Commissioned by

HIGH LEVEL PANEL *for*
A SUSTAINABLE
OCEAN ECONOMY

BLUE PAPER

Technology, Data and New Models for Sustainably Managing Ocean Resources

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About this Paper

Established in September 2018, the High Level Panel for a Sustainable Ocean Economy (HLP) is a unique initiative of 14 serving heads of government committed to catalysing bold, pragmatic solutions for ocean health and wealth that support the Sustainable Development Goals (SDGs) and build a better future for people and the planet. By working with governments, experts and stakeholders from around the world, the High Level Panel aims to develop a roadmap for rapidly transitioning to a sustainable ocean economy, and to trigger, amplify and accelerate responsive action worldwide.

The Panel consists of the presidents or prime ministers of Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau and Portugal, and is supported by an Expert Group, Advisory Network and Secretariat that assist with analytical work, communications and stakeholder engagement. The Secretariat is based at World Resources Institute.

The High Level Panel has commissioned a series of Blue Papers to explore pressing challenges at the nexus of the ocean and the economy. These Blue Papers summarise the latest science, and state-of-the-art thinking about innovative ocean solutions in technology, policy, governance and finance realms that can help to accelerate a move into a more sustainable and prosperous relationship with the ocean. This paper is part of a series of 16 papers to be published between November 2019 and June 2020. It examines existing and breakthrough technologies, such as drones, artificial intelligence and blockchains, and the associated challenges and possibilities they pose for ocean management and improving understanding of ecosystems and human interactions with the ocean. It also explores potential markets that could stimulate demand for ocean data, and ways in which public and private players can drive the deployment of these new models.

This Blue Paper is an independent input to the HLP process and does not represent the thinking of the HLP, Sherpas or Secretariat.

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Foreword

The High Level Panel for a Sustainable Ocean Economy (HLP) commissioned us, the co-chairs of the HLP Expert Group (a global group of over 70 content experts), to organise and edit a series of "Blue Papers" to explore pressing challenges at the nexus of the ocean and the economy. The HLP identified 16 specific topics for which it sought a synthesis of knowledge and opportunities for action. In response, we convened 16 teams of global content experts. Each resulting Blue Paper was independently peer-reviewed and revised accordingly. The final Blue Papers summarise the latest science and state-of-the-art thinking on how technology, policy, governance and finance can be applied to help accelerate a more sustainable and prosperous relationship with the ocean, one that balances production with protection to achieve prosperity for all, while mitigating climate change.

Each Blue Paper offers a robust scientific basis for the work of the HLP. Together, they provide the foundation for an integrated report to be delivered to the HLP. In turn, the HLP plans to produce by mid-2020 its own set of politically endorsed statements and pledges or recommendations for action.

The lack of observations and data has historically been a major limitation for understanding the ocean and the impacts of human activities. This Blue Paper examines the role that ocean data and technology could play in securing a better understanding and stewardship of the ocean and its resources. The paper highlights emerging data and technology developments in the field, as well as ways in which these developments can be applied to ocean management. The paper identifies priority actions to leverage the current technology and data developments and facilitate achievement of a sustainable ocean economy: harnessing information from the ongoing ocean data revolution, sharing such information widely to benefit innovation, and using data to improve ocean management. The paper offers an up-to-date overview of status and opportunities in a rapidly evolving field which has the potential to significantly influence the global ocean economy. We suggest that this is a must-read for everyone interested in ocean sustainability, including experts, innovators, managers and decision-makers in the private and public sectors.

As co-chairs of the HLP Expert Group, we wish to warmly thank the authors, the reviewers and the Secretariat at the World Resources Institute for supporting this analysis. We thank the members of the HLP for their vision in commissioning this analysis. We hope they and other parties act on the opportunities identified in this paper.

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Key Messages

- Effective management of resources has been hindered by a lack of information about how humans are impacting the ocean.
- There is an explosion in new data and technology for the ocean at the moment, and with it enormous potential for advances in the understanding and stewardship of ocean resources.
- Coordinated efforts by industry, researchers and governments can create advanced sensor networks that provide high-resolution, real-time information about the ocean to anyone who needs it, an "Internet of Things" for the ocean.
- However, significant technical and non-technical barriers exist to creating an equitable, open and accessible digital ecosystem for the ocean. To capitalise on the revolution in data and technology, breakthroughs are needed on several fronts.
- Vast stores of ocean data are in the hands of governments, researchers and industry but are unstructured, inaccessible and unusable. These data should by default be made open and available through data tagging, federated networks and, where possible, data lakes.
- Technology can leverage vital innovations in management. Real-time information and automation can allow robust and nimble adaptation to changing conditions and create new accountabilities in government and in business. An urgent priority is to ensure that these new capabilities are available to all ocean stakeholders.
- Overcoming market barriers is critical to fostering successful innovation that supports science and management in the future. Capturing the extraordinary potential of technology will require action by governments and others to foster the needed innovations for all those who have a role in ocean stewardship, by creating new market incentives for innovation, new public–private instruments for investment and new business models.

1. Introduction

We are in the middle of an explosion in new data on the ocean, creating enormous potential for advances in our understanding and stewardship of ocean resources. An exponential increase in the number and variety of ocean observing systems and other new data sources has created the prospect of a digital ocean ecosystem. Advances in processing techniques and visualisation are rapidly expanding our ability to extract information from those data, and are enabling a wide array of tools to provide real-time information in actionable form to decision-makers, such as policymakers, resource managers, resource users, consumers and citizens.

To capitalise on this revolution in data and technology, we will need breakthroughs on several fronts. A first imperative is to end the balkanisation of data to create a new era of open and automated data access – so that the data now locked in the servers of government agencies, businesses or researchers are much more broadly available – and to enable the flowering of an ocean Internet of Things (IoT). A second priority is to harness this revolution to support vital innovations in management. Real-time information and automation can allow robust and nimble adaptation to changing conditions and create new accountabilities in government and in business. A third priority is to create the incentives, investments and business models that will support the innovations that are needed not just by wealthy governments and resource users but by all who depend on the ocean and have a role in sustaining the ocean's future. In this paper, we outline the most promising avenues to create this open, actionable and equitable digital ecosystem for the ocean.

2. The Data Explosion

2.1 Fostering New Scientific Understanding of the Ocean

Walter Munk once said that the 20th century would be known as "the century of undersampling" (Munk 2012). The ocean is 10 trillion times more opaque to light than the atmosphere. This means that we cannot observe the ocean system by looking at it, as we can with terrestrial ecosystems. Instead, we must place our devices inside the ocean itself. The ocean and its ecosystems change on both small and large scales in time and space. A typical phytoplankton growth rate is to double every 1–10 days, and while the average ocean depth is about 3,700 m, most of its photosynthesis occurs in the upper 100 m. At the same time, ocean currents move slowly both horizontally and vertically, causing the ocean to act as the "memory" of the Earth system. Organic carbon that is created in the upper ocean may be buried in deep ocean sediments for millennia. Changes in our land and atmosphere will have an ocean signature for decades or centuries. To end "the century of undersampling" will require a fundamental transformation of our observing systems. We need to sample the ocean on its own intrinsic scales, not on the scales that are dictated by our current technical capabilities.

Over the last three decades, there has been an exponential increase in the number and variety of ocean observing systems. From profiling floats such as Argo (e.g. Freeland and Cummins 2005) to cabled observatories (e.g. Kelly et al. 2014), our understanding of ocean dynamics has been transformed through these new tools. And these observing systems are not just in the ocean, but they are also in space. Beginning with the launch of SeaSat and the launch of the Coastal Zone Color Scanner on NIMBUS-7 in 1978, ocean remote sensing has moved from experimental missions in support of the research community to continuously operating systems that support a wide range of management and application needs.

New communication pathways are opening up a vision of a connected ocean, although the fundamental physical properties of seawater will never enable the same level of ubiquitous communications that we have with land and atmospheric observing systems. Cabled observatories, such as the US Ocean Observatories Initiative (Smith et al. 2018), now bring data ashore directly to the Internet. Acoustic modems, although limited in data throughput, can provide a level of connectivity that may eventually enable heterogeneous "swarms" of platforms to behave as a coordinated network. Hybrid systems of both underwater and ocean surface vehicles are now being tested, with the surface vehicles acting as data "mules," receiving low-bandwidth acoustic data streams from the underwater vehicles and converting them into high-bandwidth radio data streams for transmission to aircraft or satellites. With the emergence of high-bandwidth communications based on networks of hundreds to thousands of small satellites, there is promise of gigabit/second networks everywhere over the surface of the world ocean.

With advances in microelectronics and mechanical design, there has been a rapid increase in the type of measurements that can now be made in the undersea environment. Beginning with measurements of physical properties (temperature, conductivity, velocity, etc.), we can now measure a wide variety of chemical and biological properties in the ocean environment. For example, flow cytometry, which was originally designed as a tool for human blood cell analysis, is now being used in situ to identify a wide variety of microorganisms in the ocean (e.g. Lambert et al. 2016). These instruments are being used to identify harmful algal blooms (HAB), as well as in a wide range of ecological studies (Seltenrich 2014). Environmental DNA analysis is becoming a powerful tool for understanding ecosystem composition, and such analyses can now be made in situ, not just through laboratory analysis of water samples (Kelly et al. 2017).

The variety and capability of these new sensing systems are continuing to increase, and they are now being deployed on a broader range of platforms.

These examples can be viewed as adapting traditional lab-based techniques to the ocean environment through processes such as miniaturisation, lowering power requirements and automation. However, there are also sensing tools that are fundamentally new. For example, new methods of manufacturing fibre-optic cables are enabling sensors to be embedded within the fibre (Rein et al. 2018). Undersea fibre-optic cables are critical conduits of global information flows, carrying over 95 percent of international data, and more are rapidly being added as bandwidth demands increase, creating huge opportunities to expand ocean sensing (Wrathall 2010). Designers are exploring the possibility of embedding both processing and communication semiconductors within these fibre-optic fabrics, thus creating a dense network of smart sensors and allowing fibre-optic cables to act as both sensors and platforms. Fibre-optic sensors in sea-floor cables are also being used for a wide range of environmental sensing, including seismic activity (Joe et al. 2018).

The variety and capability of these new sensing systems are continuing to increase, and they are now being deployed on a broader range of platforms. For decades, sensors were mounted on fixed buoys or attached on ships. With miniaturisation and power reduction, sensors are now being deployed on underwater passive platforms, such as Lagrangian drifters or buoyancy-driven gliders, or on self-propelled devices, such as the REMUS (Stokey et al. 2005). The same holds for platforms on the sea surface. The Wave Glider (Thomson and Girton 2017) can traverse entire ocean basins, and also remain in areas that are simply too hostile for conventional ships. Saildrone (Cokelet et al. 2015) is pursuing a different model for ocean data acquisition. Rather than sell individual vehicles that are managed by the end user, Saildrone provides "mission as a service," where the user defines the mission plan (types of data, location, etc.) and then Saildrone designs and manages the mission.

These new platforms have greatly expanded our sampling "footprint" in both time and space. We can sample over longer time periods and greater spatial distances than with fixed buoys and a few ships.

The "always on, always connected" ocean (Abbott and Sears 2006) could soon be a reality, with the decreasing costs, improved performance and increasing availability of data. Munk's "century of undersampling" could be drawing to a close. However, there remain both technical obstacles and opportunities.

On the technology side, power availability continues to be challenging. Slow-moving or passive devices, such as floats and gliders, can sample the ocean for many months but they can only cover a small area. Therefore, their ability to observe rapidly changing processes or to map large areas is severely limited. Self-propelled systems require significant power to move through the ocean, as power requirements increase non-linearly with speed. Such systems simply run out of battery power.

Power-harvesting systems are being developed for platforms that operate on the ocean surface, such as the Wave Glider or Saildrone. These platforms can harvest wind and solar energy as well, thus enabling them to remain working for months to years. Bottom-mounted systems that rely on microbial fuel cells are being deployed as well. These fuel cells harvest energy by taking advantage of the natural oxidation of organic material at the sea floor (Reimers and Wolf 2018). New approaches in battery technology, such as aluminium-based systems that use seawater, show promise for greatly increasing battery capacity.

Along with power, the undersea environment is challenging for communication and navigation. Unlike the terrestrial environment where radio frequencies can support WiFi and cellular networks as well positioning systems such as GPS, the ocean lacks such fundamental infrastructure. The ocean is nearly opaque to electromagnetic radiation, and therefore we must rely on acoustic signals and other approaches to provide the basics of communication and navigation.

Acoustic modems are increasing their capability to transmit data, but the amount of data that can be transmitted remains substantially smaller than what we can achieve on land. However, as microprocessors continue to decrease in size and power requirements, and increase in computational performance, we are beginning to develop on-board systems that process and analyse the data on the platform and transmit only the results rather than the entire observed data stream. For example, a resource manager may only need to know if a harmful algae species is present or not, rather than detailed information on every species of microbe in the water. Long fibre-optic cables may string together swarms of platforms that can then communicate with a single data "mule," which can carry the data to the surface. Next-generation Internet-capable microsats are capable of delivering high bandwidth anywhere over the world ocean. While the ocean will always be a difficult environment for high-bandwidth communication systems, distributed intelligence in undersea networks shows promise in overcoming this basic physical obstacle.

Navigation systems are showing similar signs of improvement. A small number of precisely located undersea beacons could serve as anchor points for platform swarms and networks that rely on relative distances from each other to create a precise "cooperative" map. Following Metcalfe's Law of networks, the value of the network increases non-linearly with the number of nodes in the network. Thus, such smart swarms show promise in delivering increasing value with regard to navigation and operational efficiency.

In addition to the technical obstacles to our vision of an always on, always connected ocean, there are many non-technical barriers as well. Our ability to sustain long-term ocean observing systems is always under threat. A recent report by the US National Academies of Sciences, Engineering, and Medicine (NAS 2017) documents both the importance of long-term ocean observing systems and the inability of governments to sustain these systems. Numerous reports on the global ocean observing system also highlight these issues. Long time series have enabled significant growth in our understanding of ocean processes, but every year is a struggle to sustain costly and often remote infrastructure. Even the Argo system, with roughly 3,800 floats, must expend significant political and financial resources to try to make modest increases in the number and capabilities of these profiling floats (Roemmich et al. 2009).

The majority of ocean instrumentation is developed primarily to meet the requirements of the science community, and therefore the requirements of cost and schedule are often restricted with respect to the science needs. Most ocean instruments and platforms are expensive and often crafted by hand. There is only a small commercial market to counteract the pressures from the science community to build state-of-the-art, one-of-a-kind instruments. Even systems that are "transitioned" from the science lab to the commercial sector often remain focused on the small market of ocean science. There is little incentive (or pressure) for the funding agencies to engage in any sort of sustained design effort that would encourage an extensible architecture that supports the development of multipurpose instrument systems. Instead, solutions are generally monolithic, with their design focused on meeting the specific needs of a specific science question. Thus, technology lock-in and a relatively slow pace of instrument system evolution are characteristics of scientific ocean observing tools and the generally undercapitalised commercial instrument developers in the field.

Buck et al. (2019) describe a parallel environment in the world of data systems that are built around "portal and download," with little regard to how data will be used within a framework of user-driven services. They propose a fundamental rethinking of data systems architecture, where data are democratised, enabling users to build their own knowledge systems. In a sense, rather than a pre-defined data organisation structure, tagged data would reside in unstructured data lakes where the schema are written as the data are accessed.

Much as data lakes are transforming machine learning and analytics, a similar development environment needs to be created for ocean observing systems that would enable knowledge services to be driven by the user.

There is considerable work to do to define and realise such a vision, but if we are to develop adaptive and flexible management approaches to our changing ocean, we will need to rethink how we both collect and deliver data. Much like natural ecosystems, these knowledge ecosystems will deliver critical services.

2.2 Monitoring Human Activity

Technology is changing our ability to understand ocean ecosystems, and how humans are using (and abusing) them. Effective management of resources has been stymied by a dearth of information about how humans are impacting the ocean. The big advances that are generating new opportunities for scientific data collection present parallel opportunities to improve oversight of human activity at global and local scales.

At the global level, increasing access to satellite technologies has enabled real-time, precise vessel tracking. Where once ships operated largely out of sight of regulators, the ubiquity of GPS has allowed governments to mandate that most commercial vessels carry Automated Identification System (AIS) devices, which automatically track and transmit their location. Knowledge products, such as Deep Sea Mining Watch and Global Fishing Watch, publish this information online, allowing anyone to look at what vessels are doing on the world ocean.

The proliferation of increasingly powerful imaging satellites has also been an important development in understanding global impacts on the ocean. Imaging satellites can track changes to coastal and ocean ecosystems, and can be used to understand coastal development patterns, monitor nutrient run-off and track pollution from ships.

Drones offer similar imaging at a more granular level. Drones are a cost-effective way of reaching offshore areas, allowing managers to see what is happening at a distance through real-time video streaming.

Drones can also be equipped with chemical sensors, supporting a wide variety of management uses. In Denmark, drones are being flown over the exhaust of shipping vessels, for example, allowing enforcement agencies to determine whether ships are using legally mandated low-sulphur fuels.

Drones are also being used in the water. Autonomous underwater vehicles and swarms of sensors can gather visual and chemical information on vessels. Drones and buoys equipped with acoustic sensors are particularly powerful in understanding human activity. Sound travels great distances in the ocean and different types of vessels have different acoustic signatures. Acoustic sensors can allow managers both to identify when vessels are operating in areas where no vessels are allowed, such as marine protected areas (MPAs), and to identify specific malefactor vessels.

Sensors on vessels provide another level of detail. Video cameras on fishing vessels and even on fishing nets can be used to monitor fish catch and potentially to identify labour abuses (Michelin et al. 2018). These cameras can be coupled with gear sensors that activate when fishing gear is deployed, giving regulators robust insight into where fishing is actually taking place.

Chemical sensors on smokestacks and in the water are being used to monitor water and air pollution to determine compliance with environmental regulations. These sensors also contribute important scientific data to world meteorological organisations, which use sensors on ships for critical in situ data from remote areas to support weather forecasting.

Connected sensors are also a building block for efforts to create traceability in supply chains. The IoT opens the door to robust tracking of all types of maritime goods from the moment they are harvested or produced through ports to their destinations throughout the value chain. Digital tracking will introduce critical efficiency and transparency in global supply chains.

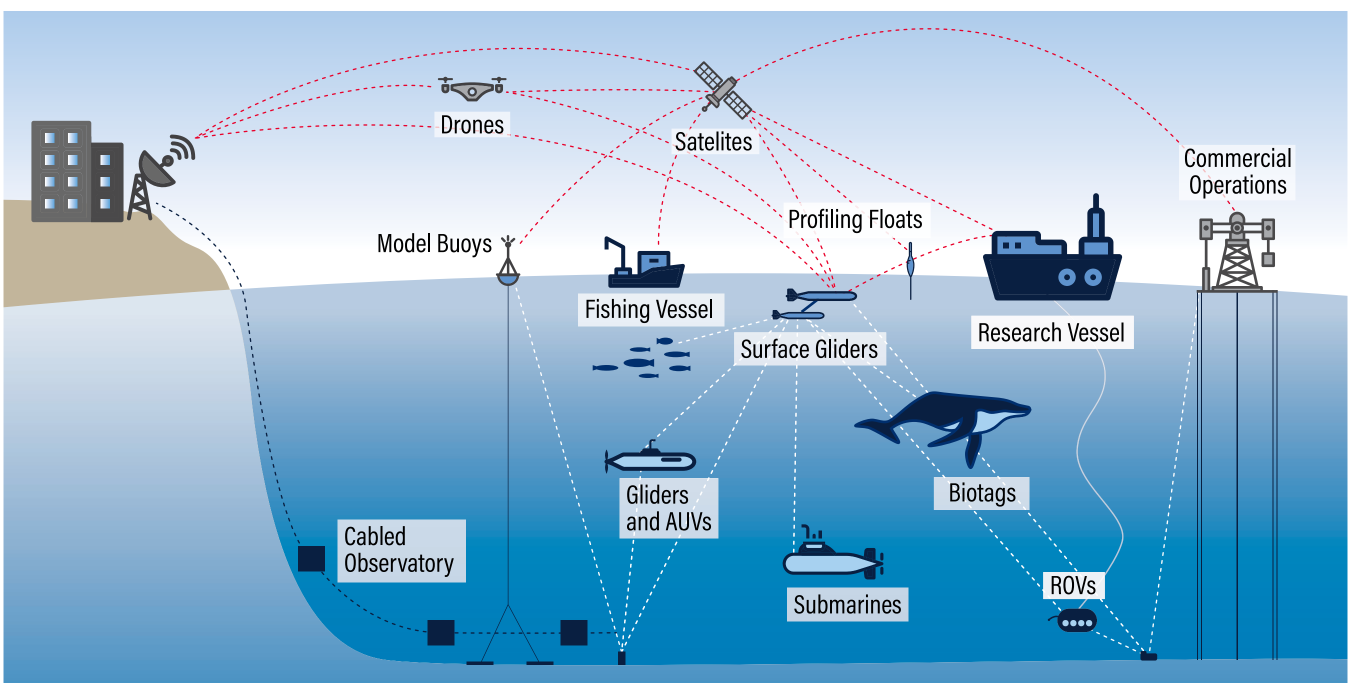
Lastly, social media and the increasing connectivity between people give new insights into human actions. Mining social media data and the dark web can illuminate labour abuses and other illegal activity that historically has been nearly impossible to penetrate

(Greenemeier 2015). Online forums can illuminate how and why resource users are flouting regulations, information not generally communicated accurately to regulators but critical for developing effective management (Shiffman et al. 2017). Social media is also providing new sources of data for scientists. Citizen science apps allow members of the public to submit photos for species identification, leading to updated species distribution maps as well as the discovery of new species (Silverman 2016). Photo submission can also help regulators target problem areas: in Los Angeles, citizen tracking of plastic pollution along the Los Angeles River identified the most important spots for intervention (Thompson 2019). Scientists are using Twitter reports of flooding to generate high-resolution urban flooding maps to improve model accuracy and forecasting (Wang et al. 2018).

2.3 A Vision of an "IoT" for the Ocean

The dramatic increase in intelligent, connected devices is enabling a vast array of new services on land. The IoT phenomenon is in its infancy, but the prospect of trillions of connected devices is driving technologies in both network communications (e.g. 5G) and microprocessors. This is not just a simple scaling up of the Internet; it will require a fundamental shift in our software design and network architectures. Developers will no longer think solely of "dumb" sensors feeding high-speed data ingestion systems. Instead, computational power will be pushed out to these "edge" sensors. Workflows will be intelligent, driven by the services being provided. The pressures of near real-time data flows and derived services will require that "time to insight" becomes a fundamental metric. While the traditional historical analyses (and associated data ingestion engines) will continue to be important, these new real-time flows will grow hugely in significance.

Figure 1. An Ocean Internet of Things



Source: Authors.

Thinking about an IoT for the ocean will still require new approaches to data communications and sensor location. Terrestrial systems can rely on satellite-based positioning systems and radio networks, whereas ocean systems cannot. But, over the next decade, we can expect that an IoT model will begin to become a reality (Figure 1). The availability of powerful microprocessors that consume small amounts of energy will enable networks that transmit small, but information-rich messages (e.g. sensors that identify harmful algal bloom species on board and then transmit a simple presence/absence message). And as the number of these sensing platforms increases, and they communicate with each other, Metcalfe's Law of networks, where the value of every node in the network increases with each new node added, will come into play in the ocean.

The vision of an IoT for the ocean will only be realised if the private sector, governments and researchers ensure that ocean sensors are interoperable and network architectures support connected, smart sensors (Cater & O'Reilly 2009). Without concerted efforts to achieve these goals, business as usual could lead to a plethora of disconnected sensors all generating proprietary data types that do little to achieve the potential of a connected IoT for the ocean. It is also essential that smart sensor networks are compatible with different types of data access regimes, including open access. New platform and sensor types may minimise the need for researchers and managers to gather their own data, but these platforms are often costly. Effort must be made to ensure that, where possible, the data generated by these platforms are available to relevant researchers and managers and not locked in high-cost proprietary systems.

IoT sensors are also vulnerable to attack. While the security and privacy concerns that are relevant for smart sensors located in the home are less pressing in the ocean, the vulnerability of sensor networks could make large-scale manipulation of data inputs relatively easy (Li et al. 2015). Governments, industry and researchers must work together to develop network architectures that overcome these concerns.

3. Tapping into the Explosion in Data Sources

The explosion in new data about the ocean has the potential to reshape how we understand and manage the ocean. Ocean management has long been impeded, and often defeated, by a lack of timely, accurate and relevant information on the condition of ocean resources (Cvitanovic et al. 2015) and on human activities and their impacts. New technologies are vastly increasing the collection of data, and the urgent challenge is to ensure that these data are available and useful to ocean management.

Data alone are not inherently useful (Kelly 2014). Relevant information must be extracted, combined with information from other sources, and translated into a form that is easily understandable, timely, actionable and accessible for decision-makers (Bradley et al. 2019). The importance of effective knowledge translation cannot be overstated amid the rise of “big data” in the ocean, but historically it has been a weakness in the science–policy interface (ELI 2014). The key challenge ahead is to create a “digital ecosystem for the ocean,” which makes diverse ocean datasets available and translates that data into actionable information for decision-makers.

3.1 Making Data Available

“Water, water everywhere, nor any drop to drink.” Although Coleridge was referring to the ocean, the same could be said about ocean data. We may be drowning in a sea of data but cannot find the information we need to increase our knowledge or to make science-informed decisions. Quantitatively, the amount of unstructured data gathered and managed annually by organisations within the government, research and business sectors is growing exponentially. Qualitatively, this shift is even more radical, as the conceptual framework for data management moves from a historic, disaggregated and static model to one that is based on dynamic, unstructured and collaborative use. Knowledge extraction will require new tools to enable new levels of collaboration, visualisation and synthesis – this is not just scaling up traditional workflows to accommodate greater volumes. Data will be broadly dispersed, as will the teams that come together to work on specific economic and science issues, and these many-to-many networks will constantly be changing as the needs for collaboration change. As a result, new frameworks are required that provide a systematic basis for data management, analysis and collaboration, rather than ad hoc aggregations of independent components (Buck et al. 2019.)

In the next 10 years, frontier efforts are aiming to create a “digital ecosystem for the environment” (Jensen and Campbell 2018), which aggregates many sources of data to provide timely and high-quality information to decision-makers. There are numerous initiatives that have set out to create this digital ecosystem, from the Global Ocean Observing System hosted by the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) (“a truly integrated global ocean observing system that delivers the essential information needed for our sustainable development, safety, wellbeing and prosperity,” GOOS 2019) to private sector efforts like REV Ocean’s Ocean Data Platform (“a global, unifying ocean data platform [that] will enable unbiased research and facilitate a data-driven debate, leading to better decision-making and enable more successful conservation and utilization of ocean resources,” REV Ocean 2019). Most current efforts focus on combining datasets into one centralised database, which is a more powerful version of the traditional portal–download data model (Buck et al. 2019).

Efforts to create unified data platforms have faced daunting challenges, however. Datasets are often not consistent or interoperable. Data holders are often reluctant to share data because, once data are combined, they lose control over how their data are accessed and used (Piwowar 2007). Lastly, there are few incentives (either financial or professional) to expend the considerable effort necessary to make datasets available on a sustained basis.

Outside of the ocean, Google and other technology companies have created various tools, such as Google's BigQuery, that crawl the web combing and combining diverse datasets to mine insights. These tools provide new ways to access datasets that previously would not have been interoperable, but they face many of the same challenges as ocean-focused solutions. Researchers and governments do not share their data in ways that allow these tools to access the information, and the incentives needed to tailor these tools to ocean problems do not exist.

We must now rethink our fundamental strategy (and culture) and move decisively towards a data architecture that allows diverse datasets to be accessed automatically by researchers and managers. Universal data tagging standards are the essential foundation for this new wave of ocean data infrastructure, allowing data to be combined in federated data networks and data lakes that support verified and automated global access. Federated data networks offer the potential to liberate ocean data that are currently locked in private sector and government databases, while data lakes create new opportunities to combine data in ways that support real-time management needs and enable the development of new (and sometimes unanticipated) data-driven services.

Tagging standards

Standardised data tagging and metadata protocols are the first step in making ocean data globally accessible. Standardised metadata include normal indicators, such as where and when data were collected, and how. Tags build on this, indicating whether and how data can be stored, transmitted and used, and its suitability for management and enforcement decision-making. Data tagged appropriately can be made automatically available to users that meet the criteria specified in the tags. Data owners can update data tags at any time, ensuring that access restrictions can be changed as needed. Some have raised concerns about reliance on federated networks for scientific purposes, namely that federating the data removes the connection between the data provider and user and may make it difficult to convey the nuances of how the data were collected (Buck et al. 2019). Tagging can overcome these concerns (Bar-Sinai et al. 2016; Crosas et al. 2015; Sweeney and Crosas 2015).

Creating data networks based on tagging may also allow new types of knowledge to be included more comprehensively in management decisions. Traditional knowledge that does not meet standardised scientific requirements, but which is increasingly recognised as an important part of management decisions, can be included with the appropriate tags (Berkes 2010). Historical data from diverse sources, such as ships' logs, newspapers and menus, can be included to bolster understanding of historical baselines (Thurstan et al. 2015).

Federated data networks

Tagged data can be stored and connected through federated data networks, allowing researchers and managers access to diverse ocean data. Global standards allow disparate datasets to be queried and relevant information extracted (WEF 2019). A trusted broker creates and maintains the system, including access verification and other trust-promoting tools (Buck et al. 2019).

Federated data networks can be used to overcome commercial and other confidentiality concerns. They are currently being used successfully in several contexts. They have been particularly attractive to those in healthcare as they provide a way to access data without violating the many privacy laws that govern how health data are shared. Creating systems where the actual data are not shared, but instead external queries can gather the needed information from the data, allows researchers critical access to healthcare data while protecting the privacy of patients.

Data lakes

Where users are willing to relinquish some control over their data storage, data lakes can be included as nodes within larger federated data networks. Data lakes move data onto cloud architecture, which is designed to scale and bring data closer to the processing pipelines.

This type of computing architecture and the workflow pipelines running on top of these cloud solutions is not new. From early mainframes to the virtual machine operating system released by IBM in the 1970s, the concept of shared access to services has emerged and evolved because of the commodification of the entire Internet ecosystem (from microprocessors to services).

Data lakes rely on service-driven data schema rather than pre-defined schema used in “data warehouses” and are particularly promising for scientific data where compute needs are intensive and concerns over data privacy are low (Stein and Morrison 2014). This presents a significant change in the way data users access and use data by implementing, at scale, tightly coupled compute and storage, as well as services. This pipeline creates more efficient access to data and the ability to produce insights at scale.

Anticipated growth in observing technologies driven by advancements in radio telecommunications (5G, satellite and other radio technologies) pose significant challenges for data ingest and archive volumes that are growing exponentially. Distribution for the science community has become a logistics problem of moving assets in order to produce useable products. Efficient utilisation of a data lakes architecture places data close to compute and provides access to countless building block services that enable and expedite science discovery for data users.

Data lakes can enable new workflows that will change the way science is done across multiple domains. These new workflows will create new modelling approaches that help address algorithmic and analytical variability, which has led to reproducibility errors in the present system of science workflows. Adopting a cloud services approach through data lakes eliminates downloading and data transfers, thus allowing researchers and the public to interact and work with data directly, and move only the finished derived products or user experiences to achieve scale.

Data lakes present a path forward for the scientific community, and when built on universal tagging standards can be integrated into ocean data networks that allow automated data access and use for a diverse set of stakeholders. The United States Geological Survey (USGS) and National Oceanic and Atmospheric Administration (NOAA) have successfully transitioned some of their satellite remote sensing data into cloud-based data lakes, and have seen their user base rise exponentially as a result (NCE 2018). Data lakes can unlock new value by allowing users to analyse many data types and opening ocean data to a broader range of users.

Data lakes present a path forward for the scientific community, and when built on universal tagging standards can be integrated into ocean data networks that allow automated data access and use for a diverse set of stakeholders.

Together, tagging, federated data networks and data lakes offer the promise of vastly expanding the ocean data available, and broadening access:

- **Access to more data:** Data tagging coupled with federated data networks enables the liberation of data that are currently locked away because of security, commercial or privacy concerns. The most notable of these data are those collected by defence departments and private sector companies, many of which have collected robust, long-term datasets on ocean conditions for decades. These data are sometimes classified (in the case of defence departments) or confidential (in the case of industry), even when much of the data are on oceanographic conditions with no associated security risk. New standards for data tagging could allow data collected by industry and militaries to automatically be available to researchers, for instance, after any security or time embargos have been met.
- **Accessible to more users:** Tagging allows automation of data access and thus makes it both simpler and more efficient (Sweeney and Crosas 2015). Currently, researchers and managers rely on one-off agreements between parties to allow access to needed data. In robust tagged systems, these

As these solutions come online, governments and others must also ensure that data networks and lakes are accessible to everyone.

agreements can be built into the data from the beginning. If parties are verified research institutions, for example, data tagged with "academic research" as an allowable use will automatically be available to these institutions on specified terms.

This type of automated access also creates avenues for more equitable access to data. Currently, many marine datasets are in principle available to other researchers. In practice though, these datasets are often only shared with known research partners or top academic institutions. Executing complex Memoranda of Understanding (MOUs), which often take months to be agreed on, is an insurmountable barrier to entry for smaller institutions and resource-constrained managers.

When combined with the reach provided by federated data networks, automating data use can provide managers with access to actionable information as they need it. Specialised apps can be built on top of data networks that are tailor-made to address common management questions and provide robust knowledge solutions.

- **Access globally:** Federated data networks and data lakes can enable global data access for scientists, managers, communities, consumers and others, but it is essential that they are built with these goals in mind. Without coordinated efforts by governments, research institutions and technology service providers, there is the danger of these solutions becoming additional siloed pieces in an already fragmented ocean data landscape.

As these solutions come online, governments and others must also ensure that data networks and lakes are accessible to everyone. Federated networks and data lakes are promising in part because of the business models they enable, which allow data to be stored for free while the knowledge services built on top of the data, or the increased speed generated by storing data closer to computations, generate revenue. These models, discussed further in Section 4, can support widespread, free access to data. Governments must work with web service providers to ensure that these systems are fulfilling this promise and not just providing data access to those that can pay (Borowitz 2019). The data-scarce areas where additional data are most needed to guide marine management are also the ones that are least likely to be able to pay for data access.

Beyond ensuring equitable access to data, governments also need to address the important privacy and security concerns raised by open data. Network architectures must ensure that data integrity is protected throughout the data lifecycle, including quality assurance mechanisms that prevent false data from being added to data networks (Buck et al. 2019). As personal devices, such as mobile phones, and video monitoring tools are increasingly sources of data for ocean management, it is essential that the privacy of users is built into management systems. Additionally, as governments open up access to ocean data, they need to be mindful of potential social and economic costs – open access may provide a de facto subsidy to some private sector actors, for example, or provide avenues for policy influence to those that are best equipped to make use of the data (Johnson et al. 2017).

Opening up access to data will require new incentives for governments, companies and researchers to make their data available. Government can lead the way directly – by taking bold steps to help create and contribute to federated data networks. Governments can also require that a condition of access to public resources – whether the resources are fish stocks and mineral deposits or funds for coastal management or for research – is a commitment to sharing the data produced.

International cooperation around the UN Decade of Ocean Science for Sustainable Development (2021–2030) provides a unique opportunity for concerted action to overcome existing barriers and make real progress towards integrated ocean data (Ryabinin et al. 2019; UNESCO and IOC 2019). It is essential that this opportunity is not wasted.

3.2 Extraction of Information and Translation

Recent innovations are improving our capacity to translate data into useful information. Advanced processing techniques coupled with new visualisation portals enable a wide array of digital decision support tools aimed at providing actionable information to decision-makers (Lathrop et al. 2017).

Rapid advances in artificial intelligence and machine learning (AI/ML), including the emergence of deep learning methods such as neural networks and machine vision, have great promise for ocean data (LeCun et al. 2015). As the variety and volume of ocean data increase, there are similar efforts to use AI/ML tools to derive insights and, more importantly, predictions regarding complex processes, such as large-scale rainfall patterns or severe storms, and eventually even more complex systems that involve ecosystem resilience and human activities. For these complex systems, where deriving mathematical formulations and collecting reproducible data are extremely difficult, big data and AI/ML have become especially appealing.

Within the physical domain, AI/ML have shown potential as a means to substantially improve traditional methods for systems predictions. For example, the US Bureau of Reclamation recently sponsored a contest on sub-seasonal climate forecasting for rainfall patterns in the western United States. The best-performing team relied on AI/ML methods to outperform the benchmark forecast model (Soeth 2019). NOAA is developing a comprehensive strategy to integrate its enormous volume of data with its numerical models using AI/ML approaches to tackle long-standing challenges in Earth system forecasting, such as hurricane tracks and intensity (Bayler 2019).

Much of the appeal of these new methods rests on the fundamental difficulty of developing a mathematical framework for complex, multiscale processes. For example, the microphysics of clouds cannot be resolved at the scales possible in global climate models. Moreover, the processes are difficult to measure as well. However, these processes cannot be ignored and therefore must be parameterised. New methods rely on stochastic formulations of these processes, which are then coupled with the deterministic models of larger-scale processes (e.g. Palmer and Williams 2008). With the advent of AI/ML techniques, it is a fairly straightforward intellectual leap to move from stochastic/deterministic models to AI/ML models.

Phenomenal improvements in AI/ML have enabled better understanding of complex processes, such as language, than is possible with traditional approaches.

Phenomenal improvements in AI/ML have enabled better understanding of complex processes, such as language, than is possible with traditional approaches. This has led some scientists to claim that “big data” represents a new scientific paradigm (e.g. Hey et al. 2009). In complex, multiscale processes, AI/ML appears to overcome the challenges in understanding the linkages between these processes, where traditional scientific approaches have been unable to provide any conceptual foundation or mathematical framework. In fact, some have asserted that this means the end of the scientific method, which is based on the connection between reason-driven experiment (or data collection) and analysis based on mathematics and modelling.

Coveney et al. (2016) and Succi and Coveney (2019) provide an extensive review of the interplay between big data and the scientific method. These authors argue that “big data” must work in partnership with “big theory,” even when the work of mathematical formulations is difficult and slow. AI-based models are extremely fragile, rarely working outside of the specific data domain in which they are developed. Succi and Coveney (2019) note four key points:

1. Complex systems are rarely based on Gaussian distributions.
2. Complex systems are highly sensitive to small errors, so datasets are never "big enough."
3. Correlation does not imply causation, especially as the links become more remote as the size of the datasets increase.
4. Too many data are as bad as no data.

While we can expect AI/ML to help guide our observing systems and our analyses, we must continue with the fundamental science and mathematics of complex systems.

Beyond better forecasting and analysis of scientific datasets, AI/ML have also unlocked new potential for management. Advancements in computer vision, for instance, allow marine species to be automatically identified from video footage. This opens the door to a new era of electronic management in fisheries, replacing human observers – who are often harassed and in some cases even killed – with video cameras. ML algorithms can automatically review the video footage captured by these cameras to determine what species are being caught and whether vessels are operating legally, at a much lower human and monetary cost than taking observers on board.

More powerful AI/ML analysis techniques also support the creation of advanced knowledge products to support key ocean management needs.

More powerful AI/ML analysis techniques also support the creation of advanced knowledge products to support key ocean management needs. Global Fishing Watch, for example, provides a global window on fishing, by providing visualisation of fishing activity through the GPS devices (AIS) required on large vessels. Using ML algorithms to analyse the large amount of data coming from these vessels, Global Fishing Watch can identify when and where a vessel is engaged in fishing activity, classify the type of fishing, and detect other behaviours such as trans-shipments and potentially illegal incursions into protected areas. Similar techniques are being employed by a large new class of enforcement tools that use ML to identify illegal behaviour on the ocean. AI/ML capabilities are foundational to analysing the volumes of data provided by emerging technologies and newly networked data, supporting a new generation of knowledge products for managers.

AI has enormous potential to translate the growing flood of ocean data into information that is relevant – and vital – for research, and for the use and management of ocean resources. To realise the potential will require better access to data, through the federated networks and data lakes described above. It will also require innovations in ML. While current methods to train neural networks require vast labelled datasets, emergent methods are able to learn from relatively few labelled points (Reichstein et al. 2019). These methods provide a path forward for many ocean problem sets where the quantity of labelled data are extremely low. As these new methods come online, predictive modelling for ocean management will become exponentially more powerful.

Beyond issues of data availability, current ML suffers from intensive computational requirements. The future will see exponential increases in available compute power, enabling more powerful understanding of our ocean. However, increases in compute are fuelled by significant energy expenditures. The future of ML compute must come from renewable sources.

AI/ML solutions are currently highly tailored to specific ocean problems. For instance, image recognition algorithms are trained to identify individual fish species and may be very difficult to adapt to recognise other fish species. Computational and methodological improvements unlock new possibilities to move beyond hyper-specific ML prediction to generate new cross-cutting understanding of ocean conditions. Advances in modelling that combine ML techniques with physical modelling can combine both data-driven and theoretical insights to generate robust, interpretable results that are testable against physical realities (Reichstein et al. 2019). Applying these methods to broad datasets can move beyond single-problem insights to demonstrate new relationships between diverse ocean conditions.

While ML shows promise, there are significant issues of bias that also need to be addressed before it is widely adopted in management. ML outcomes are only as good as the data they learn from. Existing inequity can be exacerbated in cases where complex machine learning algorithms are being used to identify illegal behaviour (such as in the case of many advanced tools for monitoring illegal fishing) (Stas Sajin 2018). If, for instance, an algorithm looks at past enforcement actions to build a model that predicts the likelihood of future illegal activity, this algorithm will solidify any historical bias in which types or flags of vessels have been most often targeted for enforcement. AI/ML algorithms can also be susceptible to false or “spoofed” data. Small pieces of inaccurate or manufactured data can lead to erroneous results and inferences from these complex, but fragile, algorithms (Amodei et al. 2016). Emerging work in AI interpretability may help to overcome these issues by allowing managers to see into the black box of AI to identify systemic biases and to elucidate the basis for management outcomes so that they can be legally enforceable.

4. Harnessing the Technology Revolution to Transform Ocean Management

In recent decades, there have been important innovations in ocean management and in using markets to incentivise more sustainable use of ocean resources. Technological advances offer the opportunity to leverage those innovations, creating new capabilities, new incentives and new accountabilities (Table 1).

4.1 Public Management

Historically, the ocean has been managed as a public good. Public management has had limited tools, and has been constrained by politics, practicalities and a profound lack of information. The result of these limitations has been a reliance on regimes that are static and often crude, and that sometimes create perverse incentives.

Innovations in management

In recent years, there has been increasing emphasis on ecosystem-based management (EBM) for managing marine systems. EBM shifts away from traditional, siloed management of individual resources or uses to consider the ecosystem as a whole and the full range of human activities within it (Long et al. 2015). Successful EBM regimes require a wealth of scientific data to understand and predict the complex relationships and dynamics in marine systems. EBM must also be nimble in responding to changing ecosystems and stakeholder needs and interests, requiring an integrated approach to ocean management.

Two innovations in governance – dynamic management and rights-based management – have shown particular promise in aligning capabilities and incentives with sustainability. Emerging technologies can leverage these policy tools to increase the effectiveness of marine management.

Dynamic management: Ocean management has always been challenged by the fact that resources and conditions are constantly changing. With the increase in climate and other stressors, that challenge will only grow. Yet ocean management has typically been static – relying on fixed areas, seasons and catch limits. Dynamic management strategies allow managers to make near real-time adjustments as conditions change (Maxwell et al. 2015). In fisheries, this has meant a transition from, for example, static spatial limits on fishing that are set at the beginning of a season, to dynamic closures where the allowed fishing area can be adjusted based on the status of stocks, the presence of bycatch species and other key indicators. Dynamic management is the essential underpinning of a new generation of responsive, ecosystem-based marine spatial planning.

Technological innovations have made dynamic management possible. New tools for monitoring ocean conditions and for communicating with geographically dispersed resource users allow managers to make rapid decisions and disseminate them widely. In one striking example of dynamic management in action, a series of hydrophones were attached to buoys in the busy shipping lane approach to Boston Harbor. When the hydrophones detect the song of endangered right whales, this information is automatically transmitted to ships approaching the harbour and reduced speed limits are imposed (Laist et al. 2014). By allowing vessels to maintain high speeds when whales are not in the area, this approach reduces ship strikes on whales while maximising shipping efficiency. Other examples of dynamic management include the dissemination of real-time information on high-risk areas for turtle bycatch to fishers in Hawaii. A recent study found that in the California drift gillnet fishery, a highly dynamic fishery that is difficult to manage, implementing dynamic spatial closures could significantly reduce the percentage of total area closed to fishing to achieve the same conservation goals (Hazen et al. 2018).

Rights-based management: Policies that focus on shifting incentives to achieve management goals represent another important frontier in marine policy (Lubchenco et al. 2016). For fisheries, many jurisdictions have taken steps to better align the incentives of resource users with long-term sustainability by instituting rights-based management (RBM). RBM regimes seek to eliminate the traditional problems associated with common pool resources by assigning property rights in the resource to the resource users (Nyborg et al. 2016), either through quota systems that assign a percentage of fish catch to each user (Individual Transferable Quotas) or through territorial rights that give stakeholder groups exclusive rights to fish in a specific area (Territorial Use Rights for Fishing (TURFs)).

When designed correctly, RBM has proven to be a highly effective management solution (Lubchenco et al. 2016). To succeed, leaders must build consensus among stakeholders before policies are implemented. They should develop a regime that combines strong property rights with reputational and behavioural incentives and ensure that rights are protected with enforceable sanctions (Crona et al. 2017).

RBM is not a silver bullet to solve fisheries management, however. Some note that giving fishers a quota of fish stocks is not the same as a true property right, and may lead to continuing management issues in the future as incentives for fishers are not fully aligned with the long-term viability of the fishery (Bromley 2016). Others note that inequity may be reinforced by the distributional choices made in allocating quotas, which are often based on historical catches, rewarding those with the most economic clout (Guyader and Thébaud 2001).

For fisheries, many jurisdictions have taken steps to better align the incentives of resource users with long-term sustainability by instituting rights-based management.

Some systems have found creative solutions to these challenges. In some industrial fisheries in the Bering Sea, for example, a percentage of the fish catch is allocated to coastal communities as Community Development Quotas (Haynie 2014). Coastal communities are able to fish or lease their quotas to fishing companies and invest the revenues. These programmes have been successful in helping to alleviate some of the largest equity concerns around the privatisation of fisheries (Carothers 2015).

These new models of governance – ecosystem-based, rights-based and dynamic – are helping managers meet the challenges of managing the many pressures on ocean resources. New technologies – from more powerful sensors to smart contracts – offer opportunities to build on these policy innovations, creating a new era in ocean management that transforms both capabilities and incentives.

Making management robust and nimble

The years ahead will see significant advances in our ability to collect data on resource conditions and uses with high spatial and temporal resolution, and to translate those data into actionable information for users and managers. The continued proliferation of satellites and ocean-going drones will expand capability to monitor activities on and in the water. Video cameras on fishing boats and on nets will allow fishers to more precisely control their catch and will enable increasingly

These capabilities will become increasingly vital to effective, ecosystem-based ocean management as climate change and other stressors disrupt ocean systems.

granular management and accountability. Flocks of communicating sensors in the water will be able to identify emergent problems and swarm to investigate (Jaffe et al. 2017).

These capabilities will become increasingly vital to effective, ecosystem-based ocean management as climate change and other stressors disrupt ocean systems. It will be essential to have real-time information on ocean conditions to be able to manage heatwaves, shifting fish stocks, harmful algal blooms and other upheavals.

New technologies enable a better understanding of how humans are using marine ecosystems. Monitoring data on human use can guide enforcement efforts, allowing more targeted deployment of enforcement solutions focused on providing data in near real time that meets legal evidentiary requirements. New options, from drones that allow visual monitoring of distant water areas (e.g. ATLAN Space) to mandatory tamper-proof GPS-enabled devices on fishing vessels, provide this information to enforcement officials.

Real-time data supports integrated approaches to ocean management. Integrated ocean management (IOM) creates comprehensive management plans to reconcile competing uses of the ocean and ensure ecosystem health (See Blue Paper 14 on “Integrated Ocean Management”). IOM tools, such as marine spatial planning, are important pieces of the ocean management landscape but require extensive data on both ecosystem baselines and human uses of the ocean.

Technological advances could have profound value for helping fishing communities manage their resources. In small-scale fisheries, for instance, small GPS trackers enable fishers to accurately track where they fish each day. Apps like mFish allow fishers to use their smartphones to receive critical data on weather, market prices and other conditions, while at the same time using their phones to collect key data about what they catch and where. Fishcoin allows buyers to compensate small-scale fishers for collecting data they need, paying them in mobile-phone minutes through a blockchain. Blockchain technology can also help small producers connect to global supply chains.

A future of robust management based on better information is not assured. Even when relevant data are available, managers often do not get the information they need because data are not available to them, or because they do not have scientists working with the data to address the most policy-relevant questions (McConney et al. 2016). Even decision-support tools designed explicitly for marine managers are often so technical that only programmers are able to use them (Stelzenmüller et al. 2013). Non-governmental organisations (NGOs) and interdisciplinary research organisations have been important players in bridging the science–policy divide, allowing research priorities to be developed collaboratively with scientists and managers (Sutherland et al. 2011).

Automating management through smart contracts

In the next decade, technology will not only expand the potential for dynamic management regimes, but also open new frontiers for completely automated management. Dynamic management still typically relies on the human process of translating data into management decisions. Coupling dynamic management with the possibilities opened up by smart contracts, among other technologies, creates the opportunity to automate some areas of marine management.

In other industries, smart contracts are the cutting edge of regulatory compliance efforts. Smart contracts rely on verification – once the agreed conditions have been met, smart contracts execute automatically (Le Seve et al. 2018). For instance, smart contracts for travel insurance can automatically send compensation to passengers when online flight trackers report that their flights have been delayed by a pre-agreed amount. These smart contracts are generally based on distributed ledger technologies, so that they are immutable and tamper-proof. Automatic execution reduces opportunities for corruption and fosters transparency.

When these contracts are connected to environmental sensors, there is the potential to automate aspects of environmental management (Jensen and Campbell 2018). Smart contracts have already been used to facilitate peer-to-peer water management in Australia (Le Seve et al. 2018). Water rights are notoriously complex to manage and transfer. Smart contracts allow for easy transfer of water quotas between users depending on agreed upon conditions (for example, if a user uses less than their monthly allotment, a sensor can automatically detect this and transfer the remainder immediately to another party at an agreed rate). In the case of ocean pollution control, for example, sensors placed on ship exhaust could automatically fine companies when the concentration is above allowable levels.

Combining the technological innovation of smart contracts with the policy innovation of dynamic management has the potential to reshape how marine management functions. Replacing tasks that currently require human verification with smart contracts and other tools can free up management resources to be spent in more critical oversight functions that require human attention.

In fisheries, governments and industry working could create near-automated port entry systems based on increasingly powerful monitoring capabilities. This "global entry" system could provide expedited entry into port for fishing vessels that meet predetermined transparency requirements, such as sharing of AIS data, electronic monitoring on board the vessel, and release of information on permits and ownership. Fisheries agencies can use these data to ensure that the vessels are at low risk of illegal, unregulated and unreported (IUU) fishing, and in turn provide preferential clearance and processing while in ports. This type of system can incentivise good behaviour by fishers, while at the same time reducing the impact of corruption by port officials.

Box 1. Case Study – Preventing Bycatch

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) uses high-frequency (HF) radar data to understand the relationship between the sea state and the small Pacific bluefin tuna (< 30 kg) catch by the setnet. The observations are acquired in quasi real time, every 30 minutes, and are posted immediately (usually within one hour) as a surface current map on JAMSTEC website. These setnets are able to register when current patterns are likely to lead to mass bycatch of restricted tuna and alert the local fishers of the potential risk of young tuna entering their setnets in large numbers. The setnet fishers can, therefore, prepare themselves for releasing the young tunas based on the alert. See Appendix A for more detail.

Automated systems can also be used to strengthen mitigation measures. Timely detection and forecasting of environmental threats, such as storms, heatwaves and harmful algal blooms, can be directly linked to automated systems that pre-emptively protect ecosystems. These systems are already beginning to be used in storm water management: predictions of impending storms or detection of water quality parameters outside the normal range automatically trigger additional treatment measures to prevent nutrient loading (Klenzendorf et al. 2015; Lenhart et al. 2018), as well as in the power sector where heatwave predictions trigger cooling curtailments. This should be expanded to link real-time threat detection and forecasting to automatic mitigation action in other contexts. Threat forecasting for harmful algal blooms, for instance, has become highly advanced in order to prevent human health impacts. Linking bloom forecasts

Automated systems have the potential to make RBM an even more powerful, and more equitable, management tool by facilitating effective enforcement and efficient exchange of fisheries rights.

with automatic reduction in fertiliser application in neighbouring areas or increased water treatment could help to not just predict but mitigate these and other types of environmental threats.

Automated systems have the potential to make RBM an even more powerful, and more equitable, management tool by facilitating effective enforcement and efficient exchange of fisheries rights. Additionally, new tools like blockchain provide for new, more transparent and reliable ways to transfer quotas quickly without many of the transaction costs that have plagued these systems in the past.

Blockchain advocates go further, pointing towards a future of decentralised management and the complete disappearance of the state (Atzori 2015). With governance based entirely on smart contracts, they argue, managers are no longer needed to create regulations and ensure compliance. In the marine governance system a future where managers are completely removed from the picture is unlikely. Creating regulations is a complex process that involves negotiations among many stakeholders, coupled with an understanding of ecosystem dynamics, which requires human decision-making. Knowledgeable managers thus remain important. One can envision a future, however, in which much of the burden of implementation and enforcement is alleviated by automation.

There are hazards. Although blockchain-based options create immutable records, these records are only as good as the information put into them. Smart contract solutions thus must include robust measures for assuring the accuracy of the data upon which they depend. Stakeholder participation can be part of a data verification system (Jensen and Campbell 2018). If industrial permits, for instance, rely on the clean-up of certain environmental conditions, local stakeholders can verify that conditions have been met by submitting evidence such as photos.

Automated management also raises the spectre of a dystopian future where decisions are made based on complex and opaque algorithms with no human judgement. Governments should only adopt automated management when they have robust processes in place for dispute and review of automated decisions. Automated management should also only be applied to management problems where metrics are quantitatively verifiable (e.g. changes in ocean temperature) and results do not compromise fundamental civil liberties. These criteria need to be evaluated for each proposed application on a case-by-case basis. In the case of alterations to fishing areas or allowable gear types, for example, automated management can allow rapid, real-time changes as oceanographic conditions change without compromising protected legal rights. On the other hand, while AI algorithms can be used to identify probable illegal fishing vessels based on their behaviour, they cannot be a sufficient basis for automated enforcement action because the basis of the determination is unspecified and the consequences could be criminal liability.

Automated management can shift human management resources from routine, numerical determinations to more complex ecosystem-level analysis and decision-making. When coupled with stakeholder engagement, incentive-shifting and improved baseline data, automated and dynamic management will help to support successful ocean governance and integrated ecosystem-based management.

4.2 Harnessing the Market

In the private sector, the transparency and traceability enabled by technological advances can create new incentives for more sustainable practices.

Over the past 20 years, the Sustainable Seafood Movement has demonstrated the potential for market actors – including consumers, retailers, processors, fishers – to incentivise better management of fisheries.

Independent certification of fisheries and chain of custody through supply chains, such as through the Marine Stewardship Council, and ratings systems, such as Seafood Watch, help buyers to identify seafood from well-managed fisheries. A growing number of multinational companies have taken increasingly active roles in promoting sustainable seafood, including: retailers such as Walmart and Tesco; the leading tuna processors, through the International Seafood Sustainability Foundation; and 10 of the largest seafood companies, through Seafood Business for Ocean Stewardship (SeaBOS).

Table 1. Technology Enables Innovations in Management

		MANAGEMENT INNOVATIONS			
		Dynamic and automated management	**Integrated ocean management**	**Rights based management**	**Harnessing the market**
ENABLING TECHNOLOGIES	**Sensors**	In-situ, remote and vessel-based sensors enable highly granular observations of current ocean conditions	Autonomous vehicles, profiling floats and other new sensor platforms allow previously unreachable areas to be studied	Low cost sensors support community management of marine resources	DNA barcoding and other biotechnology tools can verify product identity throughout the supply chain
	Communication networks	5G networks and satellites enable real-time transmission of ocean data to managers and resource users	Acoustic networks, cabled observatories and satellite transmission can link distant sensors to shore	5G and cellular networks allow fishers and other resource user to access and participate in resource management	Apps that use blockchain can create an immutable record of product movement
	Data systems	Data lakes and federated networks provide access to the data from different sources needed to support dynamic management	Data lakes can give scientists access to unstructured data that supports many different kinds of analysis	Local data networks allow resource users to share and access relevant data on resource use and conditions	Federated data networks allow industry to share relevant data while respecting privacy and ownership concerns
	Data processing	Advanced modelling analytics support near real-time data processing and analysis	Machine learning enables new analysis of large and previously disparate datasets	Modelling can better predict resource use and allocations	Machine learning can be used to analyze large volumes of industry information for compliance
	Knowledge tools	Blockchain combined with near real-time sensor data can be used to create smart contracts that automate management decisions	Near real-time vizualizations of ocean conditions provide critical information for managers	Daily maps based on new data and modeling are being used in fisheries to maximize catch and reduce protected bycatch	Apps and other tools illuminate the supply chain for consumers at the point of sale

Source: Authors.

In recent years, growing consumer concern over fish provenance, coupled with corporate interest in supply chain control, have sparked significant momentum towards supply chain traceability. In 2017, 66 companies signed the Tuna 2020 Traceability Declaration, pledging that all tuna they buy will be completely traceable by 2020. More than 30 major companies, including SeaBOS, have signed up to the Global Dialogue on Seafood Traceability, specifying the key data elements to be collected in their supply chains and creating standards for IT platforms to ensure interoperability.

Many are looking to blockchain and other distributed ledger technologies to support supply chain traceability. As noted above, however, these systems depend on the reliability of the data on the provenance of goods entering the system, and therefore depend on the market creating strong incentives for driving transparency through far-flung supply chains (Hardt et al. 2017). Emerging technology offers the prospect of increasingly robust transparency – providing near real-time information on where boats are fishing and what they are catching – and traceability from the moment of catch to the supermarket shelf.

In recent years, growing consumer concern over fish provenance, coupled with corporate interest in supply chain control, have sparked significant momentum towards supply chain traceability.

Publicly available vessel tracking data are now being used to track larger vessels (Kroodsma et al. 2018). As more countries share the more granular data they already collect, and as satellite surveillance capabilities expand, a much larger proportion of the global fishing fleet will be tracked. Global Fishing Watch, for example, aims to expand its coverage from 60,000 vessels today to 300,000 by 2029. Continued progress in developing AI and ML tools to process data from video monitors and satellites will also expand the ability to monitor fishing activity. This growing transparency will be matched by continued improvements in traceability, through genetic tools, sensors and electronic tags or QR codes that can be used to track fish through supply chains and verify source and species.

These data systems have the potential to enable buyers, such as processors and retailers, to ensure that the fish they buy is legal and meets their environmental and social standards. Providing actionable information at the moment of the decision may also spur sustainable choices on the part of consumers. Apps at the point of sale can display these data for consumers, showing them where fish is caught and how it has been processed and shipped. Allowing consumers access to data on whether fish have been illegally caught or are contaminated with mercury or microplastics, for instance, could inspire more informed decisions.

Historically, fishers have closely guarded information about where they are fishing. High-level information on the most productive areas has been available for decades, however, leading to the globalisation of effort by the major fishing nations (McCauley et al. 2018). Global Fishing Watch and other platforms protect more granular information on where vessels are moving in response to daily fluctuations in fish stocks by placing a 72-hour delay on the release of vessel location.

Stringent transparency and traceability requirements can make it harder for small-scale fishers to sell into global supply chains. The cost of vessel tracking systems is already out of reach for most small fisheries. Low-cost traceability apps built on smartphones provide a promising option for these small-scale fishers, but companies will need to accommodate these types of solutions in their traceability systems. Agreement on global standards, like the Global Dialogue on Seafood Traceability, can also facilitate the development of tools.

As technology continues to improve and leaders in the seafood industry act on their commitments, there is the clear prospect that full transparency and traceability will become the expectation of the marketplace and the cost of doing business, and usher in a new era of accountability.

4.3 Ensuring That Technology Promotes Sustainability

Over the course of history, advances in technology have generally led to increased exploitation of ocean resources – more powerful boats and fishing gear have transformed fishing from a coastal activity to a global industry and driven many fish stocks into decline; deep-water platforms and drilling innovations have enabled massive extraction of oil resources and soon, possibly, minerals on the seafloor. The rapidly expanding capabilities in information technology described above could similarly accelerate exploitation – helping fishers track down every last fish, for example. These new capabilities thus come with two imperatives. The first is management – as the ability to exploit resources expands, effective management of those resources will be ever more vital. The second is accountability – information on resource conditions and use must be public, so that users of public resources are accountable to governments, to markets and to the public.

To realise the potential of new technology to support sustainability, it will be essential that these new capabilities are available not only to well-funded governments, companies and institutions, but also to governments and communities with more limited means. This requires both that ocean data are widely accessible and that the hardware and software to access those data are available and affordable. Low-cost technologies based on smartphone capabilities are one promising avenue, taking advantage of the increasing ubiquity of smartphones to allow both access to global information and the generation of locally relevant data. This can enable better management and increased accountability, and facilitate access to global markets. However, capacity-building is needed to ensure that the physical and intellectual infrastructure exists to support these advances in all areas of the globe.

In this report, we have focused principally on the explosion in new data on ocean health, resources and resource use – from new sensors and other sources – and the increasingly powerful technologies for extracting information from those data to enable research and action. Advances in genetics and biotechnology mean that those fields also have great potential to play a central role in sustaining ocean resources. Research on the genetics of coral, for example, is helping scientists identify species that are more resilient to heatwaves, and thus better equipped to thrive in a warming ocean. Researchers have developed new microbes that can break down plastics in the ocean or oil from oil spills.

Biotech may also have a role in mitigating the environmental impacts of aquaculture, including: the destruction of coastal habitats to build fish farms; pollution from the use of pesticides and antibiotics; and a massive increase in demand for fishmeal and fish oil, harvested from wild stocks, to use in feed. New strains of fish, bred to be resistant to disease can reduce the need for antibiotics. New plant-based feeds are reducing the need for fishmeal and fish oil.

Gene drives can eliminate invasive species and restore ecosystems by introducing altered genes that promote the inheritance of a certain genetic variant (in the case of invasive species, often a variant that makes organisms infertile) (Esvelt and Gemmell 2017). These solutions have the potential to eliminate invasive species populations that have wreaked havoc on ecosystems and been nearly impossible to control using conventional methods. However, introducing altered genes is akin to introducing another invasive species into an ecosystem – one that can invade any viable population with consequences beyond what we are capable of predicting.

Some innovators are now aiming to reduce overfishing by producing seafood without relying on fish. Companies, such as Finless Foods, Wild Type and BlueNalu, are cultivating tuna, shrimp and other seafood in laboratories. Cultured seafood has the potential to protect wild fish stocks while having a significantly lower overall environmental footprint and a reduced risk of contamination (a major problem in high trophic-level fish species due to the bioaccumulation of mercury and other heavy metals in wild populations) (Stephens et al. 2018)

5. Fostering Technological Innovations for the Ocean

Sustainable use of the ocean will require new technologies for researchers, managers, resource users, coastal communities, companies, consumers and others who have a stake and a role in ocean stewardship. Technologies that are important for ocean stewardship typically face significant barriers, however – debilitating start-up capital costs, regulatory constraints and lack of clear revenue streams (OECD 2019). Technological innovation in the ocean has therefore been largely driven by government and large-scale commercial interests. For some other needs, such as scientific instrumentation, small markets have often led to hyper-specific solutions that lack commercial applicability, creating an environment of technology lock-in. Many needs are simply unserved.

Overcoming these market barriers is critical to fostering successful innovation that supports science and management in the future. The landscape of innovation is complex. To capture the extraordinary potential of technology to enable ocean stewardship will require action by governments and others to create market incentives for innovation, as well as new public–private instruments for investment and new business models.

5.1 Creating Market Incentives for Innovation and Diffusion

Both governments and private actors have critical roles to play in incentivising the technological innovations that will be needed to safeguard the health and sustainable use of the ocean.

Governments

The history of environmental policy has shown that strong, technology-forcing regulations drive innovation. Regulations that place limits on pollution, such as automobile or powerplant emissions, for example, have repeatedly spurred technological innovation by industry to lower the cost of reducing emissions. In the same way, the International Convention for the Prevention of Pollution from Ships (MARPOL) has incentivised innovation across that sector. In addition, the recent International Maritime Organization mandate requiring the global shipping fleet to halve its greenhouse gas emissions by 2050 has already spurred major technological advances in vessel propulsion, creating the prospect that zero-emission vessels may enter into service by 2030. Similarly, government requirements for monitoring and safety provisions on vessels have created markets for technologies that enable companies to achieve and demonstrate compliance.

Government regulation can also be vital in driving the diffusion of new technologies into large-scale application. In recent years, for example, there have been many innovations that could significantly reduce bycatch in fisheries, but many have not been widely implemented. Stronger government restrictions on bycatch could quickly drive the widespread adoption of those solutions.

The ocean is a patchwork of regulatory jurisdictions, but experience in other sectors demonstrates that actions by individual authorities can nonetheless drive progress. Measures to promote the use of solar energy in Germany and a few other jurisdictions spurred massive innovation in that sector globally, for example. The US mandate that required shrimp catchers to use turtle exclusion devices (TEDs) led to global adoption and innovation in TEDs (Yaninek 1995). Individual governments can incentivise innovation in the ocean by adopting forward-looking technology-forcing regulations, without waiting for international action.

Specifically, governments should prioritise forward-looking technology-forcing regulations that target real-time monitoring of fishing, shipping emissions, mineral development, coastal development and pollution, and that create public accountability. Some technology solutions already exist in these areas. Government could radically increase innovation by building on these tools. In the case of fisheries, mandates by major seafood-catching countries (such as European Union countries, the United States and Japan) that all vessels use electronic monitoring, for example, could spur a wave of innovation, speeding up the translation of existing AI expertise from the technology sector to ocean management.

Governments can also drive innovation in less direct ways. The barriers to innovation are often information gaps: the technology community is unaware of the specific problems that managers need to solve, while managers do not have the technical expertise to know what solutions are possible. By bringing together managers and technology companies, governments can catalyse the development of innovative management tools that use readily available resources. For example, in the Caribbean, MPA managers and technology experts worked together to develop low-cost acoustic sensors that are being used, together with smartphones, to detect vessel activity in areas that are off limits to boats. When the sensors detect an acoustic signature, the mobile phones are programmed to send a text to local enforcement agencies, allowing effective, low-cost enforcement of MPAs.

Creating a national account for the ocean can make the economic benefits of innovation in the ocean clear. Current GDP-based models of national accounting do not effectively capture these benefits, and as a result ocean innovation is often undervalued. Using a suite of indicators to understand ocean production, income and sustainability can spur economic investment, innovation and stewardship (see Blue Paper 8, “National Accounting for the Ocean & Ocean Economy”).

Trade and import controls extend a government’s influence beyond its own territory. Requirements to ensure that imported products were legally produced or comply with labour or environmental standards spur innovations to create transparency and traceability in supply chains. The US Lacey Act, for example, has required importers to demonstrate compliance with the laws of producing countries. Under the EU 2008 IUU fishing regulation, the European Commission has blocked imports from countries with inadequate controls on illegal seafood products, and has issued “yellow cards” to others as a warning that imports will be blocked unless stronger measures are put in place.

Private sector

Crucially, private sector action can often play a similar role in creating market incentives for innovation. Over the past two decades, many global companies have begun to address issues of environmental impacts and labour conditions in their businesses and in the far reaches of their supply chains. The Sustainable Seafood Movement, described above, is a leading example. The Global Plastic Action Partnership is another. As companies drive changes in their own operations and raise standards for their suppliers, they create opportunities for innovators to develop technologies that can improve environmental performance or provide greater accountability and sustainability across supply chains.

Commitments by companies to transparency and traceability in their supply chains illustrate the potential. Companies are beginning to capitalise on the rapidly expanding capabilities for monitoring activities on the ocean – through remote sensing, for example, and video or other monitoring on board vessels and in the water – in order to gain greater visibility and stronger accountability across their businesses. In this way, they can drive both improvements in technology and reductions in cost, and these capabilities will then become increasingly available to less-developed markets. Similarly, growing corporate interest in traceability spawns new solutions, such as the recently launched blockchain platform OpenSC. Tech innovators partnering with NGOs and big seafood companies can extend that capability to small-scale fisheries, as Fishcoin is now pioneering, using blockchain to compensate fishers for the collection of key data on their fishing and enabling traceability.

Commitments by companies to transparency and traceability in their supply chains illustrate the potential.

International standards

Finally, both governments and the private sector can play important roles in setting the standards for technology that enable a fertile ecosystem for innovation. There are many examples of past collaborative efforts between the private sector, governments and academia to create new standards, but the Internet is one of the most useful examples (Abbate 1999). In this case, a government agency (the US Defense Advanced Research Projects Agency – DARPA) worked with a small number of academic researchers to create the basic structures of the Transmission Control Protocol/Internet Protocol (TCP/IP) to serve ARPAnet, the forerunner of the Internet. TCP/IP was then widely adopted by the Internet community as a result of a DARPA mandate to all of its contractors to use ARPAnet. The initial standard-setting by government, and the subsequent buy-in by the private sector, was successful in launching a standardised Internet platform and unleashing a wave of innovation.

International agreements can also play a role in creating global market demand for new technological innovation for the ocean. The Port State Measures Agreement (PSMA) by the Food and Agriculture Organization of the United Nations (FAO), for example, creates new requirements for port monitoring and control that are applied globally and that will require technological innovation in data collection and sharing to achieve. Agreements like PSMA also often include goals for technology transfer and capacity-building that commit governments to ensuring that developing countries have the same access to promising management solutions (Harden-Davies 2017).

International agreements can also play a role in creating global market demand for new technological innovation for the ocean.

5.2 Mobilising Investment

The current landscape of ocean innovation is centred in highly capitalised private sector industries, such as oil and gas, industrial fishing and shipping, and government-funded defence departments. This has been the case for the past century, and consequently many of the technologies now used by scientists and managers were developed under government defence contracts or for marine industrial use. Examples of this include many deep-sea submersibles and autonomous vehicles, with technological underpinnings pioneered by defence departments before being adopted by scientists. Similarly, innovations in the oil, gas and fishing industry that allow companies to work on submerged infrastructure or increase detection abilities of fish schools have been widely adopted beyond these industries. As with government defence efforts, these profitable industries are able to support significant research and development (R&D) expenses beyond what is generally feasible for marine researchers or managers.

This model has been successful in many ways. Capitalising on the market power of industry and government to develop technological solutions for the ocean has allowed scientists and managers to take advantage of innovation without high capital expenditures. The government model of investing in early-stage technologies has led to important advances. This happens both with investments through R&D programmes as well as through direct investment in the innovations needed for government purposes, particularly the defence industry. Both of these avenues have yielded critical marine innovations without which managers would have significantly less technological capacity than they do today.

Relying on the trickle-down of commercial and defence technologies is not sufficient to fill the needs of marine managers and other ocean stakeholders. For instance, gaps in information about marine ecosystems that are not commercially valuable may not be filled by technologies aimed at efficient oil extraction or target detection. The development of technologies to fill these gaps lags behind those incentivised by the strong market forces of industry.

Overall, environmental innovations have been notoriously underrepresented in the new wave of technological innovation. In the United States, for example, total federal expenditure on R&D is about US$125 billion. Of these expenditures, the amount spent on space flight and space research is about $10 billion; less than $2 billion is spent on the ocean sciences. Moreover, in the United States and elsewhere, government funding tends to go to early-stage research and dries up in later stages of development (OECD 2019).

In recent years, private investment has expanded beyond traditional marine industry R&D, with venture capital funding and start-up accelerators focused on ocean innovation. These avenues lag far behind the funding available in other industries, such as energy and healthcare, but provide potential avenues for scaling up technology solutions with strong business models.

Several specialised technology accelerators focused on the ocean are providing early-stage funding to innovative technologies that advance the sustainable use and management of marine resources (e.g. Katapult Ocean and the Sustainable Ocean Alliance). The start-ups funded are tackling issues ranging from seafood traceability to the development of bioplastics and wave energy. These solutions present important steps towards solving ocean issues in cases where innovation offers the potential for strong market returns.

Large prizes are also incentivising ocean technology innovation. These prizes are funded by a mix of individuals, companies and large foundations. XPRIZE, for instance, has been successful in incentivising the development of breakthrough technologies such as private spaceflight and autonomous ocean mapping robots. While these prizes have spurred important progress technologically, there are significant concerns about whether these developments will be able to scale given current market constraints (Kremer and Williams 2015).

Considerable academic research has been devoted to identifying the driving frameworks for innovation. These frameworks are complex, adaptive systems that rely on the participation of a wide range of actors, including public, private and research institutions. Other sectors provide a roadmap for what this ecosystem could look like. Agriculture has faced many of the same problems in technology innovation and adoption as the ocean has, including a fragmented producer landscape, lack of technology incubation support and high resource investment requirements. Partnerships that bring together a mix of institutions, from private sector investment to government incubators and philanthropic efforts, are able to overcome many of these barriers (WEF 2018).

> Overall, environmental innovations have been notoriously underrepresented in the new wave of technological innovation.

For the ocean, the Organisation for Economic Co-operation and Development (OECD) has specifically recommended bringing together a diverse group of actors to spur innovation in “ocean economy innovation networks” (OECD 2019). These networks provide many potential benefits by leveraging complementary innovations at different points in the innovation stack and by providing technology transfer to developing countries. These multisector approaches are more likely to foster complementary innovation that increases the potential impact and uptake of new technologies. By combining multiple technologies in layered systems, the impact of technologies can be exponentially increased (OECD 2019). For example, innovation ecosystems that allow developments in sensor processing to happen in parallel with new communication and platform tools both unlocks unique collaboration but also ensures that emerging technologies are plugged into larger ecosystems of innovation.

Technology clusters such as those recommended by the OECD have already been successful in moving innovation in ocean industries from early, government-funded stages to thriving multi-commercial markets. The Norwegian Centres of Expertise Maritime CleanTech cluster, for example, has been pivotal in driving the adoption of clean energy innovations in cruise and ferry lines. By creating a platform for collaboration between emerging players innovating in the clean energy space, established industry, and government and academic researchers, this cluster drove the development of the first fully electric car ferry, among other innovations in zero-emission and hybrid vessels. Moving forward, similar blue technology innovation clusters should be created to help emerging technology solutions achieve adoption and market penetration. On the other hand, although there is a plethora of these clusters, many of them have struggled to achieve sufficient momentum to be self-sustaining. In these early days, it is essential that governments focus on enabling market demand as well as market supply. Too often these innovation clusters rely solely on a "build it and they will come" model. Creating partnerships between market pull and market push is a role that government should be encouraged to perform.

Box 2. Case Study – Creating New Market Opportunities

In Japan, the declining number of operational fishing boats together with the declining number of fishers – due to ageing and other factors – is emerging as an important issue, especially for sustaining the exploration-type fisheries on the coast and offshore. For this reason, it has become more difficult to search for fishing grounds, and the fishers are forced to continue with their inefficient fishing operations. One of the solutions for bringing back the efficiency in the operation is to deliver highly accurate information about fishing grounds to reduce fuel consumption. With that aim, JAMSTEC started research and development on the advancement of fishery forecasting technology for squid, which is one of the most important species for the fisheries of Aomori Prefecture. The outcome was a squid fishing ground forecasting system that provided fishing ground information in real time, and was so successful with fishers that it was transferred to the private sector for routine operational distribution of the information.

5.3 Creating New Business Models

Beyond investment and regulation, innovation in business models can also create new ways to make the economics work to support data access and collection by marine managers and other stakeholders. There are also opportunities to further exploit existing market opportunities that are currently underdeveloped. Research in energy and other markets has shown that the pace of innovation is highly related not only to public investment in R&D, but also to market growth (Bettencourt et al. 2013).

The provision of ocean data by governments is viewed as an important public good, but the costs associated with this can be significant. In addition to the direct economic costs, additional indirect costs of open data include the potential subsidy of private sector activities and the creation of inroads for corporate influence, and the need to be considered in relation to the purpose and potential benefits of open access data (Johnson et al. 2017). For ocean and environmental data, several models exist to help support research and management databases.

Most existing research databases rely on public funding, from governments, universities or other research institutions, with a minority also generating revenue through use and access fees (OECD 2017).

The cost of storing large quantities of data can be prohibitively high. Several creative solutions exist though. NOAA, for instance, reached an agreement with Amazon Web Services (AWS) for storage of key ocean data. Having NOAA data on AWS servers brought data significantly closer to the computation needed to support key knowledge services – for example, weather forecasting – and drove traffic to AWS (Barr 2015). In return, NOAA was able to store petabytes of data on the AWS servers at no cost to the taxpayer.

Innovation in business models can create solutions that are able to meet both management and industry needs. Several approaches are showing promise.

Segmentation

Existing commercial markets for satellite data, for instance, are strong. Many new companies, such as Planet Labs and others, provide slightly degraded data free of cost to researchers. The cost of collecting these data is borne by the commercial entities paying for the data, and the degraded data are of sufficiently high quality to support research use. These secondary markets are important opportunities for ocean management and other uses.

Data services

Data networks can be supported by the knowledge products built using them. Already, ocean and climate data are being used as the basis for complex insurance decisions, targeted weather forecasts for precision agriculture, and other lucrative knowledge products. Companies like Descartes Labs and others have been successful in this model (Jensen and Campbell 2018). These "data as a service" models can also create opportunities to sustainably support research databases over time (OECD 2017).

Markets for data and knowledge services can also support new innovations for gathering data. Low-cost and distributed sensor systems that are able to gather data at very high resolutions, which directly support commercially valuable knowledge outcomes, for example, have clear market use.

Innovations in payment

Innovations in payment can drive data collection and traceability throughout the supply chain. Fishcoin, described above, is one example – paying fishers for their data with mobile-phone minutes. Other blockchain-based solutions in agriculture show promise in linking consumers directly to small-scale producers, allowing consumers to directly pay small-scale farmers, for instance, that use desired production techniques. Coupling these payment innovations with new data services can allow citizens to participate more directly in environmental conservation. In China, a tree planting app that allows citizens to donate money to reforestation efforts and then track their growth over time using satellite imagery has already planted over 13 million trees (Thompson 2019).

6. Opportunities for Action

We are poised on the threshold of a digital ocean. To realise that vision, and to enable a flowering of new capabilities to understand and steward ocean resources, governments, companies, researchers and civil society must each do their part. There are six critical steps:

1. **Capitalise on the UN Decade of Ocean Science for Sustainable Development to create a global data network that provides broad and automated access to ocean data.**

   Vast stores of ocean data currently in the hands of governments, researchers, industry and others can |be made available to all through data tagging, federated networks and, where possible, data lakes.

   a. UNESCO should build on existing efforts to establish global standards for metadata, query and data tagging that allow existing datasets to be interconnected and automatically accessed.

   b. Governments, industry and research institutions should use those standards to make their data broadly available in a global federated data network.

   c. Data holders and cloud service providers should collaborate to create data lakes within that network to facilitate access to large scientific datasets and enable development of new data services.

   d. Investment in capacity-building should ensure that these data are available, useful and affordable to all ocean users.

2. **Liberate ocean data.**

   Enabled by federated networks, data holders should establish a new default – that ocean data are broadly available to other users unless there are compelling security, proprietary or other interests.

   a. Governments should:

      i. provide public access to all data collected by defence and security agencies that can be shared without compromising security interests;

      ii. mandate use of AIS and share essential data on fisheries, including vessel ownership, licences and tracking for all fishing vessels; and

      iii. require that any user of ocean resources, such as fisheries, minerals or coastal land, is required to make their environmental data available to the public.

   b. Industry should make the environmental data they collect accessible to scientists, managers and the public.

   c. Scientific researchers should, by default, make their data available to all.

3. **Create an "Internet of Things" for the ocean.**

   Coordinated efforts by industry, researchers and governments can create advanced sensor networks that provide high-resolution, real-time information about the ocean to anyone who needs it.

   a. Governments should develop new open standards for underwater communications and positioning.

b. The private sector should work with governments and researchers to ensure that sensors are interoperable and data are generated in standardised formats.

c. Security and privacy standards need to be developed for terrestrial IoT systems, and these should be adopted for marine IoT systems as well.

4. **Automate ocean management based on near real-time data on ocean conditions and resource use.**

   a. Governments should expand use of dynamic management and, where possible, automate management with smart contracts. These solutions are particularly promising in fisheries management, where stock limits, fishing areas and allowable gear types can be automatically updated based on changing conditions.

   b. Governments should automate mitigation measures to create immediate responses to acute environmental threats, from storms to heatwaves to nutrient fluxes. Forecasts that show impending harmful algal blooms or storms, for instance, could automatically trigger reductions in fertiliser application and increased storm water treatment to proactively protect ecosystems.

   c. Governments and companies should collaborate to create mechanisms for data-based proof of compliance. A voluntary "global entry" system for fishing vessels, for instance, could allow expedited access to ports for vessels that provide information on their ownership, permits and activities to managers – creating incentives for transparency and compliance.

5. **Create incentives for innovation.**

   Existing markets do not incentivise many of the technological innovations that are needed for ocean stewardship and research. Governments and companies can change that.

   a. In regulating ocean activities, governments should design regulations to spur innovations that will enable more effective management, such as requiring real-time monitoring of fishing, shipping emissions, mineral development, coastal development and pollution.

   b. Companies should require full transparency and traceability in their operations and supply chains – to spur both better management of resources and innovation in technology, and enable consumers to hold producers accountable and reward better management.

   c. Governments should partner with the private sector to create innovation clusters in areas of market demand that support cross-sectoral collaboration and link emerging technology research and innovation with established industry players.

   d. Governments and companies should support innovative business models that combine commercial viability with support for management, such as governments and large companies who are buying data from, for example, private satellite and drone providers, making that data available in delayed or slightly degraded form for research and management uses.

6. **Mobilise capital for technologies for under-served markets.**

   Many markets for ocean technologies do not offer commercial returns. We thus need innovative financial instruments that can leverage the different expectations and risk tolerances of different investors. Governments, philanthropies and private investors should join forces to:

   a. create blended finance facilities that combine risk reduction, impact capital and market capital; and

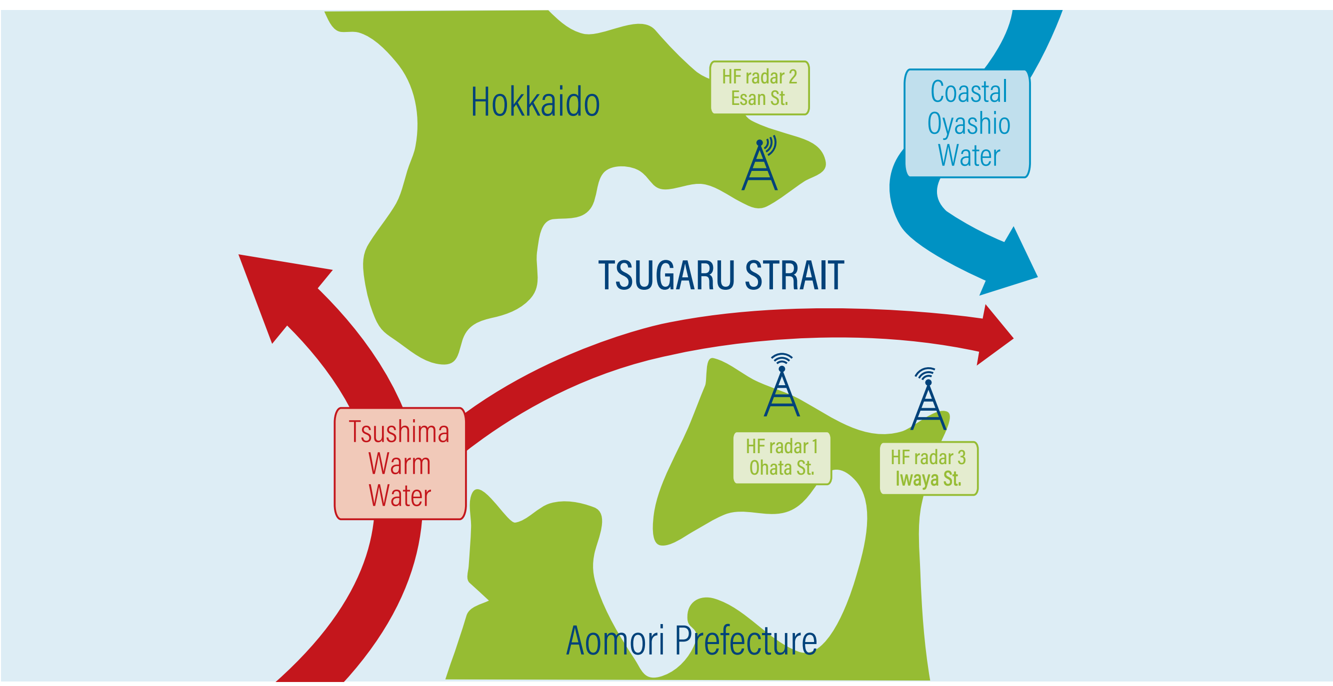
   b. invest in the development of low-capital technologies and training for developing countries, coastal communities, citizens and consumers to conserve, manage and sustainably use ocean resources.

Appendix A: Case Studies of Technology Deployment by JAMSTEC

The ocean, seas and coastal zones have diverse and vibrant ecosystems as well as other resources vital for the sustenance of human lives on Earth. In the spirit of sustainable management of these resources, scientists at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) have conducted a few pilot studies. In a specific case study, high-frequency (HF) radar data were applied to understand the relationship between the sea state and the small Pacific bluefin tuna (< 30 kg) catch by the setnet. JAMSTEC has been observing the spatial distribution of surface current velocity in the eastern Tsugaru Strait and the surrounding area since 2014 with an HF ocean radar system (Figure A1).

The observations are acquired in quasi real time, every 30 minutes, and are posted immediately (usually within one hour) as a surface current map on the JAMSTEC

Figure A1. Locations of the HF Radars



Source: Mutsu Institute for Oceanography (MIO)/RIGC/JAMSTEC (2019) website (http://www.godac.jamstec.go.jp/morsets/e/top/). The data are publicly available and the maps can be accessed by desktop or mobile/smartphone devices. An analysis of the website's access logs suggests that the fishers working in this area might be the main users of this website.

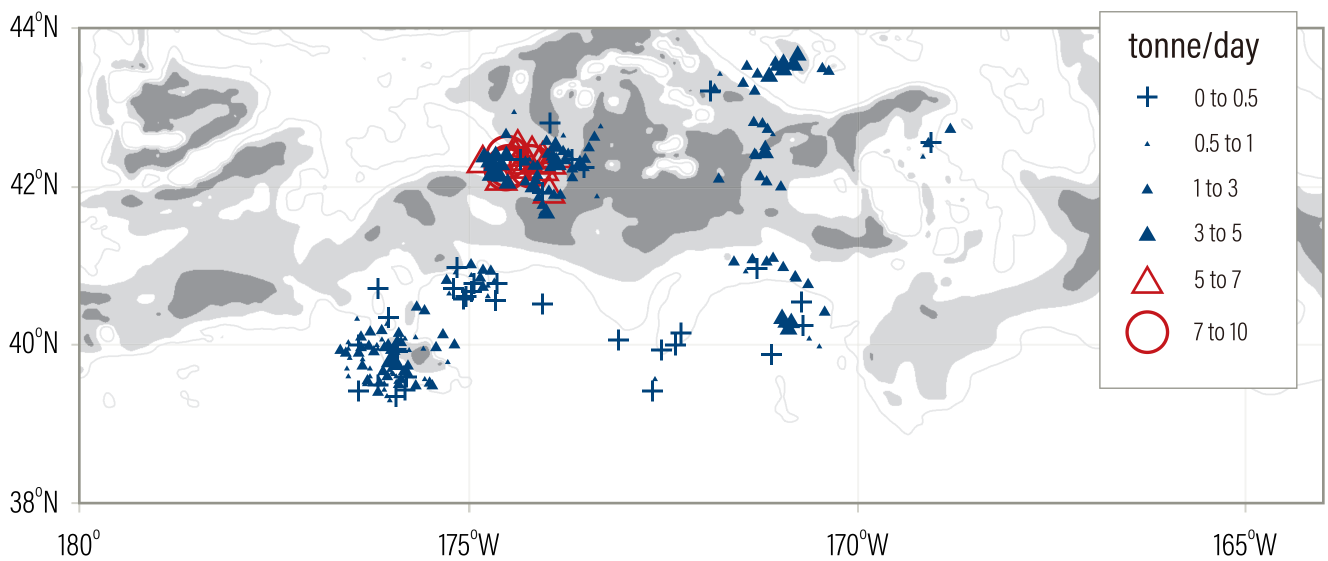
In the fall of 2017, mass bycatch of small tunas was registered by just two setnets near the HF radar measurement area. The surface current pattern observed by the HF radar at the time indicated a typical current pattern in this area. The catches of such small tunas are strictly restricted to maintain the stocks of the prized fish. Based on this pilot study, the local current data along the coast from the HF radar are now routinely used for safely releasing small tunas from the setnets. For example, when a surface current pattern similar to 2017 was observed in August 2018, a researcher at a local fisheries research institute, Hakodate Research Center for Fisheries and Oceans, immediately alerted the local fishers of the potential risk of young tuna entering their setnets in large numbers. The setnet fishers could, therefore, prepare themselves for releasing the young tunas based on the alert.

JAMSTEC researchers also try to apply the numerical simulation techniques to fisheries using a super-computer. The declining number of operational fishing boats together with the declining number of fishers – due to ageing and other factors – is emerging as an important issue, especially for sustaining the exploration-type fisheries on the coast and offshore. For this reason, it has become more difficult to search for fishing grounds, and the fishers are forced to continue with their inefficient fishing operations. One of the solutions for bringing back the efficiency into the operation is to deliver highly accurate information about fishing grounds to reduce fuel consumption. With that aim, in the financial year 2010, JAMSTEC started research and development on the advancement of fishery forecasting technology for squid, which is one of the most important species for the fisheries of Aomori Prefecture. In this research, JAMSTEC developed a squid fishing ground forecasting system and provided fishing ground information in real time. JAMSTEC conducted a demonstration experiment to deliver ocean forecasts to fishers through a web-based system. An ocean circulation forecast was conducted every week for two fishing seasons (June–August and January–March), a mathematical model was applied to estimate the fishing ground based on a statistical relationship between the ocean environment and the fishing ground and catches, and the results were provided to fishers through our website (Figure A2). In addition, fishing ground positions and fish catches reported by fishers in real time every day were used to fine-tune the model to reproduce the information in our predictions. This demonstration experiment made us realise that there is a strong aspiration from fishers to continuously receive fishing ground forecast information in real time. In order to meet the operational demand in real time and to maintain sustainable fishing, the developed technologies were transferred to the private sector for routine operational distribution of the information.

The declining number of operational fishing boats together with the declining number of fishers – due to ageing and other factors – is emerging as an important issue, especially for sustaining the exploration-type fisheries on the coast and offshore.

JAMSTEC is also operating a set of ocean state forecasting models on a super-computer targeting a wide range of spatio-temporal scales from global/seasonal to nearshore/hourly for various other marine applications. The seasonal forecast aims at representing the effects of global climate modes, which are important for seasonal forecasts of basin-scale sea surface temperature variations, obtained from several atmosphere–ocean coupled model forecasts. Nowcast/forecast operations of the ocean currents and the mesoscale eddies are performed by high-resolution ocean circulation models driven by atmospheric weather forecasting products. A main target region of the ocean current forecast is the

Figure A2. Map of the Potential Fishing Ground on 20 July 2012



Notes: The potential fishing ground and fishing points in the central North Pacific from 38 degree North to 44 degree North in latitude, from 164 degree West to Dateline in longitude. The fishing point and the amount reported by fishing vessels are denoted by symbols (plus, triangle and circle). The potential fishing ground is shown as the Habitat Suitability Index (HSI, contours), which is normalised between 0 and 1. The contour interval is 0.2. Light grey shading indicates HSI values over 0.6 and dark grey shading indicates those over 0.8.

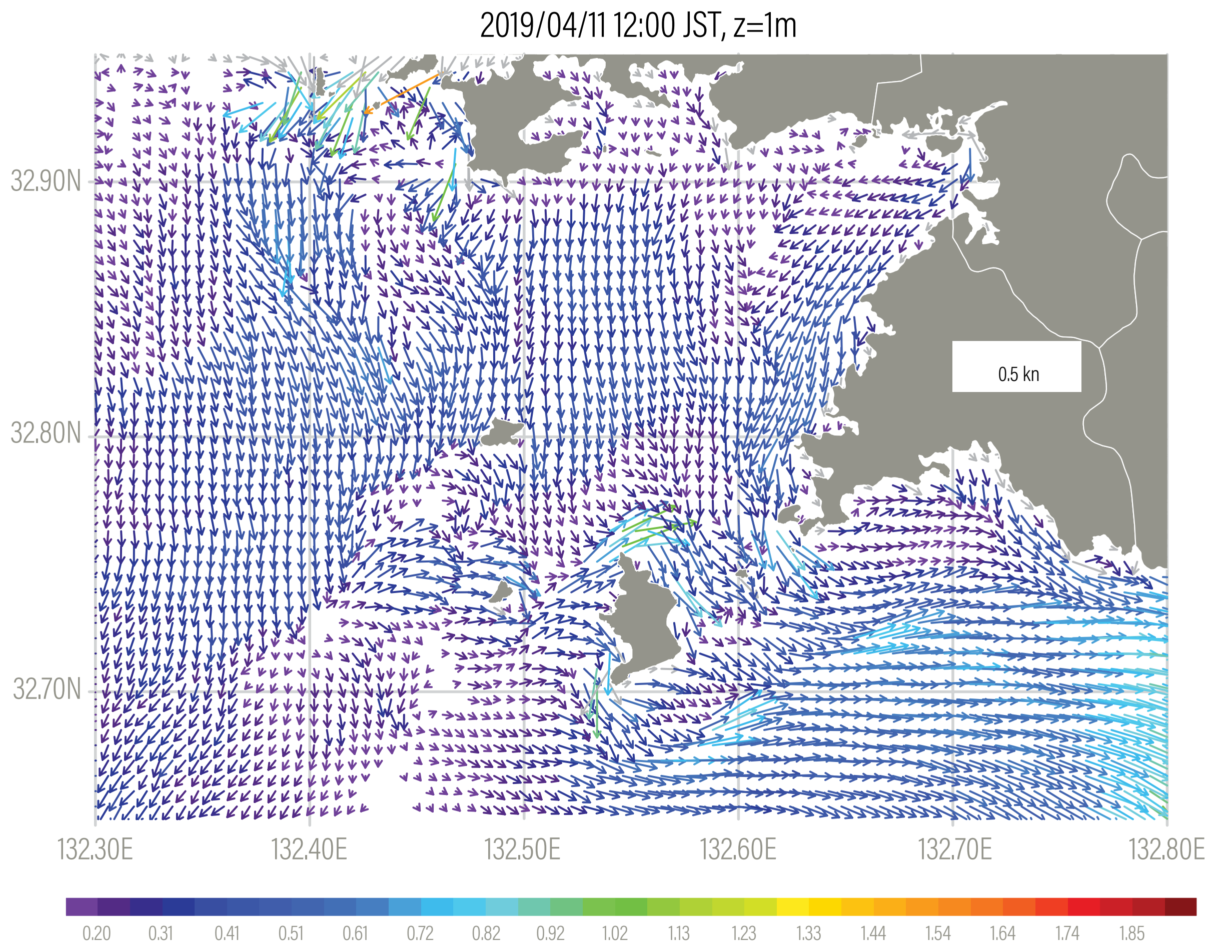
Source: Information Engineering Program (IEP)/VAiG/JAMSTEC

North Western Pacific around Japan. Detailed behaviours of the major ocean currents, including the Kuroshio/Oyashio path variations, are predicted every day, and the resulting information is provided to shipping companies for planning optimal ship routes and safe navigation. In addition, currents in some of the targeted areas are highly resolved by utilising downscaling techniques. Figure A4 shows an example of downscaling applied to Sukumo Bay, which is located in the Shikoku region of the western part of Japan. The local ocean currents in the bay are forecast every day with a 200-m resolution, and the forecast information is directly provided to the local fishers for their use (In Japanese) (http://www.jamstec.go.jp/jcope/vwp/sukumo500/).

JAMSTEC has from time to time held meetings with the fishers of the area, to exchange views and to explain the coastal environment based on our research results. Based on the outcome of these discussions on such occasions, it became apparent that local fishers wish to stabilise their profit rather than maximise the catch; in other words, they wish to ensure production consistency. More specifically, some of their desires are to:

- reduce the number of days with no catch, which would prevent wasting fuel;
- avoid extreme over-catch to avoid the fall in prices; and
- avoid catching juveniles to increase cost-effectiveness.

Figure A3. Map of the Potential Fishing Ground on 20 July 2012



Notes: Arrows and colours indicate direction and magnitude (in knot) of surface ocean currents, respectively.
The figure shows surface current

Source: APL/VAiG/JAMSTEC

All these desires are key to sustainable fishery and it is very impressive that fishers have already recognised them through personal experience. To achieve such a sustainable direction, fishers have requested that JAMSTEC provide the following information and data in real time for their operations:

- Three-dimensional distributions of temperature, currents and current-rip from a few hours ahead for coastal fishers to a few days ahead for offshore fishers, to avoid going to an unsuitable area for fishing
- Positions of “hot spots” of specific fish species to avoid over-fishing
- Details of spawning grounds and juvenile habitats to avoid fishing there

JAMSTEC is now at the initial stage of such R&D to meet these requirements and hopes to provide those data and information to the fishers in the near future. In spite of the enormous scientific and technical challenges, research towards such a sustainable goal should be one of the most important missions for science and societal well-being. Therefore, JAMSTEC researchers are now exploring the possibility of forecasting surface current velocity several hours ahead in the Tsugaru Strait by harmonic and pattern analyses as the first step to respond to the requests of local fishers.

A more comprehensive real-time data acquisition system from wider areas of the ocean, as well as advanced simulation models, is required to produce practically useful forecasts. In order to realise such a system, the development of lightweight automated observational instruments (sufficiently easy to use that they can be mounted on fishing boats) and the improvement of technology in data aggregation, processing, large-scale high-speed computation and information distribution services are indispensable. Furthermore, there is a scope to develop overseas non-commercial and commercial applications in the future after domestic operationalisation of the system and its nationwide adoption.

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Abbreviations

AI	artificial intelligence
AIS	Automated Identification System
DARPA	US Defense Advanced Research Projects Agency
EBM	ecosystem-based management
FAO	Food and Agriculture Organization of the United Nations
HF	high-frequency
HLP	High Level Panel for a Sustainable Ocean Economy
IOC	Intergovermental Oceanographic Commission
IOM	integrated ocean management
IoT	Internet of things
IUU fishing	iIllegal, unreported and unregulated fishing
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
ML	machine learning
MPA	marine protected area
MOU	Memorandum of Understanding
NOAA	United States National Oceanic and Atmospheric Administration
OECD	Organisation for Economic Co-operation and Development
PSMA	Port State Measures Agreement
R&D	research and development
RBM	rights-based management
SeaBOS	Seafood Business for Ocean Stewardship
TCP/IP	Transmission Control Protocol/ Internet Protocol
TED	turtle exclusion devices
USGS	United States Geological Survey
VM	virtual machine

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