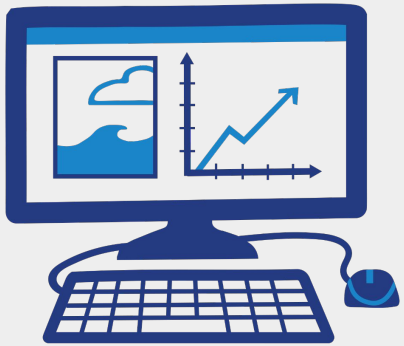


Major New GFDL Coupled Climate and Earth System Models

Mitchell Bushuk, Baoqiang Xiang

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

Overview of GFDL Coupled Models

The first coupled ocean-atmosphere model

786 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 26

Climate Calculations with a Combined Ocean-Atmosphere Model

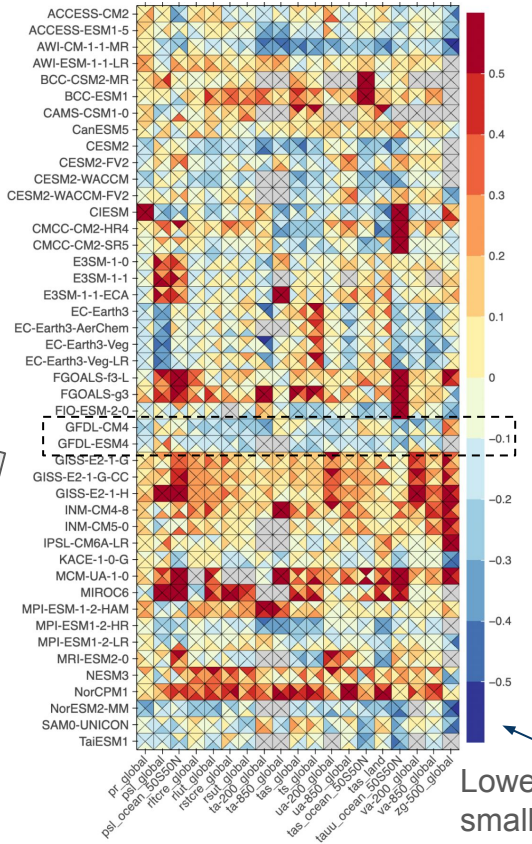
SYUKURO MANABE AND KIRK BRYAN

Geophysical Fluid Dynamics Laboratory, ESSA, Princeton University, Princeton, N. J.

13 March 1969 and 6 May 1969

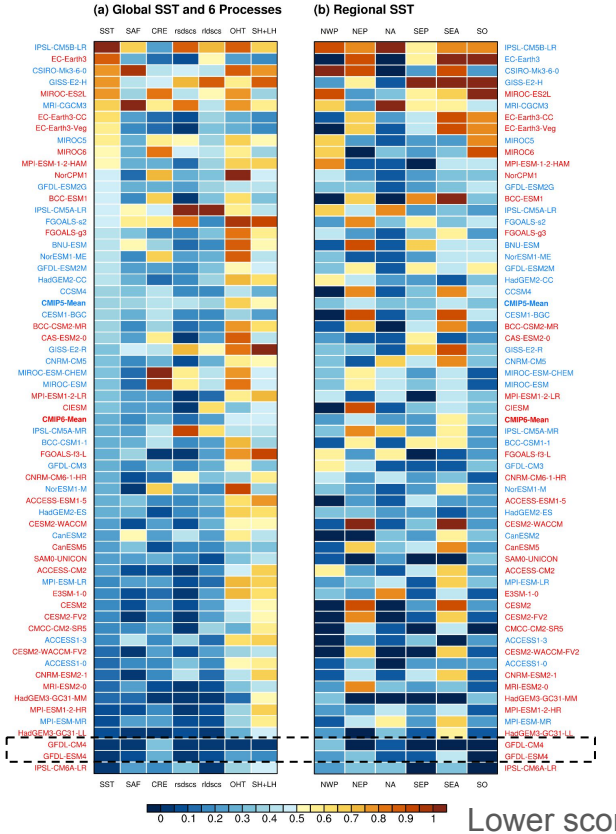
Manabe Model (R15 and R30)	IPCC FAR CMIP1 & 2	~ 1990 ~ 1997
CM2 **CM2.5, CM2.6, FLOR**	CMIP3	~ 2004
CM3 **ESM2M, ESM2G**	CMIP5	~ 2011
CM4, ESM4.1 **SPEAR, CM4X**	CMIP6	~ 2018
		present
CM5 2028	**ESM4.5** CMIP7	~ 2026

Performance of GFDL Models in CMIP6

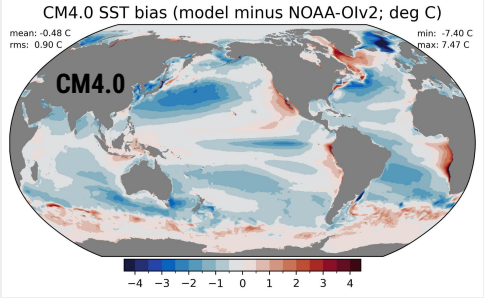


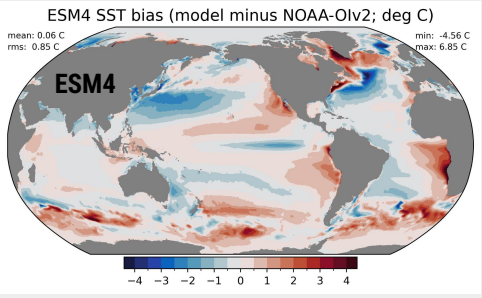
Lower score = smaller biases

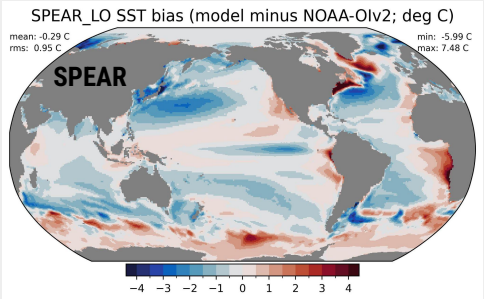
GFDL's 4th Generation Coupled Models are amongst the best in CMIP6

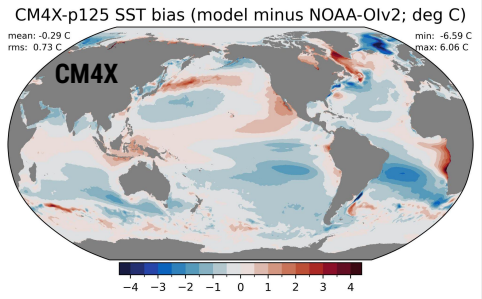


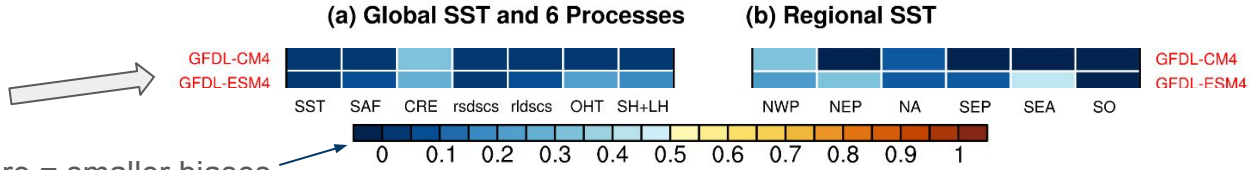
Mean SST Bias





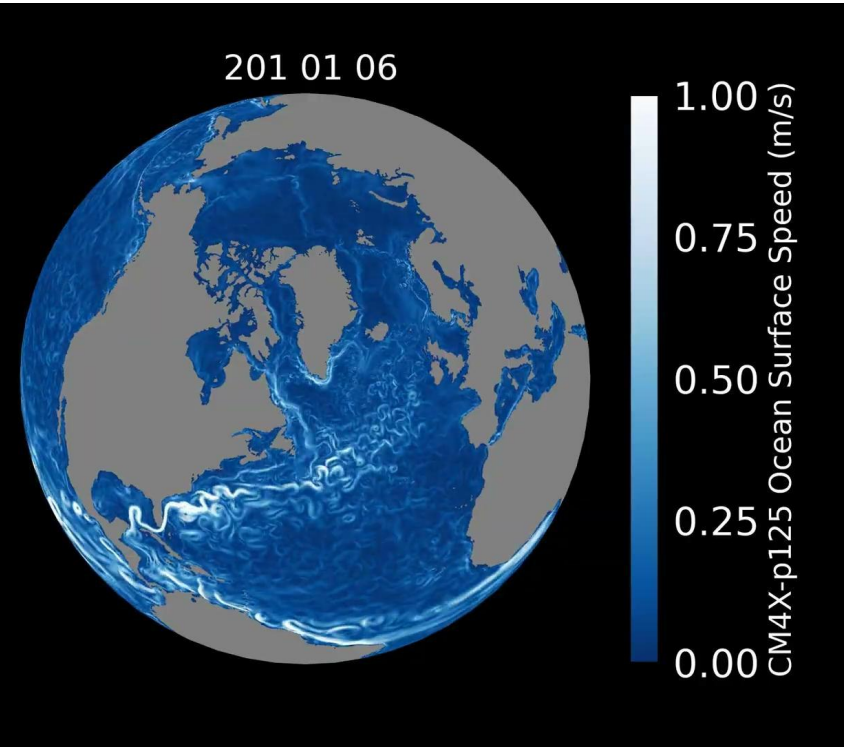




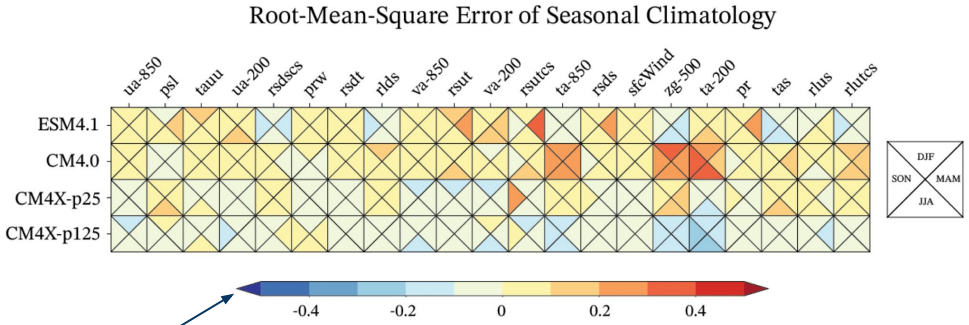


Lower score = smaller biases

Success of GFDL's 4th Generation Coupled Models: CM4X



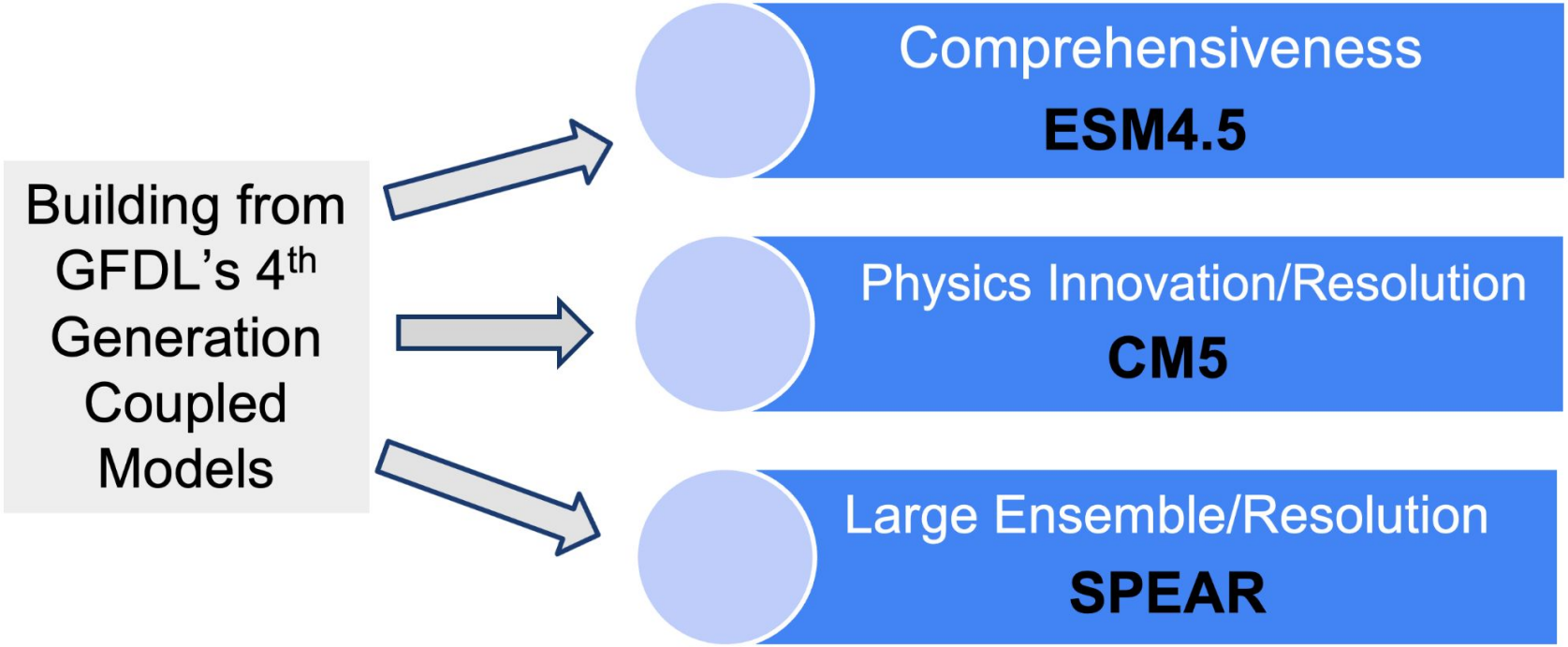
- CM4X[1]: Two recently developed **high-resolution** coupled climate models.
  - CM4X-p125: **1/8° ocean/ice; 50km atmos/land**.
  - CM4X-p25: **1/4° ocean/ice; 50km atmos/land**.
- Both CM4X models improve upon the biases of CM4 and ESM4.
- 1/8° configuration has very low thermal drift.
- See Pre-Req slides from S. Griffies for more information.



Lower score = smaller biases

1: Griffies et al. Part I, Part II, *Submitted to JAMES*

Ongoing and Future GFDL Global Coupled Model Development



GFDL's New Earth System Model, ESM4.5: "Fast Track" contribution supporting IPCC/AR7

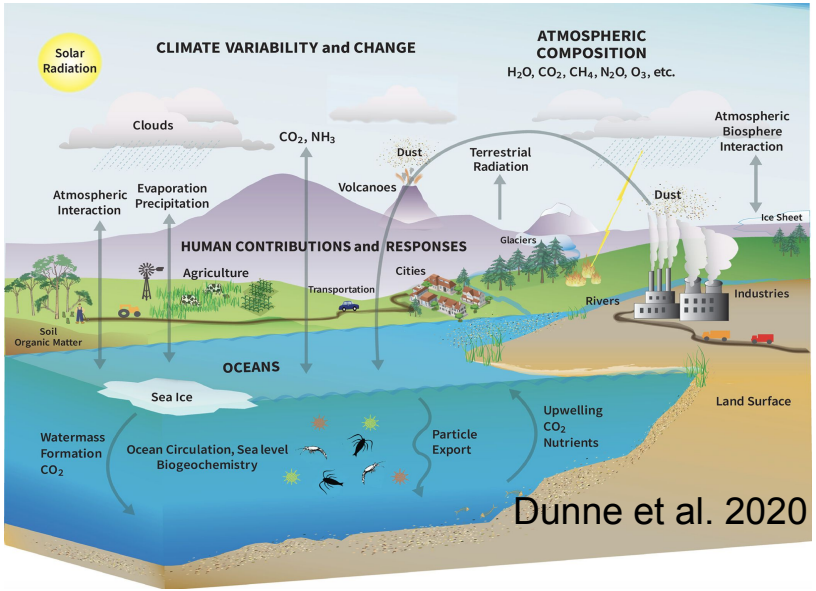
Core Science Priorities

A. **Historical Earth System Changes:** Faithfully represent historical climate change, CO_2 responses and chemistry-climate interactions driven by emissions to assess changes in the Earth System.

B. **Climate Risks and Tipping Points:** Determine risks associated with stabilization at various global warming levels, including the likelihood of a wide range of tipping points (e.g. TIPMIP).

C. **Climate-Ecosystem Interactions:** Evaluate implications of too much or too little water for managed and unmanaged ecosystems, including at the sub-grid stakeholder relevant scale.

D. **Climate Mitigation and Intervention:** Evaluate the viability and implications of climate change mitigation strategies including climate intervention techniques (e.g., CDR, SRM).



Novel ESM4.5 Capability Goals and Model Features

A. Historical Earth System Changes

Merge recent GFDL successes in climate and Earth system fidelity; Snow-dust-albedo interactions and snow physics improvements; Improved surface turbulent exchanges, Sea salt emissions; Reproduce historical temperature and CO_2 record.

B. Climate Risks and Tipping Points

Interactive fire emissions; Sub-grid hydrological heterogeneity; Treeline parameterization for high latitudes and altitudes; Next generation soil microbial carbon representation

C. Climate-Ecosystem Interactions

Global coastal/shelf/slope marine ecosystems with expanded biodiversity and improved physiology and chemistry; Land management complexity; Improved soil carbon-microbial interactions and processes.

D. Climate Mitigation and Intervention

Improved representation of plant biogeography and land and ocean carbon sinks; Improvements to natural and anthropogenic aerosol and chemistry interactions; Applications with CO_2 emissions and removal forcing.

GFDL ESM4.5: Model Configuration and Timeline

	ESM4.1	ESM4.5
Atmos. Physics	AM4.1; 100km, 49 levels	AM4.5; 100km, 49 levels
Atmos. Chem	AM4.1-atmos-chem	AM4.5-atmos-chem
Land	LM4.1; 100km	LM4.5; 100km
Ocean (MOM6)	OM4; 1/2°, 75 levels	OM5; 1/4°, 75 levels
Sea Ice (SIS2)	OM4; 1/2°, 5 category	OM5; 1/4°, 5 category
Ocean BGC	COBALTv2 (33 tracers)	COBALTv3 (40 tracers)

Timeline:

June 2025: Code frozen

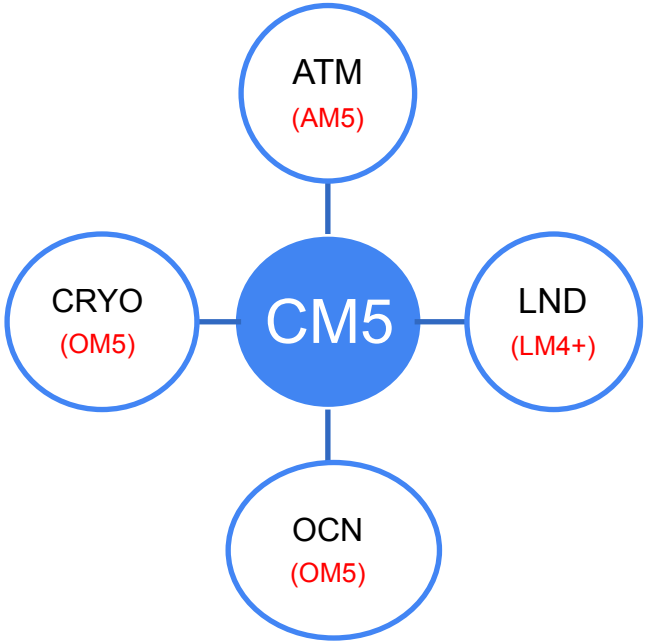
March 2026: Spinup and Historical runs complete

Dec 2026: Deliver Fast Track data to ESGF

GFDL's Next-generation Coupled Climate Model (CM5)

The goal of CM5:

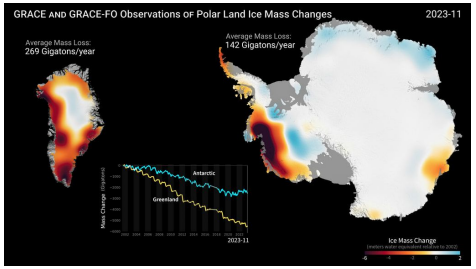
The CM5 system will unify efforts across GFDL to develop a seamless modeling tool that supports **NOAA's mission** to skillfully predict regional and global **extreme events**, while addressing **stakeholder needs and societal challenges**.

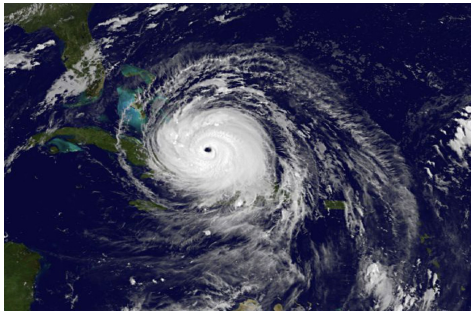


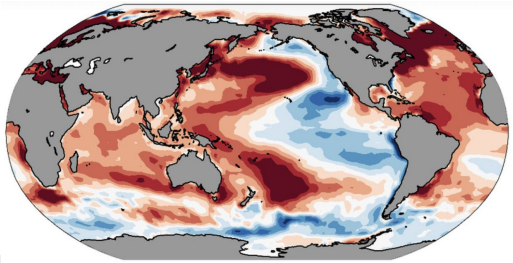
Coupling through
Flexible Modeling System (FMS)

CM5 Grand Challenges

- How will global and regional **sea levels** evolve, including the response to changes in **Earth's ice sheets**?
- How will the likelihood of **extreme** weather and climate events change over time?
- How does the **historical and future pattern of surface temperature** change relate to variability and anthropogenic forcing?
- How can CM5 results be utilized to meet **NOAA stakeholder needs**, enhance research partnerships and meet social challenges?







Target Resolutions and Timelines

CM5-LR (targeted completion 2026):

- *100-km AM5/LM4+ and 25-km OM5*
- *Target throughput 8 yrs per day on 4096 cores (e.g. **1.7%** of Gaea C5)*

CM5-HR (targeted completion 2028):

- *25-km AM5/LM4+ and 8-km OM5*
- *Target throughput 5 yrs per day on 70,400 cores (e.g. **30%** of Gaea C5)*

CM5-LR will likely participate in the DECK and ScenarioMIP simulations as part of CMIP7. GFDL will be among **the first modeling groups** to provide the capability of synchronous coupling between the **ice sheets** and other model components.

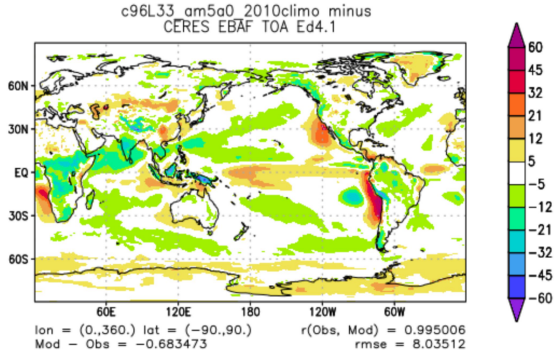
AM5 Development Highlights

Model component	AM4.0	AM5
Radiation	Sea/ESF (1999)	RTE-RRTMGP (2019)+GFDL Cloud Optics
Convection	Double Plume Convection (DPC)	Non-equilibrium convection DPC (Zhang et al. 2024)
Boundary Layer	Lock et al (2000)	Eddy Diffusivity Mass Flux (EDMF) (Han and Bretherton 2009)
Cloud Microphysics	Rotstayn-Klein	Morrison-Gettleman-2 (Guo et al. 2020, 2021)
Aerosol-cloud interaction	Liquid only (Ming et al. 2006)	Dust and temperature-dependent ice nucleation (Fan et al. 2019)
Aerosol chemistry	Simplified	Updated aerosol emissions and deposition
Land	LM4	LM4+
Air-sea flux algorithm	COARE3.5	HWRF version 2017
Orographic gravity wave drag	Garner et al (2005)	Updated Garner et al. (2005)
Non-orographic gravity wave drag	Alexander and Dunkerton (1999)	Beres et al. (2004)
Stratospheric ozone	Prescribed	Linear ozone (Lin and Ming 2021)
Dynamical Core	FV3 v2017	FV3 v2023

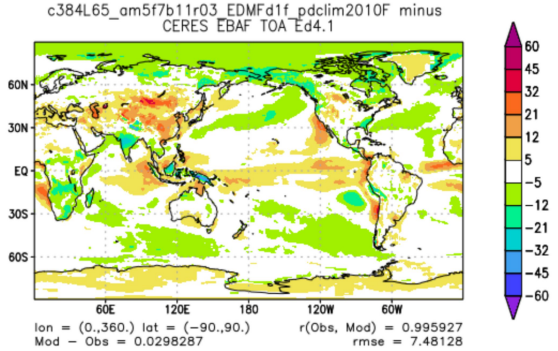
Implemented Ongoing

Improved Stratocumulus Simulation

AM4 (100 km)



Prototype AM5 (25 km)



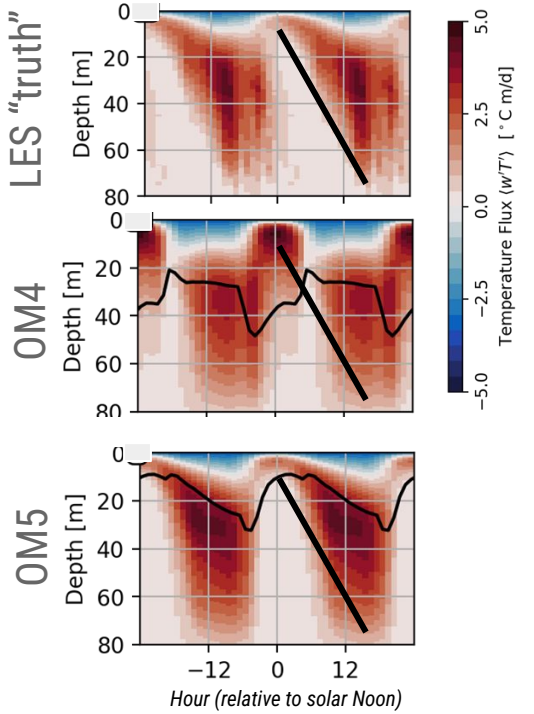
Bias of TOA shortwave absorption

OM5 Development Highlights

Physics	OM4	OM5
Interactive Ice Sheet component	N/A	MOM6-IS (Sergienko et al., *in prep*)
Non-Boussinesq ocean	N/A	Hallberg et al. (*in prep*)
Modern Equation of State	Wright (1997)	Roquet (2015)
Improved surface and Bottom Boundary layer mixing	ePBL and BBL (Legg et al. 2013, Reichl and Hallberg, 2018)	Improved ePBL and BBL (Reichl et al. 2024, Griffies et al. submitted)
Internal wave mixing	Harrison and Hallberg (2008)	Improved mixing in high-latitudes; Ray tracing scheme (Dussin et al., in prep)
Submesoscale mixed layer eddies	Fox-Kemper et al. (2011)	Bodner et al. (2023)
Sea ice ridging	N/A	Icepack Column Physics
Improved ice-ocean coupling	Concurrent coupling	Fast dynamic coupling (Morrison et al., *in prep*)

Implemented Ongoing

Improved diurnal cycle of tropical mixing



hour 0: noon

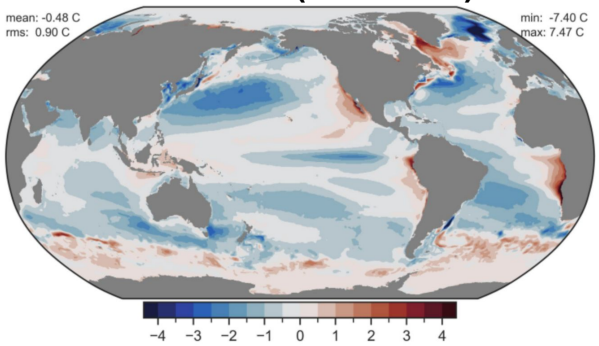
Reichl et al. (2024)

Preliminary results from a prototype CM5-HR simulation (SST, ENSO)

CM4
(100 km AM4)

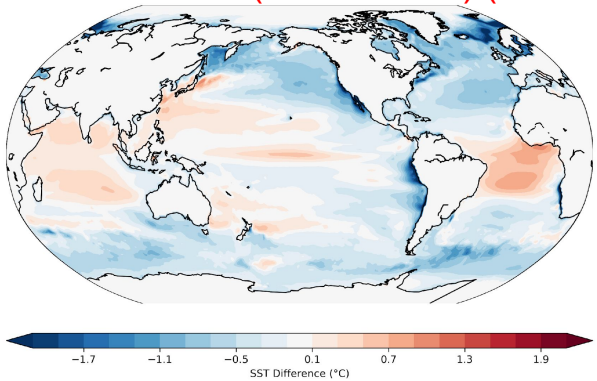
Prototype CM5-HR
(25 km AM5, 25 km ocean)

SST bias (CM4-obs)

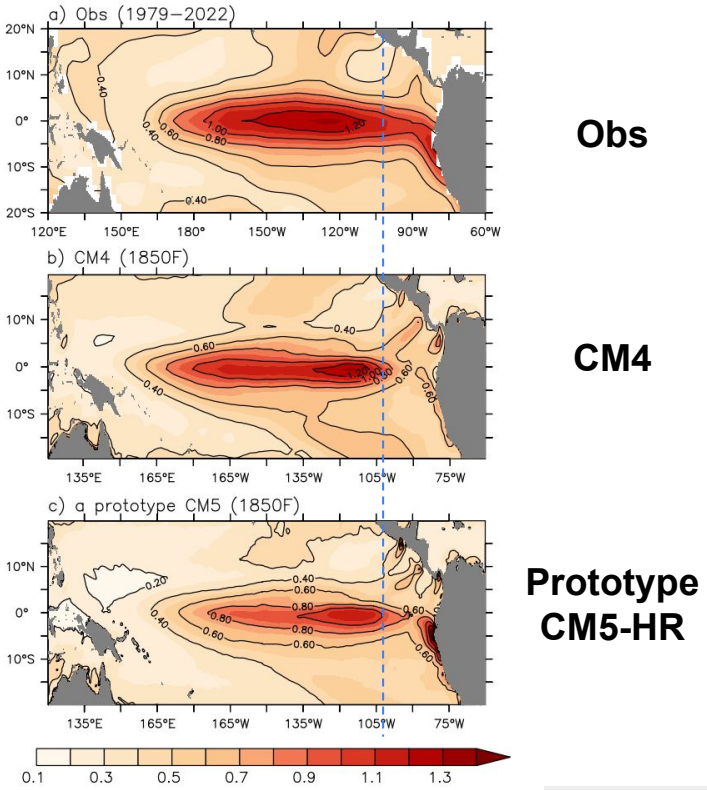


Held et al. 2019; Griffies et al. 2024

SST difference (CM5 – CM4) (1850F)



Wintertime ENSO



Obs

CM4

Prototype CM5-HR

Preliminary results from a prototype CM5 simulation (TCs)

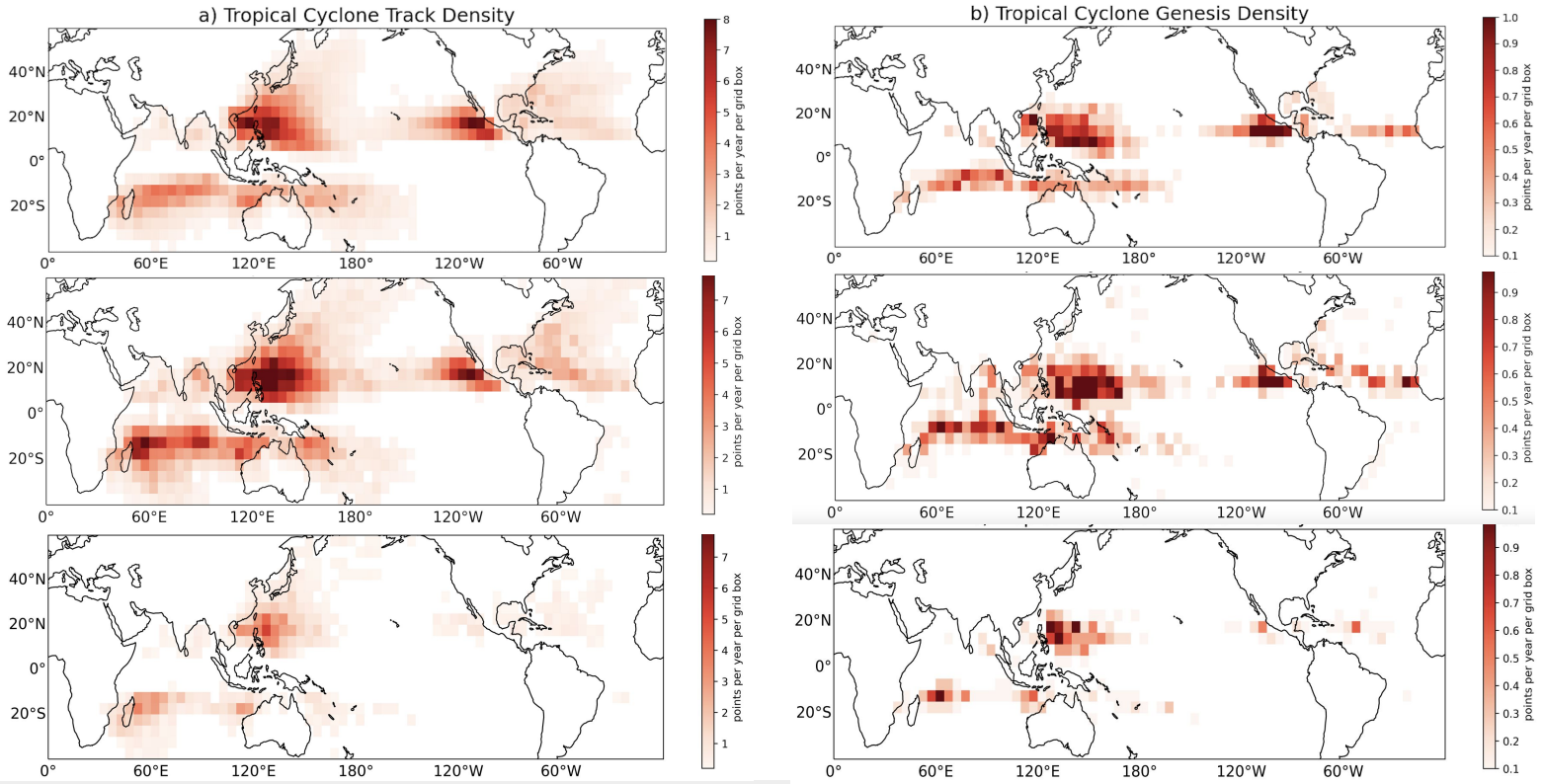
TC Track density

TC Genesis density

Obs

Prototype CM5-HR (1850F)

Prototype CM5-LR (1850F)



New GFDL Coupled Models to Address NOAA Mission Objectives

	SHiELD (2020 & onward) Weather to Seasonal Data-Initialized Physical Prediction	**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
FV3 dycore Atmosphere	**SHiELD** 3 to 13 km; 91 Level	**AM4** 25 to 100 km; 33 Level	**AM4.5** 100 km; 49 Level	**AM5** 25 or 100 km; 65 Level
Atmospheric Chemistry	Simple Aerosols	Simple Chemistry & Aerosols	Full Chemistry & Aerosols	Simple Chemistry & Aerosols
LM4 Land	**NOAH LSM** (Initialized **LM4.2i** planned)	**LM4.0/LM4.2** Ecosystems	**LM4.5** Ecosystems, Fire, Snow	**LM4+** Orography Aware
MOM6 / SIS2 Ocean / sea-ice	**Mixed Layer** (**OM5** planned)	**OM4**-derived 1° to $^{1}/_{12}$°; 75 Layer	**OM5** ¼°; 75 Layer	**OM5** (non-Boussinesq) ¼° to $^{1}/_{12}$°; 75 Layer
FMS Coupler & Infrastructure	**Atmospheric Ensemble Data Assimilation**	**Ensemble Data Assimilation**	**COBALTv3 Ocean Ecosystems**	**Interactive Dynamic Ice Sheets**