<u>Final report</u>
Project Title: Ocean physical-biogeochemical interactions in the CMIP6 and E3SM Earth System Models
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1. What are the major goals of the project?

The primary objectives of this project are to quantify the spatio-temporal linkages between physical climate and ocean biogeochemical variables in the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM), in CMIP6 Earth System Models (ESMs), and in historical observations, to evaluate the E3SM's ability to reproduce the observations, and to develop a solid diagnostic package to do so. It will revolve around four hypotheses and will focus on key physical and biogeochemical processes that regulate the upper ocean carbon and oxygen cycling: water mass distribution, ventilation, and biological production. We hypothesize that these processes, taken together, control mean state and changes in the oceanic inventories of carbon and oxygen, and explain two major issues that state-of-the-art Earth System Models face in their representation of carbon and oxygen cycling. First of all, current generation ESMs consistently underestimate the (multi-) decadal variability of the ocean carbon uptake and the dissolved oxygen (O2) content. Secondly, ESMs disagree over the sign of predicted O2 changes in the tropical oceans under global warming scenarios. These disagreements imply fundamental differences in the sensitivity of physical and biogeochemical processes among the ESMs. Inter-model differences and biases impact not only the representation of oxygen cycling but also that of other important elements such as nitrogen, phosphorus and carbon so that ESM-based predictions of ecosystem health or their applications to fisheries research are hindered.

The three major objectives of this proposal are to:

1) Evaluate the performance of CMIP6 ESMs with a focus on E3SM in representing observed patterns of physical/biogeochemical variables, leveraging the growing collection of historical datasets.
2) Test hypotheses about the mechanisms controlling the variability of ocean carbon uptake and dissolved oxygen content.
3) Characterize climate patterns in physical and biogeochemical variables and their spatiotemporal linkages in both E3SM and in the observations through a robust diagnostic package.

The research team comprises of Takamitsu Ito and Annalisa Bracco at the Georgia Institute of Technology, with the collaboration of Yohei Takano and Luke Van Roekel at the Los Alamos National Laboratory. This grant supported the postdoctoral researcher Lyuba Novi at Georgia Tech and the Ph.D. student Qi Zhang. Ito's research focuses on the theory and models of large-scale ocean circulation and biogeochemical cycling, and the effect of climate variability on the global carbon and oxygen cycles. Bracco's interests include ocean transport, climate dynamics and predictability, and the adoption in climate research of data mining algorithms from mathematics, nonlinear dynamical systems and computer science.

2. What was accomplished under these goals?

We completed the analysis of E3SM and CMIP6 earth system model's physical and biogeochemical fields focusing on O_2 and carbon trends and variability using new diagnostic packages including information entropy (IE), δ-Maps, and carbon flux decomposition. We also completed the analysis of the air-sea CO_2 flux changes in relation to the weakened Atlantic Meridional Overturning Circulation (AMOC) and the analysis of ocean deoxygenation. Finally, we completed the publication on the biases in the observational and modeled ocean deoxygenation rates. In total, there are **9 peer-review publications** generated from this project. Here, we summarize these results in three groups focusing on (1) ocean deoxygenation, (2) air-sea carbon exchange, and (3) new diagnostics and machine-learning (ML) approaches

(1) Ocean deoxygenation

This project first updated the observational estimate of global ocean oxygen content and its temporal trends. We constructed a global, full-depth gridded dissolved oxygen data set using optimal interpolation, providing 5-year moving averages from 1965–2015 with quantified uncertainties arising from unresolved variability and mapping errors. The estimated multi-decadal global oxygen decline is −281 to −373 Tmol per decade, a more conservative range than previous studies. Because regions far from observations are assumed to have zero anomaly relative to climatology, the results likely represent a lower-bound estimate of historical global oxygen loss. This result was published as **Ito (2022)**. To evaluate the biases and uncertainties of the observation-based estimates, **Ito et al., (2024)** used E3SM1-1 together with CMIP6 Earth System Models to evaluate the biases and uncertainties in oxygen distribution and trends. Model outputs are sub-sampled according to the spatial and temporal distribution of the historical shipboard measurements, and an optimal interpolation method of **Ito (2022)** is applied to fill data gaps. Sub-sampled results are compared to full model output, revealing the biases in global and basin-wise oxygen content trends. The optimal interpolation underestimates the modeled global deoxygenation trends, capturing approximately two-thirds of the full model trends.

Next, we focused on understanding the underlying mechanisms. Using a numerical model and sensitivity experiments, we investigated how vertical and isopycnal mixing affect both the mean oxygen state and its response to warming. The results were published as **Ito et al (2022).** The results show that oxygen loss patterns are highly sensitive to mixing parameterizations, with tropical oxygen trends even reversing sign depending on mixing strength. Enhanced isopycnal mixing alters the advective–diffusive balance in the tropical thermocline, raising mean oxygen levels while amplifying transient oxygen declines. These findings offer a first-order explanation for the divergent tropical oxygen responses seen across climate models.

To further understand the mechanisms, we examined the linkages between the upper ocean (0-200m) oxygen (O_2) content and stratification in the North Pacific Ocean in four Earth System Models (ESMs) including E3SM, an ocean hindcast simulation, and ocean reanalysis data, and this work was published as **Novi et al., (2024).** Variability and trends in oceanic oxygen are governed by the balance between physical supply, primarily through ocean ventilation, and biological consumption. This study uses Isopycnic

Potential Vorticity (IPV) as a dynamical proxy for ventilation, exploiting its quasi-conservative nature and derivation from temperature and salinity.

(2) <u>Carbon cycle trends and variability</u>

Carbon dioxide is naturally exchanged between the surface oceans and the atmosphere. This exchange is driven in part by the human-induced increase in atmospheric carbon dioxide levels, but a range of natural physical and biological processes can also impact the rate of this exchange. Our goal is to quantify and understand the effects of physical, biological, and human-induced drivers of ocean-atmosphere carbon exchange. Through the analysis of air-sea carbon fluxes, we discovered that regional carbon uptake tends to reach its maximum several decades earlier than the time of maximum growth in atmospheric pCO_2. This appears to be a salient feature of CMIP6 models. We determined the two mechanism behind this early saturation of North Atlantic carbon uptake including (a) weakened subduction due to weakened AMOC and (b) reduction of surface alkalinity associated with the freshening of surface water in the subpolar North Atlantic. The Ph.D. student, Qi Zhang, completed the analysis and published the results in the journal of Frontiers in Marine Sciences in the spring of 2024, as **Zhang et al., (2024)**.

We further developed a new diagnostic framework is developed to explain the individual contributions of multiple physical, biological, and anthropogenic processes. We do this in three steps. First, we explain the method using a very simple representation of the ocean carbon cycle known as the "box model". Second, we apply the framework to a more realistic, three-dimensional simulation of the Southern Ocean which is rigorously tested to represent observed carbon dioxide exchange rates. Finally, we simulate a human intervention in ocean-atmosphere carbon exchange through a computational experiment adding iron or alkalinity to the surface ocean. The techniques developed in this paper can be used across a broad range of natural and human-induced processes to estimate the responses of ocean-atmosphere carbon exchange. The result is published in Global Biogeochemical Cycles as **Ito and Reinhard (2025).**

(3) **<u>New diagnostics and machine learning approaches</u>**

The Earth's climate is complex, and climate models are far from perfect. Here, as an innovative technique to evaluate and improve earth system models, we propose employing methods stemming from dynamical systems and manifold learning. Manifold learning is based on the idea that the observed data of a system reside on some lower-dimensional surface, or manifold, embedded in a higher-dimensional space. By characterizing the manifold, we explore the dynamics of high-dimensional and complex climate fields in a simpler but comprehensive way. We argue that this approach provides a physically sound way to evaluate models by quantifying dependencies among variables and their feedbacks in time and space, and to visualize the climate-system attractor—the set of states toward which the climate system tends to evolve. We then showcase such a framework in the tropical Pacific, where the ENSO reigns, in observations and two state-of-the-art climate models. Our work sets the stage for manifold learning approaches to climate modeling and climate prediction, which is a first step toward developing simpler models to simulate the evolution of the effective degrees of freedom of the climate system. These new models will be physically grounded and will exploit novel artificial-intelligence approaches. This result is published as **Falasca and Bracco (2022).**

We further developed a recurrence-based information entropy metric from nonlinear dynamical systems theory as a measure of climate predictability potential. The method is applied to boreal-fall sea surface temperature variability in the tropical Pacific and Indian Oceans, where predictability is largely controlled by ENSO and the Indian Ocean Dipole. Entropy is evaluated in CMIP5 historical and RCP8.5 simulations and compared with reanalysis data. While substantial discrepancies are found between models and reanalysis, no robust changes in future predictability emerge across models. The largest model biases occur in the equatorial Pacific and Indian Ocean, likely linked to deficiencies in simulating the ocean mean state and inter-basin connectivity through the Indonesian Throughflow. This work was published as **Ikuyajolu et al (2021).**

The techniques developed in above two studies were applied to diagnose the mechanism behind the North Pacific oxygen variability in **Novi et al., (2024).** Variability and trends in oceanic oxygen are governed by the balance between physical supply, primarily through ocean ventilation, and biological consumption. Using diagnostics of information entropy, δ-maps, and extreme-event analyses, the study assesses the predictability, variability, and coupling between IPV and oxygen. These results highlight the potential to monitor tropical Pacific oxygen changes using sparse oxygen observations combined with more widely available IPV estimates, while underscoring greater uncertainty in applying this relationship in extratropical regions.

3. What opportunities for training and professional development has the project provided?

This project supported two female junior scientists at Georgia Tech. They made significant progress in this project with first author papers published in recent month.

Qi Zhang is a Ph.D. candidate at Georgia Tech. She graduated from Xiamen University, China with a MS degree in Marine Sciences. She is now a Ph.D. student in the Ocean Science and Engineering Program at Georgia Tech, and she is focused on the analysis of air-sea carbon fluxes. Ms. Zhang published her work on linking AMOC and air-sea CO_2 flux of the subpolar North Atlantic as **Zhang et al. (2024).**

Ljuba Novi is a postdoctoral researcher at Georgia Tech. She is an oceanographer and climate scientist previously trained at the Institute of Geosciences and Earth Resources which is part of the National Research Council in Pisa, Italy. She is an expert in climate sciences and data science algorithms. Her work on linking the IPV and O2 is published as **Novi et al., (2024).**

4. How have the results been disseminated to communities of interest?
To date, 9 peer-review journal papers were published as listed below.
Year 1
[1] Ito T. (2022) Optimal interpolation of global dissolved oxygen:1965-2015, Geoscience Data Journal, 9, 167-176, doi:10.1002/gdj3.130
[2] Ikuyajolu, Falasca and Bracco (2021) Information Entropy as Quantifier of Potential Predictability in the Tropical Indo-Pacific Basin, Frontiers in Climate, 17, https://doi.org/10.3389/fclim.2021.675840

Year 2

[3] Ito, T., Takano, Y., Deutsch, C., & Long, M. C. (2022). Sensitivity of global ocean deoxygenation to vertical and isopycnal mixing in an ocean biogeochemistry model. *Global Biogeochemical Cycles*, 36, e2021GB007151. https://doi.org/10.1029/2021GB007151

[4] Falasca, F. and A. Bracco, (2022), Exploring the Tropical Pacific Manifold in Models and Observations, Phys. Rev. X. 021054, doi: 10.1103/PhysRevX.12.021054

Year 3+

[5] Zhang Q, Ito T and Bracco A (2024) Modulation of regional carbon uptake by AMOC and alkalinity changes in the subpolar North Atlantic under a warming climate. Front. Mar. Sci. 11:1304193., doi: 10.3389/fmars.2024.1304193

[6] Liu, G., Tagklis, F., Ito, T. *et al.* Drivers of coupled climate model biases in representing Labrador Sea convection. *Clim Dyn* **62**, 3337–3353 (2024). https://doi.org/10.1007/s00382-023-07068-z

[7] Ito, T., Garcia, H. E., Wang, Z., Minobe, S., Long, M. C., Cebrian, J., Reagan, J., Boyer, T., Paver, C., Bouchard, C., Takano, Y., Bushinsky, S., Cervania, A., and Deutsch, C. A., (2024), Underestimation of multi-decadal global O_2 loss due to an optimal interpolation method, Biogeosciences, 21, 747–759, https://doi.org/10.5194/bg-21-747-2024.

[8] Novi, L., A. Bracco, T. Ito, and Y. Takano, (in press), Evolution of oxygen and stratification in the North Pacific Ocean in CMIP6 Earth System Models, Biogeosciences, bg-2023-129.

[9] Ito, T., & Reinhard, C. T. (2025). A new framework for the attribution of air-sea CO_2 exchange. *Global Biogeochemical Cycles*, 39, e2024GB008346.