Changes in eddy kinetic energy from 1950 to 2050 in the EERIE ensemble of eddy-rich climate models

European Eddy-Rich ESMs
https://eerie-project.eu

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Motivation, methods, model evaluation

The ocean circulation is expected to change in a warming climate. A poleward shift of subtropical gyres and western boundary currents has been observed over the past decades and is reproduced in climate models (Yang et al., 2020). It is thought to result from changes in the atmosphere, namely, the expansion of the Hadley cells and the poleward migration of the midlatitude jet streams. Martínez-Moreno et al. (2021) have analyzed EKE trends observed by altimetry over the period 1993-2019. They conclude that surface eddy activity has increased in eddy rich regions at a rate of 2-5% per decade. They find the increase significant south of 35°S and in the boundary currents of the southern hemisphere, but not globally due to the strong interannual variability in the tropical Pacific ocean. Although some trends may not be detectable yet, they may become more visible in the future. In a pioneering study, Beech et al. (2022) have found long-term trends in CMIP projections with the AWI-CM1-1-MR coupled model. The strongest signal is a poleward shift of EKE in most eddy-rich regions. An intensification of EKE is projected in the ACC, Kuroshio, Brazil and Malvinas currents, while a decrease is projected in the Gulf Stream. **Here we revisit these results using high resolution models developed in the context of HighResMIP and the EERIE project.**

METHODS : in the EERIE project, four coupled ocean-ice-atmosphere models are run for HighResMIP or CMIP simulations, at resolutions of at least 10km. The global NEMO (Nemo, 2022) e-orca12 configuration at 1/12° with SI3 sea ice is used by the MetOffice MOHC (coupled with UM atmosphere, Roberts et al., 2020). It is also used by BSC, coupled with the atmospheric model ECMWF-IFS. AWI uses FESOM2 (Danilov et al., 2017), a finite volume ocean model also coupled with ECMWF-IFS. The ICON coupled model, on an icosaedric grid, has been developed by MPI-M. The ocean component has a 5 km resolution and the atmosphere 10km (Kang et al, 2026). Here we also consider the earlier MOHC model HADGEM-GC31-HH (also using e-orca12 for the ocean).
In order to facilitate comparisons with observations, we consider the geostrophic eddy kinetic energy (EKE), computed from the model daily averaged fields of sea surface height. Comparison with satellite observations is made for the period 1995-2014.

Overall, the performance of the coupled EERIE models is comparable to forced ocean models (Chassignet et al, 2020). The Gulf Stream region is shown as an example. The EKE patch has differences with observations typical of the 1/10° to 1/12° models; note that Chassignet et al. (2023) find improvements when moving to higher resolution, 1/50°.

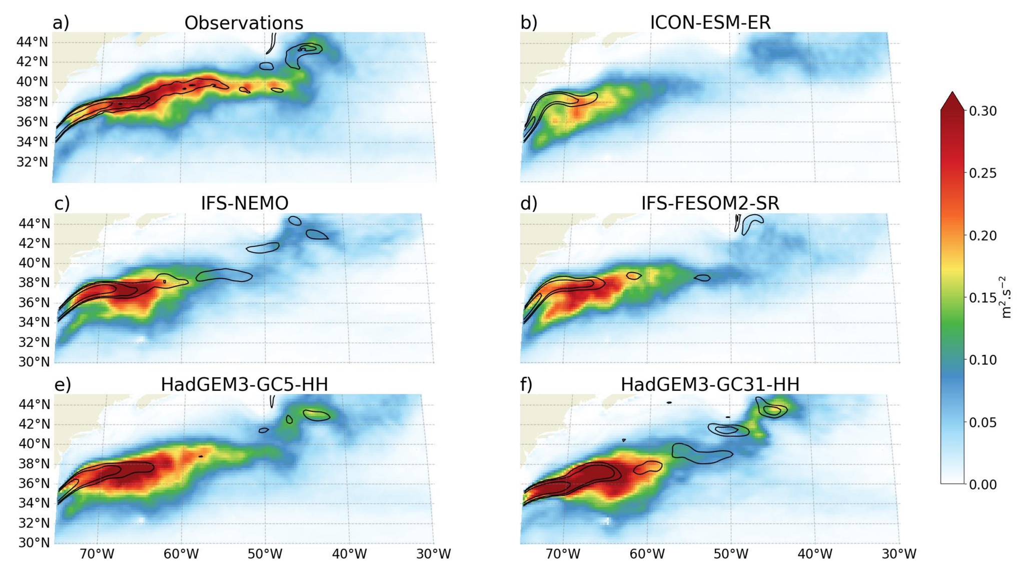

Figure 1: Geostrophic EKE (colors) averaged over the period 1993-2023 in the Gulf Stream region, and mean kinetic energy (black contours, for 0.05, 0.1 and 0.3 m²/s²), for observations and models.

EKE trends over the observation period, 1993-2023

Martinez-Moreno et al (2021) as well as Barceló-Llull et al. (2025) observe increases of EKE in eddy rich regions. Here we compute EKE time series from 1993 to 2023 in the same regions as these authors, but with a consistent eddy-mean decomposition (using SSH anomalies referenced to the 1993-2023 period). No significant trend is observed in the Gulf Stream, but a positive trend is observed in the Antarctic Circumpolar Current (ACC) and the Kuroshio. In this spatially–averaged view, the models reproduce the observed trend in the ACC but not in the Kuroshio.

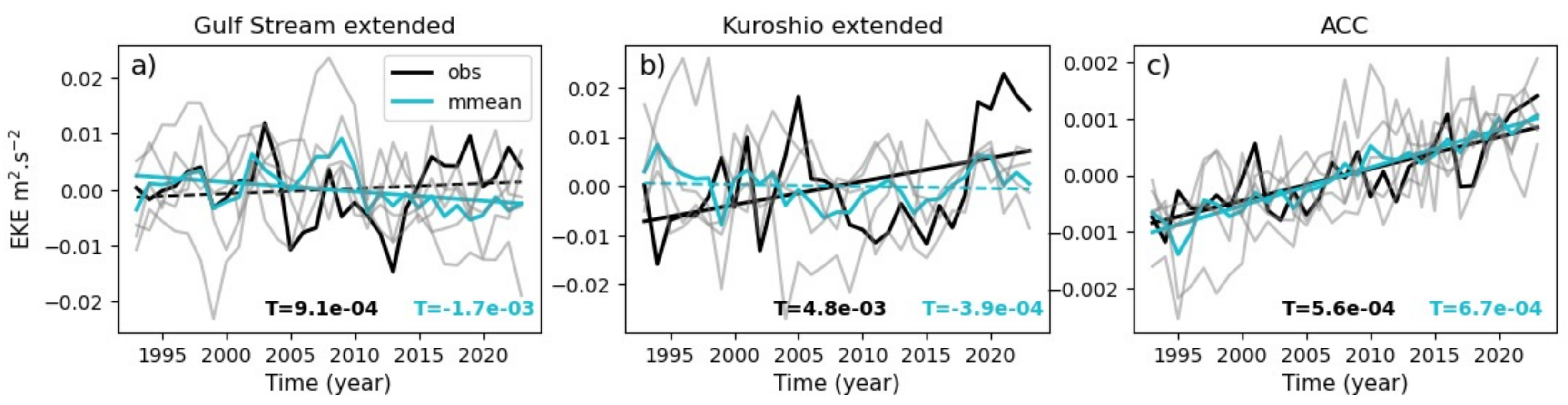

Figure 2: time series of EKE anomaly (relative to the 1993-2023 mean)., averaged in regions (two regions outlined in black in figure 3, and the ACC). Individual models are represented in grey, observation in black and the multi-model mean in cyan (ICON excluded for the Kuroshio extended region). The trends of the latter two time series are represented by solid lines when significant at the 90% level and by dashed lines otherwise. Their values are indicated in units of m2.s-2 per decade.

The existence of poleward shifts in western boundary currents (Yang et al., 2020, Martinez Moreno et al., 2021) means that when averaging over large regions of strong EKE, negative trends equatorward can cancel the positive trends poleward. This is illustrated in figure 3. In the Gulf Stream, models show more significant trends than observed, with a clear poleward shift. In the Kuroshio, the observed EKE increase is almost entirely due to the apparition of the large meander after 2015, a feature linked with internal decadal variability (Hirata et al., 2025). It is thus expected that coupled climate models do not capture the timing of this large meander. On the other hand, the poleward shift signal is remarkably reproduced by the models.

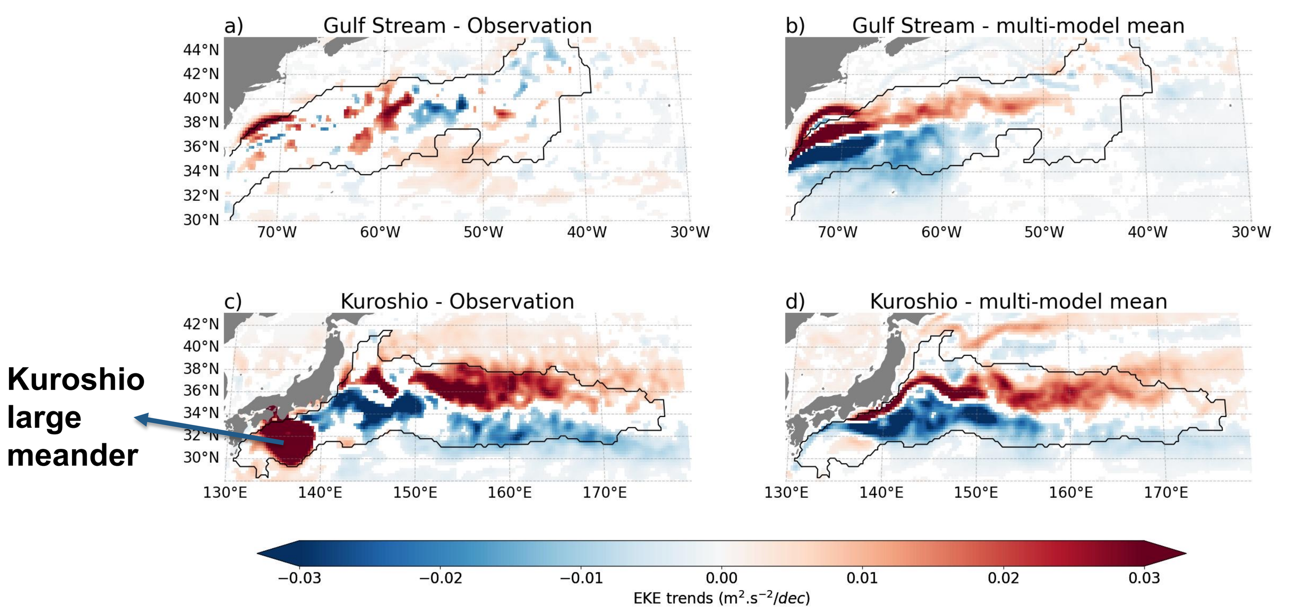

Figure 3: EKE trends over the period 1993-2023 in observations and for the EERIE multimodal mean (the ICON model is excluded from the multi-model mean in the Kuroshio region due to a strong bias)). Trends are plotted only where their absolute value exceeds their standard error.

EKE changes from 1950 to 2050

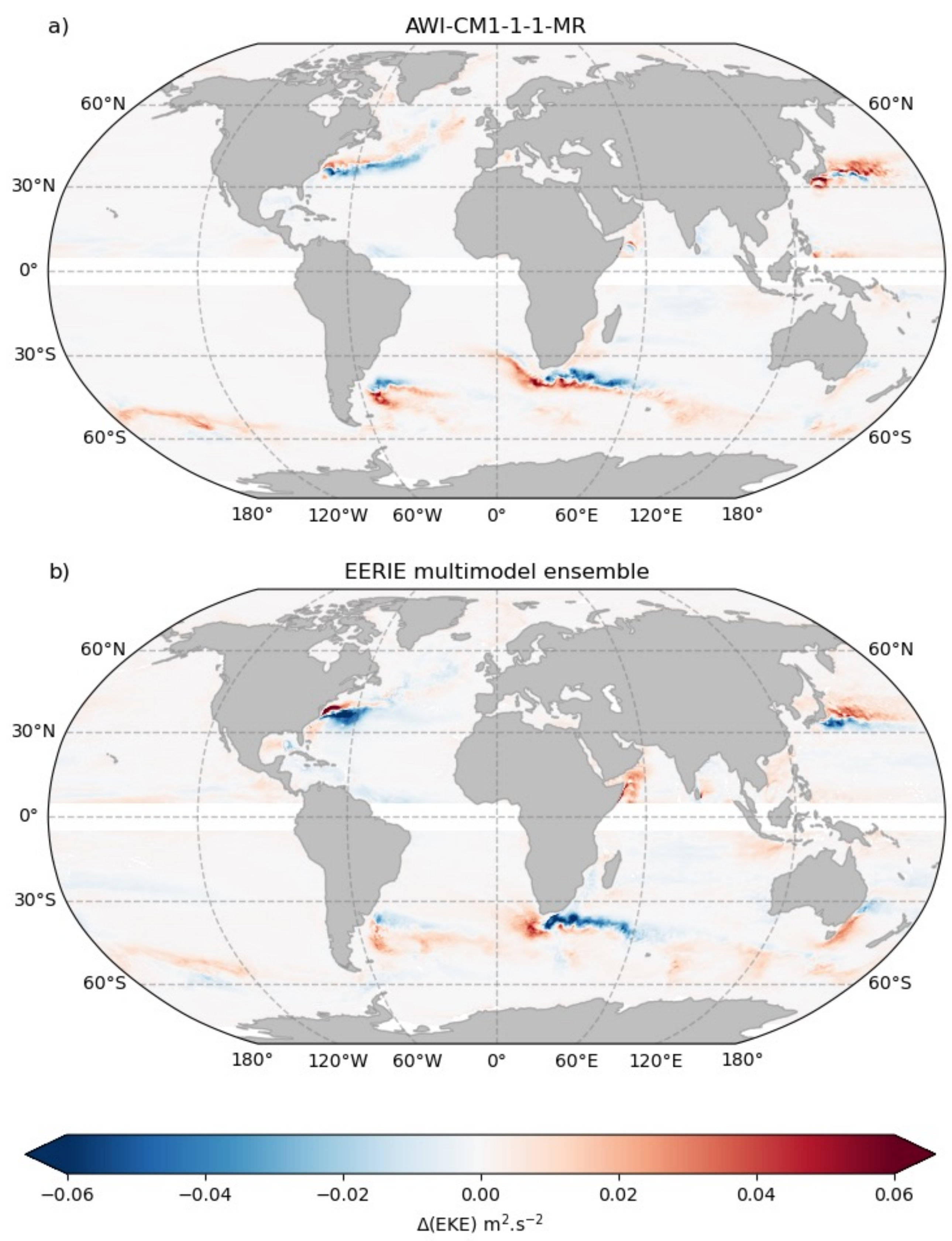

Figure 4: Change in the ensemble-mean EKE between the periods 1951-1970 and 2031-2050. a): averaged for the five members of an earlier version of the AWI model (Beech et al., 2022) and b): averaged for five high resolution EERIE models. Units are m²/s². There is no data between 3°S and 3°N because the EKE is the geostrophic component only, computed from SSH.

We compare the multi-model mean of 5 EERIE /HighResMIP models with the single model, 5-member ensemble of Beech et al. (2022). Although Beech et al. considered a longer future scenario (CMIP protocol, up to 2100), the EKE difference computed here between 2050 and 1950 is quite similar to the change over a longer period (comparing figure 4a with Beech et al.'s figure 2c). The EERIE multi-model mean projects a continuation of the poleward shifts in the coming decades, in the Kuroshio, the Gulf Stream and the Agulhas retroflexion region, and to a lower extent to other regions as well. The EKE is projected to continue its intensification in the ACC and in the Cape Basin. The latter result is in agreement with the increase in the Agulhas leakage diagnosed in the high resolution CESM model (Großelindemann et al., 2025).

Conclusions and perspectives

EKE is expected to change in a warming world. The similarity of its evolution between 1950 and 2050 for the five high resolution models considered here, and **the consistency of the EERIE multi-model mean with the earlier model ensemble of Beech et al.** (2022), suggest that part of this evolution is due to anthropogenic forcing. There is a clear dipolar pattern in many eddy-rich regions. This is suggestive of a poleward shift of the mean currents, which may already be happening in the Gulf Stream, the Kuroshio and the Agulhas retroflexion.

Some of these results are part of Deliverable D6.2 of the EERIE project ("Report on the eddy effects on the large-scale ocean", https://zenodo.org/records/22010366)

Eddy-rich coupled models reproduce forced surface EKE changes over the past decades with some skill and are remarkably consistent in projecting future changes. More in-depth analysis is needed to characterize western boundary current variability and trends over the water column, and to understand their impacts. Collaborations between EERIE and the U.S. MESACLIP project would be valuable to increase the ensemble size.

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