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

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P01

Sea-ice embedment in NEMO using Brinkman Volume Penalisation.

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The sea-ice component of the IPSL model (NEMO-SI3) currently represents mobile ice (sea-ice and icebergs) as levitating above the ocean. While exchanges between the two phases ensure the conservation of heat, freshwater, and salt, this approach introduces non-physical dynamic responses associated with freshwater fluxes. Recent advances using Brinkman Volume Penalisation (BVP) techniques in ocean models [1,2] have shown promising results for the modeling community. Here, we extend the use of BVP in NEMO-SI3 to embed sea ice into ocean layers, by introducing a time-varying solid fraction (here, multi-category ice) within fluid cells. Compared to existing ice embedding techniques, such as the surface loading and vertical levels squeezing method [3], this framework naturally accommodates multi-category ice, as well as sea-ice and iceberg grounding. We developed idealized embedded-ice test cases, demonstrating the advantages of BVP embedding, notably the handling of ice advection and water mass displacement as well as three-dimensional distribution of thermodynamic fluxes along the ice draft. We compared the results with the Campin et al. (2008) formulation and with the traditional levitating-ice approach. Finally, we conducted experiments with the penalized ice implementation in a 1D-thermodynamic test case and in a global forced ocean-ice configuration.

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P02

Improved Antarctic Shelf Water Mass Representation in a Global Ocean–Sea Ice Model

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The UK Global Ocean and Sea Ice configuration (GOSI), developed under the UK's Joint Marine Modelling Programme (Guiavarc'h et al., 2025), underpins a wide range of applications, including climate and Earth system modelling. Recent development efforts have focussed on improving Antarctic Circumpolar Current transport and associated sea surface temperature bias in the Southern Ocean (Storkey et al, 2025). However, persistent temperature and salinity biases on Antarctic continental shelves remain a challenge (Hutchinson, 2023).
This study presents ongoing work using the 1/4° eddy-permitting configuration to enhance the representation of water mass properties on the shelves and dense water overflows. Key developments include the implementation of localized multi-envelope (ME) terrain-following vertical coordinates (Bruciaferri et al., 2024) around the Antarctic shelves. These improvements aim to better capture the cascading of dense water masses and formation of Antarctic Bottom Water.
Future plans include opening ice cavities and extending ME coordinates under the ice shelves to improve their representation. These enhancements are essential for advancing the realism of climate and earth system models and improving climate projections.

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P03

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Abstract Title: Enhancing the African Ocean Biodiversity Atlas through Advanced Ocean Modeling: Bridging Theory, Computation, and Ecosystem Applications.

Abstract: This presentation explores the application of advanced ocean modeling techniques to enhance the African Ocean Biodiversity Atlas, a critical component of regional marine conservation efforts. By integrating state-of-the-art computational models with ecological and oceanographic data, we aim to improve understanding of biodiversity distribution, habitat dynamics, and ecosystem interactions along Africa's coastlines. The modeling framework bridges multiple scales from local habitats to regional ocean systems enabling more accurate predictions of species migrations, habitat changes, and the impacts of climate variability. These insights support the development of targeted conservation strategies, such as Marine Protected Areas (MPAs), and facilitate data-driven decision-making for sustainable management of marine resources. Moreover, the models serve as vital tools for simulating future scenarios under climate change, aiding in resilience planning and ecosystem restoration. This approach aligns with the goals of the UN Ocean Decade, promoting innovative, science-based solutions to safeguard Africa's rich marine biodiversity. Ultimately, advanced ocean modeling provides a powerful means to bridge scientific theory and practical applications, fostering a more comprehensive and dynamic African Ocean Biodiversity Atlas for sustainable ocean stewardship.

Keywords: Biodiversity, Africa, UN Ocean Decade

Link: https://oceandecade.org/actions/african-ocean-biodiversity-atlas/.

P04

Coastal-trapped waves along the western European shelf

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Coastal-trapped waves (CTWs) are an important source of sub-inertial variability along continental shelf margins. They have been identified as important mediators of coastal sea level along and across the European shelf and of shelf-ocean exchange. Generally, the attention regarding CTWs has been restricted to explaining the high correlation of local sea level with remote sea levels and winds [1, 2]. Despite several local studies, the CTW spectrum, cross-shelf modal structure, and energy budget along the European shelf have not been properly quantified along the entire wave path.

The primary objective of this study is to characterize CTWs along the western European shelf in a regional CMEMS reanalysis of the Iberian-Biscay-Ireland region. Propagating northward along the eastern Atlantic, CTWs are transformed by changes in bathymetry, stratification, Coriolis, friction, and mean flow, affecting their phase velocity and modal structure. We found wave properties through an alongshelf correlation analysis and cross-shelf empirical orthogonal function analysis. We compared these properties with the theoretical dispersion relation and modal structures to validate the presence and propagation of CTWs along the western European shelf.

The CTW spectrum and the associated modal structures and dispersion relations enable research into the (de-)energization of CTWs. Reconstructing this energy budget is essential to distinguish the forcing mechanisms that contribute to CTW generation. Using the characterized CTW spectrum, we set up simplified numerical experiments to identify the key dynamics to which CTWs of varying frequency are subject along the European shelf. Finding these dynamics and their frequency dependence will improve the understanding of how CTWs shape sea level along Europe.

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P05

Strengthening BMKG Capacity in Ocean–Atmosphere Interaction for Drought and Rainfall Forecasting in Eastern Indonesia

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Eastern Indonesia, particularly East Nusa Tenggara (NTT), frequently experiences drought, irregular rainfall, and climate extremes that are strongly influenced by surrounding ocean conditions [1]. For BMKG, understanding these processes is important because forecast performance in this region often changes from one season to another and can become difficult to interpret during periods of persistent dry conditions [2]. The 4th COMMODORE Workshop is relevant because it focuses on the role of ocean processes, ocean–atmosphere interaction, and numerical modeling in climate prediction. The workshop will also provide insight into how ocean conditions, uncertainty, and ocean–atmosphere coupling are represented in numerical models used for climate prediction. Participation in this activity will strengthen my capacity to better understand how surrounding ocean conditions influence rainfall variability and drought over eastern Indonesia, as well as why forecast uncertainty and forecast failure can occur. The knowledge gained from this workshop will support my work in subseasonal climate analysis and improve the interpretation of BMKG rainfall forecasts, particularly for drought and extreme rainfall monitoring in NTT and surrounding regions. After the activity, the experience and materials obtained will be shared internally within BMKG to support climate services and future forecasting activities.

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P06

Global biogeochemical modelling with ICON-O-FABM/ECOSMO E2E using locally refined computational meshes

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ICON-O [1] is the ocean component of the ICON Earth System Model framework, newly developed by the German Weather Service and the Max Planck Institute for Meteorology, which is used for climate simulations as well as weather forecasts [2].
ICON-O uses a global triangular grid that can be locally refined using software developed in-house [3,4], allowing, for example, straits or specific coastal regions to be modelled at high resolution while saving computational time. By implementing the FABM framework [5] in ICON-O, the model is opened up to a wide range of marine biogeochemistry modules.
In an initial feasibility study, we are thus coupling the ECOSMO E2E [6] ecosystem model with ICON-O and attempting to resolve oceanic biogeochemistry on a global scale as well as within the Baltic Sea itself in a single simulation.

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P07

Parameterising eddy-driven transport of Circumpolar Deep Water across Antarctic continental slopes

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The onshore transport of warm Circumpolar Deep Water (CDW) plays a crucial role in shaping Antarctic shelf water properties and driving ice shelf melting. The highest net onshore transport of CDW aligns with regions of dense water export, such as the Cape Darnley region in East Antarctica -— one of the primary sources of Antarctic Bottom Water. In an eddy-resolving ocean model, wintertime downslope flows of dense water can generate eddy-driven transport of warm, modified CDW across the shelf break onto the continental shelf. However, at the coarse resolutions typical of climate models, this warm water transport is absent and must be parameterized. The Gent and McWilliams/Redi (GM/Redi) scheme, a standard parameterization for mesoscale eddies, improves simulated hydrographic fields and restores warm water transport across the shelf break. However, when high constant GM/Redi coefficients typical of coarse resolution models are used, the on-shelf transport of warm water is overestimated. This overestimation occurs because the GM/Redi scheme does not account for the suppressive effect of sloping bottom topography on eddy-driven transport. To address this, we implement a topography-aware GM/Redi scheme that reduces parameterization coefficients over steep continental slopes, thereby simulating the eddy-suppressive influence of bottom topography. This improved scheme outperforms the traditional GM/Redi approach by better representing both mean hydrographic fields and cross-slope warm water transport.

P08

Effects of Horizontal Discretization on Triangular and Hexagonal Grids on Linear Baroclinic and Symmetric Instabilities

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As global ocean general circulation models are run at eddy-permitting resolutions, reproducing accurate growth rates of baroclinic instabilities is a major concern when choosing a discretization of the equations of motion. From this viewpoint, we analyze discretizations on triangular and hexagonal grids with different types of variable staggering used in several ocean circulation models. By extending the linear baroclinic instability analysis in the Eady configuration to discretizations on more complex grids, several numerical subtleties are revealed. In comparison to discretizations on quadrilateral grids, the analyzed discretizations are less robust against unstable spurious modes, partly created by the mesh geometry. Some of the subtleties arise because spurious modes on staggered triangular and hexagonal grids do not adhere to Galilean invariance. As a consequence, their growth rates demonstrate a dependence on the alignment between the background flow and the grid, as well as the strength of a uniform background flow. The interactions with spurious modes become more significant on the axis of symmetric instabilities where the physical and spurious branches of instability are more difficult to separate in wavenumber space. Our analysis shows that in most cases moderate biharmonic viscosity and diffusion suppress spurious branches. However, one needs to carefully calibrate the viscosity and diffusivity parameters for each of the considered discretizations in order to achieve this.

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P09

GPU Implementation of Implicit Filtering for Ocean Spectra

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Sequential filtering (coarse-graining) offers a robust alternative to Fourier analysis for estimating ocean energy spectra and cascades. While implicit sequential filtering enables direct spectral extraction on native unstructured meshes, avoiding interpolation errors. Its application to high-resolution global models poses significant computational and numerical challenges.

This work complements the theoretical framework by focusing on technical implementation and algorithmic optimization. We present a highly scalable, Python-based framework using a two-phase strategy. The initialization phase leverages JAX for Just-In-Time (JIT) compilation, enabling the rapid assembly of discrete Laplacian operators directly from complex meshes. The solving phase utilizes GPU acceleration via CuPy, employing optimized sparse matrix operations to efficiently handle systems with tens of millions of degrees of freedom.

Matrix conditioning remains a critical bottleneck. The condition number of the system matrix degrades rapidly with increasing filter scales and higher filter orders, causing severe Conjugate Gradient (CG) solver stagnation at large scales. To mitigate this, we solve the system using a residual (perturbation) formulation, which significantly improves stability. Furthermore, we demonstrate that employing a high-pass filter formulation accurately resolves steep spectral slopes using only the well-conditioned first-order Laplacian, bypassing the numerical pitfalls associated with higher-order filters.

We demonstrate practical efficiency using direct output from a 1-km unstructured FESOM2 simulation of the Arctic Ocean (exceeding 11 million surface nodes). Our optimizations reduce computation time to merely seconds per filter scale on a single GPU, delivering a powerful, regridding-free tool for routine spectral diagnostics in exascale ocean modeling.

P10

Diagnosing Numerical Mixing in the Global Finite-volumE Sea-Ice Ocean Model (FESOM2) Using Discrete Variance Decay

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Tracer advection schemes in ocean general circulation models not only transport water masses but can also introduce artificial mixing. Such mixing can be intentional or spurious. The intentional component comprises parameterized isopycnal mixing, representing unresolved eddy effects on coarse grids, and physical turbulent mixing related to shear and buoyancy processes. In contrast, unintended numerical mixing arises from issues such as misalignment between isopycnal surfaces and geopotential layers, artificial isopycnal diffusion, or cabbeling effects (Banerjee et al., 2023). While some numerical mixing is beneficial for suppressing grid-scale noise, much of it remains uncontrolled and can distort simulated water mass properties.

To quantify such effects in the global Finite-Volume Sea-Ice Ocean Model version 2 (FESOM2), we employ discrete variance decay (DVD) diagnostics and examine two formulations. The first, following Klingbeil et al. (2014), estimates variance decay from fluxes of second moments derived via volume decompositions within grid cells. The second, proposed by Banerjee et al. (2023), reformulates DVD in terms of first-moment fluxes by shifting the reference point from cell centres to cell faces.

Applying both methods to FESOM2, we find that the Banerjee et al. (2023) formulation provides broader diagnostic capabilities. It enables not only estimation of the local DVD rate but also separation into distinct contributions from different mixing processes. This allows a direct comparison of the relative roles of physical mixing and spurious numerical effects, offering new insights into how tracer variance decays in ocean circulation models.

P11

Approximate Solutions of Time-Fractional Swift Hohenberg Equation Using Quintic Hyperbolic B-Spline Functions

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Fractional calculus, an extension of traditional integral calculus, boasts a rich history spanning three centuries, mirroring the longevity of its classical counterpart. In contemporary times, it continues to evolve and find novel applications in various fields. It has been opening its wings larger and larger to cover the real world applications in science and engineering. Fractional calculus has emerged as a powerful tool for enhancing the precision of modeling real-world physical phenomena. It enables a more accurate translation of physical problems, offering a fresh perspective on their solutions. Fractional derivatives, in particular, prove invaluable for describing the hereditary characteristics of variables and materials. This distinct advantage sets them apart from conventional integral-order models, which often overlook such effects. While various analytical approaches have been employed to tackle fractional order boundary value problems, their complexity in terms of time and computation sometimes necessitates the exploration of dependable numerical techniques. Consequently, a substantial array of numerical methods has been developed to investigate these type of problems. This endeavor aims to pioneer a novel and efficient numerical approach for approximating solutions to a specific class of fourth-order time fractional Swift-Hohenberg equations, employing quintic hyperbolic B-spline functions. The time derivative of non-integral order has been defined in the Caputo's sense. There are different formulas for fractional derivatives but Caputo's formula attracts comparatively more attention of researchers due to its useful properties. The quintic hyperbolic basis B-spline functions have been empolyed for space discretization, while forward finite difference scheme has been applied for time discretization. The method has been tested on some problems subject to end conditions arising in different physical applications. The numerical results have been compared with the known exact solutions. All the numerical computations have been performed using Mathematica 12.

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P12

A low-storage Runge–Kutta framework for nonlinear free-surface ocean models

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We present a comprehensive low-storage Runge–Kutta framework for nonlinear free-surface ocean models that is stable across the coupled barotropic–baroclinic modes and conserves tracers up to machine precision. We present two different formulations that depend on the time discretization of the coupled barotropic mode: (i) an implicit free surface discretization and (ii) a split–explicit free surface discretization. Our stability analysis reveals that the split–explicit implementation requires advecting the tracers with an averaged barotropic transport velocity, not only for tracer conservation reasons, but also to maintain baroclinic stability. By adapting exact variance budget diagnostics to multi-stage integrators, we are able to directly quantify the contribution of temporal discretization to numerical mixing. Across three idealized test cases spanning the linear to fully turbulent regimes, the three-stage Runge–Kutta formulation produces up to 50% lower numerical mixing than the Adams–Bashforth time discretization with the same spatial discretization. The framework is implemented in Oceananigans, providing the ocean modeling community with a practical path toward more accurate ocean simulations.

P13

Downscaled climate projections for the Arabian Sea

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Global warming is accelerating sea level rise, storm surges, and marine heatwaves, with severe consequences for marine ecosystems and societies. The Arabian Sea is a hotspot of vulnerability, where sea level rise exceeds the global average and coral reefs, mangroves, and deltas face inundation. Coastal cities, ports, and offshore energy infrastructure are also at risk, threatening millions of people and critical assets. Developing reliable projections for the Arabian Sea is therefore urgent. CMIP6 climate projections are widely used to assess future changes and guide decision-making, but their coarse resolution (0.5°~1°) and omission of tides and river inputs limit their accuracy in marginal seas. To address these limitations, this study applies a high-resolution (0.04°) configuration of the MIT General Circulation Model (MITgcm) to dynamically downscale outputs from selected CMIP6 models. The regional model incorporates detailed bathymetry, tidal forcing, and river inflows, enabling more realistic simulations of ocean processes and improving projection reliability. An ensemble of downscaled simulations was constructed using seven CMIP6 models selected for spatial accuracy, variability, and statistical independence. The model domain spans 32°E~77°E and 3°S~30.5°N, with 64 vertical layers. Bias corrections were applied to atmospheric forcing and ocean boundary conditions using ERA5 and GLORYS12V1 reanalysis. Eight major rivers and eight tidal constituents were included. Simulations cover 1980~2014 for the historical period and 2015~2100 for four SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). Validation demonstrates that the downscaled simulations significantly improve the representation of sea level, temperature, mesoscale eddies, and regional circulation compared with GCMs. Results project considerable future sea level rise, stronger stratification, and circulation changes in the Red Sea and Arabian Gulf. Ongoing work focuses on marine heatwaves, eddy variability, and upwelling, with the analysis being extended to the entire Arabian Sea. By integrating global projections with regional modeling, this study provides improved downscaled projections and essential insights for scientists, policymakers, and planners addressing climate risks in the Arabian Seas.