Addressing Ocean Noise Pollution in the Artificial Intelligence Era: Regulatory Challenges and Future Responses

Abstract: The accelerating advancement of artificial intelligence (AI) is reshaping approaches to ocean governance, offering novel opportunities to address one of the ocean's most pervasive and underregulated threats - anthropogenic noise pollution. This paper examines how AI technologies are being applied to identify, monitor, and mitigate ocean noise, and explores the regulatory, ethical, and institutional challenges that accompany their use. It argues that while AI can enhance the precision and efficiency of marine monitoring - through automated noise classification, predictive mapping, and real-time data analytics - its deployment also exposes significant governance gaps within the existing international legal framework. These include issues of data sovereignty, accountability, transparency, and equitable access to technology. Drawing on developments under the United Nations Convention on the Law of the Sea (UNCLOS), the Convention on Biological Diversity (CBD), and recent International Maritime Organization (IMO) guidelines, the paper proposes a coherent regulatory strategy grounded in algorithmic accountability, ethical oversight, and global cooperation. It concludes that AI should be governed as a public-interest technology within ocean governance, reinforcing rather than undermining the international rule of law and environmental justice in the marine domain.

Keywords: artificial intelligence; ocean noise pollution; marine environmental law; data governance; algorithmic accountability; environmental ethics

1. Introduction

The accelerating development of artificial intelligence (AI) has generated growing recognition of its potential to transform the management of ocean-noise pollution. Ocean noise - encompassing both surface and underwater sound[1] - refers to anthropogenic acoustic energy that interferes with the communication, navigation, and social behaviour of marine organisms, disrupting predator - prey interactions and degrading marine ecosystems [1].

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1 Some international organizations, such as the General Fisheries Commission for the Mediterranean (GFCM), established and administered by the United Nations Food and Agriculture Organisation (FAO), and Ocean Care, an international law of the sea environmental organisation with special consultative status with the United Nations Economic and Social Council (ECOSOC), have increasingly prioritized concerns about underwater noise. This paper examines the application of artificial intelligence (AI) to ocean noise management, focusing on the contributions and challenges posed by AI. To encompass the full scope of these issues, a broader definition of ocean noise is adopted for this study, including both over-the-water and underwater noise.

Major contributors include commercial shipping, underwater construction and blasting, active sonar, and oil and gas exploration, which together have filled the world's oceans with persistent low-frequency noise [2]. Ocean-noise pollution has emerged as one of the most serious anthropogenic threats to marine fauna and the overall health of ocean ecosystems[3][4][5].

A significant policy milestone in this field occurred in January 2024, when the International Maritime Organization (IMO) adopted its *Revised Guidelines for the Reduction of Underwater Radiated Noise from Commercial Shipping*, encouraging vessel-design improvements, operational controls, and data collection to reduce underwater noise [6]. Yet despite decades of research and growing international attention, ocean noise remains a largely unresolved global environmental challenge. Existing legal and policy frameworks lack the capacity for continuous, real-time monitoring and adaptive regulation-gaps that emerging digital technologies such as AI are uniquely positioned to fill.

AI may be understood as a system a system capable of processing data and information in a manner that emulates intelligent behaviour, typically incorporating elements of reasoning, learning, perception, prediction, planning, or control[7]. As the core driver of the Fourth Industrial Revolution, AI is increasingly applied to marine governance and environmental management. In the context of ocean noise, AI supports signal classification[8], intelligent noise mapping, predictive modelling, and automated traceability, enabling regulators to identify pollution sources, assess risks, and evaluate policy interventions with unprecedented accuracy[9]. These capabilities promise to transform marine environmental protection but also impose high demands on the governing legal and regulatory systems.

Existing research on AI in marine ecological conservation has predominantly concentrated on the scientific and technical dimensions of noise mitigation, focusing on model performance, classification accuracy, and data integration. Such studies highlight AI's potential contributions in signal classification, source separation, noise mapping, and automated monitoring to support adaptive management. However, they also reveal well-documented risks, such as data leakage[10], algorithmic bias[11], and opaque decision-making[12], which directly affect the legitimacy and accountability of AI-driven marine governance. Most research to date has addressed these challenges through scientific and engineering solutions aimed at improving algorithmic accuracy. In contrast, relatively little attention has been devoted to the regulatory and legal implications of AI in ocean-noise management, particularly in relation to data governance, accountability, explainability, cross-border oversight, and liability.

This paper addresses that gap by examining the regulatory challenges arising from the integration of AI into ocean-noise governance and by proposing legal and institutional reforms to ensure responsible and equitable deployment. Specifically, it analyses how existing international legal frameworks can accommodate AI applications while maintaining coherence with fundamental environmental principles and the rule of law.

The paper proceeds as follows. Section 2 explores the applicability and emerging trends of AI in addressing ocean noise within the existing international regulatory framework. Section 3 analyses the key regulatory and ethical challenges raised by AI-driven approaches, including impacts on the rule of law, maritime order, and data security. Section 4 proposes forward-looking responses-conceptual, institutional, and technological - to align AI applications with international legal obligations while promoting innovation and cooperation. Section 5 concludes by reflecting on how AI can be responsibly harnessed to support sustainable and resilient ocean-noise management in the decades ahead.

2. The Application of AI in Addressing Ocean Noise under the Existing Ocean-Noise Regulatory Framework

2. 1 The Applicability of AI and its Trends in Addressing Ocean Noise

In recent years, AI has advanced rapidly within marine-environmental protection, enabling new forms of observation, modelling, and decision-support. The convergence of oceanography, data science, and machine learning has markedly improved research quality and understanding of the marine environment[13]. Applied to ocean-noise governance, AI can harmonise management standards, reduce monitoring costs, and strengthen the implementation of international and domestic regulatory frameworks.

2.1.1 Classification and Standardisation

AI is highly effective at recognising and classifying complex acoustic signatures. Convolutional-neural-network (CNN) models can differentiate among biological, ambient, and anthropogenic sounds with accuracy above 96%[14]. Projects such as Whale FM and ORCA-Sound have successfully analysed cetacean calls and shipping noise using machine-learning algorithms[15], producing large, standardised datasets for research and policy. As these techniques mature, the diffusion of shared ontologies, labelled training sets, and validation protocols will create a technical foundation for globally consistent noise metrics and regulatory standards.

2.1.2 Automation and Cost Reduction

AI-enabled automation alleviates the traditional tension between ecological protection and economic efficiency. The U.S. National Oceanic and Atmospheric Administration (NOAA) now deploys autonomous underwater gliders equipped with hydrophones and onboard machine-learning models that detect, classify, and upload acoustic data with minimal human intervention[16]. Comparable analytics enable predictive maintenance by diagnosing shaft misalignment, propeller cavitation, and hull fouling through vibration and sound patterns, allowing early repair that both reduces underwater-radiated noise (URN) and prevents costly failures. These capabilities accord with the IMO *Revised Guidelines for the Reduction of Underwater Radiated Noise* (2023)[17], which emphasise design, maintenance, and operational measures for ship quieting.

2.1.3 Source Identification and Enforcement

Expanding passive-acoustic-monitoring (PAM) networks allow AI to locate and identify dominant noise sources through hydrophone arrays and data fusion[18]. When integrated with big-data modelling, dynamic noise-mapping [19], and vessel-tracking systems such as the Automatic Identification System (AIS), regulators can pinpoint major contributors, tailor mitigation measures, and evaluate policy effectiveness over time[20]. These analytical functions strengthen evidence-based enforcement and enable risk-based inspection regimes, improving compliance with national and international noise-management obligations.

2.1.4 Towards Integrated and Predictive Governance

Looking ahead, AI is expected to drive a transformation from fragmented, reactive management toward integrated and predictive ocean-noise governance[21]. Researchers foresee multidimensional data fusion - linking acoustic, climatic, fisheries, and ecological indicators - to construct intelligent analytic frameworks for cumulative-effects assessment and adaptive policymaking[22]. This transition embeds AI within the broader architecture of global marine governance, combining predictive modelling, algorithmic accountability, and transparent data sharing. In doing so, AI enables a shift from narrow pollution-control measures toward building ecological resilience, supporting long-term ecosystem recovery and adaptive capacity. If properly harnessed, it represents a pivotal force for proactive, rather than defensive, ocean-noise management.

2.2 Application of AI under the Ocean-Noise Pollution Regulatory Framework

Ocean-noise pollution has evolved from a regional environmental issue into a global governance concern. Although the 1982 United Nations Convention on the Law of the Sea (UNCLOS) does not explicitly define underwater noise as “pollution[23]”, its broad definition of marine pollution in Article 1(1)(4) - covering “the introduction by man, directly or indirectly, of substances or energy into the marine environment … which results or is likely to result in deleterious effects" - clearly encompasses anthropogenic sound, it provides a framework for addressing ocean noise issues[24]. Likewise, the *Convention on Biological Diversity* (CBD) formally recognised, in Decision XII/23 (2014) [25], that underwater noise can have significant adverse impacts on marine and coastal biodiversity. The European Union's *Marine Strategy Framework Directiv*e (MSFD)[26] also treats underwater noise as a pressure affecting "Good Environmental Status", noting that even marine-protected areas cannot be fully insulated from shipping and industrial sound[27].

Global treaties, as critical instruments for addressing ocean noise[28], provide the institutional foundation for integrating AI technologies into ocean-noise management. Their open-textured provisions on observation, monitoring, and scientific cooperation allow for technological innovation without the need for amendment. Under Articles 194, 204 and 212 of UNCLOS, States must take "all necessary measures" to prevent, reduce, and control pollution of the marine environment, including by "observing, measuring, evaluating and analysing" harmful effects. These obligations do not prescribe specific methodologies, thus accommodating new tools - such as machine-learning algorithms for sound classification or predictive acoustic mapping - that enhance precision and continuity in monitoring.

Similarly, the CBD's Articles 7, 12 and 17 require Parties to identify, monitor, and exchange information on activities likely to have significant environmental impacts. Through these provisions, AI can serve as an instrument of compliance, improving real-time assessment and data exchange for biodiversity-relevant acoustic pressures. The interpretative flexibility of these global instruments ensures that AI-enabled systems can be adopted consistently with existing duties of due diligence, best-available technology, and continuous assessment.

Regional treaties addressing ocean noise based on shared ecological environments and governance needs among neighboring countries[29], demonstrate characteristics of regional coordination and adaptability in the application of AI. At the regional level, instruments such as the *Helsinki Convention* (1992)[30], the *Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area* (ACCOBAMS, 1996)[31] and the *Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas* (ASCOBANS, 1992)[32] demonstrate how regional coordination can facilitate the adoption of AI. These treaties promote shared monitoring, harmonised data standards, and cooperative risk assessment.

The *HELCOM Monitoring and Assessment Strategy* (HELCOM 2021)[33] operationalises this approach through "unified indicators, coordinated monitoring procedures and shared databases," providing a ready platform for AI-based acoustic-data analytics. Likewise, ASCOBANS and ACCOBAMS Resolutions on "Integrated Data Collection and Management Systems" and "Marine Debris and Noise Insulation Networks"[34] advance interoperable regional architectures that could incorporate AI-supported modelling and real-time analytics. By fostering consensus, encouraging policy coordination, and institutionalising data-sharing mechanisms, these regional regimes create regulatory space for AI to enhance cross-border ocean-noise governance while maintaining ecological coherence.

Soft-law instruments, though non-binding, play a crucial role in enabling experimental, adaptive regulation of AI applications[35]. Their flexibility allows rapid policy iteration in response to technological change[36]. The IMO*'s Guidelines for the Reduction of Underwater Radiated Noise from Commercial Shipping* (MEPC.1/Circ.833, 2014)[37] and the *Revised Guidelines* (MEPC 2023/10)[38] encourage data collection, technological innovation, and voluntary adoption of noise-reduction measures. They explicitly reference a three-year Experience-Building Phase (EBP) to gather feedback, demonstrating a governance model that welcomes AI-driven experimentation in ship-design optimisation, acoustic prediction, and compliance monitoring.

Similarly, the *International Whaling Commission's* (IWC) *Resolution 2018-4*[39] invites "the voluntary adoption and transfer of technology" to mitigate underwater noise, leaving space for states to trial AI-based detection or mapping tools within a cooperative, non-adversarial setting (IWC Resolution 2018). These instruments employ recommendatory and guiding language rather than prescriptive mandates, allowing iterative adjustment as empirical understanding improves. Their open, learning-based nature provides a fertile testing ground for AI-supported monitoring, risk analysis, and standard-setting, helping to bridge the gap between scientific innovation and binding international norms.

2.3 Regulatory Gaps in Applying AI to Address Ocean-Noise Pollution

Although the current regulatory framework for ocean-noise pollution is sufficiently flexible to accommodate emerging technologies through broad interpretation, it provides no explicit guidance or legal standards for AI. The rise of AI is fundamentally reshaping global ocean governance, revealing a series of regulatory and normative gaps within existing frameworks.

2.3.1 Absence of Targeted AI Norms

Existing global instruments - most notably the UNCLOS and the CBD - emphasise "best available technology" and "continuous monitoring" as guiding obligations for states. Yet, these provisions offer no operational criteria for AI-driven systems, leaving ambiguity about the boundaries of responsibility, accountability, and lawful use of algorithmic tools. Similarly, regional conventions such as the *Helsinki Convention*, ACCOBAMS, and ASCOBANS encourage cooperation and data sharing but lack institutional mechanisms to address autonomous decision-making, algorithmic bias, or cross-border data governance.

Soft-law instruments - such as the IMO guidelines and the IWC resolutions - remain valuable for their flexibility and experimental orientation, yet their non-binding character limits their capacity to generate uniform global standards. As AI technologies become increasingly self-learning, self-optimising, and opaque, frameworks that rely primarily on general principles rather than specific, enforceable rules are unable to ensure effective and consistent outcomes.

2.3.2 Limitations of Environmental-Law Principles

The fundamental principles of international environmental law - including prevention, cooperation, and sustainable development - remain central to environmental protection[40]. However, they were formulated within a human-centred and state-centric legal paradigm that predates the advent of algorithmic decision-making[41]. Consequently, these principles struggle to capture the systemic, autonomous, and data-driven character of AI.

AI's ability to learn, predict, and act autonomously introduces a new mode of technological agency that undermines the predictability, accountability, and inter-state coordination on which these principles rely. Contemporary environmental regimes remain anchored in static legal obligations[42], whereas AI-driven systems depend on real-time feedback loops, dynamic optimisation, and probabilistic reasoning. This disjunction erodes the normative stability of international environmental law, creating mismatches between the speed of technological evolution and the pace of legal adaptation.

2.3.3 From Norm-Driven to Data-Driven Governance

The integration of AI into ocean-noise regulation signifies a structural shift from norm-driven to data-driven governance. Algorithmic efficiency and optimisation increasingly replace the traditional reliance on ethical and ecological principles, risking the marginalisation of human-centred and ecosystem-centred values. Moreover, AI's technical complexity reinforces the unequal distribution of technological power, privileging actors - mainly in developed economies - with advanced computational infrastructure and data access.

This dynamic not only widens the gap between developed and developing states in their capacity to monitor and mitigate marine noise but also challenges the legitimacy of global ocean governance. The problem does not necessarily stem from flaws within the existing legal system but rather from a misalignment of cognitive logics - between a normative framework grounded in stability and consent, and a technological paradigm defined by rapid iteration, uncertainty, and automation.

In the near term, policy innovation and institutional design - rather than new treaty-making - may provide the most practical avenue for progress. Strengthening coordination among global, regional, and sectoral institutions; embedding algorithmic accountability mechanisms; and promoting equitable access to AI capacity are crucial steps to bridge these regulatory gaps until more specific and binding international rules emerge.

3. Regulatory Challenges in Addressing Ocean Noise Pollution in the AI Era

The rise of AI presents profound challenges for the international governance of ocean noise. While AI can enhance detection, mapping, and regulation of underwater acoustics, its integration into ocean governance also exposes significant conceptual, ethical, legal, and institutional gaps. These challenges concern the adequacy of existing governance frameworks, the resilience of the international rule of law, and the allocation of accountability within a rapidly evolving technological landscape.

3.1 Challenges to Existing Ocean-Noise Governance Concepts and Ethics

A key barrier to effective AI-enabled ocean-noise management lies in the lack of conceptual and theoretical foundations supporting its use. Many regulatory approaches still rely on traditional paradigms that overlook digital innovation and data-driven governance. As a result, AI's potential to enhance marine environmental protection often remains under-realised.

3.1.1 Conceptual Gaps

In practice, "smart governance" in marine management frequently follows a supply-driven logic[43], where technology developers identify promising tools and then retrospectively seek governance applications. This reactive approach leads to fragmented pilot projects, duplication of effort, and weak alignment with established legal obligations such as the precautionary principle, ecosystem-based management, and cumulative-effects assessment. Without a coherent framework that begins with governance needs - such as identifying dominant sources of URN or assessing proportional mitigation measures - AI applications risk becoming piecemeal and, at times, counter-productive.

3.1.2 Ethical Dilemmas and Bias

Conceptual and ethical challenges are deeply intertwined[44]. Claims of technological neutrality are largely untenable[45]: AI systems encode human choices at every stage of design, from data selection and labelling to model architecture and performance thresholds[46]. These embedded choices determine who benefits, who bears costs, and which impacts are deemed significant.

For instance, the Listening to the Deep Ocean Environment (LIDO)[47] project employs an AI-based global network of seafloor monitoring stations to analyse ocean noise in real time. However, if training data disproportionately represent certain regions or sound types, the model may misidentify noise hotspots - under-protecting vulnerable ecosystems or over-restricting legitimate activities. Such biases directly affect the fairness and effectiveness of regulatory responses.

3.1.3 Opacity and Accountability

Technical opacity exacerbates these ethical concerns. Many high-performance AI models - particularly deep-learning systems - operate as “black boxes”, making it difficult to trace how classifications or predictions are generated[48]. If inputs are biased, the outputs will replicate those biases; and if propagation conditions change (e.g., due to temperature or salinity shifts), performance may drift without detection. External scientists, regulators, and NGOs often lack access to algorithmic design documents, error audits, or decision logs.

As Lawrence Lessig famously observed, “code is law” – and by extension, in AI governance, “code is justice[49]”. When environmental rules are implemented through opaque code, contestability, accountability, and public trust can erode. This underscores the need for transparent AI governance frameworks that ensure algorithmic explainability, independent auditing, and participatory oversight in marine environmental management.

3.2 Challenges to the International Rule of Law

The integration of AI into ocean-noise monitoring also tests the foundations of the international rule of law, raising questions of sovereignty, state responsibility, and legal attribution.

3.2.1 Non-Interference and Sovereignty

The principle of non-interference remains central to the international legal order[50]. However, AI systems often require extensive cross-border data collection for training and validation[51]. The acquisition of biological and acoustic data within another state’s territorial sea or exclusive economic zone (EEZ) can implicate sovereignty and the consent regimes governing marine scientific research (MSR) and environmental monitoring under the UNCLOS.

Even where data are lawfully collected, technological dependence on foreign-developed AI systems may generate subtle forms of leverage or influence. Control over datasets, models, or maintenance contracts can allow external actors to shape research priorities, public communication, or even policy discourse - potentially infringing upon the principle of non-intervention in domestic affairs.

3.2.2 Evolving Subjects of the Law of the Sea

Traditionally, states have been the principal subjects of the law of the sea. Yet the growing influence of technology companies, defence contractors, and research consortia challenges this paradigm. Data have become a new source of power[52]: entities that control critical acoustic datasets and AI models can influence marine governance decisions and operational choices. For example, scenario-aware AI systems developed by Roke Manor Research in the United Kingdom are now used by the Royal Navy to assist in maritime situational assessment - demonstrating how private technological capacity can rival or even exceed that of states. The concentration of such expertise in private hands risks diluting state sovereignty and complicating the delineation of public and private responsibilities in ocean governance.

3.2.3 Attribution and Liability

AI also complicates the allocation of legal responsibility among flag states, coastal or port states, operators, and technology providers. If autonomous platforms - such as unmanned surface or underwater vessels - enter foreign waters, collide with other ships, or cause ecological damage, attributing liability becomes problematic[53]. Multiple actors - including software vendors, data service providers, and state authorities - may share responsibility, yet existing law provides no clear guidance for such distributed agency.

Furthermore, when AI systems misclassify acoustic events or produce faulty environmental predictions, questions of liability arise: should responsibility rest with the state relying on the output, the operator, or the developer? The emergence of human-AI co-decision-making further risks “strategic scapegoating”, where decision-makers deflect blame onto algorithms[54]. Preventing such evasion requires clearly defined accountability chains, robust due-diligence standards, and mechanisms for independent auditing.

3.3 Challenges to Marine Order Posed by AI in Ocean-Noise Governance

The deployment of AI in ocean-noise management introduces complex risks to the stability of the global marine order, affecting maritime security, the rights of developing states, and the equity of international cooperation. These challenges extend beyond technical or environmental considerations, touching on sovereignty, power distribution, and global justice.

3.3.1 Maritime Security Risks

The integration of AI and autonomous technologies into maritime domains amplifies security vulnerabilities. As highlighted in recent strategic assessments, the Fourth Industrial Revolution has equipped non-state actors - including insurgents, criminal groups, and terrorists - with tools and capabilities once reserved for powerful states[55]. Profit-driven private vendors may sell autonomous or analytic systems to such actors without robust export controls, facilitating misuse in surveillance, navigation disruption, or cyber interference.

For instance, reports indicate that Somali pirate groups have already employed drones for maritime reconnaissance, mapping shipping routes, monitoring vessel defences, and timing attacks, thereby complicating traditional maritime-security governance. Looking forward, the widespread availability of low-cost unmanned platforms combined with open-source AI models could enable stealth reconnaissance, sensor spoofing, or covert mapping of marine infrastructure, challenging attribution, interdiction, and response mechanisms under existing international frameworks[56]. These developments blur distinctions between civilian and military technologies, creating regulatory grey zones for the law of the sea and maritime security enforcement.

3.3.2 Equity and the Rights of Developing States

Safeguarding the rights and developmental interests of developing countries is central to maintaining global marine order[57]. Yet, the integration of AI into ocean governance may deepen existing inequities. Disputes over maritime boundaries, resources, and navigation rights often intertwine with sensitive issues of sovereignty and geopolitics. As ocean-based economic activities expand, pressures on shared marine resources will intensify, leading to potential conflict driven by unequal benefit distribution, fluctuating resource quality, and the compounded effects of climate change[58]. Without reliable mechanisms for inclusion and benefit-sharing, these tensions could destabilise regional governance frameworks and heighten the risk of disputes among coastal and island states.

At the domestic level, many developing states face structural limitations in integrating AI technologies into marine environmental management[59]. Persistent capacity gaps in research, data infrastructure, and regulatory design impede access to the AI tools required for effective noise monitoring and biodiversity protection[60]. Financial and technical barriers - ranging from insufficient funding for AI hardware to shortages in specialised personnel[61] - further constrain national implementation. Consequently, while AI promises to enhance monitoring precision and reduce costs over time, its high entry threshold risks restricting developing countries' right to technological participation and sustainable development.

3.3.3 Asymmetries in International Cooperation

Globally, AI-driven ocean governance reflects entrenched power asymmetries. Advanced economies, particularly in North America and Europe, dominate the production of AI models, datasets, and standards. These assets underpin industrial and strategic advantages that can translate into technological dependency for developing nations. In international standard-setting, industrialised states often prioritise their domestic regulatory interests[62], marginalising the voices of less-developed counterparts.

Such asymmetry can foster technology-conditioned access, where cooperation or data-sharing becomes contingent on political alignment or economic concessions - amounting, in practice, to coercion or "digital blackmail". This dynamic undermines the spirit of equitable participation enshrined in UNCLOS Part XIV and contradicts the Common Heritage of Mankind principle underpinning marine governance. Unless addressed through fair data-sharing agreements, capacity-building, and transparent standard-setting, AI may inadvertently reinforce geopolitical hierarchies and weaken collective efforts to achieve equitable and sustainable ocean governance.

3.4 Challenges to Data Security

AI systems deployed for ocean-noise monitoring depend on vast quantities of acoustic and environmental data, creating new vulnerabilities for data security, confidentiality, and privacy. Unlike generic AI-safety concerns such as misinformation or content manipulation[63], ocean-acoustic data have operational, commercial, and strategic sensitivity. Across the entire data lifecycle - collection, transmission, storage, processing, and dissemination - AI-driven systems generate information that, if inadequately protected, can expose states, industries, and individuals to significant risks.

3.4.1 Operational and Strategic Sensitivities

Raw or partially processed acoustic records can reveal vessel routes, port calls, machinery conditions, and activity patterns. When intercepted, such data may facilitate illegal fishing, smuggling, piracy, or sabotage, undermining maritime security. Many datasets also contain distinctive URN or acoustic signatures of research, commercial, or military vessels. If these signatures are released, they may inadvertently expose sensitive information about vessel design, propulsion systems, or research operations, potentially constituting breaches of national security or commercial confidentiality.

3.4.2 Transmission and Infrastructure Vulnerabilities

Transmission security represents another critical weak point. The data collected by AI sensors usually needs to be transmitted over a network to a central server for processing[64], marine communications infrastructure - including satellite relays and subsea fibre-optic links - remains fragile, and oceanic sensor data transmitted to onshore servers are vulnerable to interception or tampering if end-to-end encryption is insufficient. Weak authentication protocols or outdated cryptographic standards can permit unauthorised access, data modification, or insertion of false signals, threatening the integrity of global monitoring networks. The leakage of even limited datasets may enable pattern recognition of vessel activity in strategic areas such as straits or EEZ boundaries, with cascading geopolitical and economic consequences.

3.4.3 Privacy and Legal-Compliance Risks

Beyond state and commercial interests, privacy risks may also arise. Although ocean-noise monitoring primarily targets non-human sounds, incidental recordings can capture human voices, crew identifiers, or vessel-registration details. Under modern data-protection regimes - such as the European Union's *General Data Protection Regulation* (GDPR)[65], Australia's *Privacy Act 1988*, Brazil's *Lei Geral de Proteção de Dados* (LGPD)[66], and China's *Personal Information Protection Law* (PIPL)[67] - controllers must ensure lawful processing, informed consent where applicable, data minimisation, and secure international transfers. Failure to uphold these obligations can result in substantial regulatory penalties, litigation, and reputational harm.

In transnational ocean-noise research, sensors deployed across multiple jurisdictions often collect mixed datasets combining environmental, commercial, and personal information. Without robust encryption, anonymisation, and risk-based disclosure protocols, the release of unredacted acoustic waveforms or vessel tracks could infringe privacy expectations, contravene national-security laws, and undermine international confidence in cooperative monitoring frameworks.

4. Future Responses to Addressing Ocean Noise in the AI Era

The challenges outlined above reveal that the sustainable and equitable application of AI in ocean-noise governance cannot rely on technological advancement alone. Achieving a fair, transparent, and resilient system of marine environmental management requires a coordinated institutional response spanning international law, state cooperation, governance ethics, and data-protection frameworks. A forward-looking approach must therefore integrate legal, technical, and ethical dimensions to ensure that AI serves as a tool for sustainable ocean stewardship rather than a driver of new inequalities or risks.

4.1 Revising Concepts to Enhance the Effectiveness of AI in Ocean-Noise Governance

Enhancing the effectiveness of AI in ocean-noise management requires two interconnected shifts: (i) modernising the management paradigm and (ii) embedding neutrality and ethics into AI design and deployment. Together, these reforms will strengthen the fairness, transparency, and adaptability of ocean-governance frameworks.

4.1.1 Modernising the Management Paradigm

Regulating ocean noise in the AI era demands that it be reframed as a transdisciplinary socio-ecological-technical challenge. Knowledge generation must integrate marine science, computer science, environmental law, maritime operations, and public policy, while drawing on the perspectives of diverse stakeholders [68], including Indigenous communities and civil society. This cross-domain approach helps to overcome the "island effect" of fragmented governance, fostering joint problem-definition and more coherent, collaborative research.

A needs-driven and data-driven paradigm should replace reliance on expert intuition and siloed datasets. Successful integrated marine management depends on coordinated assessment of sources, causes, and consequences across sectors[69]. Regulators should quantify uncertainty, define explicit risk thresholds, and articulate trade-offs among conservation, navigational safety, and industrial activity. Structured needs assessments must precede deployment, identifying real-world constraints, desired outcomes, and measurable performance indicators. Continuous feedback loops - monitoring model performance, user experience, and stakeholder input - should guide adaptive improvement and ensure that AI systems evolve alongside changing ocean conditions and policy goals.

Treating AI systems as "living services" - auditable, versioned, and updateable - ensures that technical models remain aligned with operational, ethical, and societal expectations. Broad participation from government agencies, academia, industry, Indigenous groups, and NGOs enhances legitimacy and ensures that technological decisions reflect public and ecological values rather than purely technical or commercial priorities. This inclusivity reinforces the transparency and accountability of decision-making and aligns AI-driven ocean-noise management with principles of democratic environmental governance.

4.1.2 Embedding Neutrality and Ethics

Claims of technological neutrality in AI are untenable in practice. Every AI system encodes value-laden choices through its problem framing, data labelling, and model configuration. Building trustworthy and equitable AI therefore requires embedding ethical safeguards by design. The full benefits of AI will not be realised without deep cooperation across domains, disciplines, nations, and cultures [70].

To this end, the formation of diverse, multidisciplinary development teams is critical. Representation across gender, geography, discipline, and culture helps mitigate bias and ensures that model design reflects pluralistic values. Developers and operators should adhere to internationally recognised ethical-AI frameworks, which emphasise transparency, fairness, explainability, and accountability throughout the system lifecycle.

Periodic ethics and environmental impact assessments, combined with third-party audits and open-data principles, should be used to evaluate system performance and ensure alignment with societal goals. Independent ethics committees and multi-stakeholder review boards should be established to assess high-impact AI deployments in marine contexts. These bodies - drawing on global instruments such as the United Nations Educational, Scientific and Cultural Organization's (UNESCO) *Ethical Principles for AI Governance* (2023)[71] - can issue advisory opinions, review documentation, and promote compliance with human rights, biodiversity, and environmental protection norms. Embedding these institutional safeguards will enhance public trust, ensure algorithmic fairness, and strengthen the moral legitimacy of AI-based ocean-noise governance.

4.2 Establishing an International Legal System for AI Addressing Ocean Noise

To ensure that AI becomes a reliable partner rather than a destabilising force in ocean-noise governance, the international legal response must rest on three mutually reinforcing pillars: (i) no AI exceptionalism, (ii) state primacy with defined duties for non-state actors, and (iii) paired legal–technical accountability.

4.2.1 No AI Exceptionalism: Applying the Law of the Sea to Digital and Autonomous Sensing

AI activities in the marine domain should be governed not as exceptional cases but as extensions of existing obligations under the UNCLOS. Coastal states exercise sovereign rights within their EEZs and retain jurisdiction over marine scientific research (MSR) conducted therein, subject to duties of environmental protection, due regard and environmental-impact assessment (EIA). Consequently, any AI-enabled acoustic or digital collection of data inside another state's territorial sea or EEZ without prior consent would breach these established rules.

International courts have consistently underscored duties of cooperation, prior notification and joint fact-finding for transboundary environmental risks. In *Pulp Mills on the River Uruguay* (Argentina v Uruguay)[72], the International Court of Justice (ICJ) confirmed EIA as a customary obligation and emphasised procedural cooperation between states. These precedents support the application of consent, due-regard, and EIA duties to AI-mediated ocean-noise monitoring. Accordingly, cross-border acoustic data flows should occur only through diplomatic agreements, regional-seas arrangements, or joint-monitoring zones, using interoperable FAIR (Findable, Accessible, Interoperable, Reusable) standards that incorporate sovereignty, security, and transparency safeguards.

4.2.2 Reaffirming State Primacy and Specifying Responsibilities for Non-State Actors

While much AI capacity resides in private entities, international law places ultimate authority and accountability on states. The International Tribunal for the Law of the Sea (ITLOS) has elaborated a due-diligence model requiring states to adopt appropriate laws[73], exercise vigilance and ensure compliance by private operators under their jurisdiction[74]. Applied to AI, this model demands that states license autonomous platforms, enforce minimum standards for safety, accuracy, and auditability, and maintain a chain of responsibility from developer to operator.

Where scientific purposes are claimed to justify intrusive activities, international jurisprudence scrutinises purpose and methodology, not labels. In *Whaling in the Antarctic* (Australia v Japan)[75], the ICJ found Japan's programme unreasonable in relation to its stated scientific aims. By analogy, "scientific" AI deployments for marine research must likewise satisfy good-faith, objective criteria and remain open to verification through transparent publication of protocols and datasets.

4.2.3 Pairing Legal Rules with Technical Enablers: An Accountability-First Model

Effective governance requires coupling legal norms with technical mechanisms to enable attribution and responsibility. The principle of effective control should guide attribution: accountability follows those who design, procure, deploy, supervise, or rely on the AI system. Implementing algorithmic accountability demands clear documentation of decision pathways, explainable-AI techniques, and traceable audit trails.

As AI is an auxiliary tool, human oversight remains central. Research identifies three tiers of human control over AI: (i) recognition ability, (ii) task type, and (iii) degree of supervision[76]. Accordingly, assessments of legality and responsibility for AI-driven actions in ocean-noise management should depend on the extent of human control and the fulfilment of due-diligence obligations by the state or individual user. Embedding these accountability structures within the international legal system will ensure that AI enhances, rather than undermines, the rule of law in the global ocean.

4.3 Strengthening International Cooperation to Maintain Maritime Order in the AI Era

Maintaining maritime order in the age of AI requires an integrated approach that both safeguards ocean security and upholds the rights and interests of developing states. The application of AI to ocean-noise management introduces transboundary risks that demand a cooperative, precautionary, and equitable governance framework.

4.3.1 Applying the Precautionary Principle and Ensuring Safety-by-Design

A sensible starting point is the precautionary principle, embedded in international environmental law and reflected in the 1992 Rio Declaration and subsequent soft-law instruments. States can operationalise this principle by requiring cross-border corporate due diligence for AI systems deployed at sea, in line with the UN Guiding Principles on Business and Human Rights and the updated OECD Guidelines for Multinational Enterprises on Responsible Business Conduct. Under such due diligence frameworks, operators and vendors must identify, mitigate, and report safety, security, and environmental risks throughout the AI lifecycle and across supply chains.

In practical terms, this approach can be embodied through safety-by-design standards that include authenticated command and control, tamper-resistant audit logs, geofencing, positive-identification beacons, human-in-the-loop overrides, and secure remote-shutdown functions for high-risk use cases such as high-intensity acoustics or swarming unmanned craft. These obligations align closely with flag-state duties to exercise "effective jurisdiction and control" over vessels, including autonomous and remotely operated systems, as recognised in Art 94 of the UNCLOS. They also complement the International Maritime Organization's (IMO) ongoing Maritime Autonomous Surface Ship (MASS) work, which seeks to codify minimum design and operational requirements for AI-enabled maritime technologies[77].

4.3.2 Building Cooperative Maritime Security Mechanisms

With accountability frameworks in place, cooperative security measures can harness advanced sensing systems, unmanned aerial vehicles (UAVs), and autonomous surface or underwater platforms to detect anomalies - such as covert acoustic mapping or unauthorised sonar trials - and to facilitate rapid attribution and de-confliction. Regular multinational exercises, real-time hotlines, and incident-notification protocols can operationalise the duty to cooperate under UNCLOS (Arts 197–200), developing common playbooks for the interdiction or disablement of rogue unmanned systems. The IMO's 2023 *Revised Guidelines on Underwater Radiated Noise* provide a technical baseline for mitigation through quieter technologies and operational controls, which may be incorporated into procurement standards and port-state-control checklists. In turn, states can integrate these guidelines with environmental-impact-assessment duties under UNCLOS Art 206 to address high-energy acoustic activities in a lawful and transparent manner[78].

4.3.3 Promoting Equity and Capacity-Building for Developing States

Equity remains a cornerstone of sustainable ocean governance. Developing states must be co-authors of the rule-set and co-beneficiaries of the technology, ensuring that AI does not exacerbate existing inequalities. UNCLOS Part XIV and the IOC Criteria and Guidelines on the Transfer of Marine Technology[79] already frame obligations for capacity-building and technology transfer, while the 2023 Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement) [80]expands this architecture with specific provisions on technology transfer, capacity-building, and a clearing-house mechanism.

To implement these commitments, states and international organisations - such as through the IMO's Integrated Technical Cooperation Programme - should fund open standards, shared testbeds, and fellowship schemes that allow developing countries to deploy and regulate AI for ocean governance without vendor lock-in. Enhanced South-South cooperation, including regional data-trust frameworks, joint acoustic baselines, and pooled incident-response teams, can level the playing field and strengthen collective maritime security[81]. This cooperative model embodies the principle that sustainable development and ocean stewardship can be achieved through mutual assistance among developing nations, promoting inclusivity and long-term stability in the global maritime order [82].

4.4 Enhancing Data-Protection Mechanisms for AI-Enabled Ocean-Noise Governance

Safeguarding data security and personal privacy - while enabling the safe, large-scale use of AI for marine environmental protection, particularly ocean-noise management - requires a coherent blend of technical and governance safeguards. The goal is to embed trust by design, ensuring that AI systems can be deployed broadly without compromising legal compliance, environmental integrity, or social licence.

4.4.1 Global Rules and Privacy-by-Design

States should promote the development and adoption of interoperable international standards for AI governance and data protection so that ocean-noise programmes satisfy both domestic and cross-border requirements[83]. Standards issued by recognised bodies can anchor shared controls for security-by-design (e.g. secure development lifecycles, threat modelling) and privacy-by-design (e.g. data minimisation, purpose limitation, informed consent, and retention limits). Technically, AI pipelines should integrate modern privacy-preserving computation methods - such as differential privacy, homomorphic encryption, secure multiparty computation, trusted-execution environments, and federated learning or analytics - allowing model training and inference without centralising raw acoustic or geolocation data. Algorithmic design should be transparent and testable, supported by independent red-team exercises and reproducible evaluations to verify resilience.

4.4.2 Shared Access with Guardrails

To facilitate cooperation while preventing data leakage, states should establish an international marine data-sharing framework grounded in formal agreements that define permitted purposes, user roles, onward-transfer restrictions, and audit rights. Continuous oversight - through real-time system monitoring, immutable logging, and third-party audits - enables the prompt detection and containment of threats. An accompanying incident-response playbook should outline severity tiers, notification timelines, cross-jurisdictional coordination procedures, and post-incident forensics. Operational readiness can be reinforced by tools such as Security Information and Event Management and Security Orchestration, Automation and Response (SIEM/SOAR) systems, complemented by regular tabletop exercises.

4.4.3 Data Trusts for Sensitive Materials

For high-risk datasets, including audio revealing vessel identities, locations, or culturally sensitive soundscapes, an international maritime data trust can provide an additional layer of stewardship[84]. Public or quasi-public trustees would hold and manage such data on behalf of contributors under fiduciary obligations to ensure ethical, private, and secure handling. This requires rigorous data classification and provenance tracking (e.g. ISO 19115-style metadata[85]), encryption at rest with hardware-secured key management, and strict access controls based on least-privilege principles (RBAC/ABAC), just-in-time credentials, and segregation of duties. For data in transit, Transport Layer Security (TLS 1.2 or higher) with mutual authentication should be mandatory; outdated Secure Sockets Layer (SSL) protocols must be retired. Default practices should favour pseudonymisation, anonymisation, and controlled release, such as sharing derived features rather than raw audio, accompanied by use logging and periodic independent audits.

4.4.4 Lifecycle Governance

Robust protection must extend across the entire data lifecycle. Programmes should adopt end-to-end governance policies covering lawful collection and consent (where required), curation and quality assurance, standardised labelling, retention and deletion schedules, and cross-border transfer assessments that respect data-sovereignty constraints. Model-governance documentation should include dataset “datasheets”, algorithmic model cards, and uncertainty reporting, with reproducible pipelines to ensure traceability and contestability. Embedding these mechanisms will help maintain accountability, transparency, and public confidence in AI-assisted ocean-noise governance.

5 Conclusion

Harnessing AI to address ocean noise is both necessary and inevitable. When properly designed and governed, AI can harmonise monitoring and management standards, lower operational costs, and enhance the enforcement of international and domestic regulations. Yet, its integration also raises complex questions concerning the international rule of law, maritime security, equity between developed and developing states, governance ethics, and the protection of sensitive environmental and personal data. Responding effectively to these challenges requires coordinated action across multiple, mutually reinforcing dimensions.

First, the international legal architecture must evolve in step with AI. States should work toward a coherent legal system for the marine domain that integrates physical space, cyberspace, and the Internet of Things. Such a system must reaffirm the primacy of the State within the law of the sea, while recognising the indispensable role of private and scientific actors operating under state supervision. It should also advance a co-governance model in which technical standards and legal norms are co-developed and mutually enforceable - embedding technological accountability within the broader framework of international law.

Second, the maritime-security implications of AI demand comprehensive and cooperative responses. States should strengthen rules-based inter-state relations, expand joint exercises and technical exchanges, and deploy advanced capabilities - satellites, UAVs, and distributed sensor networks - to detect, attribute, and deter risks in real time. Equitable participation is essential: developing countries must have an enhanced voice and share in the benefits of maritime-security cooperation, ensuring that responsibilities and technological advantages are distributed fairly across regions.

Third, the effectiveness and legitimacy of AI in ocean-noise governance depend on renewing conceptual foundations and embedding neutrality and ethics throughout the AI lifecycle. This entails constructing a cross-disciplinary theoretical framework linking marine, computer, and environmental sciences; adopting demand-driven, data-driven decision processes that quantify uncertainty and trade-offs; and installing structured needs-assessments and feedback mechanisms from system design through deployment. Ethical assurance should be institutionalised through independent ethics committees, third-party audits, and open yet responsible data practices. Diverse development teams and broad stakeholder participation - including government, industry, academia, Indigenous and local communities, and civil society - will minimise bias and enhance public trust.

Fourth, robust data-protection and cybersecurity mechanisms are indispensable. A comprehensive strategy must combine technical and managerial safeguards: interoperable international standards for AI data governance; privacy-preserving computation techniques such as differential privacy, federated learning, and homomorphic encryption; clear incident-response protocols; and, where data sensitivity is high, international maritime data-trusts that steward access under fiduciary duties, strict encryption, and auditable controls. These measures will allow the benefits of AI to be realised without compromising confidentiality, security, or legal compliance.

Looking ahead, as AI algorithms and enabling technologies continue to mature, their contribution to marine environmental governance will expand - alongside new regulatory challenges. Future research and policy development should therefore re-examine and, where necessary, recalibrate the principles of sovereignty, jurisdiction, and cooperation to ensure that international law keeps pace with innovation. With deliberate preparation and principled reform, AI can be harnessed as a responsible, transparent, and accountable instrument - capable not only of mitigating ocean-noise pollution but also of strengthening the rule-based order for sustainable ocean governance.

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[1] United Nations Sustainable Development Goals, United Nations. "A Commitment to Reduce Ocean Noise Pollution." 2017, https://sdgs.un.org/partnerships/commitment-reduce-ocean-noise-pollution. Accessed 20 October 2025.

[2] Jones, Nicola. "Ocean uproar: saving marine life from a barrage of noise." Nature 568.7752 (2019): 158-162. https://link.gale.com/apps/doc/A582020506/HRCA?u=anon~d63cd97&sid=googleScholar&xid=8116c8ca.

[3] Scott, Karen N. "International regulation of undersea noise." International & Comparative Law Quarterly 53.2 (2004): 287-323.

[4] Van Dyke, Jon M. "Whales, submarines and active sonar." (2004): 330–363.

[5] Tanaka, Yoshifumi. The international law of the sea. Cambridge University Press, 2023.

[6] International Maritime Organization. "Addressing Underwater Noise from Ships - Draft Revised Guidelines Agreed." 28 Apr. 2023, www.imo.org/en/MediaCentre/Pages/WhatsNew-1818.aspx. Accessed 20 October 2025.

[7] United Nations Educational, Scientific and Cultural Organization. "Recommendation on the ethics of artificial intelligence." (2021).

[8] Mishachandar, B., and S. Vairamuthu. "Diverse ocean noise classification using deep learning." Applied Acoustics 181 (2021): 108141. https://doi.org/10.1016/j.apacoust.2021.108141.

[9] Li, Yixue, et al. "Machine learning techniques in maritime environmental sustainability: A comprehensive review of the state of the art." Computers and Electrical Engineering 124 (2025): 110395.

[10] Ghouse, Mohammed, Manisha J. Nene, and C. Vembuselvi. "Data leakage prevention for data in transit using artificial intelligence and encryption techniques." 2019 International Conference on Advances in Computing, Communication and Control (ICAC3). IEEE, 2019. doi: 10.1109/ICAC347590.2019.9036839.

[11] Akter, Shahriar, et al. "Algorithmic bias in data-driven innovation in the age of AI." International Journal of Information Management 60 (2021): 102387. https://doi.org/10.1016/j.ijinfomgt.2021.102387.

[12] Peters, Uwe. "Explainable AI lacks regulative reasons: why AI and human decision-making are not equally opaque." AI and Ethics 3.3 (2023): 963-974. https://doi.org/10.1007/s43681-022-00217-w.

[13] Camps-Valls, Gustau, et al. "AI and remote sensing in ocean sciences." Frontiers in Marine Science 10 (2024): 1248591. https://doi.org/10.3389/fmars.2023.1248591

[14] Mishachandar, B., and S. Vairamuthu. "Diverse ocean noise classification using deep learning." Applied Acoustics 181 (2021): 108141. https://doi.org/10.1016/j.apacoust.2021.108141.

[15] Shamir, Lior, et al. "Classification of large acoustic datasets using machine learning and crowdsourcing: Application to whale calls." The Journal of the Acoustical Society of America 135.2 (2014): 953-962. https://doi.org/10.1121/1.4861348.

[16] NOAA Fisheries. "Passive Acoustic Technologies." Accessed 20 October 2025.

[17] International Maritime Organization. The Revised Guidelines for The Reduction of Underwater Radiated Noise from Shipping to Address Adverse Impacts on Marine Life. 2023, https://wwwcdn.imo.org/localresources/en/Documents/MEPC.1-Circ.906%20-%20Revised%20Guidelines%20For%20The%20Reduction%20Of%20Underwater%20Radiated%20NoiseFrom%20Shipping%20To%20Address...%20(Secretariat).pdf. Accessed 20 October 2025.

[18] Parsons, Miles JG, et al. "Sounding the call for a global library of underwater biological sounds." Frontiers in Ecology and Evolution 10 (2022): 810156. https://doi.org/10.3389/fevo.2022.810156.

[19] European Environment Agency. "EU Noise Policy WG4 on Noise Mapping." 2002, https://www.eea.europa.eu/publications/NOS02/file. Accessed 20 October 2025.

[20] Yang, Duo, et al. "Research Progress of Artificial Intelligence in Intelligent Fisheries Breeding in Prediction and Health Management Systems." (2024). doi: 10.20944/preprints202411.0149.v1.

[21] Jain, Swapnil, and Akshat Jain. "Unified AI Architectures for Smart Infrastructure: Cross-Domain Applications in Energy, Finance, IoT, and Secure Digital Services." https://www.researchgate.net/publication/392237743.

[22] Yang, Duo, et al. "Research Progress of Artificial Intelligence in Intelligent Fisheries Breeding in Prediction and Health Management Systems." (2024). doi: 10.20944/preprints202411.0149.v1.

[23] United Nations. "United Nations Convention on the Law of the Sea." 10 Dec. 1982, www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf. Accessed 20 October 2025.

[24] McCarthy, Elena. International regulation of underwater sound: establishing rules and standards to address ocean noise pollution. Boston, MA: Springer US, 2004. https://doi.org/10.1007/1-4020-8078-6_2

[25] Conference of the Parties to The Convention on Biological Diversity. "Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at its Twelfth Meeting", 6-17 October 2014. https://www.cbd.int/doc/decisions/cop-12/cop-12-dec-23-en.pdf. Accessed 20 October 2025.

[26] Official Journal of the European Union. "Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive)." 25 June 2008, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0056. Accessed 20 October 2025.

[27] McPherson, Craig, et al. Great Barrier Reef underwater noise guidelines: discussion and options paper. Great Barrier Reef Marine Park Authority, 2017.

[28] Scott, Karen N. "International regulation of undersea noise." International & Comparative Law Quarterly 53.2 (2004): 287-323.

[29] ASCOBANS Underwater Noise Working Group, "Terms of Reference for the Joint Noise Working Group of CMS, ACCOBAMS and ASCOBANS." https://www.ascobans.org/en/working_group/underwater_noise?utm_source=chatgpt.com. Accessed 20 October 2025.

[30] Helsinki Commission. "Convention for the Protection of the Marine Environment of the Baltic Sea Area." 9 Apr. 1992, https://helcom.fi/about-us/convention/. Accessed 20 October 2025.

[31] Secretariat of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area. "Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS)." 24 Nov. 1996, https://accobams.org/documents-resolutions/agreement-text/. Accessed 20 October 2025.

[32] Secretariat of the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas. "Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS)." 13 Sept. 1991, https://www.ascobans.org/en/documents/agreement-text. Accessed 20 October 2025.

[33] HELCOM, "HELCOM Monitoring and Assessment Strategy."2013. https://helcom.fi/wp-content/uploads/2020/02/Monitoring-and-assessment-strategy.pdf. Accessed 20 October 2025.

[34]Joint CMS/ASCOBANS/ACCOBAMS Noise Working Group, "Joint CMS/ASCOBANS/ACCOBAMS Noise Working Group." 25-27 February 2014. https://www.cbd.int/doc/meetings/mar/mcbem-2014-01/other/mcbem-2014-01-submission-cms-en.pdf?utm_source=chatgpt.com. Accessed 20 October 2025.

[35] Shelton, Dinah, ed. Commitment and compliance: The role of non-binding norms in the international legal system. Oxford University Press, USA, 2003. https://books.google.com.hk/books?hl=en&lr=&id=cRstxKpRnrcC&oi=fnd&pg=PR11&dq=+Commitment+and+Compliance:+The+Role+of+Non-Binding+Norms+in+the+International+Legal+&ots=cq3-Kck4Yj&sig=1M-Je-g3CC_FfzjSBUdxtgAlw8A&redir_esc=y#v=onepage&q=Commitment%20and%20Compliance%3A%20The%20Role%20of%20Non-Binding%20Norms%20in%20the%20International%20Legal&f=false.

[36] Abbott, Kenneth W., and Duncan Snidal. "Hard and soft law in international governance." International organization 54.3 (2000): 421-456. https://doi.org/10.1162/002081800551280.

[37] International Maritime Organization. "The Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life." 2014, https://www.nrdc.org/sites/default/files/wat_14050501a.pdf. Accessed 20 October 2025.

[38] International Maritime Organization. "The Revised Guidelines for The Reduction of Underwater Radiated Noise from Shipping to Address Adverse Impacts on Marine Life." 2023, https://wwwcdn.imo.org/localresources/en/Documents/MEPC.1-Circ.906%20-%20Revised%20Guidelines%20For%20The%20Reduction%20Of%20Underwater%20Radiated%20NoiseFrom%20Shipping%20To%20Address...%20(Secretariat).pdf. Accessed 20 October 2025.

[39] International Whaling Commission. "Resolution 2018-4: Resolution on Anthropogenic Underwater Noise." 2018, https://archive.iwc.int/pages/download.php?ref=17766&ext=pdf&alternative=5654&noattach=true&k=54738b00ab. Accessed 20 October 2025.

[40] Ma Xiangcong. "On the Fundamental Principles of International Environmental Law." Legal Studies 05 (1993): 85-95. doi:CNKI:SUN:LAWS.0.1993-05-013.

[41] Cassotta, Sandra. "The development of environmental law within a changing environmental governance context: towards a new paradigm shift in the Anthropocene era." Yearbook of International Environmental Law 30.1 (2019): 54-67. https://doi.org/10.1093/yiel/yvaa071.

[42] Sand, Peter H., and Jeffrey McGee. "Lessons learnt from two decades of international environmental agreements: law." International Environmental Agreements: Politics, Law and Economics 22.2 (2022): 263-278. https://doi.org/10.1007/s10784-022-09572-9.

[43] Jiang, Huaxiong, Stan Geertman, and Patrick Witte. "Smart urban governance: An alternative to technocratic "smartness." GeoJournal 87.3 (2022): 1639-1655.

[44] Gill, Amandeep S., and Stefan Germann. "Conceptual and normative approaches to AI governance for a global digital ecosystem supportive of the UN Sustainable Development Goals (SDGs)." AI and Ethics 2.2 (2022): 293-301. https://doi.org/10.1007/s43681-021-00058-z.

[45] Gao, Qifan, and Hongyu An. "Technology-neutral Illusion: The Ethical and Social Challenges in the Age of Artificial Intelligence." Sociology, Philosophy and Psychology 1.2 (2024): 33-40. https://doi.org/10.70267/frygj645

[46] Zimmerman, Anne, et al. "Values in AI: bioethics and the intentions of machines and people." AI and Ethics 3.3 (2023): 1003-1012. https://doi.org/10.1007/s43681-022-00242-9.

[47] "Acoustics and Marine Mammals." Listening to the Deep Ocean Environment, LIDO, http://listentothedeep.com/acoustics/index.php. Accessed 20 October 2025.

[48] Von Eschenbach, Warren J. "Transparency and the black box problem: Why we do not trust AI." Philosophy & Technology 34.4 (2021): 1607-1622. https://doi.org/10.1007/s13347-021-00477-0.

[49] Lawrence, L. Code and Other Laws of Cyberspace. New York: Basic Books, 1999. Print.

[50] Naigen, Zhang. "The principle of Non-interference and its Application in Practices of Contemporary International Law." Fudan Journal of the Humanities and Social Sciences 9.3 (2016): 449-464. https://doi.org/10.1007/s40647-016-0126-y.

[51] Mishachandar, B., and S. Vairamuthu. "Diverse ocean noise classification using deep learning." Applied Acoustics 181 (2021): 108141. https://doi.org/10.1016/j.apacoust.2021.108141.

[52] DE GREGORIO, G. "Constitutional Law in the Information Society: Protecting Fundamental Rights and Democracy in the Age of Artificial Intelligence." (2021).

[53] Boviatsis, Michael, and George Vlachos. "Sustainable operation of unmanned ships under current international maritime law." Sustainability 14.12 (2022): 7369.

[54] Shank, Daniel B., Alyssa DeSanti, and Timothy Maninger. "When are artificial intelligence versus human agents faulted for wrongdoing? Moral attributions after individual and joint decisions." Information, Communication & Society 22.5 (2019): 648-663. https://doi.org/10.1080/1369118X.2019.1568515.

[55] Murray, Williamson. "Technology Converges; Non-State Actors Benefit." Hoover Institution. 2019, https://www.hoover.org/research/technology-converges-non-state-actors-benefit. Accessed 20 October 2025.

[56] Sayler, Kelley M. "Artificial intelligence and national security." Congressional Research Service 45178 (2020). https://www.congress.gov/crs-product/R45178.

[57] Derrig, Rián, et al. "Protecting the ocean in the contemporary international order: Capacity-building and technology transfer from the Stockholm Declaration to the BBNJ Agreement." The International Journal of Marine and Coastal Law 39.3 (2024): 571-582.

[58] Boonstra, Wiebren Johannes, et al. "Understanding and analyzing the complex causality of conflicts over marine environments through process tracing." Maritime Studies 22.2 (2023): 19. https://doi.org/10.1007/s40152-023-00306-4.

[59] Tolba, Mostafa Kamal. Sustainable development: Constraints and opportunities. Elsevier, 2013. https://books.google.com.hk/books?hl=zh-CN&lr=&id=wehsBQAAQBAJ&oi=fnd&pg=PP1&dq=Sustainable+development:+Constraints+and+opportunities&ots=WGh4iiXHMr&sig=2WyuZAmYYFiXX-CU3-

1rdCn2t7g&redir_esc=y#v=onepage&q=Sustainable%20development%3A%20Constraints%20and%20opportunities&f=false.

[60] LessWrong. "The AI Governance Gaps in Developing Countries." 1 May 2023, www.lesswrong.com/posts/cM7sR7seBRwtxctGY/the-ai-governance-gaps-in-developing-countries. Accessed 20 October 2025.

[61] Kejriwal, Mayank. "AI in Practice and Implementation: Issues and Costs." Artificial Intelligence for Industries of the Future: Beyond Facebook, Amazon, Microsoft and Google. Cham: Springer International Publishing, 2022. 25-45. https://doi.org/10.1007/978-3-031-19039-1_2.

[62] Bermeo, Sarah Blodgett. "Aid allocation and targeted development in an increasingly connected world." International Organization 71.4 (2017): 735-766. doi:10.1017/S0020818317000315.

[63] Derner, Erik, and Kristina Batistič. "Beyond the safeguards: Exploring the security risks of chatgpt." arXiv preprint arXiv:2305.08005 (2023). https://doi.org/10.48550/arXiv.2305.08005.

[64] Chang, Zhuoqing, et al. "A survey of recent advances in edge-computing-powered artificial intelligence of things." IEEE Internet of Things Journal 8.18 (2021): 13849-13875. doi: 10.1109/JIOT.2021.3088875.

[65] European Union. "General Data Protection Regulation." https://gdpr-info.eu/. Accessed 20 October 2025.

[66] Brasil. "Lei Geral de Proteção de Dados Pessoais (LGPD)." https://www.gov.br/esporte/pt-br/acesso-a-informacao/lgpd. Accessed 20 October 2025.

[67] China. "Personal Information Protection Law of the People’s Republic of China." https://personalinformationprotectionlaw.com/. Accessed 20 October 2025.

[68] Wisz, Mary S., et al. "100 opportunities for more inclusive ocean research: cross-disciplinary research questions for sustainable ocean governance and management." Frontiers in Marine Science 7 (2020): 541934. https://doi.org/10.3389/fmars.2020.00576.

[69] Newton, Alice, and Michael Elliott. "A typology of stakeholders and guidelines for engagement in transdisciplinary, participatory processes." Frontiers in Marine Science 3 (2016): 230. https://doi.org/10.3389/fmars.2016.00230.

[70] ÓhÉigeartaigh, Seán S., et al. "Overcoming barriers to cross-cultural cooperation in AI ethics and governance." Philosophy & technology 33 (2020): 571-593. https://doi.org/10.1007/s13347-020-00402-x.

[71] UNESCO. "Ethics of Artificial Intelligence. " https://www.unesco.org/en/artificial-intelligence/recommendation-ethics. Accessed 20 October 2025.

[72] International Court of Justice. "Judgment of 20 April 2010." 2010, https://www.icj-cij.org/node/103232. Accessed 20 October 2025.

[73] The International Tribunal for the Law of the Sea. "Responsibilities and obligations of States sponsoring persons and entities with respect to activities in the Area." 2011, https://www.itlos.org/index.php?id=109. Accessed 20 October 2025.

[74] The International Tribunal for the Law of the Sea. "Request for an Advisory Opinion submitted by the Sub-Regional Fisheries Commission." 2015, https://www.itlos.org/index.php?id=252. Accessed 20 October 2025.

[75] International Court of Justice. "Judgment of 31 March 2014." 2014, https://www.icj-cij.org/node/103213. Accessed 20 October 2025.

[76] Zhang Weihua." New Challenges of Artificial Intelligence Weapons to International Humanitarian Law." Politics and Law Forum 37.04 (2019): 144-155. https://kns.cnki.net/reader/flowpdf?invoice=ZDXvmD%2F4sRCiYQE8D31bW3dfYfaACHOtCnjt6ZN1KUeMB54CaOtuPPozPKtr8uA5TSaQymRfZELxx3Uu%2FmpvtToA%2FyZMw0fZFrXxp%2F6El%2FOguhaAATNzdY7DTGq0ldYU0PGxfF6twjaxKzBzEMj6KYzrX2lHwg33q7Zvo3rTC3A%3D&platform=NZKPT&product=CJFQ&filename=ZFLT201904013&tablename=cjfdlast2019&type=JOURNAL&scope=trial&dflag=pdf&pages=&language=CHS&trial=&nonce=00279D8C5BFD4302B63ED7B449E245CC&cflag=pdf.

[77] International Maritime Rescue Federation (IMRF). "IMO: Maritime Safety Committee Convenes for 110th Session at IMO Headquarters." https://www.international-maritime-rescue.org/news/imo-maritime-safety-committee-convenes-for-110th-session-at-imo-headquarters. Accessed 20 October 2025.

[78] International Maritime Organization. "Technical Cooperation Planning And Reporting." https://wwwcdn.imo.org/localresources/en/OurWork/TechnicalCooperation/Documents/ITCP%20Annual%20Report%20Documents/TC%2074-3%20(2023).pdf. Accessed 20 October 2025.

[79] Intergovernmental Oceanographic Commission. "Ioc Criteria And Guidelines on the Transfer of Marine Technology." https://www.scor-int.org/SCOR_CB/CB-Bremen/IOC_Tech_Transfer.pdf. Accessed 20 October 2025.

[80] United Nations. "Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction." https://www.un.org/bbnjagreement/en. Accessed 20 October 2025.

[81] Human Rights at Sea. "OP-ED: UNCLOS, Flag States, IMO and Accountability." 23 May 2021, https://www.humanrightsatsea.org/news/op-ed-unclos-flag-states-imo-and-accountability?utm_source=chatgpt.com. Accessed 20 October 2025.

[82] Gray, Kevin, and Barry K. Gills. "South-South cooperation and the rise of the Global South." Third World Quarterly 37.4 (2016): 557-574. https://doi.org/10.1080/01436597.2015.1128817.

[83] Cihon, Peter. "Standards for AI governance: international standards to enable global coordination in AI research & development". Future of Humanity Institute. University of Oxford (2019): 340-342. https://cdn.governance.ai/Standards_-FHI-Technical-Report.pdf.

[84] Delacroix, Sylvie, and Neil D. Lawrence. "Bottom-up data trusts: Disturbing the 'one size fits all approach to data governance." International data privacy law 9.4 (2019): 236-252. https://doi.org/10.1093/idpl/ipz014.

[85] International Organization for Standardization. "ISO 19115-1:2014." https://www.iso.org/obp/ui/#iso:std:iso:19115:-1:ed-1:v1:en. Accessed 20 October 2025.