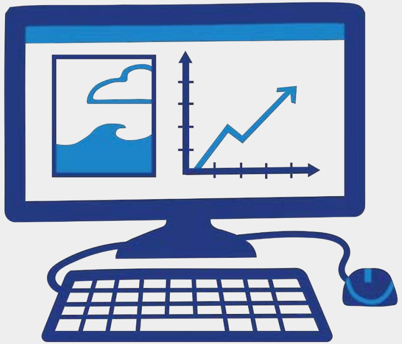
Opportunities and Challenges of High-Resolution Ocean Climate modeling



In CM5, should we directly simulate the ocean mesoscale (i.e., eddy remove parameterizations), or should we parameterize it?

Stephen Griffies, GFDL

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?

GFDL is positioned to answer the question about the value and feasibility of direct simulations of the ocean mesoscale for dec-cen research and projections

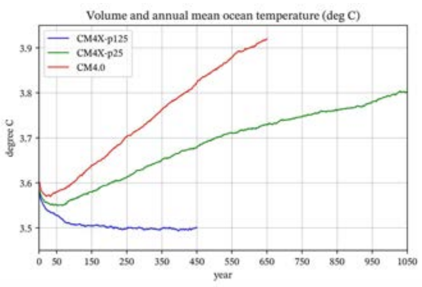
- GFDL has invested decades of research and development into ocean physical parameterizations, ocean numerics, and computational methods.
- This investment, along with increased computer power, motivate the question: is it feasible and strategically smart to increase our focus on a direct simulation of ocean mesoscale for studies of decadal-to-centennial scale climate dynamics?
- Work with the CM2.5/CM2.6 hierarchy (from 2012 to 2020 using MOM5), and the new CM4X hierarchy (from 2020 to today using MOM6), provides critical information (pros and cons) to guide us in answering this question.

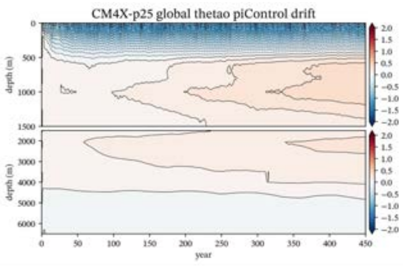
Necessary conditions to directly simulate the ocean mesoscale

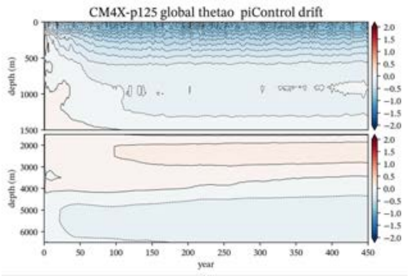
- Fine grids (vertical and horizontal) that resolve key mesoscale features such as baroclinic instabilities, boundary currents, jets, transient eddies, ventilation, etc.
- Accurate numerical methods that respect the critical importance of vertical stratification, even when confronted with 1000s of mesoscale eddy turnover times that allow for seemingly small numerical errors to accumulate to degrade centennial-scale climate simulations. The MOM6 vertical Lagrangian dycore respects this need.
- Accurate physical parameterizations of processes acting below the mesoscale (e.g., submesoscale, boundary layers, internal gravity wave mixing).
- Results from a new hierarchy of GFDL coupled climate models (CM4X) point to the value of approaching these three qualities for use in piControl and historical simulations. Such models are referred to as ``Mesoscale Dominant Ocean Climate Models".
- We require increased computational capabilities to pursue this approach.

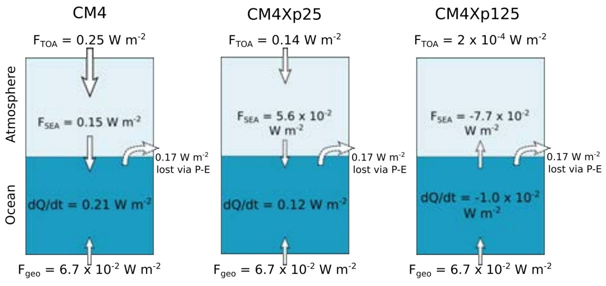
Thermal equilibration of piControl with a model approximating mesoscale dominance

- Comparing two climate models with every detail identical <u>except</u> for ocean grid spacing (CM4X-p25 with ¼ degree ocean and CM4X-p125 with ⅛ degree ocean).
- Stronger eddies in CM4X-p125 render a piControl simulation that equilibrates after ~150 years with ~400 ZJ less ocean heat than present-day (consistent with obs estimates), whereas the coarser ocean in CM4X-p25 remains unequilibrated after 1000 years (common with other climate models).
- Previous generation (CM4.0) is even further away from thermal equilibration than CM4X.

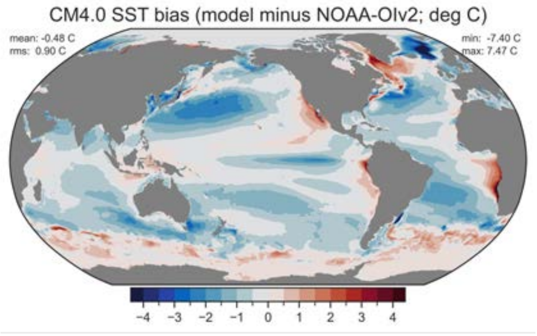


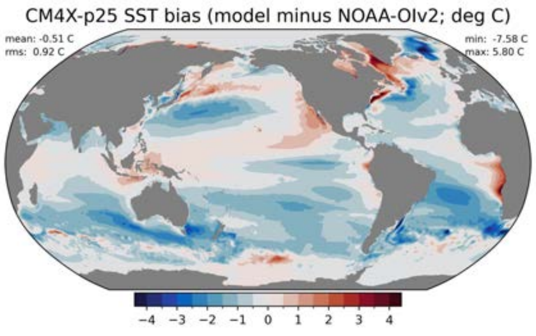


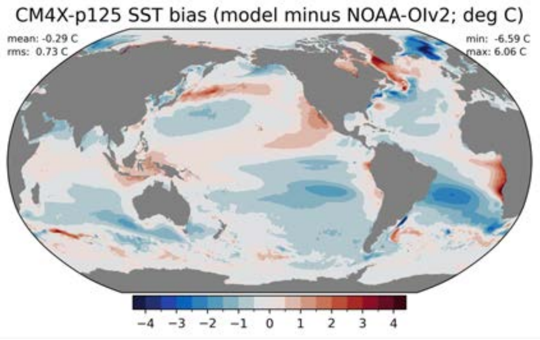




Enhanced ocean eddies in CM4X-p125 lead to reductions in coupled model historical SST biases relative to CM4X-p25

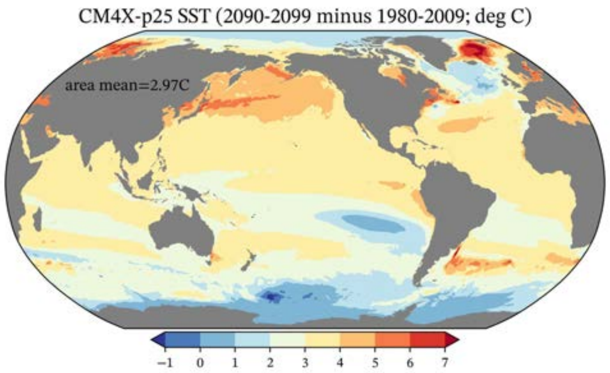


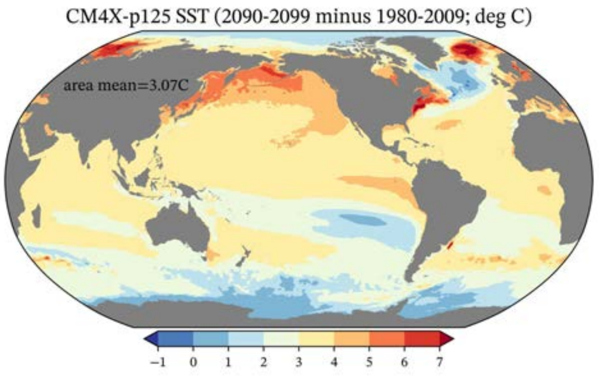


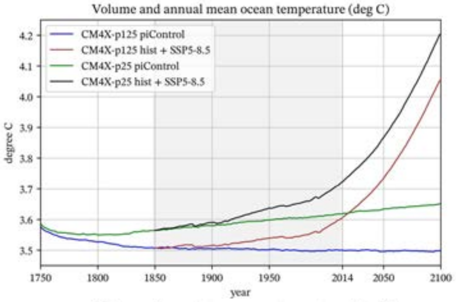


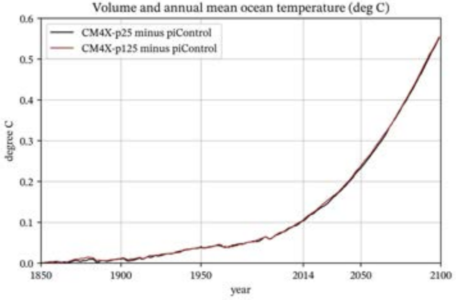
- CM4X-p25 is comparable to CM4.0 biases (though note CM4X uses 50 km C192 atmosphere whereas CM4.0 uses 100 km C96).
- CM4X-p125 has about 20% smaller global mean RMS bias, and 40% smaller max/min bias.
- There remain areas for improvement (not all ocean related). Even so, refined ocean does significantly reduce SST biases in the CM4X hierarchy.

Although CM4X-p125 has far less drift than CM4X-p25, their climate responses under SSP5-8.5 are quite similar



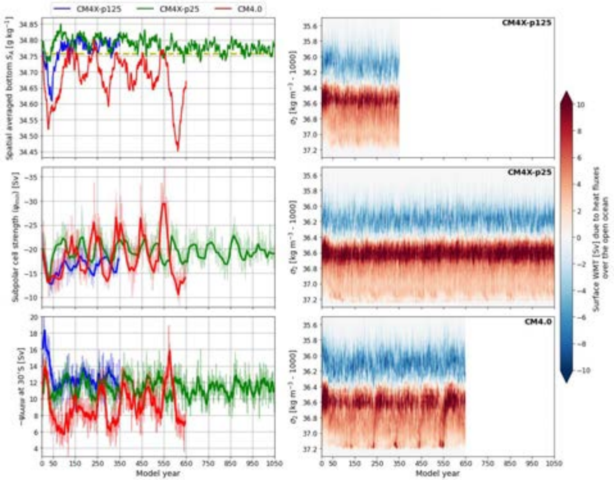


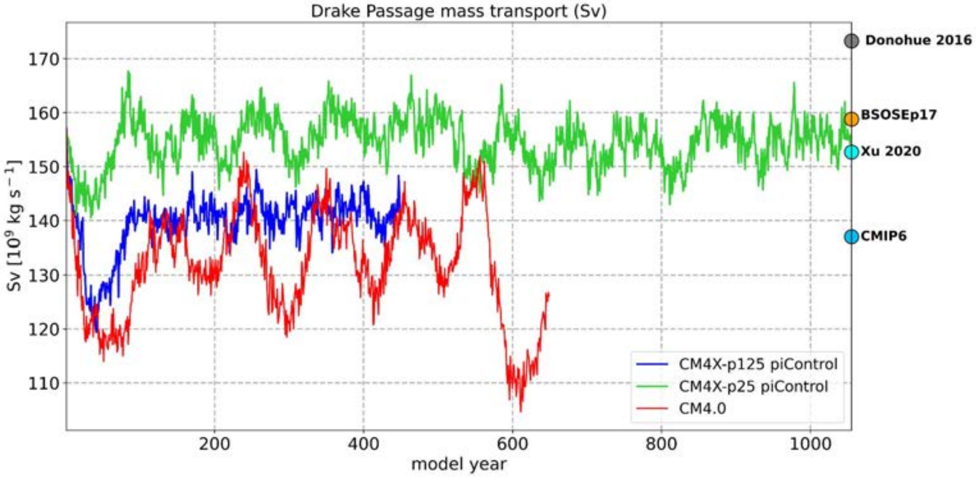




- Similar SST pattern changes and global mean ocean volume changes.
- This result lends support for GFDL's plans to use a ¼-degree and 1/12-degree ocean component for CM5.

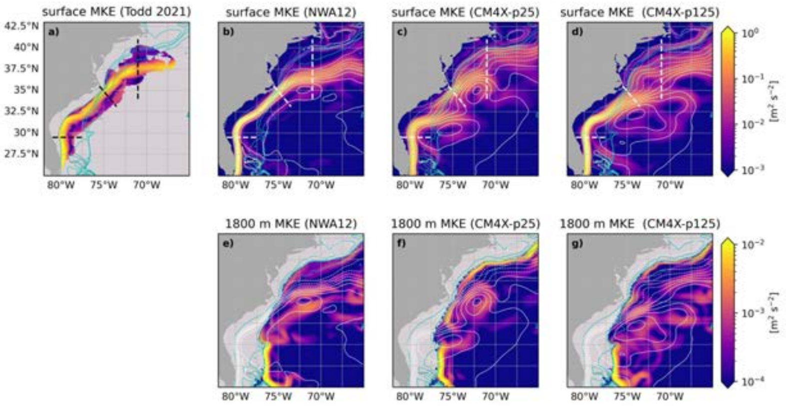
CM4X does not have the unphysically large Southern Ocean polynyas that plague CM4.0

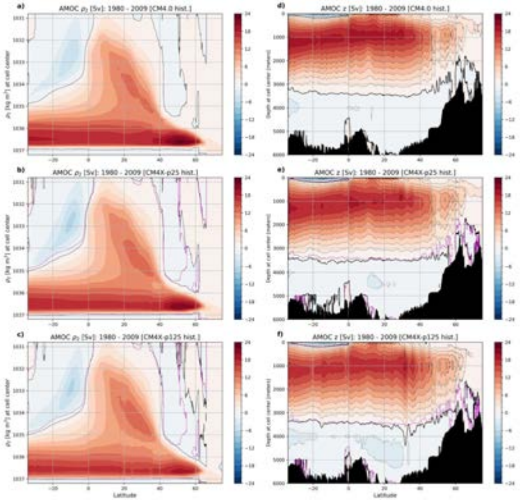


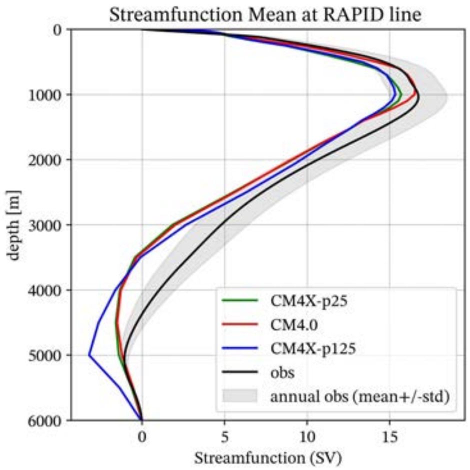


- Further tests are required to uncover the mechanisms for eliminating the unphysically large Ross Sea polynyas. Some suggestions based on SPEAR point to the importance of snow-on-land ice albedos.
- CM4X is more fit-for-purpose than CM4.0 in studies of Southern Ocean melt experiments.

Challenges remain: Gulf Stream too diffuse and AMOC too shallow

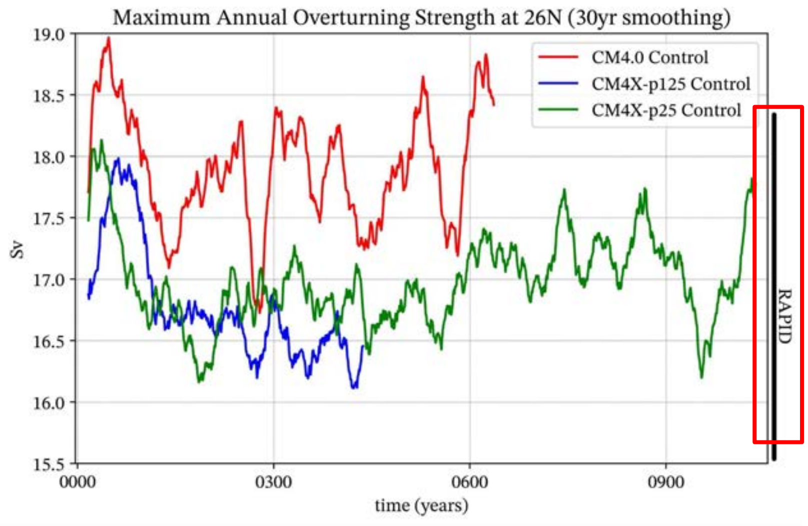


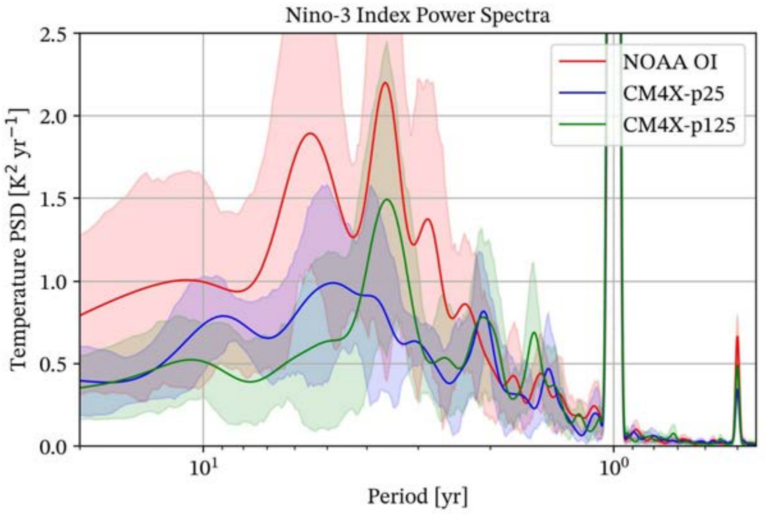




- Gulf Stream biases: flow is too diffuse downstream of the separation, perhaps due to over-dissipation.
- Deep branch of the AMOC is too shallow, suggestive of too much entrainment at the overflows, perhaps due to over-reliance on z-coordinates in weakly stratified deep water formation regions.

Challenges remain: Weak AMOC variability and ENSO variability





- AMOC variability in CM4X is generally weaker than RAPID measures, and weaker than CM4.0.
- ENSO variability in CM4X is weaker than NOAA analysis and weaker than CM4.0.
- Causes for these variability changes remain under investigation.

Challenges remain: Migration to GPU architectures

- High-resolution models place greater pressure on existing resources.
- MOM6 is being migrated to GPU systems.
  - Platform-independent directives (OpenMP), broad vendor support (Nvidia, Intel, AMD)
  - Compatible with existing modern object-oriented codebase
  - Successful migration of critical components of the dynamic core:
    - Pressure gradient force
    - Coriolis force
    - Horizontal viscosity
  - CPU and GPU results are bitwise-identical
- Work is being conducted in collaboration with our MOM6 consortium partners.

Closing remarks

- Mesoscale eddy admitting/active simulations require careful examination of the pros and cons of including eddy parameterizations versus direct simulation of the mesoscale.
- There are areas in need of parameterizations, particularly for the ¼-degree models (e.g., restratification in high latitudes, boundary currents).
- Even so, it has proven difficult to include parameterizations that provide a net positive, with approaches used for coarse models (e.g., Gent-McWilliams) overly dissipative of eddies and boundary currents.
- An alternative targets refined numerical methods (e.g., advection schemes) to allow for a reduction in dissipation that enhance energetics of the resolved scales.
- Finer grids also help with representing topographically constrained flows (e.g., exchanges with marginal seas or estuaries) and allow us to explicitly include new phenomena like the astronomical tides.
- Although we are not ready to conclude that removing mesoscale parameterizations is optimal for the ¼-degree class of models, at ⅛-degree and finer we arguably should run without eddy parameterizations.

References

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