

Dialogues with Industry

Background Paper

Accelerating Ocean Enterprise Growth
in Future Markets: Developments,
Disruptions and Vision

Table of Contents

Background on the <i>Dialogues with Industry</i>	3
Markets and Market Viability Background and Terminology	5
Dialogue 1: Impacts of Dual-Use on Ocean Technology	6
Shifting Acquisition Strategies	8
Effect of Dual-Use	9
Potential Data Impacts	9
Summary of Dual-Use Benefits and Risks	10
Overcoming Market Fragmentation	10
Dialogue 2: Carbon and Biodiversity Credit Markets	11
Carbon Methods Landscape	13
Carbon Credit Market Financial Instruments	14
Carbon Credit Financial Instruments – In Use	14
Underdeveloped Financial Instruments	15
Technologies to Measure Biodiversity	16
Biodiversity Credit Market Financial Instruments	17
Financial Instruments – In Use	17
Underdeveloped Financial Instruments	19
Overcoming Market Fragmentation	20
Dialogue 3: The Ocean Enterprise in the Age of AI	20
AI Trends Within the Ocean Information Value Chain	22
Current Uses of AI in Global Ocean Conservation and Obstacles	24
Examples of AI as a Market Catalyst	25
Highlights of Ocean AI Efforts	25
AI Impacts and Benefits Analysis	26
Acknowledgements	27
AI Caveat	27
Planning Team	27
Reference List	29
Appendix 1: Markets and Market Viability Terminology	37
Appendix 2: Biodiversity Credit Markets Supplementary Material	39
Appendix 3: AI Radar Diagram Supplemental Information	40
Appendix 4: Artificial Intelligence Supplemental Material	43

Background

The Ocean Enterprise Initiative is a global effort that spearheads innovation, thought leadership, and economic development within the Ocean Enterprise. It is led by the Marine Technology Society (MTS), Global Ocean Observing System (GOOS), National Oceanic and Atmospheric Administration (NOAA), and Industry (Kongsberg Discovery).

The [Dialogues with Industry](#) (hereafter *Dialogues*) are a signature pillar of the Ocean Enterprise Initiative. The first, September 2022 – January 2023, explored how to mature the Ocean Enterprise to deliver essential societal, economic, and environmental benefits. This culminated in the [Dialogues with Industry Roadmap](#)^[1] (hereafter Roadmap). The Ocean Enterprise Initiative is the structure to implement recommendations from the Roadmap, guided by three goals:

- Improving the Marketplace
- Collaboration to Grow and Impact Change
- Shaping the Future

The second *Dialogues*, January – February 2025, focused on Harmful Algal Blooms. Access the summary report [here](#). The third *Dialogues*, October – November 2025, focused on the Future of Ocean Observing. Access the summary report [here](#).

The fourth *Dialogues* will focus on emerging markets. The Ocean Enterprise has successfully developed products and services for well-defined, mature markets. However, future growth lies in more complex terrain: emerging markets characterized by fragmented demand, diverse regional contexts, and overlapping but poorly coordinated information needs.

In these markets:

- Demand is distributed across geographies and sectors.
- Individual use cases are too small to sustain markets for observations and instruments.
- Regulatory, environmental, and economic conditions vary by region and industry.
- Existing data standards and governance models do not fully support solutions to market.
- Innovative potential exists but is constrained by market fragmentation.

The success of the *Dialogues* stems from bringing together all components of the Ocean Enterprise, public, private, and academia, for facilitated discussions that consider the entirety of the Ocean Information Value Chain, from observation to user, as depicted in **Figure 1**^[2]. The *Dialogues* provide a foundational framework for understanding the obstacles holding back the development of an ocean observing market. They aim to identify the demand, relevant stakeholders, challenges, and opportunities necessary to unlock economic potential while meeting the increasing need for actionable ocean information.

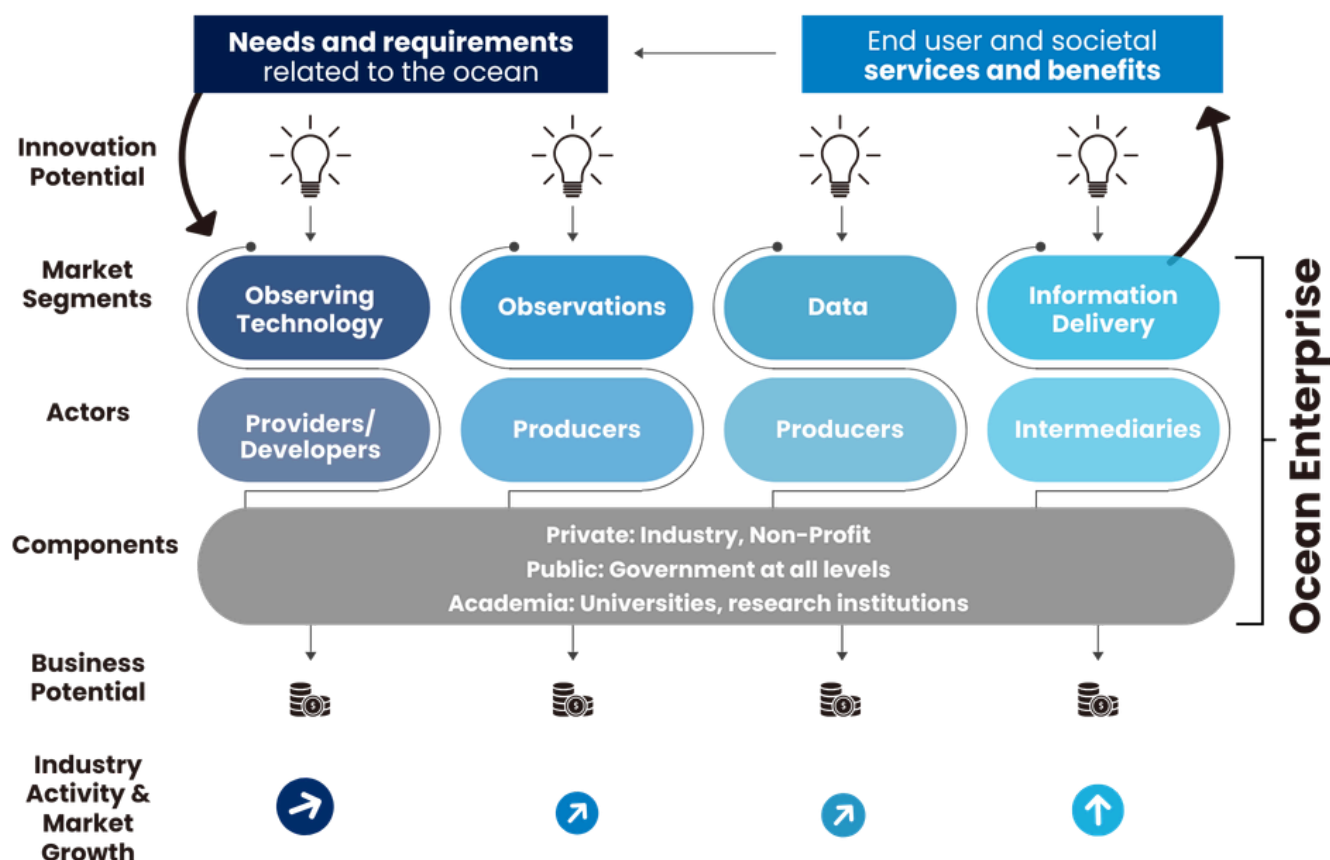


Figure 1: This graphic, introduced in the *Dialogues with Industry Background Paper* dated 1 September 2022, illustrates the Ocean Enterprise and its interconnected components and activities within the Ocean Information Value Chain. The blue discs at the bottom of the graphic represent the present level of private industry participation in each segment, providing an estimate for the current relative market size in comparison throughout the Ocean Information Value Chain. The arrows indicate our estimate of private industry growth potential in each area (vertical is high). Innovation may offer opportunities across market segments and could be commercially utilized, indicating that the market has not reached full saturation and there may be room for further development.

The *Dialogues* are market-driven discussions in which technical and scientific issues are addressed in the context of market dynamics. The objective of the *Dialogues* is to develop actionable pathways that the Ocean Enterprise can implement to advance the democratization of ocean observation and accelerate the recognition of ocean observing as an independent market.

The fourth *Dialogues* includes three discussions focused on market dynamics in three areas: Dual-use, Carbon and Biodiversity Credit Markets, and Artificial Intelligence (AI). This paper provides context by reviewing terminology, concepts, challenges, and opportunities. Because these markets are still developing, some incompleteness, uncertainty, and inconsistency should be expected; in fact, those conditions are part of the reason for convening the *Dialogues*. This background paper brings available information together in one place and examines what these activities may mean as marketplaces for the Ocean Enterprise. It also seeks to broaden understanding of these markets through an Ocean Enterprise lens, while acknowledging that the current information is uneven and represents what can be discerned now rather than a complete picture. Presenting this information, even where it is patchy, is useful for identifying how these markets are taking shape. Differences in clarity across the three markets may also indicate differences in their maturity, structure, and readiness for broader engagement.

Markets and Market Viability

Background and Terminology

The Ocean Enterprise functions as a **portfolio of markets** of varying sizes and degrees of maturity. While the term "Ocean Enterprise" describes a cohesive domain or business cluster, its individual components range from established industrial sectors to emerging niche markets.

- **Mature "Legacy" Markets:** These stable markets include the manufacture and sale of established observing technologies, such as navigation aids and sensors for offshore oil and gas production. They are characterized by high sales volumes and established economies of scale, allowing fixed costs to be spread across many units.
- **Developing "Growth" Markets:** Markets focused on the production and delivery of specialized observations and information products are often less mature. Examples include verification data for blue carbon credits or offshore wind site assessments, where sales volumes and economies of scale are still expanding.
- **Nascent "Frontier" Markets:** These emerging markets often target highly specialized needs for data or information. Many of these markets could be characterized as "micro-markets" that consist entirely or almost entirely of unmet demand. In these cases, no goods or services are being commercially provided because expected revenues are unlikely to cover production costs. The financial viability of micro-markets can be improved by adopting interoperability standards or "market bundling" that modify goods and services to meet the requirements of multiple user groups simultaneously.

This characterization of the Ocean Enterprise relies on fundamental business and economic concepts that are explored in more detail in the remainder of this section (see Appendix 1 for more information about markets and market viability).

Key Terms:

- **Maturity:** This term describes the overall development stage of a market. For emerging markets, it reflects how close they are to achieving sustainable viability. For existing markets, it reflects their level of sophistication, stability, efficiency, and institutional strength.
- **Micro-Market:** A market characterized by overspecialization that leads to a small number of buyers, making it difficult to achieve scalability and market viability.
- **Fragmentation:** Refers to situations where micro-markets exist, limiting overall market viability. Defense considerations, lack of communication between the Ocean Enterprise sectors, and low barriers to entry for producers can lead to further fragmentation even where the observational requirements are identical. When markets are fragmented, with each instrument or data product hyper-specialized for a narrow set of buyers, average costs can become prohibitively high, hindering market viability. An important goal of this dialogue series is to identify strategies to overcome fragmentation, allowing for economies of scale that support sustainable market growth.
- **Interoperability Standards:** These are technical or data standards designed to accommodate multiple uses, enhancing compatibility across different markets.

- **Market Viability:** Market viability refers to the ability of a market to sustain itself financially, ensuring that sales cover both fixed and variable costs while generating a profit. Understanding this concept is crucial for evaluating the potential success of ocean-based observational technologies.

The effects of market regulation. Less regulated markets allow producers to enter and exit more easily and respond more quickly to the influences of supply and demand. Lower entry costs enable smaller firms to participate. This can accelerate innovation, growth, and competition but can also lead to undesirable outcomes. For example, unregulated markets tend to underproduce beneficial public goods when commercial revenues are insufficient to cover production costs. The lack of data standards can reduce interoperability, and the lack of data sharing requirements can reduce the overall societal value of the observations. Government regulation can address many of these limitations but can also impede innovation, increase production costs, and reduce market competition when smaller firms cannot meet regulatory or procurement requirements. Compliance can require additional resources for reporting and other administrative activities, disproportionately affecting smaller firms. Differences in regulations across jurisdictions can also contribute to market fragmentation.

Private sector vs. public sector markets. Markets dominated by commercial customers tend to emphasize cost, speed, and product customization. This allows producers to respond quickly to the influences of supply and demand in both production and pricing. However, the commercial demand for customized products and proprietary data can limit the broader societal value of these products. Markets dominated by government agencies, research laboratories, intergovernmental organizations, and other public sector entities are shaped by the budgeting processes of these organizations, open-data mandates, competitive procurement rules, and requirements for transparency. Public buyers often accept higher unit costs in exchange for standardization, interoperability, and data that can be shared under FAIR (findable, accessible, interoperable, and reusable) principles, but they can also introduce slower decision cycles and political risk.

Dialogue 1: Impacts of Dual-Use on Ocean Technology

The ocean is a domain for civilian scientific inquiry, supporting fisheries management, ecological monitoring, and environmental research. A pronounced global shift is underway; however, in which the infrastructure, data, and technologies of the Ocean Enterprise are increasingly applied to both civilian and military applications. For example, Europe is deliberately building a dual-use maritime technology strategy, not just seeing accidental overlaps between civilian and military uses. European Union (EU) research funding and defense cooperation are converging around maritime and underwater technologies, with European Defense Fund allocations rising and programs like ETLAT II supporting acoustic systems useful for both ocean monitoring and submarine detection. Allocations for research and technology cooperation reached approximately €255 million in 2024, rising from €239 million the prior year, with projections of €367 million by 2027.^[3] A substantial share targets maritime and underwater technologies with explicit dual-use applications. Strategic pressure in the Indo-Pacific is making autonomous long-range maritime surveillance an immediate requirement, tying Australia's maritime technology

sector closely to defense programs. Australia is building a dual-use maritime technology sector through national defense investment, rather than through Europe-style multilateral research frameworks. The 2026 Integrated Investment Program committed A\$425 billion over the next decade, with about 41% directed at a maritime capability acquisition portfolio.^[4] A\$4.8 – A\$5.8 billion is allocated for subsea warfare and uncrewed maritime vehicles, supported by broader autonomous systems investment.^[5] More examples are detailed in **Table 1**.

Table 1: Global Dual-Use Development Examples

Country	Prior Civilian Focus	Dual-Use Development	Key Initiatives
Africa (Gulf of Guinea states)	Fisheries management, anti-piracy monitoring, coastal resource management	Gulf of Guinea nations are integrating ocean monitoring into broader maritime security systems, with growing participation in multilateral naval exercises and EU-supported surveillance programs.	Yaoundé Architecture for maritime security; Gulf of Guinea Operation GUINEX V (April 2025); EU SEACOP VI initiative.
Australia	Marine biodiversity monitoring, reef science, fisheries management	Undersea autonomous systems research and development through AUKUS Pillar II; joint underwater vehicle and acoustic communication development with Japan.	AUKUS Pillar II Maritime Big Play program; Australia-Japan underwater robotic and autonomous systems agreement (January 2024); Indo-Pacific Maritime Surveillance Collaboration (May 2026).
China	Oceanographic research, seabed mapping, fisheries	National Seafloor Scientific Observation Network incorporates acoustic monitoring alongside environmental research; civilian research vessel data applicable to undersea situational awareness. ^[6]	National Seafloor Scientific Observation Network (East China Sea and South China Sea segments); 42-vessel ocean survey program (2024 to 2025).
France	Seabed mapping, undersea infrastructure	France 2030 investment plan and the Ministry of Armed Forces' "Mastery of the Seabed" (MFM) program.	Undersea systems capable of operating at depths of up to 6,000 meters, equipped with cutting-edge sensors and tools designed to support a range of missions including protecting undersea infrastructure and safeguarding maritime interests.
Germany	Baltic Sea ecology, fisheries science, hydrographic surveying	Autonomous underwater vehicle delivered for the Baltic Sea ^[7] intelligence, surveillance, and reconnaissance; P-8A Poseidon maritime patrol fleet acquired for sea surveillance and submarine monitoring.	AUV delivered under Kurs Marine 2035+ program (February 2026); 8 P-8A Poseidon aircraft (over 3 billion euros, from November 2025); proposed NATO Baltic infrastructure hub.

Country	Prior Civilian Focus	Dual-Use Development	Key Initiatives
South America	Amazon basin and Atlantic biodiversity research, coastal fisheries	Expanding South Atlantic maritime domain awareness; integration of ocean monitoring into multilateral naval exercise frameworks alongside African partner states. ^[8]	India-Brazil-South Africa (IBSAMAR) naval drills (October 2024); US-led Obangame Express and French-led African Nemo exercises (2025).
United Kingdom	Hydrographic surveys, ocean science, fisheries	Dedicated ocean surveillance vessel deployed for undersea infrastructure monitoring; participation in NATO Baltic and North Atlantic maritime security frameworks.	Multi-Role Ocean Surveillance Ship (HMS Proteus); AUKUS Pillar II; EU Action Plan on Cable Security (February 2025).

Shifting Acquisition Strategies

The landscape of the defense procurement is shifting toward a venture capital (VC) model. For example, within the United States, the defense infrastructure has embraced a Silicon Valley ethos, aiming to transform the defense industrial base into an incubator for tech startups capable of building "cheaper, smarter, and smaller" weaponry. This aggressive infusion of military capital into the private sector raises critical questions about the future of both civil and military markets.^[9]

The United States Defense Innovation Unit (DIU), launched in 2015 to accelerate the United States Department of Defense’s adoption of commercial technology, is now in its third strategic iteration. The DIU was created out of necessity: commercial technology (AI, autonomous systems, advanced sensing) was advancing faster than traditional military procurement could track. Silicon Valley startups are now reshaping defense supply chains rather than the reverse.

This shift is underscored by significant legislation and financial milestones:

- **Venture Capital Activity:** As of Q2 2025, VC activity in defense tech had already reached \$28.1 billion, surpassing the full-year 2023 total. For the full year, private VC defense technology deals reached \$49.9 billion in 2025, nearly double 2024 levels.^{[10],[11]}
- **Legislative Mandate:** The 2024 National Defense Authorization Act (NDAA) codified and expanded DIU’s role as the principal liaison between the Department of Defense and entrepreneurs, startups, commercial technology companies, and venture capital sources.^[12]
- **Other Transaction Authorities (OTAs):** Allow government-commercial partnerships to materialize in months rather than years. Concurrently, the Office of Strategic Capital (OSC) is scaling federally backed financing options across 31 critical technology categories, including AI, marine autonomous systems, and advanced manufacturing. While initial equipment finance products deployed up to \$984 million in direct project loans, the long-term project envelope across expanded OSC initiatives is projected to scale significantly over the coming federal budget cycles, intensifying the integration of private venture equity into national security priorities.^{[13],[14],[15]}

Effect of Dual-Use

The military's demand for ocean observational data is rooted in operational necessities, specifically, mine warfare, anti-submarine warfare (ASW), and maritime domain awareness. Systems like Argo floats and moored buoys, originally developed for scientific research, now occupy a legal and operational gray zone where data collected for scientific purposes can have defense implications.* [16],[17],[18]

The trajectory of instruments like Argo floats illustrates the friction between science and defense. Once a scientific platform is adopted for military missions, several consequences follow:

- **Classification Thresholds:** Data that would otherwise be shared openly may be classified or withheld.
- **Regulatory Burdens:** Export control regimes like International Traffic in Arms Regulation (ITAR) and Export Administration Regulations (EAR) may be applied to previously "open" hardware and software.
- **Access Restrictions:** Partner nations may make access to their Exclusive Economic Zones (EEZs) even more difficult if they perceive autonomous scientific gliders as surveillance assets. [19]

Current legal frameworks were not designed for this level of complexity. The United Nations Convention on the Law of the Sea (UNCLOS) regulates Marine Scientific Research (MSR) based on ship-based activity. It is currently ill-equipped to determine whether an autonomous underwater vehicle conducting dual-use missions in an EEZ constitutes "innocent passage" or "military surveillance." [18]

Potential Data Impacts

The Global Ocean Observing System (GOOS) and its Regional Alliances are built on built on FAIR principles and open-access cloud infrastructure framework.^[20] The Defense structure has different priorities for the data. This creates a structural impasse: the strict data-siloing required by sovereign defense programs is fundamentally incompatible with open-access and FAIR. While historical precedents like the dual-use application of the Sound Surveillance System (SOSUS) demonstrate that military infrastructure can yield immense scientific dividends under shared stewardship, the modern Indo-Pacific security environment lacks a clear governance framework to bridge this divide.^[21]

A difference in timelines may also be a challenge; in the civil sector, data policies contain the term "as soon as practical", whereas the defense infrastructure actively embracing startups and venture-backed companies to build military capability at commercial speed, sits in structural tension with the open-access, minimum-delay norms that underpin international ocean science. The norm of sharing data will face direct pressure if platforms shift to military ownership or dual-use classification, in turn creating an effect that extends well beyond formally classified programs. European maritime defense investment creates friction with these norms. As EU-funded programs deploy autonomous underwater and surface platforms with dual-use sensor payloads across the North Sea, Baltic Sea, and broader European maritime approaches, questions arise about whether data collected under defense classification can remain consistent with GOOS open-access commitments. Because Australia's primary oceanographic data pipelines feed directly into GOOS Regional Alliances, its foundational monitoring has traditionally

*See also UK Ministry of Defense, Contract Award Notice, Project HECLA (OCDS: ocds-h6vhtk-04e545), 26 March 2025, confirming MoD procurement of APEX Argo floats for Anti-Submarine Warfare (ASW) oceanographic intelligence collection.

operated under open-access, minimum-delay data mandates. However, the scaling up of uncrewed platforms under AUKUS Pillar II introduces a profound operational friction.^[4] When defense-funded autonomous assets collect critical hydrographic, acoustic, and thermal profiles across sensitive Indo-Pacific choke points, the resulting data pipelines run directly into national security classification barriers.^[18]

Another important aspect is interoperability as mentioned above. GOOS largely relies on open standards such as NetCDF, ERDDAP, etc., whereas defense organizations often operate with NATO standards (e.g. STANAGs), proprietary formats, classified networks, and Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) architectures that are not always directly compatible with scientific data infrastructures. As a result, additional developments, for example by platform or sensor manufacturers, may be required to ensure that ocean observations can be readily integrated into defense information systems.

Summary of Dual-Use Benefits and Risks

Table 2: Dual-Use Impact Benefit Analysis

Impact Category	Potential Benefits	Key Risks
Funding	Surge in platform investment; new pathways for dual-use firms.	Military procurement "crowding out" civil science funding.
Data Access	Expanded sensor networks and accelerated R&D.	Classification "chills" open sharing; data silos.
International	Enhanced maritime domain awareness.	Erosion of trust; export controls limiting joint research.
Legal	Formalized liaison between national security and entrepreneurs.	Conflict between GOOS open-data mandates and national security needs.

Overcoming Market Fragmentation

Defense and commercial users often require the same underlying data product for entirely different applications, creating a natural but underexploited basis for shared procurement and infrastructure. A naval commander and an offshore wind developer both need high-resolution current profiles, salinity data, and acoustic propagation models, but one uses them to predict sonar range and the other to plan cable installation windows. A fisheries manager and a submarine navigator both depend on thermocline data, one to locate fish aggregations, the other to determine acoustic shadow zones.

The case for overcoming fragmentation is underscored by the clear opportunities to leverage

dual-use applications of ocean data across various industries. Industries that appear structurally unrelated (insurance underwriting, aquaculture, port logistics, offshore mining, and fisheries management) all consume the same foundational ocean data: temperature, salinity, current velocity, wave height, seabed topography, and biological activity.

The demand for marine information and ocean data has exploded across sectors, driven by the need for accurate oceanographic information for safety, offshore planning, and environmental monitoring, with the global market growing at over 7% annually.^[23] Yet the market remains fragmented: each sector tends to commission bespoke data collection, leading to duplicated deployments, inconsistent data standards, and gaps in spatial coverage.

Dialogues 2: Carbon and Biodiversity Credit Markets

While carbon sequestration and biodiversity provide direct benefits, e.g. reduced flooding, more fishing outside of marine protected areas, this background paper focused on carbon and biodiversity credits which link to the Ocean Enterprise as related to Measurement, Reporting, and Verification (MRV) requirements and technologies and data that support them.

Biodiversity Credits: As awareness of marine ecosystem value grows and environmental markets mature, new financial mechanisms are emerging to channel private capital toward conservation and restoration at large scales. Carbon and biodiversity credit markets are becoming central to this shift, creating the economic architecture through which marine ecosystems can generate sustainable revenue. However, realizing this potential depends heavily on the ability to accurately measure, report, and verify ecological outcomes. The biodiversity credit market assigns monetary value to measurable conservation or restoration outcomes, species habitat, ecosystem condition, and ecological function, so that private capital can be directed toward protecting nature.^[24]

Carbon credits: The carbon credit market is a financial system where carbon credits (typically one metric ton of carbon dioxide equivalent, or CO₂e) can be bought, sold, or traded. These markets establish prices for carbon emissions, creating a financial incentive for companies and governments to reduce their greenhouse gas output.

Multiple distinct carbon markets exist. Blue carbon credits are tradeable units of verified carbon dioxide reduction or removal generated by protecting, restoring, or sustainably managing coastal and marine ecosystems, including mangroves, tidal salt marshes, and seagrass meadows. These are distinct from green carbon (carbon stored in terrestrial forests and vegetation) and from marine carbon dioxide removal (mCDR) approaches such as ocean alkalinity enhancement, direct ocean capture, or biomass sinking, which are generally more technological and often applied further offshore. Companies pursuing mCDR can also generate credits once their removals are measured, reported, and verified; those credits are then sold, often to corporate buyers seeking to offset emissions or meet net-zero targets.

The Ocean Enterprise can provide the essential Measurement, Reporting, and Verification (MRV) infrastructure needed to transform both blue-carbon ecological functions and mCDR activities

into tradeable carbon and biodiversity credits. This positions it as a critical enabler of these nascent but rapidly growing environmental markets. Between 2014 and 2025, approximately 7 million Blue Carbon Credits (BCCs) were issued globally, yet the market remains deeply supply-constrained: as of late 2025, only 19 of 94 registered blue carbon projects worldwide were actively generating credits, a bottleneck rooted primarily in the technical complexity and cost of underwater MRV rather than any lack of ecological potential.^[25] Similar MRV challenges currently constrain the integrity and scaling of mCDR credits.

Accurately measuring carbon sequestered in tidal sediments cannot be achieved through periodic manual sampling alone. The spatial variability of sediment carbon stocks and the demands of ongoing temporal monitoring require remote sensing and sensor-based technologies that current MRV frameworks are only beginning to incorporate.^[26] Three structural challenges define the near-term horizon for the Ocean Enterprise in this space. First, although Essential Ocean Variables and related scientific frameworks already provide a foundation for marine observation and are actively used, the financial and methodological infrastructure needed to translate those standards into consistent, verifiable carbon baselines remain incomplete. A known gap, for example, is the absence of a carbon EOV element that fully covers marine sediments, even though inorganic carbon and dissolved organic carbon variables already exist. Second, the physical complexity of the marine carbonate system makes MRV more challenging. Third, the high cost of establishing and maintaining monitoring infrastructure means individual projects often struggle to reach financial viability on carbon revenue alone. This creates a strong incentive for approaches that verify models at representative sites and then scale results using extent or other proxies, while designing single deployments that can serve multiple revenue streams simultaneously. Despite the technical and cost barriers, the potential scale of marine carbon removal exceeds what is feasible on land, underscoring the strategic importance of overcoming the MRV constraints.^{[27],[28]}

A strategic opportunity lies in this convergence: because carbon sequestration and biodiversity are functionally coupled in ecosystems such as mangrove and seagrass meadows, coastal restoration projects can generate stacked credits combining carbon and habitat co-benefits, substantially improving project economics.^[29] For organizations with existing sensor infrastructure and data management capabilities, this convergence creates a natural opportunity to serve both credit streams from a single monitoring deployment, reducing the per-credit cost of MRV. Global policy is accelerating buyer-side demand. Target 19 of the Kunming-Montreal Global Biodiversity Framework (KM-GBF), adopted by 196 parties at the United Nations COP15 in December 2022, commits signatories to mobilizing at least \$200 billion per year from all public and private sources for biodiversity by 2030, while Target 3 sets a committed target to conserve 30% of the world's coastal and land areas by the same date.^[30]

Taken together, the market trajectory supports pursuit. Value estimates of the blue carbon credit market varies widely, from under \$100 million to almost \$10 billion. Any single figure should be treated with real caution; the reliable signal is the direction of rapid growth from a small base, not the specific dollar amount. This variation itself suggests both measurement and definitional issues, which is not uncommon for emerging markets. Blue carbon credits already trade at a significant premium to terrestrial offsets, reflecting their scarcity and strong co-benefits, while the supply constraint created by MRV complexity is precisely the gap the Ocean Enterprise is positioned to fill.^[31] With existing sensor infrastructure and data management capabilities, this represents a viable and differentiated market, provided investment is directed toward standardization and multi-use data architecture rather than single-project deployments.

Carbon Methods Landscape

The [State of Carbon Dioxide Removal](#), 3rd edition, 2026 is an excellent reference and provides an independent global assessment of carbon dioxide. The figures below are taken from that report to provide an overall context of the Carbon Dioxide Removal methods and how those associated with the ocean fit into the overall context (**Figures 2 and 3**).^[32]

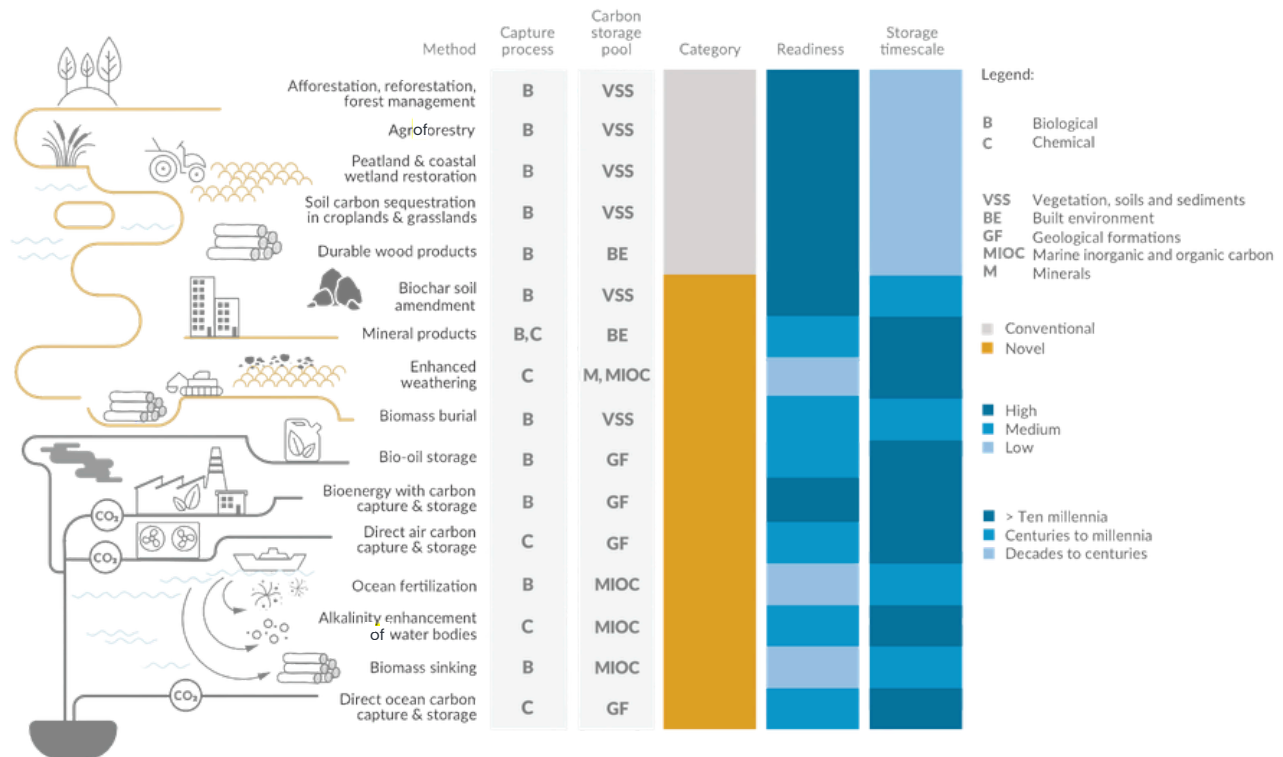


Figure 2: Summary of CDR methods, characterize as "conventional" or "novel", and readiness. Credit: The State of Carbon Dioxide Removal, 3rd Edition.

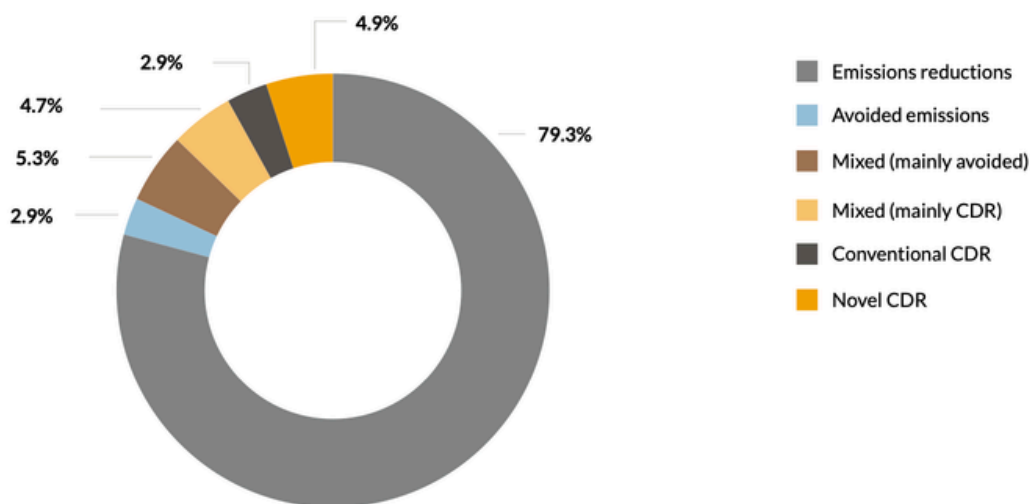


Figure 3: Composition of VCM across project types. Credit: The State of Carbon Dioxide Removal, 3rd Edition.

Carbon Credit Market Financial Instruments

There are two types of carbon markets: compliance markets and voluntary carbon markets (VCMs).^{**} Compliance markets are government-mandated cap-and-trade systems. These systems reduce greenhouse gas emissions by setting a firm limit ("cap") on pollution and issuing a corresponding number of emission allowances.^{***} Companies that reduce emissions below their allotted limit can sell excess allowances; those exceeding their allotted limit must purchase additional credits. In contrast, voluntary carbon markets allow companies and organizations to purchase credit voluntarily to offset emissions, often to meet environmental, social, and governance (ESG) goal or net-zero commitments.^[33]

Regarding the Ocean Enterprise, there are at least two main dimensions worth noting in relation to carbon markets. The first involves shipping and maritime operators and the compliance obligations they face as carbon markets and emissions regulations continue to expand. The second involves ocean ecosystems (mangroves, seagrasses, salt marshes, etc.) which represent one of the largest and least exploited opportunities for carbon sequestration and generating carbon credits.

Carbon Credit Financial Instruments – In Use

Table 3 presents the carbon credit financial instruments currently in use within mandatory regulatory frameworks that may be applicable to the Ocean Enterprise. Each table entry reflects a real market that the Ocean Enterprise is either already participating in or may be required to engage with as emissions regulations tighten. The purpose of this table is to identify specific financial instruments, who/how they operate, and why they matter specifically to ocean-based industries.

Table 3: Carbon Credit Financial Instruments****

Type	Credit Name	Description
Compliance	European Union Allowances (EUAs) (~€43 billion auction revenue) [†]	Globally, this is the most liquid financial instrument for carbon markets, traded on Intercontinental Exchange. Since January 2024, the EU Emissions Trading System (ETS) has included maritime shipping, covering cargo and passenger ships of 5,000 gross tonnage and above calling at EU ports. Surrender obligations phase in at 40% of verified 2024 emissions, 70% for 2025, and 100% from 2026 onward, making EUAs a growing compliance instrument for marine operators. ^[34]
Compliance	California Carbon Allowances (CCAs) (\$1.53 billion) ^[35]	California's cap-and-trade program, linked with Quebec through the Western Climate Initiative since 2014, is relevant to marine shippers on Pacific routes and West Coast ports. Extended through 2045 in September 2025, it may eventually link with Washington State. ^[36]
Compliance	Regional Greenhouse Gas Initiative (RGGI) Allowances (\$9.718 billion) ^[37]	RGGI covers the northeastern US states and is primarily a power-sector program. It is relevant for coastal power generation and port energy infrastructure rather than marine vessels. ^[38]

Type	Credit Name	Description
Compliance	Blue Carbon Credits Mangroves (Verra VM0033)	The most mature financial instrument for blue carbon markets. Verra's VM0033 covers tidal wetland and seagrass restoration and underpins most verified blue carbon credits in circulation, predominantly from mangrove projects. ^{[31],[39],[40]}
Voluntary	Mangrove and Saltmarsh VERs (\$498 million)^[41]	The most operationally mature blue carbon instrument. Verra's VM0033 covers tidal wetland and seagrass restoration and underpins most verified blue carbon credits in circulation, predominantly from mangrove projects. ^{[31],[39],[40]}
Voluntary	Seagrass Carbon Credits	Seagrass credits remain at an early development stage. Projects are being explored in Japan, the US, Spain, France, Italy, and the UK under methodologies including VM0033, but verified credits are not yet available at commercial scale. Challenges around additionality, permanence, and the complexity of seagrass biogeochemistry have slowed development relative to mangrove and saltmarsh credits. ^{[25],[42],[43]}

The most established and flexible carbon credit financial instruments in **Table 3** were designed for land-based industries and have only recently begun to diversify into the ocean economy. The EUA's, California carbon allowances, and Regional Greenhouse Gas Initiative allowances have only recently been adapted to accommodate ocean-related activity. While the most ocean-focused credit markets, such as Blue Carbon credits from mangroves and wetlands, are experiencing growth, they currently have less market depth, transparency, and investor interest compared to more established options. The table captures the current market transition, one where the Ocean Enterprise operators who engage early can have a meaningful advantage while these institutions are still in the nascent stage.

Underdeveloped Financial Instruments

Table 4 lists the carbon credit financial instruments that do not yet exist in any verified or thoroughly established way. Each entry reflects a scientific or commercial approach that is in the research or pilot phase but has not crossed into the area where investment is confident and credible. The legal instruments may be unavailable, not because the science is unproven, but because the financial, regulatory, or methodological framework required to bring them to market has not been developed fully.

^{**}See EU Emissions Trading System for an example: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

^{***}<https://www.edf.org/climate/how-cap-and-trade-works>

^{****}The total market value is defined differently across these markets for all tables. For compliance markets, it typically means annual auction revenue or total outstanding allowance value; for voluntary markets, it trends towards total transaction value. Values are stated where available.

[†]European Commission, climate.ec.europa.eu

Table 4: Underdeveloped Financial Instruments

Credit Name	Description
Kelp and macroalgae sequestration credits ^{[44],[45],[46]}	Kelp forests are highly productive, but 2026 fieldwork by De Leo et al. shows rapid deep-ocean degradation may limit long-term biomass permanence. Early frameworks, including Martocello III et al. (2026), are working to standardize accounting metrics.
Ocean alkalinity enhancement (OAE) credits ^{[47],[48],[49]}	OAE adds alkaline minerals to seawater to accelerate carbon absorption. The market remains nascent, though Isometric Registry established a verified protocol in 2024; scaling is limited because major legacy registries such as Verra have not broadly approved these open-ocean methodologies.
Direct ocean capture credits ^[50]	Electrochemical systems extract dissolved CO ₂ from seawater but remain pilots with no verified credit standard.
Compliant carbon unit ^{[51],[52],[53]}	The IMO approved its Net-Zero Framework in April 2025, creating the first global carbon pricing mechanism for international shipping. Key details—guidance, certification schemes, and unit definitions—are expected in 2026, so practical application and operational requirements are still being defined.

The science of how the ocean stores and releases carbon has moved well ahead of the market's ability to act on it. Agreed measurement standards and governance frameworks for most ocean-based carbon approaches are still being developed, leaving even the most promising technologies at the pilot stage. What is missing is not scientific understanding, but the development across investors, regulators, and other stakeholders about how ocean carbon will be governed and valued. Until that groundwork is laid, the financial instruments in **Table 4** remain possibilities rather than products.

Technologies to Measure Biodiversity

Examples of the technologies being used to generate the biodiversity data for biodiversity credits markets include:

Genetic/molecular

- **eDNA metabarcoding:** Filtering seawater to capture shed genetic material, then sequencing it to identify which species are present. It's becoming the backbone of marine biodiversity credit methodologies because a single water sample can give a comprehensive picture of multiple species, cutting field effort and cost dramatically compared to traditional surveys. New automated eDNA samplers can collect and preserve eDNA *in situ* with no human interaction, improving safety and scalability.

Acoustic

- **Passive acoustic monitoring (bioacoustics):** Underwater microphones that pick up marine mammal calls, fish choruses, and reef soundscapes. It's increasingly paired with eDNA because bioacoustics reveal seasonal and behavioral patterns ("when"), while eDNA identifies a broader range of species, including rarely observed ones ("who").

Remote sensing and robotics

- **Satellite data** (sea surface temperature, chlorophyll) to flag productivity hotspots.
- **Autonomous underwater vehicles / Remotely Operated Vehicles (ROVs) / drones** for visual surveys and habitat mapping.
- **Internet of Underwater Things (IoUT)** networked sensor systems, often AI-enhanced, designed to reduce human intervention, cut power and bandwidth needs, and scale processing to assess marine biodiversity across large spatial and temporal areas.

AI/ML as connective tissue

- **Machine learning (ML)** is layered on top of all the above for species identification from images/audio and to process eDNA sequencing data at scale; monitoring is increasingly complemented by remote sensing, drones, and machine learning to expand spatial coverage, with ML supporting species identification across taxa via deep learning.

Structures for standardized sampling

- **Autonomous Reef Monitoring Structures (ARMS):** Deployed devices that passively collect settling organisms for standardized biodiversity comparison across sites; used in large eDNA reference projects.

Biodiversity Credit Market Financial Instruments

For the Ocean Enterprise, the biodiversity financial instruments matter because the ocean constitutes over 90% of the planet's habitat and is one of the primary repositories of the world's biodiversity, yet the biodiversity credit market is almost entirely terrestrial (United Nations, Marine Biodiversity and Ecosystems). This represents both the biodiversity market's most significant blind spot and its largest latent growth opportunity (see Appendix 2 for more resources).^[54]

Financial Instruments – In Use[‡]

Table 5 presents the biodiversity credit market financial instruments available to Ocean Enterprise operators, ranging from compliance obligations tied to development permits, to voluntary credits generated by coastal and marine ecosystem restoration. Unlike the carbon market, where at least a handful of ocean-specific financial instruments are actively traded, the biodiversity credit market has produced very few instruments with any meaningful marine content. Most of what exists today was designed for terrestrial use and is only beginning to be adapted for coastal and ocean contexts.

[‡]Some examples are for context only, as they are terrestrial examples.

Table 5: Biodiversity Credit Market Financial Instruments

Type	Credit Name	Description
Compliance	England's Biodiversity Net Gain (BNG) (Terrestrial) ^[55] (£325 million) ^{[56],[57]}	Mandatory since February 2024, BNG requires all new developments to deliver a 10% net gain against a standardized metric and is being explored for coastal use.
Compliance	US Wetland Mitigation Banking (Terrestrial) ^{[58],[59]} (\$2.5 billion) ^[60]	The most established marine economy-adjacent compliance instrument: coastal wetland mitigation credits for tidal marshes and mangroves can be generated and traded, with Ocean Enterprise MRV infrastructure supporting credit integrity. It is the closest existing model to a marine biodiversity compliance instrument.
Voluntary	Coral reef restoration credits ^{[61],[62]} (\$1.6 billion) ^[63]	Australia's Reef Credit Scheme (GreenCollar, 2020) is the closest reef biodiversity credit model. It issues tradeable units for verified reductions in land-based nitrogen and sediment pollution entering the Great Barrier Reef catchment, bought by governments and private buyers. It is a blueprint for biodiversity credit schemes, but no standardized methodology yet exists for direct in-water coral restoration crediting.
Voluntary	Mangrove habitat bank units ^{[64],[40]}	Credits are being issued that combine carbon and biodiversity benefits from mangrove restoration, representing a more commercially mature ocean-related biodiversity instrument.

The financial instruments in **Table 5** focus on the land/sea boundary, covering mangroves, coastal wetlands, and intertidal zones rather than the open ocean. The most operationally developed options, including England's Biodiversity Net Gain framework, US wetland mitigation banking, and Terrasos habitat units, all have their roots in terrestrial or estuarine policy rather than ocean governance. Coral reef and fisheries linked credits remain at the pilot or conceptual stage. Stacked credits combining carbon and biodiversity benefits represent the most commercially promising near-term opportunity, allowing developers to generate revenue from two markets from the same coastal ecosystem. The following sections describe the gap between what is available today and opportunities the ocean-related biodiversity markets are missing.

Underdeveloped Financial Instruments

Table 6 maps the biodiversity market credits that ocean-related markets currently lack. Where the carbon market at least has a handful of ocean-facing market credits in early circulation, the biodiversity market has almost none. Each entry represents a real ecosystem, a plausible financial structure, or a governance mechanism that scientists and policymakers have identified as important, but which has not yet been translated into anything a buyer can purchase or a seller can verify. The significance of these absences goes beyond market immaturity; it highlights a critical gap in achieving the commitments outlined in the Kunming-Montreal Global Biodiversity Framework, which commits governments to protect 30% of the ocean by 2030.^[30]

Progress is constrained by the lack of financial instruments that would allow private capital to contribute to that goal.

Table 6: Underdeveloped Financial Instruments for Biodiversity Credit Markets

Credit Name	Description
Marine Protected Area (MPA) credits ^{[65],[66],[67]}	The Global Biodiversity Framework's 30x30 target creates a mandate for marine conservation, but late-2025 tracking shows international funding remains billions short. No standardized, verified MPA credit exists, leaving private capital without a credible mechanism to close the gap.
Coral reef condition index credits ^{[68],[69]}	Standardized reef health metrics, coral cover, rugosity, and species diversity, could generate tradeable credits when verified improvement occurs. Photogrammetry and environmental DNA (eDNA) make this technically feasible, but institutional frameworks, standards, and verification systems are not yet established.
Deep-sea ecosystem credits ^{[70],[71],[72]}	Deep-sea mining pressure is rising, but biodiversity protection and offset mechanisms are absent. No credit methodology, baseline data, or governance framework exists for deep-sea biodiversity offsets.

Table 6 indicates that, the further from the shoreline, the less the market has developed. Credit markets for intertidal and coastal restoration are at an early stage but at least exist. Credit markets for open ocean ecosystems, including deep-sea habitats, high seas marine protected areas, and offshore biodiversity baselines, are not fleshed out in any verified format. The open ocean sits largely outside national jurisdiction, which makes it structurally difficult to establish property rights and legal commitments that underpin credit instruments. Closing these gaps will therefore take more than methodology development. It will require international agreement on who has the authority to issue, verify, and retire credits for ecosystems that are, by their nature, a shared global resource.

Overcoming Market Fragmentation

The conceptual case for shared infrastructure between carbon and biodiversity markets rests not on their similarities, as they are meaningfully different, but on the shared underlying problem each is trying to solve: how to convert an invisible public good into a tradeable private asset with integrity. Both markets must prove that a claimed outcome occurred, that carbon was sequestered or that habitat conditions improved. Both must demonstrate that the outcome would not have happened without the credit revenue. Both must manage the risk that the outcome is later reversed. And both require registries, unique identifiers, and disclosure frameworks to prevent double counting and build buyer confidence.^{[73],[74]}

In the ocean, carbon and biodiversity are not parallel concerns that happen to share a policy agenda. They are co-located and functionally coupled in the same ecosystems. A single mangrove forest sequesters carbon in its waterlogged soils,^[75] provides nursery habitat for commercially important fish species, protects coastlines from storm surge, and supports the livelihoods of coastal communities. Coral reef regulates local water chemistry, sustains a quarter of all marine species, and generates the fish biomass on which hundreds of millions of people depend for food security.^[76] Separating these into distinct credit instruments is not just administratively complex but is also ecologically artificial.

This functional coupling creates a practical argument for shared infrastructure that goes beyond efficiency. Satellite monitoring of a mangrove restoration project generates data that are simultaneously relevant to its carbon stock and its habitat condition.^[77] A verification audit of a coral reef credit would collect the same biological measurements as a blue carbon baseline assessment of the same site. An additionality assessment for a Marine Protected Area credit would draw on the same counterfactual analysis as a blue carbon permanence evaluation. Building these systems twice, in parallel, for separate carbon and biodiversity registries, would duplicate cost and risk producing incompatible conclusions about the same ecosystem. The case for shared marine environmental credit infrastructure is therefore not merely conceptual. It is a practical consequence of how ocean ecosystems function.

However, as this is a fledgling and costly market, limited sensor purchases hinder commercial viability.

Dialogues 3: The Ocean Enterprise in the Age of AI

AI can be a market disrupter or catalyst. The Ocean Enterprise functions as the primary data infrastructure of the blue economy, providing the enabling technology and generating the observational inputs upon which AI systems across every downstream sector increasingly depend. The global ocean economy is currently valued at approximately \$2.5 trillion per year, and as maritime activities grow more complex, traditional approaches face mounting limitations in

real-time monitoring, cross-domain coordination, and decision-making efficiency.^[78] While specific AI forecasts for the Global Ocean Enterprise are not readily available, the global Maritime Artificial Intelligence market size was valued at USD 6.22 billion in 2025. This market is projected to grow from USD 8.78 billion in 2026 to USD 139.4 billion by 2034, exhibiting a compound annual growth rate of 41.28% during the forecast period.^[79] The potential for the AI market specific to the Ocean Enterprise could be expected to experience similar growth.

A recurring pattern across multiple industries is that AI, when applied to large volumes of existing or openly available data, can extract analytical outputs that previously required dedicated physical measurement infrastructure. AI trained on decades of archived observational data are being used to produce global weather forecasts that have the potential to outperform traditional systems without the need for additional physical sensors, which may weaken the economic case for expanding weather buoy networks and upper-air instruments.^[80] Although it should be noted that there are significantly more atmospheric data than marine data driving these forecast models. Other AI applications have achieved similar results by outperforming leading operational forecast models using only historical data with no new observations.^[81] When enough historical or open data exists, organizations can stop buying hardware and start computing the measurements that hardware would have provided. For observational instrument markets, this represents a structural demand-side disruption, not because physical measurement becomes unnecessary, but because AI shifts the cost-benefit calculation against expanding physical networks and in favor of extracting more from what is already known. While this is true in general, the question is whether there is enough ocean data already such that this could apply to ocean data in a significant way already.

At the same time, AI is generating upward market pressure through bundling. AI also opens other perspectives, particularly in the processing of acoustic data, camera data, eDNA, etc. By enabling the integration of fragmented data streams across jurisdictions, sectors, and providers, AI allows disparate micro-markets to be consolidated into commercially viable enterprise products at a scale previously inaccessible. This dynamic is particularly significant in emerging ocean economies, where AI is enabling market formation rather than simply market optimization. Realizing this potential depends, however, on the governance layer: the scientific literature identifies the absence of coherent frameworks for transparency, validation, and data interoperability as the primary constraint on AI adoption across marine domains.^[82] Markets will therefore look different not only because some segments grow faster than others, but because AI is redrawing the boundaries between hardware, data, and intelligence as distinct sources of commercial value, rewarding those positioned at the integration layer and placing structural pressure on those who remain anchored to physical asset provision alone.

AI Trends Within the Ocean Information Value Chain

1	Automated image, video, and acoustic interpretation
2	AI-based data quality control, calibration, and anomaly detection
3	Predictive maintenance and asset health analytics
4	Edge AI for onboard processing, compression, and event triggering
5	AI perception, sensor fusion, and navigation for autonomous platforms
6	Adaptive mission planning and reinforcement learning
7	Multi-vehicle coordination and intelligent swarms
8	AI-ready ocean data and machine-learning operations infrastructure
9	Multi-source data fusion, gap-filling, downscaling, and super-resolution
10	Synthetic data and simulation-to-sea training
11	Data-driven ocean forecasting and learned emulators
12	Physics-informed and hybrid AI/learned parameterizations
13	AI-enhanced data assimilation and inverse modeling
14	Ocean digital twins and AI-enabled what-if decision support
15	Geospatial, Earth-system, and multimodal foundation models
16	Generative-AI copilots and natural-language ocean interfaces
17	Knowledge graphs, semantic AI, and machine-actionable interoperability
18	Trustworthy AI: uncertainty, explainability, causality, and assurance
19	Quantum-enhanced AI and computing for Earth-ocean systems
20	AI-enabled underwater robotic intervention and manipulation
21	AI-enabled data visualization and product generation

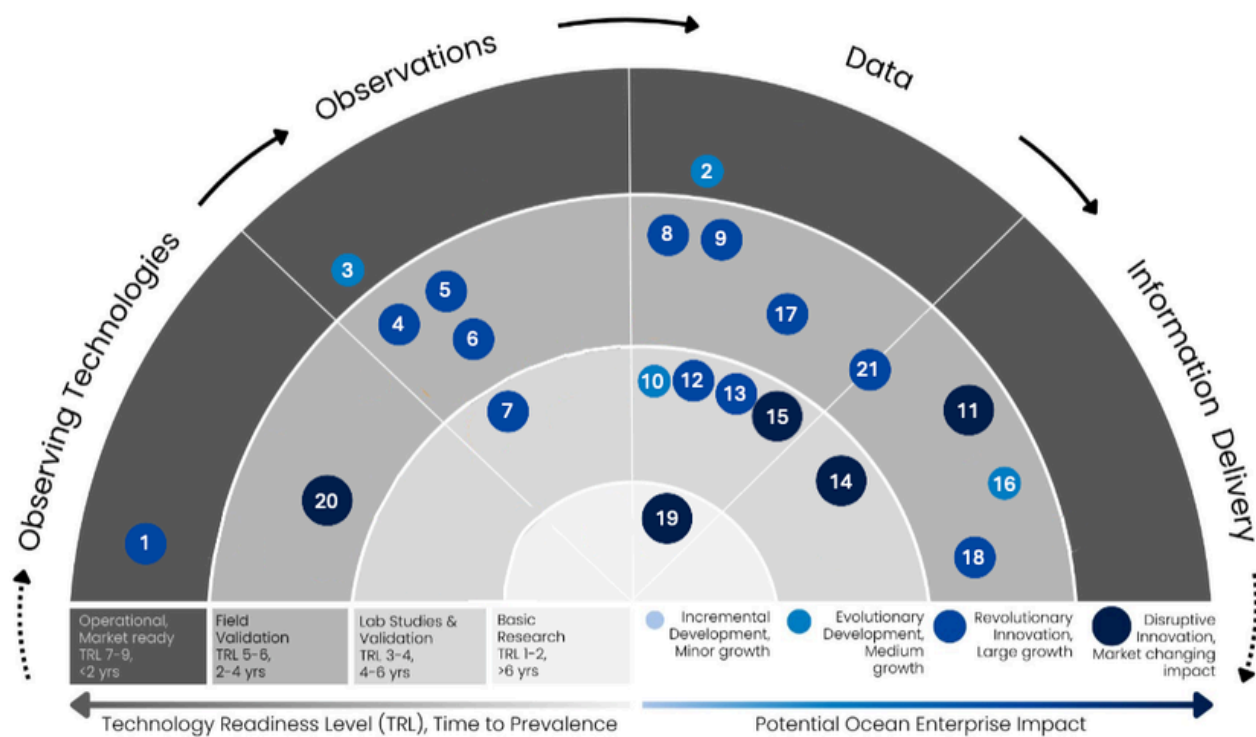


Figure 4: Radar chart showing the readiness levels and time to prevalence as well as potential impacts on the Ocean Enterprise of AI technologies and infrastructure of the Ocean Value Chain.

AI technologies advancements and infrastructure will continuously improve and disrupt the Ocean Enterprise. In **Figure 4**, we mapped the prevailing trends, along with estimates of technological readiness, time to prevalence, and their potential impact on the Ocean Enterprise across the Ocean Information Value Chain (**Figure 1**). The center of the diagram represents lower technological readiness and a longer time before a market impact can be expected. The radially longer the distance, the more mature the trend and the shorter the expected time to full impact. The potential impact of a trend is depicted by the point size. Some trends appear in more than one market segment.

Figure 4 supports the argument that AI is already being used across the Ocean Information Value Chain, with its strongest near-term influence likely being in the later stages of the chain (data processing, integration, analysis, decision support, and market-facing product), rather than only in the initial collection of observations. This is an estimate based on the authors' perspective. This pattern is comparable to the "private industry growth potential" as indicated by the arrows in **Figure 1**. AI is expected to reshape the Ocean Enterprise within a relatively short timeframe, especially over the next two to six years, by turning fragmented ocean data into more usable, scalable products. This timeline may be conservative given the rapid advancements within AI. This could make AI both a catalyst for new markets and a disruptor to existing business models, particularly where value shifts from physical sensing hardware toward data integration, analytics, and decision-support services.

See Appendix 3 for more in-depth information on rationale for the radar chart.

Current Uses of AI in Global Ocean Conservations and Obstacles

The [Open Communications for the Ocean](#) (OCTO) conducted a survey from November to February 2025 on the use of AI in the global ocean conservation and management field. The following graphics are taken from their [snapshot](#).^[83]

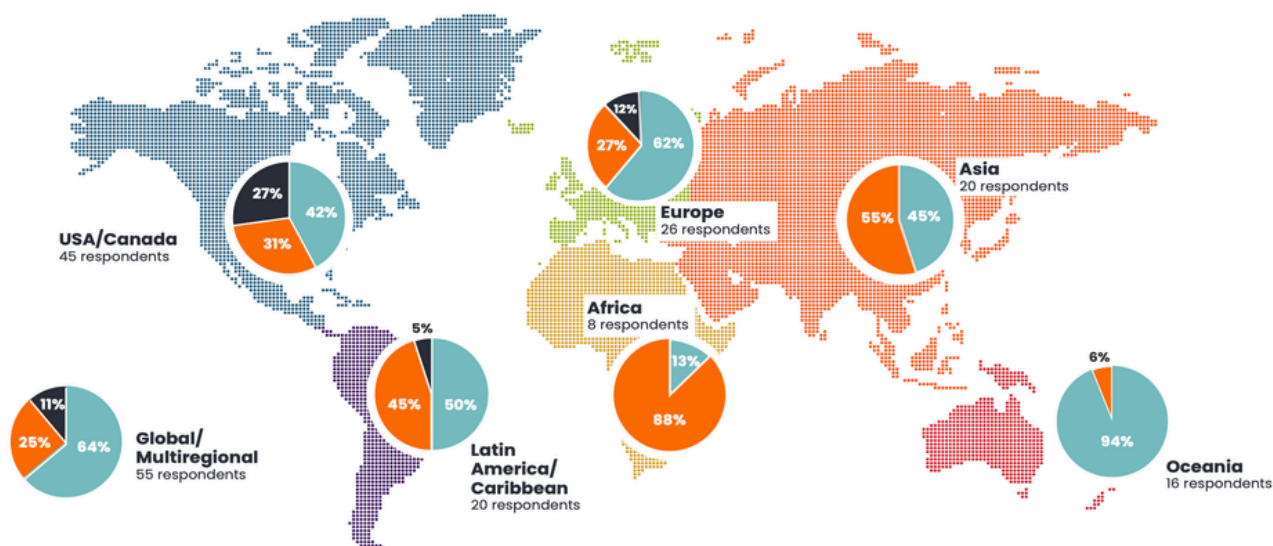


Figure 5: Percent of respondents (190) using AI. Credit: OCTO, 2026.

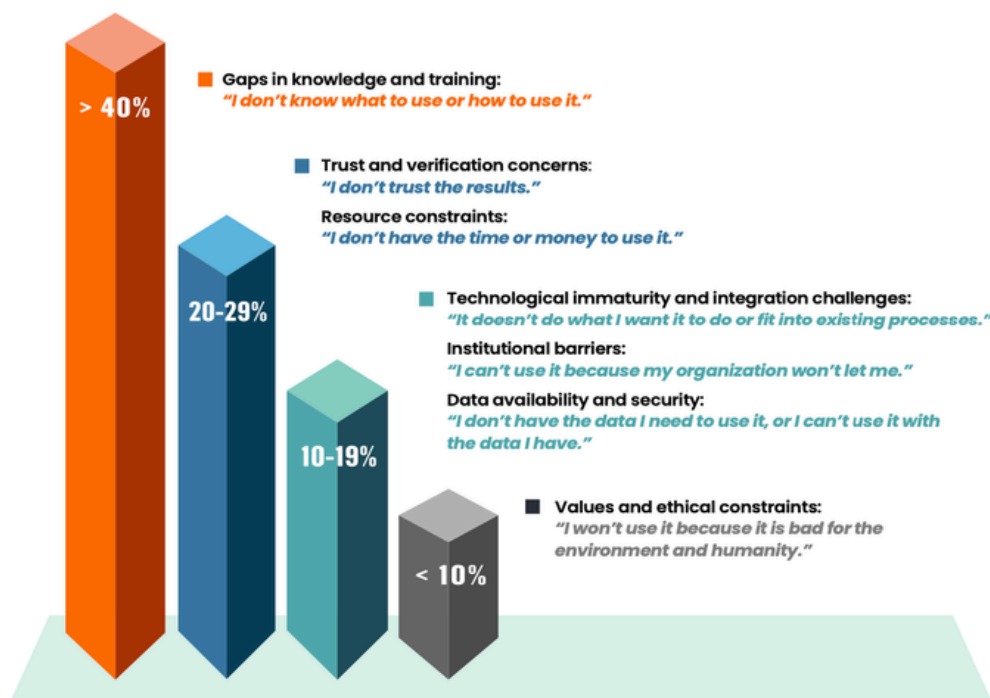


Figure 6: Obstacles of using AI. Credit: OCTO, 2026.

Examples of AI as a Market Catalyst

Market Facilitation through Data Integration

AI acts as a primary catalyst for mergers and acquisitions by enabling firms to bundle fragmented data assets. AI-intensive companies identify and acquire data-rich targets to extract latent value from disparate datasets that were previously underutilized. This strategic integration creates market viability where individual entities once struggled to scale.^[84]

Architectural Reconfiguration for Viability

AI reconfigures organizational coordination by consolidating fragmented tasks across marketing, logistics, and finance into a unified strategy. This structural shift allows firms to bridge the gap between niche specialization and mass-market viability by creating a cohesive functional architecture.^[85]

Supply Chain Resource Aggregation

AI-driven risk management allows small and medium-sized businesses to bundle supply chain resources effectively in volatile environments. By enabling supply chain re-engineering, AI transforms disjointed logistical data into a cohesive and manageable market strategy that ensures smaller players remain competitive and viable.^[86]

Highlights of Ocean AI Efforts

Table 7: Sampling of AI Efforts for the Ocean

Country	Initiative	Key Objective
Australia	AIMS – Deployment Guidance System (DGS)	Combines marine robotics and artificial intelligence to place young corals, housed in purpose-built devices, across the reef in locations where they are likely to grow to adulthood
Europe	OceanEye (€50 million from Horizon Europe in 2026–2027)	European Digital Twin of the Ocean, a high-resolution digital replica of the ocean that will integrate observations, models and advanced computing to provide interactive simulations and decision-support tools, with full operational capability targeted for 2030.
Europe	Copernicus Marine Service	AI reshaping how ocean forecasts are developed, corrected, and delivered.

Country	Initiative	Key Objective
Europe	Digital Twin Ocean	Develop a consistent, high-resolution, multi-dimensional and near real-time virtual representation of the ocean, combining ocean observations, artificial intelligence, advanced modelling operating on high-performance computers and accessible to all.
Global	Open Ocean Project	Integrate satellite coverage, machine learning, AIS/VMS vessel-tracking data, and fused remote-sensing sources to create an open, comprehensive map of industrial and commercial ocean activity.
Global	BlueConneX	Trusted AI-powered platform providing global insights and tools to map, analyze, and connect the Ocean Enterprise.
Japan	Ocean Cleanup	AI tools such as ADIS, predictive modeling, drones, and satellites to identify plastic hotspots, forecast debris accumulation, and guide more efficient cleanup efforts in Japan's coastal and urban watersheds.
United States	NOAA/IOOS Ocean Technology Transition (OTT)	Accelerate the transition of novel ocean technologies from development to implementation and commercialization with a focus AI for analysis and quality assurance/quality control.
United States	NOAA/GOMO Innovation Project	AI and data management tools to evaluate the impact of observations, better inform and guide observing system design and data management.
United States	FathomNet	AI tools to accelerate the analysis of ocean visual data.
United States	GUARDIAN	AI classifier integrating acoustic data from moored, shipboard and uncrewed oceanographic systems to monitor and analyze distribution and ecology of the critically endangered whales.

AI Impacts and Benefits Analysis

- Observing System Design – how, when, and where to deploy sensors to get the highest quality data for lowest cost
- Gap filling – use of deep learning, artificial neural networks (ANNs), and Graph Neural Networks (GNNs) as interpolators for ocean observing data gaps; risk – hallucinated data erodes trust
- Data processing – implementing real-time flags for anomalous data points, AI-powered filtering to remove acoustic/visual noise
- Data curation – trained annotation algorithms for improved metadata (increases access and findability)

See Appendix 4 for additional sources on AI as a market disrupter or catalyst.

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AI Caveat

In conducting research for this engagement, TBD Economics used AI tools to assist with source identification and background research. All analysis, findings, and written deliverables were developed by TBD Economics professional staff. TBD Economics' full AI Policy is available upon request.

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Appendix 1: Markets and Market Viability Terminology

What is a Market? A market can be defined as a physical or virtual space where buyers and sellers interact to exchange goods or services. This exchange typically involves buyers providing money in return for products or services offered by sellers. Understanding the fundamental components of a market is essential for engaging in the dialogue on growing new markets for ocean-based observational technology and data.

The Role of Contracts and Legal Mechanisms. Contracts and other legal mechanisms are essential in facilitating market transactions by:

- **Establishing Terms:** Contracts define the terms and conditions of the exchange, including pricing, delivery, and obligations of both buyers and sellers. This clarity helps mitigate disputes and ensures that both parties understand their commitments.
- **Risk Management:** Legal agreements can outline the responsibilities for risks associated with the product or service, such as liability for defects or delays. This can enhance trust in the transaction and encourage participation in the market.
- **Ensuring Compliance:** Contracts can also include clauses that ensure compliance with regulatory standards; this is particularly important in markets involving technology and environmental data.
- **Facilitating Financing:** Legal mechanisms often underpin financing arrangements, such as loans or investment agreements. These can provide the necessary capital for companies to develop and bring their products to market.

Key Components of a Market:

- **Buyers and Sellers:** At the heart of any market are the participants who trade. Buyers, including individuals, businesses, and governments, seek to acquire goods or services that meet their needs. Sellers, ranging from manufacturers to service providers, offer these goods or services in exchange for money.
- **Interaction and Exchange:** The act of trading itself is a crucial aspect of market dynamics. This interaction can take various forms, from face-to-face transactions in a physical venue to online purchases through virtual platforms. Contracts and other legal mechanisms play vital roles in formalizing these exchanges, outlining the terms, conditions, and obligations of each party involved.
- **Market Forces:** Prices and quantities sold in a market are heavily influenced by supply and demand dynamics. When demand for a product increases, prices tend to rise, encouraging sellers to supply more. Conversely, if supply exceeds demand, prices may drop, prompting sellers to reduce production.

- **Venue:** Markets can operate in physical spaces, such as ocean technology trade shows and industry exhibitions, or in virtual environments such as online ocean data portals, commercial instrument sales platforms, and subscription-based information services. Both types of venues facilitate the exchange of goods and services, though the mechanisms may differ.
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Key Elements of Market Viability:

- **Fixed Costs:** These are the upfront costs associated with developing products and services. In the context of ocean-based technologies, fixed costs may include expenses related to research and development, design, prototyping of physical products, or the establishment of IT infrastructure and data collection systems for data products.
- **Variable Costs:** Variable costs represent the additional expenses incurred when producing or selling an extra unit. Variable costs can include materials, labor, and distribution expenses.
- **Sales Volume and Breakeven Points:** The breakeven point is the number of units that must be sold to cover both fixed and variable costs. Achieving this volume is critical for market survival.
- **Economies of Scale:** As production increases, fixed costs are spread over a larger number of units, effectively reducing the average cost per unit. For example, if the fixed costs for developing a new ocean sensor technology amount to \$1 million, selling 1 unit means the entire fixed cost must be covered by that single unit. However, selling 1 million units allows the fixed cost to be distributed at just \$1 per unit cost, making this technology more affordable and accessible.

Appendix 2: Biodiversity Credit Markets Supplementary Material

The table below details the current market status, institutional perspectives, and developmental hurdles facing global marine biodiversity credit mechanisms.

Table 8: Biodiversity Credit Market Additional Resources

Citation/Reference	Type & Market Focus	Key Point & Core Framing
Blue Marine Foundation. (2023). Biodiversity credits: Silver bullet or snake oil? Blue Marine Foundation Analysis.	NGO analysis / article	Marine biodiversity credit markets are currently extremely underdeveloped compared to terrestrial ecosystems. Framing: "Marine biodiversity credit markets, in particular, are virtually non-existent."
Blue Marine Foundation. (2023). Drivers of Demand for Marine Biodiversity Credits. Blue Marine Foundation Market Report.	Market report	Biodiversity credit initiatives are emerging primarily on land while marine spaces remain strictly early-stage. It frames marine biodiversity credits as a developing market opportunity rather than a mature financial asset class.
Aide, T. M. (2024). The Biodiversity Credit Market needs rigorous baseline, monitoring, and validation practices. npj Biodiversity, 3(1), 30.	Peer-reviewed journal article	Characterizes global biodiversity credit frameworks as fundamentally "nascent" , noting that unresolved baseline and methodological challenges are heavily amplified in complex marine systems. Supports the reality that marine markets lag far behind land-based ones.
Ecosystem Marketplace. (2024). An Ocean of Potential: State of the Voluntary Carbon Market. Forest Trends Association Report.	Environmental finance article	Identifies blue carbon and general ocean finance as significantly undercapitalized relative to their immense ecological significance. It frames ocean-based natural capital finance as a sector that remains "largely untapped."
International Marine Mitigation Bank (IMMB). (2023). Marine Mitigation and Biodiversity Credits Asset Framework. Industry Platform Analysis.	Industry / market platform	Highlights a severe scarcity of structured marine biodiversity credit mechanisms alongside highly fragmented market infrastructure. Positions marine mitigation credits as an exceptionally rare, emerging asset class.
Reuters. (2023). Biodiversity credits coverage: Inside global voluntary conservation schemes. Reuters News Analysis.	News analysis	Notes that global biodiversity credit models are broadly in their infancy and overwhelmingly concentrated in terrestrial conservation . Reinforces the reality that marine biodiversity finance is isolated and limited compared to land systems.
IPBES. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Díaz, S. et al. (Eds.). IPBES Secretariat.	Global scientific assessment	Comprehensively documents severe global marine biodiversity degradation but identifies a total absence of mature, scaled marine biodiversity finance mechanisms. Highlights the critical mismatch between urgent ocean degradation and active conservation finance attention.

Appendix 3: AI Radar Diagram Supplemental Information

ID	Short Radar Label	Why Ocean-Enterprise Impact	Definition/Scope	What Must Be Accelerated
T01	Automated image, video & acoustic interpretation	Transforms high-volume raw imagery and hydrophone records into detections, counts and alerts; reduces expert-review backlogs and enables broader coverage.	Automated species/target detection, classification and counting from optical, sonar and passive-acoustic streams.	Model transfer across regions/species; labeled benchmark data; human review for consequential decisions
T02	AI-based data quality control, calibration & anomaly detection	Improves reliability and reduces manual QC, but usually augments rather than replaces the observing system or market.	Automated flagging, drift detection, cross-sensor consistency checks and learned calibration for ocean measurements.	Community QC benchmarks; traceable flags; uncertainty estimates; standards-based integration
T03	Predictive maintenance & asset health analytics	Can materially lower downtime, ship visits and lifecycle cost, but mainly improves existing products and services.	Models infer impending sensor, power, propulsion, communications or platform failures from telemetry and usage history.	Failure datasets; fleet-scale telemetry; digital configuration records; explainable maintenance recommendations
T04	Edge AI for onboard processing, compression & event triggering	Breaks bandwidth and energy bottlenecks, supports near-real-time response and makes long-duration autonomous observing more productive.	Runs inference at the sensor or vehicle to filter, summarize, compress or prioritize data before transmission.	Low-power accelerators; robust models; update mechanisms; graceful degradation; field benchmarks
T05	AI perception, sensor fusion & navigation for autonomous platforms	Enables safer, more capable AUV/USV/ROV operations and can reduce dependence on ships and continuous piloting.	Fuses sonar, camera, inertial, acoustic and environmental inputs for localization, obstacle avoidance and target awareness.	Long-duration trials; safety cases; rare-event testing; common interfaces; navigation in GPS-denied conditions
T06	Adaptive mission planning & reinforcement learning	Allows platforms to pursue dynamic fronts, blooms, plumes or targets and allocate scarce energy where information value is highest.	Continuously replans sampling paths and behaviors in response to sensed conditions, forecasts and mission priorities.	Safe RL; interpretable objectives; simulation-to-sea transfer; operator override; mission-level validation
T07	Multi-vehicle coordination & intelligent swarms	Coordinated heterogeneous fleets could increase spatial-temporal coverage and resilience without linear growth in operators.	Distributed AI coordinates multiple AUVs, USVs, floats or aerial systems for cooperative sensing and task allocation.	Underwater networking; decentralized planning; collision avoidance; mixed-fleet standards; scalable field trials
T08	AI-ready ocean data & machine-learning operations infrastructure	Reusable, documented, accessible training data and operational pipelines accelerate nearly every other AI trend and lower entry barriers.	Curated data, metadata, labels, provenance, APIs, compute and MLOps practices designed for reproducible AI development and operation.	FAIR/CARE alignment; persistent identifiers; benchmark datasets; provenance; model registries; monitoring

ID	Short Radar Label	Why Ocean-Enterprise Impact	Definition/Scope	What Must Be Accelerated
T09	Multi-source data fusion, gap filling, downscaling & super-resolution	Creates more complete and locally useful ocean products from sparse, heterogeneous observations and models.	ML combines satellite, in situ, acoustic, model and contextual data to fill gaps or increase effective spatial/temporal resolution.	Independent validation; uncertainty maps; conservation constraints; bias testing in data-sparse regions
T10	Synthetic data & simulation-to-sea training	Reduces labeling needs and improves rare-event coverage, but is primarily an enabling input to other AI systems.	Physics simulations, generative methods and digital environments create labeled training and stress-test data.	Validated simulators; domain randomization; provenance; tests for synthetic bias and leakage
T11	Data-driven ocean forecasting & learned emulators	Orders-of-magnitude faster ensembles and rapid scenario generation could change the economics and accessibility of forecasting services.	Neural forecasting systems learn ocean-state evolution or emulate computationally intensive ocean and coupled models.	Ocean-specific benchmarks; coupled air-sea-ice models; stable long rollouts; operational reliability; ensembles
T12	Physics-informed & hybrid AI / learned parameterizations	Combines physical consistency with AI speed and can improve unresolved processes, extrapolation and trust.	Embeds conservation laws, numerical models or scientific constraints into ML and learns unresolved model components.	Conservation-aware architectures; cross-regime tests; uncertainty; reproducible intercomparison projects
T13	AI-enhanced data assimilation & inverse modeling	Can extract more value from sparse observations, accelerate state estimation and improve observing-system design.	ML accelerates or augments the combination of observations and models to estimate ocean state, parameters and sources.	Operational testbeds; uncertainty propagation; differentiable models; robustness to missing and biased data
T14	Ocean digital twins & AI-enabled what-if decision support	If trusted and connected to live observations, twins could create new decision markets for hazards, ports, energy, conservation and climate adaptation.	Continuously updated virtual ocean systems combine observations, models and AI for prediction, scenario testing and decisions.	Interoperability; sustained observations; governance; latency targets; validation; decision-centered design
T15	Geospatial, Earth-system & multimodal foundation models	Reusable pretrained models could sharply reduce data and expertise barriers across many ocean tasks and enable capabilities not economical as stand-alone models.	Large pretrained models learn transferable representations across satellite, in situ, text, bathymetry, imagery and other modalities.	Ocean benchmark suite; multimodal alignment; small-data adaptation; compute access; bias and uncertainty evaluation
T16	Generative-AI copilots & natural-language ocean interfaces	Can broaden access to analysis and reporting, but hallucination, provenance and domain validation limit autonomous use in high-stakes decisions.	Conversational systems help users discover data, generate code, summarize evidence, create reports and query models in natural language.	Retrieval from authoritative sources; citations; domain evaluation; permissions; human approval; audit logs

ID	Short Radar Label	Why Ocean-Enterprise Impact	Definition/Scope	What Must Be Accelerated
T17	Knowledge graphs, semantic AI & machine-actionable interoperability	Connects otherwise siloed data, models, assets and concepts, improving discovery, automation and cross-sector reuse.	Semantic models represent relationships among ocean variables, platforms, places, events, standards and decisions.	Shared ontologies; APIs; identifiers; mappings to existing marine standards; governance and stewardship
T18	Trustworthy AI: uncertainty, explainability, causality & assurance	Trust and quantified uncertainty are gating factors for safety-critical autonomy, forecasts, regulation and resource decisions; success unlocks wider adoption.	Methods and governance that make AI robust, interpretable, traceable, secure and appropriate for consequential ocean use.	Ocean risk tiers; uncertainty calibration; causal evaluation; red-teaming; monitoring; human accountability
T19	Quantum-enhanced AI & computing for Earth-ocean systems	Could eventually enable analysis, optimization and scenario exploration across data volumes and interacting variables beyond practical classical limits, transforming how society understands and responds to climate change, ocean acidification, sea-level rise and other coupled global challenges	Quantum-enhanced and quantum-native AI algorithms, optimization methods and computing architectures applied to multimodal foundation models, coupled Earth-ocean modeling, complex-system simulation and large-scale environmental decision support	Fault-tolerant quantum hardware; efficient classical-to-quantum data encoding; scalable quantum algorithms; demonstrated quantum advantage; hybrid computing workflows; Earth-ocean benchmarks; uncertainty and validation methods
T20	AI-enabled underwater robotic intervention & manipulation	Could transform underwater work by allowing autonomous or supervised robotic systems to inspect, grasp, connect, repair, recover, install or collect objects without continuous human piloting. This could substantially reduce ship time, personnel risk and intervention cost while enabling persistent subsea operations	AI combines 3-D optical, sonar and other perception; object and worksite recognition; task-level decision-making; grasp and motion planning; force-aware manipulator control; and outcome verification to perform physical underwater work from autonomous, remotely operated or crewed vehicles. Applications include defense, offshore energy, infrastructure maintenance, scientific sampling, pollution and debris collection, aquaculture and environmental remediation	Robust underwater 3-D perception; manipulation in low visibility and currents; force/tactile feedback; dexterous end effectors; task generalization; failure recovery; simulation-to-sea training; human supervisory control; safety assurance; standardized vehicle/manipulator interfaces
T21	AI-enabled data visualization & product generation	Could transform decision making and response; spur economic development	AI used to visualize ocean information enabling faster, earlier signals, fusing disparate data; enabling scenario exploration	Standards, robust LMLs, trust in the outcomes

Appendix 4: Artificial Intelligence Supplemental Material

The table below outlines case studies and institutional evidence regarding the economic substitution of physical instruments via machine learning models.

Table 9: Additional sources on Artificial Intelligence

Citation/Reference	Type & Market Focus	Key Point & Core Framing
Virtual Sensors for Smart Data Generation and Processing in AI-Driven Industrial Applications. IntechOpen (2022).	Industrial Applications	Identifies three macro drivers for AI virtual sensors replacing physical ones: cost of scaling devices, need for resilience without redundant hardware, and parameter estimation in impossible-to-reach locations.
Tassot, C. et al. (2022). A Review of Multisensor Data Fusion Solutions in Smart Manufacturing. Sensors, MDPI / PMC.	Smart Manufacturing	AI data fusion enables smaller, cheaper sensor arrays to deliver analytical outputs that previously required large physical deployments. Extracting more from the same data means fewer physical instruments are needed.
Burton Taylor International Consulting / TP ICAP (2024). Integration of AI is Reshaping the Business of Market Data Providers. Traders Magazine.	Financial Markets (Analogous Data Sector)	AI compresses the data-to-insight pipeline, requiring smaller raw data inputs. It reduces the volume of primary data acquisition needed, eroding the traditional business case for buying expansive physical data infrastructure.
Machine learning for numerical weather prediction. ECMWF Technical Memorandum (2023).	Meteorology / Institutional Weather	The world's pre-eminent meteorological center acknowledges that AI models (trained on archived data) have surpassed its operational forecasting system. This highlights that massive investments in physical observation networks face substitution from AI requiring no additional observations.

Dialogues with Industry Background Paper

Accelerating Ocean Enterprise Growth
in Future Markets: Developments,
Disruptions and Vision

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