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Editorial: Constraining uncertainties in hindcasts and future projections of marine deoxygenation

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Editorial on the Research Topic
Constraining uncertainties in hindcasts and future projections of marine deoxygenation

Ocean deoxygenation is a key stressor for marine ecosystems and biogeochemical cycles (Gruber, 2011; Breitburg et al., 2018). Climate projections based on Earth system models (ESMs) suggest that the global oxygen inventory will undergo a significant decline over the next century under persistent greenhouse gas emissions (Bopp et al., 2013; Kwiatkowski et al., 2020). Oxygen minimum zones (OMZs) located close to productive eastern boundary upwelling systems (EBUSs) and the Arabian Sea may expand or shift in spatial extent dramatically, thereby impacting regional marine habitats (Stramma et al., 2012) and ecosystem services (Lachkar et al., 2023). However, ESMs and coupled ocean-biogeochemical models have struggled to reproduce or underestimate the observed oxygen trends and variability over past decades, indicating that key physical and biogeochemical processes are still poorly represented (Oschlies et al., 2017; Tjiputra et al., 2018). This makes it challenging to mechanistically attribute the observed oxygen changes in the past decades and limits the fidelity of long-term model projections. In addition to the sparse observations, this difficulty also stems from the fact that oxygen distribution and variability in the ocean are driven by a complex interplay of wide range of mechanisms acting at different temporal and spatial scales, making it difficult to simulate it accurately in models. These mechanisms are related to both ocean circulation (strength of wind-driven circulation, meridional overturning, water mass formation rate, and mesoscale activity) and biogeochemical cycles (export production, remineralization rate, ecological communities, microbial loop, and anaerobic N-cycle processes). The latter is particularly poorly constrained by the limited observations. Owing to the increasing uncertainties, the models participating in the Coupled Model Intercomparison Project phase 5 and 6 (CMIP5/CMIP6) effort do not generally agree on the magnitudes of oxygen decline and OMZ expansion (Cabré et al., 2015; Kwiatkowski et al., 2020). Therefore, the scientific community urgently needs to identify and reduce uncertainties related to the key physical and biogeochemical processes governing the oxygen budget to improve our confidence in predicting the impact of climate change on marine ecosystems and biogeochemical cycles.

The five studies published in this Research Topic address an urgent issue and can be categorized into three subjects: 1) analysis of model ensembles and their robustness for hindcasts, 2) application of model ensembles for determining future changes, and 3) application of a single model to unveil the mechanisms governing the observed variability.

Three studies have been conducted on the first subject. Abe and Minobe highlighted the uncertainties in the oxygen inventory trends of ESMs simulations from the surface down to 1000 m in the North Pacific from 1958 to 2005; They used 204 ensembles from twenty CMIP5 and CMIP6 models, which revealed that this uncertainty depends more on the internal variability of each model than on the differences in model configuration; it is also strongly affected by the model-dependent decreasing trends, with varying magnitudes, of oxygen inventory in the subarctic North Pacific, the spatial pattern of which is similar to the observations. They demonstrate that the changes in oxygen inventory in the North Pacific are mostly due to changes in circulation rather than changes in oxygen respiration, which is consistent with previous studies. However, CMIP5/CMIP6 models do not accurately reproduce the observed relationship between sea surface temperature and oxygen, indicating a missing or incorrectly parameterized mechanism.

Koelling et al. assessed the performance of climate simulations of the nine models in the Ocean Model Intercomparison Project phase 1 of the CMIP6 (CMIP6-OMIP1) in reproducing the observed oxygen inventory trend between 1950–2015 in the Labrador Sea, where considerable oxygen was introduced into the deep ocean via air-sea oxygen exchange, deep water formation, and export of oxygen by physical processes (advection and mixing). They showed that all models underestimated the magnitude of oxygen change, although the simulated temporal trends (interannual and decadal trends) were similar to the observations. They suggested that this underestimation is possibly attributed to the smaller simulated amount of air-sea flux of oxygen into the ocean and might also be affected by unrealistic deep convection and biased mean oxygen profiles in the models.

Takano et al. analyzed oxygen content trends in the upper ocean (0–700 m) in forced ocean-only model simulations (OMIP1 and OMIP2) and fully coupled runs (CMIP6 Historical). They reported that the oxygen trend during the last five decades for the CMIP6 Historical simulations was consistent with the most recently published synthesis of oxygen observations (Ito, 2022), whereas the simulated trends from the OMIP1 and OMIP2 simulations were much smaller in magnitude and showed opposite directions to each other. Their analysis revealed that the deoxygenation trends in the CMIP6 Historical were influenced by the differences in the background mean states affected by the different model spin-up times, whereas for the OMIP1 and OMIP2, the inter-model uncertainties stem from the differences in atmospheric forcing (such as surface wind) products.

In terms of the second subject, Shi et al. projected future changes in the summer hypoxia frequencies of the coastal California Current using the simulation results of nine fully coupled CMIP6 models. Because the simulated results of dissolved oxygen from 1993 to 2020 were different in magnitude and variance across the models, they adopted a model-specific threshold value for defining hypoxia and applied empirical bias adjustments to each model outputs using a hindcast simulation of ocean circulation and biogeochemistry. This allowed each model to reproduce hypoxic event frequencies in the coastal region that were more consistent with the observations. Using the hindcast-adjusted model outputs, they found that hypoxic events increased consistently across models in magnitude and spatial extent with global warming during the 21st Century. This study also highlighted several limitations to using bias-adjusted coupled model simulations to assess future projections, such as the need for greater temporal and spatial observational coverage to improve model validation at regional scales.

To address the third subject, Kim et al. performed a suite of model simulations in order to investigate the mechanism controlling the observed decrease in dissolved oxygen concentration in the deep and bottom waters of the Japan Sea during the last few decades using one coupled physical-biogeochemical model. They concluded that the observed decrease is mainly ascribed to halted deep convection exceeding 2000 m depth in the Japan Sea since 1970, drastically reducing ventilation. The concomitant increasing primary production and respiration in the deeper layer also accelerate the oxygen decline.

Several outstanding issues remain to be addressed regarding constraining uncertainties in hindcasts and future projections of marine deoxygenation. However, the articles published in this Research Topic made some headway in better understanding the uncertainty intrinsic to hindcasts of marine deoxygenation in CMIP5/CMIP6 models. They further provided several methodologies to better understand the root of projection uncertainties and examples of using CMIP6-based future climate projections for regional studies of deoxygenation and their limitations. Their findings confirm that conducting sensitivity tests is highly useful for mechanistically understanding the specific processes acting on marine deoxygenation. Recently, remarkable progress has been made in eddy-resolving and regional model simulations coupled with ocean biogeochemistry, providing new research avenues to explore the effects of mesoscale and sub-mesoscale processes on the oxygen cycle and identify the role of model resolution in improving model biases and model-observation discrepancies (Montes et al., 2014; Vergara et al., 2016; Karstensen et al., 2017; Frenger et al., 2018; Busecke et al., 2019; Eddebbar et al., 2021).

In addition, Abe and Minobe used a large ensemble of CMIP6 experiments which allows robust separation of natural variability and forced response, time of emergence, and exploration of the predictability of oxygen from seasonal to decadal timescales. These two topics should be further addressed in future studies.

Finally, the novel findings revealed by the articles on this Research Topic promote future works on the reduction of uncertainty in physical and biogeochemical representations in models, which will accelerate progress in marine deoxygenation studies, and furthermore highlight the need for expanding and sustaining the oxygen monitoring network to validate models and improve our dynamical understanding of marine deoxygenation independently. These efforts (e.g Grégoire et al., 2021) are being undertaken within an international framework, such as the Global Ocean Oxygen Decade (GOOD).

Author contributions

MS: Writing – original draft. OD: Writing – review & editing. TI: Writing – review & editing. JT: Writing – review & editing. YE: Writing – review & editing.

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Conflict of interest

Publisher's note

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