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High seas in the cloud: the role of big data and artificial intelligence in support of high seas governance – The Sargasso Sea pilot

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This article examines the future governance of areas beyond national jurisdiction (ABNJ) in the wake of the new 2023 United Nations Agreement using the work on the Sargasso Sea as a prototype. After discussing the legal framework and current challenges facing the ABNJ regime, some details are provided on open ocean data collection technologies, including big data and artificial intelligence (AI), used in support of ocean governance. Based on a technology-enabled ocean governance cycle, the role that data, information technology and data-science can play in incorporating empirical scientific knowledge into policy and decision-making is examined with a focus on the open ocean. The article concludes with a vision of future high seas governance based on the 2023 Agreement and how big data and AI can play a crucial role in meeting the exciting challenges that the new agreement poses.

KEYWORDS
big data, artificial intelligence, machine learning, high seas, biodiversity, 2023 BBNJ Agreement, Sargasso Sea

1 Introduction

On 19 June 2023, the United Nations (UN) Intergovernmental Conference (IGC) formally adopted the final text of the historic Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (2023 Agreement) (UN, 2023). The 2023 Agreement represents the result of more than two decades of discussion and five years of negotiations (Freestone, 2019). Although formally an implementing agreement to the United Nations Convention on the Law of the Sea (UNCLOS) (UN, 1982), it contains provisions which substantively develop the existing high seas regime of UNCLOS.

Once it comes into force, the Conference of Parties (COP) to the Agreement will have the power to, *inter alia*, designate marine protected areas (MPAs), and other "area-based management tools" (ABMTs) on the high seas. This represents an unprecedented advance in the powers available to the international community to protect the open ocean. If the treaty comes into force in time, it could assist States in meeting the Kunming-Montreal Global Biodiversity Framework target for the protection of 30% of the ocean by 2030 by including substantial areas of the high seas (CBD, 2023). However, the designation of large high seas MPAs, which are, by definition, more than 200 nautical miles from land, will also pose a major challenge to their proponents. As well as negotiating with existing intergovernmental sectorial management organizations in the ocean space, proponents will need to undertake a baseline assessment of a high seas area and activities taking place there, across potentially vast areas of open ocean; identify key risks and issues; put together a convincing case for its protection; show evidence of effective stakeholder consultation; develop an effective management regime; and put in place realistic and affordable supervision and monitoring protocols.

All ocean conservation and management mechanisms for areas beyond national jurisdiction (ABNJ), such as those envisaged by the 2023 Agreement, will require exponential access to data regarding open ocean areas. ABNJ occupies nearly 50% of the surface area of the planet, but our knowledge of these areas is limited. As of 2022, only about 23.4% of the seafloor has been mapped (Seabed 2030, 2023); our knowledge of ocean life declines as we move away from the coast and deeper into the ocean (Webb et al., 2010).

Thus, there will usually be a need to collect and process large amounts of data—so-called "big data"—from a large number of diverse sources across ecological, economic, scientific, and industrial domains. The term "big data" is of course not a simple and unified concept, it refers to great volumes, varieties and velocities of data on oceanic variables, a wide range of human activities, plus available animal telemetry; collecting and integrating this is a complex challenge. These tasks rely on a suite of monitoring, sensing and analytic technologies, including the full gamut of earth-observation, surface, and sub-surface remote sensing and *in situ* sampling capabilities for data gathering; onboard processing of data and communication to onshore databases or "the cloud"; the big data and data-sharing technologies that allow for this multi- modal information to be stored, retrieved, and utilized; and data processing, analytics, and insights tools that make sense of the information. These analytic tools could include machine learning (ML) and artificial intelligence (AI) methods (from mature rules-based approaches to emerging novel techniques or methods such as reinforcement learning and generative AI deep learning), but these will likely be adjunct to existing statistical methods and models.

This article aims to signpost how we anticipate future ABNJ governance to look and how a generation shift in sensing and analysis capabilities is likely to influence that vision. It will show how some of these emerging tools have been used in various domains and their advantages as well as some challenges and potential constraints. The initial experience of the Sargasso Sea project will be used to highlight the possible role of big data and AI in developing an accurate assessment of the status of a large marine ecosystem (LME) whilst working to develop a holistic approach to its conservation. Since it began in 2010 (Freestone and Morrison, 2012), the Sargasso Sea project has grappled with the challenges of developing effective conservation measures for a 4 million km^2 area in the North Atlantic sub-tropical gyre (Freestone and Morrison, 2014; Freestone, 2021). It is currently in the process of undertaking a major Socio-Ecosystem Diagnostic Analysis (SEDA) of the Sargasso Sea, a custom-built tool for conducting the first such analysis for a high seas site. The SEDA is a new approach for ABNJ which has been modified from the tried-and-tested Transboundary Diagnostic Analysis (TDA) which has been used for several decades now to identify the status of LMEs which are within national jurisdiction (i.e., exclusive economic zones). The SEDA aims to consider the ABNJ (in this case, the Sargasso Sea) to see if it constitutes a LME Ecosystem on the basis of the various criteria that have been used successfully for TDAs but without the presence of national jurisdictional bodies. This will be the first time that the SEDA approach will be used within ABNJ. The SEDA is financed by a grant from the Global Environment Facility (GEF), supported by the Fonds Français pour L'Environnement Mondial (FFEM). This is very much a "work in progress", but the project is keen to demonstrate leadership in the use of big data and AI in management and governance related to ABNJ.

The Sargasso Sea is an ideal potential prototype area for this work. Under the leadership of the Government of Bermuda, the Sargasso Sea project began as a working test case to discover how the iconic high seas ecosystem of the Sargasso Sea could be conserved "under existing agreements", that is, UNCLOS and the sectoral high seas governance organizations (Freestone and Morrison, 2012). Since the signing of the Hamilton Declaration on Collaboration for the Conservation of the Sargasso Sea in 2014 (Freestone and Morrison, 2014), progress has been slow. The Sargasso Sea Commission (SSC) has only achieved one legally binding conservation measure to date, namely, the closing of seamounts in the Hamilton Declaration "area of collaboration" to bottom trawling through the Northwest Atlantic Fisheries Organization (Diz, 2016). The lessons learned from the Sargasso Sea now assume global importance for the implementation and development of the new regime of open ocean governance.

After discussing the legal framework and current challenges facing the ABNJ regime, some details are provided on open ocean data collection technologies, including big data and artificial intelligence, used in support of ocean governance. Based on a technology-enabled ocean governance cycle, the role that data, information technology, and data science can play in incorporating empirical scientific knowledge into policy- and decision-making is examined with a focus on the open ocean. The article concludes with a vision of future high seas governance based on the new 2023 Agreement and the ways in which big data and AI can play a crucial role in meeting the exciting challenges that the new agreement poses.

2 Challenges facing the ABNJ regime

The commercial use of the ocean in general, and especially of the high seas, can be seen as a classic tragedy of the commons (Hardin, 1968). As human demand for ocean resources has increased and technology has developed, human activities have reached the most distant areas of the ocean (Swartz et al., 2010; Watson and Tidd, 2018) and deeper into its depths (Morato et al., 2006; Watson and Morato, 2013), as have their negative impacts (Ramirez-Llodra et al., 2011). Fishing fleets are often heavily subsidized to search for fish further from their home shores (e.g., Sala et al., 2018) into the most remote and inhospitable areas of the ocean (Watson and Tidd, 2018), diminishing resource availability and causing significant ecological damage. Likewise, exploration for oil and mineral resources takes place further from land (e.g., Kaiser, 2022). The mining of seabed minerals from deep-sea ecosystems in the exclusive economic zone (EEZ) of coastal States and in ABNJ now seems technologically feasible even if the long-term environmental and ecological impacts remain unclear (Amon et al., 2022). International communications and the global internet are dependent on a vast and growing intercontinental network of submarine cables (Bischof et al., 2018; Buerger and Liebetrau, 2021). International vessel traffic has more than quadrupled in the last thirty years (Tournadre, 2014). Autonomous ships are in development (e.g., Levander, 2017) and autonomous platforms for science and military purposes are already in use in the ocean (e.g., Petillot et al., 2019). New activities are emerging in ABNJ such as genetic sampling (Leary et al., 2009) or "ocean fertilization" (Freestone and Rayfuse, 2008). Land-based sources of pollution, including plastic waste and greenhouse gas emissions, although primarily taking place far from the high seas, add to the existing far-reaching negative impacts of human activities on high seas ecosystems, impacts which continue as manifestations of the climate and biodiversity crises in the ocean (IPCC, 2018; Rogers et al., 2022; Halpern et al., 2008).

All these developments have taken place within a very rudimentary legal framework for high seas governance established by UNCLOS. Negotiated when many of the riches of ocean biodiversity and its resources were unknown, in many ways UNCLOS reflects a world view now half a century old. Nevertheless, its overarching framework provides important general principles, such as the requirement to "protect and preserve" the marine environment (Article 192).

UNCLOS envisages a range of different zones that a coastal State may claim measured from its coastal baselines, including a territorial sea up to 12 nautical miles (nm) in which it has full sovereignty and an EEZ up to 200 nm in which it has sovereign rights over the resources of the seabed and water column. Coastal States also have an inherent right to claim a continental shelf (CS) with sovereign rights over the seabed resources. If that CS physically extends beyond 200 nm the coastal State may also claim extended CS zones calculated in accordance with the complex formulae set out in Article 76. The ABNJ encompasses both the high seas (effectively the water column down to immediately above the seabed) and the seafloor beyond the 200 nm limits, or the extended CS, whichever is further.

The seafloor beyond national jurisdiction is referred to as the "Area". The Area is designated as the "common heritage of mankind" under Article 136, with the International Seabed Authority (ISA) charged with managing seabed mineral exploration and exploitation activities "on behalf of mankind as a whole" (Article 153). However, concerns have been raised over both potential impacts of mining on seafloor and water column biodiversity, and potential conflicts of interests in the management system (Cuyvers et al., 2018; Amon et al., 2022). The absence of a comprehensive legal regime that includes water column activities affecting the seafloor has been thrown into sharp focus by recent attacks on subsea infrastructure and the recognition of the strategic importance of the seafloor to States in terms of submarine cables and structures such as pipelines (e.g., Bueger et al., 2022).

The legal regime of ABNJ has been called the "unfinished agenda" of UNCLOS (Freestone, 2016). Article 87 provides for "freedom of the high seas", making it clear that the high seas are open to all States, whether coastal or landlocked. But the listed freedoms are not unconditional and may only be exercised "under the conditions laid down by this Convention and by other rules of international law" and must be exercised by all States with due regard for the interests of other States (Freestone, 2009). Any regulation or restriction on activities in the high seas can only be imposed by international treaty; however, those treaties are only binding on the States that are parties to them. Further, enforcement essentially remains the task of the State parties to the treaties that apply to ABNJ, namely, the flag State of vessels on the high seas. Not all States are effective in exercising monitoring, control and surveillance (MCS) and ensuring compliance with regional and international agreements and codes of conduct, for example, in regard to illegal, unreported and unregulated (IUU) fishing (e.g., Le Gallic and Cox, 2006; Agnew et al., 2009; Flothmann et al., 2010; Liddick, 2014). Legal gaps, which allow flag-hopping and concealment of vessel ownership, exacerbate implementation of enforcement measures (e.g., Galaz et al., 2018; Petrossian et al., 2020). These are persistent and intractable problems in many parts of ABNJ and national waters.

Several organizations have formal "competence" over human activities on the high seas—notably the regional fisheries management organizations (RFMOs), the International Maritime Organization (IMO) and the ISA, but these are sector-specific or regional in nature. Overall, the prevailing view is that most implementation is poor, exacerbated by entrenched interests and lack of transparency (Freestone, 2016). A review by the United Nations Development Program (UNDP) and GEF of various LME projects highlighted the need for more formal coordination arrangements and agreements on roles and responsibilities between the mandated regional bodies managing living marine resources to support ecosystem management and to establish a single governance process for each LME (Vousden, 2017). This was poignantly highlighted by the IGC negotiations for the 2023 Agreement (Freestone, 2019). RFMOs only regulate fishing, indeed only target species or a specific region; IMO regulates vessel traffic movements and vessel- source pollution. As noted above, the ISA has similar limited competence. There is no formal body with an overarching holistic competence or mandate that can address jurisdictional gaps or cumulative impacts of activities in ABNJ.

To address some of these issues, in 2004, the UN General Assembly (UNGA) established an *ad hoc* working group to study issues relating to the conservation and sustainable use of marine biological resources in ABNJ that culminated in the 2023 Agreement addressing the regime for marine genetic resources taken from ABNJ and the sharing of benefits as well as the development of capacity-building and technology transfer (see Freestone, 2019; Rogers et al., 2021). Most importantly for present purposes, the 2023 Agreement develops rules for the conduct of environmental impact assessments for new and/or proposed activities in ABNJ, including strategic impact assessments at the global or regional level. It sets out a new regime for the development of ABMTs in ABNJ, including the establishment of MPAs, to enable the more effective protection of high seas and deep seabed ecosystems, habitats, and species. That regime includes the international recognition of protective actions taken by a range of management bodies, including the COP to the Agreement. The COP will have the authority to authorize environmental or even strategic impact assessments which could, for the first time, offer a holistic approach encompassing cumulative impacts from all sectors (UN, 2023, arts 27–39).

3 Technology, big data and AI for ocean governance

Dynamic oceanographic processes play a crucial role in the environmental variability of the ocean over a wide range of scales and consequently have a major influence on marine biodiversity. These open ocean processes also link ABNJ to coastal environments as well as the communities which depend on the latter for their livelihoods. Popova et al. (2019) identified the ecological connectivity between ABNJ and coastal zones as critically important and a necessary part of any negotiation process for an international legally binding instrument. Although the level of exposure to ABNJ influences varies strongly between countries and not all areas of ABNJ are equal in their impacts on the coastline, some areas of ABNJ are in urgent need of protection because of their potential downstream impacts on the coastal populations, particularly Least Developed Countries. The indirect negative impacts of activities within ABNJ, such as overfishing, non-sustainable industrialization, and pollution, affect oceanographic, cultural, and ecological connectivity to coastal waters, and these should be addressed in any management processes related to ABNJ.

Consequently, an understanding of these processes is fundamental to the ability to conduct effective ecosystem assessment or diagnostic analyses to facilitate the identification of areas for protective measures or the implementation of other spatial planning and management measures in support of the conservation or sustainable exploitation of marine resources. This is particularly the case for open ocean areas beyond national jurisdiction, such as the Sargasso Sea. This is underlined in the age of rapid climate change that, beyond the well-documented rise in global sea levels, appears to be associated with a range of other impacts, including increased incidence of marine heat waves, species distribution shifts, ocean acidification, and thermal stress on coral reef (Diaz et al., 2023) and other ecosystems (IPCC, 2019). Emerging ecosystem-based assessment management frameworks will thus need to be both spatially explicit and incorporate available environmental data directly in order to better understand the couplings between various bio-physical processes and account for the impacts of habitat variability on ecological management units and marine ecosystem services.

A range of tools is being deployed to monitor human activities and natural variation and anthropogenic change in the natural environment and provide the evidence necessary for effective preventive or remedial action for both activities and their impacts. Scientific observation of such remote areas has traditionally relied on ocean-class research vessels deploying sophisticated equipment; these are extremely expensive to build and operate, and are generally only available to wealthy coastal States (Rogers et al., 2021). Likewise, enforcement action in ABNJ, deploying traditional patrol vessels and aircraft, is extremely challenging and prohibitively expensive, as well as being subject to jurisdictional issues in terms of acting against illegal or non-compliant activities. Even as more of these tools are being deployed, a broad array and range of sensors are in place or under development to measure a wider range of oceanographic parameters at scale. The quantities of data that are collected by these means are inevitably massive and proliferating in type and volume. Producing them in real-time or near real-time in order for enforcement or other management actions to be taken, as well as handling and integrating them, poses significant technological challenges, potentially exceeding those of other domains with mature big data approaches (Hashem et al., 2016; Meijer and Bolívar, 2016; Allam and Dhunny, 2019; Munim et al., 2020).

The most prominent open ocean observation technologies that can acquire these data on the open ocean are outlined below. The operational challenges of incorporating this volume and variety of environmental data in support of assessment and governance of ABNJ and some technologies to deal with them, notably, cloud computing and artificial intelligence/machine learning frameworks, are also explored briefly below.

3.1 Open ocean observation capacity

The waters of affluent coastal nations that possess national oceanographic observing infrastructure tend to be heavily instrumented and are routinely observed (at least on the continental shelf and in the EEZ). However, systematic, long-term, and broad-scale environmental data on essential variables of open ocean marine ecosystems relies heavily on sustained *in situ* observations through programs coordinated under the Global Ocean Observing System (https://www.goosocean.org/), operated under the auspices of the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization, and satellite-based observations of key near-surface ocean variables from the national space agencies comprising CEOS, the Committee on Earth Observation Satellites (https://ceos.org/). Currently, much of this information comes in the form of raw observational data and higher level data products obtained and distributed via automated means from ships, autonomous sampling platforms, and by automated remote sensing mechanisms.

Autonomous platforms for monitoring physical and, increasingly, biogeochemical, and biological parameters in the ocean include ARGO floats, Saildrones, gliders, and long-range autonomous underwater vehicles (Johnson et al., 2009; Furlong et al., 2012; Hobson et al., 2012; Riser et al., 2016; Gentemann et al., 2020). For example, *in situ* observations from the network of ARGO profiling floats provide invaluable data on the vertical structure of large areas of the global ocean down to mesopelagic depths Argo. What is Argo? https://argo.ucsd.edu/ [Accessed August 5, 2024]. Critical adjuncts are broad- scale remote sensing measurements of ocean surface properties from ocean observing satellites, essential, continuous climate data records that span over three decades, for example, in the case of altimetry (Srinivasan and Tsontos, 2023). Improvements in the availability and quality of high-resolution earth-observation imagery with global, regular coverage also provide the possibility for highly detailed observation of fixed areas. Indeed, the most useful insights for ocean ecosystem assessment, and ultimately for ocean management, will come from the integration of the complementary satellite and *in situ* datasets in support of ecosystem studies, coupled with the utilization of those key observations in operational physical circulation models enabling possible forecasting of future ecosystem states. Ocean ecosystem models, such as digital twins, that improve extrapolation from small areas of detailed measurement to wider ocean spaces, supported by wide-area earth observation, will play an important role in creating a quantitative characterization of ocean ecosystem dynamics.

Remote sensing and tracking from satellites (e.g., Rowlands et al., 2019; Drakopulos et al., 2022) can provide early warning of threats (Swingedouw et al., 2020). For example, in the Caribbean, it has helped identify *Sargassum* inundation events at an early stage (Hu et al., 2016). It can also detect anomalous events provided there is some baseline from long-term data. Global Fishing Watch (GFW) (https://globalfishingwatch.org/) aims to provide objective evidence of compliance or noncompliance with regulatory measures, while introducing a previously unknown measure of public accountability (e.g., Selig et al., 2022; Welch et al., 2022). Technology innovators like SATIM are developing vessel detection and classification catalogues at scale for SAR imagery; detailed, real-time, classification of vessels from satellite or airborne imagery is already the art of the possible.

Likewise, platforms of opportunity, including both vessels and fixed infrastructure, can improve sensor coverage, particularly in the ocean areas most affected by human activity. This will add complexity to the data gathered; if participation at scale can be encouraged, for example through environmental and social objectives, a vast stream of opportunistic data may be made available. This will introduce new information sources and challenges to ocean models and analytic tools, but also practical challenges of verification and validation of data quality and veracity. There has been some limited success with this approach in monitoring *Sargassum* in the Caribbean (Hu et al., 2016).

Whilst framed from the ecological perspective, advances in earth observation, sensing, and analysis already do and will continue to deliver great benefit to situational awareness of human activities and when required, assist with subsequent enforcement (see further below). Data from planet- and space-based sensors across the electromagnetic spectrum are used to gather information to illuminate human activity in order to determine whether it is legal or not. Coastal or fixed floating sensors can monitor reasonably large areas of the seas, but once in ABNJ their range considerably limits their ability to gather data to create a clear and persistent picture of human activity.

The automatic identification system (AIS) was originally designed as a short-range ship-to-ship information sharing platform designed to reduce the chance of collision at sea. It is now viewed globally from satellite-mounted sensors. Similarly, vessel monitoring systems (VMS) mandated by some nations for all vessels fishing in their waters can provide an effective picture of fishing activity allowing monitoring and, if necessary, interdiction activity. However, the limitation of both systems is that they can be turned off—becoming so-called "dark vessels". The Visible Infrared Imaging Radiometer Suite (VIIRS) and synthetic aperture radar (SAR) (Paolo et al., 2024), which are not affected by weather and availability of sunlight, offer highly detailed, time-sensitive data from a multitude of space-based sensors. Should a vessel operator turn off their AIS or VMS transmitter to hide their whereabouts and activity, this array of other sensors can be used to "illuminate" the situation. Satellite-based SAR sensors produce very high-definition imagery of ever smaller-sized vessels. Revisit times measured in hours not days and non-polar orbits that keep the satellite in permanent solar view, thus providing constant power to onboard batteries, facilitate the concentration of sensor time on areas of the ocean with the most human activity, making it difficult to navigate the ocean completely unseen—so long as awareness of monitoring needs queues and schedules this capability pro-actively. A limitation of the VIIRS satellite is its ability to derive measurements of ocean conditions under cloudy conditions. Additionally, the Advanced Microwave Scanning Radiometer (AMSR) provides measurements under cloudy conditions in both open ocean and coastal areas. Combining these two measurements can provide both high-resolution and gap-free data.

Electromagnetic frequency transmitter fingerprinting (i.e., electronic intelligence), a relatively old technology, is also becoming more available. Each transmitter on a vessel (e.g., radar for navigation, V/UHF radio for ship-to-ship communications, satellite telephones) has a unique frequency fingerprint, meaning that whenever or wherever it is turned on, if it is “in view” of a suitably configured detector (e.g., satellite-based), its position can potentially be determined. Terrestrial or aircraft/drone-based systems can detect vessels operating in coastal waters or perhaps the EEZ; however, they will not easily cover the high seas and ABNJ, although ultra-long endurance autonomous air vehicles are currently in development (see https://www.sciencedirect.com/topics/engineering/high-altitude-long-endurance). On its own this “fingerprint” detail might not be sufficient, but when fused with multi-source data from other planet- and space-based sensors, a complete and compelling picture can be created and presented to appropriate law enforcement agencies for further action or to provoke changes in illicit behavior.

3.2 Big data operational challenges

The ability to select, access, integrate, and utilize the suite of observational datasets from within the sea of data made available from these open ocean observation technologies and decades of marine scientific research represents a big data problem at several levels. Given the proliferation of both satellites providing incrementally higher resolution observations, both spatially and spectrally, and derived datasets from a growing number of data producers, product selection, particularly for less expert users of earth observation data, constitutes a significant challenge. Furthermore, access to the range of data necessary for interdisciplinary ecosystem applications is complicated for users to navigate. A wide range of such data archives are maintained by an equally wide range of national and international agencies, each with different jurisdictions and thematic focuses. Access to these invariably requires heterogeneous data searches and then acquisition mechanisms.

Considerable progress on aspects of data interoperability has been made with the progressive convergence and wider adoption by both satellite and certain *in situ* data provider communities of both file and geospatial metadata standards and controlled vocabularies for earth science data (Hankin et al., 2010; Snowden et al., 2019). However, uptake by the producers of principally biological datasets has not been sufficient to allow useful interoperability (De Pooter et al., 2017; McMahon et al., 2021; Sequira et al., 2021). Further harmonization and convergence is also needed for the data server technologies that serve the range of interdisciplinary data from the various oceanographic data archives (Snowden et al., 2019). Seamless, consistent access to data across different agency/domain repositories remains a constraint even where data are maintained and served in interoperable form consistent with earth science data standards. However, for all this big data to be truly effective in facilitating improved ecosystem assessment and governance of large open ocean areas such as the Sargasso Sea, automated aggregation and analysis workflows involving extensive, heterogeneous interdisciplinary ocean data will be critical.

Big data technologies and initiatives such as CEOS Ocean Variables Enabling Research and Applications for GEO (Group on Earth Observations) (COVERAGE) play an important role in addressing these challenges and facilitating the work of projects in the open ocean such as the Sargasso Sea GEF Project and the complementary SARGADOM project financed by FFEM which covers the Eastern Tropical Pacific Thermal Dome as well as the Sargasso Sea (Sargasso Sea Commission, 2023b). COVERAGE, established by the U.S. National Aeronautics and Space Administration (NASA) in 2016, aimed to improve access to inter-agency, multivariate satellite data on key ocean parameters and tools for their integration with *in situ* observations in support of Open Science and interdisciplinary marine applications for societal benefit (Tsontos et al., 2022). Such initiatives enhance accessibility to big data through tools and services that extract regional remote sensing data. There is also a related need for the implementation of technology platforms delivering value-added data services; a set of advanced core capabilities (including visualization, analytics, and harmonized data access services); and data that can be reused and augmented as necessary, and that are cloud-enabled and can be spun up and scaled agilely to support a suite of emerging regional applications. This is the critical gap that COVERAGE, the funding for which unfortunately expired at the end of 2022, sought to address in collaboration with the Sargasso Sea Commission.

Data transparency and accessibility consistent with FAIR principles (Tanhua et al., 2021) and adoption of Open Science (https://open.science.gov/) is a further challenge because RFMOs, States, and private bodies alike are often reluctant to share data, typically for reasons of commercial confidentiality and risk to competitive advantage. However, data unavailability (and obfuscation) prevents real scrutiny and—for the global ocean commons—impedes governance. Enshrining data transparency and sharing mechanisms in applicable agreements could facilitate ecosystem analysis and governance. The form these mechanisms take will necessarily be nuanced. Encouraging a culture of transparent operations, with fairness of ocean use guaranteed through mutual visibility, will help ensure that each stakeholder has confidence others are not misusing the ecosystem. Steps towards this are to the benefit of governance as transparency weakens the influence of entrenched interests on policy decisions.

3.3 Big data infrastructures and cloud computing

The ability to manage, process, analyze, and synthesize the growing volume of remote sensing data for the global ocean has been advanced by the advent and increased uptake of cloud computing, and the development of cloud optimized science data formats and multi-dimensional data structures (data cubes) (Giuliani et al., 2019). Cloud infrastructures provide both scalable, elastic storage and computing resources that can facilitate the development, efficient deployment, and end-to-end lifecycle management of data intensive software applications and workflows involving earth observation data (Vance et al., 2019; Gomes et al., 2020; Smith et al., 2022). The availability of a wide range of services from commercial cloud vendors reduces the cost burden of computing infrastructures, thus facilitating improved access to necessary computing resources and integrated AI services (e.g., Amazon Web Service Tensor Flow, Google Earth Engine) for big data analytics application development at different scales of operation and resourcing.

Complementary open-source data cube technologies, such as the Open Data Cube (https://www.opendatacube.org/) and the Apache Foundation Science Data Analytics Platform (SDAP) being implemented by COVERAGE and others (https://sdap.apache.org/), provide geospatial data management and analysis platforms that can be deployed and function performantly in cloud environments. By aggregating, ingesting, and indexing large collections of earth observation data, and by providing consistent, interoperable data storage and access mechanisms, data cubes address primary constraints typical of conventional file-based systems and achieve additional performance gains with the implementation of parallel computing frameworks.

3.4 The growing role of AI in big data analytics

As the capabilities and uses of AI have increased, a spotlight has been shone on the potential issues and negative consequences of its use, such as biased outputs or behavior, often resulting from non-representative training data, and the potential for misuse because of poorly communicated shortcomings (such as factual inaccuracies). Nonetheless, for some time machine learning (ML) and AI have provided indispensable tools in the processing and interpretation of vast amounts of data, and are involved in a modern approach to ocean governance. The range of ML/AI applications involving satellite ocean data is growing and is an active area of research in the earth sciences, although it is still far from being an established methodology with broad and evenly distributed operational use. This places an important and necessary focus on trustworthiness. If sophisticated AI approaches are to be practically employed in aspects of ocean governance, the technical and human dimensions must be addressed and complemented by robust processes that are designed to maximize AI transparency and resilience to known and future shortcomings. The proliferation, and successes, of AI and ML approaches in other areas of science and monitoring (e.g., medicine, physical science and automation) demonstrates their benefits to widely ranging analytic tasks.

An area where mature AI methods are being applied to significant benefit is vessel analysis from satellite data (and additional data sources such as AIS and VMS), particularly towards vessel detection and classification from earth-observation imagery (Weiya et al., 2014; Li et al., 2020), trajectory prediction, and behavior analysis highlighting industrial activities such as fishing (de Souza et al., 2016). This facilitates analysis of human activity on the ocean and monitoring and enforcement over open ocean areas. Such methods have been applied to great effect by organizations such as Global Fishing Watch.

Another critical application of relevance to big data and biodiversity is the application of ML to the detection of ocean fronts that often serve as biological hotspots and movement corridors (see, e.g., Lary et al., 2018; Ardabili et al., 2020; Malde et al., 2020; Sonnewald et al., 2021; Li et al., 2022). Models of ocean physical parameters such as sea surface temperature are also being improved using AI approaches (e.g., Meng et al., 2023), and there is clear potential to also improve aspects of climate and weather models (Rüttgers et al., 2019; Kashinath et al., 2021). It is anticipated that the application of AI/ML to detection of ocean fronts will also coincide with improvements in satellite technology that allow for retrieval of sea surface temperature and other remotely sensed parameters at greater spatial resolutions.

Overall, it is clear that AI and ML approaches have a growing and increasingly well-proven role to play in supporting ocean governance, monitoring, and enforcement. Whilst the maturity of methods and analytic tools vary, the examples presented above illustrate the benefits of applying ML and AI methods to each process of the technology-enabled ocean governance cycle (see further below). A substantial technology development effort will be required to mature and validate these approaches. However, considering the complexity of analyzing and modelling ocean ecosystems, and the scale of big data involved, it is difficult to foresee a future where ML and AI approaches do not play a significant role in aspects of ocean governance.

The Sargasso Sea is planning to play a leading critical role in the development and utility of these types of technology. It is already a pilot area for enhancing stewardship through AI and was a pilot site for COVERAGE (see above). Big data and AI innovations also form part of the SSC work program for its two major grants on strengthening the stewardship of the Sargasso Sea (Sargasso Sea Commission, 2023a, b). The SSC has so far demonstrated the need for an improved high seas regulatory environment, it is now planning to demonstrate strategies for implementation of improved high seas governance using big data and AI, emboldened by the finalization of the 2023 Agreement.

4 Technology-enabled open ocean governance: the relationship between policy, governance and data/AI solutions

Effective ocean governance should be an important mechanism to advance the goals of conservation, sustainable use, and ecological regeneration of the ocean. It should contain a strategy to advance those goals and to manage human activities. It is informed by, and includes, a range of economic, scientific, ecological, and financial activities and policies, covering all events in the ocean space, at local, regional, national, and global levels. The process of establishing governance should be granular, transparent, consultative, equitable, and, ultimately, evidence based. Ocean governance necessarily involves action, response, and enforcement. Here, “governance” is used as an overarching concept that includes structures and institutions as well as management mandates and powers, but could also be linked to macro-economic and geo- political drivers and indicators, food security, conservation objectives, and the predicted evolution of ocean ecosystems under climate change (see, e.g., Sala et al., 2021).

The importance of data and technology in open ocean governance cannot be overstated. Ocean ecosystems are complex, and effective governance will require cross-sectoral strategies and governance frameworks that are specifically designed with this in mind. The disconnect between the information capture and scientific analysis processes and the required interpretation of these scientific findings into advisory and guidance proposals for managers and decision-makers has been recognized as a major constraint to effective governance both within LMEs and for any future strategy for wider ocean management (Vousden and Stapley, 2013). However, basing governance decisions (captured in a legal and regulatory framework) on the use and analysis of the widest possible sources of data has the potential to lead to truly innovative solutions. This includes considering the networking of a range of observational platforms and the social and institutional contexts in which they operate (Drakopulos et al., 2022). An ideal scenario is one where there is interplay whereby innovative technology helps to formulate and justify policy, as well as to implement regulatory measures. Our growing ability to interpret, predict, and monitor through the use of technology may enable the development of highly nuanced measures responsive to evolving ocean ecosystems. Ultimately, this could lead to more targeted regulation, based on a deeper scientific understanding and substantially improved sensing and monitoring.

This section examines the interface between the wider challenges of governance of the ABNJ and, in particular, assesses the role that data and data technology can play in incorporating empirical scientific knowledge into policy- and decision-making. Based on the technology-enabled ocean governance cycle, the role of technology in support of data collection, analysis, and policy-making for open ocean governance, and support of monitoring and enforcement in ABNJ are each examined in turn.

4.1 Technology and data collection, analysis and policy-making to support open ocean governance

The more effective use of big data and AI tools—which include the data sharing/big data architecture, ML and AI methods for ecosystem monitoring, analysis, and enforcement discussed above—may provide specific solutions for open ocean governance and could lead to a generational capability enhancement. However, at present, the ability to harness these multiple data sources for the purposes of effective conservation management and subsequent enforcement is limited, representing a foundational issue for the success of the new regime established by the 2023 Agreement.

The relationship between governance and technology is not simple. There are barriers to access that must be considered carefully. Candidate technologies must be scalable and have pathways towards ubiquitous use, all while meeting wider societal requirements. FAIR data and Open Science principles (Tanhua et al., 2021; Chakravorty et al., 2022) formalize many of these values and the technical requirements they suggest, and would serve the needs of ocean governance data systems well. A further challenge is the investment involved; advanced solutions, such as those built on AI, may be costly to develop, and only economically viable through provision of long-term services. However, their development may be necessary to explore the forms that technologized governance can take and to establish the evidence necessary to generate action. It is clear that the introduction of governance can spur wider investment (see, e.g., Gerhard et al., 2019; Orhon et al., 2021) but, until that point is reached, there is clearly some advantage in pilot activities that can enable and "de-risk" the use of the technologies discussed here.

A more sophisticated understanding of the minimum requirements for the sharing of big data and analysis services for ocean ecosystems is required. The barrier is not necessarily unwillingness to share, but maximizing accessibility and broad usability while minimizing the cost for data gatherers to open their data for public use and meeting the technical challenges of interoperability (see above). Agreeing to and developing user-oriented platforms for data sharing could address this issue, as could providing better funding for data sharing (e.g., grants) to support the costs of preparing data for sharing (e.g., standardization) and maintaining it once available. There appears to be an important and yet unfilled role for a public organization or a group of such organizations to develop agreed international standards for data gathering and data sharing while protecting the interests of commercial and other data partners. This could be a role for the COP to the 2023 Agreement to take on as part of its technology transfer and capacity-building mandates.

Two existing high seas data collection initiatives that support open ocean governance are worth noting here, namely, the LME methodology used by the GEF and the Sargasso Sea SEDA. The GEF has financed a wide range of projects throughout coastal ecosystems and ABNJ, mostly implemented though the UNDP, which are designed to improve the conservation and management of the transboundary resources of LMEs (GEF, n.d). The common methodology starts with a Transboundary Diagnostic Analysis that collects as much data as possible from whatever sources are readily available globally, including those discussed above. The TDA aims to identify and confirm (with credible scientific and socioeconomic evidence) what the priority impacts are that are threatening the welfare and sustainability of the LME, its goods and services and dependent communities. The TDA then undertakes a causal chain analysis to establish what is causing or driving these impacts, provides a diagnosis of what the root causes are as well as the barriers preventing mitigation or removal of these root causes. In this context, the TDA is a factual summary of the existing problems and constraints to effective and sustainable management within an LME (Vousden, 2017).

The next step is the development of a Strategic Action Program (SAP) defining, agreeing, and formally adopting future governance measures; this directly depends on the foundational data collection and analysis undertaken during the TDA stage, but is also highly reliant on ongoing monitoring and assessment of change once the SAP is under implementation, therefore requiring further effort and investment in data collection and analysis.

For the Sargasso Sea, a similar but modified approach will be tested though the custom-designed high seas SEDA, which is designed to include a review of existing and potential stewardship and governance options for existing organizations and institutions with responsibilities and interests in the Sargasso Sea area and identification of measures needed for the conservation and stewardship of the ecosystem, with a particular focus on a collaborative stewardship regime for the long-term conservation and sustainable use of the Sargasso Sea (Sargasso Sea Commission, 2023a). The SEDA will inform a SAP, which will require ongoing, long-term monitoring of changes in the ecosystem. Supporting this by big data and AI capabilities will be an iterative and/or continuous process, whereby these methods not only implement measures to protect and manage the Sargasso Sea ecosystem, but continually support and refine it. This also requires a continuing resource flow. The challenges facing the Sargasso Sea epitomize the generic issues addressed at the global level by the IGC negotiating the 2023 Agreement (Freestone, 2019; UN, 2023). The framework for future cooperation developed by the Sargasso Sea project and the sources of data that it relies upon will have wider significance for the governance of other high seas areas once the 2023 Agreement is ratified and begins to be implemented.

To begin the process of recommending a high seas conservation measure within an intergovernmental organization, the development of a robust science case is crucial, and must demonstrate that the conservation needs are both urgent and significant. However, it is practically challenging for ocean managers and non-data scientists alike to understand what a good choice of data looks like for their purpose. This is doubly significant for developing nations for whom there may be financial challenges as well as substantial knowledge and expertise gaps. Researchers and scientists are trained to aim for the highest levels of confidence in their evidence and reporting. Meanwhile, managers and policy-makers need advice and guidance on the results arising from scientific analysis and what these might mean within the broader picture of governance needs and management responses (Vousden, 2015). Where threats and impacts to the ecosystem are identified, they need to know what options are available to them to react to any new knowledge or changes in the ecosystem *status quo* in terms of both adaptive management approaches and potential policy adoption or amendment. Developing a mechanism for translating the outputs from data capture, analysis, and long-term monitoring into policy and management level guidelines is an essential step which is all-too-frequently overlooked.

Effective ecosystem governance requires detailed, accurate environment/ecosystem baseline data that can support the selection of indicators and environmental performance targets, as well as regular monitoring of the indicators against the baseline to identify new indicator requirements to reflect changes in the ecosystem. Big data approaches can assist in fine-tuning the process of identifying threats and impacts and selecting appropriate indicators for monitoring by analyzing the information computationally to reveal patterns, trends, and associations. Big data and AI processes can also reduce the amount of time taken to identify these concerns and to strengthen the evidence needed for adaptive management. With more rapid access to data processing and results, adaptive management can become faster and more proactive while remaining evidence-based and not losing the strength of justification for active responses. This is a really important potential advantage that can be derived from the use of big data and AI.

One mechanism that might integrate extremely well with the big data and AI approach is the "weight-of-evidence" approach (Vousden, 2015). Vousden points out that this approach is being tested by GEF projects as a way to deal with the rapidly evolving changes within LME management and governance areas. Such an approach adopts a strategy of reviewing scientific evidence that may not meet the formally accepted "95% plus" confidence interval but which nevertheless can establish a sufficient weight-of-evidence based on the existing information that scientists and their peers feel comfortable in agreeing defines a clear indication or trend and that gives managers and policy-makers sufficient confidence upon which to act. Furthermore, it helps identify data-poor areas and issues which fall below any level of confidence for reaching scientific conclusions or any strength of certainty. These can then be focused on where it is clear that they relate to emerging or on-going issues with potentially high impacts or threats. This approach is not intended to replace scientific rigor as recognized through the confirmation of high confidence intervals; on the contrary, it allows for the more obvious trends of concern to be identified and for scientific research and data analysis to then be focused on those specific issues and levels while providing justification for fast-tracking appropriate levels of support and funding (Vousden, 2015). It also aligns well with the concept of precaution now enshrined in the 2023 Agreement.

4.2 Technology to support monitoring and enforcement in ABNJ

While the discussion so far has concentrated on the use of data and the potential for big data in relation to ecosystem analysis and policy development, there is also a huge and, as yet unrealized, potential for monitoring and enforcement of policy measures. Efficacy of active ocean governance regimes can be substantially reduced by limitations in monitoring and enforcement. This is particularly true for Small Island Developing States, for whom enforcement beyond immediate coastal waters can be a major financial and capacity challenge. That said, the ever decreasing cost and growing ease of access to earth observation and other forms of remote sensing and monitoring should see less wealthy nations being able to take a more active role in monitoring and enforcement.

Arguably, the most remote ocean spaces pose the most difficult challenges in terms of gathering suitable data to fully understand the dynamics between the marine ecosystem and maritime activities affecting the sea space. Remote sensing and analytics tools have had considerable success in reducing illegal fishing in some areas, such as around the Ascension Islands, and in the practical and economic implementation and enforcement of large-scale MPAs in remote areas (Rowlands et al., 2019). A combination of sporadic vessel patrols, satellite tracking of vessels using AIS and licensed fishing vessels by VMS, and coastal waters using satellite-borne SAR, proved effective in detecting levels of compliance amongst fishing vessels within and outside of the Ascension EEZ, implementing a new conservation and management ordinance, and, notably, identifying the risk posed by vessels carrying hazardous cargoes transiting the EEZ (Rowlands et al., 2019). The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has implemented highly effective, precautionary, ecosystem-based management with the objective of conserving Antarctic marine life using data reported by fishing vessels and by scientific observers placed on vessels as well as data from large-scale, multi-Member cooperative scientific surveys (https://www.ccamlr.org). The Western and Central Pacific Fisheries Commission (WCPFC) uses VMS to monitor fishing vessels authorized by flag States to fish for highly migratory fish species in the Convention Area in areas beyond the jurisdiction of the flag State(s). Data collected is used to ensure compliance with conservation and management measures, fisheries scientific analysis and sound fisheries management decision-making in the Convention Area. The VMS data is integrated with other MCS frameworks, such as the Regional Observer Program, the Record of Fishing Vessels, the IUU Vessel List and operational fisheries data, so that integrated analyses of these and other data sets support efforts to combat IUU fishing (WCPFC, 2022). Monitoring and enforcement will also represent a major challenge for any attempts at stewardship or the implementation of management measures in ABNJ.

As demonstrated in the discussion above, the collection and management of data is an issue already touching every level of ocean governance, from the scientific data needed to make the case that a particular ocean area is under threat or in need of protection, to the need to monitor dynamic and remote ecosystems over time, and the need to enforce regulations over remote open ocean areas. It is this enhanced data gathering that enables the generation of a big data picture; this in turn underpins most AI analytics. These are each separate elements of technology and, most crucially, work is needed at all those layers, including development and implementation of technology; agreements for data and insights sharing across government, private, third sector, and academic organizations; and capacity-building and solution sharing. Some of the underpinning technological solutions will be translations of leading solutions already proven in other domains, but others may need to be bespoke solutions for the ocean domain designed for the specific challenges of vast geospatial data of highly varied and different modalities (ocean physical, biological, human activity, etc.).

5 Conclusion: a vision of future high seas governance

Anthropogenic pressures are putting huge stressors on the ocean environment. Greenhouse gas emissions are warming the ocean and changing its chemical composition with rapidly increasing acidification. IUU fishing is still widespread and adds exponentially to existing pressures on fish stocks and on non-target species within the food chain. Plastic pollution in the ocean is universal and not diminishing despite increasing awareness of its detrimental impacts.

The finalization of the 2023 Agreement presents a major opportunity to move the whole agenda of open ocean governance and conservation forward. Defining and perfecting the relationship between data analysis (including ML/AI solutions) and management, policy, and overall governance strategies for the ocean, particularly the high seas areas, has never been more critical and imperative as it is today in the presence of such a rapidly changing global environment and the growing dependence of humanity on essential yet finite resources.

The use of big data, ML, and AI has the potential to provide new dimensions to the international agenda for the conservation of ABNJ. The innovative work of the COVERAGE project and the ongoing pioneering work of Global Fishing Watch (GFW) have demonstrated that there are indeed ways to access information about the vast open ocean spaces beyond national jurisdiction. These emerging remote sensing and monitoring systems, coupled with existing biodiversity information systems such as the UNESCO-IOC Ocean Biodiversity Information System (OBIS) network can provide open-access data to support ABNJ management. This information can be used for analytic work like the planned Sargasso Sea SEDA. Such systems also have enormous potential for ongoing environmental monitoring and, as the Ascension Island, CCAMLR, and WCPFC experience shows, ultimately for unprecedented compliance and enforcement actions over open ocean areas and the corresponding deterrent effect of this activity. The model of open access data sharing which GFW has pioneered is a poignant image for the future.

But we are not there yet. The amounts of data involved are truly enormous and the ability to process and manipulate these enormous amounts of data is not yet freely available. As discussed above, the technology is nearly there, but it is still at an early stage of development, and it still requires large capital investments and outlay. To date this has been sourced largely from public investment, such as NASA, or through philanthropic funding (e.g., GFW), but there is an unfulfilled potential role for others, particularly the private sector. It is also important to highlight that the SAR data mentioned are currently only collected on continental shelf/nearshore regions. So space agencies will need to prioritize data collection in ABNJ in the future.

Systematic collection of useful open ocean data still remains a challenge. Remote sensing already has the potential to provide astonishing levels of detail and granularity of ocean images—but that too is prohibitively expensive at present for all but government and major commercial operations with deep pockets. The collection of data involves a much wider spread of potentially important and useful information and possible suppliers. Given sufficient incentives and encouragement, there is an existing plethora of ocean users who could become data gatherers of opportunity—using commercial vessels, recreational craft, and others means to provide a range of information to supply further granularity and detail to the large-scale data that already exists. What could be sufficient incentives for the commercial users of the ocean to participate more enthusiastically in the collection and sharing of data? Despite the exponential explosion in the tonnage of ocean-going vessels (Tournadre, 2014), very few commercial operators have agreed to carry monitoring equipment on board their vessels (see, e.g., Maersk, 2022). Fishing vessels, however, present a limited vessel of opportunity as they are notoriously reluctant to share the exact location of their catches because of competitive pressures, and the information they are forced to report is often not accurate in many other respects. However, fish are a common resource and their management is an important component of ocean governance; there must surely be better ways to electronically monitor activities on board fishing vessels without giving away sensitive and commercially valuable geographical co-ordinates. Analysis from other fields and sectors shows that perceptions of data rivalry are not necessarily well founded, and the greatest economic benefits can be realized through non-rivalry data sharing (Jones and Tonetti, 2020). This can be an unintuitive point, but an important one, illustrating not least the benefits of big data and the mutual advantages from sharing.

As set out in the technology-enabled ocean governance cycle, the wider picture is not the technology itself but the way that it can be focused to support analysis and the implementation and enforcement of measures related to more effective high seas governance. A robust data and analytics infrastructure should be able to link ecosystem monitoring and analytics to wider governance and commercial activities while also generating better models for their long-term protection. Further, it should be designed with application programming interfaces that enable integration, but also protect the integrity of the data itself.

The 2023 Agreement is built on a shared vision of the conservation and sustainable use of the biodiversity of marine areas beyond national boundaries (UN, 2023). This shared vision requires concrete actions to implement it—notably at an ocean basin or ecosystem level—such as the Sargasso Sea. The challenge of analyzing and then monitoring these huge open ocean systems in an environmentally sustainable way requires a different level of collaboration in the collection and processing of the information from a wide variety of sources. Think of it as *"Seven 'Cs' for the high seas"*: careful Consultation, clear Communication, and close Collaboration to enable effective Coordination, to reach Consensus and the necessary Compromise to deliver the Conservation of the most critical environment of our only planet.

Author contributions

DF: Resources, Methodology, Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. KB: Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. KG: Writing – review & editing, Writing – original draft, Conceptualization. PH: Writing – review & editing, Writing – original draft, Conceptualization. KF: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. AH: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. AR: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. FS: Conceptualization, Writing – review & editing, Writing – original draft, Project administration. VT: Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Data curation. JV-C: Writing – original draft, Investigation, Data curation, Conceptualization. DV: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

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Supplementary material

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