Final Report-SC0019344 Improving the representation of isopycnal mixing in E3SM

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The DOE-supported Energy Exascale Earth System Model (E3SM) is a major attempt by the Department of Energy to develop a new Earth System Model using unstructured grids, which allow for the model to concentrate resolution where it is most needed and avoid numerical artifacts experienced by previous Earth System Models (ESMs) using regular grids in which the lateral resolution becomes extremely fine as the resolution shrinks at the poles. This effort required rewriting many of the algorithms previously developed for regular grids.

One algorithm that was problematic in the first version of E3SM was the representation of mixing due to turbulent ocean eddies with scales smaller than the model grid. These mesoscale eddies are the primary way by which tracers are stirred along density surfaces in the ocean interior. In particular, the process of isopycnal mixing exchanges fresher, more oxygenated waters from polar regions with saltier, nutrient-rich and oxygen poor waters from tropical regions. Previous work in our group has shown that this mechanism is vitally important for bringing oxygen into poorly ventilated tropical regions (Gnanadesikan et al., 2012, 2013) and plays a significant role in determining the uptake of anthropogenic carbon dioxide (Gnanadesikan et al., 2015). However, in E3SMv1 this process was turned off, as turning it on caused the model to become unstable. Additionally, the rate of isopycnal mixing is directly proportional to a mixing coefficient A_{Redi} whose value varies from less than 400 m^2/s to 2000 m^2/s across contemporary climate models. The main thrusts of this proposal therefore were to

1. Improve the numerics of isopycnal mixing in E3SM.
2. Identify ways in which climate models are sensitive to the isopycnal mixing coefficient
3. Develop better representations of the isopycnal mixing coefficient.

Task 1: Improve the numerical representation of isopycnal mixing in E3SM

We were able to identify the reason for this instability, which stems from nonlinearities in the equation of state. The reason for this can be seen by noting that that if there is no variation in salinity, density will be a function of temperature alone. But then lines of constant density should also be lines of constant temperature. It turns out that if we compute the slope of a density surface S_ρ

$$S_\rho = -\frac{\partial\rho/\partial x}{\partial\rho/\partial z}$$

Using density from an equation which has a nonlinear relationship between temperature and density say $\rho = \alpha_0 T + \alpha_1 T^2$ then in finite difference form, where horizontal differences are computed between box 1 and box 2 and vertical differences between box 2 and box 3

$$S_\rho = -\frac{\alpha_0(T_1 - T_2) + \alpha_1(T_1^2 - T_2^2)}{\alpha_0(T_2 - T_3) + \alpha_1(T_2^2 - T_3^2)} * \frac{\Delta z}{\Delta x} \neq \frac{(T_1 - T_2)}{(T_2 - T_3)} * \frac{\Delta z}{\Delta x} = S_T$$

So that the finite-difference density slope and finite-difference temperature slope will be different. As a result, isopycnal mixing will generate fluxes where none should occur, potentially driving instability. The solution to this is to locally linearize the equation of state so that

$$S_\rho = -\frac{\partial\rho/\partial x}{\partial\rho/\partial z} = -\frac{(\partial\rho/\partial T)_{ref}(x) + (\partial\rho/\partial S)_{ref}(\partial S/\partial x)}{(\partial\rho/\partial T)_{ref}(\partial T/\partial z) + (\partial\rho/\partial S)_{ref}(\partial S/\partial z)}$$

This solution was implemented by the Petersen group at LANL into the E3SM ocean code, and is part of the low-resolution version of E3SMv2.

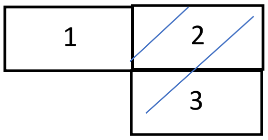


***Figure 1:** Illustration of a situation that leads to generation of spurious maxima and minima in grid-based climate models.*

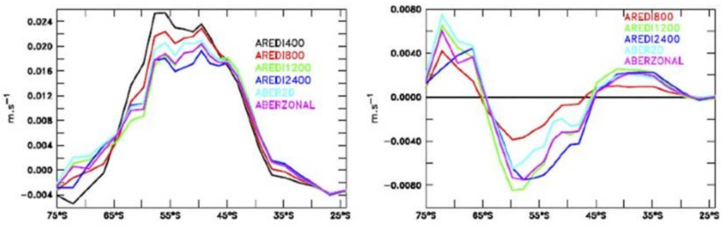
Work was also done to examine a tendency of grid-based isopycnal mixing pameterizations to violate the second law of thermodynamics. The problem arises because when one takes a system of three boxes, as below in Fig. 1, with density surfaces sloping from lower left to upper right. Suppose there is some property with a high value in Box 3 and zero values in Box 1 and 2. Mixing along the density surfaces will cause this quantity to rise in Box 2. But this represents a flux from denser to lighter water. In order for there to be no net transfer of tracer across density surfaces, a flux to "balance" this will be generated from Box 1 to Box 2, creating negative values in Box 1.

Preliminary solutions to this issue were developed during the first year of the proposal and presented at the E3SM meeting. Basically, they involve only performing mixing in cases where all three boxes are connected by density surfaces. The implementation of this scheme was interrupted by the pandemic, but we anticipate following up on it in future work.

Task 2. Identify ways in which models are sensitive to isopycnal mixing

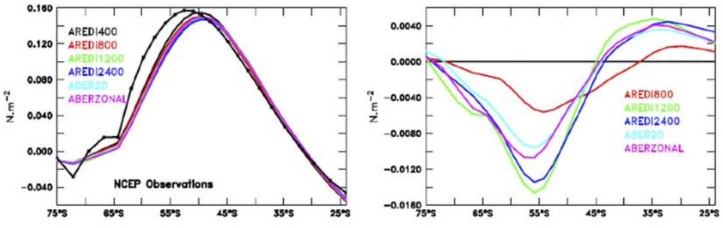
This task ended up being a key focus of the work done in this proposal. In particular, we identified a key role for isopycnal mixing in modulating the exchange of surface and deep waters resulting from convection in high latitudes. We had previously performed a set of experiments in which isopycnal mixing was varied in a coarse-resolution version of the GFDL Earth System Model, enabling us to run simulations for many centuries.

As part of this proposal we examined the impacts of changing isopycnal mixing in the Southern Ocean, an area where E3SMv1 had previously exhibited significant biases. In Ragen et al. (2020), we found that increasing isopycnal mixing resulted in a reduction of the strength of the world's largest ocean current, the Antarctic Circumpolar Current (Fig. 2a,b). The size of changes are significant, with mean velocities dropping by ~25% across the range of models. Notably, the mean changes are often quite a bit larger than those found in Drake Passage, which is often taken as an index of the Circumpolar Current. We found two mechanisms behind this change. First, increasing isopycnal mixing increases the transport of salt into the surface waters of polar regions, driving an increase in convection and warming the atmosphere. This causes a smaller gradient in temperature between the polar regions and the tropics and causes a relaxation



(A) Zonal mean velocity

(B) Zonal mean velocity difference from AREDI400



(C) Zonal mean wind stress

(D) Wind Stress difference from AREDI400

Figure 2 Illustration of how changes in the magnitude/distribution of the eddy mixing coefficient can affect the vertically and horizonally averaged eastward velocity of ocean water and wind stress.From Ragen et al. (2020). Four constant values (400, 800, 1200 and 2400 m^2/s comparable to the range used in contemporary climate models are used as well as two fixed spatially dependent distributions based on satellite altimetry). (a) Mean eastward velocity. (b) Difference in mean eastward velocity from lowest mixing case. (c) Mean wind stress. (d) Difference in mean wind stress from lowest mixing case.

of the winds. However the range of changes in winds is only about 10%, much smaller than the changes in mean velocity. We showed that a secondary impact of the mixing changes involved background stratification. Some of these impacts propagate from the Northern Hemisphere, where higher mixing allows for the (unrealistic) opening of deep convection in the Northwest Pacific.

We also found that changing the mixing coefficient substantially altered convective activity in the Southern Ocean, with high mixing suppressing intermittent formation of open waters (polynyas) in the Southern Ocean and low mixing allowing for a regular cycle of this mixing. An analysis of the dynamics of the low-mixing case was published in Gnanadesikan et al. (2020) showing that it could be understood as a coupled oscillator. Convection within the Weddell Sea warms the atmosphere and causes winds to shift northward (similar to what is seen in Ragen et al., 2020). This reduces the upward mixing of salty water along the Prime Meridian, decreases the export of fresh surface water from the surface Southern Ocean. Both of these processes allow for buildup of a fresh,light surface watermass that then propagates into the Southern Ocean, and shuts off convection. With convection shut off, the atmosphere cools, the winds strengthen, and the process works in reverse. Increasing lateral mixing shuts this loop off. Followup work is planned to look at why this is the case- does the direct impact of increasing lateral mixing prevent salinity anomalies from building up? Or is it that increasing lateral mixing decreases the vertical gradient of salinity, preventing changes in winds from forming such anomalies?

Additionally, as part of this proposal we ran simulations in which we instantaneously quadrupled atmospheric CO2. This is a strategy that is often used within the climate modeling community to identify the fingerprint of climate change. However, such an approach basically assumes that the impacts of climate change are linear. We evaluated this assumption by comparing the results to previous simulations where CO2 was doubled.

In Bahl et al. (2020) we examined whether this resulted in nonlinear responses in biogeochemical fields. In particular, we examine whether the 4xCO2 case can be used to predict the change associated with a doubling of CO_2. While we find that it can do so for global SST and biological productivity within our model suite, it does not do so for regional productivity, hypoxia, and calcite supersaturation. Areas affected by the deep convection (such as the Labrador Sea) are particularly important here, as convection in such regions may shut off when CO2 is quadrupled but not when it is doubled. Increasing isopycnal mixing was found to have important impacts on this result.

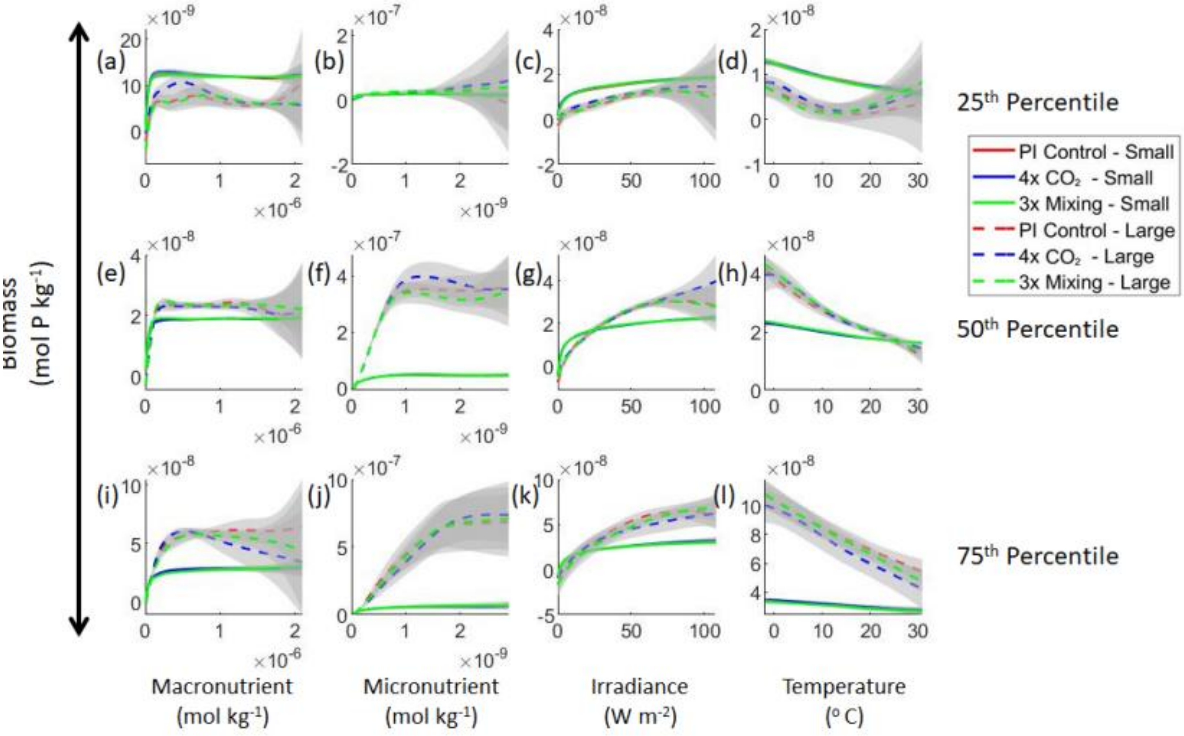


Figure 3: Relationships between environmental parameters and two classes of phytoplankton biomass in an Earth System Model. In each plot one variable is varied while the other 3 variables are held constant at some percentile (shown on the right). The red lines show the control simulation. Blue lines show the impact of tripling the background mixing coefficient (corresponds to AREDI800 and AREDI2400 in previous figure) and green lines show the impact of instantaneously quadrupling CO2.

We also tried to examine whether the uncertainty around isopycnal mixing can result in shifting ocean ecosystems into fundamentally new states. We did this by developing a machine learning method that links plankton biomass to environmental conditions. In Holder et al. (2022) we showed that the apparent relatonships that emerged were extremely stable to changes in mixing, as well as to changes in CO2 (illustrated in Fig. 3). A number of followup papers are in progress applying this method to CMIP6 models and remote sensing products.

Finally, we examined whether the uncertainty in deep mixing could affect the cycling of bioactive metals. We did this using the OCIM inverse model, which has developed a number of circulations with different levels of deep isopycnal mixing which match modern distributions of radiocarbon. The results, as reported in Cui et al. (2022) for Cu are largely negative (similar results have been found for Ni and a manuscript that includes this result is currently in revision).

Task 3: Develop better respresentations of isopycnal mixing

Finally we spent a lot of time thinking about and synthesizing the uncertainty around the isopycnal mixing coefficient. In general, the values used in climate models tend to be far smaller than values measured by observational networks. In an important review, published in a volume on Ocean Mixing (Abernathey et al., 2022) we summarize some of the key issues driving this uncertainty.

A key point is that the mixing coefficient can generally be written as a velocity times a length scale. The classic way of modeling the velocity as that associated with the mesoscale eddies, which can be well described as $\sim S_\rho * N * L_{Ro}$ where N is the buoyancy frequency and L_{Ro} , the Rossby radius, is the spatial scale of the eddies. This yields relatively skillful predictions of velocity, with high values in boundary current regions. However, the length scale is often also taken as proportional to the radius of deformation. However, boundary currents have been shown to suppress mixing. One suggestion from this work is that it is the variation in this term, which is vastly overestimated in boundary currents that accounts for much of the difference between observational and theoretical estimates. Exploratory work was done to try to code this in realistic models.

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