HPC-TRES

High Performance Computing Training and Research for Earth Sciences

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National Institute of Oceanography and Applied Geophysics

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Foreword

The Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (National Institute of Oceanography and Applied Geophysics) - OGS and CINECA, the largest Italian computing centre, drew up an agreement[1] to implement a training program focussed on High Performance Computing (HPC) applications for Earth Sciences, the **"HPC Training and Research for Earth Sciences" (HPC-TRES)**. The program is co-sponsored by the Minister of University and Research (MUR) under its extraordinary contribute for the Italian participation to activities related to the international infrastructure PRACE – The Partnership for Advanced Computing in Europe[2].

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, litosphere and biosphere) and numerical models, the latter considered as a strategic cross-cutting element for modelling activities. These objectives will be pursued through the use of national and European HPC infrastructures and services in the framework of PRACE, the optimization of algorithms and numerical codes, the optimal management of "Earth Sciences Big Data", and the graphical visualization techniques for multidisciplinary applications in the Earth Sciences, also in the frame of the "Blue Growth" strategy.
Therefore, HPC-TRES agreement will establish, sponsor and oversee **training and research awards** (i.e. contributes for training and research activities set up according to current regulations that regulate scholarships – to be also used for masters and specialized courses in HPC -, research grants and PhDs) that will support the research lines **scientific plan**[3] **of the HPC-TRES program**.

Some Italian research groups and institutions (INGV-Pisa, CNR/ISAC, CNR/IGG, CMCC, ICTP-ESP), where the external members of the HPC-TRES Steering Committee lead their research activities and personally contributed to define the scientific plan of the HPC-TRES program, have already subscribed the HPC-TRES initiative, offering logistic support and hospitality to the winners of the training and research awards sponsored by OGS.
OGS recognizes the scientific excellence of the hosting institutions as strategic to the educational and professional growth of the awarded young researchers. OGS is committed to extend the participation to the scientific plan to other national research groups involved in HPC applications for Earth Sciences (2016: MOX-Polimi, ENEA-SSPT, INGV-SST, INGV-CNT, Univ. Bicocca, CRS4; 2017: EURAC, ARPA-FVG; 2018: CIMA; 2019: Univ. Trieste; 2020: Consorzio LAMMA; 2021: Univ. Trento; 2022: INAF-OATs; 2023: Univ. Cagliari), so that these groups could propose new training and research activities for the next HPC-TRES Calls.

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 HPC-TRES programme was structured into a Joint Research Unit (HPC-TRES JRU)[4].

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[1] OGS BoD document n. 7.4.2014, date 18/06/2014.

[2] www.prace-ri.eu

[3] The scientific plan was initially written by the HPC-TRES Steering Committee, jointly appointed by OGS and CINECA (OGS BoD document n. 15.9.2014, date 18/12/2014) and composed by scientific experts involved in different HPC applications for Earth Sciences. It is annually updated with new research lines.

[4] OGS BoD document 14 ADW, date 25/02/2021.

This document presents the scientific plan of the HPC-TRES programme, gathering the research lines proposed and carried out by Italian researchers belonging to the HPC-TRES network. The research lines are structured into five topics: HPC for Oceanography and Biogeochemistry modelling (A), HPC for Solid Earth modelling (B), HPC for Earth System modelling (C), HPC for Climate Sciences (D), and "BigData" in Earth Sciences (E). Each research line lists the Principal Investigator (PI) and collaborators, along with references to current or past HPC-TRES grant fellows.

Topic A: HPC for Oceanography and Biogeochemistry modelling

Line A1. Biogeochemical forecast skill assessment for Operational Oceanography

In the frame of the European initiatives for Operational Oceanography (e.g. Copernicus Marine Environment Monitoring Services - CMEMS, http://marine.copernicus.eu/), this research line aims at providing numerical tools able to evaluate and improve the reliability and the uncertainty of the operational forecasts produced by coupled physical-biogeochemical models. This activity has important consequences for: 1) support environmental agencies and other stakeholders with useful indications related to the definition of the targets for the Good Environmental Status, as described in the Marine Strategy Framework Directive, and 2) assess the climate projections impacts on the marine biogeochemistry and ecosystems.
Biogeochemical models have different degrees of complexity, and are usually characterized by a high number of parameters: the global sensitivity analysis approach must be based on a large number of independent simulations, such as an ensemble of $O(10^4)$ members, in order to evaluate the model sensitivity to each parameter. HPC can greatly support this activity by widening the ensemble set, initially to assess the model sensitivity (as in the PRACE GSENSMED project), and then to effectively support operational forecasts.
Optimization of data assimilation (DA) schemes for the operational biogeochemical modelling constitutes another strategic activity of this research line. Presently, the computational time requested for the convergence of the DA scheme for one single day of analysis is comparable to that one necessary for the completion of a 17-day operational run in the CMEMS workflow for the short-term forecasts of the Mediterranean Sea biogeochemistry.
The multi-platform and multi-variate data assimilation constitutes a state-of-the-art issue of this research line. In the frame of the CMEMS-MASSIMILI project, we have developed a novel DA system to assimilate the data provided by the Mediterranean Bio-Argo floats network into the CMEMS operational model, which is now operational.

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Line A2. Evolution of Individual-Based Models towards exascale computing ("Exafish")

Currently most of the biogeochemical and ecosystem models are still based on the assumption that living organisms are homogeneously distributed over the volume defining a model domain cell, as if they were dissolved chemical compounds. In fact, while it is obvious that organisms are discrete entities and should be regarded as such, the use of Individual-Based Models in describing marine biogeochemistry and ecosystem dynamic has been hindered by the intrinsic complexity of the system to be described and the computational load required for comprehensive simulations over realistic spatial domains. The possibility offered by recent HPC developments might give a new boost to this field. A challenge is to describe the time evolution of the interaction between different typologies of organisms within a food web, each type being defined by an ensemble of slightly different individuals. A second challenge is to use exascale computing to simulate the spatial-temporal dynamics of the resulting huge number of interacting organisms by means of a Lagrangian approach. A third challenge is the analysis of the huge amount of data provided as model output, possibly also in order to derive ecologically based subgrid parametrization of biogeochemical and ecological processes.

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Line A3. Simulations of behaviours, responses, and adaptive and evolutionary characteristics of marine ecosystems

The goal of this research line is the development of new model paradigms and techniques, aimed to simulate behaviours, responses, and adaptive/evolutionary characteristics (also referred to as "traits") of the marine ecosystems, with a strong dependency on natural drivers (e.g. increasing of the temperature field) and anthropic pressures (e.g. environment management), and in relation to transport.
The new models will provide more realistic estimates of the effects related both to global long-term climatic changes and to local environmental policies on marine ecosystems and their resources. To this scope, novel algorithms will be designed and/or implemented to better represent transport processes, and their relationships with biogeochemical ones. This activity will request new ad hoc parameterization/discretization developments of the biogeochemical components, possibly also in a Lagrangian framework and using an individual based approach, together with novel programming techniques, and therefore covering technological and scientific challenges. The added value will be constituted by the development of new tools useful for ecosystem modeling and environmental management, contributing to the rise of a new ecological modelling community.
The resulting model will be used also to describe the levels of risk exposure to pollutants for coastal regions and biologically relevant marine areas. An additional challenge is the use of HPC capabilities to study transport patterns of target species and assess spatial-temporal transport-based connectivity, in order to increase the knowledge on marine ecosystems interdependence.

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Line A4. Parallelization of hydrodynamic finite element models

Hydrodynamic finite element models (FEMs) can be used to perform high-resolution simulations of areas characterized by complex geometry and bathymetry, such as lagoons, estuaries, coastal areas, lakes (though some FEMs are also applied for global ocean simulations[5]). Such models can be often legacy codes originally written for sequential

[5] e.g. FEOM, see http://www.awi.de/en/research/research_divisions/climate_science/climate_dynamics/methods/finite_element_ocean_model_feom/

execution, which appear today significantly limited given the possible applications able to exploit the larger availability of HPC resources.
An application of this research line is the parallelization of the Shallow water Hydrodynamic Finite Element Model (SHYFEM).

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Line A5. New algorithmic approaches for ocean models at exascale

Access to large computational capabilities allows increasing both the resolution and the complexity of ocean models/simulations. However, the efficiency of the current models has to be improved. One of the main limits is the low scalability of legacy codes on many core architectures, usually compromised by the data movement intended at different levels, such as communication, memory access, I/O, etc.
The research line aims at the re-design at algorithmic level of target ocean numerical models through the following steps: (a) definition of the main bottlenecks to the efficiency of parallel codes and the exploitation of the peak performance of the new generation HPC systems, (b) investigation of algorithms and innovative architecture-oriented technologies for the optimisation and parallelization of numerical simulation codes codes, and (c) exploitation of new approaches based on Domain Specific Languages (DSL) to guaranties performance portability, easy support for heterogeneous architectures (i.e. GPUs), separation of concerns between model development and HPC optimization.

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Line A6. Multi-component operational modelling systems for Regional Environmental Protection

Numerical modeling plays a key role in supporting the activities of the Regional Environmental Protection Agency of Friuli Venezia Giulia (ARPA FVG), providing quantitative cause-effect relationships within the DPSIR conceptual framework (Driving forces, Pressures, State, Impacts, Responses). ARPA FVG already manages operational modeling chains, based on the some numerical models running on the regional HPC facility (http://gridfvg.e-science.it/) such as WRF (for mesoscale numerical weather prediction system), FARM (for air quality forecast and assessment), SPRAY (for airborne pollutant dispersion at meso and microscale) and INEMAR (for regional Atmosphere Emissions Inventory). Further, many of ARPA functions deal with marine and coastal environment monitoring and management, whose area of interest includes the Gulf of Trieste and the Marano-Grado Lagoon.
Some specific needs have been identified, requiring an integrated, multi-component modeling system to be gradually assembled and set up in operational mode. In particular, short-term operational products (thermohaline fields and currents forecasts at ~5 days, both in Gulf of Trieste at ~1 km resolution and in Marano-Grado Lagoon at ~0.1 km resolution), medium-term

operational products: solar penetration, oxygen and chlorophyll concentration forecasts (same requirements as above), long-term operational and non-operational products. The latter are strategic both for sea (oil spill trajectory forecasting, forecasts and back-trajectories of transport of floating marine debris, forecast, assessment and scenarios of pollutants and nutrients dispersion from marine outfalls, forecast, assessment and scenarios of diffusion of pollutants carried by Tagliamento –microbiological- and Isonzo –mercury- rivers) and for the lagoon (assessment and scenarios of sediment transport and lagoon morphology).
Even if models and methods are already available and well assessed for each of the topics considered in the project, still some scientific and technological challenging efforts can be easily foreseen in the operational requirements for the modeling systems and in data collection, organization and management (in particular dealing with pollution sources and freshwater/groundwater inflows).
This research line should benefit from results expected from Line A4, "Parallelization of hydrodynamic finite element models".

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Line A7. Numerical models for sound propagation in stratified water basins

The propagation of an acoustic signal in a non-uniform field is a subject of paramount importance, given the growing and uncontrolled noise pollution present in the oceans, which has been reported for years by the scientific community, as a cause of severe discomfort against many underwater animal species. Marine fauna, especially cetaceans, rely on sound for a variety of life functions. Therefore, building on the need to understand the impact of underwater noise on marine fauna, the "bioacoustics" research field aids in investigating the potential shifts in animals' frequency of vocalizations and masking induced by exposure to anthropogenic noise.
The characterization of the noise source may be reproduced very accurately using Large Eddy simulations, coupled with the Ffowcs Williams and Hawkings model. The first reproduces in detail the noise sources: among the others, airguns for geological intrusive explorations, the wake of a propeller or the implosion of a cloud of cavitation bubbles. The acoustic model acts as a post processor on dynamic fluid data; it provides a time dependent pressure signal in specific points in space. The weak point of this approach, which appears as the state of the art in hydroacoustics and has become coveted by most shipbuilding companies, is that it assumes a uniform medium.
This assumption is somewhat oversimplified, since the underwater environment is by far not uniform, meaning that the water density changes in space due to variation of temperature and salinity along the water column. This causes the variation in space of the speed of sound. Also, the bottom and the free surface cause relevant effects of reflection and refraction. Idealized studies of the propagation of sound emitted by point sources in a stratified environment are present in recent literature.
In the present research line, the analysis will be extended to the more interesting case of more complex noise sources as those mentioned above. Specifically, the tailed characterization of the acoustic source and its propagation in stratified environments. The software used is an open source software, named OpenFoam, and it is suitable for modifications and additions of new modules. Tests and possible validations of the developed model can be based on cases of practical interest, such as ship propellers and airguns. The study will be carried out

numerically, taking advantage of high performance computational platforms. In fact the problem under investigation will require the use of unsteady massive parallel-architecture simulations over grid topologies composed of 10^8-10^9 grid cells. Also, the parallelization of the acoustic solver will certainly be performed, in order to optimize the computational process.

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Line A8. Study of the evolution of chlorophyll fronts through high resolution models, HF radars and data assimilation

To assess the impact of anthropogenic pollutants on marine and coastal ecosystems (including HNS, plastic marine litter, organic micropollutants, etc.) a large number of multi-disciplinary skills and tools is needed, such as observation systems (in-situ and satellite) and numerical models. Numerical models are fundamental tools to get a three-dimensional description of the main physical and biogeochemical processes, both to analyze past situations supported by observations, and to make predictions. Although models suffer from uncertainties that need to be reduced to make more accurate assessments, their support is essential in several fields. As an example, the space-time evolution of productive oceanic features (chlorophyll-a fronts), strictly depending on oceanographic flow field, is necessary to study the feeding habitat of a number of marine species. Satellites with low revisit time provide valuable observations of chlorophyll fronts but are not sufficient to characterize its subsurface structure. On the other hand, the modelling of the trajectory of pollutants of punctual and widespread origin, may suffer from the uncertainties affecting the hydrodynamic models output. Therefore, we consider necessary: 1) to increase the resolution of the numerical models in use, to allow the representation of fundamental physical and biogeochemical features for ecosystem assessments, currently not well described in most of the (operational) models in use; 2) to reduce the uncertainty of such models through data assimilation. The realization of such a model necessarily requires the support of high-performance computational tools.
The proposed activity will implement a combined physical-biogeochemical model in the North-Western Mediterranean area including the PELAGOS Sanctuary (a Specially Protected Areas of Mediterranean Importance). The area is of great importance both for the occurrence of significant oceanographic processes (including the development of the North Mediterranean current and deep water formation), and for the remarkable presence of marine mammals suffering from numerous threatening factors (ingestion of plastic marine litter and hydrocarbons). It is then important to rely on accurate numerical models to identify feeding habitats of cetaceans and assess the risks associated with the potential compresence of pollutants.
The benefits associated with the assimilation of data on a regional scale model will be assessed comparing the results from the use of already available models. Observations will include satellite data (available through CMEMS) and additional data coming from the HF radar network present in the North-Western Mediterranean, and made available through SICOMAR, IMPACT, SICOMARplus and SHAREMED projects.
In the first part the activity involves the implementation of models and procedures for reducing uncertainties. In the second part, the evolution of chlorophyll fronts will be analyzed. Comparisons between model outputs and satellite data will be carried out, together with the

results of feeding habitat models and cetacean sightings, available through the GIAS project, and in collaboration with other entities operating in the PELAGOS Sanctuary.

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Line A9. Development of a coupled 3D biogeochemical model for Hg cycling in the Mediterranean Sea

Coupled physical-biogeochemical-pollutants models can increase our understanding of pollutants' fate. Mercury (Hg) is a persistent pollutant of great concern due the biological interconversions to methylmercury (MeHg) in marine water, leading to bioaccumulation in plankton and trophic transfer to higher trophic levels resulting in increasing MeHg concentrations (biomagnification). Within the PRIN project ICCC (Impact of Climate Change on the biogeochemistry of Contaminants in the Mediterranean Sea), we developed a coupled model to simulate Hg cycling in the Mediterranean Sea based on the OGSTM-BFM transport-reaction coupled model, routinely used as the backbone of the biogeochemical component of the copernicus CMEMS135 Mediterranean system.

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Line A10. Development and implementation of a new bio-optical model for marine biogeochemical models

Improving the performance of the biogeochemical model system operational within the Copernicus Marine Environment Monitoring Service (CMEMS) is significantly related to the capacity of the model to correctly reproduce the interactions of the optical properties with the circulation and the biogeochemical cycles. The development of an optical module (with the aim to be embedded in the operational workflow) that may inherently solve the extinction coefficient as a function of the biogeochemical and physical properties, rather than being externally imposed as a parameter (e.g. from satellite measures), is the goal of this activity, which was the main objective of the CMEMS BIOPTIMOD service evolution project. Further this activity is connected to the H2020 SEAMLESS project where data assimilation is combined with bio-optics. The developments proposed in this research line are beneficial not only for operational oceanography but for the climate studies also, where, in the case of future projections, it is not possible to constrain the water turbidity with optical satellite observations but the optical properties have to be simulated as emergent properties.
In the framework of the BIOPTIMOD project we developed an ocean-atmosphere radiative transfer model that resolves the multispectral propagation of light, discretized in ~30 discretization bins, along the water column, and describes its interactions with phytoplankton, detritus and colored dissolved organic carbon. The forward model is based on a *3-streams* formulation resolving a direct stream, scattering and back-scattering. An inverse adjoint model based on the same assumptions of the *3-streams* forward model has been developed in the BIOPTIMOD project, whose scope is to infer biogeochemical properties according to the propagation of light. Future developments involve the testing of the forward and inverse

models on different cases and the inclusion of novel processes like raman scattering and fluorescence.
Technological developments regard the update of the atmosphere radiative model (OASIM model) with modern Fortran directives, in particular considering the fault tolerance aspect that is important in operational applications.
The possibility of porting the optical model, both its atmospheric and in-water components, into the GPU paradigm appears relevant especially in the foreseen transition from multispectral to hyperspectral applications, the latter characterized by hundreds light discretization bins.

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Line A11. Network of relocatable high-resolution short-term forecasting systems for monitoring the marine environment

Numerical models play an increasing role in the management of the marine environment by supporting the activities of several stakeholders such as environmental agencies, local authorities, tourist offices, aquaculture industries, fishermen and fishing companies. In such a context, digital twins of the ocean are also developed. One of the main challenges in ocean modelling is the increase of temporal and spatial resolution of the simulations, in order to allow a more realistic representation of both hydrodynamic and biogeochemical processes in coastal areas. Furthermore, data assimilation algorithms that integrate observational data sets into models' trajectories are essential to improve the accuracy of both hindcast and forecast products. Such datasets include surface temperature and chlorophyll concentration from satellite, in-situ data and surface currents from HF radar measurements. Lastly, the realistic representation of all the components of the earth system (atmosphere, ocean, land, cryosphere, biosphere, including humans) and the relationships among them is a further challenge for an increasingly accurate monitoring of the marine environment.
A relocatable forecasting system for short-term ocean forecasts has been developed at OGS: the system is based on the coupled physical-biogeochemical model MITgcm-BFM, and it is initialized and forced by the Copernicus Marine Environment Monitoring Service (CMEMS) and other available operational products (e.g., atmospheric forcing, river discharge rates, satellite data, in-situ measurements). The model can be implemented in selected areas of the Mediterranean Sea by downloading the open-source codes from GitHub, then installing and configuring the whole operational system (hydrodynamic and biogeochemical model and operational chain) according to the users' specific needs. This kind of forecasting system relies on the intensive use of supercomputing facilities, such as multi-node, parallel HPC platforms. Such platforms are essential to ensure a prompt solution of complex algorithms and ensemble simulations on high-resolution domains and the efficient storage of a large amount of I/O files. A network of local models could cover several sub-basins and coastal areas of the Mediterranean, enhancing the forecasting capabilities of CMEMS and involving local stakeholders in synergical monitoring activities.

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Line A12. Development and implementation of a stochastic marine biogeochemical model

In the last decades scientists have widely and deeply studied the role of random fluctuations on the dynamics of natural systems. The studies range from population dynamics, infectious diseases and epidemics, to bioinformatics, neuroscience and biological evolution. Important dynamical effects induced by the presence of stochastic processes have been also evidenced in natural ecosystems, in the bacterial growth in food products, and in the inception and development of diseases due to genetic mutations.
All these examples indicate that noise should not be considered merely as a source of disorder and uncertainty, but as a necessary and fundamental ingredient to correctly describe the dynamics of open systems and to unveil intriguing and counterintuitive effects.
This research line is devoted to include in marine biogeochemical models the effect of noise in terms of environmental fluctuations (e.g., temperature, solar irradiance), biogeochemical parameters (e.g., growth rate, nutrient affinity) and in general multiplicative noise on the population concentrations.
The investigation proposed addresses both simplified theoretical models in low dimensionality 0D, 1D, 2D models (e.g. Logistic, Rosenzweig - MacArthur, Fisher - Kolmogorov - Petrovski - Piskunov), GOTM-FABM-BFM in 1D and full blown 3D biogeochemical models like OGSTM-BFM used in the CMEMS MedMFC service.
Furthermore, this activity is connected to the H2020 SEAMLESS project where data assimilation is combined with stochastic modelling. The developments proposed in this research line are beneficial not only for operational oceanography but for the climate studies also, where, in the case of future projections, accounting for different regimes of stochastic fluctuations could be relevant.
Technological developments regard the update of the code including the fluctuation generators and the implementation of convenient infrastructures to perform simulations with a large number of members in order to perform robust statistical analysis.
The possibility of porting the OGSTM-BFM model on GPU will be investigated in order to optimize the realization of a large ensemble of stochastic simulations.

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Line A13. Numerical simulation of sediment transport within contourite depositional systems influenced by thermohaline bottom currents flowing along the continental slopes

Fluid-dynamics processes and hydro- and morpho-logic constraints control the developments of bottom-current deposits (contourites), which are priceless for paleoclimate studies, exploration of hydrocarbons and polymetallic nodules, geohazard, legal extension of continental shelf, and ecosystems and microplastics distribution.
This research line aspires to answer the following open questions: 1) what is the specific local fluid-dynamics process that controls the triggering and evolution of a contouritic sedimentary body and its morphology? 2) why does a bottom current-controlled contouritic deposit develop in a certain specific hydro-geo-morphological context?

To address the first question, ad hoc numerical simulations on an ideal setting are being developed and implemented to investigate the formation and evolution process of a contouritic drift, highlighting sediment transport and redistribution phenomena due to secondary circulations. A PhD thesis of the University of Trieste is investigating the interaction between the suspended sediment sourced by turbidity currents flowing cross-slope and the along-slope transport within contour currents. A turbidity flow along a straight inclined channel leading to an expansion table covered by sediment and swept by a transversal contour crossflow is considered. Initially, the two types of currents are independently analyzed to better understand their critical characteristics. Subsequently, the turbidity current will be analyzed in the case of contour crossflow, with particular attention to the possible mechanisms of sediment transport and contourite drift evolution.
The type of analysis to be conducted raises important computational issues, related to the need to accurately represent the dynamics of a highly non-stationary phenomenon in both time and space. To enable the investigation of representative domains, a thorough assessment of wall modeling techniques will be carried out, with the objective of avoiding the direct resolution of the near-wall viscous layer and, consequently, reducing the computational cost of the simulations.
Further developments to address the second question, will aim to combine, for the first time, a regional circulation modelling with basin morpho-sedimentary information to highlight seabed dynamics associated to deep thermohaline currents. This approach will imply to map the values of seabed shear stress and/or turbulence kinetic energy at the regional basin scale and analyse the results considering known critical shear stress to highlight areas of potential seabed mobility and the subsequent morphodynamic patterns.

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Topic B: HPC for Solid Earth modelling

Line B1. Numerical simulation of earthquake ground motion in three-dimensional models of the Earth's crust

Earthquake scenarios based on the solution of the wave equation in three-dimensional viscoelastic heterogeneous media represent a promising tool for seismic hazard studies. Our research group relies on HPC to perform physics-based numerical simulations of seismic waves in order to explain site specific anomalies in the observed earthquake ground motion, known as site effects. These effects are mainly due to a heterogeneous spatial distribution of elastic properties in the Earth's crust but Earth's surface topography may play a role in that, as well.
In order to perform numerical simulations in cases with negligible topography, we make use of our own parallel code FPSM3D (Klin et al. 2010) which is based on the method for the solution of differential equations known as "Fourier pseudospectral method" and which relays on a simple discretization of the spatial domain in to a structured grid. The accuracy of the method and the applicability of the code was confirmed with the participation of our group to a comparative exercise of numerical simulations of ground motion generated by earthquakes in sedimentary basins (Chaljub et al., 2015). The parallelization of the code uses a hybrid scheme based on the two protocols MPI and OpenMP and it is constantly updated with improvements in computational efficiency and in the complexity of the physical model to be treated. Recently, we applied FPSM3D to the modelling of seismic wave propagation in the Po Plain (Italy) (Klin et al. 2019). The study evidenced the role of the heterogeneous geological structure of the Po alluvial basin in the long duration of the ground motion that was observed during the 2012 seismic sequence.
In order to perform numerical simulations in the cases with prominent topography we rely instead on the established open source parallel code SPECFEM3D_Cartesian (Peter et al. 2011), which is based on a complex – but more versatile – discretization of the spatial domain with an unstructured mesh. In a recent study (Primofiore et al. 2020), we used numerical simulations with SPECFEM3D to put in evidence possible effects of topography on the earthquake ground motion in the specific case of Arquata del Tronto, a municipality located in the epicentral area of the 2016 seismic sequence in Central Apennines.

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Line B2. Microseismicity data processing

The goal of the project consists in the implementation and testing of a procedure that takes advantage of HPC resources for the automatic detection and location of microseismic events with a local network of receivers in a noisy environment. The use of automated procedures for the detection and location of microseismic events is essential, because of their high number. However microseismic signals are generally characterized by a very low signal to noise ratio that affects the performance of automated standard procedures. Several alternative approaches have been proposed in recent years, among which the most promising consist in the calculation of the probability distribution over a discretized parameter space. HPC techniques are neccesary in order to apply efficiently these methods.
Our research group manages the seismic network of Collalto, an infrastructure aimed at monitoring the natural and induced seismicity in the field of natural gas storage called "Collalto Storage" near Treviso (http://rete-collalto.crs. ogs.it). With the methods under implementation

we aim to alleviate the limitations due to the overlap of environmental noise on the recorded signals, to lower the magnitude of completeness and to allow a moment tensor inversion in order to make possible studies that discriminate between natural and induced seismicity. These studies are of increasing interest because of the growing perception of the risk associated with exploitation of earth resources.

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Line B3. Seismic Laboratory development (SEISLAB)

The simulation of waves' propagation in complex media is a key activity of the Seismic Laboratory at OGS (SeisLab), used to study rock properties and building 3D models of the Earth. Its applications include energy resources (both hydrocarbon and geothermal), fresh water catchment, CO2 sequestration, seismic hazard, civil engineering and mineral resources in general. High-resolution Earth models, however, require massive calculations, which can be carried out only by parallel, high-performance computing. A toolbox is being developed that allows non-specialist, but computer-literate users, to run high quality simulations of wave propagation to solve geological problems. Research and software development is still on-going and new tools are added and integrated in the existing framework.
One of the leading-edge technologies being addressed is the full-waveform inversion. A few elements of this method are available, as numerical modeling techniques, while others need further developments. One of these is a multi-dimensional optimization solver for highly non-linear object functions, where the parameter number may reach many millions, with constraints that may be both relative and absolute. For example, a rock may have a known range of properties from laboratory measurements (absolute constraint) and a maximum change with respect to nearby formations (relative constraint), if the related geological model suggests so. As the related simulations are computationally very expensive, an optimal minimization strategy can provide a major reduction of the computing costs. Methods as the "Pattern Search" are envisaged to be adopted and optimized, in addition to genetic algorithms and possibly newly created approaches.
Recent research activity involves the mathematical analysis of the solution of Maxwell's equation for electromagnetic wave propagation in layered media. A new approximation of the integral equation solution has been developed, based on two different minimization algorithms, based on the quasi-Newton BFGS method and on the global optimization method Simulated Annealing.

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Line B4. High level hybrid programming code for geodynamic simulations

The deformation of Earth surface is the result of several forces that act inside the planet: complex models based on theoretic numerical simulations are needed to understand how the Earth surface evolves.
Starting from well-known numerical methodology already used among the geodynamic scientific community, a new software suite PyGmod (Python Geodynamic Modeling) has been developed in the last year. Unlike common simulation code written in Fortran or C the programs of this suite are pure Python for more than 90%, implementing a parallel schema that takes advantage of the new architecture of the last HPC machines. As the most recent HPC facilities are characterized by a distributed shared memory architecture, the code uses standard MPI coupled with a multi-threading parallelization algorithm to speed up some critical (atomic) parts that can benefit of it. Since the OpenMP A.P.I. is not directly accessible by Python, the threading system has been developed with Cython. A real time visualization library, mainly based on Matplotlib, has been developed to inspect results during the computation.
The application simulates large-scale geodynamic processes involving the interaction of tectonic plates, the generation of magma, surface topography evolution, mineral phase changes, etc. The code will be mainly used to understand the dynamic of continental rifting.
Tests have been already done on multi-core machine in house and are now going live on some HPC facilities (GALILEO) provided by CINECA in the ISCRA PYGEO project.

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Line B5. Multiphase flow modelling of explosive eruption dynamics

This research activity focuses on the atmospheric dispersal of the products of explosive activity, namely volcanic gases and pyroclasts, i.e., dispersed particles produced by the fragmentation of the liquid magma in the volcanic conduit. To describe the interaction between the eruptive mixture constituents, this research has been primarily carried out by means of the three-dimensional Eulerian-Eulerian multiphase flow models (describing gas and individual particle classes as interpenetrating and interacting fluids) and equilibrum-Eulerian models, with potential new applications focusing on Eulerian-Lagrangian modelling.
HPC research will be aimed at the understanding of specific multiphase flow processes whose features are still mostly unknown, and specifically: gas-particle turbulence and its control on the dynamics of volcanic plumes; the role of supersonic regimes and shock waves generated during explosive phenomena; the dynamics of particle and velocity stratification in pyroclastic density currents.

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Line B6. Non-equilibrium dynamics in magmatic systems

The unpredictable evolution of volcanic unrest crises is strongly dependent on the complex, non-linear dynamics of magma storage and plumbing systems. Non-equilibrium multiphase

flow models are required to describe the interactions among liquid magma, solid crystal phases and exsolved volatiles, which ultimately determine the eruptive potential.
HPC research will aim at the implementation of a three-phase solver within the OpenFOAM framework, capable of handling the specific thermodynamical and rheological equations that characterize magmatic mixtures. The mathematical formulation and the modular, object-oriented numerical implementation will allow to easily include the different constitutive terms, such as viscosity, solubility, crystallization and diffusion models, to quantify their impact on the overall system evolution.
The method of moments will be used to describe the space-time evolution of crystals and bubbles populations in terms of the moments of their respective distribution functions, without the need to retain the microscale details. This will provide a very efficient way to deal with the very different length and time scales that characterize magma dynamics at depth.

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Line B7. Environmental impact of explosive volcanic eruptions and volcanic hazard

The assessment of explosive volcanic hazards (mainly associated to ash fallout from convective plumes and catastrophic pyroclastic density currents) requires a methodology to take into account the high level of uncertainty in initial and boundary conditions, the limited knowledge of the physics of volcanic phenomena and the limitations associated to numerical resolution. Coupling deterministic models (such as PDAC, Vol-CALPUFF and OpenFOAM) with statistical analysis tools (such as DAKOTA) has demonstrated to be effective for simple scalar models. However, coupling of complex 3D parallel models would require a careful code and workflow design, data assimilation, control of load balancing and appropriate sampling of the parameter space to reduce the computational cost of probabilistic analysis.
New HPC applications will focus on: inversion of observation data (such as thermal infrared and visible images of volcanic plumes); coupling between atmospheric and three-dimensional ash dispersal models; ensemble simulation of eruptive scenarios.

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Line B8. Detection of slow slip transients before strong earthquakes

Many strong earthquakes are preceded by one or more foreshocks, but it is unclear how these foreshocks relate to the nucleation process of the mainshock. Laboratory and theoretical studies have proposed that earthquakes are preceded by a nucleation process where stable, slow rupture growth develops into unstable, high-speed rupture within a confined zone on a fault. The devastating earthquake that struck Japan in early 2011 was apparently preceded by small, repeating quakes that migrated slowly to where the disaster took place. Slow slip at the base of the crust was observed also for the 1999 Mw 7.6 Izmit (Turkey) earthquake. If this kind of premonitory slow slip behavior also precedes other strong earthquakes, its knowledge should have critical implications for earthquake prediction and risk assessment. It is therefore essential to inspect thoroughly seismic records of other well-recorded earthquakes in search

of similar nucleation processes. Here, we plan to study the seismicity and possible slow slip events related to the last relevant earthquakes that struck Italy. To detect the presence of possible slow slip events would be of fundamental importance to understand whether or not the seismic sequence is a precursor of strong earthquakes. Our study will try to confirm the role of the slow slip transients as a possible precursor of strong events. Results will impact on operationally qualified, regularly updated seismicity forecasting systems able to provide advisories to the public and authorities in terms of short-term probabilities of future strong earthquakes.
HPC resources are needed to perform efficient cross-correlations of daily continuous seismic waveforms for a large number of recording channels and reference "template earthquakes". The testing phase, for some specific strong earthquake, requires applying the method in retrospect, including months of recorded data before the main event. Distributed calculations allow to exploit a flexible approach to signal time windows, frequency bands, cross correlation thresholds, and other parameters controlling the overall flux and specific parameters of the complex seismic sequences before the strong earthquakes.

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Line B9. Fast GPU-based tsunami simulations and its application to Probabilistic Tsunami Hazard and Forecast

Tsunami wave simulation is characterized by a wide range of spatial scales (from a few meters to thousands of kilometres), typically with time steps on the order of seconds over a simulation that can span several tens of hours. A typical single event tsunami scenario simulation can be normally conducted on a laptop within a time frame of a few hours; however, several factors can significantly increase the computational requirements in tsunami simulations. Firstly, the computational requirements can be increased largely by both the size of the domain or the spatio-temporal resolution. Secondly, the computational requirements are also increased due to the huge number (sometimes as much as tenths of millions) of simulations needed to explore the uncertainties in the tsunamigenic source variability, producing, at the same time, a massive output of data, for example in probabilistic tsunami hazard. In this sense, I/O, pre- and post-processing operations and analyses can also be regarded as a big-data problem. Finally, large computational efforts are necessary to enable real-time tsunami simulations (e.g. for early-warning purposes), for instance towards facilitating local high-resolution inundation simulations before an event strikes. All these reasons make tsunami modelling one of the most challenging scientific areas for HPC nowadays, particularly in the field of GPU computing where recent code developments revealed very promising (e.g. HySEA tsunami simulator).

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Line B10. Imaging and numerical geophysics

The activity is focused on the development and use of mathematical models and advanced information technologies for designing and producing industrial HPC applications for exploration geophysics.
In just a few decades, exploration geophysics has enormously enhanced the capacity to identify and exploit natural resources. The introduction of surveying techniques and high resolution numerical reconstruction have enabled prospectors to see through the earth and develop a clearer understanding of its structure, going well beyond empirical good sense. Such developments in prospecting technology have led to an explosive growth in the field of imaging science.
In seismic imaging, the topic of the present research line, transitioning compute-intensive applications from prototype to industry-ready production software for high-end local clusters of thousands of compute elements is a significant undertaking. Computational complexity must be organized on the available architecture, optimizing parallelization and data movement strategies (mpi, peer-to-peer, thread-based), while taking into account the granularity of the computational infrastructure (fiber, nodes, cores, file systems) and avoiding competition in accessing the resources. Reliability, fault tolerance and recovery mechanisms are topics of special concern in HPC software design for data imaging, especially when the processing of a single job may require several weeks even on powerful supercomputers.
Altogether, this know-how makes the difference between a research prototype and a stable HPC product devised for breakthrough science and industrial production. The project will be concentrated on the development of a 3D elastic reverse-time-migration (eRTM) application for the concurrent processing of very large volumes of seismic data.

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Line B11. Geologic structure of Italian seas and near land areas by inversion and forward modeling of geophysical data

During the last forty years several geophysical data such as gravity and magnetic has been recorded by OGS in Italy over land and sea areas. These records are fuzzy, not uniform and corrected according to old and sometime different methods. OGS wants to recover all the data, organizes them in a coherent and usable database. This new dataset will be used to do a 3D gravity inversion and thermo-mechanical modeling of the lithosphere in some key areas: the Northern Adriatic Sea, the Friuli Plan, the Sicily Channel and the Southern Ionian Sea. The research activities are organized in three main steps:

1. Collection of every gravity data recorded by OGS from 1965 and apply new correction methodologies. The coupling of old data with Satellite derived ones will improve accuracy and will reduce some gaps in the data coverage. If some areas will show a poor coverage new gravity surveys will be planned. The new dataset will be managed and stored in a GIS database.
2. The new gravity dataset will be used to do a 3D gravity inversion with the parallel software GRAV3D (https://grav3d.readthedocs.io/en/v6.0/). The inversion is solved as an optimization problem with the simultaneous goals of: minimizing a model objective function; generating synthetic data that match observations to within a degree of misfit consistent with the statistics of those data. This software is suitable for large problems since it implements a Message Passing Interface (MPI) interface and is able to take advantage of multi CPU computer for the inversion. Existing seismic and tomographic

data will aid the forward inversion in the studied areas. The gravity modeling will provide a detailed picture of the density structure of the lithosphere.

3. The density distribution in the lithosphere is the key to understand the vertical and horizontal movement/adjustment of the lithosphere (isostasy). The shape and geometry of lithological layer inside the lithosphere reflects its thermo-mechanical state. How the lithosphere behaves depends on its rheological stratification, temperature distribution, vertical and horizontal stresses. The lithosphere geometry can be modeled by solving the 3D flexural equation and fit the calculated surface to those extracted by the forward gravity inversion. Furthermore, if the flexural modeling is coupled by the seismic, tomographic data and stratigraphic data a backstripping and reconstruction of the isostatic movements of the area can be achieved. This method is tedious and time consuming since it needs the calculation of several solutions of the 3d flexural equation changing several parameters. The use of and MPI based algorithm can speed up the computation since several solutions can be calculated at the same time. All the software needed for the calculation has been developed by OGS. The parallel code is written in Python, some other utilities are written in Matlab and Python.

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Line B12. Estimation of impacts caused by seismic scenarios in selected study areas

Earthquakes can cause a wide range of impacts to human societies, disrupting buildings, infrastructure and services. Damage can occur both directly, due to the ground shaking, and indirectly, e.g. as a consequence of seismically-induced tsunamis or landslides. Damage maps due to seismic scenarios are extremely helpful for the emergency management in active seismic areas, but their generation requires knowledge on the hazardous phenomena, the exposed assets and their vulnerability or fragility. We aim at assessing expected damages for selected seismic scenarios in target areas, including, but not limited to, northeastern Italy (Poggi et al., 2021; Scaini et al., 2021). We will develop, test and apply a procedure (based on ground motion forecasting and/or numerical modeling of different hazardous phenomena) that can be useful for assessing scenario-induced losses, as required for Civil Protection purposes, but also for long-term territorial planning.

We plan to collect seismological data from the OGS networks in a structured and standardized manner, using existing tools or developing internal ones. In order to account for the uncertainty in defining the parameters to be adopted in the scenarios calculations (e.g. seismic source parameters, GMPES, exposure model and fragility curves), we propose to adopt a Monte Carlo approach to initialize each run with a sampled set of parameters. The resulting set of intensity measures and damage/loss distribution will provide a more comprehensive picture of the expected event impact. Damage calculations will be performed with the OpenQuake program (Silva et al., 2012) and/or with specific methods developed in-house (e.g. Poggi et al., 2021; Scaini et al., 2021, Petrovic et al., 2023). In order to increase the usability of results, we will produce different graphic formats (ex. maps, videos, interactive plots) that grasp the complexity of results, yet in a clear way. Such products could support authorities and actors involved in medium and long-term planning in the selection of risk reduction measures and their priorities.

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Line B13. Improving the understanding of site-city interactions for better earthquake risk mitigation

Since earthquakes can neither be prevented nor predicted, improving the planning of urban areas is an important issue to reduce damage to built environment and human losses in the long term. Planning of urban areas may be significantly improved if the variability of ground shaking over short distances that is known to occur during earthquakes is taken into account. When an earthquake occurs, besides the alterations of waves in the shallow geological layers, the interactions between single buildings and the soil might also contribute to modification of ground shaking, and thus, to seismic risk. In urban areas, these interactions are not limited to interactions between single buildings and the soil, but include interactions of an entire city and the soil. Since these interactions are not understood in detail as yet, they are not taken into account in the planning of urban areas and seismic risk assessment and mitigation. Until now, most studies on these effects have been carried out by numerical simulations without the possibility of a comparison between the predicted and the observed seismic wave field. Only a very limited number of analyses tried to tackle the problem based on empirical data sets.
The project aims at improving our understanding of interactions taking place between buildings and the soil and among buildings through the soil during earthquake shaking by using both a unique empirical data set and numerical modeling. Better understanding of the interactions between buildings and the soil may contribute in the long term to identify areas of higher seismic risk and thus, to a better preparedness in case of an earthquake. Furthermore, this knowledge could be included in guidelines for standard risk assessment and mitigation approaches in urban areas. Finally, improving urban planning in the long term by taking SSI and SCI effects into account, can contribute to reduction of seismic risk.

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Line B14. Imaging and modeling of river banks and levees

River banks and levees are continuously subjected to natural events (animal activity, flow erosion, floods, ...). Thus, these structures represent dynamical systems that can know drastic - and even catastrophic - changes.
In Italy, the need to evaluate, monitor and anticipate the risks related to these structures has led to many monitoring and measuring campaigns by several companies and institutes for the last decades. However, the scope of each of these campaigns was usually very local, and the techniques employed were very diverse (from historical logs and visual observation to both geotechnical and geophysical measurements). Carrying the effort to build a large scale model and methodology to study and consolidate efficiently the structure of river banks and levees, the DILEMMA project involves 3 multidisciplinary entities (POLIMI, OGS, and UNIPR), each having their own set of competences.
In order to accurately model the structure and behavior of river banks, geotechnical parameters have to be extracted from physical measurements (EM, GPR, DUALEM). Using geotechnical and/or geophysical methods (and combinations thereof), relevant parameters can be inverted from the measured data. These inversion methods require the proper modeling of

the associated forward problem for each method, namely: being able to reproduce the measured data with synthetic records. Solving for either the forward problem or the inverse problem can prove computationally intensive, even in an HPC environment. OGS participates to the DILEMMA project by lending both its expertise and experience in the development and optimization of numerical modeling codes for geophysical applications in an HPC environment.

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Line B15. GNSS data processing and deformation modeling

The Global Navigation Satellite Systems (GNSS) represent an undeniable important source of globally extended data for a wide range of applications, from the crustal deformation analysis to the near-surface processes monitoring (i.e., landslides, bridge and dams damages, ice sheet movements, etc.), surveying and many others. Furthermore, recent years have seen the development also of several applications dealing with multi-constellation and multi-frequency signals, supported with cutting-edge processing algorithms devoted to the integration of different sensors and improvements of error mitigation procedures.
In the previous years we used the HPC resources to test and to optimize the procedure to analyze the GPS data using the GAMIT-GLOBK software package. HPC resources represent the best approach to robustly evaluate the GNSS time series and velocity field in a short time. Updated time-series for each GNSS site and velocity field results are now available for the North-eastern Italy and surrounding regions (Tunini et al., 2024).
The next developments aim to: 1) explore the multiple constellation data, i.e., the combination of the well-known GPS data with the data from Galileo, Glonass and Beidou satellite constellations, in order to reduce the orbital artifacts in the time series; 2) analyze the high frequency GNSS data, to obtain a kinematic solution to estimate the coseismic displacement; 3) analyze the time series and model the crustal deformation with softwares like SHELLS (Bird et al., 2008), Pylith (Aagaard et al., 2008) and/or with specific methods developed in-house. Thanks to the HPC resources it will be possible to explore systematically the effect of input uncertainties in the results.

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Line B16. Modelling of gas hydrate and free gas by using seismic and laboratory data

Clathrate hydrates are crystalline structures where water molecule cages host gas molecules. Natural deposits of methane hydrates are mainly found at the margins of the continental platforms, where the formation is favored by the presence of organic material and the appropriate pressure and temperature conditions. Natural gas hydrates constitute the largest reservoir of natural gas on the planet.
The methane contained within the crystalline structure can be replaced by carbon dioxide by an exchange thermodynamically favourable. Recently, an innovative technological solution for the extraction of methane from marine gas hydrate and the simultaneous sequestration of

carbon dioxide in a single process have been developed in the frame of the PRIN project named "Methane recovery and carbon dioxide disposal in natural gas hydrate reservoirs". The obtained fuel is neutral in terms of climate-changing emissions and therefore equivalent to renewable energy sources.
The PRIN project is devoted to obtain a body of knowledge, significantly beyond the state of the art on chemical, physical and geotechnical properties of marine gas hydrate and on the CH_4-CO_2 replacement mechanism.
In this context, we propose to develop a theoretical geophysical model of the marine natural gas hydrate reservoir by using theoretical models and direct measurements, including laboratory data.
The first part of the work is devoted to complete an overview of the marine natural gas hydrates environments and their characteristics available in literature, such as concentration and composition, petro-physical properties, depth, geothermal gradient and pore water salinity. OGS selects natural marine sediment samples already available at National Antarctic Museum in Trieste, recovered at the natural gas hydrate reservoir in the Antarctic Peninsula. The sediments' elastic and geotechnical properties are estimated in laboratory or extracted from literature, as well as the properties (pH, conductivity, salinity and concentration of main elements) of water present in the marine sediment samples. The main target of this part is to give indication for the synthetic reproduction of natural hydrate sediments in laboratory.
The idea of this project is to determine a refined theoretical model applicable to a natural gas hydrate reservoir. It could be used to characterize a possible natural site for CO_2 hydrate storage. Theoretical models, available in literature, are adopted and modified in order to fit the experimental data provided by the PRIN project.
Moreover, our idea is to link the sediments' elastic properties to electrical properties to extrapolate electrical properties from seismic measurements and elastic properties form electrical or electromagnetic measurements in situ. To reach this target, we use the measurements of the elastic and electrical data during the planned laboratory experiments. If a disagreement is observed between laboratory measurements and theoretical curves, the theory is modified until a good fit will be obtained. Results is fed into the elaboration of a novel model combining all laboratory data available.
Finally, the resulting theoretical approach is used to model real cases designed by using seismic data analysis. This requires high computational resources because each analyzed seismic line is long more than 100 km and the depth of investigation is more than 1 km. Clearly, to better compare the laboratory measurements and modelling on real data a high resolution is required. So, grids with order of magnitude of meter is necessary. Moreover, the utilization of Cineca resources will allow us to model at the same time more lines, allowing checking immediately the results at the intersection of the lines. In addition, in order to improve the final results, it is necessary to test different runs with different parameters in order to determine the best choice. The programming languages will be Fortran.

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Line B17. Quantum Computing for Seismology

Quantum computers can potentially solve certain classes of problems in science much faster than any existing classical computers. Research in this field is growing exponentially, together with the development of hardware with an increasing number of qubit. Recently review in literature shows that on the most advanced quantum processor it is now possible to perform tasks tenths of thousands faster than on the most advanced traditional HPC system. This "quantum supremacy" is sustaining the acceleration in the effort to create a larger and scalable quantum computer, able to support practical use cases.

In parallel, quantum computing (QC) researchers are focusing in the new quantum programming paradigms requested by this revolution and in particular: a) identifying quantum algorithms characterized by a speedup, even limited, if compared with the corresponding classical algorithm; b) using the quantum approach to perform calculations on classical HPC system in order to gain significant benefits in terms of algorithms efficiency without using a quantum hardware.

Disciplines such as Chemistry, Biology, Finance or machine learning application are already benefiting from recent advances in QC. In contrast, geophysics has yet to satisfactorily explore the new paradigms. At the moment, applications of QC to geophysical problems are rare and simplified while there is a great potential for addressing computationally expensive problems, such as large-scale seismic inversion. Two main reasons prevent the use of QC within the geophysical community. First, geophysicists are not familiar with the logic and concepts associated with QC. Second, not all problems can be mapped on a quantum computer. It is therefore essential that geophysicists begin to interact with the QC community.

A fast and direct approach is to use QC in the field of geophysics that use machine learning algorithms, taking advantage of theoretical work of AI in QC. Nevertheless, Quantum algorithms can be used also to solve algebraic problems, as the solution of a linear system of equations, used in many areas in applied science as seismic wave simulations. Given an N-dimensional problem the best classical algorithm offers a computational time proportional to N. However, a quantum computer can solve the linear system of equation in running time log N, a logarithmic speed-up compared to the classical computer.

Among the quantum algorithms, the quantum annealing has been applied in seismic inversion as tomography or seismic source definition. The scientific project for this topic is to explore and encode quantum algorithms of classical geophysical problems, toward the application of QC paradigm to real case, in particular in tomographic imaging and seismic source inversion.

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Line B18. Automatic monitoring of seismic sequences

Recent advances in seismic detection through artificial intelligence and waveform template matching techniques have led to more detailed earthquake catalogs. The possibility of following quasi-real-time seismic sequences using non-standard detection techniques could help in a prompt understanding of variations in the background seismicity rates and earthquake clustering, providing functional parameters to characterize the evolving phenomena. We developed dedicated codes to implement a real-time computing procedure to follow the evolution of the earthquake sequences in the Veneto region by exploiting our monitoring infrastructure, the past archived waveforms, catalogs and software. A machine learning approach has been used in the input/output validation and for improving automatic phase picking, earthquake detection and association.

We aim to utilize this prototype for NE Italy, extending and combining different machine learning and template matching approaches.

Our proposal is focused on conducting experiments utilizing GPUs and cloud computing resources at Cineca. The main goal is to set up tools and improve methods for applying quasi-real-time unconventional techniques to improve the monitoring service.

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Line B19. Application of Full Waveform Inversion to vintage OGS data

The great development of Full Waveform Inversion (FWI) in recent years has completely changed seismic processing and especially velocity modelling and seismic imaging. The technology of FWI has now matured and the development of hardware has made the computing costs of FWI affordable, at least for industry and large research clusters with high-performance computers. FWI is a data fitting procedure aiming at estimating a model of subsurface parameters, in particular the subsurface velocity model. FWI is based on the minimization of an objective function measuring the mist between the recorded data and the data simulated through numerical propagation within the current model. For computational reasons the inversion is usually faced as a local minimization problem solved via iterative methods. FWI has the advantage that it takes into account all propagation effects compared to ray-based methods and has been shown to produce models with higher resolution compared to conventional velocity modelling methods.
Most of the applications that have delivered on the promises of FWI are associated with acquisitions in Oil & Gas exploration, which use high-quality data. For instance, one key factor in achieving good FWI results is the use of low seismic frequencies, which can help to avoid cycle skipping (i.e., converging on a local minimum). Additionally, extended seismic streamers can enable deeper penetration of the transmitted energy, which is beneficial for FWI. However, in the case of vintage surveys where the low-frequency signal-to-noise ratio is poor and the maximum offset is limited, extra efforts are required to achieve good FWI results.
In this research project, FWI will be applied to selected vintage seismic lines of OGS dataset together with advanced processing techniques of seismic processing and imaging. The aim is to characterise areas in the Mediterranean and in the Antarctic continental margins with complex geological features related to fluid plumbing systems (such as presence of fluids, free gas, Bottom Simulating Reflectors, mud mobilisation, mud volcanoes) that still are a challenge in the seismic analysis. They could represent a serious geohazard for slope stability and as well as ecosystem hot spots. For this purpose, home codes and codes freely available in the research community will be used.

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Line B20. Hydrogeological modelling

In the last years, OGS has improved activities related to hydrogeological topics, with attention to fluid-dynamics modelling. Recently, OGS has been involved in the " INEST – Interconnected

Nord-Est Innovation Ecosystem" PNRR project. iNEST is the ecosystem for innovation of the Italian northeaster region, namely a web of interconnections between research bodies, both public and private, whose aim is to develop a "nest of synergies" amid the multiple vocations of the territory, through the implementation of digital and ecological transition technologies. In particular, the activities of this line are dedicated to research and technology transfer activities in the area of maritime, marine and inland water technologies. In this context, OGS has activated a PhD project with the scope of developing a conceptual and numerical model to characterise regional geothermal resources and their interaction with shallower aquifers, by integrating geophysical and geological data. In addition, this project will contribute to the development of a digital twin model of the North Adriatic area. In recent years, a regional study has been started with the scope of studying offshore aquifers, a potential reserve to face climate change, and their connection with onshore aquifers, also through the activation of a PhD project. Since November 2022, OGS has been involved in the COST ACTION "CA21112 - Offshore freshened groundwater: An unconventional water resource in coastal regions? (OFF-SOURCE)" dedicated to the study of offshore aquifers, in which Dr. Giustiniani is the leader of a working group. This new topic will require the use of HPC resources for the management of the data necessary for the developing of conceptual models and for hydrogeological modelling.

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Line B21. Near real-time physics-based ground shaking simulations based on urgent computing

Earthquakes pose a significant threat worldwide, endangering human life, property, and economic stability. Therefore, after an earthquake, it is crucial to quickly assess the distribution of ground shaking and predict the potential extent of damage so that effective mitigation measures can be taken. The system currently in operation at the Seismological Research Centre (CRS) of OGS calculates ground shaking in near real-time using the U.S. Geological Survey (USGS) ShakeMap software, which is based on empirical ground motion models with their inherent limitations. To overcome these limitations, we are developing a complementary tool that uses physics-based ground shaking simulations. This tool integrates a kinematic description of an extended seismic source and captures the complex propagation of seismic waves through the region's heterogeneous subsurface, taking into account its geological characteristics and topography. To ensure rapid access to the huge computational resources required for these simulations, we leverage supercomputing facilities, including urgent computing, to expedite the process and reduce the time-to-solution. The tool has been developed as the pilot use case of the PNRR TeRABIT project (Terabit Network for Research and Academic Big Data in Italy), which aims to enhance and federate three strategic digital research infrastructures located in Italy. The computational elements composing the are presently under development. The research activity includes both seismological aspects, such as refinement of the 3D velocity model and the assessment of the uncertainties related to ground motion estimation, as well as computational advancements related to the near real-time use of the infrastructure, such as the management of different scenarios during a seismic sequence. The ultimate goal is to improve the model's ability to predict ground shaking in near real-time during a seismic emergency to support civil protection authorities.

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Topic C: HPC for Earth System modelling

Line C1. High-resolution simulations of convective processes in the Earth System

Convection is an essential process in the Earth System, transporting heat and material in the atmosphere, the oceans, subsurface aquifers and the Earth mantle. At the same time, convective processes represent a paradigmatic example whose study has led to the development of many new ideas on the nonlinear dynamics of complex systems. The simulation and analysis of convective processes requires sophisticated simulation methods and powerful computing resources, to resolve the many scales at work. This research project is devoted to the development and implementation of numerical methods for high-resolution simulation of convective processes in the Earth System.
Research activities will include a first part devoted to simulating convection in idealized configurations, and a subsequent phase dealing with the application to a specific geophysical setting (atmosphere, ocean, or subsurface flows), to be defined based on the background of the fellowship recipient and the research priorities. From a technical viewpoint, this line aims to contribute to the development and improvement of numerical codes for convection simulations. From a scientific viewpoint, the research will lead to an increased understanding of convective processes in the Earth System and to specific applications.

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Line C2. Optimization and parallelization of a new non-hydrostatic dynamical core for use in high resolution climate models

The next frontier in regional climate modeling is the development of models that can reach the convection permitting horizontal resolution of 1-5 km and can thus provide climate information at scales more relevant for impact applications. This requires the use of efficient and scalable non-hydrostatic dynamical cores in climate models so that long climate runs at these resolutions can be conducted. Towards this goal, a new non-hydrostatic dynamical core is being developed at ICTP, based on a finite element, semi-lagrangian, semi-implicit numerical framework, which is highly accurate without having stability constraints. A key aspect of this development is the capability of this code to scale efficiently on massively parallel machines. The aim of this project is to optimize the code of this dynamical core in order to make it highly scalable on different HPC platforms and thus applicable in a wide climate modeling context, including the new version of the ICTP regional model RegCM5.

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Line C3. Physical-Biogeochemical online coupling for Mediterranean Sea

One of the main HPC challenges in oceanography modelling is the increase of the model spatial resolution to potentially allow more realistic simulations of the coastal areas. In an exascale paradigm, a multi-model approach will be able to simultaneously simulate the Mediterranean

Sea at different spatial resolutions and on different sub-regions, conveniently calibrating the resolution increment and the boundary conditions between the basin and sub-basin scales. Online coupling between physical and biogeochemical components is envisaged as one of the issues to be tackled

The goal of this research line is to start developing an online coupling between biogeochemical and physical models for the Mediterranean Sea to be applied both for operational applications and climate projections. Background experience for the present activity is the online coupling between MITgcm and BFM implemented at OGS for the Northern Adriatic Sea with collaboration of UTMEA-CLIM section of ENEA.

The perspective view is the development of a regional system for operational forecasts specifically designed for the Northern Adriatic Sea, including numerical models (coupled model physics-biogeochemistry, eventually extended to upper trophic levels) and observational data sets necessary for data assimilation (of surface chlorophyll, in-situ data, surface currents).

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Line C4. Development of a library of HPC tools for the parallel implementation of p-adaptive discontinuous finite element methods applied to geophysical flows

Discontinuous finite element methods have been gaining in popularity for large scale geophysical applications. They are also a natural environment to take advantage of adaptive approaches in which the degree of the approximating polynomials is chosen locally and dynamically, in order to minimize memory occupation and computational cost. However, this poses major challenges to the parallel efficiency of the resulting methods, since a greater effort to achieve optimal load balancing is required. At present, no general HPC infrastructure for efficient and natively adaptive implementation of DG methods on massively parallel is available.

The purpose of this research line is to move towards the development of such a tool especially tailored for the simulation of fluid dynamics problems in climate dynamics, oceanography and volcanology. This development will rely heavily on the preliminary results already achieved in the previous cooperation among the proponents.

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Line C5. Numerical modeling of past and present interactions between polar ice sheets, ocean circulation and bathymetry

The Greenland and the Antarctic ice sheets are losing mass at an increasing rate. The Greenland ice sheet is mainly subject to intense surface summer melt and a few of its ice-streams lying on the bed below sea level experiences subglacial melt due to ocean warming. The Antarctic ice sheet is mainly subject to sub-glacial melting below its ice shelves (marine termination of inland glaciers) and a few surface melt at the ice shelves surface. The melting occurring within ice shelves cavities can potentially triggers self-sustain dynamical instabilities of the grounding

line, further amplified where the bedrock slopes landward. This is the so-called “Marine Ice Sheet Instability”, MISI. Such an instability can lead to multi-meters sea level rise in a few decades to centuries, as shown by the last sea level projections from the IPCC Assessment Report Working Group 1, in August 2021.
Little is known about the physical mechanisms related to the interactions between the ice sheet dynamics, the ocean circulation and the morphology of the bed. This research focuses on understanding those interactions, in the present, but mainly in the past. In fact, direct observations of such interactions at present are scarce, and also challenging. Paleo-archive related to such processes can help to improve some of the physical aspects of the numerical models of ice sheet dynamics, ocean dynamics, critical to improve the sea level projections and the ice sheet-ocean evolution. The interpretation of such paleo-archives necessitates the understanding of the sedimentary processes occurring in polar margins, i.e., erosion (glacier advance on the bed), transport (ocean current and ice sheet) and deposition (ocean currents, gravity-driven) of sediments. Numerical models integrating those processes over different timescales from daily to millennia have been recently developed.
For this specific research topic, three types of numerical models are used and implemented, dynamical ice sheet models (PISM, UFEMISM), ocean circulation model (MITgcm) and a sediment flux model (SEDFLUX2). Investigating the interactions requires two different types of approach, idealized (to disentangle the effect of single processes) and realistic (applications to real cases around Antarctic and Greenland or other polar margins). The validation of the ice-sheet-ocean-sediment system is based on existing sediment cores and seismic profiles or polar margins (to which OGS contributes through its own polar campaigns). To optimize the information of such paleo-archives, we will consider a machine learning approach. Algorithms will be developed and applied to those data to identify specific climate-related or glacio-isostatic adjustment sedimentary patterns. Those two approaches, numerical modeling and machine learning, will require a statistical approach based on several ensembles of simulations. Thus, large HPC resources are necessary to the achievements of the objectives.
This research topic is supported by several National Italian Project for Antarctic Research (PNRA) and National Italian Project for Arctic Research (PRA): PNRA-ANTIPODE (PI: Florence Colleoni, OGS); PNRA-COLLAPS (PI: Laura De Santis, OGS); PNRA – GRETA (PI: Tommaso Tesi, CNR-ISP); PRA-Past-HEAT (PI: Tommaso Tesi, CRN-ISP).

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Line C6. Development and optimisation of a Regional Earth System Model to estimate climate change impacts for the Euro-CORDEX and Med-CORDEX regions, including the development of a machine learning method for extreme events in the Mediterranean region

Regional climate modeling research is rapidly moving towards the development and application of fully coupled Regional Earth System Models (RESMs) including different components of the climate system, such as the atmosphere, oceans, land, sea ice, marine and atmospheric biogeochemistry. The Earth System Physics section (ESP) of the International Centre for Theoretical Physics (ICTP), develops and distributes to a large scientific community a RESM system based on the RegCM regional modeling framework. The ICTP RegCM-ESM model currently includes coupled atmosphere (RegCM5), ocean (MIT-GCM), land (CLM4.5),

hydrology (CHyM) and chemistry/aerosol components. Using as input meteorological variables produced by the RegCM (e.g. temperature, precipitation or surface and subsurface runoff), along with topographic information from a Digital Elevation Model, CHyM can calculate realistic discharge from river basins, which in turn generates an input (discharge) for the hydraulic model.
A series of activities are planned within this research line:
i) The completion of the direct coupling between the river routing component and the hydraulic component using a physically based hydraulic model, in order to develop and optimize a three-model chain including the atmospheric regional climate model RegCM, the hydrological model CHyM and the hydraulic model CA2D. This coupling requires extensive computing resources due to the complexities of all the individual components, and it thus critically relies on an efficient implementation on different HPC platforms.
ii) The off-line coupling of the Biogeochemical Flux Model (BFM) to the whole RegCM-ESM chain to include marine biogeochemistry (see also lines D1 and D3) and perform computationally intensive climate scenarios simulations, also in the framework of the Med-CORDEX initiative.
iii) A development of a machine learning method with the aim to complement and support the model ability to detect, attribute and project high precipitation convective events (HPCE) and tropical-like cyclones (Medicane) in the Mediterranean region in a climate change scenario. Extensive HPC resources are needed for the machine learning method optimisation for both high resolution HPCE and Medicane detection.

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Line C7. Development of a High Performance hydrological model

The GEOtop hydrological scientific package is an open-source integrated hydrological model that simulates the heat and water budgets at and below the soil surface (http://geotopmodel.github.io/geotop/). It describes the three-dimensional water flow in the soil and the energy exchange with the atmosphere, considering the radiative and turbulent fluxes. Furthermore, it reproduces the highly non-linear interactions between the water and energy balance during soil freezing and thawing, and simulates the temporal evolution of snow cover, soil temperature and moisture. The core components of the package were presented in the 2.0 version (Endrizzi et al, 2014), which was released as Free Software Open-Source project. Recently, in the framework of the HPC-TRES MHPC master program, a code version 3.0 was released (Bortoli et al, in prep.). A software reengineering was performed: the code was translated in C++, and new efficient data structures were introduced to create a robust and stable scientific open software package. This research line aims (I) to improve code modularity to manage in a flexible way a complex state-of-the-art hydrological model like GEOtop and integrate it into wider workflows, as weather forecast or regional climate models; (II) to perform a code parallelization using a mixed OpenMP/MPI approach, with the implementation of numerical codes for parallel computation of the surface energy budget and of the Richards equation.

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Line C8. Development of a Regional Earth System model for the Northern Adriatic Sea area

An accurate representation of the dynamics and interactions among the different components of the climate systems (atmosphere, ocean, land, cryosphere, biosphere, in perspective also including humans) is challenging and of paramount importance for the development and assessment of adaptation and mitigation strategies.
From this point of view, Earth System models (ESMs) can respond to the need of having modeling tools able to address this challenge. ESMs have been initially developed to simulate present and future evolution of climate on global scale, and are now being used to simulate the climate dynamics on regional domains such as the Mediterranean and its sub-basins. However, reducing the size of the investigated area while increasing model resolution and complexity still requires an important effort in terms of computational load and data storage.
Recently, a high-resolution configuration of the Regional Earth System Model RegCM-ES has been developed and tested over the Northern Adriatic Sea area (hereafter RESM-NAd). The components of RESM-NAd are the Regional Climate Model (RegCMv5) at 3 km resolution (convection permitting) for the atmosphere, the MIT general circulation model (MITgcm) at 700 m (non-hydrostatic) for the ocean, the hydrological model CHyM at approximately 1 km for the river discharge, the land surface scheme CLM4.5 and the urban model UCLM to simulate land processes and urban climate. The run of each component and exchanges of forcing fields among different components is managed by a driver based on the Earth System Modeling framework (ESMF) libraries. The next step will be the inclusion of the marine biogeochemistry module BFM.
The initial purpose of this research line is to build up a high resolution dataset of the present physical and biogeochemical state of the North Adriatic Sea area. Then, RESM-NAd will be used to simulate the future evolution of the climate of the area under different emission scenarios.
The high resolution simulations with RESM-NAd requires an intense computational effort: in the present configuration (760 cores on Leonardo facility hosted at Cineca) one month of RESM-NAd simulation takes almost 4 hours (i.e. 3040 core-hours; SYPD = 0.5). Thus for five years it takes approximately 10 days of computation. Though we are oriented to optimize the time-to-solution of RESM-NAd, the use of HPC remains fundamental.

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Line C9. Coupled Solid Earth and climate carbon cycle models to assess the geological drivers of climate

Over geological timescales, the Earth's carbon flows between surface and deep reservoirs such as the atmosphere, oceans, lithosphere, and mantle in an exchange called the geological carbon cycle. Emissions of carbon bearing compounds from tectonic plate boundaries are a critical input of carbon into the ocean and atmosphere, whereas the output of carbon from the surface reservoirs is primarily driven by chemical weathering of silicate rocks exhumed through erosion of tectonically uplifted terrains. By preventing all of the Earth's carbon from entering into the oceans and atmosphere or being stored within rocks, the geological carbon cycle keeps the Earth's temperature relatively stable on the long term, like a global thermostat, linking the evolution of life and climate to plate tectonics. Quantifications of temporal variations in surface carbon influx and outflux and assessments as to the underlying mechanisms are an essential step toward a comprehensive understanding of the natural carbon cycle and a top-priority objective of the IPCC (www.ipcc.ch).

Advanced numerical petro-thermo-mechanical geodynamic and landscape evolution models allow rigorous quantifications of surface carbon emissions and consumption accounting for a broad variety of proxy data and virtually all possible tectonic scenarios and boundary conditions. Climate and climate carbon cycle models allow assessing the climatic response (lato sensu) to changes in surface carbon influx and outflux also accounting for the feedbacks with other climate forcings (e.g., weathering). However, geodynamic, landscape evolution, and climate models are commonly used independently because coupling models that solve external and internal Earth dynamics at a global scale is obviously computationally challenging.

In the frame of this research line, HPC will be used to overtake this challenge optimizing and coupling available and newly developed numerical geodynamic (e.g., I2-3ELVIS), landscape evolution (e.g., stream-power and/or linear diffusion erosion laws) and climate carbon cycle models (e.g., GEOCLIM). The required degree of coupling between numerical models will be set by specific application designed to quantitatively characterize the geological drivers of past climate trends (and possible climatic feedbacks on solid Earth dynamics) during target time windows covering a broad range of timescales (103-107 years). We envisage large sets of numerical simulations with coupled numerical solid Earth and climate carbon cycle models performed at the highest possible resolution over regional or global scales and allowing for forward as well as inverse modeling applications.

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Line C10. Development of an Earth System Model of Intermediate Complexity

A spectrum of models of various complexity is used in modelling the natural Earth System. Depending on the nature of questions asked and the pertinent time scales, there are, on one extreme, conceptual, more inductive models, and, on the other extreme, three-dimensional comprehensive atmosphere-ocean general circulation models (AOGCM) operating at the highest spatial and temporal resolution currently feasible. Earth system Models of Intermediate Complexity (EMIC) bridge the gap between the two. The present project focuses on the development and use of an EMIC for the study, modelling and understanding of interannual, decadal and centennial climate variability, predictability and change. We propose to develop and use the EMIC in two stages.

First, we will build the physical model (PHASE 1), consisting of an atmosphere-ocean-sea ice general circulation model . The model will use the three-dimensional primitive equations for both ocean and atmosphere but will be simplified from a "state-of-the-art" coupled climate model in terms of atmospheric physics and parameterization schemes. These simplifications will provide considerable savings in computational expense and, perhaps more importantly, allow mechanisms of climate variability/change to be investigated more cleanly and thoroughly than with a more elaborate model. For example, the coupled model is expected to allow integrations of several millennia as well as sensitivity and parameter studies with relative modest computer power. This phase will consist on the coupling, development and

optimization of the model. We will build on the MOM version that already includes OASIS. This phase is expected to last between 6 and 12 months. All model components are open-source.
Then, building on PHASE1, an Earth system Model of Intermediate Complexity (EMIC) will be developed (PHASE 2), with sub-models for different components of the climate system (e.g., ocean biogeochemistry, land-vegetation, atmospheric chemistry, ice sheet model, etc.). The EMIC will consist of the ocean model MOM and the atmospheric model SPEEDY, communicating through the OASIS coupler. The model components will be coupled through OASIS, which will take care of passing fluxes to and from the different modules.
The EMIC will be used for studies of present, future and past climates, with a focus on decadal and longer variability and the role of the ocean in driving the climate system. This phase is expected to draw expertise from external collaborations, visiting scientists and PhD students who will further develop the model as a community effort. The development and use of the EMIC will be a collaboration between ICTP, OGS, ECMWF and CINECA.

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Topic D: HPC for Climate Sciences

Line D1. Climate studies of natural drivers and anthropic pressures on Mediterranean Sea marine ecosystems

Mediterranean Sea is an extremely heterogeneous sea basin in terms of physical forcings and biodiversity, and can be considered as a very sensitive area to the climate change effects on its ecosystems. The projections of the socio-economical effects related to climate change can be provided by integrated regional modelling (or Regional Earth System modelling), based on the coupling between ocean-atmosphere models, biogeochemistry models that involve the whole trophic chain, from plankton to big predators ("End2End" models), and socio-economical models. This approach, partially implemented in some EU-projects (e.g. PERSEUS, OPEC), is characterized by the computational challenge that could efficiently support simultaneously interacting, inter-dependent codes running on high-resolution grids for multi-annual integration periods, and that produce large amount of data.
Given the high uncertainty related to the sensitivity of the biogeochemical models to their parameters, the aim of this research line is the exploration of an ensemble of multi-decadal simulations (generated according to different initial and boundary conditions) of the Mediterranean Sea biogeochemistry, in order to evaluate the impact of the natural drivers (linked to climate change) and anthropic pressures (linked to environmental policies) on the marine ecosystems. This topic is extremely strategic in the frame of the Marine Strategy Framework Directive (MSFD)[6].

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Line D2. Global climate modeling for paleoclimate and tipping point studies

Numerical global climate models and Earth-system model represent invaluable tools to address the study of past climatic fluctuations, an essential step to obtain the baseline of climate variability against which to project current climate change, to understand the mechanisms of climate variability also in conditions different from present day, to study major nonlinear feedbacks in the climate system, to understand tipping mechanisms and the impacts of crossing tipping points. Technically, however, such simulations require HPC approaches and large ensembles, at a considerable cost. This research project focuses on the implementation, tuning and use of the state-of-the-art global climate model EC-Earth for ensemble paleoclimate simulations and tipping point studies both at standard high resolution and developing a specific lower resolution configuration. This requires adaptation of the model parameterizations and parameter tuning, development of boundary conditions and implementation of forcings. The ultimate goal is to obtain a model configuration suitable for such studies and the production of ensembles of global paleoclimate simulations to obtain estimates of natural climate variability in the centuries before anthropogenic greenhouse gas emissions.

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[6] http://ec.europa.eu/environment/water/marine/directive_en.htm

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Line D3. Coupling of marine biogeochemical models to a regional Earth System model framework

The interest is steadily growing within the regional climate modelling community on the development of fully coupled Regional Earth System Models (RESMs), aimed at addressing climate system interactions at the regional to local scale. Within this context, a component noticeably missing in most current RESM efforts is marine biogeochemistry, which on the other hand is of high interest in global change studies.
In particular, ICTP is currently developing a coupled RESM including atmosphere (RegCM), ocean (MIT-GCM) and land (CLM) components. At the same time, OGS has developed and used a range of marine biogeochemistry and ecosystem models, so that a clear opportunity exists to develop a collaboration aimed at the integration of a marine biogeochemistry component within the ICTP regional model system.
Target of this project is to carry out such an exercise with specific applications to the Mediterranean region, addressing in particular the issue of the sensitivity of coupled processes to the complexity of the biogeochemistry model components.

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Line D4. Role and effects of air-sea coupling in the climate variability of the Mediterranean Sea

Ocean mesoscale in the Mediterranean Sea is characterized by a Rossby deformation radius of 5-10 km. In consequence, the SST often shows narrow and sharp fronts as well as filaments with associated strong temperature gradients that can significantly modify the air-sea interaction and affect the climate evolution. Ocean mesoscale also plays a crucial role in the main mechanism of heat uptake by the ocean, namely dense water formation, which modelling requires both atmospheric and oceanic high spatial resolution that present GCMs are not able to achieve. A detailed analysis of how air-sea coupling at high resolution can modify the regional climate, and consequently the global climate, is still missing in the literature. There are some indications that it can provide an added value to RCMs in both present climate and future scenarios, but the mechanisms underlying such impact are not completely understood. Global climate modelling should therefore benefit from this research line as it will give clues for the future design of GCMs. This research line aims to highlight the role played by air-sea coupling in both regional climate variability and future projections for the Mediterranean area.
This research project focuses on the tuning and use of a state-of-art Euro-Mediterranean regional climate model for hindcast and future climate simulations in the context of the recently approved CORDEX Flagship Pilot Studies. The regional climate model is composed by RegCM4 and MITgcm interactively coupled via ECMF tool. The goal is to perform a set of climate simulations for evaluating the impact of high-resolution ocean component on air-sea coupling. Both present and future climate simulations will be performed with the ocean component at a resolution of 1/16º with a 1/64º zooming in the main straits (i.e. Gibraltar).

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Line D5. High resolution simulations of extreme meteorological events

Heavy rains, hurricanes, wind storms constitute major hazards for populations and societies. Our ability to predict them is severely limited and modelling frameworks are an important tool for understanding the relative role of individual processes and mechanisms involved in their development. Different aspects will be investigated in this research line, including the role of orography in enhancing precipitations, the direct and indirect effects of aerosols on cloud formation and stability, the two-way interaction with the sea surface and its role in affecting air stability and wind intensity as well as upper ocean mixing and internal wave propagation. The investigations will be performed by means of atmospheric models, regional ocean models, and coupled models, both in idealized and realistic configurations. The present line presently includes 2 tasks.
Task 1 "Air-sea interactions at the submesoscale" - The upper ocean responds passively to the atmosphere at large scales, where winds are negatively correlated with sea surface temperatures. At smaller scales, the atmosphere responds to sea surface thermal structure and currents by modifying the near surface wind and the boundary layer stability depending on enthalpy and momentum air-sea fluxes. In turn, the submesoscale structure generates intense vertical motion that impact the redistribution of heat and nutrients in the upper ocean. In this project, small scale interactions between the atmosphere and the ocean will be investigated using the regional ocean model ROMS and the atmospheric model WRF either in standalone or in coupled configurations, in some cases including a wave model at the interface. Part of the project is done as a study for the ESA Earth Explorer 9 prospective mission"Harmony" (formerly known as Stereoid).
Task 2 "Extreme meteorological events in the Alpine region". - The scientific activity consists in performing high resolution numerical simulations of selected heavy rain events in the Great Alpine Region. This will allow the study and the understanding of the convective scale processes that often contribute to the intensification of the precipitations, even in cases triggered by frontal dynamics and/or orographic lifting. Outputs from the state-of-the-art global climate model EC Earth performed following the CMIP5 protocol, available at 25, 40 and 80 km resolution for 30-year long intervals both for the historical period (1979-2008) and for the RCP8.5 scenario (2041-2070), will be used as boundary conditions for a dynamical downscaling experiment using the Weather and Research Forecast model on a 4km x 4km grid over the Great Alpine Region. The model will be run for the 30 year long periods described above for different simulations of the present and future climate ensembles. Up to three two-way nested domains will be used, to downscale from the grid spacing of EC Earth to the 4 km grid spacing, using intermediate domains such that each domain reduces the grid size of about a factor 3 from the coarser one.

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Previous HPC-TRES grants: Mostafa Hamouda (UNIMIB-PhD/HPC-TRES-2017-03), Fabien Desbiolles (UNIMIB/HPC-TRES-2020-10)

Line D6. Ensemble simulations of paleoclimates, extreme climates and exoclimates

Climate dynamics on Earth has been characterized by large variability, going from Snowball conditions, when the planet was largely covered with ice, to the equable climates of the Cretaceous and Paleogene, that was several degrees warmer than the current conditions with a small temperature difference between the poles and the equatorial regions. Such past climates are formidable test grounds for our understanding of the climate system, and need to be described by comprehensive approaches including geological, biospheric, cryospheric, oceanic and atmospheric components. These extreme climates, as well as abrupt climate changes and shifts, can be studied by a hierarchy of models that range from simple, one-dimensional Energy Balance Models, to Earth System Model of Intermediate Complexity, to full-blown Global Earth System Models. Similarly, the climate on extraterrestrial planets and moons is a challenging scientific problem that requires the development of new ideas and parameterizations, describing the dynamics of atmospheres with a completely different chemical composition (Venus, Titan), flows in electrically-conducting ice-covered oceans (Enceladus, Ganymede, Europa), as well as issues related to planetary habitability and exoplanetary climates (for example, Kepler 452b).
The exploration of these challenging systems requires developing large-ensemble simulations taking into account all possible values of unknown parameters and forcing factors, thus fully residing in the area of High Performance Computing blended with the development of new approaches to the analysis of climate variability and dynamics.

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Line D7. Extreme rains in complex orography areas: high resolution meteorological modelling on heterogeneous computing architectures (high performance computing, cloud computing, grid computing)

The extreme precipitation events in complex topography regions, such as coastal areas of the Mediterranean sea, can produce, especially in densely urbanized areas, sudden floods with high socio-economic impacts. The climate change effects already under way will contribute to exacerbate this situation, making such events likely more frequent.
The specific objective of the research activity is therefore the development of a system that supports the characterization of extreme precipitation events in areas with complex topography, with the ultimate aim of contributing to improve the hydro-meteorological early-warning systems.
The system must be able to use both data acquired in real time and historical datasets for the reliable and timely execution of high-resolution meteorological simulations (about 1 km), also supported by data assimilation techniques and in probabilistic multi-physics mode, on high-level computing systems performance and cloud computing infrastructure. In addition, the system must allow integration with various analysis and post-processing and data transfer procedures as well as further coupling with hydrological and impact modeling.

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Line D8. HPC applications for climate and geophysical studies of Earth-like planets

The study of exoplanets is one of the leading and most rapidly expanding research fields in astronomy of the last decades. More than 4,000 exoplanets have so far been discovered and the emphasis of exoplanetary studies is now increasingly shifting to characterizing their atmospheric, surface/oceanic, and geophysical properties. Of particular interest are terrestrial-type planets with temperate climates, like the Earth, as they are the best candidates for the search for habitable environments and life outside the Solar System. The observational data available for these planets are steadily increasing and in the immediate future we will be able to observe their atmospheric spectra with new facilities, such as the ESA mission Ariel. At the same time, thanks to the application of interferometric techniques in the (sub)millimetric spectral range allowed by ALMA (Atamaca Large Millimetre/submillimetre Array), we are in the position of observing the very first stages of planet formation and link the geochemical and geophysical properties of terrestrial planets to the planetary birth environment.
The present project aims at studying the properties of terrestrial-type planets with the aid of HPC techniques. The main topics that will be tackled are: (1) the link between atmospheric and surface/oceanic properties and (2) the origin of the geochemical and geophysical properties. To address the first point we will use dedicated climate models which treat the radiative transport in a sufficiently accurate way to allow the construction of synthetic atmospheric spectra that will be essential for the interpretation of the observed spectra. The required climate models need to combine the detailed physical modelling of the Earth with the flexibility required to study the broad spectrum of physico-chemical conditions of terrestrial exoplanets. Models of this type have already been developed at the Trieste Astronomical Observatory (INAF), in collaboration with climatologists operating at the CNR (IGG Pisa, ISAC Turin) and at the Polytechnic of Turin. To study the origin of the geochemical and geophysical properties of terrestrial exoplanets, including the origin of the oceans, we will use state-of-the-art dynamical and collisional models of the formation of terrestrial-type planets capable of accounting for the chemical evolution of their birth environments. Models of this type have already been developed at the Trieste Astronomical Observatory (INAF) and the Astronomical Observatory of Turin (INAF).
The applications of HPC techniques will be a common feature of these studies, that will cast light on several aspects of the physics of planets like the Earth. Most of the models discussed above have already been extensively parallelized and vectorized to operate in modern HPC environments and are subject to continuous improvement and expansion by our group. Some of them take advantage of the high computational throughput offered by GPU computing.

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Line D9. Machine-learning approaches for Earth System Models: parameterisations, downscaling, accelerated spin-up, and more.

The Earth System modelling community faces new opportunities through a combination of increased computing power and the potential for application of Artificial Intelligence (AI). However, these opportunities come with the associated challenges of increasing data volumes

and the need to navigate the rapid development in the application of the AI field. There has been a rapid growth in research into the application of AI and associated machine learning techniques throughout the environmental modelling process chain in recent years. The use of AI as replacement of model parameterisations represents one good example of this, both to increase model speed and to improve model skill: the replacement of parametrizations for representation of cloud microphysics has been an active research area, and has shown the feasibility of using deep learning approaches for climate model parameterization. Another field in which AI techniques have been tested is model downscaling, including bias correction, and model output processing. Some of them allow one to adjust not only the univariate distributions but also their inter-variable and inter-site dependence structures, opening the way for multivariate estimates that can be used for impact studies. Other studies have looked at downscaling using Generative Adversarial Networks that allow for uncertainty quantification and using deep learning to downscale meteorological variables.
At the state of the art, the increase of the resolution in the Earth System Models is strongly limited by the cost of the preparatory simulations called "spin-up". Such simulations, whose length is of the order of hundreds of years, are necessary as all the components of the climate model must be brought to thermal and radiative equilibrium, an equilibrium which is achieved by the slowest elements of the climate system - the deep ocean above all. Running hundreds of years at high resolution (finer than 25km mesh) is not currently feasible even on most advanced HPC, thus severely limiting the effective feasibility of high-definition climate simulations necessary to obtain reliable climate projections. Given the large amount of data currently available through the most recent coupled model intercomparison projects - such as the Earth System Grid Federation (ESGF) archive - it would be possible to exploit AI approaches to develop on or more data-driven spin-up techniques which could reduce the computational cost of spinup integrations at least by an order of magnitude. A deep neural network can be trained to estimate the evolution and the distribution of the oceanic heat content as a function of surface fluxes: this will go with a series of short integrations with the coupled system so that it might be possible to achieve a faster convergence of the system. Developing and improving such methodology could lead to savings of hundreds of thousands of core hours, marking a breakthrough for climate integrations and supporting international activities focused into high resolution such as Destination Earth.

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Topic E: “BigData” in Earth Sciences

Line E1. Large scale data analysis for climate data

In the climate domain the analysis and mining of large volumes of data has become central to scientific discovery, as well as the use of Machine Learning/Deep Learning approaches, for solving key issues related to climate change applications.
In particular, the multidimensionality, volume, complexity, and variety of climate data require specific solutions able to (1) support the management and analysis of large datasets, (2) provide array-based functionalities, and (3) support the scientific analysis process through parallel solutions able to deliver results in (near) real-time.
The objective of this research project is to identify, extend and apply scalable big data analysis solutions running data intensive tasks on High Performance Computing (HPC) machines to address climate analysis needs and issues in (near) real-time. The work will relate to (1) requirements concerning the analysis of large volumes of scientific data (e.g. climate/weather), with a specific focus on multidimensional datasets; (2) the analysis, extension and customization of big data solutions for climate data analysis and visualization, to support a large number of scientific use cases; (3) exploration and evaluation of novel approaches for efficient analysis of climate model data (e.g. in-situ, in-transit). These solutions will address scalability in terms of new storage models/systems and data partitioning, efficiency in terms of I/O and parallelization strategies, interoperability requirements by adopting well-known standards at different levels (data formats, communication protocols, etc.). Moreover, the research activity will take into consideration the efficient use of Machine Learning/Deep Learning for the development of new approaches for downscaling and detection, tracking and forecast of Tropical Cyclones. In addition, ML/DL approaches will be explored to develop Hybrid Modeling in the climate change domain. Hybrid Modeling combines deterministic approaches with predictive ones.
In particular, critical kernels (compute intensive) of the climate model are supposed to be replaced with predictions of data-driven algorithms. The aim is to speed-up the execution time of the model, reducing also its memory usage.

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Line E2. Map-reduce approach to Regional Climate modelling pre/post-processing activities

This proposal refers to the idea of evaluating some of Big Data tools/techniques developed for big data activities for industry, in the scientific area of Earth Science. More specifically the goal of this proposal is to test and investigate the use of Hadoop, a widely used Big Data framework, its Distributed File System (HDFS) and its MapReduce data-driven computational engine to run the preprocessing and the post-processing phase of a climate experiment involving a regional climate modeling tool on a HPC cluster.
In the context of Climate modeling, a considerable amount of time is spent in processing huge volume of data, either in preparing model input and analyzing the large amount of data

produced by the simulations. Application codes used to process the data are usually written in Fortran language, and most of the datasets used in the climate modeling community are in the NetCDF format making the adoption of Hadoop not straightforward at all [1].
To achieve the overall goal Hadoop's logic should be modified to allow in a transparent way both 1) code execution using all the pre/post processing tools and 2) dataset management on HDFS without any modification on the original dataset. To standardize the execution environment on Hadoop, and to make the approach as much portable as possible, the usage of Container-based Virtualization with Docker will also be considered.
The proposed case study will focus on the RegCM Regional Climate Model tool developed by the ICTP and its preprocessing and post-processing programs, but the success of this project would bring benefits also to the entire Earth Science community when dealing with similar use cases, and to the wider extent of filling the gap between modern Big Data platforms and scientific codes in general.

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Line E3. Data management, preservation and curation activities of the National Oceanographic Data Center (NODC)

EMODNet Chemistry (coordinated by OGS) is the European Marine Observation and Data network focused on the groups of chemicals relevant for MSFD Descriptors 5, 8 and 9, aiming to unlock and make available European marine data resources from diverse sources in a uniform way.
The assembled data, data products and metadata are hosted on a structured repository on a cloud environment, made available by CINECA. A series of nodes presently host horizontal gridded maps produced with DIVA (Data-Inverse Variational Analysis) made available through an in-house WMS service and in-situ data, properly discovered, analyzed and visualized with a standard, OGC compliant, WPS service. The data discovery and access service enable users to have a detailed insight of the availability and geographical extent of archived data. This repository hosted in the CINECA cloud represents a wealth of information scientifically aggregated and validated, accessible via the EMODnet Chemistry portal.
The Italian National Oceanographic Data Center (NODC) managed by OGS is going to be replicated at CINECA, together with a web service environment to satisfy the needs of European projects asking for continuous access to data and metadata and national collaborations.

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Line E4. High Performance Data Science for Climate Change Research

The main goal of this research line focuses on the design and implementation of High Performance Data Science tools, frameworks and environments to enable climate change research on big datasets. The research will target the analysis, mining and learning of climate datasets, such as, among others, those from CMIP and CORDEX. The activity will be at the intersection of HPC, Big Data and Data Science applied to climate change research and it will take into account FAIR data principles and Open Science vision. It will link to the European Data Strategy with a specific focus on the climate change data spaces. The activity will include the implementation of user-centered data science use cases in the climate change domain implemented over HPC infrastructures. The work will link to the ENES Climate Data Infrastructure (ENES CDI) and the Earth System Grid Federation (ESGF) as well as European Initiatives related to the European Open Science Cloud (EOSC) and FAIR data principles. The research activity will be developed in the context of the High Performance Climate Informatics Laboratory at the University of Trento, with the support of the "Distributed Systems & Networks" and "Data Intelligence" research programs of the DISI Department.

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Line E5. Analysis and modelling of large-scale datasets from seismology and geophysics

The intention is to improve our capacity of processing and analyzing large volumes of data or reanalyzing data repeatedly in an efficient way in order to allow for the full exploration of the parameter space. Therefore, we are developing innovative platforms for large scale data analysis (Big Data) and are combining these with well-established processing and analysis algorithms used in seismological and geophysical research. We anticipate that the availability of efficient and scalable tools will lead to the development of innovative analysis methods, which were not accessible before.
This research project proposes to develop and implement a Data Analytics platform, and to apply, adapt and evaluate tools from the Big Data / Data Analytics environment for the processing and analysis of big volumes of seismological and geophysical data. We intend to use products from the Apache Hadoop ecosystem, especially Apache HDFS, Spark, Flink, HBase, MongoDB to create new scientific or operational applications or to port existing applications onto this platform.

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Line E6. Application of the wave equation datuming for marine seismic data

The quality of reflection seismic data is very important for seismic processing and interpretation. It depends on factors, such as the seismic characteristic of the Earth's surface, complexity of the subsurface, and technical equipment used in the acquisition stage. The quality of vintage seismic reflection data, which needs to be reprocessed, often is comparably low because of the short maximum offsets, and low common-midpoint (CMP) fold. It is clear that it is necessary to apply advanced techniques to obtain more information. So, our target is to apply our experience on Wave Equation Datuming (WED) in order to extract more information from available seismic data. It is important to note that the data will be processed following a non conventional procedure to preserve the relative amplitudes of the reflections and to better investigate the subsoil structures.
WED can contribute to increase the signal/noise ratio reducing the coherent and incoherent noise. So, it is necessary to perform a systematic and deep study in other dataset in order to optimize the procedure and increase the seismic imaging. This research line proposes to apply

the WED in different offshore seismic dataset acquired. In particular, we propose to study the WED in the following cases: 1) shallow water where the multiple and refraction events are a strong noise and masks the primary reflections (the target of seismic acquisition); 2) areas with complex geometries that can cause strong lateral events masking the primary reflections; 3) areas characterized by strong diffractions, generally difficult to attenuate by using standard processing, which mask deeper reflections.
The WED is applied by using the open-source software Seismic Unix (SU) and the seismic dataset is vintage seismic data available at OGS. The aim is to relocate the shots and the receivers to a new datum applying WED equation. Basically, WED is the process of upward or downward continuation of the wavefield between two arbitrarily-shaped surfaces. The characterization of the velocities is crucial for WED computations and a proper procedure is to define the seismic velocity field by tomographic inversion or by using pre-stack depth migration iteratively. In our case, the input seismic data are processed accurately in order to attenuate the noise and increase the signal/noise ratio. Applying the WED to the processed seismic data by using the seismic velocity, we obtain an improved stacked section, which can help in the interpretation of the seismic data. In fact, the so-obtained seismic section will be a higher vertical and lateral resolution with respect to the conventional stacked section.
Recently, we started to use WED to improve the analysis and the interpretation of the seismic data acquired in presence of gas hydrate and free gas reservoirs. This topic is very timely because the stability and the presence of the gas hydrate could have a strong impact on climate change, geohazard and energy resource. The seismic imaging of the gas hydrate and free gas presences after the application of this approach allowed a better resolution of the complex geological features, such as the fluid flow. Moreover, the base of the free gas layer, generally masked due to peg-legs and strong attenuation, can be recognized more easily after the application of the WED.
The WED is rarely used in geophysical analysis for two main reasons: not all commercial software include this tool and powerful computational resources are required, due the complexity of the numeral computation. In fact, the WED resolves the wave equation sample by sample of all traces, combining the result in order to re-locate the energy at the right position. The present research line proposes to adopt an HPC approach to reduce the computational time-to-solution for the WED and therefore greatly increases the amount of data to be analyzed.

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Line E7. Development Initiatives for Seafloor Safety, Coastal Monitoring, and Data-Driven Innovation using ML and AI

Seabed mapping is a tool used to identify vulnerable areas of the seabed prone to hazard. Having a good knowledge of vulnerable areas of seabed allow reducing risk of disaster to coastal inhabitants and infrastructures. Moreover, detailed seabed characterization is essential for supporting the energy transition, particularly in the planning and safe installation of offshore wind farms. As part of the ongoing research framework, we are currently considering the following developments:

1. This research line focuses on the application of machine learning (ML) and artificial intelligence (AI) for the automatic identification of seafloor morphologies, with the goal of supporting marine hazard assessment, is nearing completion. A short-term research stay abroad is planned for the upcoming fall (October to January) to further develop the initial

ideas of a previously suspended doctoral project. Following the PhD thesis defense, we are exploring the possibility of securing funding—potentially through future HPC TRES initiatives and reallocated resources from unsuccessful past applications—to support a postdoctoral position starting in spring 2026. To strengthen this research direction, new collaborative ties have also been established.

2. This research line, currently funded through a PNRR RETURN grant until March, aims to develop automated analyses of coastal line variations in Calabria. This work is intended to serve as a broader model for understanding shoreline dynamics and sediment budget fluctuations driven by erosion and deposition. The focus is on identifying the impact of flash flood events within the river–submarine canyon system, with potential links to climate variability. The project is being developed through collaboration between early-career researchers and an international partner based in Toulouse (D.G. Wilson).
3. A third research line is focused on developing and integrating various techniques to support the identification of submarine instabilities. This includes the use of photogrammetric analysis based on ROV data, which is expected to involve AI and ML-based methodologies.
4. In parallel, we are promoting the establishment of a physical and/or virtual laboratory at the OGS facility in Milazzo. This initiative is intended to foster interaction between research institutions, industry, and end-users, aiming to stimulate synergies in the field of seafloor safety and to contribute effectively and innovatively to the energy transition. The activity also foresees the exchange of complex large scale and high-resolution datasets and the development of FAIR-compliant data repositories.

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Line E8. Large scale imaging problems in Applied Geophysics

Mathematical models for geophysical scenarios often lead to linear and nonlinear large scale inverse problems. Experimental data may stem, e.g., from electromagnetic induction in frequency- and time-domain (EMI and TEM), ground penetrating radar (GPR), direct current (DC) electrical resistivity, magnetic and gravity data, or seismic measurements. The underlying problem is always of large scale, since it is three-dimensional. It is often simplified to a sequence of two-dimensional or one-dimensional problems, whose solutions are not independent and need to be coupled to ensure continuity and physical consistency. The corresponding inverse problem is generally underdetermined (the solution is not unique) and strongly ill-conditioned, i.e., extremely sensitive to error propagation. Therefore, it cannot be naively solved, but it calls for suitable regularization techniques. The choice of a proper regularization term, often based on a non-Euclidean approach, is the key to promote the selection of physically significant solutions among the infinite ones available. The estimation of the parameters involved in the regularization has an essential impact on the accuracy of the reconstruction. A Bayesian approach is a powerful tool to provide a statistical validation of the computed solution, but greatly increases the computational complexity. Thus, efficient and parallelizable algorithms are essential. A proper HPC environment is fundamental for processing large datasets. On some occasions, it may be necessary to assess the quality of collected data right after their collection. This can be obtained either by a laptop endowed with computationally efficient programs for

medium sized datasets, or on a remote computer via a web interface. Both possibilities impose the availability of a robust and well tested software system.
The aim of this research project is to develop new algorithms for the numerical treatment of geophysical data and to release efficient open-source implementations. Among the topics we intend to treat: study of accurate discretization schemes for integral models, both mono- and multi-dimensional, by stratified quadrature rules; implement regularization algorithms in Banach spaces, to impose specific a priori constraints on the obtained solutions; apply uncertainty quantification approaches to satisfy known statistical distributions of the solution and the experimental noise; manage the processing of large amounts of data to optimize the performance of the developed algorithms.
The new methods will be initially implemented in Matlab, to extend the toolbox FDEMtools developed by our group for forward and inverse modeling in frequency domain electromagnetic induction surveying. The computational routines will be kept at a high level of abstraction, to be able to apply them also to time domain electromagnetic induction, DC electrical resistivity, magnetic, gravity, GPR and seismic data. Forward modeling will also be implemented for a full-waveform inversion (FWI) of GPR and seismic data. The code will then be translated to a programming language better suited for high performance computing, and linked to efficient parallel libraries. This will require the training of a young researcher, whose work will be partly devoted to software development. The assessment of the software will be carried out both on synthetic and experimental data. Large datasets concerning the Sardinian territory are already available at the Geophysical Group of our University, which is involved in the project, but we plan to gather further data during the project development.

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Line E9. AI development and deployment for habitat monitoring and ecosystem services evaluation

The sea bottom, its morphology, habitat and ecosystems, including the species inhabiting it, is still the last explored environment on Earth. The costs, time and technical requirements of studying underwater habitats has long prevented us from gaining sufficient knowledge on their functioning and structure. In the last years, new remote sensing technologies, both men operated (Remotely Operated Vehicle) and autonomous (Autonomous Underwater Vehicle, Autonomous Surface Vehicle, marine drones, fixed buoys), and improvements in existing technology such as satellite imagery (temporal and spatial resolution, improvements in sensors), have caused an increase in the capacity to acquire data under the sea surface without the necessity to deploy scuba divers, reducing costs, time, and the risks associated to working in sea depths. Nevertheless, growing quantities of data represent a challenge for the analysis, given their amount and complexity, and calls for methods able to integrate information from different sources in order to best exploit the capacity of each of them.
It is important to develop tools based on AI that can automatically analyze the acquired data to reduce the burden on the researchers. Automatic recognition of species, habitats and community composition can help reduce the gap between the acquisition and analysis of big data. This activity thus promotes the development and operational deployment of AI algorithms

able to recognize and classify, possibly over different hierarchical levels with increasing detail, features on high quality underwater images and videos in order to: recognize specific habitats (e.g., seagrass meadows, coralligenous, shipwrecks), identify and quantify the presence/occurrence of benthic and pelagic species (e.g., corals, fish schools, cephalopods, shrimps), and identify and quantify the structure and composition of whole communities (e.g., hard bottom communities, deep soft bottom communities, communities thriving around ocean vents).
Such development will strongly encourage the acquisition of new data, producing high quality maps of the sea bottom, including protected habitats. Further, the information on the composition of sessile communities and on the use and visits of mobile species of economic and conservation interest, are critical information for estimates of the conservation status of endangered habitats and species, of marine bottom and pelagic primary and secondary productivity, and of ecosystem services provided by these habitats (e.g., their use as refugia, spawning or nursery areas, stepping stones for species dispersal, carbon dioxide storage, biodiversity conservation).

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Appendix

A1. Links to institutional websites

1. CINECA: http://www.cineca.it/
2. OGS: http://www.ogs.it/
3. ICTP-Earth System Physics: https://www.ictp.it/research/esp.aspx
4. CMCC: http://www.cmcc.it/
5. INGV-Pisa: http://www.pi.ingv.it/
6. CNR/ISAC: http://www.isac.cnr.it/
7. CNR/IGG: http://www.igg.cnr.it/
8. MOX – Politecnico di Milano: https://mox.polimi.it/
9. ENEA – Dip. Sostenibilità dei Sistemi Produttivi e Industriali: http://www.enea.it/
10. INGV – Centro Nazionale Terremoti: http://cnt.rm.ingv.it/
11. INGV – Sezione Sismologia e Tettonofisica: http://www.roma1.ingv.it/
12. Univ. Bicocca – Dip. Scienze Ambiente e Territorio: http://www.disat.unimib.it/
13. CRS4: http://www.crs4.it/research/energy-and-environment/imaging-and-numerical-geophysics/
14. EURAC: http://www.eurac.edu/
15. ARPA-FVG: http://www.arpa.fvg.it/
16. CIMA: https://www.cimafoundation.org/
17. Univ. Trieste – Dip. Matematica e Geoscienze: https://dmg.units.it/
18. Univ. Trieste – Dip. Ingegneria e Architettura: https://dia.units.it/
19. Consorzio LAMMA: http://www.lamma.toscana.it/
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