High Performance Computing
Training and Research for Earth Sciences

# BOOK OF ABSTRACTS

5th Annual HPC-TRES Workshop
24 January 2023 - Trieste (Italy)

OGS Report 2023/52

National Institute of Oceanography and Applied Geophysics

Ministero dell'Università e della Ricerca

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OGS National Institute of Oceanography and Applied Geophysics

MUR Ministero dell'Università e della Ricerca

CINECA

National Institute of Oceanography and Applied Geophysics

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https://www.ogs.it/en/high-performance-computing-laboratory-hpc-tres

Available on zenodo.org

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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 5$^{th}$ HPC-TRES workshop (24$^{th}$ January 2023, Trieste)**

The 5$^{th}$ Workshop of HPC-TRES was organized by OGS at the DoveVivo Campus Trieste (ex Ospedale Militare), after two editions held online due to restrictions imposed by the COVID-19 emergency. The workshop officially started the evening of 23 January with a social dinner at the "Antico Caffe' S. Marco", an event that allowed most of the participants to start interacting and networking.

The workshop aimed at sharing a common discussion with all 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 infrastructure, also in the frame of the National Recovery and Resilience Plan (PNRR), 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.

44 attendees participated in the workshop, and 15 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. Diverse modeling studies at different spatial and temporal scales, implementation of innovative algorithms, model optimization, HPC model data management, covered different aspects of the Earth Sciences: from global to regional climate, also in a paleo perspective and with applications on exo-planets, to physical and geochemical processes in the land, atmosphere, and ocean, including impacts on marine biology and energy applications, to risk assessment in natural hazard studies.

The workshop was introduced with two keynote speeches. The first was from Carlo Cavazzoni (director of Leonardo HPC Lab), who discussed on "In a world where computing is pervasive, why we still need HPC?", pointing out the necessity of using HPC in all the present economical, scientific, and social challenges, highlighting drivers and trends of HPC and AI, including opportunities for job creation. The second keynote speaker was Mirko Cestari (HPC and Cloud Architect at Cineca), who presented the "Cineca HPC roadmap for 2023-2024", showing how the continuous upgrade of HPC resources at the Cineca national supercomputing centre (from the exascale HPC to quantum computing) supports the excellence of research and innovation in Science, the cooperation between academic and industrial communities, the training to young researchers, and the technology transfer, also promoting the competitiveness of national research at international level.

This book of abstracts includes the presentations presented during the event, the list of participants and the JRU members, as well as the abbreviations index and the acknowledgments.

The four previous workshop book of abstracts editions are available on www.zenodo.org (indexed in OpenAIRE).

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

# "Can HPC improve seismic risk assessment? The case study of Isfahan, Iran"

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Keywords: seismic risk assessment, uncertainty propagation, sensitivity analysis, disaster risk reduction

Earthquakes are a major threat to societies, as they can be extremely deadly and cause substantial damages to buildings and infrastructure (So and Spence, 2013). For this reason, disaster risk reduction strategies require reliable estimates of expected losses caused by seismic events. However, risk estimates are associated with uncertainties which are sometimes neglected in favor of simplified models, in order to provide timely results to end-users. High Performance Computing supports sensitivity analyses devoted to the quantification of uncertainties. This is made possible by reducing the computational time required and allowing for the models to be run several times in a timely manner. Here, we perform a sensitivity analysis to assess seismic risk in the city of Isfahan (Iran), which is located in a seismically active area. Seismic hazard and risk have been already assessed for the city (Kohrangi et al., 2021a,b). Starting from those studies, we vary systematically the main input parameters of the hazard model and explore the variability of the output (i.e. risk metrics such as average annual losses). We then run multiple times the model, initialized with different input parameters, taking advantage of the HPC infrastructure (Fig. 1). All calculations are run using the OpenQuake software (Pagani et al., 2014).

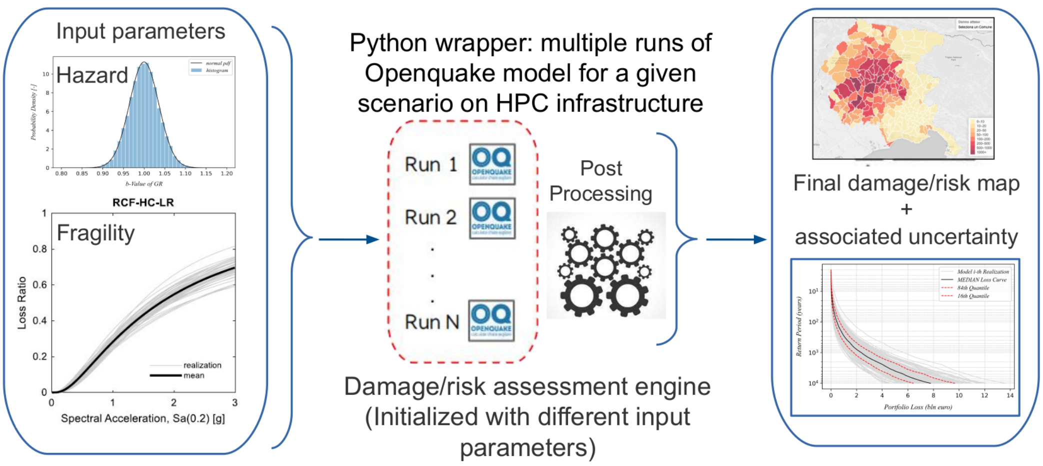


*Figure 1. Sketch of the methodology used for assessing seismic risk. Input parameters are sampled within probability density functions, and used to initialize multiple runs of the Openquake model. Results are then combined into curves that quantify the variability of outputs given a variation in the input*

Results of each simulation are post-processed and combined into curves which relate input-output relative variations and allow identifying the most sensitive parameters of the model. Results show that the uncertainty in the hazard component of the model can considerably affect the seismic risk estimates for the study area.

**Acknowledgment**

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2019-03. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support (IscraC URASS - Uncertainties in Risk Assessment for Seismic Scenarios).

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## Assessing fin whales migration in the Mediterranean sea through coupling of acoustic and satellite chlorophyll data

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Keyword : fin whales, acoustic, chlorophyll, migration, Mediterranean sea

The correlation between fin whales acoustic activity inside the Pelagos sanctuary and the dynamic of chlorophyll (satellite) was computed for the whole North Western Mediterranean basin. Using a simple methodology, we were able to link fin whales migration patterns to resources availability in their niche habitat. While fin whales are generally considered as "nomad opportunistic" in the temperate Mediterranean basin, some of their behaviors clearly answer to evolutive and reproductive constraints. Indeed, while some satellite-tracked animals shows seasonal migration (i.e. wintering around Balearic islands or Strait of Sicily), others do not show the same behavior and prefer to winter in the Pelagos sanctuary. An exceptional case shows a migration through the Strait of Gibraltar, clearly indicating that the Tagus estuary is a meeting point between Mediterranean fin whales and their North Atlantic congeners. It thus clearly appears that the population of fin whales in the Mediterranean basin is able to consider and predict environmental indicators in order to benefit from optimal feeding resources (chlorophyll fronts, eutrophic estuaries, island effects, upwellings etc.). Main perspectives of this study will be to compare fin whales movements to coupled physical-biogeochemical model forecast, aiming at assessing their seasonal presence in the Pelagos sanctuary. Doing so, crucial information could be provided to stakeholders to minimize ship strikes, first cause of non-natural death for fin whales in this area.

**Acknowledgment**

This study was performed in the frame of OGS / HPC-TRES program award 04/2021.

# Using HPC to study the compositional dimension of planet formation

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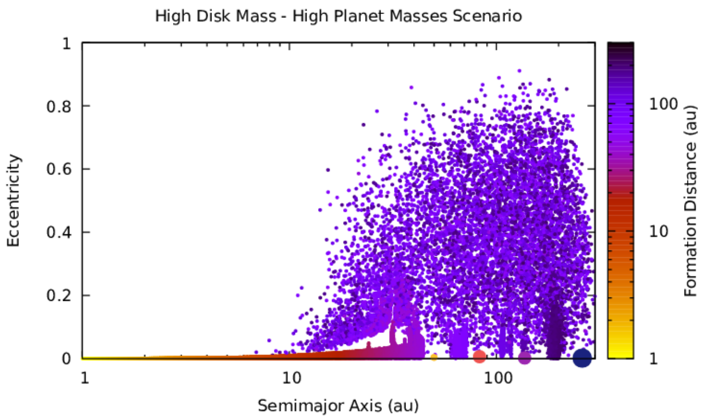
Keywords: astrophysics, planet formation, astrochemistry

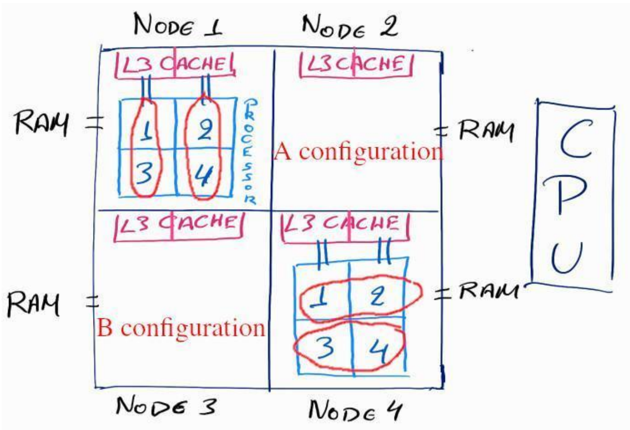
Planets, both in our or other stellar systems, are found to have a vast mass range that depends on where and when they form in the circumstellar disk that surrounds their host star, as well as the properties of said disk. To form planets that could support life the problem is threefold: *First*, the planetary body is required to have a solid surface rather than a gaseous one. In fact, if a planet is formed near its host, or late in the lifetime of the disk, then it will have a limited amount of material (gas, dust and planetesimals) to accrete from and end up as a terrestrial planet (with radius < $1.5R_{Earth}$). Otherwise, if it supersedes the Isolation Mass (), it undergoes rapid gas accretion and ends up either as a transitional planet (~$1.5<R_{Earth}<2.5$) or a gas rich planet ($R_{Earth}>2.5$) depending on the availability of gas and the time it has to accrete it (Lambrechts, M., & Johansen, A. 2014). *Second*, to support life a planet must reside inside the habitable zone, where the presence of liquid water on the planet's surface is possible. *Third*, it must also have the necessary material to support life like water and organics. These elements are found at distances much further away in the circumstellar disk than the habitable zone which points towards two possible mechanisms for creating the conditions of life in such planets. The planets either form in the habitable zone and get the necessary material delivered to them from larger distances, as it is believed is the case with Earth (e.g. Morbidelli et al. 2012, Turrini et al. 2014, Raymond & Izidoro 2017). Or they form in the regions where such elements exist and then migrate where the habitable zone is located in their host system (e.g. Miguel et al. 2019; Adibekyan et al. 2021)
We use the N-body code Mercury-Arχes to study the composition of forming planets due to their individual formation and migration histories (Turrini et al. 2019, 2021). As a case study we use the HD163296 system, an A type star at a distance of 330 light years from the Sun, that has 4 potential massive planets orbiting in its circumstellar disk. We set up 4 simulations fixing the 4 planets in set distances from the host star and changing the mass of the disk and that of planets to their upper and lower estimated limits from observational data (Isella 2016; Pinte et al. 2018; Teague et al. 2018; Booth et al. 2019).




The first goal of the study is to explore the water delivery in the HD163296 system (Turrini et al. 2019). We find that the delivery process works in inserting material inwards at orbits smaller than

30 au. However, they do not reach the habitable zone that is located at distances shorter than 10 au in this system. Therefore, we suggest that either there are more undetected planets inward from the identified one that help excite the disk further and inject more material inwards, also at the habitable zone, or the 4 planets need to migrate to be able to deliver such material in the habitable zone.

The second goal of the study is to identify the optimal NUMA mapping for future high density campaign simulations to fully exploit all physical cores of a server. The simulations were run on the same 16-cores AMD EPYC processor with 8 threads per simulation. In the first configuration every two threads of each simulation share the same cache but the cache pools of the two simulations are independent, which in the 2nd configuration each simulation can access instantaneously all available cache but the two simulations need to share the same cache pool. We find that the second configuration is 15% faster and thus the most optimal.




Currently, the code is scientifically limited as the migration and mass growth are user-defined parameters. As such, we wrote a physically self-consistent treatment of planet formation and migration to link them to the physical characteristics of the host disk. This program has been tested and will be imported into Mercury-Ar$\chi$es as a numerical library in order to run more realistic simulations of planet formation.

**Acknowledgment**

The author would like to acknowledge the support of INAF through the project PRIN INAF 2019 “Planetary systems at young ages (PLATEA)” and that of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) and CINECA through the programme “HPC-TRES (High Performance Computing Training and Research for Earth Sciences)” award number 2022-05.

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# An optimization strategy for electromagnetic inversion

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Keywords: Maxwell equations, EM response, EM inversion

The aim of electromagnetic (EM) soundings methods in geophysics is to obtain information about the conductivity structure of the earth by recorded measurements taken at the surface. One technique consists of placing a magnetic dipole above the surface. In this case, the electromagnetic induction effect, encoded in Maxwell's equations, produce eddy alternating currents in the soil which on their turn, induce response electromagnetic fields that can be used to determine the conductivity profile of the ground. Among the available instruments, the DUALEM (DUAL-geometry Electro-Magnetic; http://www.dualem.com) system is often used. The receiver couples are placed at 2,4,6 and 8 m from the transmitter coil, and typical source-receiver geometries are the horizontal coplanar (HCP configuration) and perpendicular (PRP configuration) coils.

We consider a specific application, related to the internal composition of river levees. They may collapse due to the condition of the soils that form the embankment, since water seepage throughout the embankment could generate internal erosion.

To reconstruct geophysical structures from EM measurements, an inversion procedure is needed. One typically defines a forward model for the EM response and then minimizes the mismatch between the measured data and the predicted data. The forward model used in the inversion usually consists of a set of locally horizontal homogeneous layers. Under this assumption, general integral solutions of Maxwell equations for vertical and horizontal magnetic dipoles can be derived and represented as Hankel transforms that in general are not analytically computable. Therefore, a numerical scheme is needed. Anyway, the slow decay of the oscillations determined by the presence of the Bessel function inside the integral makes the problem very difficult to handle, because traditional quadrature rules typically fail to converge. To numerically evaluate this kind of integrals, the digital filter algorithm was introduced. This method is essentially a standard quadrature rule, but the main difference is that the weights are computed by solving a linear equation obtained by imposing the rule to be correct on a set of training functions (not polynomials) for which the corresponding integral is known.

We consider a different approach based on the splitting of the integrand function in a first function, for which the corresponding integral is known exactly, and a second oscillating function that decays exponentially and for which the corresponding integral can be accurately computed by a classical quadrature rule on finite intervals.

We also consider the inverse problem of computing the model parameters (i.e., conductivity and thickness of the layers) from a set of measured field values at different offsets. For this purpose, we employ the damped Gauss-Newton method. Moreover, to avoid the dependence on the initial guess of the iterative procedure, we consider a grid of values of initial models, and we use each one to solve the optimization problem. After analyzing the set of solutions, we describe a strategy to obtain the approximate solution of the inverse problem.

Anyway, this inversion algorithm can be very expensive in terms of computational costs. The numerical experiments, carried out for the study of river-levees integrity, an important environmental problem in Italy due to the high hydrological risks, allow to estimate the errors associated with these kinds of investigations and confirm the reliability of the techniques.

The numerical methods and the associated simulations are implemented in Matlab. Moreover, in order to accelerate the minimization procedure, we run in parallel the simulations on a virtual machine equipped with the NVIDIA A100 Tensor Core GPU.

**Acknowledgement**

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2019-04.
This research has been funded by the DILEMMA project, "Imaging, modelling, monitoring and design of earthen levees"; Ministero dell'Ambiente e della Tutela del Territorio e del Mare (MATTM), under the framework "Progetti di ricerca finalizzati alla previsione e alla prevenzione dei rischi geologici" (D.D. 524 del 29 novembre 2017).

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# Parallelization of a distributed hydrological model

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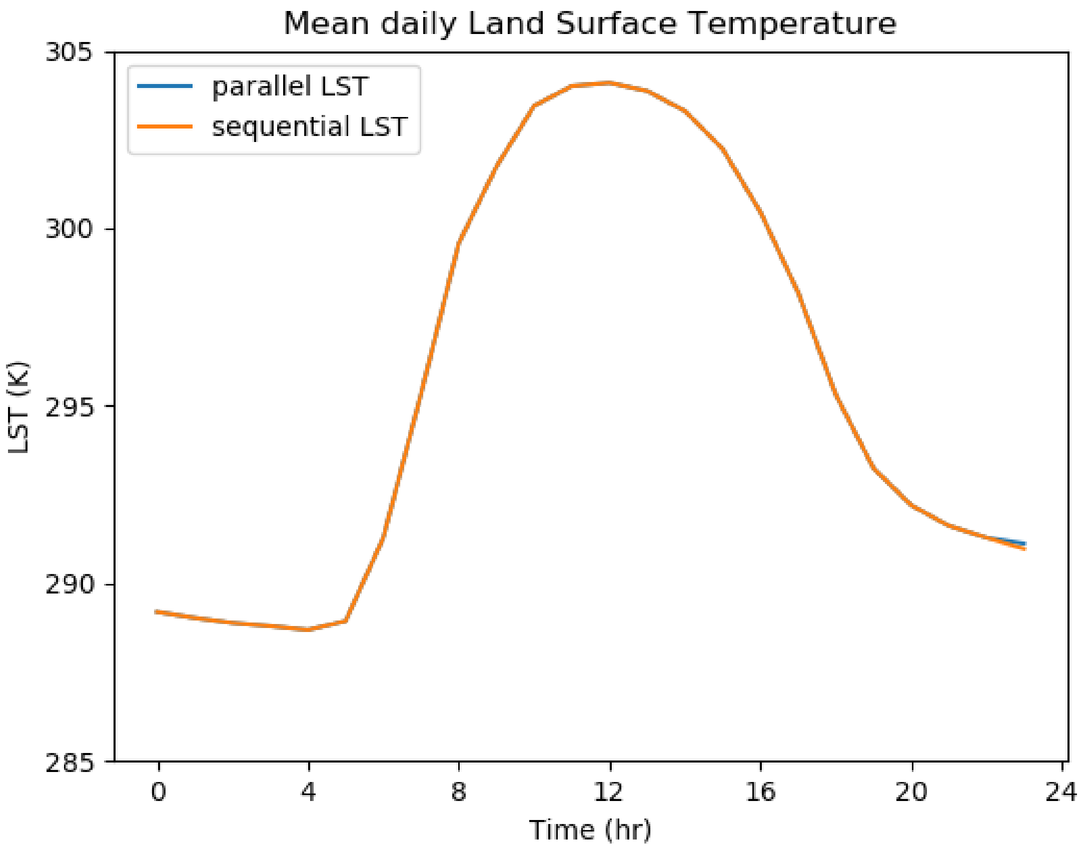
Keywords: hydroinformatics, hydrological modeling, parallel computing

The Hydrological Model Continuum (HMC for short) (Silvestro et al., 2013) is a distributed hydrological model developed and maintained by CIMA Research Foundation in Italy. It is a highly parsimonious model with distinct compartments. Every component is implemented in a modular structure. The main aim of this study is to parallelize the model using the Message Passing Interface (MPI) (Walker, 1994) paradigm.

In 2022, we tried to parallelize the model starting from the energy balance component. The energy balance is solved based on the "force-restore" approach of (Deardorff, 1978) and implemented according to the procedures of (Dickinson, 1988). The test results on the Ligurian domain are shown in the figure below.



Except for the last time step, which happens to be a bug in the sequential code, the parallel and sequential results are exactly the same.

However, the parallel run takes more time than the sequential run. Later, we realized that we implemented the parallelization in the innermost part of the computational loops. That is a typical example of what is called fine-grained parallelism. In fine-grained parallelism the amount of non-arithmetic work (like system/network/MPI communication, input-output) is more than arithmetic computation. That is the main reason for the slow parallel run.

Now, we are implementing the parallelization in the outermost part of the loop. This is to obtain coarse-grained parallelism as much as possible. We are hoping to get much better results than the fine-grained one.

**Acknowledgment**

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## Simulated Last Deglaciation oceanic circulation in the Ross Sea: ice-sheet-ocean interactions during the Antarctic Ice Sheet retreat.

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Keyword: physical oceanography, paleoceanography, ice-ocean interactions, Ross Sea, last deglaciation, Antarctica

During the last deglaciation (21-0 ka), the Antarctic Ice Sheet (AIS) in the Ross Sea retreated from the continental shelf break, where it was grounded, to its present-day configuration. The pathways and timing of grounding line retreat, as suggested by sedimentological, geomorphological evidence and by ice sheet modelling, hint for a possible role of the ocean as a trigger for AIS retreat. Overall the role and dynamics of the ocean during the last deglaciation in the Ross Sea remains largely unexplored.
We investigate this by simulating the evolution of oceanic circulation in the Ross Sea over the last deglaciation (21-0 ka), at intervals of 1000 years, starting at the Last Glacial Maximum (21 ka). The MITgcm, in a new regional implementation of the Ross Sea, including sub-ice shelf circulation, is forced by outputs of the global transient paleoclimate simulation TraCE-21ka [1], with a basin geometry consistent with the AIS configuration during retreat adapted from existing paleo ice-sheet simulations [2] and geological evidence [3].
During the early deglaciation (21-17 ka), geological evidence suggest that the AIS was grounded up to the continental shelf break, with the exception of ice shelves located in the Drygalski, the Joides and the Pennel troughs, and by 17 ka, an ice shelf developed also in the Whales Deep trough. In our oceanic simulations, cold, salty High Salinity Shelf Water (HSSW) fills the entire cavities in the Drygalski and Joides troughs, whereas the Pennel and Whales Deep ice shelves are frequently reached by relatively warm Circumpolar Deep Water (CDW).
During the Meltwater Pulse 1A (14.6-14.3 ka), the release of meltwater and icebergs in the North Atlantic yields a slow-down of the Atlantic Meridional Overturning Circulation in the TraCE-21ka paleoclimate simulation, with subsequent warming of the deep ocean and freshening of intermediate waters in the Southern Ocean. This weakens the Antarctic Slope Front in our Ross Sea simulation, fostering warm CDW intrusions beneath the Whales Deep ice shelf, causing intense basal melting.
At last, during the Holocene (11.8-0 ka), the AIS retreat and the Ross Ice Shelf gradual formation lead to an increasing open-marine portion of the continental shelf: cold and salty Shelf Water becomes widespread over the Ross Sea, reducing the intrusions of the CDW by strengthening the Antarctic Slope Front. HSSW production restores strongly only since the Middle Holocene (~6 ka).

**Acknowledgement**

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2022-03. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support (IscraB PALEOMIT, IscraC DEGLAMIT)

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## Machine Learning for Climate Change Applications

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Keywords: machine learning, deep learning, climate change, climate science, extreme weather events, tropical cyclones, climate projections, model uncertainty

Nowadays, thousands of scientists clearly demonstrated that about 97% of global warming is caused by human activities (NASA), with huge quantities of $CO_2$ released into the atmosphere and reaching an increase greater than 50% with respect to the pre-industrial era (NOAA, 2022). These changes are causing the intensification of the frequency and severeness of Extreme Weather Events (EWEs) like fires, typhoons, floods, droughts, etc (EPA, 2022). One of the goals of the present research project is to improve the understanding of the climatic phenomena by using Machine Learning (ML) and Deep Learning (DL) algorithms. In particular, these innovative tools are exploited to tackle climate-related tasks trying to overcome the limitations of traditional models, which result extremely intensive from a computational standpoint and very time-consuming. This is the main issue, needing at least a parallel implementation to be run on hundreds of thousands of Central Processing Units (CPUs) for each simulation. Concerning ML algorithms, once the network is trained, few minutes or fractions of a minute are required to make a prediction, since inference using such models is much faster than training them. Thus, these methods are significantly quicker and cheaper than conventional ones, and they already showed to be promising thanks to the high accuracy reached in climate science applications developed in the past. Moreover, they are basically data-driven approaches because they make predictions by learning complex and non-linear spatial-temporal relationships directly from data without needing the physical equation governing the phenomenon of interest to be specified. This means they can learn the system behavior also in the case it is not known very well, and this happens very frequently in climate science where physical phenomena are complex and highly non-linear. This is the reason why ML has already shown to be one of the most promising approaches in this domain.

In the present research project the focus is put on Tropical Cyclones (TCs) which are warm-core, large-scale cyclones, originating over tropical or subtropical waters, with organized deep convection (Roy and Kovordányi, 2012) and a closed surface wind circulation about a well-defined low-pressure center. In particular, the TC Detection was tackled during the second year. It starts with the classification of the presence of a cyclonic phenomenon in a particular time instant and on gridded climatic fields that result significant to its cyclogenesis. If the TC is classified as present, the following step is the identification of the geographical coordinates of its center in terms of latitude and longitude. To this aim, the dataset used during the first year of the research project for TCs track forecasting — and that focuses on the West North Pacific basin — was extended to the whole North Pacific Basin to get a higher number of TCs occurrences. The climatic fields were downloaded from the ERA5 dataset with a spatial resolution of 0.25°x0.25° and a temporal resolution of 3 hours, then divided into 144 patches of size 40x40. Each single patch is fed to the model to classify the presence/absence of the cyclone occurrence and potentially identify the position of its center The temporal coverage spans 1980 to 2020. The information about the past TCs and their trajectories was extracted from the International Best Track A1rchive for Climate Stewardship (IBTrACS) database. An Artificial Neural Network (ANN) made up of Convolutional blocks was designed, implemented, and trained for the TC Detection task. Although the results reveal some False Positives (FP) and False Negatives (FN), some TCs are entirely captured with great accuracy.

The average Mean Absolute Error (MAE) obtained during the training phase is 1.26 and during the validation phase is 2.19. The average prediction time per map is 12 s and the average prediction time per patch is 0.083 s.

Other interests of research are the generation of accurate climate model realizations and the uncertainty reduction of climate models. The latter are essential tools for investigating the climate system on different time scales and help scientists to attribute the degree to which observed climate changes may be due to natural variability, human activity or a combination of both (NOAA GFDL). Even for prescribed Carbon Dioxide ($CO_2$) concentrations, the models still exhibit uncertainties in their projections, and these uncertainties not only have not been reduced with the evolution of the models but even increased. The idea was the development of an ANN to generate global near-surface temperature maps for a specific year and in a fast way starting from the corresponding $CO_2$ equivalent value for the same year. CMIP6 near-surface temperature maps for SSP2-4.5, 3-7.0 and 5-8.5 scenarios and for 3 climate models (FGOALS-g3, MIROC6, MRI-ESM2-0) were downloaded. The temporal domain ranges from 1850 to 2100 and the spatial coverage is global. Since the temporal resolution of the maps was monthly, they were processed to get a map per year. The near-surface temperature maps produced by the model during the test phase appear nearly indistinguishable although some MAE hotspots are evident. The average MAE is about 0.5.

Concerning the future works, the errors obtained in the two tasks deserve further investigation to be reduced. The research will be extended to the use of DL models for TC Tracking task. It is performed in a subsequent phase because, starting from the positions found during the detection phase, it consists in the reconstruction of the trajectory the cyclone followed over several time instants. Furthermore, the investigation will involve the use of ML and DL techniques for the reduction of climate models uncertainty.

**Acknowledgement**

The research reported in this work was supported by OGS and CINECA under HPC-TRES program award number 2020-04. We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support (IscraC "DL-DAA").

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# Opening-closing combinations of the MOSE mobile barrier system in the Venice lagoon, from conceptual models to FEM simulations with SHYFEM

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Keywords: Venice, lagoon, circulation

The Lagoon of Venice is a natural wonder and a globally recognized treasure. Its iconic city, Venice, holds immense artistic and historical value, and the entire lagoon has been a UNESCO world heritage site since 1987. However, this historical heritage and the delicate ecosystem of the lagoon are under threat due to anthropogenic intervention and global greenhouse gas emissions. Sea level rise and subsidence have become increasingly concerning issues, resulting in the problem of "high waters" or "acqua alta". To protect the lagoon from tidal floods, the MOSE mobile barrier system has been installed at the three lagoon inlets.

The aim of the project is to provide a basic understanding of the potential use of MOSE as an ecological management tool for the Venice Lagoon, in a near future scenario where the prolonged closure of the lagoon requires adequate water circulation: in particular, the possibility of creating combinations of circulations by selectively opening and closing inlets depending on the tides is explored. This presents a number of challenges, including representing through numerical methods the rapidly changing and localized dynamics of the lagoon and its complex interaction with human-made structures.

A variety of approaches have been explored to address the problem, including conceptual models based on straightforward assumptions that have evolved through differential calculus to yield simple formulae. In addition, experiments in hydraulic tanks and numerical simulations of these experiments have been conducted, culminating in high resolution numerical simulations using SHYFEM (Shallow water HYdrodynamic Finite Element Method).

In the latter case, the problem is translated into a numerical model based on real data and a thorough examination of input parameters. Circulation simulations of the lagoon using recorded forcings, such as tide levels at the inlets, wind data, river run-off, solar radiation, temperature, and salinity, have been performed, including during the MOSE closures, and the outcomes have been compared to the model. The primary parameters that influence the exchange between the lagoon and the sea basin have been identified, and a comprehensive study of each parameter, individually or in combination, is to be conducted. Although further research is underway to refine and extend the analysis, the current findings, as depicted in Figure 1, already demonstrate the significance and complexity of comprehending lagoon dynamics.

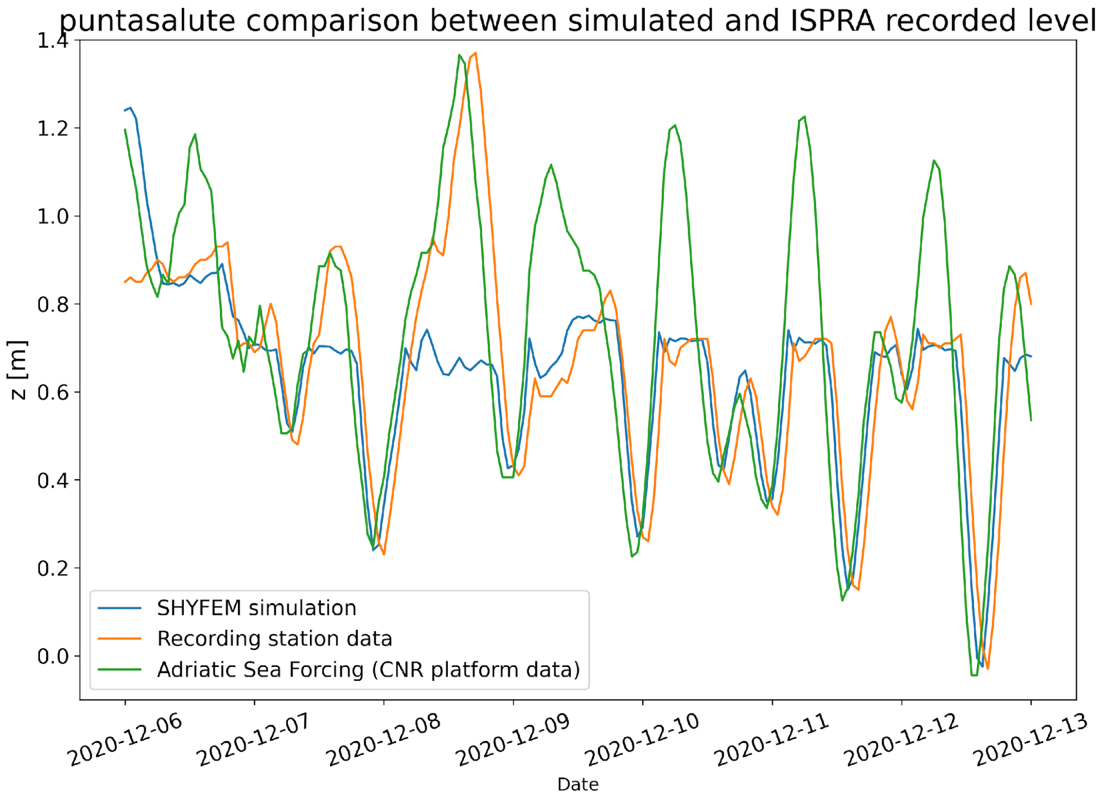


*Figure 1. Comparison between simulated and recorded data during a closure event in December 2020. The station is located in the city of Venice and represents a reference for the MOSE mobile barrier system closing operations. The simulations involve a few closures which were not performed in reality because of poor accuracy in tide forecast.*

**Acknowledgement**

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# Marine Propeller Noise Propagation in a confined canal

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Keywords: underwater acoustic, propeller, Ffowcs-Williams and Hawkings, FDTD

The Full Acoustic Analogy (FAA) has been proposed to evaluate the noise generated by an immersed object in motion. This methodology is then applied to a ship's propeller to study the propagation of noise generated in a confined channel. The development of this methodology is necessary to obtain an accurate estimate of the noise emitted by sailing vessels in order to mitigate the impact on marine fauna [1].

The FAA [2] methodology is defined in three different steps: the first is a computational fluid dynamic simulation (CFD) of the problem of interest to obtain the hydrodynamics fields velocity and pressure; in the second step the Ffowcs-Williams and Hawkings (FW-H) equation is applied to the hydrodynamics fields to obtain the acoustic pressure; and in the final step the acoustic pressure is propagated in a heterogenous domain solving the acoustic wave equation with the Finite-Difference-Time-Domain (FDTD) method [3].

The FAA methodology is then applied to a marine propeller [4] confined in a canal (Fig. 1), where the propeller is positioned at the center of the canal, 5.5 m below the free surface. Along the x-direction, open-boundary conditions are implemented, which allows the acoustic waves to exit the numerical domain and mimic an infinite canal. On the lateral and bottom boundaries, perfect reflection conditions are considered to mimic the presence of a very high-density material compared to the water present in the canal.

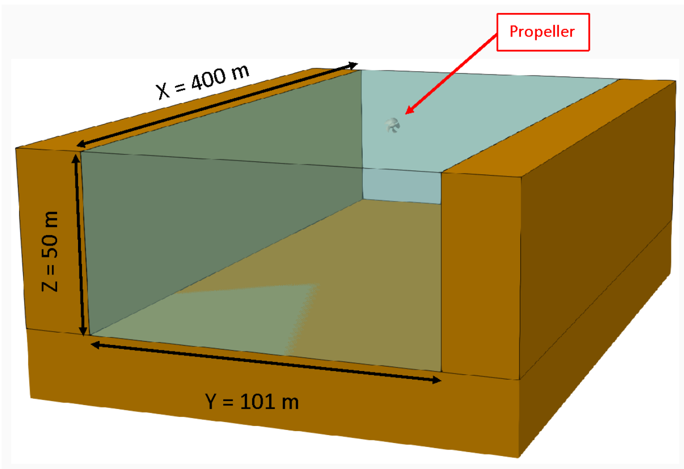


*Figure 1 - Schematic of the canal.*

In Figure 1 we show the SPL, which is an estimation of the acoustic energy, on the y-z plane passing through the propeller. The acoustic energy map shows a complex pattern. Near the free surface at the top of the plane, we observe a shadow zone of insonification. Along the bottom edge of the canal, an increase in acoustic energy is observed along with a two-zone of relative minimum. The observation of these relative minima and maxima is related to the presence of the two corners that interact with the acoustic waves generated by the propeller. Another important aspect is the fact that the acoustic field is not symmetric with respect to the center of the canal. This is caused by the rotation of the propeller, and how the acoustic waves generated interact with the free surface.

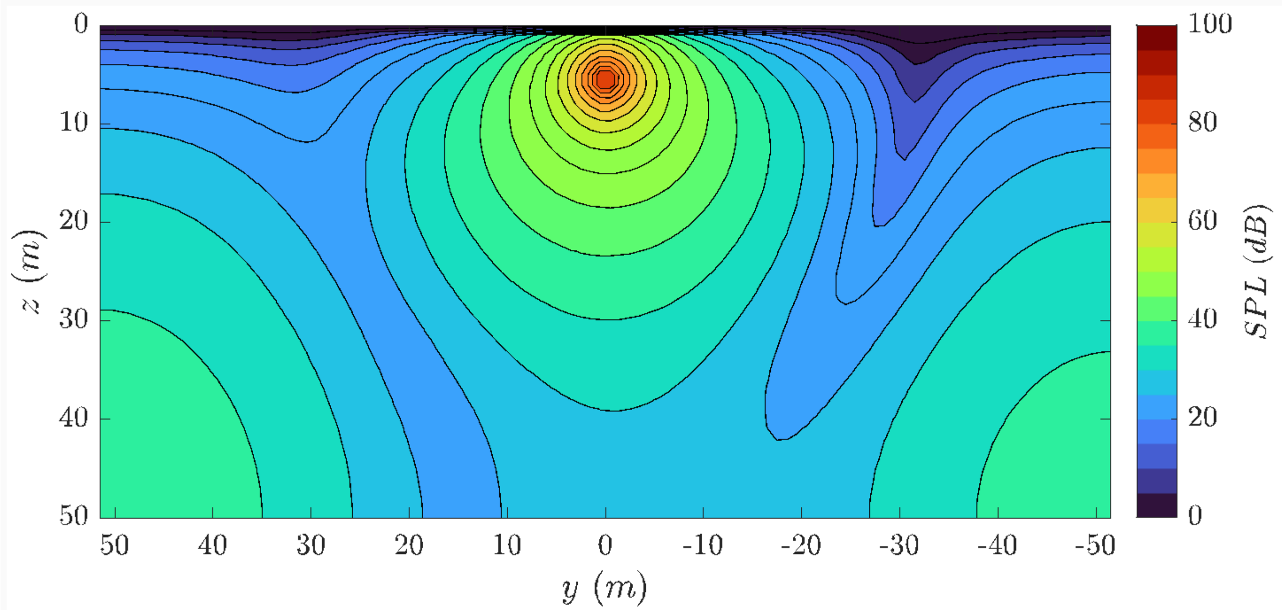


*Figure 2 - SPL of the YZ plane passing through the propeller.*

The CFD simulation required to evaluate the hydrodynamic fields was carried out using the HPC infrastructure due to the computational cost associated with the simulation. The acoustic wave equation is solved using an in-house acoustic solver written in Julia. The parallelization of the acoustic solver is based on the openMP paradigm and has been tested on the CINCA cluster.


**Acknowledgement**

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# GANs for integration of deterministic model and observations in marine ecosystem

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Keywords: deep learning, MedBFM, marine ecosystem.

Improving the capability of monitoring and forecasting the status of the marine ecosystem has important implications especially considering the changes caused by human activities. An unprecedented improvement in monitoring the oceans has arisen from satellite sensors and in situ instruments, such as float.

These instruments do not need human intervention and provide profiles while the battery lasts, however, they are expensive and thus perform relatively few measurements compared to the whole area to cover. Satellites cover with high resolution the whole marine domain but only at the surface and they suffer from cloud cover. Deterministic models have been exploited to simulate the marine environment. However, uncertainties in parameterization and high computational costs can impact their reliability and applicability.

The incorporation of machine learning offers alternative and stimulant opportunities for advancing the capacity of integrating theory, knowledge and observations to simulate the marine environment. The deep learning method proposed is based on the approach of filling missing pixels of a considered image, which is a computer vision task referred to as image inpainting. This method has been created specifically to synthesize visually realistic, coherent, and semantic plausible pixels for missing regions. We exploit its architecture to assemble a model capable of skilfully reconstructing the physical and biogeochemical variables and also to fill the information gap provoked by the inhomogeneity of in-situ observation.

The first ML model that we will introduce, named EmuMed, learns spatial and temporal relationship among the marine ecosystem variables starting from the deterministic model MedBFM output. The second ML model, that we define is InpMed, adds observations to EmuMed while maintaining the same architecture of EmuMed. We remark that modeling marine ecosystem variables by ML presents several challenges. First of all, marine datasets span four dimensions (i.e., temporal, vertical and two horizontal) which are characterized by different scales and units.

Moreover, unlike many ML applications, in geosciences we cannot rely on ground-truth data.
We select a convolutional-based architecture, as it is naturally suitable for dealing with spatial data. The main idea was to treat horizontal maps of the considered domain as images that capture the marine environment as if it were photography, where the classical RGB channels are substituted with channels representing the marine variables. Indeed, in images, the three colors channels are strongly interrelated and dependent on each other, as they need to collaborate to produce a whole range of colors. Similarly, we aim to introduce an intrinsic strong relation between marine ecosystem variables as they are also naturally correlated.

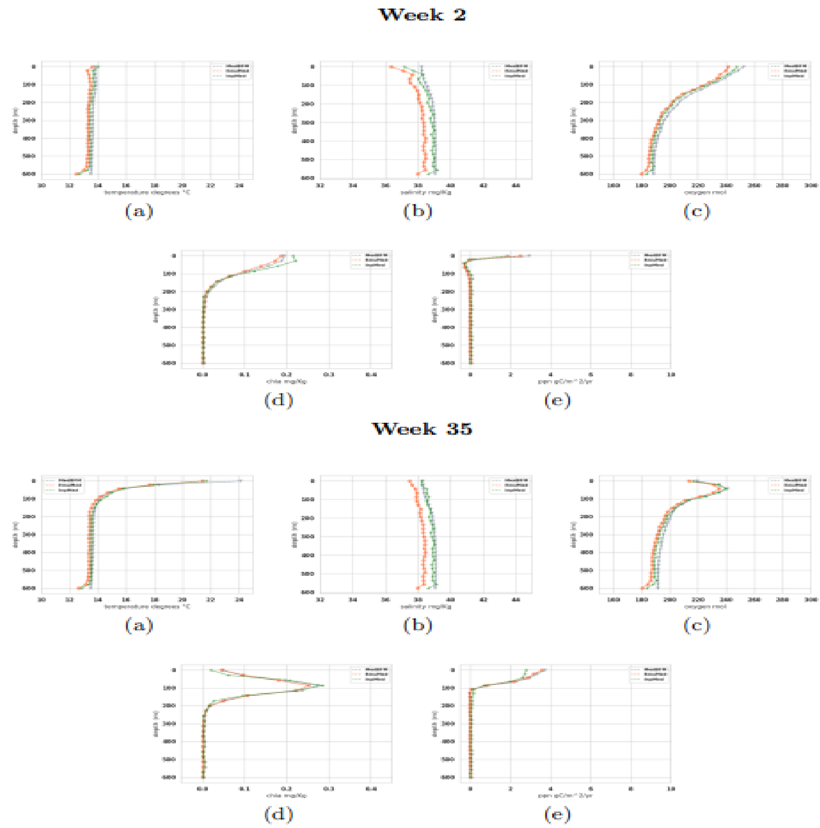


*Figure 1. Vertical profile of the spatial averages, varying with depth. Variables represented are: (a) temperature, (b) salinity, (c) oxygen, (d) chlorophyll, (e) primary production. The gray line is the MedBFM profile, the orange line is the EmuMed profile, and the green is the InpMed profile.*

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# Temporal stability and chaos in a complex marine biogeochemical model

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Although non-stationary dynamics have been observed in nature [1,2], it is still unclear whether these behaviors are inherent to ecological systems or whether they are the result of external forcings. To understand how rarely non-stationary dynamics occur in ecosystems [3], we first analyzed a complex biogeochemical model. Second, we modified the food web structure of the model to understand how the interaction network among living species affects stability. To investigate the stationary regime of the biogeochemical model, we performed a sensitivity analysis in which we perturbed all parameters and initial conditions over 35000 samples. We found that about $30\ %$ of the samples exhibit non-stationary dynamics for the living species, although the majority of these trajectories exhibit small oscillations and can therefore be considered the result of quasi-stationary dynamics. Nevertheless, such trajectories may play a key role as they may resonate with an external noise. Moreover, we distinguished chaotic from periodic non-stationary trajectories based on the Lyapunov exponents ($\sim 10\ %$ turned out to be chaotic). The rarity of large fluctuations confirms the idea that complex models are stable.

We found that one of the mechanisms leading the system to non-stationary dynamics is related to the initial phosphate content and two parameters regulating the flux of elements in microzooplankton. At low phosphate levels and high values of the latter parameters, some biological species are extinct and the trophic network adopts a chain-like structure; in such a scenario, the ecosystem exhibits non-stationary dynamics.

By changing the way the model describes the structure of the food web, we looked for the reasons for its stability. We performed a sensitivity analysis for several food webs and found that features such as omnivory and center of gravity of trophic levels are critical for the stability of the web. In particular, omnivory has a stabilizing effect only for food webs with a low center of gravity; otherwise, a destabilizing effect on the system is observed, likely due to increased predation at lower levels.

Our results support the widely accepted hypothesis that predators that can feed on a variety of prey, possibly at multiple trophic levels, are associated with stable ecosystems.

**Acknowledgement**

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# Geodetic time series and velocity field in NE-Italy

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Keywords: GPS, deformation, time-series, GAMIT/GLOBK, processing

The Global Navigation Satellite Systems (GNSS) represent a source of globally extended data of undeniable importance for a wide range of applications, from the crustal deformation analysis to the near-surface processes monitoring, surveying and many others. Furthermore, multi-constellation and multi-frequency signals, become available in recent years, favored the development of cutting-edge processing algorithms devoted to the integration of different sensors and improvements of error mitigation procedures.

North-East Italy is a tectonically interesting region since it is located on the northern front of Adria plate, which is moving against Eurasia plate with consequences on regional deformation and seismicity. OGS contributed to the regional seismic hazard assessment with the installation of a permanent GNSS network, FReDNet, consisting currently of 21 sites distributed throughout the region of interest, continuously providing real-time data and accessible through a public ftp repository (Bragato et al., 2021). FReDNet data are processed with GAMIT/GLOBK software package (Herring et al., 2018) in combination with the data coming from other geodetic networks covering the northern Italy and surrounding areas, in order to place the regional deformation in a broader tectonic context.

Since the huge number of stations (we processed data coming from ~360 sites), GAMIT/GLOBK requires to divide the stations into smaller groups with some sites in common, to process them separately, and then to combine the results. We started dividing the stations depending on their belonging to regional networks (i.e. subnetwork-1 indicates all the stations of GNSS network Antonio Marussi, subnetwork-2 indicates all FReDNet stations, subnetwork-3 indicates Veneto GPS network sites, and so on). However, due to the variable number of dismission/installation of stations with time, the subnetworks finally counted a highly variable number of stations. If we consider that a big subnetwork can play a major role in the procedure with respect to a small subnetwork, hence it is plausible to hypothesize that the different sizing of the subnetworks used in the processing may cause an impact on the results, especially in a study area where the expected horizontal deformation is of the order of few mm/yr. Furthermore, some sites in common among all the subnetworks have been repeated 4-5 times, thus overtopping other sites and potentially propagating eventual bad data to all the subnetwork solutions.

In order to overcome these issues, the year 2022 has been deputed to adjust the processing procedure by adopting a dynamic subnetting strategy which allowed to split the stations into subnetworks of similar size before being processed. Thanks to the *netsel* program included in the GAMIT-GLOBK package, the stations have been divided into groups which are different for each processing day depending on the daily data availability (Figure 1). We tested the new procedure on the Galileo100 cluster.

Furthermore, the Galileo100 calculation resources allowed us to re-process the whole dataset using the new procedure with the dynamic subnetting, to update the reference frame for the solution stabilization from ITRF08 to IGb14 (Altamimi et al., 2017), to test the effect on the resulting time series of different parameters (atmospheric tides, radiation pressure model, magnetic field, Venus and Jupiter perturbations, etc.), to obtain a new velocity field expressed in IGb14, and hence in Eurasia-fixed reference frame ETRF14 (Altamimi et al. 2017).

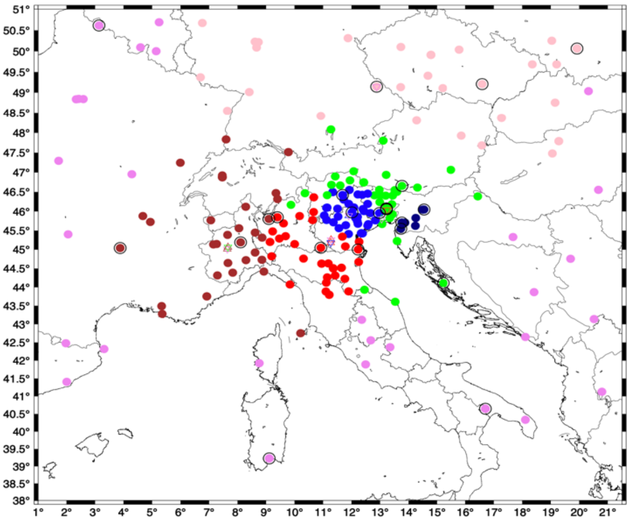


*Figure 1. Location of the stations available for one day (day 2018, 20th February in the figure). Colors indicate the belonging subnetwork. Black circles indicate the sites in common between the subnetworks.*


**Acknowledgement**

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# z-coordinates for accurate representation of free-surface flows in coastal ocean models

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Keywords: multi-layer ocean models, vertical coordinates, tracer constancy

Ocean model performances are highly related to the vertical coordinate system implemented. z-coordinate vertical discretizations, based on fixed interfaces parallel to the geo-potentials, are attractive when simulating stratified flows because the z-interfaces are well aligned to the isopycnals and the internal pressure gradient term does not suffer from pressure gradient error. However, fixed grids have issues with the moving boundary represented by the free surface. For this reason, z-coordinate ocean models are coded with a surface layer with varying but not-vanishing thickness, which limits the vertical resolution in areas with high tidal range.

We propose a z-coordinate algorithm for ocean models which, thanks to the insertion and removal of surface layers, can deal with an arbitrarily large tidal oscillation independently of the vertical resolution. The algorithm is based on a classical two steps procedure used in numerical simulations with moving boundaries (vertical grid movement followed by a grid topology change, that is insertion/removal of surface layers) which leads to a stable and accurate numerical discretization. With ad-hoc treatment of advection terms at non-conformal edges that may appear due to insertion/removal operations, mass conservation and tracer constancy are preserved. This algorithm, called z-surface-adaptive, can be reverted, in a particular case when all layers are moving, to other z-surface-following coordinates, such as z-star.

We look at a second potential drawback of fixed interfaces with a free surface. z-coordinate ocean models may be affected by additional numerical mixing near the surface with respect to z-surface-following coordinates (sigma, z-star, etc...) because of the possibly large oscillating vertical velocity triggered by the tidal oscillation. We investigate such spurious mixing theoretically and numerically, revealing the dependencies from the external forcing (tidal characteristics, stratification profile) and the numerics (vertical advection scheme, vertical grid size).

With simple analysis and realistic numerical experiments, we compare the surface-adaptive-z coordinate against z-star and we show that it can be used to simulate effectively coastal flows with wetting and drying.

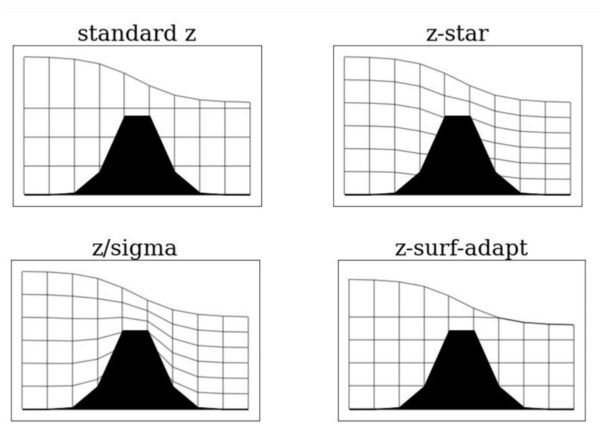

*Figure 1. Different types of z-grids. Top left: standard z-coordinate with first layer of variable thickness. Top right: z-star coordinate. Bottom left: hybridization between z and sigma coordinate. Bottom right: the novel z-surface-adaptive coordinate.*

**Acknowledgement**

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# Deep learning approach to automatically interpret Grounding Zone Wedges in Antarctic seismic stratigraphic data

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Keywords: Deep learning, Seismic stratigraphy, Antarctic ice-sheet

The interpretation of glaciogenic sedimentary features in the Antarctic marine seismic stratigraphic record, combined with lithological/age constraints from drill sites, provides many insights into past ice-sheet fluctuations. Erosional surfaces, massive diamicton on the Antarctic continental shelf and Trough Mouth Fans are associated with continental margin expansion and are good indicators of ice-stream flow during past glacial advances. Paleo-ice-stream stationarity, during ice retreat or advance across the continental shelf is indicated by the presence of stacked sediment depocenters (Grounding Zone Wedges, GZWs). Seismic interpretation is however time-consuming, and relies on expert judgment, and as such it is difficult to quantify uncertainties in the interpretation. Machine learning applications can (1) reduce the time needed for seismic interpretation, (2) provide quantitative uncertainty estimates to detected sedimentary features. Here, as a first attempt to apply machine learning to the Antarctic marine seismic stratigraphic record, we train deep Convolutional Neural Networks (CNNs) to identify GZWs. The CNNs are trained using two seismic profiles from the Ross Sea intersecting the same GZW and the deep Sea Drilling Project DSDP272 site. The seismic profiles are segmented, in order to provide a number of training examples sufficiently high. The trained CNNs are then first validated over the original, full size seismic profiles, and then applied to a seismic profile acquired from a different Ross Sea area, where a GZW feature is identified. We will discuss preliminary results, challenges and limitations in this application, which has the potential to greatly speed-up and integrate the traditional human-based interpretation.

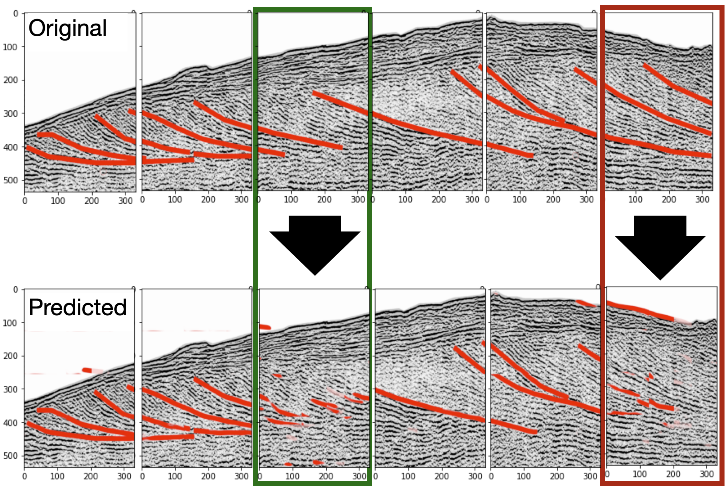


*Figure 1. Example of preliminary result obtained by Neural Networks trained with one seismic image split in 6 sub-images.*

**Acknowledgement**

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# Modeling atmospheres and climates of terrestrial planets: computational challenges

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Keywords: radiative transfer, planetary atmospheres, habitability, Archean Eon

The topic of planetary habitability stands at the crossroad between several disciplines, including astrophysics, geophysics and astrobiology, and it is related both to longstanding questions about the distant past of Earth, Mars and Venus, and new ones regarding the ever increasing number of known rocky exoplanets. Examples of these include, respectively, the still-unsolved Faint Young Sun problem (Sagan & Mullen, 1972) and the recent efforts to model the planets in the TRAPPIST-1 system (e.g. Wolf, 2017).

Planetary habitability is defined in terms of the physical conditions on the surface of a planet. Chief among these are the temperature ($T_s$) and pressure ($P_s$), that must allow for the existence of liquid water. This requirement is fundamental for the development of terrestrial life and Vladilo & Hassanali (2018) have suggested that it might be true in general for chemistry-based lifeforms. Precisely determining $T_s$ and $P_s$ is generally not possible due to the limited astronomical or geophysical data, thus the task of constraining their values falls onto climate models.

Climate models come in a large variety of complexity levels, from simple single-column, Radiative-Convective Equilibrium Models (RCEM) to 3D General Circulation Models (GCM) . Increasingly complex models are able to capture a larger number of climate feedbacks at the cost of numerical efficiency. In this presentation, we give both an overview and an example of application of the Earth-like planets Surface Temperature Model (ESTM). ESTM is an low-to-intermediate complexity seasonal-latitudinal energy balance model with an enhanced description of the diffusion coefficient (Vladilo et al., 2015, Biasiotti et al., 2022). It can capture the main climate feedbacks, such as the ice-albedo feedback, while maintaining the low computational cost required to effectively explore the planetary parameter space.

Irrespective of their structure, all climate models require a vertical radiative transfer (RT) model in order to assess the energy exchanges between the planet and outer space, by calculating the infrared Outgoing Longwave Radiation (OLR) and the Top-Of-Atmosphere (TOA) albedo. The RT model that we coupled with ESTM is EOS (Simonetti et al., 2022). EOS is a derivative of the GPU-based and open-source HELIOS (Malik et al., 2019) and HELIOS-K (Grimm et al., 2021) codes, adapted to the study of the relatively cold atmosphere of rocky and potentially habitable planets. Absorption opacity is evaluated on a finely spaced line-by-line grid using updated line lists (i.e. HITRAN2020, Gordon et al., 2022) and Rayleigh scattering is treated under the two-stream approximation, following the enhanced formulation of Heng et al. (2018). Collision-Induced Absorption (CIA) features e non-Voigtian absorption lines (e.g. Perrin & Hartmann, 1989) are also considered.

In this presentation we show two recent applications of the coupled EOS-ESTM model concerning the climates of the Archean Earth and the impact of ozone on the planetary emission spectrum. In the first case we tested 11 different nitrogen-dominated atmospheres with different amounts of CO2 (ranging from 0.01 to 0.2 bars), CH4 (ranging from 0 to 1000 ppm) and two values of N2 pressure (1.0 and 0.4 bars). The seasonal-latitudinal $T_s$ profile has been evaluated at 6 different points in time during the Archean Eon, between 4.0 and 2.5 Gyr by appropriately considering the insolation (Gough, 1981), the rotation period (Bartlett & Stevenson, 2016) and the fraction of continents (Collerson & Kamber, 1999). The average global $T_s$ has then been compared to the values inferred from geological records (Figure 1, left panel). In the second case, we tested the effect of removing an Earth-like ozone layer from a modern Earth N2-O2-CO2-CH4-H2O atmosphere on the planetary emission spectrum (Figure 1, right panel). Apart from the obvious disappearance of the O3 absorption band, the change in the vertical thermal structure of the atmosphere modifies the depth of the other absorption features, most notably the CO2. This introduces a degeneracy that must be explored in preparation for future astronomical observations of rocky, temperate exoplanets.

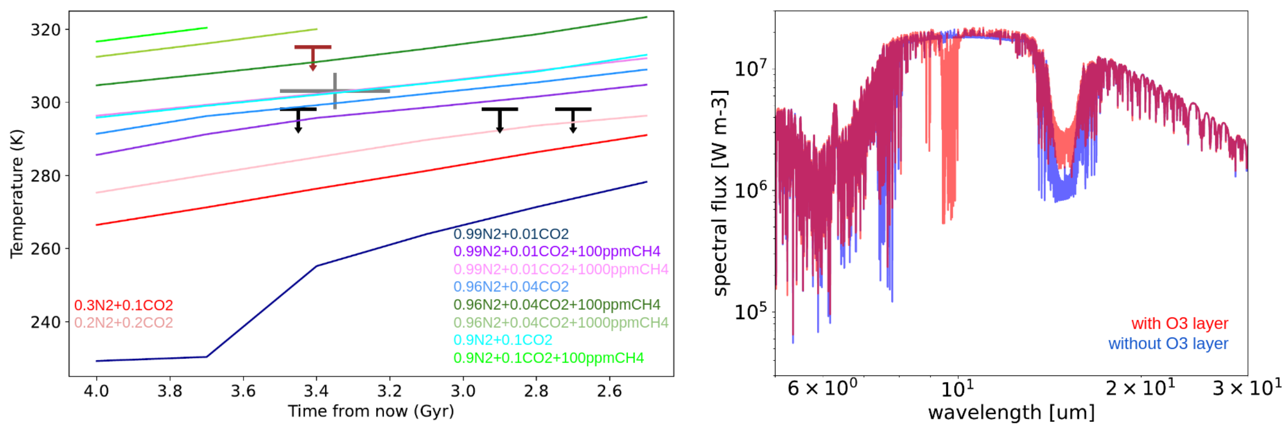


*Figure 1. Left: the average surface temperature as a function time during the Archean Eon for the different atmospheric compositions (described in the legend). Values are in bars unless otherwise specified. Brown, gray and black data points come from Hren et al. (2009), Blake et al. (2010) and Krissansen-Totton et al. (2018), respectively. Right: the synthetic planetary emission spectrum for two modern Earth-like atmospheres. The blue curve has been obtained by removing the ozone layer.*


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# Identification and petrophysical characterization of an area potentially suitable for underground hydrogen storage in North-East Italy

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Energy production from renewable sources is globally viewed as a key solution to abate greenhouse gas emissions. Utilizing renewable energy can help meet climate targets by replacing use of carbon-intensive fossil fuels in the energy sector (Edelenbosch et al., 2017; Lazarou et al., 2018).

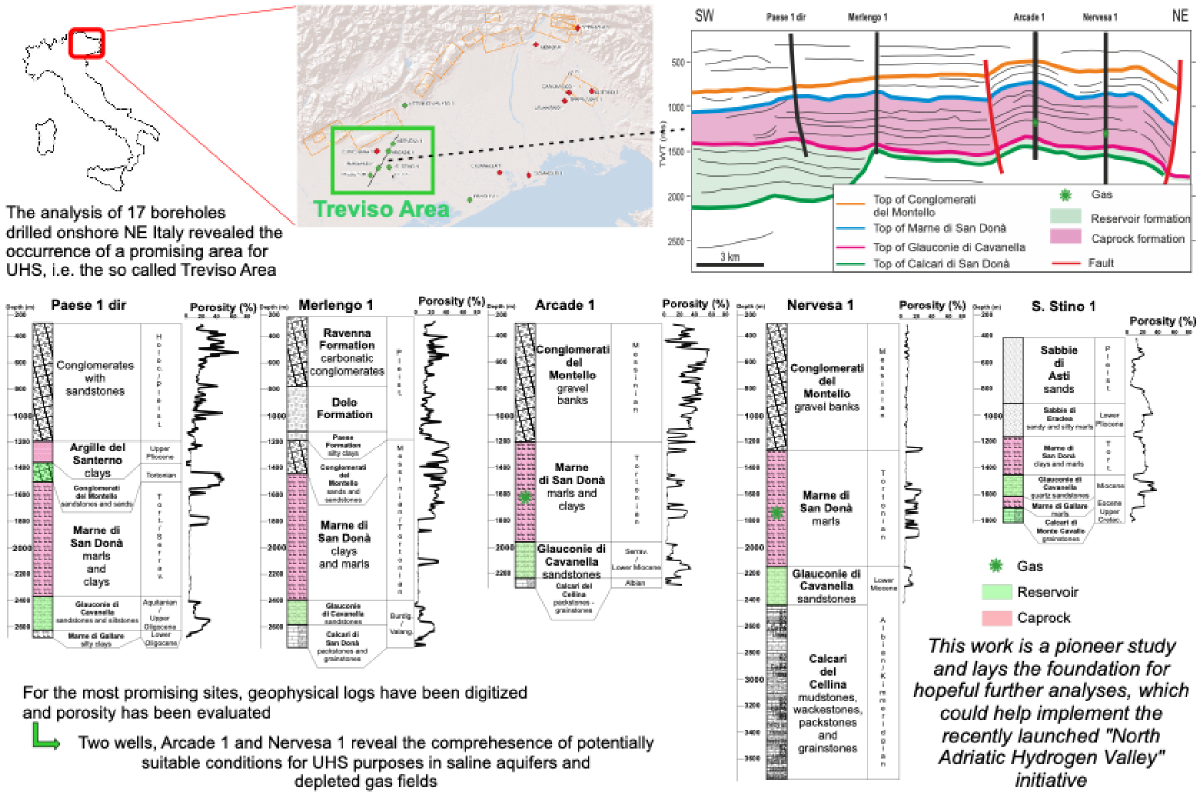
However, due to their intermittent nature, which causes energy excesses or deficits, renewable energy has to be associated with a long-term storage medium (Heide et al., 2010; Engeland et al., 2017; Muhammed et al., 2022). One of the options to balance renewable energy fluctuations is the conversion of surplus energy into hydrogen and its underground storage (Tarkowski, 2019, Heinemann, 2021). Consequently, hydrogen is an attractive option for the renewable energy industry and the transition toward a low-to-net-zero carbon society, which requires large-scale storage technologies to be developed and implemented (Hashemi et al., 2021; Pinel et al 2011; Denholm & Mai, 2019).

Our study focussed on the identification of an area potentially suitable for underground hydrogen storage (UHS) in North-East Italy, by using publicly available well data from the ViDEPI catalogue (Visibility of Petroleum Exploration Data in Italy) (https://www.videpi.com) ((Mattera et al., in press).

The target of the analysis was to find geological formations suitable for this purpose, and in particular: 1. A reservoir formation constituted by rocks with good porosity and permeability to hold the injected hydrogen (for example sands or sandstones); 2. A caprock formation above the reservoir with a very low permeability, in order to avoid any hydrogen leakage to the surface (clays or marls).
The most promising area, known as “Treviso Area”, consists of both saline aquifers and depleted gas fields, two attractive geological media for the underground hydrogen storage, widely used for $CO_2$, methane, and other gasses storage. One of the key petrophysical properties, i.e., porosity, was calculated for each of the five wells revealing conditions potentially suitable for UHS by applying empirical formulas to geophysical log data (Mattera et al., in press).

This work is a pioneer study and lays the foundation for hopeful further analyses, which could help implement the recently launched "North Adriatic Hydrogen Valley" initiative.

FIRST ASSESSMENT OF AN AREA POTENTIALLY SUITABLE FOR UNDERGROUND HYDROGEN STORAGE IN ITALY




*From Mattera et al. (in press)*

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*24th January 2023, Trieste*

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| | |
|---|---|
| CIMA | International Centre on Environmental Monitoring |
| CINECA | Consorzio Interuniversitario Cineca |
| CMCC | Euro-Mediterranean Center on Climate Change |
| CNR - ISMAR | National Research Council - Marine Science Institute |
| CNR - ISAC | National Research Council - Institute of Atmospheric Sciences and Climate |
| ECORD | European Consortium for Ocean Research Drilling |
| HPC-TRES | High Performance Computing - Training and Research for Earth Science |
| ICTP | The Abdus Salam International Centre for Theoretical Physics |
| INAF - OATs | National Institute of Astrophysics - Trieste Astronomical Observatory |
| INGV | National Institute of Geophysics and Volcanology |
| LAMMA | Environmental Monitoring and Modeling Laboratory |
| NORCE | Norwegian Research Center |
| OGS | National Institute of Oceanography and Applied Geophysics |
| POLITO | Polytechnic University of Turin |
| UNIGE | University of Genoa |
| UNIMIB | University of Milano - Bicocca |
| Unisalento | University of Salento |
| UNITS | University of Trieste |

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