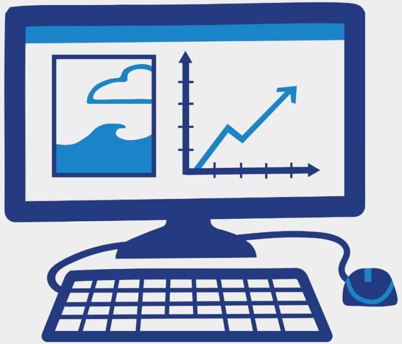


Q1: GFDL's Model Development Efforts and Their Value to NOAA and the Nation

Robert Hallberg and Larry Horowitz

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?

NOAA
GEOPHYSICAL FLUID DYNAMICS LABORATORY

5-Year Review
January 28-30, 2025

GFDL builds and uses models in support of NOAA's mission objectives

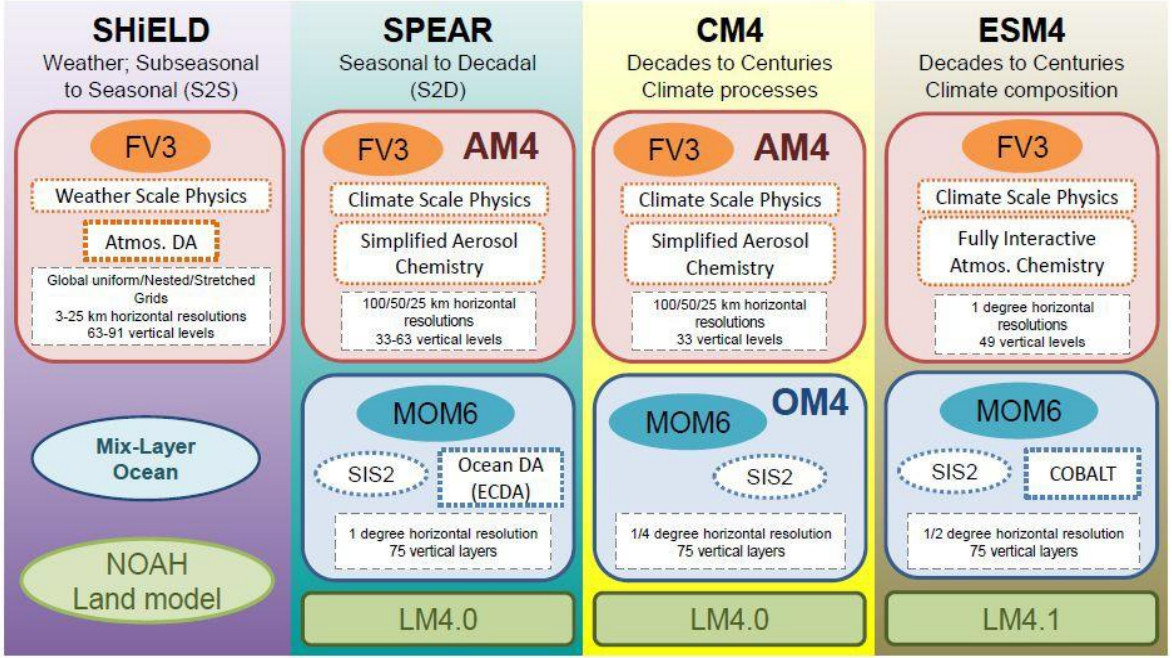
DOC Goal: Address the Climate Crisis Through Mitigation, Adaption, and Resilience Efforts
NOAA Strategic Goal: Build a Climate Ready Nation

NOAA and DOC Strategic Objectives:

- **Make Weather, Water, and Climate Forecasts Better**
  - **GFDL builds and uses models with improved physical fidelity, resolution and comprehensiveness**
    - SHiELD, SPEAR, ESM4.5, CM5 and Regional Configurations
    - FV3, MOM6 & LM4 are all being used in the latest NOAA/NWS forecast systems
- **Advance Integrated Breakthrough Climate Research**
  - **GFDL builds and uses models to enable the exploration of a broader range of phenomena**
    - ESM4.5 and CM5 will expand the comprehensiveness of Earth System processes
- **Improve Resilience of Coastal Communities and Economies**
  - **GFDL builds and uses models that explicitly represent evolving water levels, including storms, tides and long-term sea-level changes**
    - Storm-resolving atmospheric models to better understand and predict hurricanes
    - CM5 will include variants with explicit tides and interactive ice sheets
- **Detect Changes in the Ocean and Atmosphere**
  - **GFDL builds and uses models that allow for attribution of observed changes and extreme events**
- **Protect and Restore Marine Life and Ocean, Coastal and Great Lakes Ecosystems**
  - **GFDL builds and uses regional models encompassing the physics and ecosystems of U.S. coastal waters to improve management of marine resources under evolving conditions**

GFDL’s suite of global configurations (2019 review)

- Application-appropriate coupled configurations are all built from common components.
- Improvements for one application help all the others.
- Configuration resolutions, comprehensiveness and ensemble size are selected for the scientific purpose and available computational resources.



Coherent lab-wide efforts led to the 2019 vintage models, giving us a position of strength to build from.

Coherent lab-wide efforts going forward will lead to a new set of even more capable coupled configurations.

Use of GFDL modeling capabilities outside of GFDL

Within NOAA:

FV3 used in all global and regional Unified Forecast System (UFS) configurations

- NOAA/NCEP operational GFS, GEFS & SFS global forecasts
- FV3-based HAFS hurricane model (since 2023)

MOM6 used in UFS

- GFSv17, GEFSv13 & SFSv1 global & seasonal forecasts
- HAFS hurricane model (operational in 2024)
- RTOFSv3 high-resolution ~10-day ocean forecasts

GFDL Atmospheric Chemistry used in UFS-Chem

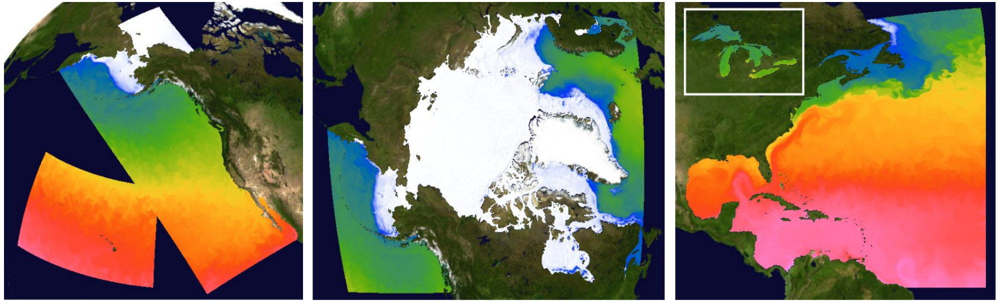
GFDL LM4 Land model available in UFS

MOM6, SIS2 & COBALT used in CEFI regional models with NOAA/NMFS and for Coastal Inundation with NOAA/NOS

- 6 regional configurations covering all U.S. waters

Beyond NOAA:

- MOM6 and FV3 used in NCAR / CESM3
- FV3 and MOM6 used at NASA / GMAO
- FV3 in Taiwan's CWA & Chinese Acad. Sci. F-GOALS
- Ai2 FV3net corrective ML system
- MOM6 used in Australian ACCESS-3 climate model
- MOM6 and FV3 used in Korean Earth System Model
- MOM6 used in Korean regional NW Pacific configs
- GFDL point icebergs used in many climate models



Open Development: GFDL leads community model development

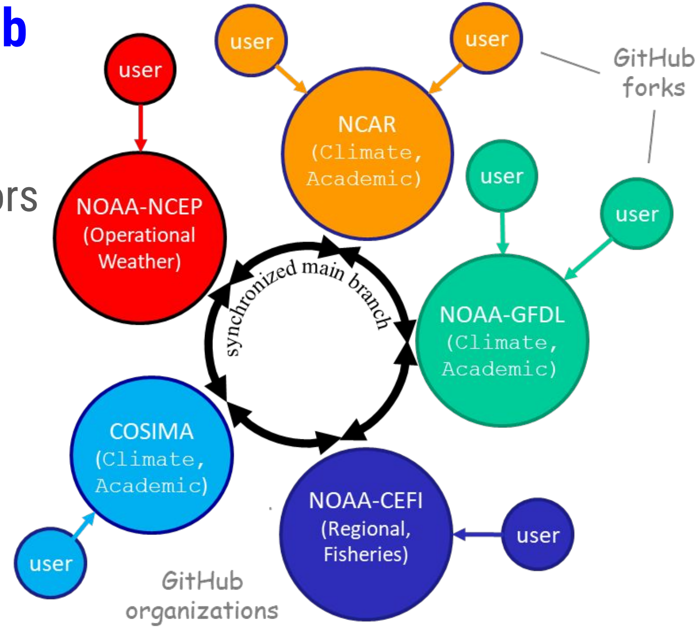
Open development of the MOM6 ocean model on **GitHub** has removed barriers to collaboration

- Complete openness has attracted partners
- 9 major institutional development hubs, scores of contributors
  - ~ 233 forks of MOM6 (as of Jan. 2025)
- Continual + independent development

Synchronization to main branch occurs by ***consensus***

MOM6 Quality Assurance is critical, including:

- Hub-specific **regression testing**
- Common code **self-consistency testing**
- Explicit software standards



GFDL's Open Development approach is consistent with NOAA's policies supporting scientific transparency, including NAO 201-118 and the Legend Act

Community of collaborators in GFDL's model development

AM5 / OM5 / LM4+ configuration development teams:

- Princeton CIMES & UCAR in GFDL
- Networks of former postdocs in academia
- NOAA/GLERL (Great Lakes submodel)

Parameterization co-development:

- Climate Process Teams (5+ teams)
- Ai2 & M2Lines Machine Learning
- NOAA/EMC (convection, turbulence, land, etc.)
- AOML/FIU Atmospheric Turbulence Project
- Duke (Chaney) Hydrology & heterogeneity
- NM Tech (Zorzetto) Snow

Formal model code co-development:

Ocean Components (MOM6, SIS2 and COBALT)

- MOM6 Consortium Hubs: NCAR; NOAA/EMC; FSU/Hycom team; NASA/GMAO; Australian COSIMA project; Korean MOM6 User Group; ESMG regional team (Rutgers & U. Alaska)
- NOAA CEFI Regional ocean-BGC MOM6 team
- NOAA CEFI ocean-BGC COBALT team
- Princeton (Resplandy Group) and other academic partner contributions to COBALT

FV3

- NASA/GMAO, NOAA/EMC, NOAA/AOML, Ai2
- Pace (Domain Specific Language port to GPUs)
- UFS community development

GFDL’s seamless system for Earth System predictions and projections

GFDL has developed a **seamless system** for numerically simulating the Earth System

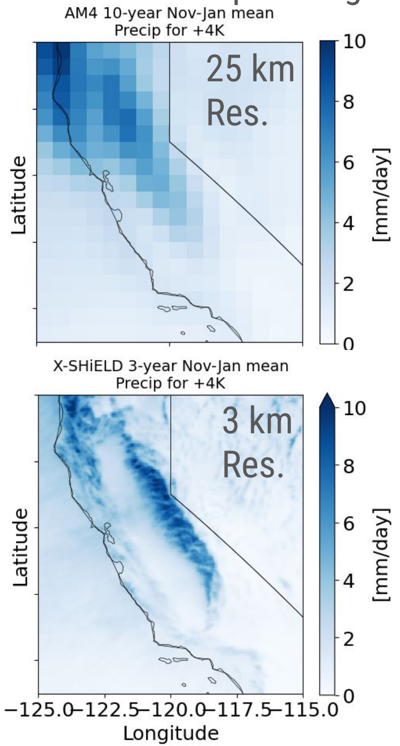
Specific configurations of this system are developed matching the intended application:

- **Model Comprehensiveness** (which phenomena of the Earth system are represented)
  - E.g., ESMs include explicit biogeochemistry and carbon cycles
- **Resolution** (which scales are explicitly admitted or parameterized)
  - E.g., Higher resolution resolves extreme weather events better
- **Ensemble Size** (for controlling natural variability or data assimilation)
  - Averaging across ensembles separates forced signals from natural variability
- **Model Turn-around Speed** (determines the time-scales that can be studied)
  - At 10 years per day, a 1000-year spinup takes over 3 months

Available computer resources constrain all configuration choices

GFDL models are “shovel-ready” to effectively use greater resources

California Precip. Changes



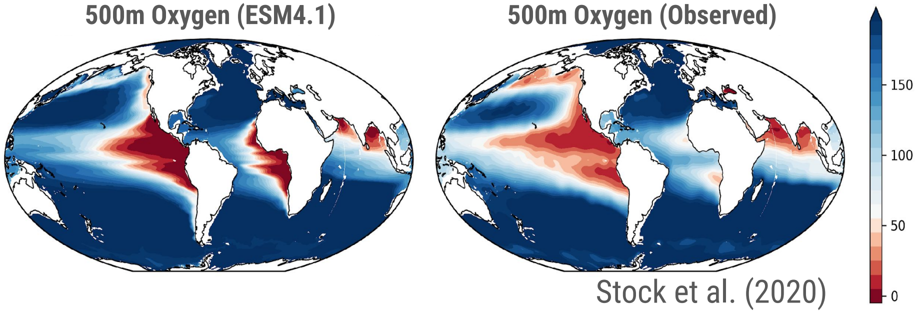
Hsieh et al. in revision at *Climate Dynamics*

New ocean modeling capabilities to fill ESM4 gaps

Gap: Biases in chlorophyll and biogeochemical cycles

- Photoacclimation scheme improves chlorophyll
- Variable N:P stoichiometry improves P-limitation
- Fast sinking detritus, anammox reduces oxygen minimum zone biases
- River runoff carbon improves coastal CO_2

Oxygen minimum zone biases in ESM4.1

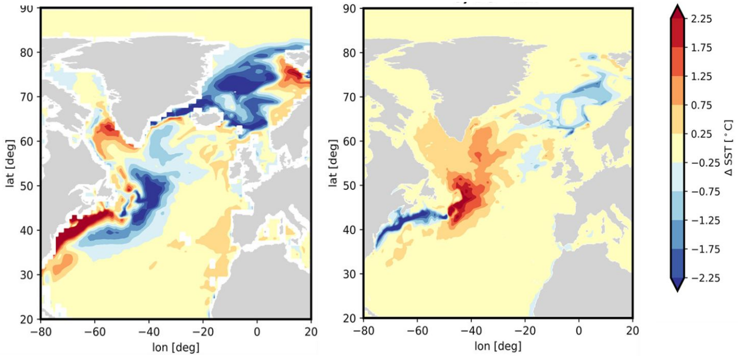


Stock et al. (2020)

Gap: Effects of under-resolved mesoscale eddies

- Increased ocean resolution in ESMs
- Energetically consistent eddy parameterizations

Impact of eddy backscatter parameterization on SST bias in OM5



Chang et al. (2023)

These capabilities will be deployed in GFDL's new ESM4.5 Earth System Model.

New ocean & cryosphere modeling capabilities to fill CM4 gaps

Gap: Direct simulation of sea level and regional patterns

- Interactive ice sheets
- Non-Boussinesq formulation
- Explicit tides with on-line gravitational self-attraction and solid-earth loading
- Improved representation of grid-scale bathymetry

Gap: Mixing-related tropical and mid-latitude biases and static (climate-invariant) mixing rates

- Boundary layer mixing improvements
- AI/ML mixing parameterization refinements
- Energetically constrained mixing
- Improved shear-driven mixing

Gap: Polar ocean and sea-ice biases

- Sea-ice physics improvements
- Numerically stable ice-ocean coupling
- More realistic icebergs
- Latitude-dependent internal gravity wave mixing

Gap: Biases in deep ocean overflows & ocean overturning circulation

- Improved vertical coordinates
- Improved representation of bathymetry
- Bottom boundary layer mixing processes
- Improved shear-driven mixing

Gap: Great Lake circulation impacts U.S. climate

- Explicitly coupled Great Lakes in OM5
- Hydraulic control (waterfalls) in ocean model

Many of these capabilities will be deployed in GFDL's new OM5 Ocean Model & CM5 Coupled Model.

New atmospheric modeling capabilities to fill SHiELD gaps

Improved ability to simulate extreme events

- New FV3 grid systems
    - Telescoping and vertical nesting, Duo-Grid
- Increased horizontal resolution in global and global-nested models
- Improved accuracy in FV3 advection operators
- Integrated 3-D turbulent mixing

Improved GFDL v3 cloud microphysics

- Inline physics for better numerical and thermodynamic consistency
- Entirely re-derived cloud and precipitation processes from first principles
- More realistic background cloud nuclei concentrations, particle-size distributions

Improved surface-atmosphere interactions

- Updated planetary boundary layer and shallow & deep convection schemes from NCEP
- Surface layer revisions to improve surface fluxes in high wind conditions
- Support for full FMS Coupler

Better initialization with ensemble data assimilation

- Mixed-PBL ensemble compensates errors of each for better analysis
- All-sky radiance assimilation for improved initialization in precipitating regions
- Data assimilation fit-to-obs useful tool to identify model errors

New atmospheric modeling capabilities to fill CM4/ESM4 gaps

Improved ability to simulate extreme events
- Increased horizontal resolution - AM5

Improved surface-atmosphere interactions
- Planetary boundary layer (Eddy Diffusivity / Mass Flux) - AM5
- Land-atmosphere tracer coupling - AM4.5
  - Wildfires, deposition, snow

Modernization of radiation code
- Rapid Radiative Transfer Model for GCMs (RRTMG) - AM5

Improved cloud microphysics
- Morrison-Gettelman v2 two moment bulk cloud microphysics - AM4.5/AM5
- Ice nucleation scheme - AM5

More comprehensive atmospheric composition
- Hydrogen chemical cycling - AM4.5
- New aerosol microphysics, aerosol activation - in progress

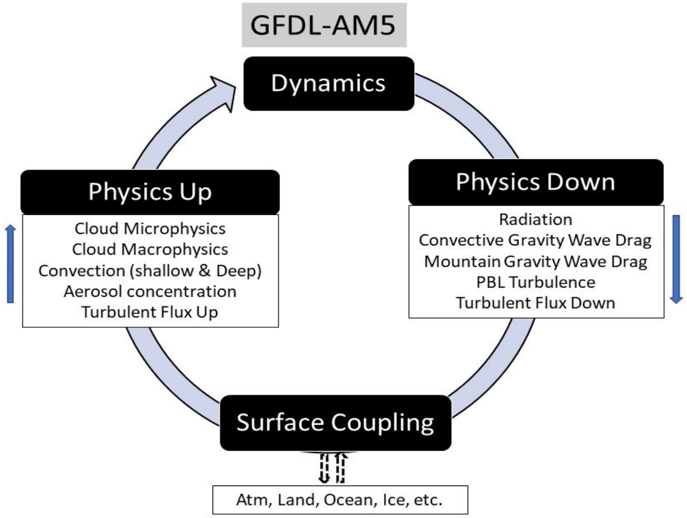
These capabilities will be deployed in GFDL’s new AM5 Global Atmospheric Model, ESM4.5 Earth System Model, and CM5 Coupled Model.

New AM5 atmosphere component

AM5 will advance NOAA's goals to increase the nation's ability to prepare for, adapt to, and mitigate negative impacts of weather and climate extremes associated with an evolving climate.

AM5 priorities are to improve:

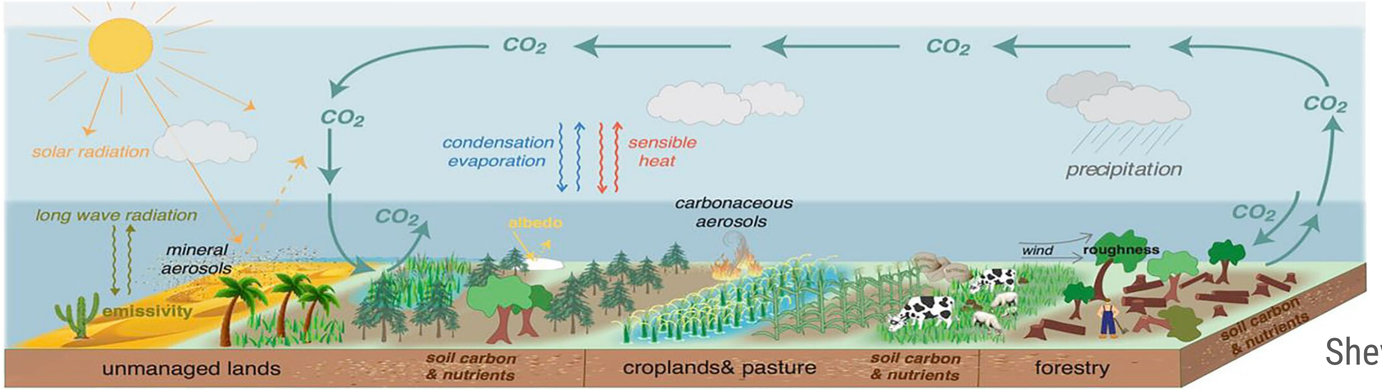
- Simulation of climate extremes with focus on U.S.
- Prediction on subseasonal to seasonal timescales
- Characteristics of 20th C. regional surface climate



AM5 includes updates to radiation, microphysics, boundary layer, gravity wave drag, convection, and land schemes.

New land modeling capabilities to fill ESM4 gaps

- Improved representation of terrestrial heterogeneity
  - Second-generation vegetation dynamics (Perfect Plasticity Approximation)
  - Orography-aware land (mountain shading, hillslopes)
- Added resistance to soil evaporation in laminar sublayer
- Interactive fire-vegetation-climate dynamics
- Comprehensive land cryosphere modeling (snow-aerosol-radiation interactions)
- Reduced carbon biases in vegetation and soils (second-generation soil microbes)



Shevliakova et al. (2024)

New GFDL Coupled Models to Address NOAA Mission Objectives

	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**

Improving representation of coupled interactions between atmosphere, land, ice and ocean

Physically motivated **implicit coupling** (e.g., land-atmosphere) has helped GFDL accurately represent Earth system feedbacks.

Addressing outstanding questions about the Earth system will benefit from expanding **direct coupling between components** (e.g., ice-ocean, ocean-land, …)

Gaps and new frontiers in Earth system coupling that GFDL is currently working to address:

- Land-ocean-ecosystem coupling
- Large circulating lakes feeding rivers
- Two-way exchange between rivers and oceans
- Changing coastlines and estuaries
- Dynamic ice sheets
- Partially submerged icebergs and sea ice

Better Coupling Can Address NOAA and DOC Strategic Objectives:

- Make Weather, Water, and Climate Forecasts Better
  - Active land-atmosphere coupling for air pollution
  - Great Lake circulation in Earth System Models
  - Ocean-to-river coupling for salt inundation
- Advance Integrated Breakthrough Climate Research
  - Great Lakes in Earth System Models
  - Partially submerged icebergs and sea ice
- Improve Resilience of Coastal Communities and Economies
  - Two-way river-to-ocean coupling for tidal estuaries
  - Wetting-and-drying tidal flats and transient flooding events
  - Dynamic ice sheets for long term sea level rise
- Protect and Restore Marine Life and Ocean, Coastal and Great Lakes Ecosystems
  - Land-ocean-ecosystem coupling including nutrient fluxes
  - Active marine-ecosystem and atmosphere coupling

For more details:
See Q1 Prerequisite Slides (Morrison, Benson/Elbert)

Challenges - Workflows for Evolving Computer Architectures & Bigger Data

Making use of evolving computers

- Modernizing code for efficiency, portability, sustainability & community development
  - Refreshing FMS & FRE code
  - Containerizing models
- Supporting a wider range of workflows
  - More modular workflow tools
  - Regional, idealized, short-timescale, etc.
  - Security issues with distributed workflows
- Change management and automated testing
  - Appropriate use of cloud computing
- Software Engineering for Novel Architectures

Handling bigger data

- Aggregating large output datasets into catalogs for increased usability and automated analysis
- Automating performance analysis via modular python tools
- Automating scientific analysis via modular python tools, Globus and ESGF protocols

GFDL's Open Development approach is consistent with NOAA's policies supporting scientific transparency, including NAO 201-118 and the Legend Act

For more details:
See Q1 Prerequisite Slides (Chilutti/Robinson)

Plan for the Q1 session

Agenda | Panelists for Discussions

1:00-2:10	Innovations in Atmospheric Modeling	L. Harris, F. Paulot, P. Lin, N. Jeevanjee, B. Zhang, H. Guo, Z. Tan, R. Benson, O. Elbert
2:10-3:00	Innovations in Ocean and Cryosphere Modeling	R. Hallberg, B. Reichl, O. Sergienko, J. Luo, S. Griffies, A. Adcroft, M. Bushuk, C. Stock
3:00-3:15	BREAK	
3:15-4:30	Innovations in Terrestrial and Coupled System Modeling	L. Horowitz, E. Shevliakova, M. Lee, S. Malyshev L. Horowitz, M. Bushuk, B. Xiang, L. Chilutti, T. Robinson, T. Morrison, J. Krasting

Each component session contains talks followed by a panel discussion.