabilities which permits longer timesteps.



Schematic showing ocean layers deformed by land ice, calved icebergs, and sea ice. Submerging icebergs is essential for coupling dynamic ice sheets to the ocean to maintain consistent pressure at the surface when calving occurs. Similarly, sea ice is submerged in the ocean as the two are dynamically linked on the timescales of gravity waves.

Coupled Innovations Become Coupled Models

The implicit coupling that is possible through the FMS infrastructure is the foundation of coupled modeling at GFDL. Scientist across disciplines bring together individual components with a focus on the fundamental physics of the Earth system. The next generation of GFDL coupled models will use both updated components and new advances in coupling including: active biosphere-atmosphere coupling, land to ocean ecosystem coupling, large lakes which connect the land and ocean, changing coastlines, dynamic ice sheets, and submerged floating ice.

	SPEAR (2020 & onward) Seasonal to Multi-decadal Data-Initialized Physical Prediction	**ESM4.5** (2025) Decadal to Century Full Earth System Projection	**CM5** (2026, 2028) Decadal to Century Physical Climate Sea Level	**Coupled SHiELD** (2027, 2028) Weather to Seasonal Data-Initialized Physical Prediction
FV3 dycore Atmosphere	**AM4** 25 to 100 km; 33 Level	**AM4.5** 100 km; 49 Level	**AM5** 25 or 100 km; 65 Level	**SHiELD** 3 to 13 km; 91 Level
Atmospheric Chemistry	Simple Chemistry & Aerosols	Full Chemistry & Aerosols	Simple Chemistry & Aerosols	Simple Aerosols
LM4 Land	**LM4.0/LM4.2** Ecosystems	**LM4.5** Ecosystems, Fire, Snow	**LM4+** Orography Aware	**LM4.2i** Initialized Land
MOM6 / SIS2 Ocean / sea-ice	**OM4**-derived 1° to $^{1}/_{12}$°; 75 Layer	**OM5** ¼°; 75 Layer	**OM5** (non-Boussinesq) ¼° to $^{1}/_{12}$°; 75 Layer	**OM5** $^{1}/_{12}$°; 75 Layer
FMS Coupler & Infrastructure	Ensemble Data Assimilation	COBALTv3 Ocean Ecosystems	Interactive Dynamic Ice Sheets	Atmospheric Ensemble Data Assimilation

Schematic showing the components of the GFDL coupled models, each column represents a configuration and the rows represent a component or code base. These coupled models represent various degrees of complexity and resolution designed to address specific objectives.

Schematic from R. Hallberg and L. Horowitz.