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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

COMPARATIVE EVALUATION OF DEEP-LEARNING ARCHITECTURES FOR SATELLITE-DERIVED BATHYMETRY FROM SENTINEL-2 IMAGERY: A CASE STUDY OVER ANZA BAY, AGADIR COAST, MOROCCO

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Accurate bathymetric data are a prerequisite for coastal zone management, navigation safety, and the monitoring of sea-level-driven shoreline change. Conventional echo-sounding surveys are costly and spatially limited, making satellite-derived bathymetry (SDB) an increasingly attractive alternative for shallow, optically clear waters [1, 2]. Along the African Atlantic margin — where hydrographic chart coverage is fragmentary and coastal vulnerability to climate-driven hazards is high — reproducible SDB workflows are urgently needed. Despite recent progress in empirical and physics-based methods [2], a systematic comparison of modern deep-learning (DL) architectures on this under-studied coast remains absent from the literature [5].

This study develops and intercompares five DL architectures for SDB over the ANZA coastal zone in Agadir Bay (Atlantic Moroccan coast): (i) a baseline two-dimensional convolutional network (SDB-CNN) [1]; (ii) a physics-informed CNN (PI-CNN) in which the loss function is regularised by a Beer–Lambert radiative-transfer residual [3]; (iii) a hybrid convolutional–bidirectional recurrent model (CNN–BiLSTM) for exploiting spectral-spatial sequential dependencies; (iv) a fully convolutional encoder–decoder network (FCNN); and (v) a multi-task Seabed-Net that simultaneously regresses water depth and classifies sea-floor substrate [4]. Six Sentinel-2 Level-2A spectral bands (490, 560, 665, 705, 842 and 1610 nm) are pre-processed through atmospheric correction, residual sun-glint suppression, and water-mask generation, and reorganised into three-dimensional spatial–spectral patches at the native 10 m grid [2, 6]. A co-registered airborne LiDAR depth raster spanning −30 to +5 m serves as ground truth for all architectures.

All five architectures share an identical training/validation/test partition, optimisation protocol, and evaluation metrics, ensuring a fair comparison [5]. On the held-out test set, the SDB-CNN achieves the most accurate global retrieval (RMSE = 3.13 m, MAE = 1.99 m, $R^2 = 0.942$), closely followed by Seabed-Net (RMSE = 3.16 m, $R^2 = 0.941$) [4], PI-CNN (RMSE = 3.24 m, $R^2 = 0.938$) [3], and CNN–BiLSTM (RMSE = 3.32 m, $R^2 = 0.935$); the FCNN trails substantially (RMSE = 5.34 m, $R^2 = 0.831$). A depth-stratified error analysis reveals that the dominant source of uncertainty lies below −20 m for all architectures, whereas the PI-CNN provides the most depth-uniform performance, consistent with findings reported for physics-constrained inversion approaches [3, 6].

These results demonstrate that the baseline SDB-CNN is the most accurate and parsimonious predictor for the ANZA bay under operational conditions, while PI-CNN and Seabed-Net are preferable when depth-stratified reliability and joint substrate mapping are required [1, 4]. The fully documented pre-processing chain, radiative-transfer formulation, and reproducible benchmark protocol constitute a transferable blueprint for SDB mapping along African Atlantic coastlines and other data-scarce margins where traditional hydrographic surveys are prohibitively expensive.

Keywords: Satellite-derived bathymetry; Sentinel-2; convolutional neural network; physics-informed machine learning; multi-task learning; CNN–BiLSTM; ANZA Bay; African Atlantic coast; coastal oceanography.

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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

Extending z-tilde in NEMO: Towards a Stable and Efficient Vertical ALE Coordinate

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General circulation models such as the **N**ucleus for **E**uropean **M**odelling of the **O**cean (NEMO) solve the primitive equations on a global mesh [1]. Because the ocean is strongly stratified, vertical physical diffusion is generally weak. However, discretization errors in the advection scheme introduce nonphysical numerical diffusion that can greatly exceed the intended parametrized physical diffusion.

Vertical coordinate systems may be time-independent (Eulerian, e.g. z- or σ-coordinates), flow-following (Lagrangian), or in between (**A**rbitrary **L**agrangian-**E**ulerian, ALE, e.g. $z^\star$ or isopycnal coordinates). NEMO v5 currently supports the quasi-Eulerian $z^\star$ and $\sigma^\star$ coordinates. Lagrangian coordinates suppress diapycnal velocities and the associated numerical diffusion, but at the cost of increased computational complexity and the risk of mesh distortion.

The z-tilde coordinate extends $z^\star$ by treating the high-frequency component of the baroclinic flow (e.g. internal gravity waves) in a Lagrangian manner, while retaining an Eulerian treatment for the steady background flow [2]. This prevents mesh distortion by construction and may also relax the vertical advection CFL constraint, typically the most restrictive on the time step [3]. Indeed, previous studies have demonstrated that z-tilde is a physically beneficial ALE coordinate, but at a non-negligible computational cost [4, 5]. Its implementation requires three additional prognostic equations: namely a time filter, a barotropic equation for the sea surface height (SSH) similar to $z^\star$, and a time-filtered baroclinic component. These may constrain the time step, while the associated 4D arrays place additional pressure on the already memory-bound NEMO code [6]. Moreover, z-tilde was originally formulated within the Robert-Asselin filtered leapfrog environment (LFRA) of NEMO v4, and porting it to the third-order Runge-Kutta (RK3) time stepping used in NEMO v5 and beyond is non-trivial.

In the broader context of introducing an ALE coordinate into NEMO, we propose several numerical developments: (1) an implicit and unconditionally stable treatment of the spatially independent time filter, (2) a split time step for the barotropic and baroclinic components operating on different time scales, and (3) a dedicated treatment of the frequency-filtered lateral divergence and SSH source terms. For a pure source-term right-hand side (RHS), RK3 degrades to second order since the RHS does not feed back into the intermediate stages and effectively becomes a midpoint quadrature rule. We therefore consider Gauss-Legendre quadrature for source terms to exploit the three RHS evaluation points more effectively.

On the computational side, we propose (4) a sparse representation of the 4D vertical scale-factor arrays with on-the-fly interpolation of missing values, thereby trading memory access for additional computation. Unlike grid coarsening, this approach still uses all values at the target resolution, although not all are stored explicitly. Its effectiveness depends on the smoothness of the vertical scale factor, which in turn is governed by the mesh-restoring terms, originally used to prevent mesh distortion. Together, these developments aim to provide a stable and efficient ALE framework in NEMO that reduces spurious numerical diffusion.

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P06

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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P07

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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P08

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.

P09

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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P10

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.

P11

Advancing Storm Surge Modelling in Southern Java Coast, Indonesia through Wave–Current Coupling

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The Indonesian Maritime Continent (IMC) exhibits complex multi-scale ocean dynamics driven by interactions among tides, waves, and atmospheric forcing. This study develops a high-resolution coupled modeling framework integrating ADCIRC-SWAN and WaveWatch III. We implemented a hybrid data assimilation scheme combining four-dimensional variational (4D-Var) and Ensemble Kalman Filter (EnKF) within a unified state-space framework. The control vector includes sea surface elevation (η), depth-averaged currents (u,v), and wave spectral energy density (E). The 4D-Var minimizes a function over a 12-hour assimilation window, while EnKF employs a 5-member ensemble to represent flow-dependent uncertainties.

Multi-source observations include Sentinel-3A altimetry (RMSE reduced from 0.18 m to 0.12 m), Sentinel-1B SAR wave data, and in-situ tide gauge measurements. The coupled system integrates shallow water equations with the spectral wave balance equation using radiation stress gradients and wave–current interaction terms. The computational domain uses an unstructured finite-element grid with ~150 m coastal resolution and ~3 km offshore resolution. Tidal forcing uses dominant constituents (M2, S2, and O1) with amplitudes on the order of 0.3–1.0 m.

Forecast Sensitivity to Observation Impact (FSOI) indicates that satellite altimetry and in-situ data contributes 20–30% of forecast error reduction. Model validation shows a significant improvement in significant wave height RMSE, decreasing from 0.40 m to 0.25 m. Application to the April 6–10, 2017 Tropical Cyclone Ernie event indicates sea water anomalies of 15–25 cm along southern Java due to wind-driven surge and wave–current interaction.

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P12

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.

P13

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.

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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.