OceanWeather - Impact of ocean eddies on climate variability in coupled climate simulation ensembles

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Mesoscale eddies are the oceanic counterpart to atmospheric anticyclones and cyclones, acting as drivers of ocean weather by introducing chaotic small-scale features into the large-scale flow. These mesoscale eddies are swirling vortices with distinct temperature and salinity compared to the surrounding waters. By redistributing heat, momentum, and nutrients, they influence ocean circulation patterns and enhance marine productivity through vertical mixing. Eddies also interact with the atmosphere, modulating heat and moisture exchange, which contributes to variations in wind patterns, storm tracks, and ultimately influences regional and global climate dynamics (see, e.g., *Small et al., 2008; Seo et al., 2023*).

The previous generation of climate models did not resolve mesoscale eddies in their ocean simulations due to limited spatial resolution. However, recent large-scale modeling efforts, such as DYAMOND (*Stevens et al., 2019*) and Destination Earth (*Hoffmann et al., 2023*), have made significant progress toward directly resolving eddies and air-sea interaction processes in coupled simulations. These advancements come with unprecedented computational demands, which currently limit these models to relatively short simulations over brief periods.

While higher resolution models can directly resolve processes that are typically parameterized in coarser models, resulting in a more accurate representation of climate states, the increased complexity and non-linearity also introduce greater chaotic behavior, which is expected to enhance climate variability (*Penduff et al., 2018; Roberts et al., 2024*). This makes interpreting individual simulations more challenging, but it also suggests that these models may provide a more realistic portrayal of the natural variability of the climate system. Typically, ensembles of simulations with coupled climate models are used to quantify this variability. However, due to the high computational demands of eddy-resolving simulations, ensembles can currently only be run at much coarser resolutions. Consequently, the impact of mesoscale ocean eddies on both large-scale, long-term climate variability and regional-scale phenomena remains an open area of research.

An alternative approach to incorporating eddies in ocean simulations is by improving eddy parameterizations in ocean models. In recent years, several energy backscatter schemes have been developed for the ocean model FESOM2 (*Juricke et al. 2019, 2020a, 2020b, Bagaeva et al., 2024*) to counteract numerical dissipation and smoothing by reinjecting lost energy at larger scales. These schemes enable eddy-resolving simulations at lower resolutions, significantly reducing the computational demands of such simulations. As a result, coupled climate simulations using so-called dynamic energy backscatter (*Juricke et al., 2019, 2020b*) in the ocean offer the possibility of the cost-efficient setup of small ensemble simulations that resolve eddy activity. Moreover, this method provides a controlled environment to assess the impact of mesoscale eddies, as a reference ensemble with dampened small-scale activity can be created by simply deactivating the backscatter parameterization, while keeping all other configuration parameters unchanged.

In this project, we plan to conduct two distinct sets of ensemble simulations using the Alfred Wegener Institute (AWI) climate model AWI-CM3 to investigate the impact of ocean weather on climate variability. One configuration will be close to eddy-resolving, using the energy backscatter scheme, while the reference configuration will be eddy-permitting, with standard model parameters. Both will use the same ocean grids. With a resolution of 30 km in the atmosphere and 10–60 km in the ocean, these simulations are sufficiently detailed at the coupling interface to directly resolve air-sea interactions at the feature level. The simulations will span the period from 1950 to 2050, with five ensemble members in addition to the control simulations for the same timeframe. Through these simulations, we aim to study the effect of eddy activity on long-term variability in large-scale ocean and atmospheric dynamics, such as the Atlantic Meridional Overturning Circulation (AMOC) and along western boundary currents. For specific periods (2010–2020 and 2040–2050), two additional ensemble simulations will be seeded for each individual member, resulting in a total of 18 ensemble members during these intervals to investigate short-term variability at the process level.

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