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4th COMMODORE Workshop on Advancing Ocean Modeling: Bridging Theory, Computation, Scales, and Applications | (SMR 4237)

21 Sep 2026 - 24 Sep 2026
ICTP, Trieste, Italy

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T01

Machine Learning in Ocean Models: From Stable Parameterizations to Conservative Emulators

Machine learning is entering ocean and climate modeling not just as a set of discrete techniques but as a continuous spectrum. At one end sits hybrid modeling, in which a physics-based general circulation model retains its dynamical core and conservation structure while data-driven closures augment or replace conventional subgrid parameterizations. At the other end sit full neural emulators that learn the evolution of the ocean state directly from data. I begin at the hybrid end, where the most readily deployable methods have emerged: data-driven mesoscale eddy closures that remain stable when used online and that generalize across resolution and configuration, machine-learned surface boundary layer mixing, and systematic error corrections learned from data assimilation increments. I then argue that the principal weakness of current emulators is not skill but physical consistency: most are non-conservative, and therefore poorly suited to the long, closed budgets that climate models demand. Conservation-aware methods do exist, ranging from loss-function penalties and architecture constraints to global mass and energy correctors, but they have been developed largely for the atmosphere and sea ice, and they tend to append conservation to an otherwise unconstrained network. I outline a pathway that instead builds emulators in the manner of general circulation models, with conservation and physical structure designed in from the start rather than enforced after the fact. Finally, I describe the longer-term ambition that motivates this program: using physics-consistent emulators, once trustworthy and fast, to learn how to accelerate the general circulation models themselves, closing a loop between the physics-based and learned ends of the spectrum.

T02

Abstract for Commodore 21-24 Sept 2026

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The NEMO ocean model has a fairly generic s-level vertical co-ordinate option that allows the model levels to follow either the ocean bathymetry resolved by the model or a smoothed ``envelope'' version of it. Sufficiently accurate calculation of the net horizontal pressure forces on the resulting steeply sloping cells is well known to be difficult and many schemes have attempted to address this issue. We focus here on two types of schemes that calculate these forces by integrating around the cell perimeters (or faces). The first type calculates the pressure forces on the faces of each velocity cell as first proposed by [1]. The second type is a re-arrangement of Song's density Jacobian scheme derived by [2]. In these schemes the density and the height along coordinate surfaces are approximated by local piecewise continuous polynomial reconstructions and the integrals are calculated by direct integration of the polynomials or by quadrature methods. Higher order schemes are obtained by using higher order polynomials. In some cases these polynomials are constrained to avoid over-fitting of potentially noisy fields. We have implemented these schemes in NEMO treating model variables as point values rather than cell-mean values. The implementation for the second type follows previously published work closely whilst that for the first type differs somewhat from previous work. We have also implemented a ``pre-processing'' step that calculates cubic reconstructions of the density profile at the deepest point in the stencil used to calculate the net horizontal forces. The ``pre-processing'' step subtracts this interpolated profile from all the other profiles in the stencil or uses it to assist the interpolation on surfaces of constant s. We present results for these schemes in a standard sea-mount test case with steep bathymetry and horizontal density surfaces in which the currents should be identically zero. We show that both types of schemes using appropriate quadratic or cubic reconstructions give currents that are about one order of magnitude smaller than those given by second order accurate schemes. This is the case even if the fields are initialised as cell-mean values rather than point values. Using ``pre-processing'' steps, one can obtain smaller initial velocities but small velocities are not retained in longer integrations. We will discuss whether: (1) a "natural", accurate discretisation can be obtained for pressure forces treating densities as grid cell averages; (2) more accurate calculation of bathymetric gradients would be beneficial; and (3) the "pre-processing" step could be stabilised.

[1] S. J. Lin, Quart. J. Roy. Meteor. Soc. **123**, 1749–1762 (1997).

[2] A. F. Shchepetkin, J. C. McWilliams, Geophys. Res. **108**, **C3**, 30390 (2003).

T03

Quantifying spurious Boussinesq contribution to seasonal cross equatorial transport

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Almost all ocean general circulation models used for climate research rely on the Boussinesq approximation. This approximation simplifies the Navier-Stokes equations by using a constant density anywhere except where coupled to gravity. In particular, the conservation of mass is replaced by a volume conservation thus removing any acoustic wave and the only place where the constant density appears is in front of the pressure gradient.

The Boussinesq model cannot represent global mean sea-level contribution from thermal expansion, which could be diagnosed accurately afterwards [1, 2], but previous studies do not support any significant Boussinesq effects in coarse resolution global ocean model [3, 4]. Here we present an updated comparison of a Boussinesq versus non-Boussinesq solutions using a state of the art global ocean - seaice model at $1/3^o$ resolution with realistic forcing from atmospheric reanalysis, thus allowing to address both the mean and inter-annual variability as well as impact on seaice solution. Difference in model numerics are kept minimal as the same MITgcm model with r* coordinate [5] is used in both cases, in height or pressure coordinates for the Boussinesq and non-Boussinesq solution.

The new results show a remarkable similarity between the two solutions, both in term of mean state and variability of key oceanic quantities (SSH, bottom pressure, integrated transport, ...), in agreement with previous studies. But the new results allow to quantify the magnitude of the spurious Boussinesq cross equatorial transport which is shown to be directly related to seasonal variations of the hemispheric heat content. This spurious transport is small compared to large scale oceanic transport but represent a significant fraction of seasonal cross equatorial transport, the remaining being related to monsoon and ITCZ seasonal migration.

[1] R. Greatbatch, J. Geophys. Res. **99** C6, 12767–12771 (1994).
[2] S. Griffies, R. Greatbatch, Ocean Modelling **51**, 37–72 (2012).
[3] R. Greatbatch, Y. Lu, Y. Cai, J. Atmos. Oceanic Techno. **18**, 1911–1923 (2001).
[4] M. Losch, A. Adcroft, J.-M. Campin, J. Phys. Oceanogr. **34** 306–319 (2004).
[5] A. Adcroft, J.-M. Campin, Ocean Modelling **7**, 269–284 (2004).

T04

Toward a global 1/50 degree model configuration

Eric Chassignet, Alan Wallcraft, and Xiaobiao Xu

In this presentation, we will introduce the steps taken toward setting up a 1/50 degree HYCOM configuration (bathymetry, atmospheric forcing, etc.)

T05

Implicit sequential filtering

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In recent publications sequential filtering (also known as coarse-graining) is applied to estimate energy or power distribution over scales in ocean flows. Compared to the traditional Fourier analysis, sequential filtering offers some advantages as it is applicable to domains of different shape and also provides spatial distribution of spectral density. However, fast convolution requires regular uniform grids, which implies interpolation for computational meshes used in ocean modeling, both structured or unstructured.

Explicit convolution can be replaced by implicit filtering based on solving a boundary value problem

$$(1 + \gamma(-\ell^2\Delta)^n)\phi_\ell(\mathbf{x}) = \phi(\mathbf{x})$$

in ocean domain D subject to no flux boundary conditions. This problem connects the field ϕ and its spatially filtered image ϕ_ℓ. Here, ℓ is the scale, Δ is a discrete Laplacian, γ is a parameter that tunes the meaning of ℓ, and n is the order of the filter. The matrix of the operator on the left hand side is symmetric and positive definite so that the problem is solved iteratively with the standard conjugate gradient method. The case $n = 1$ gives a Laplacian filter which works similarly to box or Gaussian filters. Higher-order filters are obtained for $n > 1$. They resolve steeper spectral slopes and give spectral density that is closer to that of Fourier analysis, but simultaneously require more care to obtain converging solutions.

The implicit filtering relies only on the discrete representation of the Laplacian operator. This means that the procedure can be applied for any mesh (quadrilateral or triangular, regular or unstructured), geometry (flat or curved) and for both scalars and vectors. Since only the nearest neighbors are needed to express discrete Laplacians, the solution procedure is readily parallelizable.

We present theory and implementation of the implicit sequential filtering in both low-pass and high-pass versions. The current implementation supports FESOM and NEMO meshes, but can be easily extended to meshes used by other models. Despite of the use of iterative solvers, calculation of sequential spectrum on a mesh with $\sim 10^7$ surface points can be done within several minutes.

Spectra obtained by sequential filtering behave as smoothed versions of respective Fourier spectra. They can miss narrow spectral peaks or predict peak positions at wavenumbers that are significantly different from those of the Fourier spectra. We discuss these limitations.

T06

A linearly exact filter for the leapfrog time integration scheme

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The leapfrog time-integration scheme uses three time levels for a centred second-order approximation to a first derivative in time. It has the attractive property that numerical solutions of differential equations with purely oscillatory solutions are also purely oscillatory. However, because the leapfrog scheme uses three time level it supports a second set of solutions that oscillate like $(-1)^n$ at time step $t_n = n\Delta t$. Some variant of the Robert–Asselin filter is commonly used to suppress these solutions.

The three-time-level leapfrog scheme can instead be factorised into a two-time-level scheme. For example, every solution of the two-level scheme

$$\psi_{n+1} = \left(\sqrt{\mathsf{I} - \Delta t^2 \mathsf{H}^2} - i\Delta t \mathsf{H}\right)\psi_n \tag{1}$$

for the abstract linear Schrödinger equation $i\partial_t \psi = \mathsf{H}\psi$ is also a solution of the leapfrog discretisation

$$\psi_{n+1} = \psi_{n-1} - 2i\Delta t \mathsf{H}\psi_n \tag{2}$$

The operator $\sqrt{\mathsf{I} - \Delta t^2 \mathsf{H}^2} - i\Delta t \mathsf{H}$ is unitary, so the norm $\langle \psi_n, \psi_n \rangle$ and the discrete expectation $\langle \psi_n, \mathsf{H}\psi_n \rangle$ are both exactly conserved. In this notation, the operator $-i\mathsf{H}$ would be an antisymmetric linear wave operator in geophysical fluid dynamics.

The operator $\sqrt{\mathsf{I} - \Delta t^2 \mathsf{H}^2}$ is defined as a power series in Δt. This operator is usually too computationally expensive to use for every timestep, but it can be used once to construct a second initial condition ψ_1 from the initial condition ψ_0 at $t = 0$. The solutions ψ_n generated by (1) and (2) at later timesteps $n \geq 2$ then coincide exactly in exact arithmetic. This construction of ψ_1 thus exactly suppresses the computational zig-zag mode for linear, purely oscillatory problem. More generally, for nonlinear and/or dissipative problems one can use an occasional step of (1) as a filter to suppress the computational zig-zag mode while using (2) for almost all timesteps for computational efficiency.

T07

Abstract template for 4th COMMODORE Workshop on Advancing Ocean Modeling: Bridging Theory, Computation, Scales, and Applications

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In the stratified ocean interior, diapycnal turbulent mixing is mostly caused by breaking internal waves. This type of mixing is a key driver for the upwelling branch of the meridional overturning circulation. However, mixing due to internal waves is still poorly constrained in ocean models, due to a lack of understanding of: first, how much a certain internal wave field is able to mix; second, the regional distribution of internal wave energy itself. Here, we focus on the latter problem. Applying a machine-learning clustering technique to the internal wave energy level distribution from Argo data, we partition the global ocean into a small number of coherent clusters that characterize different types of oceanic internal wave fields. We then interpret the resulting clusters in terms of the main regional controls of internal waves: the stratification configuration and the forcing mechanisms, among which internal tides, wind-driven near-inertial waves, and eddy-wave interactions.

T08

Improving the representation of internal gravity waves in ocean models: discretisation and vertical coordinate design

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Internal gravity waves are an important component of ocean dynamics and play a key role in the transport of energy and momentum across scales. Their discrete representation in ocean models, however, remains sensitive to numerical discretisation choices.

In this presentation, I will first discuss how vertical discretisation influences the accuracy of internal-wave dynamics. Using perturbation analysis of discrete eigenvalue problems, I will introduce a framework to quantify the impact of numerical choices on wave phase-speed errors. I will then show how these errors can be reduced through the design of optimised discretisations and, in some cases, optimised vertical coordinates [1]. I will also extend the discussion to the two-dimensional case, where the respective contributions of horizontal and vertical discretisation errors must be compared in order to guide optimal numerical choices. Finally, the theoretical results will be illustrated using an internal-wave test case implemented in the NEMO ocean model.

[1] *Propagation of internal gravity waves: optimal vertical discretisation and grid design based on numerical error analysis*, G. Derrida, L. Debreu, F. Lemarie, J. Chanut, QJRMS (2026).

T09

Thermodynamic consistency of down-gradient turbulent closures

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Based on exact budgets for anelastic/Boussinesq turbulence with an arbitrary multicomponent equation of state, a family of subgrid-scale closures is examined under the constraint of consistency with (i) the first and second laws of thermodynamics and (ii) invariance with respect to irrelevant thermodynamic constants [1]. The models predict turbulent kinetic energy, assume down- gradient closures for turbulent fluxes and impose certain relationships between the closures for the turbulent fluxes of heat, matter, entropy, and the work of buoyancy forces.

The local rate of entropy production is derived and it is shown that positive entropy production is guaranteed whenever the turbulent diffusions of heat and composition are positive. In the special case of a single turbulent diffusivity, an arbitrary conservative variable can be prognosed while ignoring its precise relationship to entropy. These findings show that down-gradient closures are consistent with the first and second law of thermodynamics even when they lead to a turbulent sensible heat flux up the temperature gradient. This is admissible thanks to the energy reservoir provided by turbulent kinetic energy, which can be consumed to sustain stratified turbulent mixing.

[1] T. Dubos, submitted to J. Fluid Mech. (https://arxiv.org/abs/2601.16957)

T10

Direct numerical simulations of surface wave-induced forces

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A gradient force, together with the Coriolis-Stokes and vortex force are residual surface-wave driven forces showing up in the equations of motion averaged over the wave cycle under certain assumptions. They are part of the so-called Craik-Leibovich equations, which are often used to understand surface wave-driven (Langmuir) turbulence, and to simulate the wave effects on the ocean's mixed layer in numerical models. The surface wave effects can be implemented in those models by the wave-driven forces without directly resolving the waves, which is otherwise numerically challenging. Since observational or modelling evidence for the surface-wave driven forces is only partly available, we diagnose here the Reynolds stress divergences of a two-phase model of air and water directly simulating surface waves, to compare with all corresponding forces in the Craik-Leibovich equations in a systematic manner.

We also explore the limits of the assumptions of the Craik-Leibovich equations by using mean flow of different magnitude and shear. It turns out that the Coriolis-Stokes and vortex force are very good approximations within the limits of the assumptions, and that they remain useful even beyond those limits. The gradient force, however, differs from a version put forward in the literature. The latter finding has consequences for the treatment of wave-driven turbulence in mixed layer closures, which are discussed using LES model results. We also explore ways for an energetically consistent coupling of spectral wave models to the Craik-Leibovich equations or large-scale ocean models, by extending a recent suggestion by Vanneste and Young (2026) including also the wave stress as a new wave-driven force acting on the mean flow.

T11

Separating Eddies and Waves at the Grid-Scale with a Split-Form Viscosity Scheme

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Achieving an optimal representation of fine-scale turbulence is challenging, with the desire to resolve energetic, eddy-rich flows set against the need to control spurious grid-scale noise and prevent unphysical mixing. In this work, progress is made using a new viscous parameterisation, in which turbulent dissipation is split into two parts, allowing noisy, divergent motions associated with numerical mixing to be controlled without compromising the representation of fine-scale eddies and circulation. It is shown that an appropriate dissipation for divergent motions can be composed using estimates of the ocean's internal and external wave speeds, leading to an adaptive parameterisation that evolves in space and time, and tracks the ocean's stratification. The new scheme is exercised in a submesoscale-permitting model of meanders in the ACC south of Australia, where it is found to outperform existing approaches — reducing spurious diapycnal motion in strongly eddying flows without degrading EKE or compromising vorticity dynamics, leading to favourable intercomparisons with SWOT-based observations.

T12

The parameterization paradox: when do oceanic small scales matter for climate?

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Ocean models require physical parameterizations to be computationally stable. Therefore, sub-grid-scale parameterizations are absolutely necessary for climate simulations to be possible. However, theories of coupled climate dynamics rarely include an explicit role for these parameterizations. This leaves us with a paradox: how come these algorithms enable solutions of the climate system, yet be unnecessary to explain a majority of coupled ocean-atmosphere phenomena? Is it that parameterizations are simply a computational requirement, or that the meaning of parameterizations has remained hidden to the eyes of climate scientists? In this talk I will argue that the second is true, and offer two ways to move past this paradox.

The first way forward is to include more specialized output variables in future model intercomparison projects. To argue this, I present a comparison between simplified and exact heat budgets of the upper ocean [1]. Our analyses, based on coupled runs of CESM2, show that simplified budgets based on standard output variables can often introduce biases that mask the true importance of ocean parameterizations and resolved small scale advection to climate variability.

The second way forward is to develop and popularize physical frameworks in which features of the large scale ocean cannot be explained without explicit intervention by parameterized processes. As an example, I introduce an energetic framework of the equatorial current system [2] and ask *why does the Cold Tongue float?* In this view, upwelling does not explain the existence of equatorial Cold Tongues, but rather demands that we explain why the Cold Tongue doesn't fall down into the ocean interior. Theory and accounting of parameterized processes in the E3SM coupled model show a correspondence between the available potential energy (APE) gained from upwelling and upward entrainment of cold, dense waters, and APE dissipation by parameterized processes that diabatically lower the density of Cold Tongue waters [3]. This establishes a physical framework where parameterized processes are absolutely necessary to explain the existence of a Cold Tongue.

[1] N. G. Brizuela, S. M. Kang, M. F. Stuecker, C.-Y. Lee, F. Jiang, Simplified heat budgets can yield misleading diagnoses of ocean temperature change (to be submitted).

[2] N. G. Brizuela, C.Y. Lee, A. H. Sobel, R. Seager, S. Camargo, J. Zhuo. Tropical thermocline helps power Pacific Equatorial upwelling. J. Phys. Ocean. **17**, 7531 (2025).

[3] N. G. Brizuela, Irreversible physics anchor equatorial cold tongues to the ocean surface (in prep).

T13

Why are we still making the Boussinesq approximation in ocean models?

Robert Hallberg [1,2]

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[2] *Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, USA*

The Boussinesq approximation replaces the state-dependent density in ocean model equations with a reference density except where density gradients appear. It remains a common approximation in large-scale ocean models, but it also introduces unnecessary inaccuracies that can degrade model performance and utility.

Given the range of densities found in sea-water, the Boussinesq approximation is accurate to within about 2-3% in most linear terms, but it also means that Boussinesq ocean models formally conserve the volume of water instead of its mass, so steric sea level changes cannot be directly simulated. Moreover, the Boussinesq approximation introduces systematic biases that most-strongly impact light coastal waters, it can alter the ocean model's modal structures, and it introduces an unnecessary degree of arbitrariness in ocean models via the choice of a reference density.

This presentation discusses the pedagogical and historical rationale for the Boussinesq approximation and some of the phenomena for which the Boussinesq approximation is problematic, with a particular emphasis on steric sea-level rise and total water levels. It presents the strategy that has been used in the MOM6 community ocean model [1] to convert it into an optionally fully non-Boussinesq model, and the testing strategy that is used to demonstrate that this conversion has been done comprehensively and correctly. This presentation then illustrates the advantages and minimal costs that accrue from the non-Boussinesq conversion in NOAA/GFDL's new OM5 global ocean model and related ocean model configurations.

[1] The optionally non-Boussinesq version of MOM6 is available via the main MOM6 GitHub branch at https://github.com/MOM-ocean/MOM6

T14

The role of eddy parameterizations in ocean modelling: Investigating mesoscale eddy impacts in the coupled climate system

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An accurate representation of mesoscale eddies and a comprehensive understanding of their role in the global and regional oceans remains a scientific and technical challenge. As model resolutions and computing capabilities have increased substantially in recent years, eddies in the ocean will nevertheless not be sufficiently resolved in shallow seas, the high latitudes or for large ensemble, longer climate or paleoclimate simulations. However, mesoscale eddies are crucially important due to their interactions with the mean circulation, their uptake and distribution of heat and carbon, and due to their role in tracer transports and water mass transformations. Their relevance for atmosphere-ocean coupling and feedbacks has also been highlighted and intensely discussed in the more recent literature.

We present a broad overview over several approaches used to improve the simulation and of eddies at resolutions where they cannot be explicitly resolved, are not sufficiently well represented or are still substantially impacted by numerical artifacts. These approaches include eddy parameterization choices such as optimized viscosity closures and deterministic and stochastic backscatter parameterizations and are implemented, developed and analysed within the unstructured grid FESOM2 global ocean model and in coupled climate simulations.

A specific focus of our study is the investigation of impacts of a selected subset of mesoscale parameterizations and eddy representations on coupled climate simulations. A comparative setup of ensemble climate simulations highlights the role of eddies in shaping mean ocean currents, in defining local and regional atmospheric feedbacks and impacts, and in determining large-scale changes in the climate system. This provides a qualitative and quantitative assessment of the relative impact of ocean eddies on the climatic mean state, trends and variability both in the ocean and the atmosphere. We also show that the absence of eddies substantially contributes to long standing model biases at intermediate resolutions such as the cold bias in the North Atlantic.

In addition, as part of the eddy parameterization overview, we take a closer look into the consequences of eddy parameterizations for numerical ocean modelling and what we can define as the effective resolution of a general circulation model, i.e., the resolution at which we can sufficiently trust the dynamical behaviour of the simulated flow. We analyse these aspects in a set of idealized configurations of FESOM2 – where certain processes can be isolated by removing dynamical aspects such as complex topographic interactions – and relate these findings to consequences for global setups.

T15

Periodic homogenization of permeability for upscaling topography in ocean models

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Global and regional ocean models require accurate representation of resolved topography and realistic modelling of unresolved subgrid scale (SGS) topography. The effects of SGS topography are currently modelled as a position-dependent enhanced bottom or sidewall friction $r_b(\boldsymbol{x})$ and SGS topography is simply averaged to the computational grid scale. However, because there is no rigorous way to determine $r_b(\boldsymbol{x})$, it must be manually tuned to capture important flow features, such as steering of western boundary currents and vertical mixing. A promising method of representing no-slip boundary conditions for complex topography in ocean models is Brinkman penalization, where the entire computational domain is treated as a porous medium with small porosity and permeability in solid regions (Kevlahan et al., 2015; Debreu et al., 2022). In this work, we reinterpret and extend the Brinkman approach to develop a universal algorithm for upscaling SGS topography to the grid scale. The quantitative and qualitative effects of SGS topography on the resolved flow are modelled by a 3×3 symmetric positive definite permeability matrix $\boldsymbol{K}(\boldsymbol{x})$ and porosity function $\phi(\boldsymbol{x})$. The resulting matrix-valued friction term is $-\boldsymbol{K}(\boldsymbol{x})^{-1}\boldsymbol{u}$. The matrix form captures subtle unresolved SGS effects, such as flow steering and anisotropic dissipation of kinetic energy. The permeability matrix is computed from fine scale topography data using periodic homogenization for Darcy flow. Porosity is simply the average of fine scale porosity over the coarse grid cells. We show that periodic homogenization is fast, accurate and superior to volume based averaging. Validation results are presented for two-dimensional tidally driven shallow water channel flow for a range of upscaling ratios. Coarse scale simulations using the upscaled topography give good approximations of equivalent fine-scale results for speed and total energy dissipation for upscaling ratios up to 13.

References

Debreu, L., Kevlahan, N.R., Marchesiello, P., 2022. Improved gulf stream separation through brinkman penalization. Ocean Model. 179, 102121. doi:10.1016/j.ocemod.2022.102121.

Kevlahan, N.K.R., Dubos, T., Aechtner, M., 2015. Adaptive wavelet simulation of global ocean dynamics using a new Brinkman volume penalization. Geosci. Model Dev. 8, 3891–3909. doi:10.5194/gmd-8-3891-2015.

T16

IMPROVING BAROCLINIC INSTABILITY USING CNN IN OCEAN MODELS

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Coarse-resolution ocean climate simulations inherently under-resolve mesoscale baroclinic instabilities, leading to energy loss through spurious numerical dissipation, degrading long-term simulations. We present a hybrid simulation approach that couples a coarse-resolution primitive-equation ocean model ICON-O with a convolutional neural network (CNN). The network architecture extends a previously established 2D U-Net configuration [1] by incorporating a Feature-wise Linear Modulation (FiLM) layer, enabling the model to effectively capture the distinct depth levels across the vertical water column.

Under a toy wind-forced, zonally periodic baroclinic channel experiment, we train the CNN on a paired dataset consisting of a 5 km simulation nudged toward a 500 m reference run, using the latter as the ground truth for 263 days. Using the state at day 263 as the initial condition, the hybrid model is then integrated for a subsequent 102 days in an online configuration, where the trained CNN actively applies corrections to the 5 km simulation fields.

During this online phase, the hybrid simulation substantially decreases the L_2 error of the coarse-resolution simulation to levels comparable to a 2 km run, achieving this by preventing small-scale errors from propagating to larger scales. More importantly, throughout this integration window, the hybrid model preserved the global mass balances and near-conservative properties within the ICON-O numerical core, exhibiting no signs of numerical instabilities.

In the climatological run, using independent initial conditions for both high and low resolution models, the hybrid model was capable of recovering the original mean zonal jet structure of the 500 m which was otherwise degraded in 5 km free runs. Additionally, diagnostic evaluations demonstrated that the model reconstructed turbulent statistics, improving velocity correlations from 26.4% to 57% and temperature anomaly correlations from 20% to 45%, outperforming a 2 km free-running simulation. A physical bottleneck was observed in the vertical buoyancy flux distribution due to the 2D network's inability to explicitly compute vertical gradients between depth layers, which bounded the effectiveness of the CNN. Despite this constraint, the model outperforms unassimilated simulations, providing a stable, physically consistent for improving global climate-scale simulations without relying on grid refinement configurations.

In conclusion, this work demonstrated that integrating a convolutional neural network into the 3D ICON-O model provides a viable path to circumvent the costs of finer resolution simulations. By successfully recovering structural features like mean zonal jet systems and its turbulence structure, while maintaining physical conservation laws, this hybrid framework demonstrates the potential of machine learning to serve as a powerful tool for next-generation global climate simulations.

[1] Witte M., Lapolli F.R., Freese P., Götschel S., Ruprecht D., Korn P. and Kadow C., Machine Learning: Science and Technology. **6**, 015060 (2025).

T17

Adjoint-constrained mesoscale eddy parameterization over the Antarctic continental slope

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Mesoscale eddies along the Antarctic continental slope strongly influence cross-slope exchanges, yet their effects remain largely unresolved in the coarse-resolution ocean models used in climate applications. We investigate an adjoint-based framework to optimize the widely employed Gent–McWilliams (GM) and Redi parameterizations against a high-resolution MITgcm simulation representative of Antarctic slope dynamics. Spatially varying GM and Redi coefficients are inferred by minimizing hydrographic misfits between coarse- and high-resolution simulations. The cost-function gradients are computed using the MITgcm adjoint, thereby enabling the tractable application of quasi-Newton methods to this high-dimensional problem. Performing the optimization across a range of resolutions provides insight into the 'gray-zone' regime, where mesoscale eddies become partly resolved. In parallel, the adjoint-optimized diffusivities are compared with those directly diagnosed from the eddy fluxes in the high-resolution simulation, providing an independent assessment of how well the optimized parameterizations capture the underlying physics rather than compensating for model biases. This approach reveals pronounced spatial variations in diffusivity consistent with topographic eddy suppression, with reduced GM activity over the continental slope. Overall, the results illustrate how adjoint optimization and eddy-flux diagnostics can help evaluate and constrain traditional mesoscale eddy parameterization schemes in ocean models.

T18

Towards physically-based treatment of river inputs in MOM6

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Riverine freshwater inputs are a key driver of coastal ocean dynamics, controlling stratification and mixing, with cascading consequences for nutrient cycling, ecosystem productivity, and coastal fisheries. Despite their importance, most ocean models treat river inputs in overly simplistic ways, either as augmented precipitation distributed over arbitrarily large areas or as injected directly into a single surface grid cell. These approaches fail to capture key estuarine exchange processes and associated freshwater pathways.

A parameterization for the volume flux and salinity of estuarine outflow from river discharge was previously developed and validated in the Parallel Ocean Program ocean model used within the Community Earth System Model. This parameterization, referred to as the Estuary Box Model (EBM), predicts estuarine outflow properties from river discharge, offshore salinity, and tidal forcing without requiring explicit resolution of estuarine dynamics.

Here, we describe the implementation and initial validation of the EBM in the Modular Ocean Model (MOM6). We highlight extensions of the EBM framework to support natural boundary conditions and to be compatible with the Arbitrary Lagrangian-Eulerian vertical coordinate framework used by MOM6. This work represents a step toward more physically based representations of riverine freshwater inputs in global and regional ocean simulations.

T19

Porous Cavities and Smooth Boundaries: Brinkman Volume Penalization for Ice-Shelf–Ocean Interactions in Ocean General Circulation Models

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Numerical ocean models remain essential for investigating ice–shelf–ocean interaction to estimate the fate of the Antarctic Ice Sheet in a warming climate. A persistent challenge in z-coordinate ocean models is the artificial stepwise representation of cavity geometries, which induces excessive diapycnal mixing and numerical noise beneath the ice draft. Here, we assess the potential of the Brinkman Volume Penalization (BVP) method for ice–ocean modeling, in which the ice–ocean interface is replaced by a porous region that is partially ocean and partially ice. The benefits of penalization are evaluated in a z-coordinate ocean model using an idealized ISOMIP+ configuration [1] under both warm and cold scenarios. First, smoothing the cavity with the BVP acts as an effective local increase in vertical resolution, improving ocean circulation near the grounding line and allowing strong basal melt at the ice-shelf base. Second, we show that the distribution of heat and meltwater within the penalized region reduces spurious mixing, leading to colder and fresher ice-shelf waters and a strengthened overturning circulation. Hence, the BVP approach provides a promising alternative to a melt-layer formulation as in [2], for which similar noise reduction requires prescribing a melt-layer depth that is too large and leads to excessive mixing. Finally, we show that at least four vertical grid cells are required to resolve grounding-zone overturning and to obtain strong and consistent basal melt patterns. In summary, these results provide practical guidance for improving the numerical treatment of ice-shelf cavities in OGCMs.

[1] Asay-Davis, X. S., Cornford, S. L., Durand, G., Galton-Fenzi, B. K., Gladstone, R. M., Gudmundsson, G. H., … Seroussi, H. Geoscientific Model Development, 9(7), 2471–2497 (2016)

[2] Losch, M. Journal of Geophysical Research: Oceans, 113(C8) (2008)

T20

Parameterizing isopycnal mixing via kinetic energy backscatter in an eddy-permitting ocean model

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Representing mesoscale turbulence in eddy-permitting ocean models raises challenges for climate simulations; in such models, eddies and their associated energy and transport effects are resolved either marginally or only over parts of the domain. Recently, kinetic energy backscatter parameterizations have shown promise as closure for both eddy momentum and buoyancy fluxes in the eddy-permitting regime—energizing eddies which can themselves maintain accurate large-scale stratification by slumping steep isopycnals. However, it has not been systematically explored whether such backscatter parameterizations can also serve as a closure for along-isopycnal eddy tracer fluxes. Here, I present simulations using GFDL-MOM6 in an idealized basin-scale configuration to assess whether isopycnal tracer mixing is improved, at 1/2° and 1/4° eddy-permitting resolutions, through the addition of a kinetic energy backscatter parameterization. The representation of isopycnal mixing is assessed by diagnosing the three-dimensional structure of isopycnal diffusivities via a multiple tracer inversion method. Isopycnal mixing via backscatter alone shows significant improvement and closely resembles a 1/32° eddy-resolving simulation. Backscatter-parameterized mixing also outperforms simulations with no mesoscale parameterization or with an isopycnal diffusion parameterization alone, with the latter damping the tracer signature of partially resolved eddy variability. The results suggest that parameterizing backscatter can capture key mesoscale physics in a unified framework: the inverse cascade of kinetic energy, the slumping of steep isopycnals and the along-isopycnal mixing of tracers.

T21

Scalable Multi-GPU Ocean Modeling with JAX Native Sharding: Applications in FRIDOM and pyOM3

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The increasing availability of GPU-based high-performance computing systems creates new opportunities for ocean modeling, but also requires programming models that enable efficient scaling across multiple devices. We present the implementation of JAX-native sharding in two complemantary projects: the Framework for Idealized Ocean Models (FRIDOM) and the newly developed pyOM3. FRIDOM is a modular Python framework for fluid simulations that currently supports the shallow water equations and the three-dimensional nonhydrostatic Boussinesq equations. pyOM3 is a Python reimplementation of pyOM2 and solves the hydrostatic Boussinesq equations. In both projects, arrays are distributed across multiple GPUs using JAX's built-in sharding infrastructure, enabling a unified programming model for single-device, multi-GPU, and multi-node configurations. Parallel communication is expressed through distributed array operations rather than explicit MPI calls or mpi4jax-based communication layers, which keeps the numerical implementation largely independent of the underlying hardware configuration. Besides reducing implementation complexity, this approach improves portability across HPC systems by avoiding external software layers that often require machine-specific installation and maintenance. We present strong and weak scaling results obtained on the German Climate Computing Center (DKRZ), and demonstrate excellent parallel efficiency across a wide range of problem sizes. Our results demonstrate that JAX-native sharding provides an effective and scalable foundation for both flexible fluid-modeling frameworks and large-scale ocean circulation models, highlighting the potential of modern array-programming paradigms for next-generation geophysical fluid dynamics applications.

T22

WENO reconstruction of Lie derivatives

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WENO reconstruction methods were originally designed for the transport of quantities in flux form, such as tracers. They have recently been extended to the vortex-force term in the vector-invariant formulation of the momentum equation [1, 2]. Here, we show how this can be extended further to other terms: namely, the gradient of the kinetic energy term and the vertical transport of horizontal momentum in hydrostatic primitive equations (HPE) models, as well as to the full three-dimensional transport of momentum in non-hydrostatic models. The key idea is to regard the quantities being transported as differential k-forms. The transport of a k-form is performed using the Lie derivative, which is conveniently expressed as a combination of the exterior derivative and the interior product. The exterior product ensures the mimetic structure of the discretization, while the interior product is where upwinding and WENO reconstruction can be inserted. The result is a consistent discretization of any quantity using WENO reconstruction. We demonstrate how well this approach performs on classical benchmarks. Incidentally, the framework also reveals a new discretization for the horizontal transport of horizontal momentum in HPE models.

[1] G. Roullet, T. Gaillard, JAMES, **14.2**, e2021MS002663 (2022).
[2] S. Silvestri, G. Wagner, J.-M. Campin et al., JAMES, **16.7**, e2023MS004130 (2024).

T23

The Role of Numerical Mixing in AMOC Simulations

Numerical and parameterized mixing remain important factors in simulations of the Atlantic Meridional Overturning Circulation. Here, we use FESOM as an example to investigate how the simulated overturning is affected by model resolution, including both horizontal and vertical discretization, as well as by the choice of mixing parameterizations such as Redi diffusion. By comparing a set of model configurations, we assess how numerical and parameterized mixing influence the structure and strength of the simulated AMOC, with particular attention to the subpolar North Atlantic. Although the analysis is performed with FESOM, the underlying issues are not model-specific and are relevant for the interpretation of AMOC simulations across ocean and climate models. Our results highlight the need for systematic diagnostics of numerical and parameterized mixing when assessing AMOC behavior and comparing simulations across model configurations.

T24

Chaotic Stirring in Tidally Dominated Shallow Seas:

A Case Study of the Helgoland Trap

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Tidally dominated shallow seas are characterized by significant nonlinear processes. In combination with complex topography, these processes lead to intense tidal mixing and the formation of tidal residual circulation, or rectification currents: persistent net transport induced by tides. The approximation of the mean Lagrangian velocity vector as the sum of the mean Eulerian velocity vector and Stokes drift can become inaccurate when strong horizontal velocity shear occurs over the area of particle excursion during a single tidal cycle. Under such conditions, the Eulerian–Lagrangian transformation based on a Taylor-series expansion requires consideration of higher-order spatial derivatives of the velocity components beyond first order, and chaotic stirring may arise in the Lagrangian residual flow. An analysis of a tidal model of the North Sea reveals Lagrangian chaos in the trajectories of water parcels around Helgoland and in back-barrier environments. In this work, particular attention is given to the trapping system around Helgoland associated with chaotic stirring and characterized by the presence of nearby several elliptic and hyperbolic points. This trapping system has direct implications for local biogeochemistry and ecosystem dynamics. We begin with a simulation driven only by tidal forcing, provide a detailed description of the resulting dynamics, and propose a methodology for investigating chaotic regimes. We then progressively analyse how this circulation is modified by the addition of realistic forcing.

T25

On the Haline Contribution to Conservative Temperature and Its Implications for Numerical Ocean Models

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Since the adoption of TEOS-10 as the international thermodynamic standard for seawater, Conservative Temperature has increasingly been used in place of potential temperature in oceanographic analyses and numerical ocean models because of its improved conservativeness. In practice, however, this transition has often been implemented with only minimal algorithmic changes, particularly in the treatment of surface boundary conditions and mixing parameterisations.

In this contribution, I argue that although Conservative Temperature is more conservative than potential temperature, part of its conservative content is haline in origin, a feature that has so far received little attention. This has several important consequences for numerical ocean modelling. First, the haline contribution is subject to a non-zero surface flux driven by freshwater exchanges. We show that this surface term is comparable in magnitude to the non-conservative production of potential temperature. As a result, the expected accuracy advantage of Conservative Temperature can only be realised if its freshwater-flux contribution is explicitly included, which is not yet standard practice.

Second, Conservative Temperature does not separate thermal and haline effects as cleanly as potential temperature. This introduces uncertainty in the specification of initial conditions when Conservative Temperature is estimated from in-situ temperature, with the result depending on the salinity variable employed (for example, Reference Composition Salinity or Absolute Salinity). Third, mixing parameterisations that account for the differential mixing of heat and salt are more naturally and physically formulated in terms of potential temperature than Conservative Temperature.

These results show that the two desirable properties of a temperature variable—maximal conservativeness and maximal separation of thermal and haline effects—are not fully compatible. Although Conservative Temperature is more conservative, potential temperature provides a clearer separation between thermal and haline influences. This suggests that the variable used to diagnose heat transport in ocean models need not be the same as the variable used to define temperature, and highlights the importance of distinguishing carefully between heat and temperature.

T26

Numerical Assessment of a Stochastic Large–Scale Hydrostatic Primitive Equations Model

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Planetary flows are shaped by interactions at scales much smaller than the flows themselves, with mesoscale and sub–mesoscale eddies playing key roles in mixing, particle transport and tracer dispersion. To reproduce these effects, we introduce a stochastic formulation of the primitive equations within the Location Uncertainty (LU) framework [1]. Derived from conservation principles via a stochastic Reynolds transport theorem, this approach decomposes velocity into a smooth–in–time large–scale component and a random–in–time field representing the effects of unresolved scales. Simulations have been performed with the community ocean model NEMO. To model the velocity noise term, we explore data-driven methods based on a variety of classical decomposition methods (such as Dynamic Mode Decomposition), statistics-driven approaches (through long term statistics of relevant observed or simulated fields) and model-driven methods (where limited data is involved, aiming at higher resolution models) [2, 3]. We have extended this approach to hybrid model–and data–driven constraints. Simulations in an idealised double-gyre configuration show that the LU framework enhances gyre flow predictions, improving mixing, jet structure, and tracer transport while revealing the interplay between small– and large–scale dynamics [3]. We present now results from the more realistic global ORCA 1° configuration and regional Mediterranean 1/12° configuration, that have been recently developed and that show the viability of the inclusion of stochastic modeling in more than idealized test case and its beneficial contribution.

[1] Mémin, E.: Fluid flow dynamics under location uncertainty. Geophysical & Astrophysical Fluid Dynamics. https://doi.org/10.1080/03091929.2013.836190, (2014).

[2] Li, L., Mémin, E., Tissot, G.: Stochastic parameterization with Dynamic Mode Decomposition. Stochastic transport in upper ocean dynamics. Springer International Publishing. https://doi.org/10.1007/978-3-031-18988-3_11, (2022).

[3] Tucciarone, F. L., Li, L., Mémin, E., Chandramouli, P.: Derivation and numerical assessment of a stochastic large–scale hydrostatic primitive equations model. Journal of Advances in Modeling Earth Systems. https://doi.org/10.1029/2024MS004783 (2025).

T27

A Deep-Learning-Assisted, State-Dependent Parameterization of Remote Internal-Tide-Driven Mixing

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Internal tidal dissipation provides approximately half of the mechanical energy required for the diapycnal mixing to sustain the global meridional overturning circulation. A parameterization of the Internal tidal mixing is therefore critical for both ocean and climate models. The redistribution of internal-tide energy is strongly modulated by the background eddying circulation as well as the exchange of energy with subtidal meso- and submeso-scale eddies. To reflect the influence of these processes on internal tide dissipation, we develop a state-dependent hybrid parameterization of remote internal tidal mixing with machine learning support. We first build a global internal-tide energy dataset using a global simulation dataset LLC4320, which resolves internal waves and submesoscale dynamics. A U-Net deep-learning model is then trained that ingests climate-scale-resolution circulation fields to predict the horizontal distribution of internal-tide energy and dissipation. These predictions constitute a central component of an improved remote internal tide mixing parameterization, which is responsive to circulation variability and incorporates the bidirectional feedback between the internal tide and subtidal circulation.

T28

Abstract for 4th COMMODORE Workshop on Advancing Ocean Modeling: Bridging Theory, Computation, Scales, and Applications

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Ocean circulations are strongly constrained by rotation and stratification, making potential vorticity (PV) a key dynamical property. Specifically, PV is conserved following water parcels in the absence of diabatic forcing and friction—a desirable feature for isopycnal ocean models. Here, we devise a finite-volume discretization for PV fluxes in the vector-invariant formulation of Modular Ocean Model (MOM6) dynamical core. The scheme adopts a seventh-order weighted essentially non-oscillatory (WENO) reconstruction of PV on the Arakawa C-grid while ensuring PV conservation in isopycnal coordinate. To prevent PV singularities arising from vanishing layer thickness, we propose a thickness weighting for the PV reconstruction. The scheme is evaluated against existing energy- and/or enstrophy-conserving (EEN) schemes in both idealized and realistic eddy-permitting (e.g., $1/4°$) configurations. Compared with the EEN scheme, the WENO scheme substantially reduces dispersive errors and yields a weak potential enstrophy dissipation near grid scales, permitting stable time integration without explicit horizontal viscosity. In idealized wind-driven circulation simulations, the WENO scheme yields stronger inverse energy cascade and elevated eddy kinetic energy, with more realistic ocean energetics in eddy-permitting simulations for which the energy input by surface wind stress is dissipated through bottom drag. In the $1/4°$ global ocean simulation, it produces more realistic pathways of western boundary currents, such as Kuroshio and Gulf Stream, thereby reducing their associated sea surface temperature biases. These results suggest that the WENO PV advection scheme developed here is promising for improving the simulation of ocean eddies and large-scale circulations in climate models.