nature climate change

Article

https://doi.org/10.1038/s41558-022-01478-3

Long-term evolution of ocean eddy activity in a warming world

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Supplementary Notes

1. Atmospheric component configuration and coupling

The atmospheric component of AWI-CM-1-1-MR, ECHAM6.3.04p1 (Stevens et al., 2013), uses a horizontal grid resolution based on spectral truncation at total wavenumber 127, or approximately 100 km horizontal resolution in the tropics and gradually finer resolution towards the poles (Semmler et al., 2020). The different resolutions employed by the atmospheric and oceanic model components result in a loss of spatial detail during coupling between the higher and lower-resolution grids. In the case of AWI-CM-1-1-MR, air-sea fluxes are calculated on the atmospheric grid, as is common practice in CMIP-type models. This effectively results in smoothed fields being passed from the ocean component to the atmospheric component. The damping effects of smoothed coupled fields are a common challenge in coupled climate models with high ocean-to-atmosphere resolution ratio and can affect ocean-atmosphere feedbacks relevant to mesoscale eddy activity (Ma et al., 2016; Jullien et al., 2020). Furthermore, in AWI-CM-1-1-MR absolute wind stress is coupled rather than relative wind stress. The absence of ocean surface currents in the computation can be particularly impactful in the tropics, where ocean surface velocity can be of similar order to the atmospheric velocity. Both of these challenges in coupling may have compensatory effects, and coupling schemes to improve the representation of sub-grid scale variability which is passed to the coarser grid component have been proposed (Rackow & Juricke, 2020). Nonetheless, these are issues that should be acknowledged as systematic model shortcomings in reproducing realistic eddy activity in our simulations.

2. Spin-up information

The AWI-CM-1-1-MR simulations stem from an initial ten-year ocean-only spin-up, followed by a 500-year coupled spin-up, and a pre-industrial control spin-up from which the five ensemble members were branched off at 25-year intervals beginning after 250 model-years. Each ensemble member was then run for a historic period from 1850 to 2014 using prescribed greenhouse gas forcing based on observations before beginning emissions scenario projections for the years 2015–2100.

3. Model inter-comparison

Considering the diversity of the CMIP6 ensemble, it would be advantageous to consider simulations from multiple models when projecting changes in EKE. With this in mind, the CMIP6 ensemble was searched for complementary simulations with comparable resolution and data availability. Most of the CMIP6 ScenarioMIP ensemble (Eyring et al., 2016) relies on parameterizations of eddy activity, and the highest nominal resolutions in the ScenarioMIP ensemble (25 km) can only be considered eddy-present (Hewitt et al., 2020). Moreover, most simulations do not record, or make publicly available, daily ocean surface velocity or SSH data and many rely on single-member ensembles for each emissions scenario. In particular, high resolution simulations such as HighresMIP (Haarsma et al., 2016) which produce larger datasets as grid resolution increases, tend to be single-member ensembles and record or make publicly available fewer variables at coarser temporal resolution. These datasets do not meet the basic requirements for applying the methods described here, and consequently, this analysis relies exclusively on simulations from AWI-CM-1-1-MR.

4. Data processing

Methodological information regarding the data processing steps performed by Copernicus, including approximation of gridded data from along-track observations and the computation of geostrophic velocity anomalies from sea surface height are publicly available from the Copernicus Marine Environment Monitoring Service (Legeais & Taburet, 2018). In the modeled dataset, the equatorial region between 3 °S and 3 °N, where geostrophic balance breaks down (Lagerloef et al., 1999), is represented by monthly mean data linearly interpolated to 5-day means. In both the modeled and observed datasets, February 29th was removed from the dataset to create a year evenly divisible into five-day means. The observational dataset was remapped to the FESOM grid using bilinear interpolation for a direct comparison of data, and coastal mesh nodes, those adjacent to land, were ignored to avoid boundary issues.

5. Eddy kinetic energy calculation considerations

Typically, the time varying component of ocean flow is separated from mean conditions via Reynolds decomposition: subtracting the mean conditions during a reference period from the larger dataset and interpreting the resulting anomalies as the time varying component. In many applications of time series analysis, such as assessing changes in mean conditions, a reference period is appropriate to represent the historic mean state of a variable. However, if anomalies are intended to represent variability from a mean state and that mean state is changing, the reference period approach fails when mean conditions change to the point that the reference period mean is no longer representative of typical conditions. In the context of climate change, the potential for the mean state of ocean flow to shift must be considered; ocean gyres are expected to shift poleward as warming continues (Wu et al., 2012; Yang et al., 2016; 2020), AMOC decline has been theorized and predicted by many studies (Latif et al., 2004; Rahmstorf et al., 2015; Lique et al., 2018; Boers, 2021), and global ocean circulation appears to be accelerating in general (Hu et al., 2019). Therefore, changes in the mean flow of the ocean must be accounted for when producing anomalies for EKE calculation, prompting the use of a running mean to represent the mean state of ocean flow, rather than a reference period mean.

The ensemble mean of 21-year running means from each ensemble member represents 105 data-points of reference surface velocity data intended to represent the mean state of surface flow while only losing ten years of data at the beginning and end of each time series. Due to internal variability, the ensemble members may differ slightly in their simulation of mean flow, but these differences are expected to be smaller than those stemming from seasonality or the effects of climate change, making an ensemble mean preferable for characterizing mean flow.

6. Methodological challenges

Long climate change projections of EKE bring with them new methodological challenges such as distinguishing ocean velocity anomalies form a shifting mean state, and characterizing EKE change that varies throughout the global ocean and may have non-linear or contradictory responses to multiple driving mechanisms. These challenges have been addressed using appropriately tailored methodology: a running-mean approach to allow for meaningful anomaly calculations and a difference-of-means approach to quantifying long-term change. However, weaknesses within these methods persist where mean conditions are not unimodal, such as the Kuroshio LM/NLM path, but comparison with observations indicates that the same issues likely affect observational studies and do not appear to be prominently addressed in the existing literature. The challenges identified with distinguishing EKE from bimodal mean conditions likely apply to many patterns of oscillation, and should be considered in a variety of contexts.

7. References

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Supplementary Table 1

	Basin	Modeled EKE (1993-2020) (km^4/s^2)	Observed EKE (1993-2020) (km^4/s^2)	Percentage Resolved (%)
a	Gulf Stream	0.228	0.393	58
b	Kuroshio Current	0.284	0.345	82.45
c	Agulhas Current	0.433	0.615	70.39
d	Brazil/Malvinas Current	0.120	0.195	61.43
e	Antarctic Circumpolar Current	0.247	0.489	50.52

Supplementary Table 2

	Basin	σ Modeled EKE (1993-2020) (km^4/s^2)	σ Observed EKE (1993-2020) (km^4/s^2)	Percentage Resolved (%)
a	Gulf Stream	0.016	0.029	56.21
b	Kuroshio Current	0.033	0.031	107.4
c	Agulhas Current	0.022	0.021	105.71
d	Brazil/Malvinas Current	0.009	0.013	74.02
e	Antarctic Circumpolar Current	0.013	0.017	76.05

Supplementary Table 3

	Basin	Historic EKE (1860-1949) (km^4/s^2)	Projected EKE (2061-2090) (km^4/s^2)	Percentage Change (%)
a	Gulf Stream	0.223	0.199	-10.43
b	Kuroshio Current	0.278	0.380	36.82
c	Agulhas Current	0.426	0.445	4.46
d	Brazil/Malvinas Current	0.119	0.147	23.03
e	Antarctic Circumpolar Current	0.227	0.298	31.51

Supplementary Table 4

	Name	Historic mean (Sv)	Projected mean (Sv)	Mean difference (Sv)	Percentage difference (%)	T statistic	p(T)	Information
a	AMOC	17.504	14.490	-3.014	-17.216	30.456	1.02E-123	Zonal transect of the Atlantic at 26 °N and 1040 m depth
b	Kuroshio Current Transport	9.810	10.633	0.823	8.389	-16.093	1.12E-48	Lat/lon coordinates: (29.2 °N, 121.6 °E) to (26 °N, 128 °E), 0-150 m depth
c	Agulhas Current Transport	65.833	55.731	-10.101	-15.344	23.959	1.95E-89	Lat/lon coordinates: (-32 °N, 29 °E) to (-32 °N, 32 °E)
d	Agulas Leakage	23.297	29.743	6.446	27.670	-22.811	2.46E-83	Lat/lon coordinates: (-30.83 °N, 17.8 °E) to (-43.17 °N, 7.06 °E), 0-1200 m depth
e	Brazil Current Transport	45.975	47.967	1.992	4.333	-7.316	8.23E-13	Lat/lon coordinates: (-34.3 °N, -54 °E) to (-34.3 °N, -49 °E)
f	North Brazil Current Transport	32.178	30.258	-1.921	-5.969	14.454	7.91E-41	Lat/lon coordinates: (-6 °N, -35.3 °E) to (-6°N, -25 °E), 0-1200m depth
g	Malvinas Current Transport	74.120	63.020	-11.100	-14.975	17.855	1.79E-57	Lat/lon coordinates: (-46 °N, -67.6 °E) to (-46 °N, -57 °E)
h	Drake Passage Throughflow	170.988	169.225	-1.763	-1.031	7.479	2.68E-13	Lat/lon coordinates: (-64.17 °N, -60.4 °E) to (-54 °N, -68 °E)