High Performance Computing
Training and Research for Earth Sciences

BOOK OF ABSTRACTS

6th Annual HPC -TRES Workshop
1 December 2025 - Bologna (Italy)

OGS National Institute of Oceanography and Applied Geophysics

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CINECA

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Introduction

The HPC-TRES program

The "High Performance Computing Training and Research for Earth Sciences" (HPC-TRES) is a national initiative promoted by OGS and CINECA aimed to implement a training program focused on exploiting the High Performance Computing and Data Analytics (HPC and HPDA) for applications in Earth Sciences. HPC-TRES is co-sponsored by the Minister of University and Research (MUR) under the action of the Italian Research Infrastructure **PRACE-Italy**, the MUR contribution for the Italian participation in the activities related to the European research infrastructure PRACE – The Partnership for Advanced Computing in Europe.

The major objectives of the program are capacity building, enhancement of human resources, and advanced training in the fields of Earth System modelling (atmosphere, hydrosphere, lithosphere and biosphere) and numerical models, the latter considered as a strategic cross-cutting element for modelling activities. These objectives are pursued by exploiting the national and European HPC infrastructures and services, in the framework of PRACE, EuroHPC and PRACE-Italy, by developing and optimizing algorithms, models and workflows, also in a digital twin approach, by improving the access, management and processing of "Earth Sciences Big Data", also using Artificial Intelligence (AI) tools, and by improving the graphical visualization techniques for multidisciplinary applications in the Earth Sciences. All these activities are also in line with the European actions in the frame of the Destination Earth flagship initiative and of the sustainable Blue Economy strategy, fully embedded into the European Green Deal and the Recovery Plan for Europe.

The HPC-TRES program establishes, sponsors and oversees **training and research awards** (in the form of scholarships grants as Post-Docs, PhDs, post-graduate masters) that support the research lines described in the scientific plan of the HPC-TRES program. Many Italian research groups and institutions involved in HPC applications for Earth Sciences (INGV-Pisa, CNR/ISAC, CNR/IGG, CMCC, ICTP-ESP, MOX-Politecnico di Milano, ENEA-SSPT, INGV-SST, INGV-CNT, Univ. Bicocca, CRS4, EURAC, ARPA-FVG, Fondazione CIMA, Univ. Genova, Univ. Trieste, Consorzio LAMMA, Univ. Trento, INAF-OATs) have already endorsed the HPC-TRES initiative, contributing to the HPC-TRES scientific plan.

In 2021, with the agreement between OGS, Cineca, Consiglio Nazionale delle Ricerche (CNR), Istituto Nazionale di Geofisica e Vulcanologia (INGV), Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Politecnico di Torino and Abdus Salam International Centre for Theoretical Physics (ICTP), the programme was structured into a Joint Research Unit (HPC-TRES JRU).

The 6th HPC-TRES workshop (1st December 2025, Bologna)

The 6th Workshop of HPC-TRES was organized by OGS in Bologna, at the Congress Centre of the Research Area of the National Research Council (CNR). The event was preceded by the meeting of the HPC-TRES steering committee, held during the morning of the same day. A social dinner at the "Ristorante Diana" on the evening of 1st December reunited all the participants, allowing fellows and researchers to lively interact and discuss.

The workshop aimed at sharing a common discussion with many of the research groups that contribute to the HPC-TRES scientific plan, presenting the status and the current outcomes of the research activities, highlighting the future perspectives of the national HPC and AI infrastructure and offering an opportunity of cross-discipline contamination, supported by the common HPC background which characterizes the different scientific approaches adopted by the research groups involved in the program.

25 attendees participated in the workshop (2 online): 9 HPC-TRES grantees (former or present) gave their contributions. They presented the main results of their research work, highlighting the scientific and technological challenges they have coped with, and the role of HPC in Earth system science, combining infrastructures, modelling, and applications. Key topics included advanced computing for natural hazard simulations, data-driven and multidisciplinary approaches, and integration of AI and geosciences. The event also emphasizes training and contributions from early-career researchers, fostering innovation and capacity building.

The workshop was introduced with two keynote speeches. The first was from **Eric Pascolo** (HPC Consultant for industrial applications at Cineca), who discussed on "Funding and Infrastructure for Innovation: AI Factory, HPC, and European Opportunities for Academia", who gave an overview of the current status of HPC infrastructure at Cineca and drew the possibilities for HPC and AI resources access. The second keynote speakers were **Elisa Zuccolo** and **Chiara Scaini** (respectively, senior researcher and senior technologist at OGS), who presented "UrgentShake: Numerical Simulations and HPC for Near Real-Time Seismic Risk Mitigation", an innovative application based on an urgent computing approach oriented to efficiently asses near-real time earthquake damages, developed within the PNRR project TeRABIT (Terabit Network for Research and Academic Big Data in Italy, https://www.terabit-project.it/en/).

This document includes the abstracts of the 2 keynotes and of the 9 talks presented during the event, the list of participants and the JRU members, as well as the abbreviations index and the acknowledgments.
A web page containing the program and all the presentations is available at https://indico.ogs.it/e/hpc-tres_2025.

The five previous workshop Books of Abstracts editions are available on www.zenodo.org (indexed in OpenAIRE).

For further information and enquiries contact hpc-tres@ogs.it.

Funding and Infrastructure for Innovation: AI Factories, HPC, and European Opportunities

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Keywords: High Performance Computing, Artificial Intelligence, EuroHPC, AI Factory, Innovation, SMEs, Research Infrastructure

The rapid adoption of Artificial Intelligence (AI) across science, industry, and public administrations requires access to advanced computing infrastructures, large-scale data resources, and specialized services capable of supporting the full AI lifecycle. In this context, High Performance Computing (HPC) plays a strategic role in enabling the training, testing, and deployment of complex AI models at scale.

This contribution presents the European and national ecosystem supporting AI and HPC innovation, with a specific focus on the EuroHPC Joint Undertaking, the European network of National Competence Centres (EUROCC), and the emerging network of AI Factories co-funded by the European Commission. EUROCC acts as the main entry point for companies, researchers, and public administrations, facilitating access to HPC, AI expertise, training, and innovation services at national level, while ensuring alignment with European strategies.

Within this framework, the IT4LIA AI Factory is introduced as the Italian implementation of the AI Factory model, designed to accelerate AI adoption by providing integrated access to supercomputing, cloud, and data services for enterprises, startups, academia, and public institutions. The initiative builds on the experience and support mechanisms developed within the EUROCC network, strengthening technology transfer and lowering barriers to the use of advanced computing resources.

The underlying computing infrastructure is described, highlighting the role of the Leonardo pre-exascale supercomputer and its AI-optimized LISA partition, complemented by the GAIA cloud platform and the MEGARIDE system. Together, these resources create a computing continuum capable of addressing a wide spectrum of AI workloads, from large-scale model training to data-intensive analytics and AI-enabled services.

In addition, the portfolio of services offered by IT4LIA is outlined, including data-related services, AI development and testing, compliance and trust support, sector-specific vertical solutions, and comprehensive training programs. Through the combined action of EUROCC and the AI Factory, IT4LIA aims to strengthen European competitiveness, foster innovation, and support the adoption of AI technologies by SMEs, academia, and public administrations.

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IT4LIA website : www.it4lia-aifactory.eu

EUROCC Italy website: https://euroccitaly.it

UrgentShake: Numerical Simulations and HPC for Near Real-Time Seismic Risk Mitigation

Zuccolo, E.[1], Scaini, C.[1], Bolzon, G.[1], Sciortino, V.[1], Pitari, F.[2], Rodríguez Muñoz, L.[2], Poggi, V.[1], Salon, S.[1]

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Keyword: physics-based simulations, urgent computing, rapid response to earthquakes

Earthquakes are a major natural hazard, and the rapid evaluation of ground shaking after a moderate-to-strong event is essential to support seismic emergency response. Although modern monitoring networks enable near real-time earthquake detection and magnitude estimation, operational ground-motion assessments mainly rely on empirical approaches that provide fast but simplified results. Physics-based numerical simulations offer a more realistic representation of ground shaking but have traditionally been limited by high computational costs and long runtimes, restricting their use in time-critical contexts.

UrgentShake was developed to address these limitations by exploiting urgent computing paradigms and federated high-performance computing resources. The system is described in detail in Zuccolo et al. (2025). Developed by OGS in collaboration with CINECA within the TeRABIT ecosystem, UrgentShake implements a fully automated workflow that operates without user intervention from earthquake detection to result delivery. As illustrated in Figure 1, real-time seismic alerts trigger a client–server system that connects to a dedicated virtual machine deployed on CINECA's ADA cloud infrastructure, which acts as a continuously available frontend. The virtual machine automatically prepares all required input data and job submission scripts and orchestrates the execution of simulations via secure SSH connections to multiple HPC backends, namely Leonardo, Galileo100, and the ReCAS-Bari INFN computing bubble. The workflow is executed concurrently across the different HPC systems, increasing robustness against queue delays and system-specific bottlenecks. Data management is an integral part of the infrastructure and relies on INFN S3-compatible object storage. At present, it is used primarily for storing input data, while in the future it will be extended to handle intermediate products and final simulation outputs, ensuring scalability, reliability, and secure archiving. Simulation results are automatically transferred back to the virtual machine and made available through a restricted-access Nextcloud web interface, which provides a user-friendly environment for data sharing.

To meet the strict time constraints of emergency response, UrgentShake applies a suite of urgent computing techniques, including workflow automation, scalability testing and optimal core allocation, code parallelization and optimization, precomputed mesh merging, and simultaneous multi-backend execution. The overall workflow follows a tiered execution strategy, delivering progressively refined ground shaking scenarios with release times fully compatible with operational requirements, supporting the different phases of the seismic emergency and enabling timely, informed decision-making for risk mitigation.

UrgentShake is currently in active development to further improve the accuracy of the produced estimates and is undergoing testing in Northeastern Italy, where it is integrated with the SMINO monitoring network managed by OGS (Bragato et al., 2021). Physics-based ground shaking simulations will be used as input to compute damage using an existing rapid damage assessment tool (Poggi et al., 2021). In particular, the produced synthetic seismograms allow the extraction of ground motion intensity measures required for damage evaluation. The main building typologies in the current building stock are assembled into exposure layers derived from the last comprehensive building census in Italy (Istat, 2011). Each building typology in the exposure layer is

then associated with fragility curves from literature. Using this information, the damage assessment tool estimates the number of buildings expected to suffer structural damage in each municipality. Empirical relationships can also be used to assess the number of occupants affected by these damages, as well as the expected casualties and injured individuals. These indicators are highly relevant for seismic risk management purposes, providing critical information for decision-makers and first responders.
By using physics-based simulations as input, the system will provide more reliable and realistic estimates of potential damage compared to empirical approaches, thereby enhancing seismic risk assessment in the study area. Interactions with the civil protection end users have highlighted the relevance of receiving timely information on expected damage, with estimates produced at successive time intervals and increasing level of detail (Zuccolo et al., 2025), which can be used for different purposes. Overall, UrgentShake demonstrates the value of integrating HPC, physics-based numerical simulations and damage assessment tools to support effective seismic risk management.

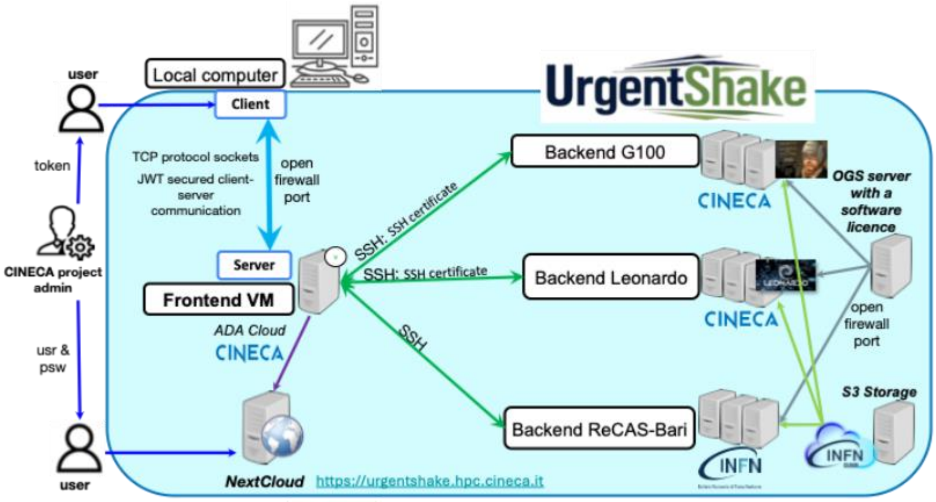

Fig.1 – Computational infrastructure of UrgentShake.

Acknowledgement

This work is funded by the National Recovery and Resilience Plan project TeRABIT (Terabit network for Research and Academic Big data in Italy —IR0000022—PNRR Missione 4, Componente 2, Investimento 3.1 CUP I53C21000370006) and supported by the National Plan of Research Infrastructures (PNIR) 2021–2027. It is also supported by National Institute of Oceanography and Applied Geophysics (OGS) and CINECA under Italian High-Performance Computing Training and Research for Earth Sciences (HPC-TRES) program Award Number 2019-03 and the Italian SuperComputing Resource Allocation (ISCRA) type C Project NUMERA (Numerical Modeling for Multi-Hazard and Risk Assessment).

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Linear and nonlinear geophysical modeling to explore subsurface properties

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Keywords: FDEM data inversion, first kind integral equations, regularization

Electromagnetic induction (EMI) techniques are among the most popular methods used in geophysical surveying for non-invasive investigation of the soil. The aim is to reconstruct specific features of the soil, i.e., the distribution of its electrical conductivity and magnetic permeability, by inverting frequency domain electromagnetic data. Data collection is allowed by FDEM devices. The observed parameters recorded by the device can be connected to the subsurface conductivity and permeability distribution by a system of nonlinear integral equations of the first kind when different device configurations are considered. The model is based on Maxwell's equations. For a nonmagnetic half-space, when the electrical conductivity of the soil is small, the complicated nonlinear model can be well-approximated by a linear integral model. Electromagnetic induction phenomena are intrinsically three-dimensional and require 3D forward modelling and inversion. However, such approach involves an elaborate mathematical model of the environment and large datasets. This is one of the reasons why one-dimensional EMI modelling is still the most widely used computational models.

Starting from measurement data, the reconstruction of the soil properties is a challenging task, as both linear and nonlinear inverse problems are ill-posed, that is, they admit infinitely many solutions, and ill-conditioned, that is, their discretization is sensitive to the presence of noise in the data. We studied both linear and nonlinear models, developing regularizing numerical methods to handle the severe ill-conditioning of the system.

A numerical method has been developed for approximating the minimal-norm solution of the linear integral model in a reproducing kernel Hilbert space [6,7]. The algorithm stems from the Riesz representation theorem and combines it with regularization tools, specifically the application of the truncated eigenvalue decomposition to the matrix of the discretized model.

On the other side, iterative procedures are commonly used to solve nonlinear inverse problems and we adopted the Gauss–Newton method. This has been possible thanks to the explicit computation of the Jacobian of the direct model [4]. When the problem is ill-conditioned, the Gauss–Newton method has been coupled with regularization techniques to transform the problem into a well-conditioned one. In particular, regularization strategies based on the truncated generalized singular value decomposition (TGSVD) [4,9] and variational approaches, such as the minimization of the Tikhonov functional or more general functionals involving a norm-p data-fidelity term and a norm-q regularization term [2], have been adopted. An open-source software for direct and inverse modeling has been released [3].

More recently, we investigated a two-dimensional linear integral model obtained from a three-dimensional formulation by integrating the kernel of the 3D integral equation along the y-axis [8]. This approach enables the reconstruction of a vertical cross-section of the subsurface, which can be naturally interpreted as an image. As a result, regularization techniques commonly employed in image processing can be effectively applied.

The effectiveness of the proposed methods has been thoroughly demonstrated in the cited papers through an extensive set of numerical experiments on synthetic data, encompassing all the considered models (1D nonlinear, 1D linear, and 2D linear), and they have also been applied to real-world applicative scenarios [1,5].

Acknowledgement

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2024-02 and by European Union-Next Generation EU, Mission 4 Component 1, CUP F53D23002700006 through the PRIN2022 project "IPIS".

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Modelling the influence of geodynamics on past and present climate

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Keywords: geodynamics, paleoclimate, paleogeography, paleolatitude

Studying warm climates of the geological past is essential for improving our understanding of the Earth's climate and carbon cycle under elevated atmospheric CO2 levels. Earth's long-term climate is mainly controlled by geodynamic processes that modulate the balance between the outgassing of greenhouse gases and atmospheric carbon removal. During the Cenozoic (the last 66 million years), Earth transitioned from a greenhouse climate in the Eocene to the current icehouse. This long-term climate cooling has often been attributed to increased atmospheric carbon consumption, potentially driven by enhanced silicate weathering associated withthe uplift of the Tethyan orogenic belt, including the Himalayas and Tibetan Plateau (Raymo & Ruddiman, 1992). Alternatively, the cooling trend has been linked to a decrease in magmatic CO2 outgassing during the progressive closure of Neo-Tethys Ocean (Sternai et al., 2020). Quantifying the relative importance of these processes requires accurate reconstructions of paleogeography, the spatial distribution of land, mountains, oceans, and their bathymetry (Markwick & Valdes, 2004). Despite its first-order control on global climate, the impact of paleogeography and its uncertainty on climate simulations remains poorly quantified.

Here, we systematically investigate the influence of paleogeography on global simulations of greenhouse climates for the early Cenozoic (66 to 34 million years ago). We performed a series of paleoclimate simulations using the IPSL-CM5A2 Earth System Model (Sepulchre et al., 2020) for several key time slices: the Paleocene (~60 Ma), the early Eocene climatic optimum (EECO, ~50 Ma) and the middle Eocene climatic optimum (MECO, ~40 Ma). We test alternative paleogeographic scenarios, with particular focus on the different reconstructions of the Neo-Tethyan region and the India-Asia collision.

We show that the choice of paleogeographic reconstruction significantly impacts global ocean circulation as well as regional temperature and precipitation patterns, with high sensitivity to changes in the paleolatitudinal position of landmasses and ocean basins. Shifts of >5° in latitude may alter the hemisphere of high-latitude deepwater formation and cause surface air temperature changes of up to 7°C. Comparisons with paleoclimate proxy records show that paleogeographic boundary conditions substantially affect proxy site locations and model–data temperature misfits. We further demonstrate that the regional climatic impact of paleogeography can rival that of a doubling in atmospheric CO2 concentration, particularly at mid-latitudes. These results highlight the critical role of paleogeography in paleoclimate modelling and the need for accurate reconstructions of paleo-topography and bathymetry to better understand past climate and long-term climate change.

For the present day, the influence of topographic features such as mountain ranges is well-understood. However, the extent to which present-day climate patterns are controlled by the geodynamic forcing on topography, known as dynamic topography, remains largely unexplored. Our simulations of global atmospheric circulation reveal that removing dynamic topography substantially changes large-scale atmospheric flow and regional precipitation patterns. These results emphasize the important connection between the deep Earth, surface, and atmosphere, and provide motivation for future studies on the links between geodynamics and global climate.

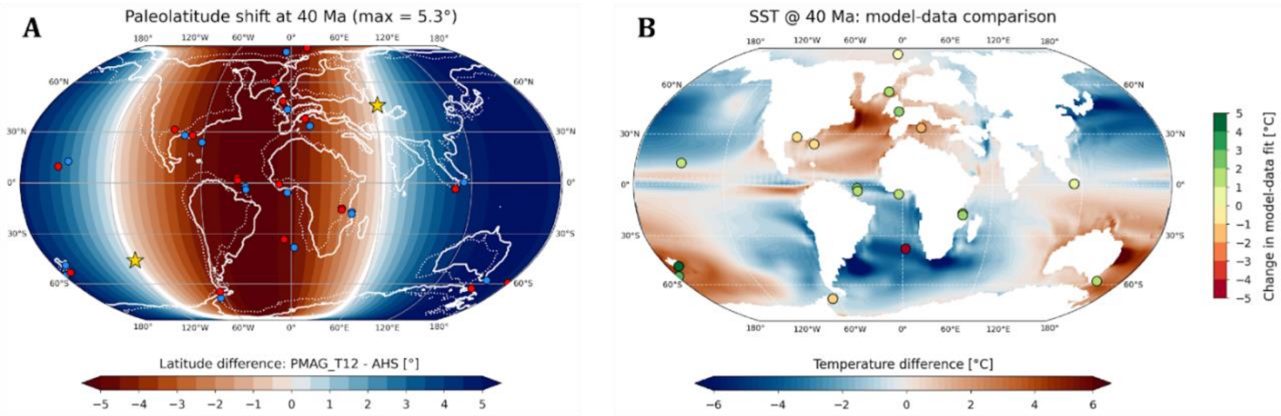

Fig. 1 – A) Paleolatitude shift at 40 Ma induced by switching from a hotspot to a paleomagnetic reference frame. Red (blue) colors show a southward (northward) shift. The shift in sea surface temperature (SST) proxy sites are shown by the red and blue circles, respectively. B) Difference in SST between the two global climate simulations. Change in model-proxy agreement is shown per proxy site: green (red) colors indicate a better or worse fit.

Acknowledgement

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2023-07.

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Machine Learning for Automated Recognition of Seabed Morphologies

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Keywords: Deep Learning, Seabed Mapping, Image Segmentation, Seabed Morphologies

The seafloor along continental margins exhibits a wide range of morphological features, which record the underlying geological and geomorphological processes. These features are composed of smaller structural components, referred to as morphological elements, whose recognition and spatial characterization are essential for interpreting seafloor evolution, evaluating marine geohazards, and informing the design and placement of offshore infrastructures, including pipelines, wind farms, and submarine cables (Chiocci et al., 2011; Chiocci and Ridente, 2011).

Although these features are critical, their mapping has traditionally relied on expert interpretation of bathymetric data. While accurate, this process is time-consuming, subjective, and difficult to reproduce consistently across large areas, especially as bathymetric datasets become increasingly detailed and spatially extensive. Such limitations became apparent in the context of the MaGIC Project (Marine Geohazards along the Italian Coasts) (Progetto MaGIC, 2007-2012), which delivered the first comprehensive geomorphological atlas of the Italian continental margins and, in doing so, generated a valuable expert-labeled dataset of seabed morphological elements.

Within the MaGIC framework, a large fraction of the mapped elements appear as thin, elongated, and often discontinuous lineaments, such as escarpments or scarps, rather than compact areal features. These characteristics pose significant challenges for automated detection. The dataset is also strongly unbalanced, with a dominant background class and several rare morphological elements. Moreover, some classes are intentionally broad or ambiguous, reflecting the interpretative nature of geological mapping. Together, these factors make automated seabed classification a scientifically relevant and technically demanding problem.

In this context, machine learning (ML) offers a promising complementary approach. Convolutional encoder–decoder architectures, and in particular U-Net (Ronneberger et al. 2015), can learn spatial patterns directly from expert-labeled examples and produce reproducible preliminary maps from bathymetry-derived inputs such as depth, slope, and curvature. However, applying deep learning to seabed morphology introduces specific challenges. As discussed before, thin, elongated elements pose challenges for conventional segmentation models; class imbalance can affect model training, and the inherently interpretative nature of expert labels makes evaluation difficult. Standard pixel-wise metrics may excessively penalize minor spatial misalignments that are negligible from a geomorphological perspective.

This work explores a segmentation framework specifically designed to address these issues. A U-Net–based convolutional architecture is trained on high-resolution bathymetric derivatives from selected regions of the Italian continental margins provided by the MaGIC Project. The framework adopts a patch-based training strategy, with a strict spatial separation between training and test areas to ensure fair evaluation. Overlapping windows are used to increase sample diversity, while a simple thickening operation is applied to thin lineaments to facilitate learning. After prediction, a light post-processing step removes small isolated regions that are unlikely to represent real morphological elements.

To assess model performance, the proposed framework combines standard pixel-wise metrics with a neighborhood-based, bidirectional evaluation measure specifically designed to capture the spatial proximity between predicted and reference lineaments. This approach better reflects geological reasoning, particularly for elongated and discontinuous features. In addition to a full multi-class configuration, the study investigates alternative class groupings. These include reduced-class formulations, obtained by merging subsets of the original classes, and a binary configuration (lineaments versus background). This allows us to analyze how class granularity affects robustness, interpretability, and practical usefulness.

Overall, the results demonstrate that deep learning can effectively support and accelerate seabed morphological mapping, bridging quantitative image segmentation with geological interpretation. The proposed approach improves consistency and reproducibility across large marine domains while preserving the interpretative value of expert-driven mapping.

Acknowledgement

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2022-07. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support (IscraC "HYPER").

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From seafloor morphodynamics to geohazard quantification: a multidisciplinary study of submarine canyon evolution along the Ionian Calabrian margin

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Keyword: submarine canyons, slope stability, underwater photogrammetry

The evolution of submarine canyon systems along the Ionian Calabrian Margin (ICM) in southern Italy, remains poorly described as their unique morphological expression and occurrence is not fully understood. By examining the interactions between tectonic activity, sedimentary processes, and shallow fluid migration, this study investigates how past and recent geological processes interact across multiple spatial and temporal scales in shaping the seabed.
The ICM hosts a complex forearc basin characterised by active tectonics and rapid margin uplift, where the interplay of structural, sedimentological, and fluid-related factors governs seabed morphology and slope stability. Through the integration of ship-based multibeam and autonomous underwater vehicles (AUV)-based bathymetry datasets, high-resolution seismic profiles, gravity cores and remotely operated vehicle (ROV) imagery, this work provides new insights into the mechanisms driving canyon evolution, headwall initiation and retreat, and slope failure processes in an area of significant geohazard potential.
Bathymetric and seismic data indicate that canyon evolution is strongly influenced by the spatial distribution of structural highs, shallow gas migration pathways and the proximity to ephemeral terrestrial rivers, better known as "fiumare". Seismic profiles revealed the presence of widespread acoustic blanking zones, chimneys, and mounded features, indicative of active or recent fluid seepage and demonstrating a close relationship between subsurface free gas and the occurrence of submarine drainage systems. These observations suggest that canyon initiation occurs through the coalescence of fluid-escape depressions, which progressively evolve into submarine gullies and subsequently into mature canyon systems through retrogressive headward erosion.
Newly acquired ultra-high-resolution datasets from AUV surveys and ROV dives provided the opportunity to identify centimetre- to metre-scale geomorphic features indicative of active erosional processes directly leading to instability along canyon walls, particularly within the Squillace Canyon system. ROV imagery revealed that fracture networks act as precursors to wall failure, evolving into spalling surfaces that promote further retrogressive failures. In addition, biological activity exerts a significant control on wall stability: benthic organisms colonize freshly exposed surfaces (Fig.1), producing intense bioturbation and localized weakening of canyon walls, thereby promoting the development of new unstable sectors. The comparable temporal scales of benthic community development and offshore infrastructure lifespans underscore the practical relevance of these small-scale erosional processes for risk assessment and early-stage infrastructure planning.
To further quantify slope stability mechanisms, three-dimensional slope stability models were developed by integrating geotechnical analysis with seabed mapping from multibeam and seismic datasets. These models demonstrate that pre-conditioning factors, such as sediment density, acoustic velocity, and slope gradient alone are insufficient to trigger landslides under static conditions. However, when earthquake-related cyclic loading is introduced with peak ground accelerations of 0.2g, the modelled factors of safety (FoS) fall below unity, particularly in areas characterized by multiple overlapping slide scars. This highlights the critical role of seismic shaking in triggering slope

failures in tectonically active areas and highlights the inherent instability of the Calabrian forearc under dynamic loading conditions.

Overall, this study presents a comprehensive, multi-scale assessment of the processes governing submarine canyon initiation and evolution along the Ionian Calabrian Margin. By integrating geomorphological, geophysical, and geotechnical datasets, our approach moves beyond conventional geophysics which provides a first-order identification of potential geohazards, toward ultra-high-resolution datasets that reveal the fine-scale processes essential to understanding slope instability. This perspective allows to clarify the timescales over which active geological processes shape and trigger canyon headwall initiation and refocuses attention on the shallowest portions of the seabed as research priorities move from petroleum exploration toward geohazard assessment aimed for renewable-energy transition purposes.

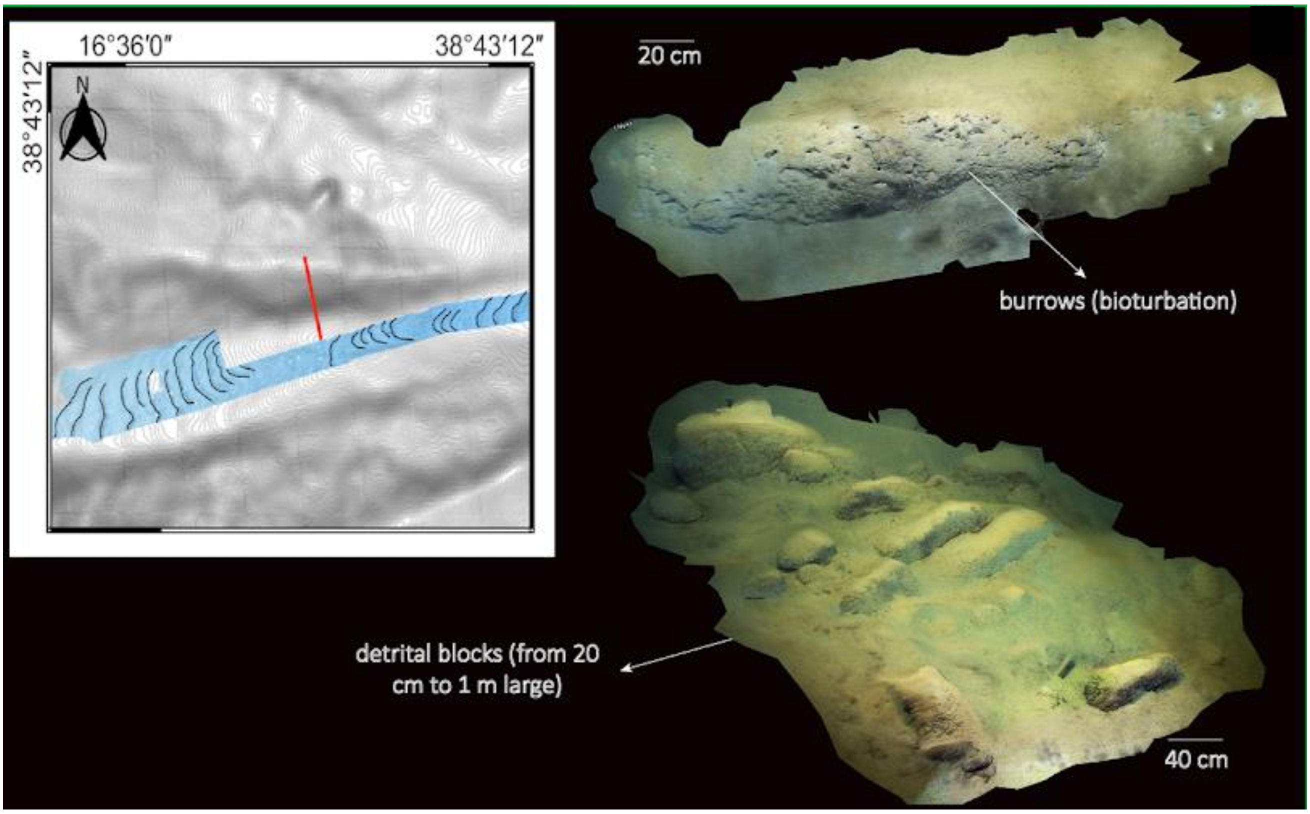

Fig.1 - Soverato canyon branch. On left: location of the ROV dive; on right: detrital blocks in the canyon thalweg in proximity of a canyon wall colonised by benthic burrowers.

Acknowledgement

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Tuning and climate sensitivity uncertainty of the EC-Earth global climate model with simulation of synthetic radiances

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Keywords: radiances, tuning, climate feedbacks, kernels

Earth's climate is driven by the balance between incoming solar radiation (primarily in the visible spectrum) and outgoing longwave radiation (OLR), mostly in the infrared. While current satellite instruments effectively monitor the mid-infrared, a critical observational gap exists in the far-infrared (FIR) - wavelengths extending up to 100μm where a significant portion of Earth's cooling occurs. The ESA FORUM mission aims to fill this critical void. By using a hyperspectral sensor, FORUM will provide high-resolution vertical profiling of the atmosphere, as different micron channels are sensitive to specific components, including stratospheric temperature, water vapor, and high-altitude cirrus clouds.

A primary challenge in climate science is the high inter-model spread in Equilibrium Climate Sensitivity (ECS) (Zelinka et al., 2020), which is largely driven by uncertainties in cloud and convection parameterizations. To align Global Climate Models (GCMs) with observations, climate scientists employ tuning. However, traditional tuning often acts as a "filter" that obscures underlying physical inaccuracies. Because the same global energy budget can be achieved through various combinations of singular fluxes, models often suffer from compensating errors. For instance, a model can achieve the correct global energy balance through compensating cloud-radiative biases, such as opposing errors across latitude bands, cancellation between shortwave and longwave cloud effects, or spectral compensations between absorption-dominated and window regions of the infrared. These radiatively equivalent but physically inconsistent states conceal deficiencies in cloud processes and distort the model's response to climate forcing, compromising the robustness of future projections.

Della Fera et al. (2023) highlighted the role of the spectral compensation of biases in the mean climate of the EC-Earth3 climate model. Building on those results, SpectFbCalc (a python-based tool, hosted on GitHub at fedef17/SpectFbCalc) analyzes OLR variations at the Top of the Atmosphere (TOA) by applying the Radiative Kernel method (Soden et al., 2008) to decompose radiative anomalies into individual physical components. Our framework integrates:

Broadband Kernels: Soden et al. (2008) and Huang et al. (2023).

Spectral Kernels: Computed using the RTTOV model (Della Fera et al., 2025).

The framework is applied to two primary contexts:

Abrupt 4xCO2 Simulations: to quantify individual feedback components (λ) and identify which physical mechanisms dominate the model's ECS and separate the climate response into the individual feedbacks.

Tuning Parameter Sensitivity: by comparing control runs to parameter tuning sensitivity experiments, we "fingerprint" the radiative impact of specific parameters. For example, we can isolate how the parameter controlling the organized entrainment rate in deep convection (ENTRORG) affects specific feedbacks or how other parameters linked to convection (DETRPEN, RPRCON) influence the Planck surface response.

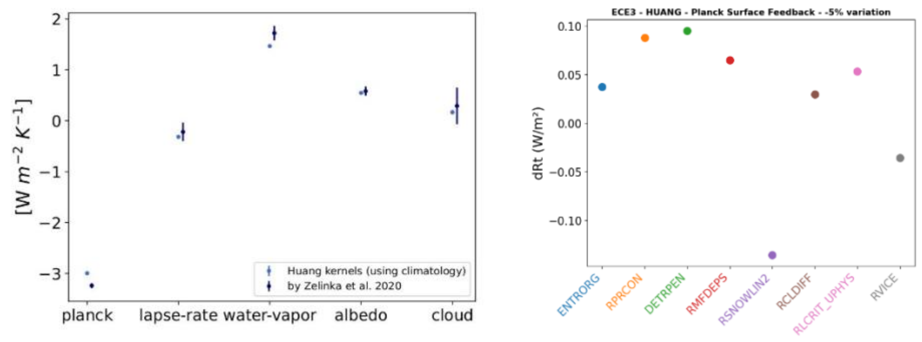

Fig.1 – Left: comparison between the individual feedbacks calculated using the software and broadband kernel computed by Soden et al., 2008, with those presented by Zelinka et al., 2020. Right: effect of tuned parameters on surface temperature by analysing the radiative anomaly.

The next phase of this research will transition from standard broadband analysis to spectral framework. By implementing spectral radiative kernels, we aim to assess climate feedbacks as a function of wavelength and to quantify the sensitivity of spectrally resolved radiances to individual tuning parameters. This approach enables the identification of compensating errors that are invisible in broadband diagnostics but emerge clearly in specific spectral regions. Crucially, forthcoming spectrally resolved observations from the ESA FORUM mission will provide an opportunity to evaluate these modeled sensitivities. While current kernel-based methods infer feedbacks indirectly from simulated atmospheric state variables, FORUM's measurements will allow a more direct, observation-constrained assessment of spectral radiative responses. This paves the way toward a semi-empirical estimation of spectral feedbacks, reducing reliance on model assumptions and enabling a more physically grounded validation of cloud and convection parameterizations.

Acknowledgement

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2024-04. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support (IscraC "HYPER").

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Enhancing Oil Spill Numerical Simulations through Bayesian Optimization

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Keywords: Bayesian optimization, machine learning, parametrization, numerical modelling

The calibration of complex numerical models is a challenge in many scientific fields, including environmental simulations (Stensrud et al., 2015). Model outputs show strong sensitivity to poorly observable physical and empirical sub-grid parameters, with computationally expensive simulations due to high spatial resolution, long integration times, and external forcing data. As a result, parameters tuning is frequently performed through expert-driven and trial-and-error procedures, limiting reproducibility and scalability (Christensen and Zanna, 2022).
High-performance computing (HPC) enables new modelling strategies, but HPC alone does not ensure efficient parameter exploration. Naïve methods such as grid or random search quickly becomes impractical in high-dimensional spaces, leading to suboptimal use of computational resources. Bayesian Optimization (BO) provides a principled framework for calibrating expensive black-box models (Frazier, 2018). Compared to other approaches (Shin and Baik, 2022, Wang et al., 2022), BO combines a probabilistic ML surrogate with an acquisition strategy to systematically explores the parameter space, driving simulations toward promising regions, account for uncertainty, and reduce the number of model evaluations.
To demonstrate this approach, we implemented an HPC-enabled workflow coupling the data-driven approach based on BO with the Medslik-II (MDKII) (De Dominicis et al., 2013) oil spill model, using satellite observations of the Baniyas disaster in 2021 for validation (Accarino et al., 2025). Key parameters affecting oil dispersion, including wind coefficients and diffusivity, were automatically optimized through a self-made Python wrapper integrating the Fortran-based MDKII with the customized Python BO engine. Leveraging the CMCC Juno Hybrid cluster, the coupled model quickly identified the optimal parameters, improving simulation accuracy by up to 25% over manually selected default settings and enhancing potential operational responses.
The results show that the proposed workflow not only automates model calibration but also constitutes an operational and reproducible pipeline capable of systematically improving simulation accuracy and agreement with satellite observations. Beyond performance gains, the surrogate model provides quantitative insight into parameter sensitivity, highlighting the physical processes that most strongly control oil spill dispersion and supporting more informed model tuning. Future work will address sensitivity to forcing data, extend validation to more complex non-stationary and chaotic systems, and explore multi-fidelity strategies and alternative BO configurations to further accelerate calibration and generalize the methodology to other computationally intensive environmental models.

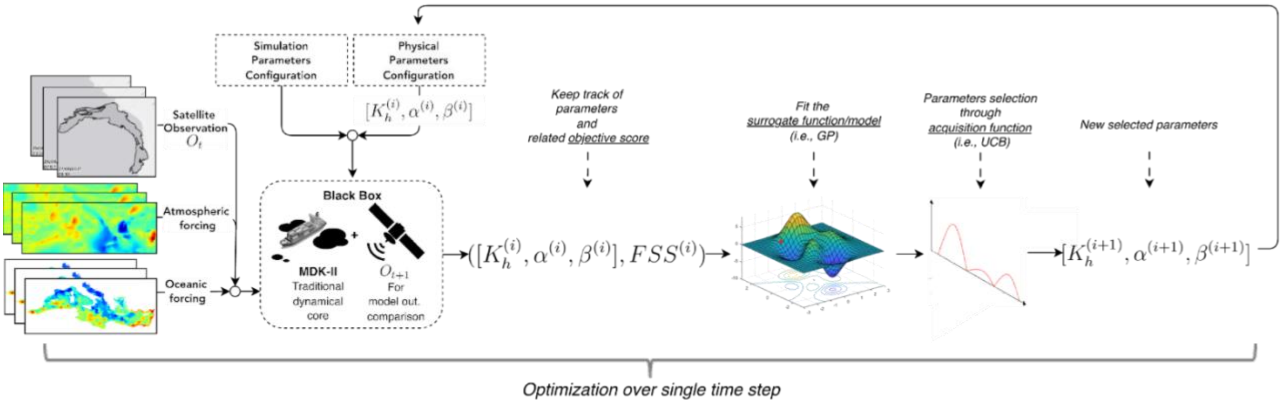

Fig.1 – Coupled BO-MDKII workflow iteration over single optimization timestep.

Acknowledgement

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2023-04. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support (IscraC "HYPER").

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Data-driven strategies to accelerate ocean spin-up in coupled climate simulations with EC-Earth4

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Keywords: climate simulations, earth system model, ocean spin-up

Despite the major upgrade to the computational infrastructure in recent years, the spin-up phase of coupled ocean–atmosphere climate models is still a major computational bottleneck, particularly for long control and paleoclimate simulations. Equilibration of the slow components of the climate system, especially the deep ocean, typically requires millennial-scale integrations, and residual drifts in temperature or salinity may offset simulated climate signals if equilibrium is not adequately reached. Reducing the computational cost of spin-up while preserving physical consistency therefore remains a key challenge in climate modelling.

Several approaches have been proposed to accelerate convergence toward equilibrium (Bernsen et al., 2008, Khatiwala, 2008), and more recently data-driven and machine-learning-based techniques have been explored, although their application to full-complexity Earth System Models (ESMs) remains limited. Within the MARTINI project, we investigate deterministic, data-driven strategies for accelerating spin-up in coupled climate models, starting from low-resolution configurations where long integrations are computationally affordable.

We employ EC-Earth4, the successor of EC-Earth3 used in CMIP6 (Döscher et al., 2021), in its low-resolution configuration (ECE-FAST), coupling OpenIFS at TL63L31 resolution (~2.8°) with the NEMO ocean model at ORCA2Z31 (~2°). This setup achieves approximately 220 simulated years per day on the ECMWF Atos HPC system with 256 cores. A long control simulation of about 4,000 years was performed and used as a reference trajectory toward equilibrium.

To accelerate spin-up, we implemented a deterministic run-and-forecast strategy. The coupled model is integrated for short segments (typically ~10 years), after which long-term trends in ocean temperature and salinity are diagnosed and extrapolated forward to generate modified ocean restart fields. The simulation is then resumed from the modified restart and iterated until convergence toward equilibrium is achieved. Empirical Orthogonal Function (EOF) analysis is employed to isolate dominant modes of variability and project them forward in time, filtering part of the internal variability while retaining the large-scale forced signal.

Preliminary results are based on comparisons between the control run and a set of accelerated simulations. The analysis focuses on three main ocean layers: surface, pycnocline (interior), and bottom. In the surface layer, where adjustment is fast and strongly constrained by air–sea fluxes, the accelerated simulations closely follow the control trajectory. The benefit increases with depth, becoming largest in the pycnocline and bottom layer, where equilibration is slowest.

To quantitatively assess convergence, we developed ad hoc diagnostics to measure the distance from equilibrium during spin-up. These metrics are based on large-scale averages and vertical gradients of oceanic properties and are designed to separate long-term drift from internal variability. Using

these diagnostics, we estimate an effective simulation gain, defined as the equivalent number of control-run years reached by the accelerated simulation at a given integration time. After approximately 100 simulated years, the accelerated runs reach a state comparable to that of the control simulation after about 150–200 years, corresponding to a gain factor of roughly 1.5–2. This gain is negligible at the surface and maximal in the deep ocean.
Overall, these results indicate that deterministic run-and-forecast strategies can effectively accelerate the spin-up of the slowest components of the climate system. Ongoing work focuses on refining equilibrium diagnostics and extending the approach to machine-learning-based methods to further improve efficiency and scalability.

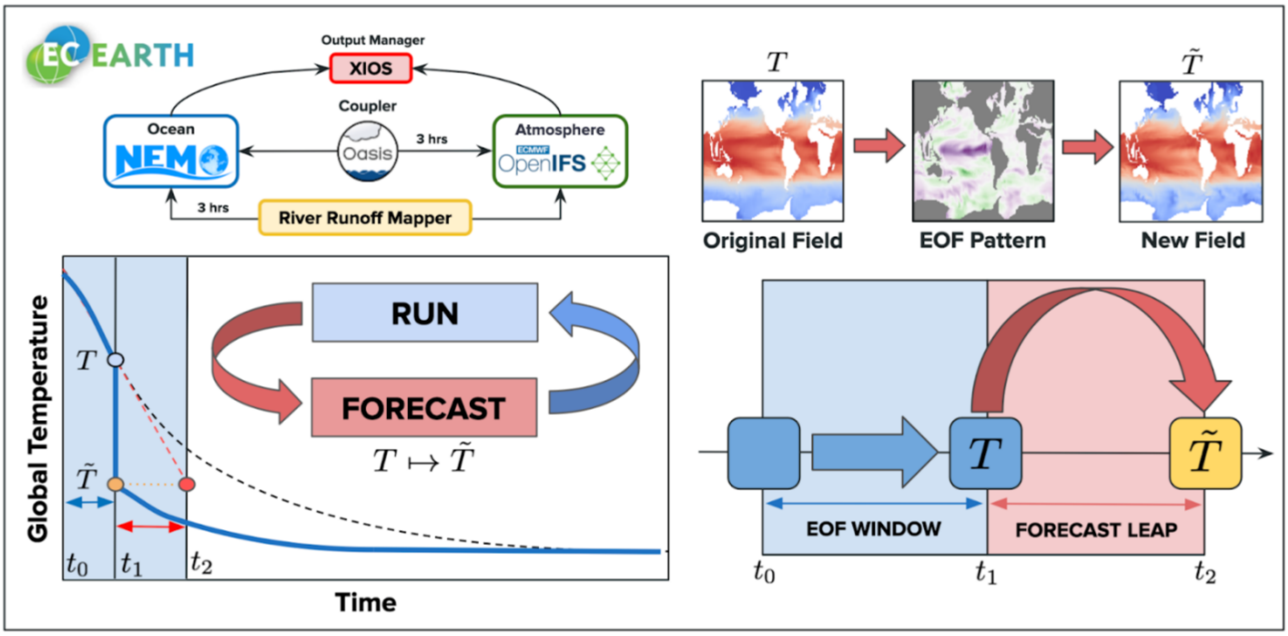

Fig.1 -Schematic illustration of the *"run-and-forecast"* spin-up strategy.

Acknowledgement

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Summer climate response to enhanced land-sea thermal contrast in an Earth model of intermediate complexity

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Keywords: atmospheric circulation, climate change, SPEEDY, land-sea contrast

Land-sea thermal contrast is one of the most relevant factors that control the shape of planetary-scale stationary waves, which affects midlatitude weather patterns (Held et al., 2002). In a changing climate, land is warming faster than the sea, because of its lower thermal inertia, reducing, thus, the land-sea thermal contrast in winter and increasing it in summer (e.g. Portal et al., 2022), with implications that have not yet been fully explored. Increasing carbon dioxide concentration and warming the oceans have been shown to have contrasting effects on the large-scale atmospheric circulation (Shaw and Voigt, 2015), suggesting that it is crucial to properly characterize the role of each forcing factor in affecting the large-scale atmospheric circulation. In the northern hemisphere, Portal et al. (2022) have shown that a reduced winter land-sea thermal contrast (1) weakens and moves poleward the mid-latitude tropospheric jet, and (2) can influence the polar vortex with wavenumber 1 and 2 signals. It remains to be identified how the enhanced land-sea thermal contrast affects the summer northern hemisphere circulation.

For this reason we employ an intermediate complexity model, SPEEDY (Simplified Parameterization, primitivE Equation DYnamics, Molteni, 2003; Kucharski et al., 2006), v42, to run two perpetual run experiments: the control experiment (CTRL), which is forced by all surface boundary conditions that represent the present-day climatology (1981-2010), and an experiment, WLND, where the land temperature is warmed with the multi-model-mean pattern of CMIP6 models land temperature in the SPS5.8-5 scenario in the time frame 2071-2100. Both experiments are run using perpetual JJA (June, July, August) conditions and last for 100 years, with the first 30 years discarded from the analyses as spinup.

By taking the difference between some relevant time-averaged fields in the WLND and CTRL run, we can identify the relevant features of the atmospheric response to the imposed land warming. In particular, the lower atmosphere gets warmer and moister in a way that the surface turbulent sensible heat flux is almost cancelled, whereas, the surface latent heat flux is enhanced over land and reduced over the oceans (Fig. 1a,b). Moreover, by computing all terms that appear in the surface heat budget, that include radiative and turbulent fluxes, it is found that the latent heat flux is the largest term in the WLND-CTRL difference. In terms of dynamical properties, the land warming produces a reduction of the amplitude of the stationary waves (Fig. 1c) and an overall weakening and poleward displacement of the tropospheric jet (Fig. 1d). This is explained via the altered thermal wind balance. Overall, the experiments indicate that a warmer land can sustain large rates of evaporation, making the atmosphere significantly moister and changing the overall dynamics, especially in the North American-Atlantic Ocean sector.

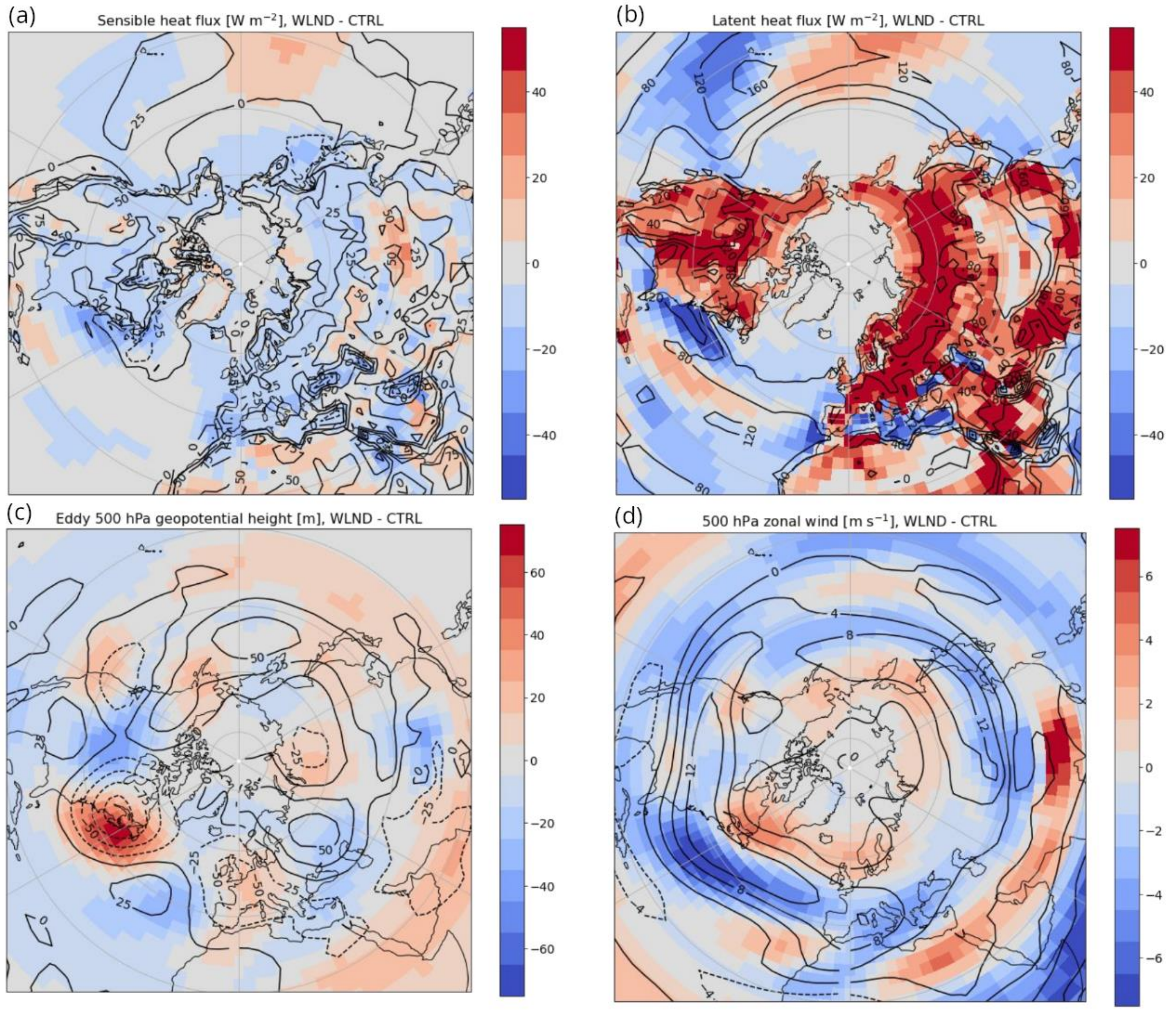

Fig.1 - Time-average difference of (a) surface sensible heat flux, (b) surface latent heat flux, (c) eddy 500 hPa geopotential height and (d) 500 hPa zonal wind, between the WLND and CTRL experiments.

Future developments of this work include the characterization of the atmospheric response in terms of storm track and Eady growth rates at daily scales. Unfortunately, SPEEDY does not properly represent atmospheric blocking events and, thus, it is not suitable to characterize how they change in a world with a significantly warmer land. The role of soil moisture also has to be properly assessed, as soil moisture strongly modulates surface evaporation, which has been shown to be important in the current experiments.

Acknowledgement

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2023-04. We acknowledge CINECA for providing high performance computing resources and support (mBI23_AmbCo, mBI25_AmbCo).

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Numerical reproducibility of the SHYFEM-MPI ocean model

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Keywords: unstructured ocean modelling, numerical reproducibility

SHYFEM (System of HydrodYnamic Finite Element Modules) is a hydrodynamic model used in weather and climate research. It solves the hydrodynamic equations using finite elements on an unstructured grid on local and global scale. Recently the MPI-parallelized version "SHYFEM-MPI" (Micaletto, 2021) has been released.

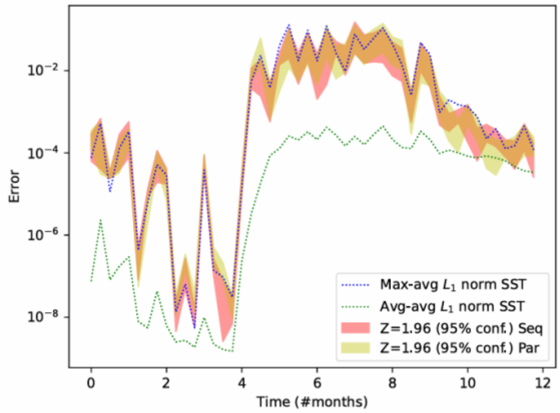
Differing computing contexts may introduce differences in output for identical runs of a numerical software, including differing

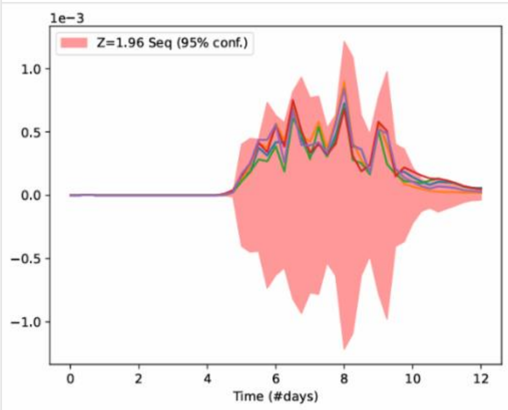
- Compiler optimisation: e.g. fused multiply add, vectorisation, etc.
- Parallelism: non-deterministic order of communication and calculation
- Hardware differences: CPU, Cache, GPU, accelerator types
- Software differences: e.g. settings and versions of external libraries

In the case of parallelism, two identical runs can have differing output (e.g. due to race conditions), effectively causing non-determinism. The cause of this is rounding error, leading for example to non-associative floating point operations (FLOP). Every time a compiler optimization or parallelization leads to a different order in the evaluation of FLOP, differences are introduced into the software.

In this talk we first consider bitwise reproducibility (BR) of scientific software. In particular, SHYFEM-MPI is BR with respect to changing MPI partitionings. However, BR restricts software development and optimisation, resulting in slower development and runtimes. We therefore consider statistical reproducibility (SR), a relaxation of BR. We define and test a type of SR, based on confidence intervals (CI) of a reference of ensemble runs. This reference is designed to capture variation of the output with respect to differences introduced by non-associativity of FLOP. A new ensemble of runs (e.g. an ensemble of non-deterministic parallel runs) is called SR if they all lie within a 95% CI of the reference ensemble run.

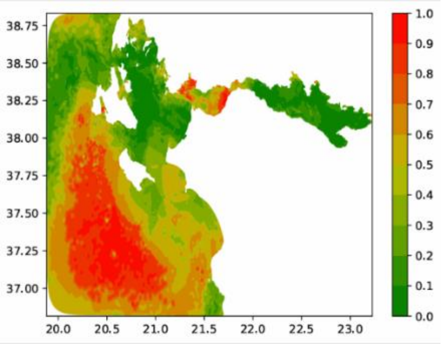
In our experiment we used a regional configuration of the model in the Mediterranean Sea around the Greek island Zakinthos. Using 10 member-ensembles, depicted in the the Figures below depict the 95% CI; the strong overlap of CI shows that SHYFEM-MPI is able to correctly reproduce the results, even in the non-deterministic configuration of SHYFEM-MPI.





__Left:__ the 95% CI of the distribution of the absolute difference of the sea-surface temperature (SST) between the ensemble runs and the ensemble mean (with maximum bandwith/standard deviation over the grid) for both the sequential (Seq) and parallel (Par) ensembles, together with the average (...-avg) L_1-norm which which is averaged (Avg-avg) or maximised (Max-avg) over the grid. __Right:__ absolute difference of the SST, averaged over the grid, between sequential and parallel ensemble runs (5 total shown) together with the CI of distribution of the the absolute difference between the ensemble runs and the ensemble mean (90% percentile maximum bandwith over the grid).

Finally, a Kolmogorov-Smirnov test shows quantitatively the similarity of the distributions of the output obtained in parallel and with grid reshuffling, shown below, in some sense quantifying the amount of non-associativity in the model. A future goal could be to use this increase the correctness of SHYFEM-MPI.



The Kolmogorov-Smirnov test of the parallel and sequential ensemble average of the L_1 distance between the ensemble runs and the ensemble mean after a year. In the green/yellow non-deterministic output may be caused by grid reordering.

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List of institutions abbreviations

CINECA	Consorzio Interuniversitario Cineca
CMCC	Euro-Mediterranean Center on Climate Change
CNR - ISAC	National Research Council - Institute of Atmospheric Sciences and Climate
HPC-TRES	High Performance Computing - Training and Research for Earth Science
ICTP	Abdus Salam International Centre for Theoretical Physics
INGV	National Institute of Geophysics and Volcanology
OGS	National Institute of Oceanography and Applied Geophysics
POLITO	Polytechnic University of Turin
UNIMIB	University of Milano - Bicocca
Unisalento	University of Salento
UNITS	University of Trieste

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