

Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System

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OCEAN MODEL DEVELOPMENT, DATA-DRIVEN PARAMETERIZATIONS, AND MACHINE LEARNING IN OCEAN MODELS OF THE EARTH SYSTEM

Workshop Report

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FRONT COVER IMAGE

Workshop graphic; abstract grids overlain on an artistic representation of ocean mixing (credit: Alyssa Johnson)

BACK COVER IMAGE

Workshop group photo at the NSF NCAR Mesa Lab Building (credit: Gustavo Marques)

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EXECUTIVE SUMMARY

Ocean modeling is undergoing a transformative phase, mainly due to advancements in computational power that enable global ocean simulations with horizontal grid spacing smaller than $1/10^\circ$, hereafter referred to as ultra-high resolution. The growing complexity of ocean models, mainly because of the incorporation of new physical processes and the inclusion of interactions with other components of the climate system, further fuels this progress. Additionally, observational programs like Argo provide essential data for model evaluation and offer valuable insights into various ocean processes. Yet, persistent biases and unrepresented ocean physics pose significant challenges that the community must address collaboratively. This workshop brought together scientists from many countries and career stages, including a strong showing of early-career researchers from the ocean, atmosphere, sea-ice modeling, ocean processes, and machine-learning communities to identify key priorities and provide actionable recommendations for advancing ocean model development and applications.

Significant progress has been made in ocean modeling over the past decades, with simulations becoming increasingly realistic and capturing a broader range of ocean processes. Nevertheless, Ocean General Circulation Models (OGCMs) still face significant challenges with large, persistent biases, particularly in critical regions such as western boundary currents and the Arctic and Southern Oceans. Incorporating previously missing ocean physics (e.g., tidal mixing, submesoscale dynamics, and ice-ocean interactions), improving numerical methods and techniques, developing idealized test cases to identify biases consistently across models, leveraging observational datasets, and incorporating Machine Learning (ML) approaches offer promising pathways to address these biases.

Insufficient observations, particularly at depth, are a major bottleneck in ocean modeling. The community should advocate for targeted observational campaigns, including expanding the Argo float deployments and other high-resolution datasets. Collaborative efforts between modelers and observationalists are crucial for designing and implementing these campaigns, ensuring that the collected data can be used to initialize and validate OGCMs, inform parameterization development, and improve model fidelity. At the same time, standardizing OGCM outputs can facilitate more efficient analyses and comparisons, especially by the academic community. However, the modeling groups require additional resources for such an undertaking.

ML has emerged as a powerful tool for ocean modeling, but its use must be carefully managed. Developing benchmark datasets and closer collaboration between ocean modeling and ML communities will be essential for building trust in ML approaches and ensuring robust applications. Critical updates to longstanding parameterizations, such as turbulent fluxes at the air-sea interface, are necessary. A paradigm shift in the formulation of mixing parameterizations, leveraging energetically consistent approaches and possibly ML techniques, is also required.

Maintaining diversity among OGCMs is crucial. This diversity fosters innovation and enhances our ability to address challenges across various dynamical regimes. Dedicated test cases, metrics for isolating mesoscale and submesoscale processes, and advances in bathymetry-aware, energy backscatter, and vertical mixing parameterizations will further refine OGCM capabilities.

Looking ahead, advancing ultra-high-resolution ocean modeling applications using Graphics Processing Units (GPUs) and/or employing regionally refined unstructured grids will be transformative. Nonetheless, coarse-resolution models will remain in use over the next decade and must be improved to reduce existing biases.

Finally, as the complexity of OGCMs grows, there is a critical need for increased support and training for students and early-career researchers, particularly in developing the skills necessary to advance ocean model development. This includes investments in educational programs and mentorship to foster the next generation of model developers. In addition to these efforts, it is critical that the community supports and recognizes model developers, whose work is becoming increasingly difficult to fund. The ocean modeling community can work together to overcome common challenges by encouraging collaboration and fostering a more expansive approach. This collective effort will help ensure that models not only advance scientific understanding but also produce results that are practical and useful for real-world applications, benefiting both the people who rely on these models and society at large.

1

INTRODUCTION

OGCM's dynamical core and sub-grid-scale parameterizations are essential for accurately simulating oceanic processes over a range of scales. Important considerations include choosing the governing equations, deciding which processes to parameterize, and selecting appropriate numerical methods, all of which significantly influence the model's performance and accuracy. Recent advancements in these areas, along with advancements in computational power, have profoundly impacted Earth System Models (ESMs). Workshops organized by both the CLIVAR Ocean Model Development Panel (OMDP) and the European Community for the Numerical Modeling of the Global, Regional, and Coastal Ocean (COMMODORE) have prioritized collaborations in these fields, including subgrid-scale parameterizations and have provided support for early-career researchers focused on model development.

OGCM applications range from coastal processes to global, millennial-scale climate projections. OGCMs must interact seamlessly with other Earth system components, including the atmosphere, sea ice, and biogeochemical cycles. Constructing a robust dynamical core requires a careful selection of equations, horizontal and vertical grids, and numerical schemes that balance computational efficiency and accuracy. With advances in computational power, OGCMs now benefit from cross-fertilization between global and regional modeling communities.

Besides recent advances in computational power, the horizontal and vertical grid spacings used in OGCMs are still not small enough to represent key ocean processes. Therefore, OGCMs continue to rely on parameterizations to represent missing, unresolved, or poorly resolved processes. Without these sub-grid parameterizations, models develop significant biases and lose accuracy, limiting their effectiveness and scope of application. Traditionally, parameterizations have been developed using a combination of observations and theoretical insights, including empiricism. Recently, ML methods have been transforming science and the world at large. The foundation of ML lies in using functions to model patterns and relationships within data, making it fundamentally a data-driven, empirical approach. The alignment of the data-driven aspects of ML with the needs of parameterizations has led to growing interest in using ML for ocean parameterization development. Beyond the data-driven opportunities for parameterizations, the prominence and computational demands of ML represent a pivotal point in the evolution of ocean modeling, and a way forward for the future of existing models needs clarification. Making use of ML in OGCMs is an imminent transition. This workshop provided a peek into the future to seek a path forward for adopting new techniques in parameterizations, modeling more broadly, and analysis.

The CLIVAR OMDP and COMMODORE jointly proposed this workshop, motivated by the need to improve dynamical cores and parameterizations in OGCMs. The workshop thus focused on ocean model development and applications, addressing a wide range of spatial and temporal scales,

from coastal applications to millennial global climate change simulations. The workshop brought together international scientists and early-career researchers from the ocean, atmosphere, sea-ice modeling, ocean processes, and ML communities to review advances in dynamical cores and parameterizations and explore opportunities, successes, and challenges of applying data-driven methodologies and ML techniques to the development and analysis of ocean models.

The ML focus of the workshop included the following topics:

- Development of data-driven and ML methodologies for sub-grid scale parameterizations
- Use of ML in ocean circulation models
- Opportunities and perspectives on future directions for ocean models

The numerical modeling focus of the workshop included the following topics:

Structured- and unstructured-grid models and numerical methods for modeling

- Equations, formulations, and vertical coordinates for modeling coastal to larger scales
- Coupling between parameterizations and the resolved fluid dynamics
- Coupling between the ocean and other components of the Earth system
- Large-eddy simulations, non-hydrostatic modeling, and process studies
- Development processes, model evaluations, testing, and test cases for ocean models

The workshop had 109 total attendees from 14 different countries, 82 of which attended in-person at the NSF NCAR Mesa Lab in Boulder, CO, with the rest attending online (Figure 1). Approximately 63% of attendees were students or early career scientists, 75% of attendees were male, 23% of attendees were female, and 2% elected not to say. Appendix C contains a full agenda with more information about the workshop schedule, including presenter information and links to presentation abstracts and downloadable files.

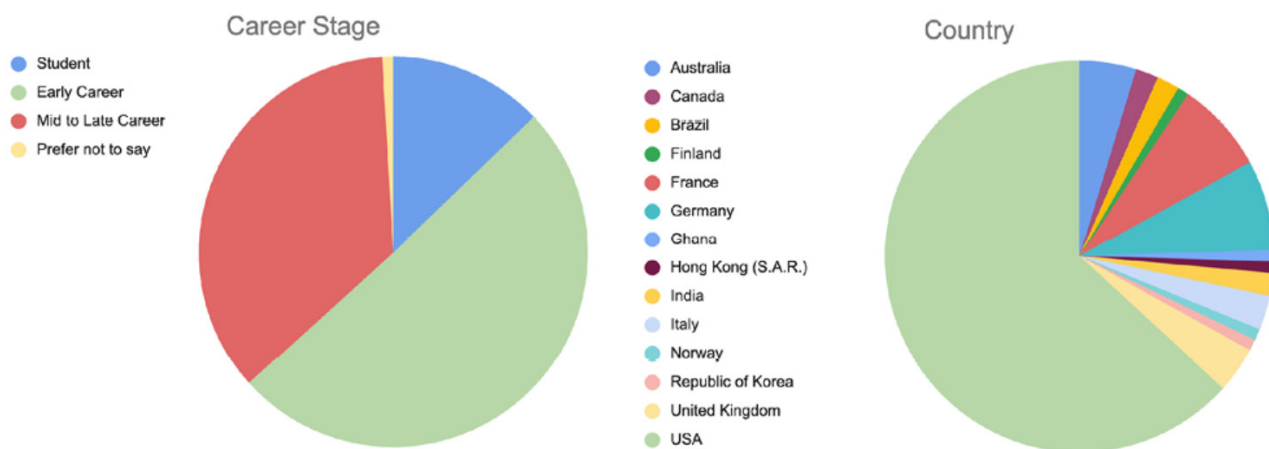


Figure 1: Pie charts displaying participants' self-identified country and career stage.

2

WORKSHOP SESSIONS

2.1 Ocean dynamics and circulation

OGCMs still exhibit large persistent biases such as incorrect separation of the Gulf Stream and subsequent mostly too-zonal path of the North Atlantic Current. The choices of physics and numerics used in a particular simulation are important, significantly impacting the quality of simulations (e.g., Korn 2024). There is evidence that adding explicit tides can improve the Gulf Stream's representation, suggesting that the impacts of tides are under-explored. While not a panacea, high-resolution simulations improve the representation of processes, leading to reductions in some of these persistent biases. There is a pressing need to understand if such improvements are for the correct reasons. Also, high horizontal resolution should go together with high vertical resolution. There is some evidence that high vertical resolution near the surface in ice-covered regions can lead to a better representation of water masses in those regions (Morrison 2024). Relatedly, there is substantial value in hierarchical modeling approaches, including process models and low- to high-resolution models, which can improve our process understanding and address if improvements in high-resolution simulations come about for the right reasons—in conjunction with appropriate observations (see below).

Evidence, in particular from the sea-ice modeling community, suggests that higher-order numerics can improve sea-ice simulations (Mehlmann 2024). While there is interest in the ocean modeling community in higher-order numerics, it takes time to implement them in the models. Also, it is not a given that such higher-order numerics will improve realistic configurations. There may also be challenges with numerical stability. Giving proper credit and acknowledgment to researchers who work on numerical methods is important as they largely remain behind the scenes. Even at national laboratories, it is getting progressively harder to fund work on model numerics and address persistent model biases. Therefore, it is very important to advocate for this type of research at all levels.

Unfortunately, there are not enough observations—with high enough spatial and temporal resolution—that can be used to evaluate especially high-resolution simulations. For example, insufficient deep observations hamper both model evaluation and model initialization of deep ocean properties. Argo observations have been extremely useful in model evaluations, including advancing our process-based understanding. The modeling community should more strongly advocate for continuing Argo observations, including deep, BioGeoChemistry (BGC), and under-ice Argo efforts.

To enable efficient and easy comparisons of model solutions, there is a desire to make output fields consistent across models in their names, grids, and formats (Maroon 2024). Such uniformity is essential for the students and researchers from the broader community.

A challenge here is that modeling groups would need additional resources for this purpose. Specifically, this effort should not come at the expense of already limited model development funds.

Key messages and recommendations:

- Ocean model simulations continue to exhibit large persistent biases. The inclusion of previously missing physics and a hierarchical modeling approach that incorporates process models and low- to high-resolution models, along with appropriate observations, have the potential to advance our understanding of processes toward addressing these biases.
- It is essential to recognize the researchers who work on model development. As such work becomes increasingly difficult to fund, the community should advocate for this type of work.
- There is a lack of sufficient observations at depth and for process-based understanding. The modeling community should strongly advocate for such observations, including various flavors of Argo observations.
- The modeling community should move towards uniformity of output datasets to expedite progress by enabling easy and efficient analysis of model simulations, especially by university researchers, noting that such an effort should not come at the expense of already limited model development funds.

2.2 Harnessing machine learning for ocean modeling

One-quarter of the workshop was devoted to presentations and discussions about ML in ocean modeling. ML is a rapidly evolving technique impacting many science domains and is already applied to many ocean and climate modeling aspects. These include i) post-processing and analysis of data (e.g., Cahill et al. 2024), ii) parameterizations of unresolved processes (e.g., Guillaumin and Zanna 2021; Partee et al. 2021), iii) merging of observations and models, and iv) emulation of numerical models (e.g., Dheeshjith et al. 2024). We saw several examples of each in both invited and submitted presentations, which indicate that ML potentially offers new and expanded opportunities for ocean modeling.

ML can be viewed as a brute force approach, deploying large data and compute resources together. This viewpoint led to a common concern: How trustworthy are the machine-learned outputs? To address this concern, the following best practices emerged: i) checking for meaningful connections between inputs and outputs, ii) ensuring that machine-learned models are physically consistent (e.g., satisfy the underlying physics), iii) testing for emergent behaviors, iv) creating standard metrics (e.g., as is done for climate model output), and v) developing benchmark datasets (which were also deemed critical to accelerate the development of ML models). Outstanding problems common to many applications in ocean ML include either a sparsity of observational data or the unwieldy volume of model data. The slow time scales of the ocean are a particular challenge for ocean modeling, and accurate conservation of properties (e.g., of heat, mass) in ML is suggested to be an important challenge to address. Just as trust in climate models grows as we learn to understand them, trust in ML models requires that we understand how ML produces the results it does. There is a need to connect with other communities beyond ocean modeling with expertise in ML, if not only because solutions can come from unexpected fields.

Key messages and recommendations:

- Benchmark datasets are critical to accelerate the development of machine-learned models.
- ML is powerful but should not be used blindly. It should be tested and understood, especially when used for projections.
- Building connections between ocean modeling and ML communities is necessary to advance ML methods, applications, and trustworthiness.

2.3 Numerical methods for ocean and sea-ice models

Model developers must deal with a new technological paradigm to keep the carbon footprint of numerical simulations under control. The time/energy/cost-to-solution for a given effective resolution is an increasingly important metric to evaluate a given numerical code. Important drivers affecting the energy consumption of numerical simulations are i) the software environment and ii) the dynamical core, including the time-integration strategy and the dissipative/dispersive properties of numerical schemes. Future developments in the numerical formulation of models should take into account the following elements:

- Central Processing Units (CPUs) and Graphics Processing Units (GPUs) present different approaches to computation. GPUs excel in handling numerically intensive operations but are hindered by memory load, making them particularly suited for high-order numerical schemes (e.g., Silvestri et al. 2024). This opens up new possibilities for the design of numerical methods. However, existing codes originally developed for CPUs may not easily benefit from GPU capabilities. To fully utilize GPU power, there's a need to reduce memory footprint and communications, necessitating a review and adaptation of algorithmic strategies to keep pace with hardware evolution.
- Increasing the resolution of OGCMs introduces new complexities. The range of physical processes to be modeled, such as tides, ice cavities, and internal gravity waves, changes at higher resolutions, making some conventional practices (e.g., low-order schemes, excess dissipation to stabilize mode-splitting {Ducouso et al. 2024}) obsolete. Higher-resolution models require more advanced numerical methods, such as two-time-level approaches like direct-space-time schemes and low-storage Runge-Kutta methods (e.g., Téchené et al. 2024). These methods are well suited to increasing the order of accuracy in space and time and work well on CPUs and GPUs.
- Refining grids and increasing numerical accuracy point to the promise of the Discontinuous Galerkin (DG) method for global ocean simulations. DG methods allow for higher-order discretization and are compatible with massively parallel computing and unstructured grids. However, the method will only be competitive if it achieves accuracy similar to conventional methods but with coarser grids (Kopera and Gahounzo 2024).
- In ESMs, improving the resolution and sophistication of discrete algorithms has reduced errors in individual components. However, to fully exploit these improvements, errors introduced by the coupling between model components must also be reduced. Improving the coupling between different components of ESMs involves minimizing coupling lag, developing flexible standard couplers, and establishing metrics to evaluate coupling errors (e.g., Marti et al. 2021; Morrison et al. 2024).

- Increasing resolution leads to higher storage demands, raising the need for techniques such as dimensionality reduction and in-situ data analysis. There are also questions about the appropriate scales of simulations—specifically, what scales should be passed between the dynamical core and submodels like BGC. This could necessitate using lower resolution for BGC models.
- Improvements in coupling techniques should also reconsider the turbulent flux formulations between components. For example, the Monin-Obukhov theory used in air-sea flux calculations is incompatible with coupling frequencies of less than one hour.
- Increasing resolution alone will not improve sea-ice models. Enhancements must also focus on physical processes and coupling mechanisms with the ocean and atmosphere. Traditional parameterizations and rheologies may fail at high resolutions, particularly when representing small-scale features like fractures and leads (e.g., Kahl and Mehlmann 2024). Elasto-brittle rheology (Dansereau et al. 2016) offers a more accurate approach at kilometer-scale resolutions, though widely-used elastic-viscous-plastic models are computationally more efficient.

Key messages and recommendations:

- Develop more systematic benchmarking of ocean models in terms of effective resolution vs. computational cost (requires dedicated semi-idealized configurations).
- Establish metrics to evaluate coupling errors between different components of ESMs.
- Encourage a complete revision of turbulent flux calculations at the air-sea interface to move away from the Monin-Obukhov similarity theory.
- Encourage “genetic diversity” among ocean models. This is the best way to collectively tackle the challenges of increasing resolution across diverse dynamical regimes.

2.4 Mesoscale eddy parameterization

Mesoscale eddies are key in transporting energy, heat, carbon, and other tracers, significantly influencing ocean circulation, water masses, and the overall climate system. However, OGCMs used in climate studies (usually run for many centuries) are typically too coarse to represent mesoscale eddies everywhere explicitly. As a result, these models must rely on parameterizations to account for these eddies.

State-of-the-art mesoscale parameterizations rely on eddy diffusivities informed by prognostic subgrid-scale eddy kinetic energy (EKE) schemes (e.g., Jansen et al. 2015). Progress has been made in representing the vertical structure of EKE using a single surface quasigeostrophic (SQG) mode (Zhang et al. 2024a). This approach yields promising results in idealized adiabatic wind-driven simulations and helps clarify the role of surface potential vorticity in driving the surface-intensified nature of mesoscale eddies. Preliminary results highlighted the potential of using SQG to constrain the vertical structure of backscatter parameterizations (Zhang et al. 2024b), where energy is reinjected into the system via a source of kinetic energy. Backscatter parameterizations are actively being explored as a possible way to reduce biases in global models (Juricke et al. 2020; Chang et al. 2023). Recent advancements include integrating backscatter schemes with traditional Gent-McWilliams (isopycnal height diffusion) and Redi (neutral tracer diffusion) parameterizations, employing stochastic and deterministic approaches (Yassin et al. 2024; Grooms et al. 2024).

Also building upon these traditional parameterizations are the recent efforts to develop “bathymetry-aware” schemes that capture eddy buoyancy fluxes across continental slopes (Wang and Stewart 2020; Wei et al. 2022; Xie et al. 2023). These schemes account for the transition between shelf and open-ocean dynamics and rely on modified subgrid-scale EKE budgets or ML techniques, such as neural networks, to predict mesoscale eddy energy across continental slopes (Wang et al. 2024).

Neural networks are emerging as a promising alternative to traditional mesoscale eddy parameterizations (Balwada et al. 2024; Everard et al. 2024). Preliminary results demonstrate superior skill in capturing the spatial structure and mean effects of eddy fluxes, as well as the full energy cycle of mesoscale eddies when compared to conventional methods. However, these techniques have so far been tested only in idealized test cases, and their effectiveness in realistic global ocean models remains to be thoroughly evaluated.

Challenges to further improvements in mesoscale parameterizations include distinguishing the effects of mesoscale eddies from those of other processes, such as the differential rotation effect (β -effect), and their interaction with topography and other motions. While high-resolution OGCMs improve the fidelity of climate-relevant metrics, it's hard to say if this is because such models resolve the mesoscale better. Understanding the complex interactions of mesoscale eddies with submesoscale and unbalanced motions, such as eddy-wave interactions and energy transfers across scales, remains a significant knowledge gap in advancing mesoscale eddy parameterizations. Lastly, the lack of a clearly defined and community-vetted test case with corresponding metrics for mesoscale eddy diagnostics hinders progress in this area.

Key recommendations and next steps:

- Encourage research aimed at disentangling the effects of mesoscale eddies from other processes, such as the β -effect, and examining their interactions with topography and other motions.
- Establish a robust test case for studying mesoscale eddies, including appropriate metrics for eddy diagnostics. Diagnostics should include the three factors that mesoscale eddies act upon, namely, 1) interfacial form stress (thicknesses fluxes), 2) momentum fluxes, and 3) isopycnal stirring.
- Encourage the development and evaluation of backscatter schemes, particularly their integration with traditional mesoscale parameterizations and the use of stochastic and deterministic approaches to improve bias reduction in global models.
- Encourage the development of “bathymetry-aware” mesoscale schemes that capture eddy buoyancy fluxes across continental slopes. As a next step, such schemes should be evaluated in global models.

2.5 Vertical mixing parameterization

Uncertainties in ocean mixing parameterizations are a major source of bias in ocean models. To overcome these uncertainties, traditional vertical mixing formulations, such as those that use vertical eddy diffusivities to relate turbulent fluxes to the gradient of the mean fluxes and the Osborn relationship (Osborn 1980), need to be replaced with energetically consistent parameterizations.

Eddy fluxes are typically parameterized using a down-gradient flux formulation, with the proportionality coefficient being an eddy diffusivity. However, during ocean convection events, the eddy diffusivity assumption fails because the primary source of turbulent transport is dense plumes that are not directly related to local gradients (e.g., coherent structures).

One approach to account for them is to use an energetically consistent integrated eddy-diffusion and mass-flux (E-D M-F) scheme (Perrot et al. 2025). This methodology, adapted from a convective atmospheric parameterization, allows for separating turbulent and small-scale energy reservoirs. Evaluations of this scheme in a single-column model using an observed oceanic convective event and results from a Large Eddy Simulation (LES) model show the new scheme to reasonably agree with observations, often out-performing other vertical mixing schemes (Perrot and Lemarié 2024). Another approach to representing the effects of coherent structures is to use stochastic modeling; an example is the Under Location Uncertainty (ULU) framework, which naturally introduces advective and backscattering terms associated with turbulence (Jamet et al. 2024).

ML can be used to mitigate mixed layer depth biases arising from uncertainty in flux gradient formulations by using neural networks that take extrinsic and intrinsic forcing parameters as input to predict eddy diffusivities. The neural networks are trained using output from a second moment closure turbulent mixing scheme (Sane et al. 2023).

Vertical turbulent diffusivities are obtained by balancing energy dissipation and the local vertical buoyancy flux (Osborne 1980). However, this relationship does not work well in regions of low stratification or where stratification changes rapidly over one model time step. One potential advancement is to obtain diapycnal diffusivities using an energetically consistent framework in which energy dissipation balances the vertically integrated effects on potential energy throughout the water column due to local mixing, integrated over a model time step (Hallberg and Reichl 2024).

Model bias is also introduced by missing vertical mixing processes. Tides, away from the surface boundary layer, dominate mixing over coastal shelves and bottom boundary layers, while internal tides radiate across basins until they reach topography and break. Yet, tidal mixing is not explicitly resolved in ocean climate models nor sufficiently parameterized. Submesoscale processes play a dominant role in the upper-ocean vertical transfer of tracers (Sinha et al. 2023) and need to be better accounted for in parameterizations. River, estuarine, and fjord mixing in increasingly fine-resolution regional coastal models needs to be parameterized. An array of vertical mixing processes challenges vertical mixing parameterization design. The latest small-scale mixing observations and ML techniques may provide an avenue to new paradigms.

Key recommendations and next steps:

- Advance vertical mixing formulations using energetically-consistent parameterizations.
- Explicitly resolve or more thoroughly parameterize tidal mixing in ocean climate models.
- Account for submesoscale processes in vertical mixing parameterizations.
- Parameterize river, estuarine, and fjord mixing in fine-resolution regional coastal models.
- Develop new vertical mixing paradigms using ML methods and the latest small-scale measurements.

2.6 Recent developments in ocean modeling

There have been a couple of recent developments for diagnostics capabilities relevant to OGCMs that rely on Arbitrary Lagrangian Eulerian algorithms to enable any vertical coordinate:

- Online tracer-coordinate diagnostics eliminate errors associated with time averaging (MacGilchrist 2024). With this capability, time-averaged diagnostics can be output in the coordinate of any arbitrary physical or biogeochemical tracer.
- A new method for online 3-D Lagrangian particle advection in a Lagrangian vertical coordinate ocean model, e.g., MOM6, allows Lagrangian particles to be employed to study transports of heat, carbon, micro-plastics, and many other tracers (Jones 2024).

Traditional water mass analysis does not deal with diabatic processes. Therefore, potential vorticity diagnostics, together with water mass analysis, would be helpful to evaluate OGCMs. Such a combined approach is yet to be available.

Diagnostic and analysis tools and scripts should be broadly available to the community. Relatedly, we should rethink our diagnostics or output file writing, as re-running a model is now cheaper than in the past while storage is still expensive.

Several missing processes that could be incorporated in the ocean models include glacial isostatic adjustment, the rising of the sea floor, explicit representation of tides, and the inclusion of the Great Lakes as part of a global modeling system (Wang 2024). For example, the latter aims to address the role of the Great Lakes in impacting the North American climate. There are some challenges with the inclusion of these missing processes. Given the smallness of the ocean modeling community, there is a need to define particular challenges and processes and address them collectively in a coordinated way. Furthermore, to support societally relevant science and decision-makers regarding, for example, climate interventions and carbon removal, the modeling community can consider these new application areas.

Surface salinity restoration used in ocean hindcast (forced) simulations remains ad hoc. It has a strong impact on model solutions. The modeling community must revisit this practice, and alternative, more physically based approaches must be devised. NOAA GFDL is making an ongoing effort to replace this approach.

Nevertheless, there are certainly challenges, including the need to recognize the accomplishments of the ocean modeling community. The solutions improve when advances in physics and numerics are included in the models. We are making progress!

Key messages and recommendations:

- Diagnostics and analysis tools and scripts should be broadly available to the community.
- The ocean modeling community can expedite progress by working together on common challenges and biases.
- The ocean modeling community should be cognizant of application areas, including providing stakeholders with information.
- There is an ongoing need to revisit the use of surface salinity restoration in forced ocean simulations.

2.7 High-resolution ocean modeling

To explicitly represent mesoscale eddies (~10-100 km) and associated mesoscale processes, an ocean model's horizontal grid spacing, at least in the deep ocean, must be at least half that of the first baroclinic Rossby radius of deformation (Hallberg 2013); at high latitudes, it reduces to less than 10 km. Fine mean currents also require mesh sizes such as these to be realistically resolved. High vertical resolution is needed to realistically simulate ocean stratification, particularly in the thermocline, and vertical mixing processes. As discussed in Session 4, using such fine resolution in very long (millennial) climate simulations requires computational resources that are currently prohibitive. However, recent hardware and modeling advances, including new ocean model formulations and unstructured grids with regionally refined meshes, provide possible avenues for advancement.

ClimaOcean¹, built on Oceananigans, has obtained unprecedented performance levels in global configurations by using a dynamical core that allows for fast computation through GPU architectures, memory efficiency, and scalable solvers. A prototype 1/48° global ClimaOcean simulation has been run stably for one year, producing a rich submesoscale eddy field (Silvestri et al. 2024; Figure 2). Unstructured ocean grids with refined meshes provide a means of placing small grid spacing anywhere in the global ocean. Small-scale processes (e.g., submesoscale and submesoscale permitting) that are not resolvable in standard high-resolution (~0.1°) global models can be simulated by placing refined meshes near boundaries and in boundary currents (Van Roekel et al. 2024). In addition, unstructured grid models can run on GPUs. However, the “learning curve” to use these unstructured grid models is steep. Also, there are challenges with small time steps because the global model needs to obey the time step constraints of the refined region.

Challenges associated with ultra-high resolution (~1 km) will extend beyond overcoming computational limitations. The parameterizations currently used in ocean models may fail regionally, necessitating the development of a new generation of scale-aware ocean parameterizations. Further, ocean and sea-ice interactions at small grid spacings may be unrealistic and need revisions. Apart from long climate simulations, there is also a need for multi-decadal ultra-high resolution ocean simulations for short-term forecasting and comparisons with observations. Very fine-resolution topography will be needed to accompany the fine-resolution ocean simulations to accurately simulate ocean currents (e.g., western boundary current extension pathways) (Chassignet et al. 2023).

¹[ClimaOcean.jl](#)

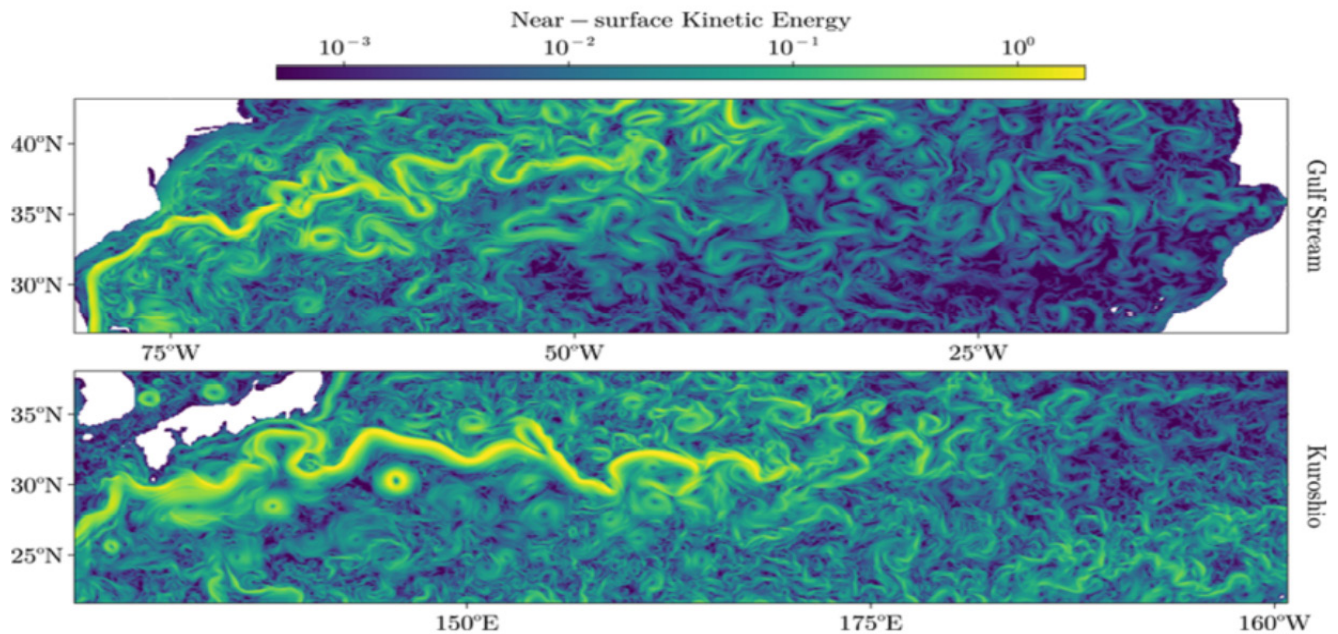


Figure 2: Near-surface kinetic energy in the Gulf stream (top panel) and the Kuroshio current (bottom panel) on March 1st from a global ocean simulation at 1/12-th of a degree horizontal resolution and 100 vertical levels that uses the novel advection scheme we introduce here as a momentum closure. From Silvestri et al. 2024. [CC](#)

If ultra-high resolution ocean models such as ClimaOcean can be further developed, there will be less need to parameterize eddies, suggesting that resources should be directed to explicit resolution. However, there is still a place for coarse-resolution models (e.g., for biogeochemistry and paleoclimate modeling), so their biases still need to be addressed. Modelers can use the next generation of ultra-high-resolution models to improve parameterizations for low-resolution models that will continue to be used over the next decade. Further, hierarchical modeling approaches provide a means to understand the importance of missing or under-represented ocean processes, leading to model improvements.

Key recommendations and next steps:

- Direct resources into explicitly resolving eddies to reduce the need for mesoscale and submesoscale eddy parameterizations by advancing and developing fast ultra-high resolution ocean and sea-ice models that run on GPUs.
- Use unstructured grids placing regionally refined meshes in the vicinity of boundaries to resolve small-scale processes (e.g., submesoscale) not resolvable in standard high-resolution ($\sim 0.1^\circ$) models.
- Develop a set of next-generation scale-aware ocean parameterizations.
- Develop hierarchical modeling approaches ranging from process- to low- to high-resolution models.
- Advance the representations of ocean and sea-ice interactions at high resolution.
- Use commensurately fine-resolution topography in high-resolution ocean simulations.
- Address biases in coarse-resolution climate models with a biogeochemistry component, as they will continue to be used over the next decade.

2.8 General vertical coordinates

The formulation of model equations and treatment of the vertical direction has long been recognized as an important aspect of OGCMs (e.g., Griffies et al. 2000). It is widely accepted that numerical errors arising from the treatment of the vertical (whether coordinate, formulation, or discretization) can lead to spurious “mixing” that artificially modifies water masses and strongly affects the numerical circulation. The problem is considered paramount at coarse and eddy-aliasing horizontal resolutions, but it is unclear at what horizontal resolutions the vertical numerical errors no longer dominate. The session saw updates on hybrid coordinate models (e.g., Griffies et al. 2020), new coordinates, analysis of optimal vertical resolutions, and the representation of topography.

General and hybrid-coordinate methods incur added complications for developers and especially for users. Diagnostics can be more complicated to implement, particularly budgets in non-native vertical coordinates, which need care to formulate. Nevertheless, the benefits to the properties of the solutions outweigh the added complexity. There is no consensus on whether any metric for assessing the spurious mixing associated with the vertical coordinate addresses all modeler’s concerns.

For new methods and models, a strong and active community is vital for propagating and supporting developments. Improved vertical coordinate representation and finer vertical and horizontal resolutions are valuable for advancing model simulations.

Key messages and recommendations:

- Developing models with low spurious mixing (presumably via better treatment of vertical direction or numerical methods) remains a priority.
- The new generation of models appears more complicated to use, analyze, and develop, so modelers need stronger support and education of the community (students, users, and developers).
- The diversity of models (distinguished by vertical formulation and/or horizontal spatial resolution) is valuable and leads to new insights.

3

RECOMMENDATIONS AND NEXT STEPS

- OGCMs continue to exhibit large and persistent biases. To address these, it is critical to incorporate previously missing physics and adopt a hierarchical modeling approach that integrates process models and low- to high-resolution simulations with appropriate observational datasets.
- The community must advocate for better support and recognition of model developers as this work becomes increasingly difficult to fund.
- There is a pressing need for improved and expanded observations, particularly at depth, to enhance process-based understanding and model evaluation. Observational campaigns, including various flavors of Argo observations, should be continued.
- The community should move toward standardization of output datasets to enable more efficient analysis, particularly for university researchers. However, the modeling groups require additional resources for such an undertaking.
- Benchmark datasets are critical for accelerating the development and evaluation of ML models, which should be implemented cautiously and comprehensively tested. Fostering connections between ocean modeling and ML communities is necessary to both build trust in and advance ML models.
- Similarly, efforts to systematically benchmark OGCMs must be intensified, including evaluations of effective resolution vs. computational cost using semi-idealized configurations. Metrics for coupling errors between ESM components are essential, as are revisions to turbulent flux parameterizations at the air-sea interface, moving away from the Monin-Obukhov similarity theory.
- Maintaining “genetic diversity” among OGCMs is critical to tackle challenges posed by increased resolution across diverse dynamical regimes. Research is needed to disentangle the effects of mesoscale eddies from other processes, with dedicated test cases for diagnosing mesoscale eddy impacts. Metrics for eddy diagnostics should encompass interfacial form stress, momentum fluxes, and isopycnal stirring.
- The development of innovative parameterizations, such as bathymetry-aware mesoscale schemes and energetically consistent vertical mixing formulations, must be prioritized. OGCMs used for climate applications should explicitly resolve or thoroughly parameterize key processes such as tidal mixing, submesoscale processes, river and fjord mixing, and ocean and sea-ice interactions. Additionally, the potential of ML methods and fine-resolution measurements should be harnessed to advance vertical mixing paradigms.
- Community-wide initiatives and collaborations are necessary to tackle common biases collectively, e.g., Climate Process Teams (CPTs). Diagnostics and analysis tools must be broadly accessible to ensure inclusivity. Developing ultra-high-resolution ocean and sea-ice models that leverage GPUs and/or employing unstructured grids with regionally refined meshes will also be key in resolving small-scale processes.

- The community must also address the challenges of coarse-resolution climate models and reduce spurious mixing.
- Finally, with the increasing complexity of next-generation models, stronger educational support is crucial for students, users, and developers.

4

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REFERENCES

- Balwada, D., P. Perezhogin, R. Abernathey, A. Adcroft, and L. Zanna, 2024: Parameterizing mesoscale eddy buoyancy fluxes using small neural networks. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/parameterizing-mesoscale-eddy-buoyancy-fluxes-using-small-neural-networks>.
- Cahill, J., E. A. Barnes, E. D. Maloney, S. R. Sain, P. Harr, and L. Madaus, 2024: Errors of Opportunity: Using Neural Networks to Predict Errors in the Global Ensemble Forecast System (GEFS) on S2S Time Scales. *Wea. Forecasting*, **39**, 1817–1831, <https://doi.org/10.1175/WAF-D-23-0125.1>.
- Chassignet, E. P., X. Xu, A. Bozec, and T. Uchida, 2023: Impact of the New England seamount chain on Gulf Stream pathway and variability. *J. Phys. Oceanogr.*, **53**, 1871–1886, <https://doi.org/10.1175/JPO-D-23-0008.1>.
- Dansereau, V., J. Weiss, P. Saramito, and P. Lattes, 2016: A Maxwell elasto-brittle rheology for sea ice modelling. *The Cryosphere*, **10**, 1339–1359, <https://doi.org/10.5194/tc-10-1339-2016>.
- Dheeshjith, S., A. Subel, A. Adcroft, J. Busecke, C. Fernandez-Granda, S. Gupta, and L. Zanna, 2024: Samudra: An AI Global Ocean Emulator for Climate [Manuscript submitted for publication to *Geophys. Res. Lett.*], <https://doi.org/10.48550/arXiv.2412.03795>.
- Ducousso, N., F. Lemarié, L. Debreu, and G. Madec, 2024: Stability and accuracy of Runge-Kutta-based split-explicit time-stepping algorithms for free-surface ocean models. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/stability-and-accuracy-runge-kutta-based-split-explicit-time-stepping>.
- Everard, K., P. Perezhogin, D. Balwada, A. Adcroft, and L. Zanna, 2024: Data-driven parameterisation of mesoscale eddies using the Eliassen-Palm flux. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/data-driven-parameterisation-mesoscale-eddies-using-eliassen-palm-flux>.
- Griffies, S.M., A. Adcroft, and R.W. Hallberg, 2020: A Primer on the Vertical Lagrangian-Remap Method in Ocean Models Based on Finite Volume Generalized Vertical Coordinates. *J. Adv. Model. Earth Syst.*, **12**, e2019MS001954, <https://doi.org/10.1029/2019MS001954>.
- Griffies, S.M., R.C. Pacanowski, and R.W. Hallberg, 2000: Spurious Diapycnal Mixing Associated with Advection in a z-Coordinate Ocean Model. *Mon. Wea. Rev.*, **128**, 538–564, [https://doi.org/10.1175/1520-0493\(2000\)128<0538:SDMAWA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0538:SDMAWA>2.0.CO;2).
- Grooms, I., N. Agarwal, G. Marques, P. Pigeon, and H. Yassin, 2024: The Stochastic GM+E closure: A framework for coupling stochastic backscatter with the Gent and McWilliams parameterization. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/stochastic-gme-closure-framework-coupling-stochastic-backscatter-gent-and>.

- Guillaumin, A.P. and L. Zanna, 2021: Stochastic-Deep Learning Parameterization of Ocean Momentum Forcing. *J. Adv. Model. Earth Syst.*, **13**, e2021MS002534, <https://doi.org/10.1029/2021MS002534>.
- Hallberg, R., 2013: Using a resolution function to regulate parameterizations of oceanic mesoscale eddy effects. *Ocean Model.*, **72**, 92-103, <http://dx.doi.org/10.1016/j.ocemod.2013.08.007>.
- Hallberg, R. and B. Reichl, 2024: Applying implicit energetics ideas to simulate full-water-column ocean mixing. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/applying-implicit-energetics-ideas-simulate-full-water-column-ocean>.
- Jansen, M. F., A. J. Adcroft, R. W. Hallberg, and I. M. Held, 2015: Parameterization of eddy fluxes based on a mesoscale energy budget. *Ocean Model.*, **92**, 28-41, <https://doi.org/10.1016/j.ocemod.2015.05.007>.
- Jamet, Q., E. Mémin, F. Dumas, L. Li, and P. Garreau, 2024: Toward a stochastic parameterization for oceanic deep convection. In: Stochastic Transport in Upper Ocean Dynamics II (B. Chapron, D. Crisan, D. Holm, E. Mémin, & A. Radomska (eds)). Springer, Cham., https://doi.org/10.1007/978-3-031-40094-0_6.
- Jones, S., 2024: Online Lagrangian particle advection in MOM6. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/online-lagrangian-particle-advection-mom6>.
- Kahl, S. and C. Mehlmann, 2024: A hybrid ice model. *Proc. Appl. Math. Mech.*, e202400105, <https://doi.org/10.1002/pamm.202400105>.
- Kopera, M., and Y. Gahounzo, 2024: A multi-layer shallow water equation model with high-order Discontinuous Galerkin method. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/h-numo-multi-layer-shallow-water-equation-model-high-order-discontinuous>.
- Korn, P., 2024: From virtual Navier-Stokes flows to numerical ocean models. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/virtual-navier-stokes-flows-numerical-ocean-models>.
- MacGilchrist, G., 2024: Online tracer-coordinate diagnostics in MOM6. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/online-tracer-coordinate-diagnostics-mom6>.
- Maroon, E., 2024: Upper-ocean bias development and the Atlantic meridional overturning circulation in OMIP simulations. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/upper-ocean-bias-development-and-atlantic-meridional-overturning>.
- Marti, O., S. Nguyen, P. Braconnot, S. Valcke, F. Lemarié, and E. Blayo, 2021: A Schwarz iterative method to evaluate ocean-atmosphere coupling schemes: Implementation and diagnostics in IPSL-CM6-SW-VLR. *Geosci. Model Dev.*, **14**, 2959-2975, <https://doi.org/10.5194/gmd-14-2959-2021>.
- Mehlmann, C., 2024: A hybrid ice model. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/hybrid-ice-model>.

- Morrison, A., 2024: Strong sensitivity of Antarctic dense water formation to surface vertical resolution. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/strong-sensitivity-antarctic-dense-water-formation-surface-vertical>.
- Morrison, T., R. Hallberg, M. Harrison, and K. Hedstrom, 2024: Improving the dynamic coupling of sea-ice and ocean models. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/improving-dynamic-coupling-sea-ice-and-ocean-models>.
- Osborn, T. R., 1980: Estimates of the local rate of vertical diffusion from dissipation measurements. *J. Phys. Oceanogr.*, **10**, 83-89, [https://doi.org/10.1175/1520-0485\(1980\)010<0083:EOTLRO>2.0.CO;2](https://doi.org/10.1175/1520-0485(1980)010<0083:EOTLRO>2.0.CO;2).
- Partee, S., M. Ellis, A. Rigazzi, A.E. Shao, S. Bachman, G. Marques, and B. Robbins, 2022: Using Machine Learning at scale in numerical simulations with SmartSim: An application to ocean climate modeling. *J. Comput. Sci.*, **62**, 101707, <https://doi.org/10.1016/j.jocs.2022.101707>.
- Perrot, M., F. Lemarié, and T. Dubos, 2025: Energetically consistent eddy-diffusivity mass-flux convective schemes: 1. Theory and models. *J. Adv. Model. Earth Syst.*, **17**, e2024MS004273, <https://doi.org/10.1029/2024MS004273>.
- Sane, A., B. G. Reichl, A. Adcroft, and L. Zanna, 2023: Parameterizing vertical mixing coefficients in the ocean surface boundary layer using neural networks. *J. Adv. Model. Earth Syst.*, **15**, e2023MS003890, <https://doi.org/10.1029/2023MS003890>.
- Silvestri, S. and Coauthors, 2024: A GPU-based ocean dynamical core for routine mesoscale-resolving climate simulations. *ESS open archive*, <https://doi.org/10.22541/essoar.171708158.82342448/v1>.
- Sinha, A., J. Callies, and D. Menemenlis, 2023: Do submesoscales affect the large-scale structure of the upper ocean? *J. Phys. Oceanogr.*, **53**, 1025-1040, doi.org/10.1175/JPO-D-22-0129.1.
- Téchené, S. and Coauthors, 2024: Gain of efficiency with a new time scheme in NEMO: Runge Kutta 3rd order. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/gain-efficiency-new-time-scheme-nemo-runge-kutta-3rd-order>.
- Van Roekel, L., S. Brus, and M. Petersen, 2024: Ocean model for E3SM global applications. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE.
- Wang, H., 2024: Connecting the Great Lakes in MOM6: Subgrid scale topography and hydraulic control. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE.
- Wang, Y. and A. L. Stewart, 2020: Scalings for eddy buoyancy transfer across continental slopes under retrograde winds. *Ocean Model.*, **147**, 101579, <https://doi.org/10.1016/j.ocemod.2020.101579>.
- Wang, Y., H. Wei, C. Xie, J. Mak, and A. Stewart, 2024: Bathymetry-aware mesoscale eddy parameterizations. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODORE, <https://usclivar.org/abstract-ocean-model-2024/bathymetry-aware-mesoscale-eddy-parameterizations>.
- Wei, H., Y. Wang, A. L. Stewart, and J. Mak, 2022: Scalings for eddy buoyancy fluxes across prograde shelf/slope fronts. *J. Adv. Model. Earth Syst.*, **14**, e2022MS00322, <https://doi.org/10.1175/JPO-D-23-0152.1>.
- Xie, C, H. Wei, and Y. Wang, 2023: Impact of parameterized isopycnal diffusivity on shelf-ocean exchanges under upwelling-favorable winds: Offline tracer simulations augmented by artificial neural network. *J. Adv. Model. Earth Syst.*, **15**, e2022MS00342, <https://doi.org/10.1029/2022MS003424>.

- Yassin, H., G. Danabasoglu, G. Maques, and I. Grooms, 2024: Re-energizing ocean mesoscale eddies: Assessing backscatter parameterizations for global ocean models. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODEORE, <https://usclivar.org/abstract-ocean-model-2024/re-energizing-ocean-mesoscale-eddies-assessing-backscatter>.
- Zhang, W., S. M. Griffies, R. W. Hallberg, Y. Kuo, and C. Wolfe, 2024a: The role of surface potential vorticity in the vertical structure of mesoscale eddies in wind-driven ocean circulations. *J. Phys. Oceanogr.*, **54**, 1243-1266, <https://doi.org/10.1175/JPO-D-23-0203.1>.
- Zhang, W., S. M. Griffies, E. Yankovsky, A. Adcroft, and R. W. Hallberg, 2024b: Sensitivity of the kinetic energy backscatter parameterization to its vertical structure in eddy-permitting ocean simulations. Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop, Boulder, CO, CLIVAR and COMMODEORE, <https://usclivar.org/abstract-ocean-model-2024/sensitivity-kinetic-energy-backscatter-parameterization-its-vertical>.

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Appendix C: Agenda

Monday, September 9, 2024		
Time (MT)	Agenda	Presenter
7:45 AM	Workshop registration	
8:30 AM	Welcome and introduction	
8:45 AM	Session 1: Ocean dynamics and circulation Chair: Gokhan Danabasoglu	
8:45 AM	(Keynote) From virtual Navier-Stokes flows to numerical ocean models	Peter Korn, Max Planck Institute for Meteorology
9:20 AM	Representation of balanced state in models of geophysical flows	Manita Chouskey, Leibniz-Institute for Baltic Sea Research (IOW), Germany
9:40 AM	Global scale-transfer of the ocean's kinetic energy and the role of the atmosphere	Hussein Aluie, University of Rochester
10:00 AM	Break	
10:30 AM	Energy pathways of the Tasman Sea internal tidal beam at three different model resolutions	Ashley Barnes, Australian National University
10:50 AM	Upper-ocean bias development and the Atlantic meridional overturning circulation in OMIP simulations	Elizabeth Maroon, University of Wisconsin-Madison
11:10 AM	Discussion	
12:00 PM	Lunch	
2:00 PM	Session 2: Harnessing ML for ocean modeling Chair: Alistair Adcroft	
2:00 PM	(Keynote) Explainable AI for Climate Prediction, Projection and Discovery	Elizabeth Barnes, Colorado State University
2:35 PM	Toward a New Parameterization of Ocean-Atmosphere Interactions Based on a Machine Learning Approach	Nicolas Ernout, Toulouse INP, LEGOS, IRIT
2:55 PM	How to model the Ocean Circulation Eddies using Artificial Neural Networks (OCEANN)	Iuri Gorenstein, Universidade de São Paulo
3:15 PM	Break	

Monday, September 9, 2024 (continued)		
Time (MT)	Agenda	Presenter
3:45 PM	Optimizing Ocean Biogeochemical Models: Harnessing satellite ocean color data spatially varying parameter estimation	Nabir Mamnun, Mercator Ocean International
4:05 PM	Deep learning based super-resolution for ICON-O	Fabricio Rodrigues Lapolli, Max Planck Institute for Meteorology
4:25 PM	Discussion	
4:55 PM	Lightning poster previews	
5:30-7:30 PM	Poster session and networking event	
7:30 PM	End of day 1	
Tuesday, September 10, 2024		
Time (MT)	Agenda	Presenter
8:30 AM	Session 2: Harnessing ML for ocean modeling (continued) Chair: Gustavo Marques	
8:30 AM	(Keynote) AI-augmented climate Simulators and Emulators	Laure Zanna, New York University
9:05 AM	Opportunities and pitfalls in automated calibration of ocean models	Gregory LeClaire Wagner, Massachusetts Institute of Technology
9:25 AM	An online, continuous learning framework for training surrogates of ocean models	Andrew Shao, Hewlett Packard Enterprise
9:45 AM	Exploring Python-based frameworks for geophysical modeling*	Tuomas Karna, Intel Corporation
10:05 AM	Break	
10:35 AM	Learning from (sparse) observations through the lens of models*	Patrick Heimbach, University of Texas at Austin
10:55 AM	(Keynote) Towards a fully machine learned Earth system model at ECMWF	Lorenzo Zampieri, ECMWF
11:30 AM	Discussion	
12:00 PM	Lunch	
2:00 PM	Session 3: Numerical methods for ocean/sea-ice models Chair: Florian Lemarié	
2:00 PM	(Keynote) A hybrid ice model	Carolin Mehlmann, Otto von Guericke University Magdeburg

Tuesday, September 10, 2024 (continued)		
Time (MT)	Agenda	Presenter
2:35 PM	Stability and accuracy of Runge-Kutta-based split-explicit time-stepping algorithms for free-surface ocean models*	Nicolas Ducouso, Service Hydrographique et Océanographique de la Marine (SHOM)
2:55 AM	Improving the Dynamic Coupling of Sea-ice and Ocean Models	Theresa Morrison, Geophysical Fluid Dynamics Laboratory
3:15 PM	Break	
3:45 PM	h-NUMO: A multi-layer shallow water equation model with high-order Discontinuous Galerkin method.	Michal Kopera, Boise State University
4:05 PM	Gain of efficiency with a new time scheme in NEMO : Runge Kutta 3rd order	Sibylle Téchené, CNRS/ LOCEAN
4:25 PM	Some insights on the spurious numerical mixing of the time-stepping of advection schemes	Adrien Garinet, LEGOS, Université Toulouse 3
4:45 PM	Discussion	
5:15 PM	End of day 2	

Wednesday, September 11, 2024		
Time (MT)	Agenda	Presenter
8:30 AM	Session 4: Mesoscale eddy parameterization Chair: Gustavo Marques	
8:30 AM	(Keynote) Bathymetry-aware mesoscale eddy parameterizations	Yan Wang, Hong Kong University of Science and Technology
9:05 AM	Re-Energizing Ocean Mesoscale Eddies: Assessing Backscatter Parameterizations for Global Ocean Models	Houssam Yassin, University of Colorado Boulder
9:25 AM	Parameterizing Mesoscale Eddy Buoyancy Fluxes Using Small Neural Networks	Dhruv Balwada, Lamont Doherty Earth Observatory, Columbia University
9:45 AM	Data-driven parameterisation of mesoscale eddies using the Eliassen-Palm flux	Kelsey Everard, New York University
10:05 AM	Break	
10:30 AM	The Stochastic GM+E closure: A framework for coupling stochastic backscatter with the Gent and McWilliams parameterization	Ian Grooms, University of Colorado
10:50 AM	Discussion	

Wednesday, September 11, 2024 (continued)		
Time (MT)	Agenda	Presenter
11:20 AM	Session 5: Vertical mixing parameterization Chair: Julie McClean	
11:20 AM	Applying implicit energetics ideas to simulate full-water-column ocean mixing	Robert Hallberg, NOAA/GFDL
11:40 AM	Derivation of an energetically consistent Eddy-Diffusivity Mass-Flux scheme for oceanic Convection	Manolis Perrot, University Grenoble Alpes (France)
12:00 PM	Lunch	
2:00 PM	Parameterizing Vertical Turbulent Mixing Coefficients for The Ocean Surface Boundary Layer Using Machine Learning	Aakash Sane, Princeton University
2:20 PM	Stochastic parameterization of general non-hydrostatic processes with a focus on deep convection*	Quentin Jamet, Institut national de recherche en informatique et en automatique (INRIA)
2:40 PM	Discussion	
3:10 PM	Break	
3:40 PM	Session 6: Recent developments in ocean modeling Chair: Gokhan Danabasoglu	
3:40 PM	Online tracer-coordinate diagnostics in MOM6	Graeme MacGilchrist, University of St Andrews
4:00 PM	Online Lagrangian Particle Advection in MOM6	Spencer Jones, Texas A&M University
4:20 PM	Connecting the Great Lakes in MOM6: sub-grid scale topography and hydraulic control	He Wang, UCAR/NOAA-GFDL/ University of Michigan
4:40 PM	Discussion	
5:00 PM	End of day 3	
5:05 PM	OMDP Meeting 1: OMIP	

Thursday, September 12, 2024		
Time (MT)	Agenda	Presenter
8:30 AM	Session 7: High resolution ocean modeling Chair: Julie McClean	
8:30 AM	(Keynote) Global ocean simulations with ClimaOcean.jl: numerical implementation, performance, and results	Simone Silvestri, Massachusetts Institute of Technology

Thursday, September 12, 2024 (continued)		
Time (MT)	Agenda	Presenter
9:05 AM	Rapid thermal equilibration under piControl forcing in a mesoscale dominant climate model	Stephen Griffies, NOAA GFDL/Princeton University
9:25 AM	High-Resolution North Atlantic Ocean Modeling: Impact of bathymetry, tides, and atmospheric forcing	Eric Chassignet, Florida State University
9:45	Sensitivity of cyclone produced ocean mixing to the Langmuir turbulence: a modeling study	Soma Mishra, Indian Institute of Tropical Meteorology, Pune
10:00 AM	Break	
10:30 AM	Advancing models of ocean mixing in the equatorial Pacific Cold tongue using an embedded LES approach	Dan Whitt, NASA/Ames
10:50 AM	Discussion	
11:20 AM	Session 8: Generalized vertical coordinates formulation Chair: Alistair Adcroft	
11:20 AM	An adaptive vertical coordinate for ocean models	Andy Hogg, Australian National University
11:40 AM	Hybrid vertical coordinate in the Bergen Layered Ocean Model (BLOM)	Mats Bentsen, NORCE Norwegian Research Centre and Bjerknes Centre for Climate Research, Bergen, Norway
12:00 PM	Lunch	
2:00 PM	A Comparison of HYCOM and MOM6 Vertical Coordinates	Alan Wallcraft, Florida State University
2:20 PM	Toward the design of a generalized vertical coordinate to properly represent vertical modes in an ocean model	Gabriel Derrida, Inria
2:40 PM	Localized multi-envelope vertical coordinates for improving flow-topography interactions in global ocean models	Diego Bruciaferri, UKMO
3:00 PM	Discussion	
3:30 PM	Break	
4:00 PM	Workshop conclusions and recommendations	
4:30 PM	End of workshop	
4:35 PM	OMDP business meeting	



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