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STRATEGIC GUIDELINES for Research Vessel *GAIA BLU*

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Introduction

The national ocean science community, encompassing numerous research organizations and universities, spans a wide range of disciplines and thematic areas. The ocean remains a “frontier of knowledge,” with fundamental information still lacking. Continued ocean exploration is essential to acquire reliable physical, chemical, biological, and geological data that can serve as a shared reference framework for humanity. To achieve this, researchers require a high-quality infrastructure capable of meeting contemporary scientific needs.

Research vessels represent a critical component of the European and global ocean observing system. As emphasized by the European Marine Board (EMB Policy Brief No. 7, 2020), these platforms are indispensable for the collection of multidisciplinary data, servicing fixed observatories, ground-truthing autonomous and satellite observations, and enabling access to extreme environments. With the European fleet averaging > 25 years of age and facing the need for renewal and modernization, the *Gaia Blu* constitutes a strategic national asset positioned within the broader European research vessel ecosystem.

This document highlights the most pressing needs and research priorities identified by the Italian scientific community for the upcoming biannual program of activities of the *Gaia Blu* vessel. It aligns with the recently approved *Research Vessel Gaia Blu: Strategic Framework for Italy's Flagship Marine Research Infrastructure*, in which the management, the technical and logistic assets, and the data-lifecycle governance are described in detail. Input from the CNR scientific community was gathered to determine which basic and applied research areas would most benefit from the support of *Gaia Blu* over the next two years.

Seven research priorities were identified that will represent the main scientific focus for the next calls of proposal of the *Gaia Blu* campaigns:

1. Understanding the ocean's role as a climate regulator and key player in the Global and Planetary changes. The *Gaia Blu* is capable of collecting measurements and samples essential to our understanding of ocean physics, biogeochemistry and atmosphere physico-chemical properties, processes that generate the three threats of the ocean (warming, de-oxygenation and acidification). Monitoring programs to capture processes of the 11 descriptors of the Marine Strategy Framework Directive are essential to bridge these gaps.
2. Reconstructing paleoclimates using marine sediment archives. Here, the *Gaia Blu's* coring and long-coring capabilities are crucial.
3. Improving geological and geophysical knowledge of the continental margins from the shelf to the basin, from the seabed to the deep Earth. This is essential to identify predisposing factors and triggering mechanisms for geological hazards (e.g. earthquakes, volcanic and other fluid-flow activity, tsunamis, landslides), assess and manage ocean resources, understand the relation between life and natural processes including catastrophic ones.
4. Expanding knowledge of the diverse life forms found in the ocean. Describing marine and oceanic biodiversity and understanding how these ecosystems work are fundamental research objectives.
5. Exploring marine pollution and anthropogenic impacts and understanding the biogeochemical cycles of man-made contaminants, including their sources, transport pathways, transformations, and accumulation within marine ecosystems.

6. Exploring underwater archaeology and improving our knowledge of underwater culturable heritage in the Mediterranean Basin.
7. Building capability in ocean sciences for the future.

The purpose of this document is to define the strategic priority research lines for future proposals using *Gaia Blu*. Several aspects of marine science have been considered and responds to national and international needs of the science community with a perspective of a decade and detailed focus for a biannual vision of *Gaia Blu* use.

In addition to direct scientific data collection, the *Gaia Blu* plays an essential operational role in the installation, recovery, calibration, and periodic maintenance of fixed marine infrastructures. Long-term observatories, deep-sea moorings, cabled systems, sediment traps, and multidisciplinary monitoring platforms require regular servicing to ensure data continuity, instrument recalibration, battery replacement, sensor upgrades, and structural integrity assessments. These operations cannot be performed without appropriately equipped research vessels capable of precise positioning, heavy lifting, and deep-water deployment. In this sense, *Gaia Blu* constitutes a critical enabling infrastructure for sustained ocean observation, ensuring the reliability and longevity of national and European monitoring networks, fully contributing to the Global Ocean Observing System (GOOS) and the associated value chain.

The rapid evolution of marine technologies — including autonomous systems, advanced sensors, AI-driven data analysis, and digital twin frameworks — requires research vessels capable of integrating and deploying large exchangeable instruments (LEXI), adapting to automation trends, and evolving toward lower-emission operational models. Strategic planning for *Gaia Blu* must therefore anticipate technological foresight and align with European modernization pathways identified by EMB (2020).

1. The role of the Ocean in global and planetary changes

Variability of physical ocean processes across temporal and spatial scales

Ocean dynamics vary across a wide range of spatial and temporal scales. Physical properties are influenced not only by large-scale circulation, but also by meso- and sub-mesoscale processes, vertical mixing, and diffusion. The distribution of biogeochemical tracers reflects the combined effects of physical transport, biological activity, and chemical transformations. These interactions are further complicated by the spatial heterogeneity of fluxes at critical interfaces—air–sea, land–sea, and coastal boundaries—where exchanges of energy and matter are particularly intense and variable. Numerical models provide a valuable framework for disentangling these complex, interacting processes. However, many fundamental mechanisms remain insufficiently understood, limiting the accuracy and predictive power of current simulations. Multidisciplinary scientific cruises are therefore essential, allowing the simultaneous observation of multiple variables and boundary conditions. These include fluxes of heat, salt, nutrients, trace elements, and various forms of carbon; rates of primary production and grazing; and the physical drivers that regulate these processes, such as currents, hydrological structure, bioturbation, and atmospheric forcing.

Advancing knowledge in this field requires high-precision, high-resolution measurements capable of resolving fine-scale gradients and temporal changes. Such observations enable calculation of spatial and temporal derivatives of key variables, providing critical insight into pressure gradients, shear dynamics, mixing intensity, and energy transfer processes. Continuous observations from fixed marine observatories, repeated measurements along historical transects, and sustained monitoring at selected reference sites all contribute to building robust datasets.

In the context of climate change, extended time series are essential to distinguish natural variability (seasonal to multiannual) from anthropogenic trends. There is no foreseeable point at which sustained observation will become unnecessary; in fact, the need for long-term monitoring continues to grow—especially in remote or logistically challenging regions, which are often among the least studied yet most scientifically significant.

Gaia Blu supports and complements fixed ocean observatories and autonomous platforms by providing calibration, validation, deployment, recovery, and multidisciplinary in situ measurements, thereby contributing to the Essential Ocean Variables (EOVs), Essential Climate Variables (ECVs), and Essential Biodiversity Variables (EBVs). Given the limited operational time available to research fleets, it is crucial to formally recognize and protect long-term observational programs. Establishing dedicated status or certification—such as through national observation services—would safeguard the continuity of these time series and enhance their strategic value for both national and international scientific communities.

A support to implement the Marine Strategy Framework Directive and assess the GES

The determination of the GES in the context of MSFD is based on fulfilling the criteria, as implicitly established by the statements summarized by the 11 descriptors of MSFD (Directive 2008/56/EC, Annex I), that describe the key traits or processes of the systems that should be primarily considered. Their assessment should be based on the values of ocean variables, associated with different ecosystem features, and human pressures and their impacts on them. These variables (human pressures and their impacts), most of which are state variables, and their related indicators are straightforward to measure (given the appropriate personnel, training and equipment) and



communicate, allowing a better common understanding across disciplines and a better information transfer, giving policy makers clearer picture of changes and trends in the ocean system.

Dedicated efforts to measure key variables to determine and assess the GES in our country's region and understanding processes driving the system represent crucial research trajectories for the *Gaia Blu* work. Moreover, analysis of descriptors in the deep-sea environment is a step-forward to be achieved using *Gaia Blu* as a suitable research platform.

Biogeochemical cycles

To fully understand the major biogeochemical cycles—particularly those of carbon, nitrogen, phosphorus, and iron—we must clarify how the diverse niches of the biosphere contribute to and regulate them. These cycles govern the exchange of matter between living (biotic) and non-living (abiotic) components of the Earth system, linking biological activity and functional biodiversity with seawater chemistry and geological processes such as continental weathering and interactions with the oceanic crust. However, our current representation of these cycles remains incomplete. A key limitation is the insufficient understanding of many biological components of the ocean, including planktonic communities, coral ecosystems, benthic habitats. Each of these environments plays a distinct and often interconnected role in nutrient transformation, carbon sequestration, and trace metal cycling.

Global environmental change is now affecting all marine habitats, with significant implications for ecosystem structure and function. A deeper understanding of these processes is essential to accurately project future ocean productivity. Likewise, ocean acidification—resulting from rising atmospheric CO₂ concentrations—can impair the ability of calcifying organisms, such as corals, molluscs, calcareous microalgae and zooplankton, to build and maintain their skeletal structures. This weakening of biological calcification may reduce the ocean's capacity to sequester carbon and disrupt ecosystem balance, with cascading consequences for food webs and biogeochemical feedback.

Overall, limited global-scale knowledge of geochemical cycles, coupled with fragmented understanding of key marine ecosystems, restricts our ability to anticipate the impacts of ongoing change and to design effective mitigation and adaptation strategies. Acidification, global warming, and deoxygenation also act together and impact the ability of oceans to sequester carbon into deep waters. The flow of carbon from the surface to the deep ocean is facilitated by physical, biological, and biogeochemical processes, generically referred to as "carbon pumps". The coupling of the biological, microbial and physical pumps that regulates the transport of organic carbon at depth and its transformation is largely underestimated. The mechanisms regulating these pumps, and the role of biodiversity in this, are still poorly understood and their contributions poorly quantified. To achieve a comprehensive understanding of marine biogeochemical cycles, coordinated, interdisciplinary research is important. Integrated approaches of ship-based observations with those from autonomous robotic platforms, satellites and outputs from coupled physical-ecosystem models shall also be considered to further expand our understanding of marine biogeochemical processes over multiple spatial and temporal scales and achieve more accurate predictions and projections.

Air-sea interactions

The majority of the Earth's atmosphere exists not only above the oceans but primarily over the open seas, making it a critical component of the climate system. Yet this vast high-seas atmosphere remains largely inaccessible, and as a result, it is far less well-characterized than coastal or terrestrial atmospheres. Our understanding of natural air-sea interactions in remote regions, far from human influence, is limited—despite the fact that such knowledge is essential for accurate predictions of

climate system evolution. While coastal atmospheric phenomena can often be monitored from land-based stations, high-seas processes require dedicated ocean-based observation platforms. A particularly promising strategic research direction for the *Gaia Blu* is the adoption of an integrated, multi-domain approach to studying coupled ocean–atmosphere processes. By leveraging the shipborne LIDAR system in combination with complementary atmospheric and oceanographic instruments, this approach enables the simultaneous characterization of atmospheric aerosols and clouds and marine optical properties. The ultimate aim is to advance our understanding of the physical and biogeochemical mechanisms that govern air–sea exchanges and shape climate dynamics. In this context, *Gaia Blu* can serve as a strategic hub for strengthening collaboration with European research infrastructures identified in the ESFRI roadmap, such as ACTRIS, ICOS and Eurofleets. By integrating shipboard observations with atmospheric monitoring networks and European naval research platforms, the vessel can play a central role in promoting data standardization, interoperability, and sharing, while also enabling cross-validation of measurements. This coordinated, Europe-wide strategy for investigating coupled oceanic and atmospheric processes positions *Gaia Blu* as a key operational node within a broader network of infrastructures dedicated to comprehensive Earth system observation.

Reactive gases in the marine atmosphere influence the formation and destruction of greenhouse gases, contribute to ozone-related UV absorption, and can induce oxidative stress in marine organisms. Of particular interest are reactions involving dimethyl sulphide, other sulphur compounds, and volatile organic compounds, which are also key drivers of secondary aerosol formation. Despite growing attention—especially in polar regions—these compounds remain poorly understood due to their chemical complexity and extremely low concentrations, which challenge contemporary measurement techniques. Advances in analytical methods partially address these difficulties, but further innovation is needed. Physical fluxes at the air–sea interface (including those of sea-spray aerosols), along with cloud formation and radiation balance, are central to climate regulation.

Ocean warming accounts for 91% of the climate system’s energy accumulation, and surface characteristics shape most heat and momentum exchanges, influencing large-scale atmospheric circulation. Low-lying clouds, linked both to ocean surface conditions and the marine atmospheric boundary layer (MABL), play a crucial role in Earth’s radiation budget, temperature regulation, and in marking large-scale circulation patterns and intraseasonal oscillations. Simultaneous sampling of surface and MABL properties remains essential, particularly in the tropics where the atmosphere absorbs the most heat from the ocean. Key processes, such as the impact of sea state on momentum fluxes and wind profiles, remain poorly quantified. At the process level, strong winds demonstrate how MABL structure governs momentum transfer to the ocean surface and the occurrence of extreme gusts. Momentum, heat and gas transfer processes are significantly enhanced by the air bubbles entrained when increasing the wind speed as a result of the Langmuir circulation and the wave breaking process. Accurate field measurements are essential to overtake the limitations of the models used at present. Documenting the links between surface conditions and mesoscale dynamics under intermediate structural regimes, alongside targeted simulations, is essential to improve predictive capabilities. Finally, climate monitoring must increasingly focus on atmospheric processes. For example, the transport and evolution of ozone and water vapor between tropical reservoirs, mid-latitudes, and polar zones remain uncertain, as does the influence of an accelerated deep branch of the Brewer–Dobson circulation on terrestrial climate, extreme weather events, and cyclones. A coordinated observational and modelling effort is critical to address these open questions and improve our understanding of coupled ocean–atmosphere processes under a changing climate.

2. Paleoclimates paleoceanography and paleoenvironments

Paleoceanographic, paleoclimatic and paleoenvironmental studies allow us to understand past dynamics and interactions among lithosphere, atmosphere, and biosphere. Such investigations provide valuable insights into long-term climate sensitivity, adaptive capacity and resilience of marine biota, and variability of biogeochemical cycles beyond the temporal resolution of instrumental and real-time observational records. This information is essential for understanding and addressing the ongoing climate and environmental changes affecting our planet and thus human society. Deep time investigations document past states of the Earth system that may represent close analogues to present conditions and help us to outline more accurately possible future environmental scenarios. Indeed, paleoceanography, like paleoclimatology, represents a key tool for testing and validating predictive models developed in the Intergovernmental Panel on Climate Change (IPCC) framework. Investigations on sedimentary archives also allow to distinguish natural forcing from impacts driven by anthropogenic activities.

In this context, the Research Vessel *Gaia Blu* can greatly contribute to the advancements with respect to these topics:

1. Collect reference marine sedimentary sequences to study past deep water circulation pattern, hydrological budget and carbon storage in the Mediterranean and outline teleconnections (e.g., North Atlantic Oscillations) and exchange of water volume with adjacent ocean basins (water outflow/inflow).
2. Provide new evidence of or insight into the “triple threat” (warming, acidification, and deoxygenation) effects on the marine fossil record by focusing on key events such as sapropel formation.
3. Acquire continuous, high-resolution sedimentary records to develop a robust, high-resolution chronostratigraphic framework aimed at constraining the timing and duration of major climatic transitions, abrupt changes, and catastrophic events.
4. Enhance availability and coverage of proxies by implementing new cutting-edge methods/techniques alongside traditional ones to decipher the nature and triggers of key palaeoceanographic and paleoclimate events. This expanded proxy toolkit achieves increased accuracy in prediction models. In turn, these improvements contribute to developing strategies and policies for climate change mitigation and adaptations.
5. Reconstruct past biodiversity dynamics at geological time scales using sedimentary ancient DNA (sedaDNA). This new paleogenomic tool allows to reconstruct history of marine ecosystems including the species generally lacking in fossils archives thus providing a more holistic overview of past biodiversity.

3. Continental margins from hazards to resources

Continental margins can be either active, such as those characterized by subduction and consumption of the oceanic crust, or passive, formed through seafloor spreading and lithosphere accretion. This distinction influences the occurrence and magnitude of geological hazards that include seismic events, submarine landslides, which may generate tsunamis, volcanic eruptions, including phreatomagmatic and hydrothermal events. Geological processes occurring over short timescales can constitute major hazards, especially when combined with the vulnerability of coastal populations.

The Mediterranean region is characterized by coastlines that are particularly vulnerable due to high-energy geological processes closely linked to the specific configuration of its continental margins. These margins commonly feature rapidly uplifting coastal mountain chains, poorly developed continental shelves, very steep continental slopes, and high sedimentation rates. Under such conditions, any geological event that disturbs the existing equilibrium, such as moderate to strong earthquakes, subsurface fluid expulsions, or similar processes, as well as increasingly frequent high-energy meteorological and climatic events, can trigger cascading effects (slope instabilities, submarine landslides, tsunamis) that significantly amplify the overall level of coastal and marine hazard.

Improving understanding of these hazards is essential for anticipating their impacts. Key research priorities include quantifying spatial deformation patterns, determining the recurrence of large seismic events, studying the influence of sediment and bedrock properties on fault activity, identifying eruption indicators, and investigating the links between fluid circulation and landslide risks. Monitoring magmatic and hydrothermal activity, as well as seabed deformation and slope movements, is critical to mitigating risk.

The distinction between passive and active margins dictates also the style of sedimentation and the type of resources found within any associated sedimentary basin, indeed the geological history of a continental margin remains the most important factor in resource mapping. Passive margins develop during the rifting of continents and the subsequent seafloor spreading, are tectonically stable and allow for the undisturbed accumulation of massive sediment layers over millions of years, including organic matter and evaporitic deposits in deeper basins and aggregates and heavy mineral placers along the inner shelf, offshore freshwater aquifers. The steady burial of organic matter under high pressure and temperature creates the ideal depositional environment for hydrocarbon generation. These conditions together make passive margins also potential sites for sub-seabed carbon capture and storage.

In contrast, active margins are characterized by subduction zones, volcanic arcs, and intense seismic activity. Sedimentary basins, such as a fore-arc or back-arc basin, are often deformed, folded, and faulted by tectonic forces. The volcanic activity associated with subduction often leads to seafloor massive sulphide deposits, which are rich in critical metals, and geothermal potential, while high-pressure subduction zones are ideal for the formation of methane hydrates.

Therefore, continental margins are primary prospective reservoirs of natural resources including minerals, hydrocarbons, renewable energy, freshwater. Sustainable and responsible exploration and exploitation of these resources require a thorough understanding of the complex physical, chemical, and biological processes occurring in and around the seabed, as well as their interactions with surrounding ecosystems.

Active Tectonics

Studying active tectonic features in submerged environments is of fundamental importance for both scientific understanding and risk assessment. While the investigation of seismogenic structures themselves is crucial for identifying earthquake sources and assessing seismic hazard, the underwater setting offers unique and often unparalleled advantages for analyzing fault kinematics and long-term tectonic behaviour.

Unlike many onshore environments, which are frequently affected by erosion, vegetation cover, and intense anthropogenic modification, the seafloor can preserve geomorphological and sedimentary features with remarkable clarity. High-resolution bathymetry and seismic reflection data allow researchers to map fault scarps, offsets, folds, and deformation patterns in great detail. In many cases, submarine landscapes provide a more continuous and less disturbed record of tectonic deformation than their continental counterparts, making them particularly suitable for reconstructing the kinematic evolution of geological structures.

Moreover, submerged environments are especially effective at recording the effects of catastrophic events such as strong earthquakes, submarine landslides, and tsunami-related sedimentary processes. These events can leave distinct stratigraphic signatures—such as turbidites or mass-transport deposits—that are often well preserved in marine basins. By identifying and dating these deposits, scientists can extend paleoseismic time series far beyond the limits of historical and instrumental records. This extension of temporal datasets is essential for improving recurrence interval estimates and refining probabilistic seismic hazard models. Therefore, the study of active faults in submarine settings is not only vital for understanding the mechanics of seismogenic structures but also represents a powerful approach to lengthening geological time series and enhancing the reliability of risk assessment frameworks.

Gravity flows, canyons and submarine landslides

Sedimentary processes are primary architects of the shaping of continental margins both active and passive. On active margins, sedimentary processes are dominated by rapid, high-energy events, because the continental shelf is typically narrow, sediment from coastal sites is funneled almost immediately into the deep-sea trough canyons. Tectonic activity may contribute to trigger massive underwater landslides and debris flows. On passive margins, the primary sedimentary process is long-term, vertical aggradation. Because these margins are tectonically quiet and have wide, shallow continental shelves, they act as massive storage zones for terrestrial sediments delivered by large river systems. The sediment transport here is often driven by sea-level fluctuations. During periods of low sea level, rivers bypass the shelf and deliver sand and mud directly to the basin via submarine canyons. This triggers gravity-driven flows (turbidity currents), which deposit large, fan-shaped accumulations of sediment at the base of the slope.

Yet many aspects of these processes remain poorly understood, including the frequency and drivers of mass-transport events and gravity-driven flows, the links between sediment transport and the action of water masses and bottom currents, the erosion-driven release of contaminant to the deep-sea, the contribution of fluid outflow to slope instability. These processes require a modern suite of observations that combine in-situ shipborne repeated geophysical investigations of both the seabed and water column, remote sensing techniques from satellite observations and the deployment of long-term observing platforms such as moorings, sediment traps, tripods, seafloor and cabled observatories to capture the interplay between oceanographic and geological processes, overflow dynamics within

bottom boundary layers, topographically steered dense water flows, and long-term changes in deep water masses.

Source-to-sink processes in extreme meteo-oceanographic events

The physical and biogeochemical processes that regulate the transfer and fate of sediments, organic matter, and contaminants across the land-sea continuum requires a multidisciplinary suite of measurements and approaches. Extreme events such as floods and storms exert a primary control on seabed reshaping, sediment remobilization, and the redistribution of pollutants and particulate matter. By integrating sedimentological, geochemical, oceanographic, and biological observations, this approach evaluates how event-driven dynamics influence benthic habitats and marine ecosystem functioning, from microbial communities to higher trophic levels. Particular emphasis is placed on source-to-sink connectivity and on identifying the conditions that determine sediment preservation, contaminant burial, or remobilization under changing climatic and anthropogenic pressures.

Coastal Erosion and Flooding

Global temperatures have already risen over 1°C during the past century, contributing to an average sea level rise of 0.2 meters. Projections suggest sea levels may rise 0.5–1 meter by 2100, substantially increasing the risk of coastal erosion, cliff instability and flooding. Local factors, such as land subsidence from tectonics or human activity (e.g., groundwater extraction), can exacerbate these risks. Currently, approximately a quarter of the world's sandy coasts are eroding at rates exceeding 0.5 meters per year. The erosion of the cliffs that make up most of the coastline tends to be linked to changes in continental climate variables, but rising sea levels exacerbate this process. Coastal flooding is primarily driven by unusually high sea levels, often the result of combined effects of high spring tides and skew surges—differences between observed sea levels and predicted tides caused by wind stress, atmospheric pressure gradients, and wave dissipation. These conditions produce wave setup, elevating water levels along coastlines. A detailed understanding of these processes requires comprehensive in situ measurements of wind stress, wave dissipation, and infragravity wave generation, particularly during storms. Presently, observations are limited to tide gauges and offshore buoys, leaving many dynamics under-sampled. Extensive hydrodynamic measurements in surge-prone zones are essential for improving predictive models and mitigating coastal hazards.

Fluid circulation, extreme ecosystems, minerals

Continental margins—both active and passive—are key reservoirs and circulation zones for various fluids, whose accumulation and movement remain significant areas of study.

Despite recent advances, many aspects remain poorly understood, including hydrothermal venting and focused fluid-flow processes and their interdependence with the microbiological component, the cycling of chemical elements and heat flows, the role of mid-ocean ridges and hydrothermal vents in global biogeochemical cycles—such as carbon, hydrogen, and trace metal cycles, the impact of hydrothermal vent systems on deep-sea ecosystems, chemistry and circulation. Addressing these questions is critical to understanding the influence of different geodynamic settings on deep-sea ecosystem diversity, extremophile communities within the deep lithosphere, the distribution of chemical elements in the ocean, and the formation of certain resources, including metal deposits and hydrogen.

Feedback from marine geology experts on this matter underscores the growing need for both multidisciplinary collaboration (bringing specialists from diverse fields together) and interdisciplinary approaches (where their knowledge, methods, and data are synthesized to address

complex seabed processes) in future research around these sites. Indeed, the processes under investigation involve strong interactions between the solid Earth and other components of the Earth system—including the biosphere, hydrosphere, and, indirectly, the atmosphere—which collectively influence responses to both natural forces and human activity. Progress in this field will require dedicated deep-sea observational strategies, high-resolution measurements, and enhanced access to seabed environments to capture processes that remain largely invisible yet are fundamental to the functioning of the Earth system.

Offshore freshened groundwater

Offshore aquifers are a largely unexplored yet potentially strategic freshwater resource in a context of increasing global water demand. Through integrated stratigraphic, geophysical, geochemical, and chronological approaches, it aims to define the spatial distribution, volumes, and internal architecture of aquifer systems preserved within continental shelves, including aquitards and confining layers. A central objective is to assess hydraulic connectivity between onshore and offshore aquifers, with implications for recharge mechanisms, long-term sustainability, salinization processes, and vulnerability to groundwater exploitation and climate-driven sea-level rise. Advancing knowledge in this field contributes to filling a major gap in global water-resource assessments and supports informed management of what is increasingly referred to as the planet's future "blue gold".

Accelerating seabed mapping

Direct sampling and geophysical measurements of the seabed have always faced significant technical and logistical challenges, leaving vast areas of the deep ocean insufficiently explored. Knowing the shape of the seafloor is fundamental for breaching the gaps in the above mentioned knowledge sectors, such as deepening the understanding of how new lithosphere is accreted and consumed especially in remote and very deep regions of the Planet, identifying hot spots of marine life, supporting sustainable resource management, predicting and mitigating the impacts of marine geohazards, enhancing tsunami forecasting and public safety, analysing sediment transport and environmental change, and planning submarine cable and pipeline routes. Moreover, seabed mapping is also primary knowledge baseline for understanding ocean circulation and improving climate models, and sea-level rise predictions.

Seafloor mapping is also essential to achieve the societal outcomes of the UN Decade of Ocean Science for Sustainable Development (2021–2030) and to support Sustainable Development Goal 14, which aims to conserve and sustainably use the ocean, seas, and marine resources. Within the framework of the Seabed 2030 Project and the global GEBCO initiative, the research vessel *Gaia Blu*, equipped with state-of-the-art technology, plays a key role in filling critical data gaps and contributing to the completion of the freely available GEBCO global digital bathymetric map with high-resolution multibeam mapping of previously unmapped or poorly mapped seafloor areas. *Gaia Blu* may be instrumental to contribute to the integration and delivery of quality-controlled bathymetric data to enhance the global GEBCO dataset.

4. Ocean biodiversity, ecosystem dynamics and habitats

Compared to terrestrial biomes, the ocean remains vastly underexplored. Understanding the ocean biome requires identifying its organisms, mapping their distribution, analysing interactions among them, and evaluating how they relate to the ocean's physical, geological, and atmospheric components. This knowledge is critical not only for fundamental science but also for understanding and predicting the impacts of climate change and human activity. Ocean exploration is strongly biased toward easily accessible regions, economically important organisms, and temperate or coastal habitats. For example, the northern Atlantic and coastal zones are far better studied than the Indian Ocean, polar regions, or deep-sea environments. Large or charismatic species are better understood than small or cryptic ones. These biases limit our understanding to local ecosystems and compromise broader insights into global ocean biology.

The strategic objective is therefore to improve the description of biodiversity across all organism sizes and water depths. Central to this effort is documenting taxonomic diversity at the species level, including their geographic distribution, relative abundance, relevant functional traits and ecological role. Sampling at depths greater than 200 meters frequently reveals new species, but sporadic sampling often limits knowledge to a few specimens. Advances in genetic and cellular techniques continuously refine species descriptions, emphasizing that our inventory of ocean biodiversity still remains incomplete. A robust taxonomic framework enables indirect monitoring approaches, such as underwater imaging and sequencing of environmental DNA (eDNA). Accurate reference databases linking DNA sequences to species are essential, as it is the characterization of functional diversity—organisms' traits, including size, diet, and behaviour—which shape ecosystem roles and helps disclose how the diversity is changing in response to climate stress and perturbations. Functional redundancy, where multiple species perform similar ecological roles, can buffer ecosystems against biodiversity loss. Genetic diversity further underpins species' adaptive capacity to environmental change. Beyond individual species, understanding ocean life requires describing communities, habitats, and ecosystems, as well as their spatial and temporal global distributions. Biological, environmental, and historical factors collectively shape organism distribution. Trophic interactions, competition, cooperation, and parasitism influence where species occur—for instance, pelagic predators such as tuna concentrate where prey is abundant. Environmental parameters, including temperature, salinity, oxygen, light, depth, and nutrient availability, also critically determine large organisms and planktonic distributions, often in highly variable, spatially dependent patterns such as upwelling zones, eddies, fronts, filaments, across light-penetration gradients or in response to extreme events. Comprehensive, unbiased exploration and monitoring across all habitats, organism sizes, and geographic regions are essential for building a complete understanding of ocean biodiversity, ecosystem function, and resilience.

Physical, biogeochemical and biological processes span over multiple spatial and temporal scales. There is not a single and observational method or platform that can provide a comprehensive and time-evolving view of the structure and functioning of marine biodiversity and ecosystems. Therefore, Essential Ocean, Climate and Biodiversity Variables must be connected, harmonized and integrated to crucially advance our understanding of ecosystems and marine life by reducing spatial and temporal biases. The coordination of *Gaia Blu* activities in connection with international observational networks and the European Research Infrastructures (e.g., Euro-Argo, ICOS, EMSO, Danubius, e-LTER, Jerico, Eurofleets) thus becomes fundamental to achieve an integrated view of our oceans. Highly innovative genetics and imaging techniques may, for instance, be linked with

innovative observations from autonomous robotic platforms as well as with remote sensing, modelling and artificial intelligence (AI) techniques to push to the forefront our current knowledge on ecosystem health and thus our prediction capability, from the surface to the ocean interior.

Fisheries and biological resources

Understanding marine biological resources and the ecosystem dynamics that underpin fisheries activities is a strategic priority for the national scientific community. In this context, CNR plays since decades a central role in fishery science, by developing advanced approaches for the observation, assessment and sustainable management of fishery resources in the Mediterranean Sea and beyond. This research work is essential for balancing the economic needs of the fishing industry with the ecological necessity to preserve Mediterranean biodiversity. Sustainable fisheries are central to global food security and for a safe future for humanity. Consequently, we must leverage research vessels and on-site monitoring to gather the data necessary for informed decision-making in both coastal and offshore areas. Achieving this requires the strategic use of research vessels and in-situ observation systems to collect critical data. Future research priorities will focus on the adaptive capacity of fishery resources to climate change. This necessitates a holistic evaluation of the synergistic effects of fishing pressure, pollution, and climatic shifts on physiological processes, population dynamics, and biodiversity patterns. To quantify the cascading effects of ecosystem state shifts - such as altered predator-prey interactions and nutrient cycling -we must employ advanced analytical approaches. Furthermore, the design of integrated management scenarios requires high-fidelity digital modeling frameworks. These tools are essential for evaluating spatially explicit strategies within conservation areas while balancing concurrent maritime uses, including renewable energy, mineral extraction, and subsea infrastructure.

Fisheries resource monitoring is regulated by the European Data Collection Framework (DCF), which is part of the Common Fisheries Policy. CNR coordinates and implements the activities of the DCF at the national level, coordinating biological sampling, environmental monitoring, and socio-economic analyses. While *Gaia Blu* is not able to support the DCF monitoring cruises that are regularly performed every year since more than three decades, as these operations would otherwise be excessively costly, impractical, or even impossible to conduct using on *Gaia Blu* (which, moreover, would divert valuable ship-time from open-sea research), it can help support specific campaigns dedicated to fisheries and biological resources management focused on:

- strengthening integrated marine observation, advancing ecosystem-based fisheries management, and enhancing technological innovation to support sustainable ocean governance and climate adaptation.
- developing an integrated and multidisciplinary framework for monitoring fish stocks and population dynamics. This will combine biological and environmental sampling, acoustic surveys, genetic approaches (including eDNA and eRNA), and ecological modeling. The systematic collection and integration of high-quality data will improve stock assessments, enable predictive analyses, and support adaptive and science-based management.
- addressing trophic dynamics, ecosystem functioning, and the cumulative impacts of fishing and climate change. Activities will include the monitoring of species distribution shifts related to ocean warming, deoxygenation, and acidification, the assessment of the vulnerability of sensitive species and habitats, and the identification of climate refugia and priority conservation areas. These efforts will contribute to marine spatial planning, biodiversity conservation, and the implementation of ecosystem-based approaches.

- fostering technological innovation on fishery science and biodiversity monitoring, by using *Gaia Blu* as a national platform for advanced observation and experimentation, to integrate automated observation systems, autonomous platforms such as gliders and ROVs, and artificial intelligence tools for automated species identification and real-time data processing.

Advancing Marine Habitat Mapping for Biodiversity and Conservation strategies

Within the framework of the EU Biodiversity Strategy 2030 and Marine Strategy Framework Directive, which aim to halt biodiversity loss and achieve Good Environmental Status in marine ecosystems, the *Gaia Blu* infrastructure conducts activities aimed at understanding deep-sea biodiversity distribution, ecological functioning, and conservation status. These efforts support the designation and management of the Natura 2000 network targeting habitats listed within the Habitats Directive and Vulnerable Marine Ecosystems. The activities include:

- Visual exploration, habitat mapping, and deployment of long-term monitoring networks to investigate how oceanographic forcing (water mass circulation, hydrodynamic regimes, biogeochemical cycles) regulate biological responses (reproduction, larval dispersal, population connectivity, community assembly).
- Investigation of how geomorphological settings interact with oceanographic processes to create heterogeneous habitats supporting distinct biological communities
- Investigation of growth dynamics, reproductive ecology, larval dispersal patterns, and colonization processes of deep-sea habitat-forming species to explore connectivity networks essential for conservation planning and restoration actions
- Population genetic analyses using eDNA to map deep-sea connectivity networks, identify genetic barriers limiting population connectivity, and identify genetically isolated populations
- Quantification of anthropogenic impacts on deep-sea ecosystems and assessment of health and degradation status of habitats to establish baseline conditions and conservation priorities for protected area designation
- Quantification of anthropogenic impacts from seabed mining, offshore wind farms, and other infrastructure on deep-sea ecosystems, including habitat alteration, noise pollution, sediment disturbance, and artificial reef effects on biodiversity; this supports baseline assessments for protected area designation and Maritime Spatial Planning.

Driving nature restoration and marine ecosystem recovery

Within the framework of the EU Nature Restoration Regulation (2024/1991), which mandates restoration of degraded marine ecosystems, the *Gaia Blu* infrastructure conducts pioneering activities aimed at developing evidence-based restoration approaches that maximize intervention success and long-term ecosystem recovery under changing environmental conditions. Activities integrate ecological understanding with engineering solutions to develop effective, climate-resilient interventions, and include:

- Development of ecosystem-based restoration solutions through systematic testing of different structure designs (mimicking natural habitats) and materials that favour habitat recovery without compromising structural stability
- Implementation of transplantation approaches combined with provision of colonization substrates to favour and support repopulation in degraded areas and accelerate ecosystem recovery

- Establishment and maintenance of long-term monitoring networks to collect data on ecosystem recovery and refine restoration protocols
- Collection of data in parallel to restoration activities to directly investigate how oceanographic processes, geological settings, and environmental change influence restoration success and long-term ecosystem recovery

Advancing Ocean Science for Climate Impact Assessment and Ecosystem Resilience

Within the framework of the European Green Deal and Climate Adaptation Strategy, which require understanding how climate change affects marine ecosystems and developing adaptive responses, the *Gaia Blu* infrastructure conducts activities aimed at quantifying climate impacts on deep-sea biodiversity and identifying climate refugia to ensure long-term ecosystem persistence under projected environmental change scenarios.

- Experimental programs to investigate reproductive ecology, larval development, settlement preferences, and physiological limits under multiple climate scenarios to determine species-specific tolerance thresholds
- Collection of data to develop predictive models to identify climate refugia, determine which climate trajectories threaten ecosystem persistence, and prioritize conservation and restoration sites with maximum long-term viability
Long-term monitoring of environmental parameters and biological responses at key deep-sea sites to detect signals of climate-driven ecosystem shifts and validate predictive models.

Advancing Ecosystem-Based Maritime Spatial Planning and Digital Ocean Solutions

The *Gaia Blu* infrastructure conducts activities in the framework of the Maritime Spatial Planning Directive aimed at providing spatially explicit knowledge of habitat distribution, ecological importance, and vulnerability to integrate conservation with sustainable blue economy development and managing competing uses of marine space.

- Creation of knowledge base for predictive and prioritization modelling to implement Maritime Spatial Plans
- Contribution to the Digital Twin of the Ocean through systematic data collection on deep-sea habitat distribution, environmental parameters, and ecosystem responses to environmental change.

5. Human impacts on marine ecosystems

Human activities exert profound direct and indirect pressures on marine ecosystems, often with long-term consequences. Fishing remains the most pervasive biological pressure, altering food webs, trophic structure, and habitat integrity, while land- and sea-use changes further modify ecosystem dynamics. Coastal and shelf seas are particularly affected by riverine inputs, which carry excess nutrients, chemical pollutants, and microplastics, while maritime transport introduces invasive species via ballast water. Even remote and deep environments are increasingly affected through long-range transport of contaminants, climate-driven circulation changes, and atmospheric deposition. The degradation of marine ecosystems compromises essential ecosystem services, including fisheries productivity, coastal protection, carbon sequestration, and cultural values, with direct socio-economic implications. These pressures disrupt ecosystem dynamics and reduce climate resilience, despite the crucial role these ecosystems play in global food security. The R/V *Gaia Blu* enables integrated, multidisciplinary assessments combining biological, chemical, and physical measurements, supporting long-term monitoring and process-based understanding of anthropogenic pressures across spatial scales. Advancing this research line supports the assessment of multiple MSFD descriptors (e.g., biodiversity, food webs, eutrophication, contaminants, seafloor integrity), particularly in offshore and deep-sea environments where observational gaps remain significant.

Cumulative and Remote Impacts

Beyond fishing, human activities impact even the most remote marine areas, including the high seas, deep ocean, and polar regions. Key pressures include artificialization, pollution, underwater radiated noise, warming, and acidification, all of which interact to alter ecosystem structure and function. Examples include:

Coastal infrastructure (ports, dikes, aquaculture) and land-use changes disrupt sediments, ship traffic along the main routes, while offshore platforms and wind farms create artificial reefs that alter food webs and currents.

Plastics, heavy metals, PCBs, and other contaminants interact synergistically, producing toxic effects far greater than individual pollutants alone. Noise and light pollution further modify ecosystem dynamics. Warming shifts species distributions and ecological niches; acidification affects calcifying organisms like corals and mollusks. Eutrophication triggers massive phytoplankton blooms, altering food chains and favouring species such as jellyfish. These pressures do not act independently but modify ecosystem structure, trophic interactions, habitat complexity, and biogeochemical functioning, potentially driving regime shifts and reducing ecosystem resilience. Understanding these cumulative impacts requires an interdisciplinary approach that combines biology, geochemistry, and physical oceanography with social sciences to evaluate human uses of the ocean, from fishing to tourism and shipping. Effective analyses must align biological and environmental observations across the same spatial and temporal scales, enabling accurate assessment of ecosystem responses to multiple simultaneous pressures. Such efforts are essential to inform sustainable management and conservation strategies.

Ocean–Human Health Nexus and Cross-Ecosystem Connectivity

Investigating the fate of emerging contaminants across coastal, offshore, and deep-sea environments is critical for understanding their ecological consequences and implications for human health, food security and socio-economic sustainability. This research examines how pollutants are transported, transformed, bioaccumulated and potentially biomagnified along the continuum from terrestrial

sources to the deep ocean, integrating physical circulation, biogeochemical cycling, and trophic transfer processes. By linking ecosystem health indicators with exposure pathways to human populations, this line supports risk assessment frameworks, MSFD descriptors, and evidence-based mitigation strategies.

Cross-Ecosystem Connectivity Under Multiple Stressors

The ocean should be studied as an integrated, multi-scale system rather than as isolated compartments. This approach evaluates the dynamic interactions among physical, biogeochemical, geological and biological processes and analyzes functional connections between coastal, pelagic, benthic and deep-sea ecosystems. Particular emphasis is placed on the transfer of carbon, nutrients, contaminants, biodiversity, and microbiomes across spatial gradients and depth layers. By assessing resilience thresholds, feedback mechanisms, tipping points, and potential regime shifts, this framework enables improved prediction of ecosystem responses under cumulative pressures such as climate change, eutrophication, deoxygenation, and pollution.

The Deep Sea as a Sentinel

Deep-sea sedimentary archives and long-term observatories provide critical records of historical contamination, climate variability and ecosystem change, positioning the deep ocean as an early warning system for emerging environmental risks. Reconstructing past pollutant deposition, biogeochemical shifts, and biodiversity responses allows for assessing ecosystem vulnerability, recovery capacity, and long-term resilience under increasing anthropogenic stress. In this context, the R/V *Gaia Blu* serves as a strategic platform for sustained deep-sea observation, multidisciplinary sampling, and integration with European monitoring infrastructures, strengthening Italy's contribution to global ocean stewardship.

6. Underwater cultural heritage

Underwater Cultural Heritage: Exploration, Risk Mitigation, and Governance

Underwater Cultural Heritage (UCH) embodies the deep-time relationship between human societies and the sea, preserving material evidence of navigation, trade, conflict, migration, and resource exploitation. Harbors, anchorages, shipping routes, fishing grounds, shipbuilding zones, and ritual maritime spaces—whether submerged or coastal—form complex maritime cultural landscapes rather than isolated archaeological sites. Shipwrecks, in particular, should be understood as strategic nodes within wider cultural, economic, and environmental systems shaped by historical dynamics and natural forces.

From an exploratory perspective, UCH represents both a scientific frontier and a strategic asset. Advances in high-resolution seabed mapping—such as multibeam bathymetry, side-scan sonar, sub-bottom profiling, and photogrammetric 3D modeling—have transformed our capacity to detect, document, and interpret submerged cultural remains. These technologies allow for non-invasive exploration at unprecedented scales.

The degradation of underwater cultural heritage is a dynamic, multi-factor process driven by the interaction of physical, chemical, biological, and anthropogenic forces. Once submerged, archaeological materials are exposed to corrosion, biofouling, sediment mobility, and geochemical alteration, processes that vary significantly depending on depth, water chemistry, hydrodynamics, and seabed composition. Metals suffer from electrochemical corrosion, wood from biological decay and microbial attack, while ceramics, glass, and composites may experience structural weakening due to abrasion or chemical dissolution.

These processes not only threaten the physical integrity of sites but can also destabilize wrecks that contain hazardous substances (e.g., WWII shipwrecks), increasing the likelihood of secondary chemical or environmental risks.

Stakeholders and Long-Term Stewardship

Effective UCH management is inherently multidisciplinary and stakeholder-driven. Archaeologists, hydrographers, environmental scientists, naval authorities, offshore industries, policymakers, and local communities all play critical roles. Programmatic management frameworks—grounded in continuous mapping, monitoring, and data sharing—enable informed decision-making, conflict prevention, and sustainable use of the marine environment.

The management of underwater archaeological sites requires a proactive and multidisciplinary approach aimed at long-term preservation and risk mitigation. Threats include looting, uncontrolled diving tourism, fishing activities, offshore development, dredging, and natural processes such as sediment displacement and biological colonization. Climate change adds further stressors, including increased storm intensity and changing ocean chemistry.

7. Ocean education and experiential training

Italy's ocean-focused education and research programs are a major asset for its higher education system, reflecting universities' commitment to marine science through undergraduate and graduate degrees. The offering of programs in marine sciences at Italian universities reflect certain geographical and historical-academic constraints, with predominance of courses addressing marine biology and biotechnology and coastal management. Educational cruises shall provide hands-on learning opportunities on a wider range of disciplines and marine knowledge, foster science outreach, and raise awareness of socio-ecological transitions and ocean sustainability.

Effective ocean education emphasizes teaching students how to ask the right scientific questions, gather and interpret ocean data, and understand the rationale and methodology behind research. "Learning at sea" is essential for this experiential approach, helping future scientists acquire practical skills while observing complex ocean systems firsthand.

Designing effective educational programs at sea requires careful consideration of:

- Target skills and learning objectives, which vary with training level (undergraduate, master's, professional development) and specialization
- Ocean systems studied, which operate across widely differing spatial and temporal scales
- Sampling strategies, as approaches that serve educational goals may not always align with research objectives

To meet these challenges, educators recommend updating methodologies along three key themes:

- Enhanced multi- and interdisciplinary approaches, integrating chemistry, physics, biology, geology, and their combinations through targeted expert-led sessions.
- Multi-platform strategies, combining vessel-based sensors, onboard observers, and other data collection tools.
- Alignment of pedagogical and scientific objectives, ensuring that educational activities complement research goals while remaining feasible within technical and organizational constraints, by bringing specialized communities together rather than attempting comprehensive but shallow training.

By integrating these approaches, Italian ocean education can continue to prepare skilled scientists equipped to address complex environmental and societal challenges. In fact, beyond academic training and student education, the long-term effectiveness of the *Gaia Blu* depends fundamentally on the availability of a highly skilled technical workforce and robust marine operations capacity. Research vessels are complex scientific infrastructures that require not only experienced seafaring crews but also specialized marine technicians capable of managing advanced instrumentation, autonomous platforms, data acquisition systems, and increasingly sophisticated digital and communication technologies. General maritime training alone is insufficient; dedicated programs tailored specifically to research vessel operations are required.