Digital Oceans

Artificial Intelligence, IoT, and Sensor Technologies for Marine Monitoring and Climate Resilience

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DeepScience

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Preface

Oceans cover over 70% of our planet's surface and play a pivotal role in regulating climate, supporting biodiversity, and enabling global commerce. Yet, despite their significance, our understanding and monitoring of oceanic systems remain limited—largely due to the vastness, variability, and inaccessibility of marine environments.

In recent years, the convergence of Artificial Intelligence (AI), the Internet of Things (IoT), and advanced marine technologies has enabled a transformative shift in how oceans can be observed, analyzed, and understood in real time. This book aims to serve as a comprehensive reference and guide for researchers, engineers, environmental scientists, and maritime professionals who are leading or supporting this digital evolution of the oceans.

The book is organized into nine chapters, each addressing a critical dimension of the smart ocean ecosystem—from sensor architectures and AI-based forecasting models to marine pollution detection, ethical concerns, and future technological trajectories. It incorporates practical case studies, global initiatives, and emerging standards to ensure relevance across academic, industrial, and policy-making domains

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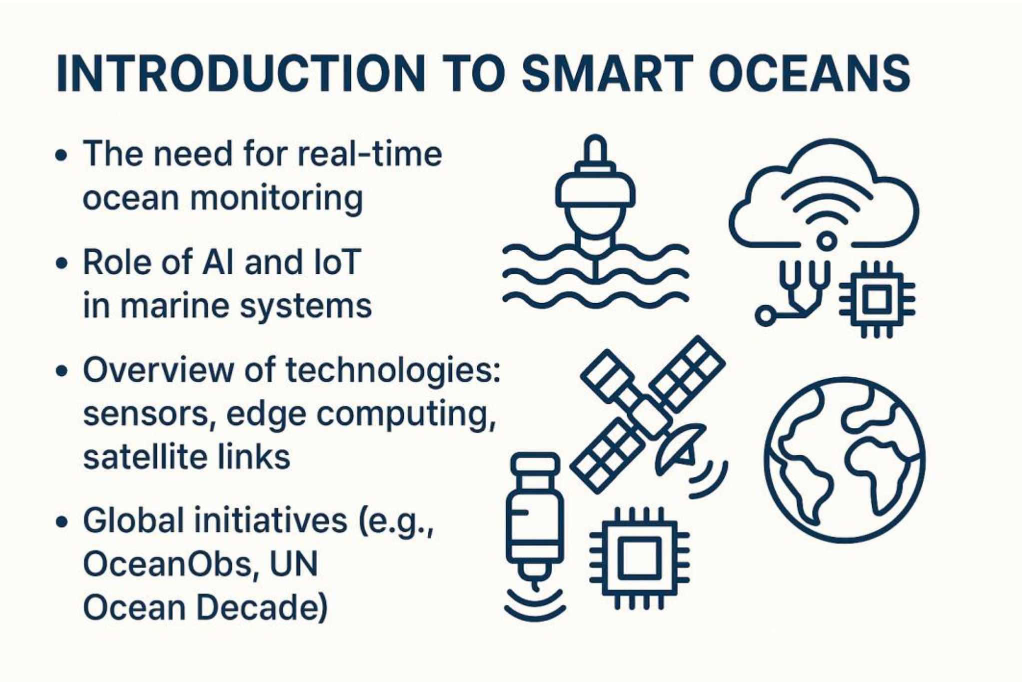
Chapter 1: Introduction to Digital Oceans

1. The Need for Real-Time Ocean Monitoring

Real-time, continuous ocean monitoring or ocean observation is essential for a number of reasons. Firstly, the oceans cover approximately 71% of the Earth's surface. This vast expanse may be remote and hard to reach, but it has a huge impact on global weather and climate patterns as well on the life and activities of humans inhabiting the land. When referred to as Global Change, the fast changes in the Earth's natural systems that are now of utmost interest to the entire world include sea level rise, increasing ocean acidification, ocean dying due to loss of oxygen, melting polar ice caps, increasing frequency of cyclone, hurricane and typhon gestures, coral reef erosion and general loss of biodiversity, desertification, and glacial recontras. Many of these changes are due to the rise of the levels of greenhouse gases in the atmosphere, particularly carbon dioxide, resulting from man-made burning of fossil fuels, or alterations in the natural systems of the Earth due to man-made or natural influences. As a result of the alarming increase in frequency and severity of unsafe global change phenomena such as tsunamis and cyclones, and changes in weather and climate patterns, continuous monitoring of the oceans is becoming increasingly important.

Technology advancements made it much easier for humans to communicate instantly with each other, confer information and share progress in all fields. Ironically enough, this technology could not be easily made to operate for the oceans simply because it was too challenging to deploy and maintain the systems. So far, monitoring of the oceans was mainly done through periodic sampling by research vessels, or acquisition of limited information from satellite remote sensing, equipped with sensors that could only acquire surface information. However, it was only in certain regions where the ships could go or where the satellite sensors could focus that any meaningful data could be collected. These methods are inherently slow compared to real-time communication devices such as radars. While the talk was going on in computers, sensors in satellites and radars observing the atmosphere of the Earth, there were no systems that could provide similar data for the oceans.



2. Role of AI and IoT in Marine Systems

The oceans are an important factor in climate change; however, we have very little knowledge of what is happening there. What we do know has been learned essentially using traditional instruments and research ships, which are relatively few and move at seas at low speed, returning data that is, on the whole for geographical logistic and economic reasons, relatively sparse and sporadic in time. The big data revolution allows the oceans to be studied better with many more data from many more sensors, returning knowledge that were until recently impossible. Such knowledge is important not only for science, for understanding the evolution of life on earth, and what we need to do to understand it better, but also for society, which has maritime activities that have economic repercussions. The combination of sensors that are installed at sea or on ships, make large numbers of observations and transmissions of data either to shore or to satellites returning data, and algorithms that analyze the data allow large amounts of information to be derived from them. This allows us to advance in the knowledge of oceanic dynamics and the improvement of services such as shipping, risk management such as tsunamis, cyclones, pirates, or pollution, surveillance and defense of coasts and deep waters, tourism, or support for infrastructure maintenance. Smart Oceans is important in the use of new approaches based on AI, ML, DL, and econometrics, which learn parameters from Big Data and extreme statistics that so far are not understood or only very crudely estimated.

3. Overview of Technologies

3.1 Sensors

Sensors are used in many Digital Oceans applications to gather data on environmental conditions, chemical properties, marine mammal populations, and equipment performance. A wide range of different sensor types are available, including: optical, motion, conductivity, magnetometer, interferometer, meteorological, pressure, ADCP, hydrophone, bioluminescence, and eDNA sensors. These sensors are often characterized by their size, power consumption, and sensing capacity. Size and power limits depend on whether the sensors are mounted on mobile buoys and autonomous vehicles or on powered vessels. Performance limits are set by noise, baseline accuracy, and temporal and spatial resolution, all of which vary within and between sensor classes. Historically, many sensors were designed to be used in conventional data collection experiments. When sensors were deployed on cabled and underwater autonomous vehicles, they were often continuously sampled. More recently, the emergence of low-cost commercial sensor packages and low-power vehicles and buoys has allowed researchers to collect data in the ocean on time scales that were previously impossible. For example, commercial electrochemical sensors can measure oxygen tension, macronutrients, and trace elements every 30 minutes. Autonomous surface vehicles equipped with cameras can continuously map the ocean surface in visible and infrared wavelengths. The scale and speed of these combined sampling efforts have transformed understanding of the ocean’s spatial scale and variability, but challenges remain on how to best relate hyperlocalized, rapidly varying observations with slower, basin-scales ocean conditions.

3.2. Edge computing

Edge computing is a distributed computing paradigm that reduces latency and improves performance by processing data closer to its source rather than relying solely on a centralized cloud server. This architecture is well-suited for smart ocean applications where real-time decision-making is essential and communications are intermittent and expensive. In recent years, systems adapting edge computing principles have proliferated in smart ocean applications, especially in examples that manage scarce bandwidth by transmitting first at the edge. Bandwidth is limited for ocean environments because there are few cell phone communications volume. Adopting edge computing not only aligns with these constraints; it is also arguably more efficient by offloading some of the processing tasks to smaller devices, comparing favorably to a traditional cloud-centric architecture. Designing new hierarchical models that balance processing loads among devices and servers with varying capabilities is an emerging area of study.

One concern unique to ocean edge computing is how to manage distributed devices, which might be sea-surface buoys, subsurface floats, or sensor networks installed on seafloor or moored mounts. Each device may perform edge processing yet also upload results and model inputs for distribution. Doing so would centralize oversight on the cloud, but with intermittent communication, devices must know when to wait for uploads, how to prioritize their data, and how to minimize the overhead during upload opportunities. Portioning model inputs across multiple devices would reduce communication loads. Charged and pre-empted by each device's battery life, devices might also startup, run, then submit models perhaps only seasonally. Overall, ideas from coalition game theory, data fusion, and distributed routing in sensor networks will help cover these facets of edge computing in the Digital Oceans.

3.3. Satellite Links

Satellite Internet and cloud computing resources are necessary to make Digital Oceans a reality. Ocean regions located far from land and not serviced by traditional commercial telecommunications mostly are left out from the digital world. Satellite communications technology has matured, bandwidths and number of satellites increased dramatically in recent years, to the point where established and new operators are now offering low-latency, high-bandwidth solutions to challenging geographical areas. Large sections of oceans are now reachable with fast and inexpensive Internet links.

Several disruptive new developments are at different stages of maturity. Mid-density but higher power satellites operating in Ku-band are beginning to offer commercial services, with big low Earth orbit constellations. LEO constellations reduce latency considerably; at the same time, they employ techniques to avoid the jamming and noise that LEO satellites suffered from in the past. Programs are looking to build more powerful and selective connectivity systems with larger high density satellites and Ultra High Frequency band. While these very small satellites won't be able to deliver full broadband Internet for the time being, they do have a niche covering areas with small to mid-density traffic requirements. Finally, small satellites are being explored by mobile operators.

4. Global Initiatives

There are a number of international/global initiatives working to support possible implementations of some of the concepts described in this book. This chapter introduces two initiatives that are related to our work. First, the OceanObs community is a major ongoing global activity around ocean observing systems. Second, the UN Ocean Decade initiates programs for societal transformation for the ocean. Both of these organizations work at an international level and deal with many different topics related to the ocean. These organizations are likely to be in alignment with some of the specific initiatives that may be created on the timescale of the Decade.

OceanObs is a convening activity of the ocean observing community for the design and evolution of the global ocean observing systems. It happens every two years through a conference, which results in a large number of white papers that collectively describe our vision for the development of the ocean observation systems. The initial OceanObs conference, held in 1999, first brought together the satellite and in situ communities towards a more integrated approach to supporting societal activities. It was at that event that we first used the term "Integrated Ocean Observing System." Because of the interest expressed by conference participants, a conference proceedings volume was published. That volume brought significant attention to that first conference and its main messages and helped attract support for the next conference, which took place in 2001. These two conferences initiated a series of conferences that include OceanObs'03, OceanObs'09, and OceanObs'13.

4.1. OceanObs

Sustained and comprehensive ocean observations, data synthesis, and predictive capabilities are critical for addressing urgent societal needs and drawing benefits from the ocean. Effective action requires science that supports sound decision-making in a timely, regular, and reliable way. The commemoration of the launch of the Global Ocean Observing System renewed commitments for sustained and comprehensive ocean observations organized in an internationally-coordinated Ocean Observing System.

Initiated in 1999 and culminating in international planning meetings, OceanObs is the primary international forum for stimulating the design, implementation, and coordination of the Global Ocean Observing System. The OceanObs meetings are convened every two years to review experiences with ocean observations; enable collaborative development of ocean observing priorities and requirements and the collective development of strategies for meeting those requirements; and motivate the development of innovative, sustainable, and equitable ocean observing systems. The next in the OceanObs series will be hosted in 2025 in Paris.

A first requirement is to promote the partnerships and effective action that are essential to enable a sustained and comprehensive GOOS underpinned by long-term collaborations involving space agencies, national and international ocean observing agencies, philanthropic foundations, the private sector, academic and research institutions, Indigenous and local knowledge-holders, and the wider coastal and ocean business community. Further requirements concern sustained and comprehensive GOOS delivery. These include setting and implementing international ocean observing priorities, policies, and protocols; enhancing equitable access to ocean observation data and products, and supporting data assimilation and model validation and calibration; and enabling innovation, adaptability, and readiness to meet new challenges as they arrive.

4.2. UN Ocean Decade

The Decade is a common program that brings together a broad community to fully connect for the first time in a century to a unified charter for global ocean and marine geography, research, and observation to peer into the future. The

2030 Agenda for Sustainable Development emphasizes the need to strengthen the knowledge base through the Decade, "in particular at the scientific level, to inform decision-making, strengthen resilience, develop solutions and build partnerships". The Decade's vision is to create the need and capacity for the development of sustained ocean and coastal observations and research by spearheading an innovative process to develop the research, ingredients, and institutions to empower Member States, regional entities, and experts to use this toolkit to overcome global challenges of sustainable development.

Understanding the ocean's warnings of impending danger is key to responding to disaster mitigation needs. The need to engage and empower people is key to developing sustainable and committed partnerships and collaborations. Progressively identify priorities of the partner countries and achieve tangible results of deploying observations-decision-making-collaboration-science partnerships locally, collaboration, and state-of-the-art observations and results. Connect diverse national and international ocean science communities working on scientific warm and cold water hooks and specific ocean observation applications and political goals. Create a multidisciplinary ocean with sustained open access for baseline scientific and societal-informed marine research and observations covering the ocean in a continuum from modeling feasibility for all vertical oceans, forecasting response to the 2030 Agenda for Sustainable Development Goals while enabling all of the nations to adhere to their respective Charters of Collaboration.

5. Challenges in Ocean Monitoring

Ocean monitoring remains a challenge, and there are many reasons why the solution to this problem is presently difficult to implement at scale. The first reason is the state of the art on ocean monitoring technologies. There are some observational technologies available on the market. The most prominent ocean monitoring solution is the mooring buoy. Mooring buoys have been widely used for different purposes through many decades. The buoy operates typically as a floating platform that supports a variety of sensors that have been deployed at different depths in the water column. Some parameters monitored by systems of multi-depth marine mooring buoys include the meteorological, wave, sea surface and underwater currents, and sea surface and underwater physical and optical properties. However mooring buoys are relatively expensive, hard to deploy, and have some important constraints such as reducing the accuracy of wind field measurements, considering that they are point measurements that do not capture the wind field variability, and additionally have a limited survival time.

Remote sensing is an important alternative to monitor the oceans, with several satellites continuously acquiring images of different parameters of interest. One important limitation of several remote sensing techniques is that they are only able to address some specific physical and chemical parameters, such as color, temperature, current, and velocity surface maps with low resolution in the spatial and temporal variability. However, there are some gaps in space and time, and given the limitations and constraints, satellite data is not enough to properly monitor the oceans. Given this scenario, there is an urgent need to develop new ocean-concept designs that are able to overcome the limitations of previously described approaches. The ocean sensor networks concept is one of the most promising solutions to address this challenge.

6. Data Management and Analysis

Managing data from smart ocean activities and projects may be challenging - including storage, access, analysis, and integration of the sensor content and other data sets. The following principles may help the activities and project leaders to better manage the data for their projects.

Data Management Plan. Projects should include a Data Management Plan explaining how the data will be stored, made available, preserved, and shared among the researchers and with the general public. The data may require substantial storage and network transfer capacity, personalized access, complex file structure organization, financial resources for archiving, shared-data long-term durability, as well as providing access and sharing procedures.

Pay Attention to Metadata. The data sets should contain extensive metadata – data about the data – for enhancing their discoverability and analysis. The power of the data lies in the capability and techniques that will be developed to analyze and visualize the immense volume of dynamic ocean-related data from diverse sources. Analysis and visualizing techniques impose constraints on how to store and structure the information. These techniques should be selected in advance, and indeed the capturing and storage system should optimize the data structures for the intended data analysis and visualization.

Harmonize the Data. The integration and fusion of diverse data sets – from different areas of the oceans, research projects, sensors, and organizations – can generate new knowledge and visualizations that would not be possible based on separate data content. Interaction between the various ocean data holders should be encouraged to discover the best ways to combine their services. In particular, the data holders should agree on data structuring and organization conventions, especially for the standardized metadata and the sensor and platform data description models.

7. Impact of Climate Change on Oceans

Climate change can no longer be regarded as a distant foreboding. Its impacts are echoing through the environment, increasingly influencing weather patterns, augmenting water levels, and shifting ecosystems around the world. As much as 94% of the excess heat trapped by greenhouse gases has been sequestered in inherently volatile ocean waters, triggering profound alterations within global currents systems, prompting melting glaciers and polar ice caps, and evidencing devastating climate events across the planet, from extreme droughts to lingering floods. It has also conspired in the rise of natural hazard events, petrifying non-linear predictions of future catastrophes. Climate change impacts the entire ocean and its associated systems, from coastal evolution to marine ecosystems and natural resources.

The ocean plays an essential role in life on Earth, regulating weather and climate, connecting countries and continents, hosting and nurturing manifold living organisms, storing vast quantities of energy and carbon, and providing resources and services for many societies worldwide. However, we are rapidly destabilizing the balance of this ostensible infinite blue system with anthropogenic emissions of greenhouse gases. Climate change impacts are expected to alter many of the physical and ecological properties of the ocean throughout this century and beyond. Physical changes due to climate change already observed or projected for the future include ocean warming and this will continue, with broad implications. The ocean has absorbed about 30% of the CO2 released by human activities since the 1750s. These changes are fundamentally altering the fundamental properties of the ocean. The ocean stores about 93% of the heat accumulation due to anthropogenic greenhouse gases. The loss of ice by melting is the cause of sea level rise.

8. Marine Biodiversity and Conservation

The ocean is Earth's last biological frontier, and home to the largest diversity of life inhabiting a variety of environments, including extreme habitats such as dark ocean trenches and hydrothermal vents. Marine life supports and regulates global climate and weather patterns, and provides enormous wealth in the form of marine resources and services; all life on Earth depends on it. However, the multitude of species and ecosystems that make up marine biodiversity, and perform essential functions for the well-being of humanity and the planet, are being lost at an unprecedented rate due to extensive human activities. These pressures are then exacerbated by the accelerating impacts of climate change. A better understanding of global and regional patterns of marine biodiversity and how biodiversity responds to anthropogenic pressures, however, is possible thanks to the robust, sustained, long-term and repeatable ocean observations that are performed by the ocean observing community. Observational activities may be augmented by the success of scientific maritime voyages of exploration, provided by today's Ocean Big Data, assisted by Artificial Intelligence.

The conservation of marine biodiversity is now a priority for many nations around the world, with ambitious national and global targets to expand the area of ocean protected from human activities, adopting policy frameworks, and encouraging public-private partnerships, while trying to ensure that these efforts are adequately planned, financed, and managed. Novel solutions to support the Blue Economy are being explored to foster sustainable development, and therein and through corporate social responsibility, sub-national and decentralized government engagement, citizen science, and international collaboration, spatiotemporal aliasing of the observing networks can be alleviated. Addressing these challenges, while guaranteeing equitable real-time access to Ocean Big Data for all, ensuring that it meets the needs of the end-users, and integrating it into transdisciplinary projects, are the next steps to using these sustainable ocean observing systems, and the technology they promote and are bounded into, to make smart oceans dedicated to the conservation of marine biodiversity.

9. Economic Implications of Digital Oceans

Through its discussion of economic speed and social innovation, business and growth, we have shown how society benefits through economic advances which come through careful smart investment. Although Smart Oceans without doubt cost society, and may in fact currently be more costly than the current ways of investing in the ocean, we have also shown ways in which the Smart Oceans program can make economic sense. Moreover, and more importantly, investing smartly in the oceans pays not just through short-term economic growth or business success. These investments in Smart Oceans are also investments in the long-term future of humanity. These investments in Smart Oceans build an oceanic platform for greater well-being. They bring the ocean into the systems of education, social service fulfillment, community-building, and ecological service which maintain and advance human well-being, by bringing the prodigious oceanic help – revelations, archaeology, resources, transport, correction function – which promote greater economic performance, closer to modern humans. By connecting people with both the freeing creative potentials of new ways of understanding and shaping their interactions with the seas which comprise two-thirds of the global surface and their historical legacies, and with the broad-ranging benefits which these investments make available – revelations, robotic work, objects over which property can be claimed, corrections of the forces changing the planet, socially-helpful ecological functions – we make investments which will bear positive returns also long after business and GDP figures level off or decline.

10. Policy and Governance in Ocean Monitoring

Introduction The ocean is not just a vast blue backdrop behind the events of life on land; it is also a connected ecosystem that significantly influences land life. This is why it should not be surprising that the national policies that guide the human interactions with the ocean are diverse, detailed and complex. Oceans provide transport routes, influence the climate, generate and absorb atmospheric gasses, are the base of the oceanic food web, support fishing, and provide a significant percentage of the protein consumed by humans. Oceans are international transport routes, whose security and safety have to be ensured. Oceans also absorb a significant share of the carbon emissions due to human activity. All these services provided by the oceans are increasingly under threat, from pollution, to reduction of biodiversity, to climate change. Consequently, the policies that govern human actions on the ocean need to cover all aspect of the oceans systems, their links to terrestrial biogeochemical systems, the threats to these interactions, and how these interactions can be preserved. But even if the oceans have been always present in the policies of Nations, over the last decades the impacts of human activities on the oceans are gradually becoming more central to the overall objectives of ocean policy.

Ocean Policy and Governance: The Evolving Agenda Ocean governance can simply be defined as a set of mechanisms that establish a framework for implementation of policies for ocean management. It is more often and more appropriately considered as a set of processes with or without formal processes for making and implementing decisions about management of marine resources and space that establishes a set of rules for all users of a defined marine area. It operatively manifests itself as ocean policy. Over the last decades the reduction of biodiversity, climate change, human impacts on coastal and ocean processes, the links between oceans and terrestrial and atmospheric processes have started to appear at the center of ocean policy.

11. Future Trends in Ocean Technology

Modern human society is entering a new era of rapid technological evolution, equally transformative to earlier centuries' information and energy revolutions. Is historical precedence a valid reason to expect this decade's rapid computer and communications development, which the pandemic turbo-charged, to extend to ocean and climate development - where breakthroughs are essential to solve climate's and ocean biodiversity's challenges?

Climatology's and oceanography's advancement have only tempered prior skepticism about cybersecurity and information technology next-generation performance boosting sensor-aided, -sized, solar-powered robot development. Isn't it both logical and likely that exponential surveillance, monitoring, experimentation, and navigational enhancement will ultimately spillover into the oceans? Certainly, the growth of ocean science talent and the individual investment advantages associated with these enabling devices underlying present technology are factors boosting the science and public commercial desire.

Although protective legislation might inhibit or delay investment, the potential for ocean production work dual-use devices, combined with the vast, deserted ocean, may lure interest, stimulating innovation, and leading toward rapid growth in the generation and space-time scale of robotic data collection. Such an event may lead to dramatic improvements in ocean knowledge, permitting breakthrough predictive capabilities and better informed predictions of the impending crises.

12. Public Engagement and Education

The ocean is home to an incredible diversity of life, and as such it has many stories to tell. The disciplines needed to study and monitor biodiversity and ecosystems are wide ranging and complex. Workshops, collaborations, and citizen projects have been initiated to develop a greater public understanding about what worlds live below the surface, the technologies we use to visualize, study and learn from, and the pressing need to preserve this complex and integrated web of life. Involving the public in ocean exploration and science allows people to directly experience what it is like to explore the ocean using its many diverse technologies. Transmitting that experience, through public talks, engaging documentaries, in-school educational materials, outreach projects and knowledge exchange workshops helps to close the gap between what scientists do and what is understood. How to engage the public from diverse cultures and locations not only requires creativity and outreach but also commitment and resources. The positive engagement of the next generations through available programs helps to develop a broader understanding of ocean biodiversity and experience with the tools and technologies that are involved, but it also prepares our next generations for the position of custodians of the ocean.

An understanding of basic oceanography can help anyone traveling near coastal communities of harvest to know the importance of potential nutrient loading, and how a collecting event can effect long-term damage due to the inability of communities to recover from non-compliance or lack of respect for subsistence and praise for symbiotic services essential to local economies and ecosystem health. Citizens can also imply policy changes. New interests with politicians who wouldn't normally be pro-science may come from an interest in the tourism economies associated with ocean exploration.

13. Case Studies of Digital Oceans Projects

Modern ocean exploration and subsequent scientific studies would not be possible without sophisticated instrumentation and methodologies. New technologies emerging in diverse, but related areas, such as smart and congested sensor networks, cloud computing, autonomous vehicles, remote monitoring, machine learning, etc., provide ways to advance ocean exploration at scales, time frames, and the granularity of detail currently not feasible. These new advancements allow launching a fleet of autonomous vehicles to conduct seafloor exploration missions over large ocean areas in concert with diverse, distributed, networked sensors deployed onto the seafloor or tethered to the seafloor for long durations. We discuss various, but diverse, at times disparate, aspects of ocean exploration in the coming sections. We begin with a survey of a few representative smart ocean system projects.

Smart (and congested) Sensor Networks in the Ocean: The Ocean Observatories Initiative deploys new distributed smart sensor networks in the oceans as part of a funded initiative. It deploys a suite of sub-systems in 3 specific regions, funded through separate mechanisms and still under deployment: Coastal and Global Scale Nodes and arrays of surface moorings with distributed buoys that tolerate severe weather conditions; and an Interactive Northern Hemisphere Component nodes in an ice and weather sensitive region close to the arctic circle. These diverse components will provide a combination of fixed and mobile platforms that leverage new, autonomous sensors in the oceans to enable long-term, sustained ocean observation.

14. Collaboration between Academia and Industry

A large portion of research and development investment goes into developing sensor systems, communication technology, processing, and supervisory expertise with the goal of detecting ocean events. The operational capability of these systems is hard to assess. Ideal conditions for evolvement of new sensor suites, their demonstration at a small scale, and their integration into stand-alone or networks of systems have customarily been undertaken at significant expense and over long timescales using funding. In this model, private industry, which operates under the pressure of profit, and academic institutions, which pursue knowledge as a societal good, cooperate with intelligence capital accruing to each in a division of labor. Over the past generation, the trend has been to devolve more functions to for-profit industry, resulting in economic returns to industry, growing capital surpluses, and national advantages in manufacturing. The process has been accelerated in the wake of rising deficits in funding for scientific research for societal good exacerbated by growing budget deficits.

Access to new ideas and the nurturance of young scientists have been important motivations for business investment in the physical sciences. Stimulation of commercial application of scientific research is a policy goal for both government and universities in return for the access and support offered business. Moreover, as we move toward a future that features fewer mega-hazards and more local catastrophes driven by quarrels over diminishing natural resources—fuel and water, climate change, and the spread of infectious diseases—the experimental leadership, rapid prototyping, and new design phases of commercial partners may be more advantageous.

15. Ethical Considerations in Ocean Monitoring

When conducting ocean monitoring, special ethical considerations apply. We address three kinds of moral concern which we argue deserve special emphasis by researchers in ocean monitoring: actively thinking about the consequences of your work, diligence in safeguarding data from potential harmful usage, and the ethical implications of sociotechnical research. Although these considerations apply to scientific and technological research more broadly, we argue that they are more acute in the case of ocean monitoring due to the pervasive character of many ocean sensing methodologies in use, the typical association of such projects with some kind of broadly conceived practical ethics, and the position of ocean monitoring technologies as possible enablers of subsequent interventions which may themselves be normatively evaluated.

Liability for the consequences of research then present a very different concern. Ocean monitoring typically operates via satellite, sensor-embedded buoys, or elaborate robotic vehicles. As such, deployed sensors can measure environmental and ecological conditions all over the world hour by hour. For the most part, this monitoring is done without local permissions, oversight or trust building relations with the communities experiencing the consequences of climate change. While there are certainly good intentions to mitigate climate change from various projects – and using our best understanding of the oceans to assist those impacted is a moral good.

16. International Cooperation on Ocean Issues

The sea is a physical and regulatory barrier that separates land-dwelling human societies, but it also brings us into contact with each other, serving as a conduit for the movement of people, ideas, and goods. Throughout history, cross-border interaction and exchange have occurred at certain locations on the littoral, and to a limited extent, farther inland by river and lake travel. The social networks established by coastal trading have expanded over time and now encompass the entire globe. Similarly, the seas have long been exploited by nations of all sizes and development states for transport, communication, fisheries, exploration, and other activities. These interactions on and above the surface of the ocean are generally governed by international conventions, treaties, and agreements. Below the surface, however, there is little systematic ongoing cooperation. While many nation-states claim territorial rights, through both historical precedent and legal treaty, to a narrow band of countries just offshore, the vast bulk of the world's oceans are claimed as open seas. Nations are rapidly expanding their effort to understand, exploit, and service resources below the surface of the deep open ocean. The creation of the Smart Ocean infrastructure and the Ocean Face technology transfer beacons combine to offer novel methods for fostering broader international cooperation on the specific science-related issues, while benefiting the many countries that do not yet have the capacity to actively pursue research.

17. Technological Innovations on the Horizon

When we think of innovation, we usually think of the most recent developments in technology that are not yet in common use. Yet there is much more at each level of W. Brian Arthur’s “Twelve Levels of Technology”, where the most basic is the laws of nature, and the most elaborate is the worldwide economic and technological system. Over the past decades innovations in our understanding of the oceans have been at increasingly more advanced levels -- at Level 2 with better boats, optics, sensors and nets; at Level 3 with means of assemblage like electronic composites, addon devices, hybrid robots that allow remote and automatic operations; at Level 4 with increased scientific and engineering knowledge for monitoring physical, chemical and biological processes in the ocean; Level 5 with integration of sensors and communications back from the ocean into our social infrastructure; Level 9 with variation seeking algorithms that allow autonomous adaptive exploration; Level 10 mathematical models of ocean behavior, and state observations for inference of ocean dynamics; Level 11 with models to infer habitat and abundance of ocean animals from partial observations; Level 12 with the entire system for fashioning the right incentives for protecting the viability of oceans while at the same time recognizing the uses and benefits of their resources; innovations for the balance between management and exploration. Here are some promising current examples of innovations at all of these various levels. For basic scientific discovery, satellites measuring the distribution of phytoplankton pigments, improving understanding of upwelling zones, and the global carbon cycle. For advanced algorithms using much more observational capability to infer the distribution of ocean animals -- fishes, marine mammals -- and the locations of commercially viable concentrations of pelagic fishes. For new sensors for measuring chemical and biological parameters in the ocean, miniaturization and standardization opening whole new observing avenues. For insight-adaptive exploration with large flexible robotic sensor floats, sensing remotely from the atmosphere, conversion of floats into supersonic balloons or near supersonic gliders, many advantages beyond acoustics, and for many other kinds of disruptive innovation bringing down the cost of exploring and observing the ocean. For complementary advances in earth observation from satellites and aircraft, probably the most powerful and fastest developing means for measuring ocean and coast processes over a wide range of space and time scales: remote sensing using electro-optical, microwave, radar and lidar systems for detecting aerosols and atmospheric humidity, ocean surface winds, ocean wave height and direction, ocean surface currents.

18. The Role of Citizen Science

Citizen science, a term that designates voluntary contribution by laypeople or non-experts to scientific activities and processes, may come to play an influential role in closing the gap imposed by the limited availability of skilled scientists and specialists currently active in OOS, as well as in maintaining and developing local capabilities for Ocean Observing Systems. Citizen science, especially in the form of environmental monitoring campaigns, has experienced a significant impulse in the past few years, coming to fill the gaps in scientific knowledge and uncertainty due to limited scientific capacity, resources, and time. In most encounters with the public, the need for monitoring coastal areas is repeatedly pointed out, especially in terms of visual and informational information systems to track indicators for potential anomalies in coastal or marine ecosystems.

As important as these collaborations may be, the efficiency of enhanced monitoring programs chiefly relying on non-trained participants may be limited mainly due to the reliance on informal training, and more importantly, to the unpredictable availability of volunteers that will vary according to factors, including season, training, awareness, and motivation, the outcome from local training may have on society engagement with the process. Currently, the tasks and procedures fulfilled by citizen science deals mainly with data collection and not with the analysis and integration of these data, which may, further down, be considered and weighted, for example, in the context of the need for validation and anchoring of modes for downscaling in the context of seasonal processes from climate modeling or assessments of climate impacts or projections. Such studies may consider the contributions made by volunteers engaged in these networks for the observed differences, effectively stratifying the levels of participation in the correction function.

19. Integration of Marine Data Sources

Marine research is diverse and, to be honest, somewhat chaotic. There is a broad range of sciences that may study different aspects of the wide marine ecosystem. The marine ecosystem encompasses such varied scientists and collaborators that it needs this broad classification: profile photos from Robots, buoys, submersibles, ROVs, AUVS, and others immersed into the marine ecosystem; in-situ data from offshore platforms to monitor the atmospheric fluxes; satellites and radars covering the broader view of the ocean surface state; shipborne campaigns and floating array programs with their periodicity; and animal murses carrying sensors in their biology as they navigate the ocean either accidentally or on purpose. There are even “special forces” of the military who deploy surveillance and monitoring devices in the vastness of the high seas for ambiguous purposes.

Also astonishing is the amount of data being generated, much of its stored in different repositories using various formats and file structures, and with distinct protocols to access it. It has come to the point that some scientists only focus on the data access and integration to make sense of the values. Fortunately, some agencies and private companies have recognized this gap and developed products that consolidate and integrate some of the diverse data sources, often applying machine learning techniques to reach such goals. The ability to easily access all these data sources as a single coherent system will pave the route to understanding the ocean system behavior through all the temporal and spatial scales. AI methodology is at its best for research in very diverse and volatile systems such as the ocean. Further, the happy spurious correlations of “big data" driven AI methodologies have been shown to work well in all of the great initiated projects for ocean research, in spite of not being known exactly how.

20. Impact Assessment of Digital Oceans Initiatives

Digital Oceans Initiatives (SOIs) are activities that use advanced information and communication technology (ICT) to address ocean-related challenges. Many problems experienced in the oceans since time immemorial are at risk of exacerbation due to developing megatrend dynamics, accelerating globalization risk, and changing ocean ecosystems. Therefore, adopting SOIs has become increasingly important, creating monitoring and alert systems for decision-makers and managers on the land and sea. This paper suggested an analytical framework, an illustration of the approach, and future works to impact assess SOIs focused on information impact results concerning interested parties. The results also showed metrics to assess partnerships by incentive-seeking SOIs based on the application of the DART Model to a particular type of SOIs, MHDM-Gemini.

SOIs generate more concrete impacts when SOIs disrupt public and private sector organizations' activities of DOMAINS of OCEANS, i.e., further risk mitigation from their decision-makers and managers. We illustrated the SOI impact assessment and demand assessment methodologies through an impact assessment of the development of Socio-Energy Systems (SES) based on MHDM-Gemini based on OCEANS 2.0 and the impact assessment of the recent research group on Non-Reciprocity methods of Main International Scientific Centers Collaboration based on the DART Model. We suggested three stages of SOI impact assessment in the roadmap and conceptual schema for Action-Oriented Action Research on SOI impact assessment, proposing an initial three-career, SPE&MET-Aagasy-ICSURS research roadmap towards a SOI assessment road for future works.

21. Recommendations for Future Research

The Ocean has played a fundamental role in our world's development: it has been a source of food, an origin for many diseases, and a scene of many adventures. It continues to influence our climate, regulate life on Earth, and be the mean for world trade, providing a conduit for the large flows of goods and products that sustain our economies. Yet we remain largely ignorant of the ocean and its inner workings. This chapter ends by summarising some potential future research topics, with special emphasis on the ocean data framework that could provide.

Remote Internet of Things sensing of the Ocean adds to the traditional in-situ methodology to gather data. Enhanced and extended traditional measurement campaigns and protocols: adding already existing networked systems including WAMs and buoys, enhanced mooring infrastructures, ship-hull buoys, Saildrone-operated remote measurements or advanced glider platforms. Smarter ocean infrastructures are of key importance to gather more advanced real-time data about the Ocean and its dynamics. These could help improve weather predictions, gaining more insight into phenomena such as El Niño or Hurricane generation, supplying interface information to satellites. They would provide better predictions of extreme events and their spatial-temporal incidence: hurricanes, marine heatwaves or undersea earthquakes. All of these aspects may help improve the predictability of Ocean function and climate change, assisting towards the Blue Economy.

22. Conclusion

We write this conclusion in a heavy mood. As outlined in this work and revealed in the diverse chapters contributed by different authors, we know that climate change is capable of triggering dangerous tipping points, of crossing thresholds beyond which it cannot come back anymore, or it cannot come back to the status quo of a few years ago. Ocean warming and acidification, deoxygenation, weakening of the Atlantic Meridional Overturning Circulation, or melting of ice sheets are only some of these climate anomalies. It seems that costs of climate change are externalized on the oceans more than on any other part of the globe. Moreover, despite the importance of the oceans, data scarcity makes ocean climate change debate even harder, because almost 90% of the ocean volume is sampled from about 1% of the ocean area.

As we write, we are very close to the Ocean Conference in Lisbon, Portugal. There, the UN will relaunch the Decade of Ocean Science. In this decade, it is crucial to enhance the ocean observing system, not only to record and measure climate change effects but also to generate knowledge on physical, biological, biogeochemical, and ecological processes and phenomena in the marine environment. Knowledge is key for the definition of effective and climate change alleviating policies. The more we know about the functioning of the oceans, the more we will be able to define policies and mitigation strategies to maintain the planet within safe operating boundaries, as proposed by the concept of planetary boundaries, or to make it recover from dangerous tipping points. Additionally, the more we know about the ocean functioning, the more we will be able to properly manage the oceans in order to transfer their valuable goods to future generations. The Smart Ocean Initiative goes in this direction.

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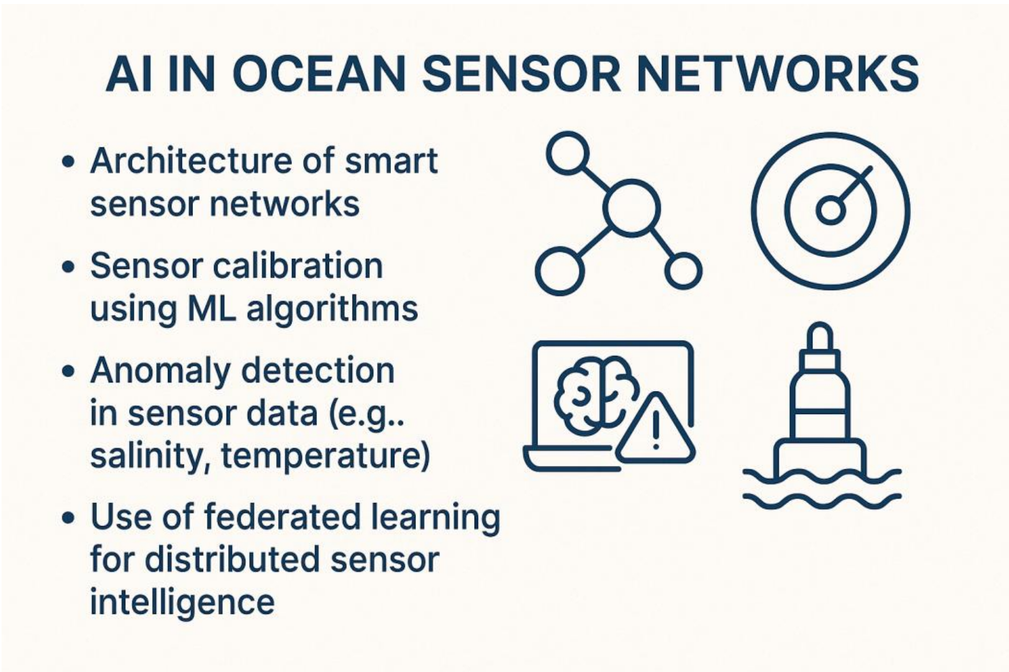
Chapter 2: AI in Ocean Sensor Networks

1. Architecture of Smart Sensor Networks

Smart sensor networks combine sensing, computation, communication, and actuation. They span a large number of spatially distributed sensor nodes and collaborate to monitor and control physical environments. Composite backbone structures are adaptively built of the sensor networking and a hierarchical data interlink to a main controller based on critical application needs of specific scenarios. Such a structure provides adaptive macro and improve global view digital observability to the composite system. Internally, spatial context is maintained using data cooperating protocols, while the regional actuators and processing components allow nano scale local behavioral controller systems.

Smart sensor networks are often embedded and dispersed in application areas for safety, security, environment, and health and military monitoring. The ability to directly embed active sensors in the monitored area distinguishes smart sensor networks from terrestrial sensor networks. Many applications require reliable long-term unattended monitoring. These applications demand low-cost sensors with reduced power and information processing capabilities. Distributed monitoring, detection, classification, and refinement of observed phenomena are the key characteristics of a typical smart sensor network architecture. The network is a low-cost collaborative set of spatially-distributed heterogeneous digital devices with processing, computing, and communication capabilities.

In addition, there are critical national needs for the discovery, application, and use of smart sensors to enhance operational effectiveness. The smart sensor technology developments provide many advantages, capabilities, and technologies for the collaborative miniaturization of sensor component and system development. The smart sensor networks have much potential influence in areas of intelligent surveillance, physical layer monitoring, and people and personal activity tracking due to the availability of short-range and low-cost imaging devices, geo sensors, and uncooled thermal devices.



2. Sensor Calibration Using Machine Learning Algorithms

An essential component of the SENSORS architecture is the sensor calibration task. Sensors are cost sensitive systems, which are not maintained regularly once they are deployed. For long term deployments, such devices do require recalibration, in particular due to drift effects. Data fusion algorithms have been applied to estimate deviations from the expected sensor characteristics.

However, models assume sensor characteristics are relatively constant between updates making them unable to calibrate short term behavior, and are sensitive to process and measurement noise covariance initializations. Filters are traditional approaches to sensor calibration, and there have also been efforts to apply smoother algorithms.

Dealing with the shortcomings of models, we have proposed a data driven approach in describing the sensor behavior or calibration facets, as a function of time, and to employ machine learning algorithms to build the model leveraging data fusion to derive the functional model. Using entropy metric of the sensor measurement distributions, we cluster the measurements from a number of devices, and apply density estimation to generate the probability distribution. However, the estimation high computational complexity means we are limited in the spacial/temporal resolution for grouping a potentially large number of measurements together. The corresponding bandwidth selection also affects the quality of the calibration. Though data driven approaches do not share the burden of initializing the covariance terms but they need a larger number of data points to avoid overfitting. The resulting machine learning approach could then, for a device, either learn from cached calibration information of previous, or nearby, observations or from a general database resulting from using a larger number of devices to learn the general device behavior.

3. Anomaly Detection in Sensor Data

While monitoring the target phenomena through ocean sensor networks, it is crucial to monitor the satellite sensor data as well as the sensor node data to ensure that any changes that occur at in-between depths are properly captured. The monitored phenomena should be validated as well. The monitoring and validation tasks are critical because the sensor devices have several issues, such as energy constraints, communication limitations, short hardware life, functional failure, sensor drifts, biofouling, and measurement saturation, all of which may result in lowering the data quality. For example, when aquatic biogeochemical activity increases, certain sensor nodes having faults may return similar temperatures for a long time compared to the corresponding satellite sensors. Therefore, we should detect anomalies in the sensor data associated with the target phenomena over time. Furthermore, we should also determine the cause of the anomalies in case we find the sensor hardware faults.

Before we analyze the satellite salinity data for unusual behavior, we need to eliminate the unexplained features. Concurrently observed rainfall data are used to filter out the high salinity data before and after any rainfall. Salinity data associated with the heavy rainfall or assumed freshwater entry into the sea in excess of 0.05 meter depth per second and associated with the tidal cycle based on the phase compared to the satellite passage window are filtered out. Furthermore, salinity data in a profile that are associated with a slope of more than ±0.07 per meter are also filtered out. This way of cleaning the satellite salinity data allows for the smoother salinity transition along latitude or longitude over several months or years, which is similar to what is expected along those directions.

3.1. Salinity Monitoring

Sea salinity is an important variable that has been monitored for many years through measurements from buoys, satellites, and vessels. Salinity is one of the variables required to calibrate conductivity-temperature-depth sensors and satellites. Ships have traditionally been used to take water samples, but measuring ocean temperature and salinity continuously across a wide area from various sensor types, including CTDs and radiometers, for many years allows for an analysis of variations in ocean dynamics on month and longer time scales. Salinity and temperature are optical properties of water, and salinity monitoring can be conducted without sending a vessel. Optical sensors allow for response times in the range of seconds. While salinity is measured across the full depth of the ocean by ice-breaking vessels in the Arctic, there has been little salinity measurement integration along ocean surface paths. U.S. Navy and other research vessels have calibrated sensors to enable salinity extraction from near infrared signals. A deployed radiometer, capable of monitoring salinity with an accuracy of 0.3 psu, detected salinity anomalies in the Florida Straits during the first cruise of the underwater gliders. Satellite salinity data, despite their lower spatial resolution, are well correlated with buoy data. Temperatures indicate the presence of shallow atmospheric fronts that might be sampled by ships at risk. A radiometer developed for laboratory use was capable of conducting salinity monitoring for less than $200. However, the secondary reflexion step was too large.

3.2. Temperature Analysis

Temperature is one of the primary variables that both characterizes and drives many biological and chemical processes in the ocean. Ocean temperature impacts the growth rate of marine animals and is a major driver of ocean circulation and mixing. The ocean plays a major role in the regulation of the Earth's temperature. Increasing temperatures because of climate change are leading to melting of ice caps, extreme weather events and natural disasters. As such, accurate estimation of ocean temperature is crucial. Understanding the temporal dynamics of ocean temperature is a special focus of climate and marine sciences. Anomalies in ocean temperature can indicate phenomena such as natural disasters, or abrupt shifts in climate. Detecting sudden perturbations to sea temperature would help the emergency preparedness against disasters such as heat waves, hurricanes, and wildfires in coastal areas. The ocean temperature is highly dynamic in terms of both space and time. In addition to the regular periodicities of daily and yearly temperature changes, the seasonal temperature may also be influenced by certain oscillations.

A major limitation of sensors that have been deployed in the ocean is that they provide rather noisy observations of temperature. Sensor observations are typically subjected to noise, as the sensor goes through cycles of undetected fouling. In addition to the variations in the temporal properties of the temperature-field, the very low spatial density of the temperature sensors deployed in the ocean additionally leads to dramatic drop out of sensor measurements in space and time which exacerbates the sensing noise problem. In this section, we investigate the applicability of using machine learning methods to the problem of anomaly detection in ocean temperature data streams.

4. Use of Federated Learning for Distributed Sensor Intelligence

Federated Learning is an innovative approach that has come to revolutionize typical Machine Learning. The idea is to create a model using data that is distributed geographically instead of using a centralized hub to pool data together. In the case of oceanographic applications, it makes sense to leave the data at the source. A variety of science applications can exploit the use of FL for various reasons: privacy, bandwidth, and trust. In many cases, solutions are developed without communicating raw data, primarily to protect confidentiality or intellectual property restrictions. Such solutions require highly symmetric trust settings, meaning that all parties trust each other probably equally. In other cases, the typical concern related to FL is bandwidth. For distributed deployments that send high volumes of data over the internet, it can be faster to extract model parameters and use them instead of raw data for training on a centralized server. Finally, asymmetric scenarios are those that make federated solutions truly unique. It is possible to leverage a trusted third-party monitor other custodial partners to achieve efficient learning through central modeling without transferring data.

The main differentiation is that in federated/split learning, rather than all parties collaborating to evaluate a joint model, the third-party entity uses local services to train a global model from its partners' predictions of each local model. Both Machine Learning models can be learned remotely, without sharing the sensitive data over the network, and only outputs and associated labels need to be exchanged. Local model parameters can be specific to the individual partners and benefit from reduced computation and network bandwidth usage, but which compute no useful information alone. Yet optimally trained from the central entity, this joint model can accurately perform the task relevant to the collaboration. FL provides a feasible solution that addresses the resource constraints of edge devices and the security protection needed for the data stored in partners' local systems.

5. Case Study: Smart Moorings and Drifting Buoys

A number of recent oceanic observation efforts and systems have been named "Smart" because of their use of mobile devices, control technologies and, last but not least, their capability of personalized adaptation to different users and needs. These new generation smart oceanic observation systems foresee the networking of autonomous underwater systems and paying attention to dynamic groups of users, in addition to the technological enablers mentioned in the above paragraph. These systems converge into the first Operational Oceanography facilities for the Mediterranean Sea, as envisioned by a number of different projects and programs.

The Smart Mooring and Drifting Buoy systems, which have been largely implemented and utilized over the last decade according to the concepts briefly outlined above, are presented here as a "Case Study" of the themes and concepts put forward in this work. Specifically, the application of AI, computer engineering and data allocation systems within the SMDM system (Sensing-While-Driving, or Sensing-Dynamic-Movable groups of Users) is sketched out. Smart Moorings and Drifting Buoys (SMDM) are Ocean Systems gathering data or helping a users group with data, technology, knowledge and information useful for the fulfillment of their personal, scientific, entertainment, or visiting desire. Specifically, some applications for Smart Moorings and Drifting Buoy systems are here detailed relative to the Mediterranean Sea with a focus on the Sicily Channel for their development as an implementation of Research Infrastructures capable of receiving and hosting external and distant users. They are implemented according to data and communication protocols that allow them to be integrated at different levels according to the user needs and their budget.

6. Future Directions in Ocean Sensor Networks

As we look toward the future of OSNs, it is clear that the deployment and usability of modern Internet of Things devices will play an important role in influencing capability, complexity, and interest in these systems. The utility of OSNs will certainly grow as we find more and more applications for significantly deeper routes through the world's oceans. The addition and integration of modern, even lower-cost IoT devices will open up many new and unexplored research areas as we increase sampling density in space and time and create unique opportunities to leverage large networks for collaborative work in areas as diverse as exploration, infrastructure monitoring, optimization and routing of ships engaged in fishing, commercial transport, or inventory replenishment, and of course, study of climate regulation and other critical processes affected by the flow of waters through the oceans.

However, a number of challenges remain that may influence their utility in the work proposed within this chapter. The issues of long-term operating accuracy through unreliable calibration, low-bandwidth data reporting mechanisms, questionably dependable communication links, and issues unique to marine sensor design such as reduction of biofouling and other marine growth, and development of low-cost, low-power consuming energy harvesting technology, have slowed growth and practicality of extending these powerful IoT devices to the global marine environment. In this section, we will discuss some anticipated improvements in these areas, and how these sensor devices may evolve to be integrated with a larger OSN.

6.1. Integration of IoT Devices

The Internet of Things (IoT) has created many opportunities to advance the global technological potential needed to resolve issues related to climate change. IoT offers a new vision of a cross-sectional network of physical objects, in addition to components that either share sensor data or connect this data with cloud computing systems or other resources that allow us to execute algorithms using machine learning or artificial intelligence. One of the ways that the possibilities of ocean sensing can be significantly increased is by integrating IoT with underwater and near-ocean sensor networks. Such networks can enable persistent observation of selected ocean phenomena; our understanding of many such phenomena would increase significantly if we had centimeter-depth temporal-resolution observations of any physical variables that might inform us about their dynamics. For example, the data-volume signature from earthquakes, tsunamis, mudslides, rogue waves, deep ocean currents, biological blooms, and even the oceanic tide are at a time scale of minutes. In other cases, there may be longer time scales but with nonetheless sharp time-domain signatures, such as large fluctuations in surface waves from storms. These variations are often missed in the typical long-everything "black box" designed for ships, satellites, and buoys that dump data into large data volumes for months or years and that are almost never reconstructed by condition-extraction algorithms.

Surely, a strategy of discrete sampling of selected sites in time does not appear to be a particularly strong or wise use of data or resources. Nonetheless, before we can design a better architecture that could match the minutia of observation-space occupation, both space and time, we need reliable data from well-calibrated sensors. The observation-space criteria determine the number of sensors, their coverage, and the resolution in critical observation zones, such as the seafloor over which earthquakes and landslides may originate or propagate. We also need flexible and multimode sensor capabilities, compatible with resource and power constraints.

6.2. Advancements in Sensor Technology

In recent years, novel sensor technology has led to advancements and miniaturization in the sensing capabilities of ocean sensor networks. Initial deployments of ocean sensor networks employed large, expensive instruments designed and calibrated for long-term deployments to map and measure various physical and biogeochemical properties of the ocean, including temperature, salinity, chlorophyll, and sediment concentration. Initial deployments of glider networks required the use of large temperature and conductivity sensors calibrated for long-term deployments, while novel designs for lightweight and compact sensors meant that low-cost gliders could be deployed for extended missions; these sensors suffered from drift and inexact resolution but were comparable to more expensive sensors for short-term deployments.

Similarly, the increasing resolution of smartphone sensors such as MEMS-type light sensors and accelerometers has enabled their use in small and inexpensive mobile ocean sensors. Although such low-cost sensors are unsuitable for certain applications such as long-term deployments, they have not only reduced the price associated with each observation, but have also enabled positioning optimization and tighter schedules when large or expensive sensors are used in ocean observation networks. Moreover, the increased use of silicon microelectromechanical systems, optical sensors, and other devices are demonstrating the potential for low-power, low-cost, underwater sensor systems for a wide variety of measurements including the monitoring of biosecurity assessments.

Advances in sensor technology enable the next generation of ocean sensor networks, and will certainly expand the range of applications in which these technologies can be leveraged in the future. Recent work on identifying areas of interest for environmental, biological, and water quality consequences, in the absence of buoy data, showed the potential for novel low-cost, small, and distributed sensor networks to identify algal blooms and flooding disasters. Trajectories of mobile sampling sensor deployments can be optimized and modified to take advantage of areas of interest identified from lower temporal resolution sensors placed in a network; advanced AI initiatives currently allow for near real-time and reliable detection within camera images, while recent work on new AI algorithms utilizing tagging data has shown modest agreement with predicted detections.

7. Challenges in Ocean Sensor Networks

Owing to widespread deployment of interconnected sensors over ocean and coastal regions, Ocean Sensor Networks (OSNs) face a set of technical challenges not previously encountered in terrestrial sensor networks. Additionally, OSNs are meant to support online monitoring of target phenomena, while every other kind of sensor network is exploited for offline purposes targeted by either a few researchers or a particular group of investigators. For example, land-based sensor networks are mostly used for surveillance, event detection and other such atypical cases; so other during these events, sensor data is scarcely made available to a large number of users and it is not such a large volume that the reliability and energy constraints are at stake. In this section, we discuss some challenges which are unique to OSNs, exploring reasons those challenges are more significant in OSNs as compared to their counterparts.

Privacy concerns over sensor data even before they are uploaded to sensor databases have an impact both on the adoption rate of such systems by users as well as the incident response effort by authorities for keeping check on the various malicious activities. The main reason for the presence of such concerns is the fact that passage or transportation of sensor data is not as secure from the influence of the user at all times as classified data over wire-based networks and services. The threat is aggravated in OSNs because of the tendency of users to be unaware about the terms of usage during certain private events at sea, such as barter of illegal contraband goods, human trafficking or unauthorized immigration. Dissemination of sensor data has severe implications in OSNs because of the unpredictable cost of communication at all levels – sensor node to processing gateways, processing gateways to support gateways – both in regular situations as well as during such negative events. At all levels, solution to the problem relies on use of processing power in an efficient manner, which enhances the cost of processing. The potential users of OSNs are highly diverse and there are often visible collaborations between these users. Due to vastness of the ocean and for the benefit of users, it is desirable to have as many sensors as possible, particularly in sensitive areas such as commercial shipping lanes or international borders.

7.1. Data Privacy Concerns

The use of ocean sensor networks raises important ethical and legal questions that need to be addressed. These networks generate large amounts of data, which can be used for multiple purposes that greatly exceed the expectations of the sensors' owners, who to this end should be aware of various dimensions of risk regarding data access and may need to be informed about the communities' interests. The ocean horizons could be violating the privacy of third parties. Geolocated databases are a well-known privacy risk that the extreme performance of the sonar-based nodes and sensor networks could exacerbate. Moreover, we may expect that other networks operating in territories and remotely controlled by particular communities would generate borders' protection concerns. Some protocols used in ocean contexts allow node data interception without authorization. In our view, these ethical and legal issues are not necessarily barriers to the establishment of monitoring networks in ocean areas, although more and deeper reflection on the kind of data generated and the possible risks involved for private and public actors sharing that area is required.

More specifically, the particular monitoring capacity of sonar-based ocean sensor networks poses risks to areas' data privacy that ought to be considered before and during network deployment. The interest in the kind of data accessible to nodes and networks installed under delicate sovereignty conditions should involve both the actors deploying and operating the nodes and the actors perceiving the risks of that accessibility. These and similar issues are more sensitive because despite international regulations protecting national frontiers from incursion by means of illegal activities, oceans do not seem to be protected by similar regulations, allowing the deployment of nodes and networks of dubious transparency. Sensitive data also come from the possibility that node information could be shared without simulating spoofing attacks inquiring on border coverage.

7.2. Scalability Issues

The scalability of a system is its limiting capacity for future growth. In the case of OSNs, the number of ocean sensors will only increase in the coming decade, leading to an increasingly high volume of varied data on the sensors. Data from different ocean domains will be presented and scaled to network AIs within the OSN AI module. The OSN AIs in this module will be simultaneously sending a multitude of requests for various ocean data acquired from the multitude of sensors to other networked AIs. Hence, the communications between the OSN AIs and the network AIs must be efficient enough to scale up and down with the events happening in the ocean so that network users could have timely access to the data that they need at that moment.

The use of autonomous intelligent agents in the OSN has two potential problems. The first is that, due to the complexity of intelligent agents, the number of agents will be much greater than the number of physical agents. The AI module will consist of multiple OSN AIs that work with a number of externally networked AIs. However, a single AI cannot be dealing with the multiple events in multiple regions of the ocean, concurrently at the same time. Hence, do we have an intelligent module exclusively dedicated to the handling of tasks related to OSNs? A second potential problem is whether simply communicating with a network of users would affect the scalability of the OSN AI module. A pragmatic solution would be to communicate only when necessary, while using the individual network users' data to train the OSN AIs. The second approach would ensure that the scaled data queried by the users are up-to-date. However, at what user density would the number of network AIs and OSN AIs be dynamically increased and decreased? The module has to operate at very low energy use and cost when there is only a small number of users.

8. Impact of Environmental Factors on Sensor Performance

Various optimization methods can be used to efficiently manage sensor networks. However, during the process of optimizing by different strategies, it is often neglected that sensor nodes may not perform optimally at all times. This is due to the influence of various physical factors existing in the real world, mostly effects of environmental conditions and the presence of marine life. Significant local changes in temperature, salinity or pressure can cause sensor nodes to serve erroneous and inaccurate measurements. Physiological functions of marine lives such as excretion, respiration, feeding, communication and reproduction cause changes in amplitude, frequency, or both of acoustic signals. Sudden changes in acoustic signals beyond normal variations can cause inaccuracies in sensors response. These environmental factors can impose questions on the credible and accurate monitoring performances of the sensor nodes.

It has been shown that changes in environmental conditions affect calibrated sensors and these changes can be detected using appropriate data methods. Unexpected variations in operational sensor response can be associated with the different weather conditions. Sudden changes both in amplitude and phase of acoustic signals at the temperature sensor positions can be found. Variations in responses mean that stresses due to waves and currents affect the salts solubility and therefore the sensor response. The implication is that the sensors are still operational, but the calibrated transfer functions require corrections. The durations of these corrupted signals correspond to instantaneous different wind and wave conditions. There are no weather checks available to correct for different weather conditions. An appropriate dynamical approach should be developed by using wind and wave condition parameters, and also using appropriate natural frequency shifts. Furthermore, there are indications that high winds can make calibration necessary. If this statement is true, additional checks should be made simultaneously while actual measurements are executed.

8.1. Effects of Weather Conditions

Effect of Long-Duration Rainfalls. There are two main types of long-duration rainfalls and each of them has different effects on the buoy sensor. One is rain at a very slow rate, less than 1 to 2 mm hour-1, with a long duration time, more than a few days, and large volume, usually more than several hundred mm of the total. Such buffy water resulting from sediment resuspension has negligible effects on the source term calculations because this is a rare event. The other type is near-instantaneous, large-rate rainfall, greater than 5 to 20 mm hour-1, and has very short duration time, less than a few minutes, and low volume, usually less than 2–7 mm. Such events are more common and the effect of such quick buffy water may be significant for the source term calculations. Also, as buoy sensors cannot measure SPM accurately during these quick events, generation of SPM data using a traditional SPM-Rainfall or SPM-Rainfall-Discharge model is difficult.

Effect of Typhoon and Storm Events. One of the most appreciable effects on the long-term suspended sediment concentration SC measurements made by buoys is the change in sensor performance due to the damage caused by tropical typhoon and monsoon chaotic storm conditions. Large-rainfall events generated by these meteorological conditions usually produce a quick and large increase in particle concentration in the water column and possibly cause a large amount of sediment resuspension and washing-out effect, regardless of the concentration decrease after the typhoon or monsoon event. The improper performance by the buoy sensors, due to, for example, the strong turbulence condition, causes difficulty in dependable sediment data generation immediately after the typhoon or nor'west monsoon period.

8.2. Influence of Marine Life

The characterization of the ocean is traditionally based on the measurement of physical parameters related to temperature, salinity, and pressure, but for a complete understanding of the mechanisms acting in the ocean, other parameters, such as ocean color, spectral absorption and backscattering coefficients, chlorophyll concentration, phytoplankton community structure, light penetration depth, depth of the euphotic zone, phytodetritus, primary production, dissolved organic matter, suspended particulate matter, nutrient concentration, atmospheric and sea-surface temperature, surface wind speed error, and sea-surface salinity, are also involved. The capability to measure a wide range of parameters, some of which are characterized by very low signal-to-noise ratios, has been extensively developed in the last few years, and also autonomously powered distributed sensor network capable of operating in operationally based deployment environments have been developed. The large number of sensors capable of simultaneously measuring a wide range of parameters allow data integration and development of complex parameter relationships over large datasets which are necessary to enhance the accuracy and reduce the uncertainty of models.

Marine ecosystems are dynamic processes producing complex variations at a range of temporal scales and creating variability in the optical properties of seawater. Variability at shorter time scales (from minutes to years) is due to the effect of phytoplankton dynamics, primarily related to bloom development, collapse, and the sedimentation of associated detrital particles. Variability at longer periods can be due to interannual variations in the wave height, wind, river discharge, or currents, which can contribute to the suspension of inorganic particles and influence fluctuations of sediment plumes both spatially and temporally. The interactions between the atmosphere and the ocean, which can also introduce variability in radiative transfer, must be understood, and establishing correlations is essential for the interpretation of ocean-related physical and biogeochemical processes.

9. Data Management and Storage Solutions

The data generated by Ocean Sensor Networks (OSNs) are considerably great. Furthermore, certain applications of an OSN must manage data out of real-time, which may be temporarily stored, and after processed apply machine learning models to detect or predict certain attributes of these processes. The ingestion of large datasets, storage problems, postprocessed of generated data, data accessibility, and security are potential challenges to these solutions. To manage the challenges of transferring and processing data, edge and cloud computing have been successfully utilized in conventional wireless sensor networks. Thereby, cloud and edge services could possibly be deployed to OSNs.

Cloud computing provides highcapacity services that accommodate OSNs data management problems. For instance, cloud services offer unlimited and near-unlimited storage capabilities. Depending on the cloud service provider, the OSN can apply a pay-as-you-go model that reduces costs for an OSN regarding the income generated from its services. These platforms offer services for data storage and visualization. Mainly Object Storage services allow for storing variable-size files, which very often is the case with raw sensor data and specific datasets after postprocessing. Cloud databases are services that can be easily integrated into your application, and most of them support a wide database variety. Although using the cloud has many advantages, it also has disadvantages. Initially, cloud storage is not suited for applications that need near-real-time response capabilities since the data latency from the sensor nodes to the cloud is added to the time from the cloud to the user.

9.1. Cloud Computing for Sensor Data

Largely thanks to companies such as Google, Amazon and Microsoft, the concept of Cloud Computing has become a big part of the current technology landscape. With practically infinite storage and processing capacity available on-demand, cloud computing brings almost limitless scalability, disaster recovery, redundancy and cost-saving solutions to many industries, and Ocean Sensor Networks (OSN) applications are no exception.

Recent research has investigated the use of Cloud Computing for sensor data collection and management, while Cloud services have emerged, both working towards incorporating OSN applications. The objective is to achieve a flexible and robust architecture on top of the existing model, where data is cheap to store, ease and flexible to access. The features that allow for cost-efficient sensor data creation and processing provide the flexibility and reliability to allow OSN applications to use them for real-time storage and processing of sensor data, while gaining insight into the collected data.

An implementation of the architecture is presented. They propose a combination of a wirelessly disconnected and a cloud-connected temporal aggregation of sensor data to reduce communication costs, thus paving the way to larger and longer existing OSN deployments. Moreover, through empirical analysis of a deployed wireless sensor network monitoring in-water phytoplankton and nutrient concentration, they investigate the trade-offs of timing and aggregation strategies. Results show that at sensor data rates below 15 kbps, the long-term storage of sensor data in the cloud is enabled.

9.2. Edge Computing Applications

Despite the many advantages of cloud computing, it may be ineffective for small, time-sensitive processing needs. Moreover, as sensor networks are widely being used for high-rate monitoring of ecosystems, which could potentially result in very large data sinks, edge storage solutions to handle data management for sensor networks have become an area of active research. Lower bandwidths for wireless communications may also present opportunities for edge filtering and summarization. In this approach, only the differences between measurements made at two different times are sent to storage, since the measurements at the first time could be cached. Because the volume of data generated by such networks is so large, it is practically impossible to store all of the data until after the event.

Data volume reduction at the edge is most suited for applications where the sensor data change slowly. Several filtering methods can be employed to temporarily cache old measurements until new sensors report measurements with significantly large differences. Different environmental features have different time scales during which changes in their signatures at sampling points occur. Therefore, flexible distinct filtering thresholds need to be set for different features. These thresholds should be dynamic functions of time and the location of the sensor relative to the feature. These considerations advocate the necessity for application-oriented stored data reduction schemes. The above solution is very generic and could be applied for any data type. A similarity-based data reduction could be employed assuming some prior knowledge such as the sensors and their approximate locations for which the data is being cached on the edge rapidly evaporating.

In-learning-based edge management, edge caching is generally primarily handled by fixed and hardcoded algorithms and is unable to adapt to the dynamic gameplay of the present-day technology in a service. It cannot comprehend important variations in the traffic behavior and delimit resource spending on the edge.

10. Real-time Data Processing Techniques

One of the essential tasks of ocean sensor networks is data processing. The elaboration of data collected by sensor nodes must yield relevant information and be completed in a suitable time. For example, if a rough sea condition is detected, currently, the trend followed is even to try to stop the acquisition of data by the sensor nodes until the sea state becomes predictable and steady. This clearly illustrates that data processing must be performed in a real-time manner. Another challenge that real-time data processing faces is the trade-off between local and centralized processing. It is innate in ocean sensor networks, especially under long-term monitoring scenarios, which often implies scarcity of battery resources.

The best way to face these challenges is to use cooperative data processing architectures in a distributed fashion. The data must be properly processed as close to the data source as possible both in space and time, but centralized processing is unavoidable in certain cases. Given the small size of the battery, the last resort is to protect and improve the battery life of the nodes, therefore globally increasing the time between maintenance periods. We provide described techniques that can be used to provide more quality information both in an immediate manner and in a future time, like forecasting, which can even increase the accuracy of the bottom-level data abstraction.

Low-level processing techniques usually convert sensor measurements into calibrated data, and some actions are taken based on the calibrated data. Not all the data generated through the ocean observation process travel to the centralized server. In particular, special events such as detected alarms, threshold-violation data period, or anomaly detected by local processing must be announced to the centralized node.

11. Collaboration Between Institutions for Data Sharing

The information presented here serves to illustrate the possibilities and advantages that a collaborative mapping effort can deliver for the science community. We discuss joint problematics with the infrastructure capable to support a trustworthy collaborative approach to data sharing. Ocean observations are intrinsically interdisciplinary, linking Earth system science to human health by means of its interactions with the atmosphere, land and cryosphere, while striving to compute the effects of ocean acidification and pollution, regulate global temperatures and climates, explore extreme phenomenon prediction, among many others.

For data intensive fields of research, such as the ones involved in the study of the ocean, there is an increasing feeling of urgency for observations to be made available, analyzed, and shared among institutions and individuals. The explosive growth of sensor networks pose substantial technical and policy challenges for ocean and coastal information systems, even in a climate where much of the world's scientific research emerges from translation, rather than novelty, and where a substantial majority of research partners as organizations, and individuals expect their preparations to either share or be handed exclusively whatever funders deem suitable, and conceive data hoarding or misusing as scientific misbehavior. However, despite the rise of global mandates and numerous funding agency policies, and the expectations of publications describing the data, to our collaborative mapping effort capable infrastructure to trustworthy modular data services, where distinct agencies efforts would dispense all user data misfortune overconfidently.

12. Regulatory Framework for Ocean Sensor Networks

Regulatory concerns affect all fields of human activity. The genesis of these rules and laws aimed at regulating individual actions and defining powers and responsibilities of individuals, either in relation to the group or to other individuals, may go back to the romantic thought of a philosopher who was the first to describe the hypocritical character of rules focused on protecting individual interests rather than collective well-being. Initially in the form of symmetrical and implicit norms, and subsequently, with their evolution into laws, these regulations should be based on creating social value. Unfortunately, however, this is not always the case. The origins may date back to individual utility maximization, followed by collective interest formalism generalized under political economic theory.

The original purpose of the creation of a regulatory framework can be found in economic theories showing that the market mechanism does not always lead to the best outcome. Divergences often happen in the presence of externalities, markets with monopoly structures, asymmetric information, and equity concerns. In a situation characterized by market failure, government intervention, in the form of pricing or regulation, is often justified. Widening Redundant Sensor Networks set up a scenario where the conventional ideas of regulation are challenged. As opposed to those conventional ideas, in the case of Research & Development-and consumption-based networks, it has been identified that these networks can be susceptible to over-regulation. To achieve these goals, it is important that partnerships including private enterprise, government, and universities are established and supported.

13. Ethical Considerations in Sensor Data Usage

Modern-day AI is applied to various data types and diverse domains. Simultaneously, there have been moves to make sensing data openly available, including citizen-sensed data, both of which have raised new challenges, including cyber-security concerns and privacy challenges inherent to the usage of sensor data. So too are these concerns also relevant to sensor data used in Ocean Sensor Networks, particularly from marine wildlife. In this chapter we cover the ethical implications from using sensed data, with a focus on animal tracking data. Many long forget issues from traditional wildlife research are made increasingly more relevant now that they can be downscaled and conducted at lower cost. At the same time new issues from data-intensive and AI-based approaches have also appeared that were previously not so much matter of scientific concern.

Tracking the movement of animals has been a central subject of ecological research for many decades. Although the ethics of wireless tracking are widely discussed in human contexts, the same is not true for animal tracking. The discussions that do exist frequently focus on concerns about the length of time or degree of invasiveness of collaring devices or about risks that extra weight may entail for species that fly, glide, or swim. Research regulations for animal movements thus often emphasize the importance of collecting data that may yield essential contributions to the discipline and of strictly adhering to the concept of the three Rs: replacement; reduction and refinement. Regulatory aspects of tracking critters are straightforward yet leave quite a few ethical concerns unaddressed. The associated debates about ethical frameworks are in stark contrast to growing public criticism of research studies that informantly use tracking devices to measure and model movement patterns and that go beyond pure exploratory explanations.

14. Public Engagement and Awareness

Ocean sensor networks provide a wealth of information about the environment that is usually hidden from sight. Instruments that measure currents, winds, temperatures, salinities, chlorophyll, and a host of other variables allow everybody to better understand how marine environments function and perform. Over time, the visibility of continuous, near real-time data in public forums has increased the general public awareness about ocean science and research. Tide gauges or CTD measurements are publicly available to visualize underwater currents, temperature, and salinity. Similarly, a myriad of other instruments deployed at various locations measure sea surface temperature, oil and gas concentrations in seawater, chlorophyll concentrations, dissolved oxygen concentrations, pH levels, pressure levels, turbidity, and suspended solid levels. Whether it be a near real-time observation using a TV camera or stationary time-lapse observations, these measured variables have been used to document the existence of marine diseases, slime occurrences, and oil spills. The research community and the public-at-large can be involved in this process by deploying commercial or home-built sensors for the benefit of many users in universities, governmental, and non-governmental organizations.

Today, a growing number of public groups leverage the power of networking services, smartphones, sensors, and other devices to act as ‘volunteers’ collecting various measurements in the environment. Known as crowdsourced observations, numerous smartphone applications exist to assist the public in monitoring water quality, algae blooms, marine debris, oil and gas spills, jellyfish blooms, and many other variable layers in the ocean explosion. By harnessing the ability of the public to obtain various types of measurements at a low cost, the research community can increase spatial and temporal coverage for many ocean phenomena, often with the same accuracy as researchers with expensive, sophisticated, and calibrated sensors.

15. Conclusion

The oceans represent a continuous and competitive ecosystem composed of several multi-domain habitats. The need to protect this ecosystem also requires an increased and continuous surveillance of its conditions, in order to track any possible ecological disturbances and take action to mitigate their effects; moreover, to understand the ecosystems' functioning, to favor a sustainable use of the ocean resources and allow circular economy processes. Ecological sustainability is how societies can act collectively to preserve the ecosystem in order to better meet the challenges related to current issues. The ocean is a dynamic system where flows push nutrients, energy and matter among the compartments that create it. A used-based approach enables the forward-looking management of the ocean and the coastal sustainable development of the sea.

The availability of customized and miniaturized sensors has been enhancing the possibility as well as the costs for deploying ocean sensor networks. The advantages of big data systems derived from sensor network deployments have increased interest in real-world testing, enabling more ecology disciplines to eventually share a variety of resources such as data, infrastructures and experiments protocols. New advanced technologies fusion provides end-users with nonlinear ocean model simulations in near real-time that integrates satellites, buoys, ships and observatories. This setup reduces the uncertainty associated with a single observation platform. It has been shown how AI can support ocean observing sensor networks for understanding how and when to exploit these observation capabilities, and how to better design learning- and task strategies for distributing machine learning tasks on sensor nodes to optimize the budget to be used for processing data.

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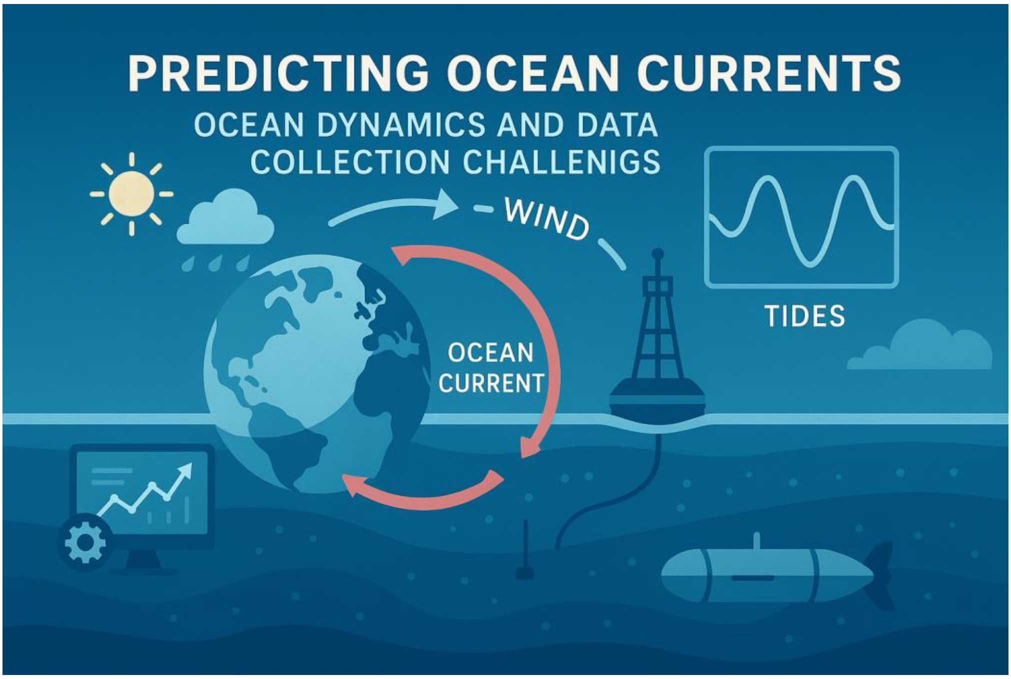
Chapter 3: Predicting Ocean Currents and Tides

1. Introduction to Ocean Dynamics

Ocean dynamics govern the movement of water within the three-dimensional, complicated and densely packed space of oceans and coastal waters. The flow field at any specific time is described by three variables, namely, the conserved mass of sea water and other variables which describe the mobility of the flow and its tendency to alter. The mass of sea water, usually called sea water density, is a function of temperature, salinity and pressure: it can be locally altered only by processes like precipitation and local temperature changes but there are many advective processes that depend on velocity field. The other field variables telling us about the mobility and disposition to alter the flow are the two horizontal velocity components, one vertical velocity component just below the water surface and the vertical gradient of horizontal velocity in the water surface layer.

In about two thirds of Earth's surface, the sea water mass is fairly homogeneous for considerable depths. Density and density derived features such as temperature and salinity can vary dramatically within a short space on the land surface but in the oceans these differences develop slowly and often need to be probed to depths of thousands of meters. Density always decreases with increasing temperature and increasing salinity. Pressure also influences density but, with temperature and salinity as variables, pressure has a negligible influence on surface density. In ocean dynamics, it is far more practical to consider the influence of temperature and salinity changes on density.



2. Data Collection Challenges in Oceanography

Oceanography is intrinsically complex due to the multifaceted influences of atmospheric, oceanic, and geologic phenomena acting at a wide range of spatial and temporal scales. Over time, a variety of technologies for both in-situ and remote sensing ocean measurement have been developed. Ocean observations are generally used to describe the current state of the ocean, assess performance of physical oceanographic models, and validate or initialize operational models deployed daily for operational forecast of currents, tides, or waves on different time and space scales. Each of these ocean state applications has different requirements for spatial and temporal resolution, physical processes represented or neglected, and acceptable levels of accuracy. These ocean state applications must inter-communicate to ensure product development is efficient and maximizes economic value.

The collection of observational data, either from in-situ measurements or from remote sensing products, can be complicated by a variety of factors. The multifarious spatio-temporal issues are due to the deep, vast, and wide-ranging nature of the ocean, where data can be missing, biased, wrong, or invalid. Temporal sparsity comes from certain locations being visited infrequently due to satellite coverage or buoy maintenance and sampling restrictions according to cost limitations. Spatial sparsity, particularly in the vertical dimension, is prevalent from moorings only able to collect data at discrete depths or logging modes of measurements that are not conveniently located at the ocean's thermocline. Data gaps can also result from sensor failure, detection limits of certain phenomena at specific property values, and scheduled data collection interruptions, including costs and constraints.

2.1. In-situ Measurement Techniques

Measurements of ocean properties have been made for centuries using a variety of primarily in-situ platforms, from wooden seagoing vessels equipped with sextants and thermometers to today's elaborate research ships using advanced Digital Sensor Systems. Most often, a ship will map a transect of a particular oceanographic quantity over a number of days, calibrate and spatially interpolate the scalar values to construct a (spatial) 2D or (temporal) 1D map and, afterward, continue the research with statistical studies, models, etc. Ships have been and will remain an important and much-used tool for ocean-measurement campaigns during field work and longer deployments of buoys, and moorings equipped with shallow and deep sensors have been used extensively for years. More recently, physically-hardened floats equipped with sensors capable of sampling vertical profiles of temperature and salinity have been deployed around the world. These autonomous floats drift throughout the ocean at various depths, servicing ASVs and uncrewed underwater vehicles. All operators must use the proper precautions to ensure safe operations in increasingly busy shipping lanes while avoiding contamination of the research equipment through meteorological disruptions.

Fixed and moving platforms are limited in temporal and spatial extent and provide only localized measurements of ocean currents. However, for accurate predictions at coastal and shelf locations, the bathymetry, geology, and hydrodynamics are complex, and high temporal and spatial resolution input data are needed. Submarine cables crossing continental shelves and slopes have been used for many years to measure bottom fishtailing motions and water pressure with high temporal resolution near cable locations, and, more recently, co-located pressure, temperature, salinity, and current velocity sensors have also been deployed in optical-fiber submarine cable networks for near-field environmental monitoring. Long-range, remote-sensing devices may be useful for ocean monitoring over larger spatial and longer temporal scales, such as hyperspectral sensors and LIDAR used for surface salinity, particulate matter, chlorophyll, and dissolved oxygen, and microwave Doppler radar for near-surface current measurements.

2.2. Remote Sensing Technologies

In-situ measurements are characterized by high resolution and low coverage, making it difficult to obtain large amounts of data. In an attempt to circumvent the need for high-cost in-situ observations over the entire domain of interest, remote sensing technologies were developed to monitor the oceans. The focus is set to the derivation of characteristics of ocean dynamics processes adopted and described for the first time using ground-based radar, such as littoral currents, tides, and long period waves through laboratory experiments or analytical models. The extracted parameters will be compared with those collected by traditional in-situ measurement systems, such as moored buoys, and evaluated for both the numerical agreement and the integrative characteristics.

Remote sensing refers to the collection of oceanographic data utilizing fixed, moving, airborne, and satellite-based devices, including scanning laser and Doppler sensors, thermal emissivity measurements, infrared sensors, LIDAR, sonar, and radar. Remote sensing technologies have advantages and disadvantages concerning spatial-temporal resolution and measurement duration as a consequence of the limitations imposed by the monitoring platform. The great benefit of remotely sensed information lies in its ability to provide data under non-in situ conditions, as long as data retrieval is frequent enough. Remote sensing can be effectively used to measure distinct physical, biological, and chemical properties of the ocean's surface and subsurface at scales that are often not feasible using in-situ collection techniques. Since the advent of satellite-borne sensors, optical and infrared sensor systems have provided data for the detection of water temperature ranges, surface color, phytoplankton concentration, and sediment transport.

2.3. Data Quality and Validation

Recent improvements in sensor technology, such as decreasing miniaturized sizes and production costs, have led to a large number of autonomous in-situ and drone-based platforms used for long-duration, continuous measurements of the ocean’s physical, biological, and geochemical properties. More specifically, low-cost platforms such as drifters, buoys, underwater gliders, as well as optical and acoustic sensors, have demonstrated great abilities to monitor fine-scale features of oceanic currents and water temperature time series at continuous time intervals. The multiplatform, multisensor measurements can cover large spatial domains, which is, however, still scarce in situ data compared to atmosphere, land surface, and shallow waters. In addition, methodologically, it is a challenge to match those observations, which are often at different and irregularly spaced time intervals, due to the different sampling strategies.

Despite the above-mentioned efforts, the data quality of oceanographic measurements is again a critical topic in oceanic science, as for many climate records. For example, long-term records of ocean temperature or velocity are of essential importance for studying climate variability, but many of these datasets contain flagged gaps in time or bad data points. Data gaps may be filled using interpolation methods, spatial and/or temporal statistical models, data assimilation into dynamical ocean models, or empirical mode decomposition. However, the filled data may remain uncertain, so it is critical to assess the interpolation, filling, construction, or any quality control methods. In particular, before and after numerical treatment or before and after data assimilation into an ocean model, it is essential to assess the data quality and enclose the uncertainty estimates.

3. Neural Networks for Current Velocity Prediction

In the last two decades, artificial neural networks (ANNs) have brought major breakthroughs in multiple research fields, establishing state-of-the-art results in applications like computer vision and natural language processing; consequently, physical systems long thought to be unfathomable through conventional methods have become wholly predictable with little to no prior knowledge of the system. As a result of these advances, many disciplines have increasingly adopted ANNs as vital tools, and the ocean sciences are no exception. Initial interest in the application of neural networks for ocean predictions dates back to the late 1980s, with their use gaining momentum after the turn of the millennium. Neural networks have since been used to reconstruct hydrodynamic variables, forecast oceanographic processes like sea surface heights, temperatures, and chlorophyll-a concentrations, and model complex physical systems like hurricanes and tides.

Neural networks are universal function approximators: given enough time and data, they are guaranteed to learn a relationship between input and output variables of any continuous function to arbitrary precision and without requiring explicit knowledge of the system to be modeled, such as the governing equations or functional relationships. Oceanographers have exploited this property to create accurate multi-day forecasts of ocean currents using only past measurements of buildup, and multi-directional wave spectra time series to predict wave impacts on beaches days or even weeks ahead of time, without requiring any prior characterization of the domain settings, measurements of external forcing, physical relationships, or even experience with the model. Other modeling efforts have relied on coupling neural network to existing algorithms, either to substitute for some of the assumptions poorly represented in the original formulation, such as turbulence modeling, or to generate the initial or boundary conditions necessary to use existing solvers.

3.1. Overview of Neural Network Architectures

Artificial Neural Networks are function approximators that organize a set of non-linear elementary functions into multiple layers, ultimately modeling increasingly abstract functions. Each layer is fully connected to the previous layer for multi-layer perceptrons, but other neural network topologies exist, including convolutional and recurrent architectures. A neural network with L layers can model functions of the form:

$$f(x) = gL(gL\text{-}1(gL\text{-}2(\ldots g1(x))))$$

where g is a parameterized non-linear function, typically a polynomial, and the parameters are simply the weights of the network. Because of their structure, multi-layered systems, also referred to as Deep Neural Networks, can be trained to a similar or better approximation error than single layer networks using a lower number of parameters if the problem satisfies some conditions. This is, however, not always the case, since multi-layered topology is more convenient but not necessary to implement successively more abstract model functions.

Artificial Neural Networks do not require data to be stationary in order to learn non-linear integrations between the input features and the output targets. This is a strong distinction with regard to both standard statistical learning techniques as well as many physics-based algorithms but cast doubt on the ability of networks to learn the relationships. Additionally, networks are typically trained using samples from the dataset that are independent of each other, although some extensions allow for training networks on sets of dependent samples.

3.2. Training Data Requirements

Neural networks are non-parametric estimators which make few a priori assumptions. As such, they require ample training data to learn from, in order to have generalization capability when predicting unseen data. Also, each network must be trained to predict currents or tides at a particular location and depth. Selection of training data can impact model performance as well. To date, most neural network ocean current prediction models have utilized temperature and salinity predicted from output of conventional models. This can limit the temporal range and resolution of the prediction dataset. Such model output can be used to develop a dataset of temperatures and salinities at all depth levels for the training of a neural network. Networks can then be trained to predict not only currents at all three components, but also potential temperature and salinity, which can be used for model initialization. Obtaining training data that allows a model to be tested at conditions reasonably similar to that at which it was developed often determines the model's usefulness.

In oceanographic modeling the challenges associated with acquiring sufficient data density at range of conditions is exemplified by the strength, range and occurrence of passage of coastal fronts, that affect internal tide amplitude, currents and structure. To alleviate this problem, the training data can be augmented by perturbing the predicted data using state-of-the-art algorithms to improve overall model predictions and, hence, increase network training dataset sizes. Other neural network applications use model output remaining after enveloping the internal tide, which models the remaining internal tide, located several hundred kilometers from where internal tide energy fluxes are comparatively weak, validating the model.

3.3. Model Evaluation Metrics

Several metrics can be computed to compare model predictions to measured data, including coefficient of determination (R2), Pearson correlation coefficient (R), root mean squared error (RMSE), and normalized root mean squared error (NRMSE). Each metric has different advantages and disadvantages. For example, RMSE is particularly effective for checking predicted parameters against categories, while R2 is more noise insensitive and provides a similar percentage of variance.

R is defined as:

where yobserved and ypredicted are observed and predicted values, respectively, and N is the sample size.

R2 is the square of R and is defined as:

If ypredicted perfectly agrees with yobserved, the value of ∑(yobserved,i – ymean)2 is zero, which makes R2 = 1, otherwise R2 will be less than 1. When ypredicted is a mean of the observations, R2 becomes zero. The advantage of R2 is that it is noise-insensitive. R2 is computed using zero mean regression, also called the uncentered regression.

R and R2 can easily be computed without considering the unit systems. But if the model tries to replicate the units of the observations, R and R2 might not be very useful. In cases where the model replications are in different units, other metrics such as RMSE or NRMSE can be used. RMSE is defined.

4. Time-Series Models for Tidal Behavior

Research on tidal behavior is usually focused on predicting future observations of the periodic signal well. However, tidal behavior is not a standard periodic function. The reported tidal harmonics model the tidal behavior by linear combinations of periodic functions. A better tidal model is usually reached if more harmonics are used. A simple linear combination of two sine waves with appropriately selected periods and amplitudes could obtain a tidal signal without a constant. Unfortunately, the periodic functions that could model tidal behavior sufficiently well usually have periods much larger than the observation interval. Thus, it takes a long time to predict tidal behavior with sinusoid functions. A better way to predict tidal behavior is to enhance time-series with models that do not give periodic predictions but produce a more generalized periodic motion shape. The standard time-series model represents the prediction at a given time by a mean value, an auto-covariance function calculated with previous data, and normally-distributed errors. The prediction is not limited to the periodicity. The auto-covariance is calculated over regular time intervals but could take different amplitudes at different points. Still, the model could not fit the tidal shape and, therefore, predict it well enough with a small number of used data, if it has large slopes.

Harmonic Analysis

The sinusoidal model assumes a harmonic function as base, and the periodic function is represented by the first sum considered on the right-hand side: where n is the number of terms (harmonics). A better fit with observed tidal data is achieved with a small number of predicted terms, and the main problem during the fit is to establish values for n, the starting phase, and the amplitudes. The tidal model is made even better if n has not only integer values, but rational values if the amplitudes and phases have not regard to be steady.

Tidal motion has a very long period, in relation to the observation record; the latter is usually composed of several periods of tidal motion. The predicted function could be fitted to the observed data throughout the entire prediction.

4.1. Harmonic Analysis

In the literature, the most advanced models for tide prediction are based on harmonic analysis. First developed in the 18th century, the procedure is based on the linear superposition of sine and cosine waves of various frequencies and known amplitudes and phases, as originally proposed based on celestial mechanics. The Fourier series was originally conceived for the case of periodic functions, which has the disadvantages that tidal frequencies are only well defined in a limited neighborhood of the actual time being modeled and that the harmonic components of the tidal prediction are not invariant under averaging, which would break down the linearity of the procedure. Further, it works best for locations close to the generating tide. In its most basic form, a harmonic prediction is expressed in the form of Sine and cosine terms arranged in two harmonics. Harmonic prediction is at the heart of the body of tidal tables published by various tidal organizations worldwide. The coefficients of the different harmonic terms, which are expressed in terms of apparent and principal semi-diurnal constituents. The program utilized is used for monitoring time series of regularity P (with and without epoch phase). By running the program to detect periods and samples of different tidal components, these data are used as inputs to estimate tidal coefficients and generate tidal predictions in harmonic form, which serve as inputs for other experimental methods presented in this section. The method is inexpensive, simple, generates predictions that can be otherwise difficult to make at locations where tide gauges are not available, and the results can be very useful to people who work in different ocean waves, meteorology, vegetation growth, bat migration, and other disciplines needing to predict tide level.

4.2. ARIMA Models

This section is devoted to a more generalized time-series model, namely ARIMA. The model is a combination of a so-called autoregressive-moving average (ARMA) model, which is fitted to the differences of the time series, possibly after the time series has been transformed to ensure that it is approximately normally distributed, together with a term for the seasonal differences if the time series is seasonal. The so-called autoregressive (AR) part of the model indicates that the temperature values for a given day, as modified by the transformation, tend to be related to its own values on previous days, say L days earlier.

Tidal periods are, of course, very small for most time series models, usually either a diurnal 24 hours or else 12 hours for those locations where the tidal waves cancel each other at the diurnal period. Any ARIMA model will have Yit correlating with Yitj at time lags equal to the period of highest or lowest tide; that is, the temperature will be related to its value from the previous diurnal or semidiurnal tidal cycle. Also, for all locations, the temperature will be related to its value from previous days. It is natural that tidal predictions should be related to weather predictions, which usually also require a multi-day time difference unless the frequency of measurements is very low; for example, at the Kevo subarctic site in Finland, the air temperature is related to its own values two days previously.

4.3. Comparative Analysis of Time-Series Models

For the work "Predicting Ocean Currents and Tides", the following is a concise yet coherent text for section "4.3. Comparative Analysis of Time-Series Models" that delivers concrete, specific, factual information relevant to the title for the section.

Harmonic analysis represents a constant tuning of the parameters, and the learning of the network could be achieved from the input-output relationship, at the same time as the possibility of adaptively changing the coefficient parameters of the network. ARIMA models allow to statistically extrapolate the fitted curves to the future when the criterions used for the evaluation of the verification of fitting by the ARIMA process, i.e., residual analysis, are satisfied. On the contrary, neural networks used to learn the relationships between inputs and outputs allow for the building of decision models with the eliminations of internal residuals. For the problem of tide prediction, hedging, and therefore limiting the error of the prediction at one stage, as long as the models to be built are quantitatively similar in the interpolation phase, we can say that the prediction with the minimum residual will not be the same according to Port, requiring models of approximate prediction for times such that the prediction of the two model predicting the Port above, remains associated.

For the modeling with neural networks, we have to use a supervised learning algorithm to associate the input data with the desired output. Then, two tidal prediction models predicting a single data are created, for forecast horizons close to the time when the model is built and that separates by two values small enough not to invalidate the tidal prediction model on the possible subsequent repetition periods. Finally, by using the two previously built models, the values in parallel to the two Port predictions are extracted, and the corresponding prediction approximations are extracted.

5. Integration with Oceanographic Simulation Models

Well-calibrated numerical simulations of the ocean can provide, at times, more accurate estimates of ocean currents than the direct observations. Therefore, to obtain even more accurate predictions of ocean currents and tides in the future, one option is to integrate the predictions provided by a data-driven approach with those from a physics-based approach. In this section, we will discuss how to couple our predictions with real-time oceanographic model simulations, and their benefits. Specifically, we will focus on two hydrostatic, free-surface ocean models: the Hybrid Coordinate Ocean Model and the Regional Ocean Modeling System.

The Hybrid Coordinate Ocean Model was developed in the 1990s primarily by researchers at the University of Miami. Since then, the existing core group of developers, operatives, and users has expanded. This model is an advanced, general-purpose ocean model that integrates the governing equations for the oceanic momentum, continuity, thermodynamic energy, salt, and biomass via a third-order, semimonthly, implicit Lagrangian scheme along meteorologically forced particle trajectories. Oceanic currents, temperatures, salinities, densities, and pollutant concentrations are then temporally extrapolated along Lagrangian trajectories during model hindcasts and predictions. An important aspect of the core of any data-driven prediction system is how to inject the predicted currents and tides from the data-driven approach into the model. This involves spatio-temporally varying adjustments to the momentum equations.

The Regional Ocean Modeling System is a numerical ocean model that solves the three-dimensional primitive equations of motion in terrain-following coordinates. The model's Finite Volume capability allows it to couple the horizontal momentum equations using a backwards-in-time scheme and to vertically integrate the continuity equation to construct the 3D velocity field.

5.1. HYCOM: Hybrid Coordinate Ocean Model

The predictions of currents used in the LBL and BBL approaches were provided at the Navy’s request by the Hybrid Coordinate Ocean Model. HYCOM is an ocean model, as defined by a set of partial differential equations that govern the movement of ocean water over its 3D domain in terms of boundary conditions and physical initial conditions, such as salinity, temperature, and pressure. The state of the art in operational ocean modeling uses numerical weather prediction technology for numerical solution of tightly coupled, time-dependent, primitive equation systems of the equations of motion, continuity, state, and thermodynamics of the ocean. These advanced numerical techniques enable simulations of ocean circulation at large scales, from the global to the basin size but with relatively coarse resolution, as well as coupled numerical solutions at the regional size but with very fine resolution for highly dynamic areas.

HYCOM has undergone tests over a number of years and is mature enough to be used in several applications, including defense-related applications. It is unique among operational models in its hybrid (or variable) vertical coordinate concept, using isopycnal coordinates in open ocean areas where stratification is the dominant feature of oceanic hydrography but three coordinates where stratification is weak, as in upwelling areas, close to land, and near the surface and bottom. Because of its variable, melt-compressed ice thickness parameterization, hybrid coordinate concept, and the fact that it is the only common operational ocean model, resulting in its acceptance for defense applications, HYCOM was chosen as the provider for all of the BBL and LBL results described in this report.

5.2. ROMS: Regional Ocean Modeling System

The Regional Ocean Modeling System (ROMS) is a free-surface, terrain-following, primitive equation ocean model specifically designed for modeling coastal and shelf seas. It is primarily developed under the direction of a researcher at a university and is extended and used within the framework of a modeling system for the marine environment. ROMS is a versatile coastal simulation model that solves the hydrostatic, primitive equations of motion in spherical coordinates with a terrain-following vertical coordinate. It uses a mixing closure to damp inertial oscillations while allowing longer adjustment time scales and potential energy solutions to be resolved. The model has been implemented and tested in a number of variable geometric and physical configurations and is designed to use available computers efficiently.

The ROMS model system computes non-hydrostatic baroclinic flows in a variety of complex, unstructured, three-dimensional (3D) geographic domains with boundary conditions at the surface, seafloor and sides. It employs four-dimensional (4D) data-assimilative variational techniques to make best use of available real-time data from the oceans. ROMS provides a computationally efficient tool for the time-dependent numerical simulation and analysis of various oceanographic flow problems, especially those related to coastal and estuarine regions and inner-shelf and shelfbreak processes, with realistic topography and bathymetry and appropriate initial and boundary conditions. In addition, the model provides a numeric simulation framework for coupling with other models such as sediment transport, wave and wind-wave dynamics, and fine and course particle tracking and dispersion. Moreover, the spatially-explicit outputs of the ROMS model provide a better approximation for the support footprints of the physical processes, thus providing better statistical inference for the model parameters.

5.3. Coupling Neural Networks with Simulation Models

In the previous Chapters, we have used only Neural Networks and Deep Learning methods to predict tides and ocean currents. These algorithms have performed really well and updated the short-term tide and ocean current predictions statistically. However, these algorithms work in the alerting mode, meaning service providers run them every time model outputs are to be analyzed, and they do not provide continuous prediction of ocean currents and tides. Continuous prediction is what simulation models are created to provide at different time intervals. Predicting quantities at different intervals or time series generation is what simulation models do.

What we propose is a hybrid method where we couple Neural Networks with oceanographic simulation models to harness advantages of both. We train Neural Networks along with outputs of the simulation model to correct for systemic error. Hybrid methods improve prediction skill and usually have a skill higher than either method used separately. Coupling simulation models and other data drives the optimization of the data-driven model with physics and the benefit of a large dataset. Implementing and integrating these hybrid models as software tools into oceanographic simulations systems allows improving forecast/nowcast skill of hydrodynamic models without internal changes into their components that are highly tuned. Moreover, the sand box of the coupled system opens interesting scientific opportunities in both directions; data assimilation into simulation model systems or reanalyses through methods using hybrid approaches.

6. Forecasting Use Cases

In addition to local applications, ocean current and tide forecasts can be valuable to many additional stakeholders, including the shipping and fishing industries, search and rescue operations, agencies that work with oil and gas, simulating the impacts of underwater disasters, and environmental protection agencies. This chapter will go over how ocean current and tide forecasting is useful to these collaborators.

6.1. Applications in Shipping

Maritime transportation is important for the supply chain, and during the foreseeable future, coastal shipping will continue to be an important component of world trade. Ships are becoming larger, which presents challenges when entering and leaving ports, along with increased impacts on local waters. Routing decisions are also being taken under considerations of reducing fuel costs and associated carbon emissions. Strong and poorly timed tidal currents can make these decisions even more complicated. Many ports are using information from the hydrographic and meteorological offices to determine optimum times for vessels to enter and leave locations. Continually updating these predictions would be a valuable service.

Ship routing is mostly focused on minimizing transit time. Predictions of wind, waves, currents, and other phenomena can be assimilated into optimal control algorithms that steer vessels along the minimum time route. As ships continue to increase in large size, these routing decisions can become even more complicated.

In addition, some of the areas for increased shipping traffic during the next decades are new and sensitive. The melting of the west polar ice cap has opened the Northwest Passage and the Northern Sea Route. Monitoring the environmental and ecological impact of these changes will be necessary. Since monitoring these oceanic and atmospheric conditions can be expensive in these remote northern areas, the use of ocean models could be helpful.

6.2. Search and Rescue Operations

Search and rescue (SAR) operations have undergone significant advancement since the initial experiments employing radiolocation systems in WWII. Indeed, while the first results of the recently deployed SAR were promising, it must be acknowledged that no system exists which provides for all individuals at sea being located alive and uninjured after a prolonged period of immersion. Nevertheless, there is an increasing demand for longer range and longer duration response operations and for the use of airborn detection devices to assist tactical SAR units. However, policymakers need information on the expected duration of SAR response operations, and on contributing or limiting factors regarding the ability of the SAR operation to assist potential victims. While this information is difficult to obtain or model for land or inland waterway operations, some conclusions can be drawn from past maritime experience and these can be used to help model maritime SAR response. If SAR continues to be conducted using the currently employed resources, with the proportional capabilities and functions outlined, the decision can be made as to whether this is a function commensurate with the observed risk. If so, then the facts can be well communicated to interested parties and the risk accepted.

The implementation of the SAR concept within Federal legislation contains an implicit acceptance of the risk presented by defined categories of accident, and provides resources in proportion with that risk. This concept is reaffirmed by the naming of the different agencies involved in the SAR function, and by the operational procedures and training which have grown around that function. If necessary, this risk-acceptance document could be further refined, by clearly defining the infrastructure, and associated attributes, used to support the SAR operation – the times available should SAR be required; the various response times to be expected; the likelihood of a successful expedition; the degradation in those probabilities; how SOSUS could be used; and the efficiency of the response.

6.3. Environmental Impact Assessments

Environmental impact assessments are conducted prior to nearshore constructions, such as dredging, bridge construction, wind farms, oil and gas platforms and pipelines, and static aquaculture. Currents can shift sediments and redispose dredged materials. Tides exert forces on the shore and in shallow waters, impacting the violence of water-borne sedimentation. Aesthetic issues pertaining to visual impact, lighting, and stimulation of stranding fishing vessels are parts of such assessments. Migratory birds may be drawn to illuminated platforms or otherwise shift their migratory routes. Benthic community analyses reveal short-term marine life injuries caused by excavation-induced releases.

Primary effects impact the organisms directly exposed. Water currents can disorient fishes during spawning and larval dispersals; relative density or velocity thresholds induce entrainment. Lethal need-to-burrow and plume-avoid threshold exceedance times can cause larval losses in shrimp stocks. Larva retention in inshore zones by currents induce penaeid larval seasonality. These cumulative larval mortality effects may be applied in risk assessment algorithms. Larval damage will be considerably worse in sediment-rich environments during storms. The severity of larval damage depends in part on the timing of natural abundances, which vary seasonally about ultimate peaks. Avoidance of intensive dredging annually during dietary requirements may reduce adversely affected population sizes and their recruitment-success shortfalls. Sediments suspended by dredging cause plumes. Plume-induced damage on catch will depend on plume area, local species and crowding densities, spatiotemporal mismatches, and local sensitivities.

Dredging may affect upweller performances and cause benthic biological community alterations, disrupting the abundance-establishing natural stocks. Wind-turbine induced environmental impacts would also include seasonal disorientation exposure risks for spawning and larval dispersal fish because of the turbulence near alternating- and direct-current power transmitting lines, especially the pylons inshore and offshore.

7. Conclusion

Predicting ocean currents is challenging, as a global ocean circulation model is difficult to derive given the number of parameters and spatial-temporal scales of interest. In recent years, however, it has become possible to take advantage of the vast wealth of data that is related to ocean movements due to the growing interest in ocean movement data collection, the growing computational resources, and the rediscovery of data-driven and physics-assisted data-driven methodologies. This wealth of data allows us to develop predictive models based on different types and configurations of neural networks, such as recurrent, convolutional, or autoencoder networks that map the input onto the output variables of interest. The growing ability we have developed over the years to predict ocean currents in an accurate and physically consistent way also allows us to predict a number of other ocean-related variables, including the ocean thermal state.

Indeed, physics upon which ocean currents depend gives neuroscientists additional information when developing accurate predictive models. Take, for example, the prediction of 3D and 4D ocean temperature fields; they can be mainly driven by the 3D ocean current fields. Moreover, even when ocean temperature is diagnosed via a conservation equation rather than a measured temperature kernel, the convolutional autoencoder captures complex patterns and learns them efficiently. We can therefore expect that using an appropriately designed neural network and accounting for geophysical considerations will allow us to predict a number of geophysical variables of interest in a better way. Global warming has also opened a Pandora box of less frequent and yet extremely damaging geophysical events; unexpected floods or extreme drought drying regions never seen it, an increasing number of hurricanes, or tropical storms that impact on regions considered too cold to be affected by them. These and other extreme weather events will likely increase the science-related applications of satellites, boreholes, buoys, and other sensors and instruments collecting geophysical data.

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Chapter 4: AI Applications in Marine Weather and Storm Forecasting

1. Introduction to Marine Weather Forecasting

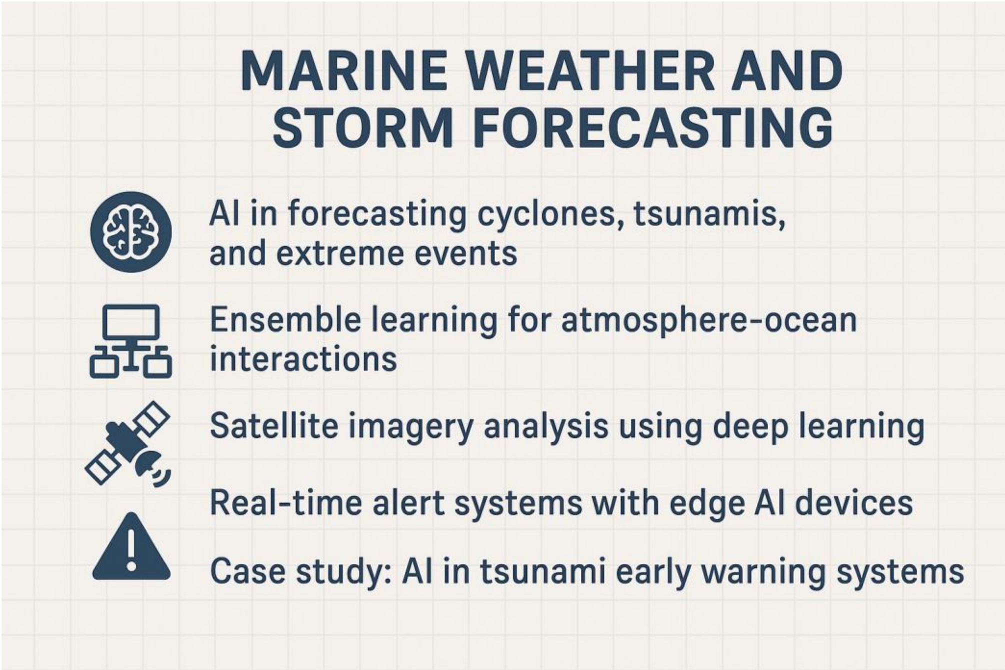
Marine weather forecasting assists in forecasting the parameters occurring on and above the oceans. The dynamical processes that govern weather conditions (such as wind, wave, temperature, precipitation, cloudiness, humidity, temperature, cyclones, etc., at and adjacent to the ocean) cover a large space. Some reasons for studying the atmosphere are: the atmosphere gives important boundary conditions for the ocean (and for the climate system as a whole); buoyancy fluxes (and clouds) mainly come from the atmosphere (impacting ocean); tropical disturbances (cyclonic or anticyclonic) propagating from the atmosphere provide the main energy of the ocean (via Rossby waves); all ecosystems depend on atmospheric conditions (wind, clouds, sea surface temperature, etc.); the atmosphere is sensitive to oceanic changes; the atmospheric response to oceanic warming has a signature in precipitation patterns; and influences the atmospheric jet streams in winter. Physical processes related to long-term shifts in atmosphere/ocean coupling are still not well understood. Research reconstructions from marine and terrestrial sediments complement information from tree-ring data in explaining the premature 21st-century warmth relative to the last millennium.

Most large-scale weather systems are driven by temperature gradients from east to west at mid-latitudes. This is related to the fact that the warmest waters are located in the tropics (and subtropics) and coldest subpolar regions. The meridional direction in which these gradients drive the atmosphere implies that the two oils of the North Atlantic and North Pacific are regions prone to intense winter storms. The capability to forecast and understand synoptic rainstorms depends greatly on the data network and the availability of computer resources. In order to predict short-term weather events, a network of meteorological buoys obtains real-time observations. This enabled scientists to ascertain the role played by the currents in the ocean circulation.

2. AI in Forecasting Cyclones

Tropical cyclones are categorized as severe weather phenomena along with thunderstorms and tornadoes. These cyclones develop from tropical disturbances, and when given conducive environments, grow into tropical depressions and intensify into tropical storms and eventually into tropical cyclones. Further intensification of cyclones leads to the development of an eye and an eye wall. While the sustained wind speeds over the neighboring land areas up to 63 kmph become damaging, intense cyclone gust winds up to 275 kmph along with storm surges and heavy rainfall over the sea and land areas lead to disasters. The resulting storm surge caused the loss of life of about 1,38,000 people and damage of about $10 billion.

It is also seen that there has been a significant increase in the frequency and intensity of global tropical cyclones over the past 40 years. Due to the disasters caused by cyclones, an early warning is a necessity of the hour. Tropical cyclone prediction relates to the monitoring of the formation, track, intensity change, lifecycles, etc. The unique complex physics and dynamical processes involved require the application of advanced Artificial Intelligence techniques like machine learning, deep neural network, etc., for enhancing predictability and providing probabilistic and deterministic forecasts. Recent advances in both hardware support and algorithmic design to utilize big data available at varied temporal and spatial resolutions have made the application of AI a serious research possibility.



3. AI in Tsunami Prediction

The prerequisite stage for tsunami forecasting is the detection of earthquakes in the ocean. Using seismic signals because they travel more rapidly than surface waves, the location of an earthquake using a small number of seismic sensors is done in a multi-stage process. The first seismogram arrivals depression are used to identify the earthquake. The magnitude is determined from the amplitude growth of the waves arriving later. Based on the location, size, orientation, and physical characteristics of the earthquake, the associated tsunami is predicted — carried out via a computationally robust numerical model. The predictions include wave height, waves first arrival time, ground shaking, and more. The tsunami forecast is important for optimizing the messages sent to the public and warning the local agencies. It is not surprising that the above scope of knowledge involves a number of uncertainties and challenges. How to potentially enhance these predictions is thus a looming question. We believe AI is capable of helping achieve this.

A convolutional neural network model modified to also encompass physics-informed loss functions via automated differentiation helps narrow the above uncertainties. While we acknowledge the need for collaboration with both geophysicists and AI researchers, we present preliminary results to demonstrate the knowledge gained from merely attempting to predict the tsunami response. The output is trained and tested on a synthetic database of tsunami waveforms generated via a linear-water-wave numerical model used extensively for tsunami research and prediction for learning the weights.

4. AI in Extreme Weather Events

More than two million people have died from extreme weather events in the past century, and over $3 trillion in property damages have been attributed to them. These statistics underscore the fact that extreme weather events impact populations all over the world. Severe storms, such as blizzards and hurricanes, along with associated phenomena like storm surge and coastal flooding, have deadly consequences. The frequency, intensity, and duration of various extreme events have all become more severe due to climate change. Hurricanes have increased in rooftop wind and rainfall intensity, and heavy rainfall has increased drastically in many regions. With more moisture in the air, flooding events are becoming more severe, affecting areas not accustomed to heavy rains. One of the main missions of meteorologists is to forecast the intensity of specific extreme weather events. Predicting their intensity and duration involves modeling the weather conditions that generate them. Unfortunately, it is still very difficult to forecast the exact influence of climate change on specific segments of the probability distribution of extreme events. Although we know that the probability of extreme events has increased due to climate change, we do not know exactly how long-term climate change will interact with the collection of processes that create specific extreme events over the next few decades. Due to Earth’s complexity, extreme event attribution relies on an ensemble of climate models and an understanding of physical mechanisms that still need to be more clearly defined. AI is being employed to help fill that gap in understanding.

5. Ensemble Learning for Atmospheric-Ocean Interactions

5.1. Overview of Ensemble Learning

Ensemble learning is one of the most successful approaches to supervised learning and it is widely used in many real applications. Although the idea of using multiple simple hypotheses to build a more elaborate model is very intuitive, it has many theoretical and implementation aspects that are not easy to understand and use. A process for designing an ensemble, which is made up of a number of heterogeneous prediction models, called base models, is to train the base models to learn the same function or a different function, and then combine them into a single more accurate model. There are two main phases in a general ensemble learning approach, the training phase where the model is built, and the application phase where the final model is used for prediction. After the training phase, the ensemble is used like a function that adds all the predictions from the base models to give the final predictions. The key idea here is that when a single model fails, there are chances that at least one or few of the base models in the ensemble will produce the correct predictions.

5.2. Applications in Marine Forecasting

Research has been carried out on the application of ensemble models in marine weather forecasting. In some systems models are used to collect information from different areas of the atmosphere and ocean, and are combined into one model using another statistical model. Systems that combine multiple models use a single and massive ocean and atmosphere model, and then use it to forecast in situations that would cause the single model to fail, while other ensemble techniques produce a forecast of a single variable, like hurricane track prediction, using a set of dynamic models that do not interact with each other. All these techniques have a cost. The dynamical models must be made to run and synchronize at regular intervals over a large area and time outside the latent region, and be able to produce and store ocean model outputs, which must be used to initialize the atmosphere models.

6. Satellite Imagery Analysis Using Deep Learning

Satellite imagery has become an indispensable tool for monitoring natural phenomena, offering a myriad of applications in fields such as meteorology, hydrology, geology, and forestry. Recent advancements in deep learning, computer vision, and image processing have significantly improved the analysis of satellite imagery across diverse domains. Initially employed for commercial applications, these techniques are now being disseminated through open-access platforms and utilized for various Earth observation tasks, including image classification, image segmentation for land cover mapping, and multi-modal applications. While the extensive use of satellite imaging in several fields seems promising, the reliability of the products is highly dependent on their specifications and the capacity to accurately assess the imaging results.

There are mainly three major techniques in satellite image processing: geometric corrections, corrections due to the atmosphere, and the normalization of the results. Satellite image segmentation in particular has been enhanced with applications of convolutional neural network architectures. Satellite imagery analysis opens up the possibility of automating weather forecasting, nowcasting, and simulating global weather models. Over the last decade, research and publications on the use of deep learning to automate satellite imagery meteorological data extraction are growing quickly. Several studies focus on creating a methodology to automate the tagging of satellite data, while others concentrate on simplifying multiclass meteorological-based algorithms. Other works use an ensemble of machine learning to preferably boost performance in the lightly segmented meteorological scene. When it comes to automating the meteorology or major events in cumulus cloud scenes, a handful of binary cloud masks are routinely referenced and stated as precursors to dedicative deep learning image segmentation networks.

6.1. Techniques in Image Processing

With the advent of Deep Learning (DL), the computerized analysis of satellite images has progressed salubriously in the last years via an increase of the implementation and performance of the associated DL tools and techniques for the proper processing of images and validation of the derived models. Primarily, the image processing involved has relied on certain key DL techniques that include Convolutional Neural Networks, ResNet, U-Net, spatial attention modules, temporal information analysis from spatio-temporal data cubes of satellite images, Long Short-Term Memory networks, spatio-temporal sequential conditions, predictors or autoencoders, spatial-temporal linear convolution modules, image segmentation with Fully Convolutional Networks, No-See-Though Generative Adversarial Networks, optical data input/output of satellite thermal data, Explained Variance Score optimization, and wavelet transformations. Apart from these primary DL techniques, advanced tools such as Multi-Layer Perceptrons and Multi-task Learning have also been used, along with sensor fusion techniques as required at hand, while image-associated variables such as remotely-sensed sea-surface temperatures, genuineness of various optical and/or thermal imagery composites are also of immense assistance in the incorporation of proper DL techniques via concurrent band passing filters or certain model procedures. Certain hybrid models comprised of machine learning tools are also in use, thus acting to synergize and capitalize both procedures.

Indeed, one of the challenges for generating the satellite-cast Data Products with Lower Uncertainty (DPLU) at hand for a majority of the DL attempts has been the validation of the used DL cachets by way of required for quality consideration and as input/output of a majority of the image processing pipelines. The higher is the parallelism of the utilized Data Products with respect to respective orthogonal, modeled/neuro refined/adjustments of the incorporated time-series imagery with respect to the events featured in the imagery of the survey, the increased integrity in the confidence of the DL attempts via the respective DPLU used is achieved in the validation by road learning/allocation functions for generation task.

6.2. Deep Learning Models for Weather Analysis

Deep Learning provides a technique of building neural networks composed of many layers between the input and the output layers. Deep Learning architectures have recently begun to improve several subjects of computer science. In the field of weather analysis, state-of-the-art architectures have shown much better performance than the existing traditional techniques. Today, large labeled datasets composed of satellite images exist, and it is possible to pre-train deep neural networks on a large dataset and then fine-tune these neural networks on small datasets. It has been shown that Deep Learning is capable of performing better predictions with fewer data than traditional technologies. Furthermore, the combination of using several pre-trained visualization neural networks with the traditional technique – Support Vector Machine – has been applied to weather dataset acquisition, showing greater accuracy than classical techniques. Many researchers are successfully exploring the use of Deep Learning in weather images and data analysis. Numerous other researchers are also using pre-trained convolutional architectures with a Support Vector Machine classifier to find severe weather events.

Techniques in weather, climate, or satellite image analysis are usually used in one of two ways. The first way is to use already detailed, high-resolution satellite images. Several studies show the capability of using convolutional neural networks to find deep convolutional features in already reconstructed clear-sky or cloudy satellite images in order to classify and retrieve cloud class, micro-physical, and optical property characteristics needed in numerically simulated, modeled, or analyzed weather, climate, and environmental data. The second way is to use the latest government-developed and opened, launched, and operated satellite imagers using coarse vertical resolution hyperspectral retrieval data as pretrained neural network input features, and then increase the horizontal resolution through the use of traditional image processing and Gaussian convolution methods.

7. Real-Time Alert Systems with Edge AI Devices

The latest breakthroughs in AI have enabled the implementation of highly complex models on consumer devices, such as smartphones and drones. These devices can execute full AI pipelines, improving the privacy of sensitive data and minimizing communication overhead and latency when transferring user data to a backend facility. Such devices are often referred to as edge devices. Implementing AI pipelines for Real-Time Alert Systems on edge devices is more complex than just transferring the AI model to an edge device. In the current world, a high volume of data is continuously streamed from a diverse set of devices. Most of this data is from IoT devices and is created with different sampling frequencies and on different time frames. These APIs must be handled to create a stream that can be input into AI models. This requires the implementation of various components, such as data value mapping, contextualization, data fusion, and rhythm coordination, forming an IoT Architecture.

This chapter will briefly introduce the Architecture of Edge AI Systems and detail our implementation of such an edge architecture for Real-Time Alert

Systems in Marine Weather and Storm Forecasting. Edge Intelligence, combined with the Internet of Things, allows distributed data processing with quick data context mapping and in-device learning. Real-time applications can benefit from a reduced response time with low latency fragmentation and high clouding availability. Yet these systems need to be guided through an architecture, indicating the desired IoT components. We present a high-level architecture clustering IoT components into devices and an IoT backend. This architecture shows a proof of concept in the field of Marine Storm Forecast with observations, meteorological forecast data, and multiple AI Inference Models that lead to different storm identification results. With our implementation and the presented architecture, we show the possible functionalities of edge devices in a cooperation with IoT backend functionalities concerning a storm early warning system. Proposed future work aims to improve the backend system's capabilities by reducing the required resources and time for actual threat location and severity prediction.

7.1. Architecture of Edge AI Systems

The rapid advancement of artificial intelligence (AI) and its increasing availability and affordability have made it possible for governments, communities, and enterprises to build intelligent real-time alert systems to improve marine space monitoring and weather forecasting capabilities. However, anticipating disastrous marine storms from models operating only on computing clusters or scheduling programs on rented servers is an arduous task requiring months of effort and substantial expense. Notably, commercial companies have established an ecosystem of disaster mitigation and space operation services using satellites and aircraft to image, scan, monitor, and predict disasters. Similarly, edge AI devices could be employed to solve the real-time triggering problem, providing synergistic support and the possibility of early triggering of disastrous storm alerts for marine weather forecasting with less expenditure and effort.

The present systems leverage existing resourceful models and processing units located at a distance, waiting for inquiries. Edge AI systems invert this process and provide the means and capabilities to the people most affected by the disaster risks using devices that are typically with them or nearby and can detect triggers and signal alerts earlier and even autonomously. We describe the architecture of these systems, tailor-made for edge AI time series-based detection and prediction problems, and exemplify its impact in the specific domain of marine space monitoring and storm forecasting. Following the recurrent temporal process characterization of most weather forecasting problems, we show how solutions to detection or prediction applications of interest in marine weather alert generations at a heterogeneous sensor system level could be developed as multi-layered deep neural networks trained with a large data repository compiled according to three application-specific policies in transfer learning mode. A simpler one-layer version of this architecture, which we call the edge AI device detection box, is mostly used for edge AI devices for detection applications.

7.2. Implementation in Marine Weather Forecasting

The implementation of computing techniques in the field of marine weather forecasting requesting for real time alerting of "high-impact extreme weather" and "hard-to-forecast" local weather phenomena is an advanced AI-based solution at edge services with a very large thinning-out of data. This differs from the traditional view of AI weather applications which often funnel large volumes of remote sensed data, either image-based alone or image+NUM data from weather numerical modeling, advanced data assimilating supporting, downscaling for very high resolution, and data-cued based supervised learning setups for many different focus marine weather phenomena or areas. Instead presented here a contrasting view of Edge AI+alpha only solutions at NWP model scale resolution. The critical objective of deploying of alerting at edge scale, and also with very high speed, is to alert at epochs before the actual marine incidences stated above lead to dire consequences. These solutions use high performance video and tracking and simulation based on in-house semi-Lagrangian based particle tracking capability rebuffed into enable fast particle tracking through very high resolution vessel cam-based volumetric fVTu varScoped and fVTI-varSPo temporal evolving 3D MHD model weather fields. AI computing for qualifying performance enablement of data-caled baseline cloud motion+object/feature selection and tracking+particle tracking through volumetric MHD flow developing over nautical HW and SW observations. This note details on the forecast alerting capability for small marine craft to AI enabled at edge device implemented precipitative cloud motion based fVTI horribly frighteningly high SOCK and deadly high SOAT capabilities MOT inferred rapid destroyer navigations through weather affected region –PCMT Soak, PCMT Soat, and PCMT Souk and warns against vessel maritime mediated timescales of observances of the associated weather induced threat.

Developed the in-house cloud motion assess capability inputting available NWP forecast but with the AI enabling enhanced particle tracking and cloud object motion track pre-processes.

8. Future Directions in AI and Marine Weather Forecasting

Among the many areas of maritime impact, we have focused attention on marine weather forecasting. Perhaps the most urgent challenge is to employ scientific understanding to guide the development of AI and ML in marine weather forecast settings and to address some clear scientific issues. There is no doubt that AI functions well in many marine issues and is growing in capacity. Applications and research interest are increasing and will become an important component of forecasting research. However, ML is not the whole answer to weather. AI and ML are generally concerned with surrogates and substitute representation of the forecast parameters, in particular, the image-building of different models. Because surrogates will remain for some time necessary, ML is likely to be frequently employed.

Scientific understanding remains crucial to QA the ML subsystems. The final challenge for research will be to develop and test a more integrated information and data function using AI and ML noting the necessity of appropriate scientific constraint and tuning. Other subjects will address, among others, the increase of add-on parameters, the improvement of tools to deal with very long lead time predictions in particular seasonal and decadal and the fusion of physical and empirical methods. Despite these challenges and caveats, it is reasonable to expect that AI will be introduced in the near future as a valued member of the MMM forecast team. These developments will probably not occur without a modest series of starting projects, but by mid-century or even earlier, the reception of primary ideas, new regimes, and creation of new specialties in Forecasting Education where physicists and computer scientists will collaborate on diverse efforts should allow the merger of new information with traditional approaches. The good news is that with these partnerships, we may begin to improve on the existing prior economies and the users need not wait until the vendor volunteers improvements for quite some time.

9. Ethical Considerations in AI Applications

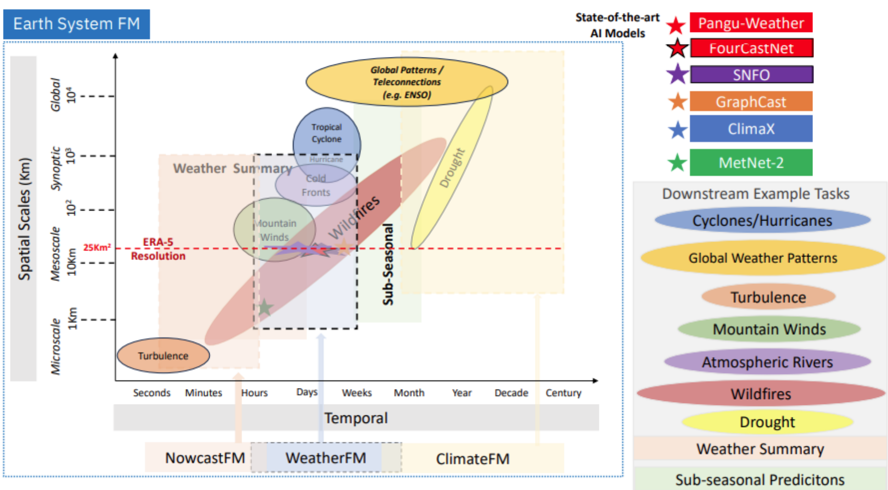
AI has demonstrated a clear benefit in assisting forecasters to analyze and assess the reliability of all model outputs for a given forecast situation. AI techniques need to further advance by including the continuous development and examination of best practices, considering the application of a number of different techniques for any given challenge, ensuring well-documented results and comparisons, and providing confidence intervals where possible. AI should not take over forecasting decisions in dangerous situations. Instead, it should be designed to provide an "intelligent assistant" function, allowing forecasters to focus their attention on particular regions of interest or on certain models of interest, guiding the forecaster through the sometimes cumbersome exploration of conflicting messages throughout the multi-model/Multi-Analysis Ensemble systems. The ultimate decision must rely on trained personnel who consider all inputs, including situational awareness, past experience and consequences of potential errors.

Training the AI techniques using datasets with human cognizance incorporated is essential. There are various ways to go about that, e.g., have the AI learn from every conference call, have the AI scrutinize manually written summaries, and/or manually annotate the data, examining the confidence and boundary cases of the AI. In addition to using human knowledge in the training phase, we must maintain human oversight of the AI. Ethics recommends that AI be applied at levels where it can still provide useful insights, while the ultimate decisions must reside by the expert forecasters, carefully weighing all aspects and potential consequences, including the avoidance of disproportionate impact from either false alarm or misses for vulnerable communities. Especially in the area of severe marine threats, AIs must be trained by humans, and the predictions constantly monitored. AI techniques can be dangerous as weather/ownership probabilities are not static.

10. Comparative Analysis of Traditional vs. AI Methods

Earthquake, cyclone, tsunami, and storm surges are natural disasters caused mainly due to atmospheric and oceanic phenomena. Among these, cyclones and storm surges are of significant concern globally because of immense destruction. The intensity of cyclones has increased in the last two decades, and the impact of storm surges has become a serious issue because of the presence of large coastal population density in many littoral countries across the globe. Even small rain storms lead to heavy loss of life with damage to industrial houses, electric grid, and telecommunication systems. Old vineyards and crops developed in areas for decades are destroyed in no time. The information in documents related to earlier hit data with metrological parameters is useful to classify minimal or small storm-related damage to structures like electric poles, mobile towers, and fragile buildings. This is analyzed before the coming of any rain storm by AI or machine learning classifiers. The classified information is passed on to the local/sub local administration so that preventive action may be taken to prevent damage. Though it may look simple, the task given to AI is not simple; therefore, the document gathering is an important task and is explained in the successive sections.

Artificial Intelligence applications are playing more and more crucial roles in each field. In doing so, they are accelerating work performance and enhancing skills, coming up with predictions and execution plans in all areas, which were only dreams to many engineers and researchers previously. Engineers are no longer involved in performing tedious minor tasks, because of well trained and applied AI functions to ease out the task. Hence, discussions are going to be there about these systems in future.



11. Challenges in Data Collection and Processing

Climate data is generated at specific time-steps and at numerous different locations. The weather conditions at the created data locations will differ considerably in a small time interval. For instance, in winter, the temperature measured at a location near the coast and at a location in tropical climate is expected to differ significantly. The time taken for the data to be created at the specific location and for its availability is also important. The generation and availability process may also involve delays when the data is received from numerous different sources. Certain natural events might lead to a specific aspect of climate data not being collected such as not mapping out vegetation data in a specific period in the future. The absence of data as well as dissimilarity of the data may lead to challenges in data pre-processing and impact the model accuracy in AI training for climate applications. However, various data pre-processing methods can be developed to ensure more accuracy during data processing and effectively reduce the mentioned issues. Such corrections to the collected data may require high-level skills and effort. However, regardless of the data pre-processing method developed, data collection period and method, as well as data availability, can affect the success of AI models for climate applications.

The success of the used AI model in predicting future values of climate parameters depends on the type, quality, quantity, and availability of the input data fed to the model. Thus, sufficient, good quality input data, available over long periods, and representing numerous different scenarios are crucial in the training of AI models for climate research. For instance, in predicting tropical cyclones, the available input data must be of sufficiently good quality, encompass many tropical cyclone scenarios over long periods of time, and also be relevant. Input model data for predicting such storms is generally limited in quantity and availability and has also been found to contain discrepancies. The prediction of future parameters can only be expected to a certain limit, and focus must be laid on other means of prediction or minimizing the associated prediction uncertainty.

12. Collaborative Efforts in Marine Weather Research

The world keeps changing, and we are all increasingly interconnected. It is even more true since the emergence of scientific and technological development. Research activities are, for the largest part, driven by collaboration among scientists, often from different disciplines. This is a logical consequence of the accelerated growth of knowledge in the last decades and the creation of many more specialties. Effectively, to efficiently answer many of the challenges that we are facing or may come across in the future, interdisciplinary work is becoming a necessity. This chapter presents different collaborative projects that were launched in the domain of marine weather and marine warning in order to show the permanently increasing interest in that domain, and the objective of the scientific community to raise awareness of the importance of that natural element in the safety and security of persons, ships and services at sea, and also for some meteorological phenomena occurring far from land that can also have a considerable impact on terrestrial activities.

13. Conclusion

AI has made great impacts in storm forecasting and marine weather due to its unique advantages including Earth system model-assisted prediction, global machine learning forecast, big data assimilation and downscaling for ultra-rapid prediction, dynamical – AI hybrid applications, and carefully designed deep neural network architectures. Comprehensive assessments, in-depth studies, and advanced applications of big data assimilation, Earth system model hybrid forecasting, different optimization methods, multiscale deep neural network architectures, and multimodality deep learning are hot topics for future research in order to enhance deep learning forecasting skills. Another focus of future research is knowledge-based deep learning applications and dynamical – AI hybrid designs for probabilistic prediction of air-sea-land interaction processes. This chapter provided a snapshot of the rapidly developing field of utilizing AI to help with marine weather and storm forecasting. We mostly emphasized deep learning and its applications. In the future, we will likely see many hybrid systems and configurations that combine the advantages of AI and ML methods with those of physics-based and statistical models and approaches. Such hybrid designs are likely to be particularly helpful in applications requiring probabilities and quantifications uncertainties for statistical risk assessment and decision making as well as for forecasting applications requiring high spatial resolution such as wind waves, storm induced sea surface temperature anomaly, wind gusts, rainfall, and storm surge, especially for landfalling tropical cyclones and tropical cyclones making extra-tropical transition. Over the years, AI and ML have matured into dynamic and useful areas for all of science and engineering, then it is likely that the new hybrids of AI and ML with established physics-based and statistical methods, and also systems that are careful combinations of subcomponents of each family could benefit the forecast skill score not only for the areas of the chapter, but also for other more general areas of weather forecasting for different areas of the Earth.

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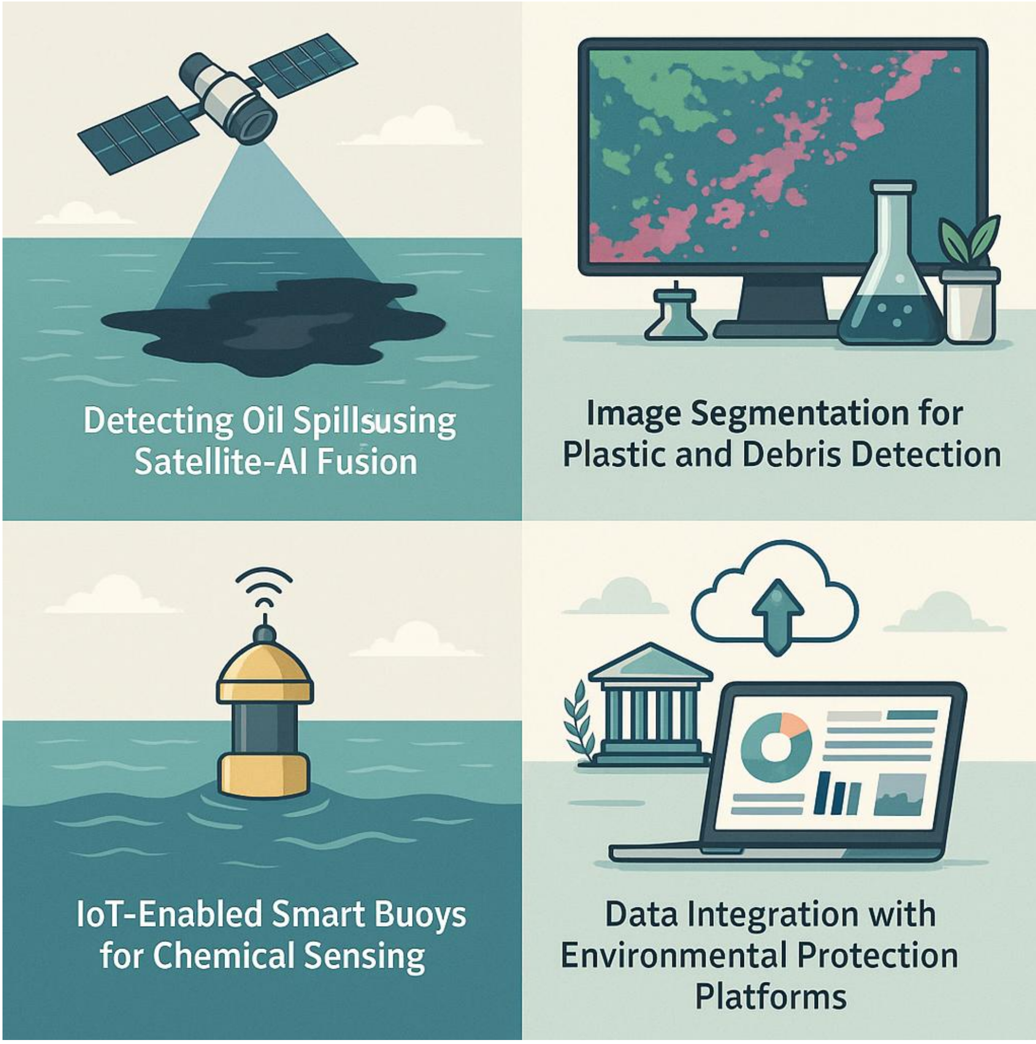
Chapter 5: Monitoring Marine Pollution

1. Introduction to Marine Pollution Monitoring

Marine Pollution, or the introduction by man into the marine environment, is overruled by any other type of pollution monitoring; in fact, marine pollution is only part of marine environment monitoring, considering the importance of our oceans on the planet. It's the oceans that absorb the major part of greenhouse gases and are responsible for life on the planet; about 70% of our oxygen is generated by Phytoplankton and, on the other hand, the oceans are the major important route of transport for goods all over the world. All of these play an important role in the life on our planet and this is why the pollution of our oceans has to be kept under control. (Zhang, 2015) (Kennedy et al., 2010) (Costa, 2018) (Flores et al., 2020)

Oceans Monitoring has two specific objectives; the first is to identify trends and assess environmental change over time for key variables; the second is to detect major unexpected events. Marine Pollution Monitoring around the world is implemented by a great number of organizations, not always totally integrated; sometimes the lack of integration leads to unproductive activities; it is quite common that an oceanographic research vessel, having the same area of operations, does the same measurement or sampling some days before or after a dedicated cruise with a cruise ship. In the following pages will be niched all the operational oceanography activities such as physical and chemical oceanography; current field measurements, sea bottom and temperature measurements, meteorological parameters, in situ wave current meter, CO_2 and O_2 measurements, marine pollution monitoring. Thanks to work done by the first international institution for oceanographic studies, it is possible to have an overall control of the ocean monitoring.



2. Detecting Oil Spills Using Satellite-AI Fusion

We operate from unidentified altitude and distance, while most of the world's systems are probably able to detect within minutes in which corner of the world the first evidence of pollution is occurring. Just after the pandemic lockdown, in April 2020, a cluster of boat traffic density minima along in the Southern of France were detected, while some restrictions were reestablished and some boats still in quarantine. Using their shape, size, and associated meteo-marine conditions Small-Boat Automatic Identification System (SBAAIS) and synthetic aperture radar (SAR) images were compared and few examples of passed by - probably without any nautical record - spambots, indicating illegal activities, were published.

In operational manner, dishes systems were put on spaces. Along the 1980s, mainly looking at larger accidental spills, two oil pollution services in the States, the Macintosh Laboratory Automatic Detection Algorithm applied on both radars mode (the system update rate algorithm is able to detect a spill after a median time of 3.2 minutes), and the Coastal Oil Spill Detection Algorithm applied on Infra_RED mode. After more than forty years the main portion of the Remote Sensing radar-based Oil Spill Detection methods (called Rangescope) still use monochrome imagery either with X band or C band.

Around 1993, with the Microlab/Toposat unearth launch by Brazil and by ALOS at the beginning of the millennium, many units were launched in the south for leisure purposes. During that initial period, some researchers tried to improve oil spill detection on Coast Guard / Navy patrol areas, where many artificial land use classification, satellite based optimization algorithms, coupling stained images, and neural networks methods tested, alone or coupled with other information or other sensors, SAR or Optical images, possible in the south. During the last decade studies using fine optical and synthetic aperture radar (SAR) opticals, satellite data are building the basis of what will probably soon be legally defined as oil spills.

2.1. Overview of Oil Spill Detection Techniques

In the past, detecting oil spills that negatively impact marine life was manually performed on-site by handling and employing outdated methodology. Thus, such monitoring is laborious and expensive. With technological advancement, however, substantial improvements that enhance the detection systems and provide real-time detection have been made. These improvements dramatically reduced cost, time, and human resources. Nowadays, various systems utilizing satellites, aerial systems, and vessels use combinations of optical, radar, thermal infrared, laser, and microwave sensors on-site or installed at remote stations to monitor oil spills and other pollutants. During the last past decades, various oil slick detection and analysis methods have been employed based on visual, infrared, microwave remote sensing data based on the models of absorption and scattering, polarization, volumetric backscattering model, phase shift model, maximum likelihood ratio test method, robust comparison method, physical-based method, dual-polarimetric shadow-based method, discrete model-based method, neural network classification method, optimized block-matching algorithm, neural network-based retrieval method, neural fuzzy inference system, pixel-based method, and in-situ surface signature model and based on wavelet transform, gradient, local Hessian, and photon counting.

Spaceborne visible and infrared sensors imaging the Earth's surface with different spatial, temporal, and spectral resolution have been mounted on geostationary and polar platforms. In the visible spectrum, some parts of oil slicks and films have lower reflectance than water regions, while other oil slick parts have very high reflectance. The positions of these slicks, as well as the generally observed color contrast between oil slicks and waters, depend on the incident, observer, and illumination angles. Over the last decades, thousands of oil spills have been detected using various sensors. Many of the methods achieve excellent performance for residual clouds and haze, as well as false alarms and undetected spills, compared to previous works. Some spill detection methods have been implemented on different satellites over sea, lakes, and rivers. However, the detection of small oil slicks less than 1 km2 remains a challenge.

2.2. Satellite Imaging Technologies

The water-to-land optical and infrared (IR) imaging spectral bands have been available for several decades via polar-orbiting and geostationary weather satellites. The advantage of this long-established capability is a global overview of the world's oceans on a daily or near-daily basis. The immense disadvantage is the low spatial resolution of satellites with imaging capabilities in these spectral ranges. The best presently available capabilities in this spectral range are around 325 meters. An additional disadvantage is that the IR bands are affected by the presence of microdroplets that are also the characteristic feature of rough sea states and, as a consequence, cannot differentiate between the rough seas with microdroplets and spilled slicks that are also rough. Almost all the available information on oil pollution in the open sea and especially on shelves and near coastal zones in the early post-accident period is based on visible light satellite imagery. Banksofting and other capabilities present and projected are derived from a set of high-resolution optical and infrared imaging satellites, operating simultaneously and including Reflectance, Franco-German PLEIADES, and China's GaoFen include both proprietary and commercial satellite operators. The latest generation of multispectral high-resolution optical satellites use panchromatic optical wavebands as well as RGB channels and their multi-mission synergy has been confirmed by data availability studies and real-time detection of hovering oil pollution.

New-generation satellites with hyperspectral sensors have recently become operational. However, hyperspectral band usage is much more limited than their multispectral alternatives, especially for the study of oil spills in the optical and spectral near-wave infrared bands, where the hyperspectral rule permits wave band absorption and where detection is usually the least problematic. Their additional advantage is that due to the very short time-scales of the first information on suspended matter characteristics features compared to those based upon visible or thermal emissions from the spill surface, more timely oil sleeking detection is possible than with conventional multispectral imaging processing procedures.

2.3. AI Algorithms for Oil Spill Detection

AI tools such as support vector machine (SVM), artificial neural networks (ANN), logistic regression (LR), Random Forest (RF), and convolutional neural networks (CNN)-based models have been extensively used for oil detection from satellite images. In this section, we briefly introduce these tools. Further, we discuss some of AI-based models with significant results.

Support Vector Machine (SVM) Algorithms for Oil Spill Detection Support vector machine (SVM) is a supervised binary classification algorithm. It is particularly beneficial in cases when the input data does not have too many features. The SVM algorithm casts the original input space into a high-dimensional space by applying a kernel function. In this space, the binary classification problem is solved by finding a hyperplane that maximizes the margin separating two classes. The classification of a previously unseen input point in the original input feature space can be performed by applying the learned SVM model and the kernel function. The SVM algorithm training and classification speed is linear concerning the number of samples in the input data, which makes SVM models attractive for big data applications. Researchers have reported good results in using SVM algorithm in detecting LI-W SSC from SAR images.

Artificial Neural Network and Logistic Regression Algorithms for Oil Spill Detection In ANN algorithm, the input data features are supplied to the input layer, which is connected to the next layer through weighted connections. The output values of the current layer become the inputs values of the next connected layer. The final output layer produces the classification of the input data. The weights associated with the connections among the different layers are learned by minimizing a suitable cost function for the training data samples.

2.4. Case Studies and Applications

Near real-time detection of oil spills is the first priority in an oil spill emergency; however, oil slicks cannot be detected until the vessel causing the spill has completely vacated the area. The time of oil slick formation is not known, and oil slicks are generally more difficult to detect in windy conditions. However, trouble is less likely to be caused to the wildlife or tourism in windy conditions when the oil slicks are becoming thinner and less visible. Although the time of slick formation is not known, research has shown that oil slicks may disappear from the sensor detection within days depending on weather and sea conditions and on the type of oil involved.

The use of visual and infrared sensors in the detection of oil slicks is limited to the detection of oil coating on the water surface. Oil slicks are easily detected using synthetic aperture radar sensors, which send microwave pulses toward the surface and receive backscatter energy. The indirect detection algorithm was used to develop the first oil spill detection algorithm. Many SAR sensor oil spill detection algorithms have been put to use to decrease the number of false detections. The role of AI in the development of SAR oil spill detection computer programs is expected to enhance the detection capabilities of AI-based oil spill detection algorithms.

Studies using multiple satellite systems report oil slick detections over the past 30 years. The advanced process reported the first operational satellite detection of oil slicks. The use of AI is adequate for training classifiers on radar oil spill detection reflectance. Hybrid AI was also found capable of joint training of oil spill and sea surface wind data useful for oil spill and wind speed characterizations. The hybrid AI model could be used to parameterize ship reflectance to allow higher probability of oil slick detection. Studies are being conducted on the use of hybrid AI in the development of ocean surface classifications with the goal of producing computer tools capable of characterizing surface conditions.

3. Image Segmentation for Plastic and Debris Detection

Plastic and debris pollution in marine ecosystems has become a major environmental issue. It accumulates on coastlines, floating in the water column. In addition, submerged, broken down, and degraded plastic pieces impact the organisms' behavior and health. Physical accidents, broken fish gear, offshore production, and ship traffic create pollution, accidents in harbors, oil spills, and marine geysers generate more damage and disperse floating debris in marine environments. Accumulated marine debris can become a navigational hazard, cause damages on vessels, and create financial losses and environmental degradation. Optical and infrared sensors on board aircraft and satellites are widely used to detect oils, plastics, algae, sediment, and other specific marine features in different spatial and temporal scales. Still, the usual task is to characterize the area with intercalated features while cannot distinguish marine debris from other features.

Traditional image processing applied to feature detection, digital techniques such as spectral signatures and color indices are not efficient. AI recently inclines to be the most efficient tool for this task, by automatically learning the most discriminative spectrum indices to separate marine pollutants from background noise. More and more supervised algorithms using satellite, aerial, and drone images have been developed and correctly applied. However, the unsupervised methodologies could be the solution when labeled data is not available or rare. We focus here mainly on the supervised methodologies: neural network and support vector machines classifiers. Their performance has been extensive but needs validation using a large dataset concerning time/space scales. Several satellite platforms available provide free or non-expensive multispectral images frequently and automatic machine learning approaches are being developed.

3.1. Importance of Plastic Detection

Marine pollution is one of the highest priority problems for climate change mitigation, with great impacts on biomonitoring and bioindicators of these ecosystems. Various types of pollution can be found in the marine environment: sediment plumes, heavy metals, oil and gas discharge, eutrophication, marine litter, plastic, etc. On a global scale, records indicate that 80 to 90% of all marine litter consists of plastics. Plastics are strong, light, flexible and resistant materials, commonly used for packaging and consumer goods. Unlike other materials, plastics have very low decomposition rates, which contribute to a large accumulation of this debris in natural environments, causing adverse effects on wildlife, ecosystems and human health. Plastic debris can be found at every corner in the world's oceans, from coastal areas to the most remote islands, from surface waters to the depths of the seabed, in the North Pole and in the Antarctic. Marine species mistake plastic for prey items, affecting their food intake and fitness, or can become entangled or perforated, creating wounds that can develop infectious diseases.

Due to their impact on ecosystems and human health, the detection, monitoring and quantification of marine plastic debris has become a major objective of many international programmes. These monitoring and quantification efforts take place at different spatio-temporal scales, from microplastics (submillimeter size) to large debris (>1 m) on beach regimes, along-shelf and cross-shelf transects (down to a few hundreds of meters depth) and to the deep sea basin (up to 10000 m depth). These surveys take place over different time scales, with a focus on single events, seasonally and on a multi-year basis. Various tools are employed to perform marine debris detection and analysis both at global scales and at specific locations, including citizen science litter clean-ups, low-, mid- and high-resolution remote sensing, aerial and underwater photography, ROVs, and static and dynamic buoy networks, among others.

3.2. Image Segmentation Techniques

The study of ocean pollution and the application of image processing began in 1978, with the photographs of the land using satellite data. From that instance, science took a step towards testing new models, techniques and the use of the deep learning approach to detect and monitor objects in the ocean and other continents. Image segmentation is a vital and important process in detecting and recognizing specific marine objects, because the extraction of segmented objects has a major significance both in terms of classification and in terms of further analysis. There are several methods for segmentation in the literature, but there are two methods that are globally studied and used more. The first method is based on a threshold, that is responsible for creating a binary image, where it creates two levels: a level outside and another inside the object. In this way it produces the exact shape of the object. The most used method applied to the ocean is threshold Otsu, because it works pretty well with problems in which foreground and background present a bimodal distribution.

The second method is the segmentation based on regions. Regioning methods usually divide the image into coherent regions with respect to a set of criteria. There are several possible segmentation criteria, but the most known methods are those that produce as a result the maximum similarity between colors in a region, both first-order and second-order statistics. The major objective of these methods is to partition the image into coherent regions that are integrable and correspond to natural schemes of objects. These methods are also called region growing. These methods assume that each object in the image can be identified with a closed representation, and generally end by presenting a segmentation which is less precise than that offered by classical pattern extraction methodologies. However, they have the advantage of how the image is divided into closed regions, in which the internal criteria set are similar.

3.3. Integration of AI in Image Processing

In the last decade, the technological developments in the field of AI have significantly impacted the field of image processing, more specifically, image segmentation where deep learning has led to remarkable strides. Seminal works in the tasks of object detection and image segmentation have popularized CNNs. A few enterprising works have applied these on remote sensing images and have shown that, with some modifications, the performance gain is immense in geophysical applications too. The reason why deep learning approaches performed exceedingly well can be attributed to two aspects. Firstly, deep networks learn a hierarchy of features from data, and these features, in the case of CNNs, are shifts and affine transforms in position space. This property of CNNs makes them extremely suited for tasks in the domain of image processing. Secondly, the availability of large labeled data sets has contributed to the success of deep learning applications.

In the case of satellite-based optical images, the Earth is often considered a repeating conveyor belt where several phenomena recur and this feature is another boon that helps us augment our data size drastically. The data augmentation approaches can be based on affine transformations, rotations, color jittering, or a combination of any of these common transformations. For some specialized applications, we can synthetically generate images using a physics-based model. With the availability of dedicated spectral data for a phenomenon, we can also resort to transfer learning by doing some fine-tuning on small data sets.

3.4. Field Applications and Results

Currently, there are several systems in existence that utilize aerial and/or terrestrial images and some form of image processing to quantify plastic debris, the majority of which are reliant on machine learning and/or computer vision techniques. A vision-based system deployed in the Northern Pacific to assess microplastic concentrations floating in the water column makes use of a specific model. However, predominantly, systems deployed for aerial imagery analysis incorporate deep learning models to be applied 'in the wild'. With regards to these plastic debris image detection systems, some results have been achieved on the classification of plastics and debris relative to a number of classes (non-plastic, plastic, vegetation, sand…) from aerial images and RGB terrestrial images, while other works detect disturbances in terrestrial images to identify plastic pollution in urban settings.

In the present work, we present results from satellite, aerial, and terrestrial systems that apply various deep learning models (those comprising real-time instance segmentation algorithms). These systems are deployed in three different settings; urban, through terrestrial images, seaside, through aerial images, and marine, where the observations are conducted through a specific float system. For the terrestrial site we present some preliminary results utilizing high-resolution aerial images to detect plastics within a test retrieved from the read after the flooding of a river. Subsequently, we deploy the systems over the terrestrial images collected at a beach. Additionally, we show results from a previous work that utilized two variants of the system to assess plastic pollution from different float altitude-relations. Results from both groundtruth-creation procedures are presented as artificial and authentic scenes. Moreover, we present results over additional deployment realizations, carried out during testing, from both architectures, to increase their plastic debris quantification coverage.

4. IoT-Enabled Smart Buoys for Chemical Sensing

Collaborations between experts from different disciplines in science and engineering are critical to designing the sensor technologies necessary to support sustained sensing and monitoring of chemical pollution in the ocean. Buoys add to the sensor network in the ocean or lake supplying near-real-time data over long periods, reducing the cost of shipboard visits and deployments.

Collaboration between scientists, engineers, and ocean experts creates sensors that make in-situ, long-term chemical monitoring practical and cost-effective. Smart buoys have been developed to continuously measure pH, salinity, and temperature in various regions, chlorophyll in coastal areas, and other parameters around the world. These buoys can be equipped with sensors to measure nutrients, dissolved organic matter, dissolved oxygen, and total hydrocarbon gas concentrations. They provide a platform for a large number of chemical sensors monitoring a wide range of compounds over long periods. In addition to buoy logistics, challenges include waterproofing components, choices of power and communication methods, data validation, sensor accuracy, and sensor lifetimes. Sensors are provided by multiple commercial vendors, optimized for shipboard or island applications, and capable of near-real-time reporting. Shipboard and autonomous vehicle sampling demonstrated accuracy compared to laboratory methods, with shipboard samples validated against the arrays in place.

4.1. Design and Implementation of Smart Buoys

Novel chemical sensing systems that are IoT-enabled can be deployed onboard buoys located in bodies of water, capable of detecting unseen and harmful events and transmitting information in real-time. Design considerations must account not only for power consumption and communication capabilities but also for regulatory standards and safety requirements; buoy stability and endurance are relevant, especially in aquatic environments. Temperature ranges and other conditions of such systems affect performance and must be considered in threshold detection limits. Sensor selection and integration are also important, as different chemical sensors require different intervention methods; e.g., electrochemical sensors require electrode cleaning, while optical sensors require interrogation at a specific time, which may not be suitable if the device is moving. The environmental sensing system is composed of a buoy and an electronic unit. The buoy was crafted using acetal material via a 3D printer at exclusive proportions, resulting in a lightweight, high buoyant strength, buoy-shape object. The dimensions of the buoy were carefully selected based on the maximum weight of the integrated components, electrical buoyancy, and measurement capabilities. A floating configuration was chosen, in which two-thirds submerge below the water level. The embedded electronics inside are associated with two critical characteristics: signal acquisition and transmission. Currently can be applied to real-time environmental monitoring, experimentation, development, testing, and implementation of different sensing technologies for monitoring of several parameters and sensors utilized for the sensing purpose. Released data will help assess water quality and pollution with the integration of optical, electrochemical, and physical sensing devices and aid decision making in the treatment of contaminated aquifers and oceans.

4.2. Chemical Sensing Technologies

Chemical sensing technologies have developed rapidly in recent times. Recently proposed optical and electrochemical meters suffer either from analyte pre-concentration, temperature dependency, sensitivity, high cost, mass, and power consumption, or they are not transportable. Successful deployment of electrochemical sensors in the harsh marine environment has been reported. The first deployed cost-effective sensors were thick-film versions incorporating screen-printed electrodes and thus allowing for low fabrication cost. However, these devices did not deliver the desired accuracy and drift performance. Presently, batch and more recently, 3D-printed miniaturized versions of commercial low-cost electrochemical sensors have demonstrated their suitability for the long-term quantification of particulates and/or the continuous analysis of dissolved metals in sea and river water. The price of commercially available ruggedized optodes has increased so that deployment at long time scales becomes affordable.

Sensing technology must be chosen according to the specific requirements and constraints of the individual chemical mission. Requests for marine monitoring include continuous online pollution monitoring, i.e., continuous, automated sampling and analyte quantification to record the variations and trends, for diagnosing potential causes of pollution incidents and quantitatively inferring the input of pollutants into the water; time- and cost-effective collection and storage of water samples and then analyzing a set of analytes and/or particularly toxic species at fixed time points, requiring temporary storage of water samples, and/or autonomous or manned bioassay campaigns to detect toxicity that degrade the water quality without necessarily quantifying the analytes involved.

4.3. Data Transmission and Communication

Over the course of several decades, many wires, radios, satellites, and so forth have linked up to form the Internet. Now the Internet joins up with the physical world, so we have the Internet fulfilling the old notion of a Fourth Dimension linking Space and Time together. IoT has become, in its short-headed way, the web connecting all of the world's sensors, including the vast majority of floating buoys and near-bottom sensors such as sediment traps. The enormous excitement about internetting smart devices without wires, the vast reduction in size, weight, and costs lie behind the internetting of sensors. The revolution of law has just begun. Already, for example, smart devices have begun to drive cars. So the Internet essentially connects sensors, actuators, and computers, whether separate devices in different physical locations around the world, or in a common device in the same location and computer carried by the device itself. When smart sinking devices started monitoring sedimentation at oil drilling sites, the communication could be done through a cable to a buoy sitting on the water surface, then floating up with the fish or drifting to the beach.

The deployment of Oil Slick Blockers for mitigation of oil spills amounts to hundreds of vessels. These devices could be called micro-probes. If the oil layer's thickness exceeds the preset threshold value and lingers for a sufficient length of time, a Fast Communication Boat is dispatched to the designated area in a smart manner. It communicates with the mini-vehicles of sludge wiping oil spills, guiding them to the oil field. The communications in the oil field are organized in a multi-hop manner using visible light. Thus, sensors can be installed on the vessels and the mini-vehicles.

4.4. Real-World Deployment and Outcomes

We deployed two sensors available for lake monitoring in close proximity from each other to evaluate the sensing technology and the wireless communication of the system. The two IoT-enabled smart buoys were deployed for 2 months during the summer of 2021. The data collected were temperature and pH levels as baseline parameters using low-cost on-board logging sensors for buoys. In the evaluation, higher resolution recorded data for temperature and pH collected by the buoys were validated against a portable sensor that was used to collect point data in the vicinity of the buoys. The results showed good correlation with point measurements for temperature data through time series validation since the patterns of temperature changes were similar. However, for pH data collected by the buoys, the data did not correlate well, since sensor drift was visible. Therefore, the buoys were recalibrated every other week to get on-board sensor readings back to baseline and increase the confidence in the data.

The deployment resulted in two lessons learned. First, the pH sensors in the buoys experienced drift. Although drift is a problem for any pH sensor, better on-board systems would result in highly trusted pH data collected by the buoys. Second, the buoys could be improved to better support the sensor systems to take samples at prescribed intervals, such as once every 10 minutes, to allow local data collection and distribution to multiple observers with local data needs, as well as having the data observed for data from any area in the country where such data could be obtained. We believe that our approach, lessons learned from the deployments, and the next improvements could be generalizable to other activities in a variety of environments enabled by using low-cost Internet of Things-enabled networks.

5. Predictive Modeling for Algal Bloom Events

Despite intensive research over the last century and a half regarding the causes and origins of algal blooms, little consensus exists. For predictive models of HABs to be effective in predicting specific future bloom events, several basic conditions must be met. First, the model used must be capable of predicting the spatial and temporal scales associated with specific bloom events in the region of the model implementation. The spatiotemporal scale of the model must match the characteristics of the predicted events. Many of the longest time-series records of blooms have been primarily based on field survey observations and tend to show much greater variance in amplitude and frequency over time than the satellite-based records, which compute the timing of potentially reproducible algal bloom events. However, these satellite-based climatologies tend to suggest that the proposed state of HABs is related to dynamic climate variability. This also may not be an accurate representation. Because of the time series records, these may predict different results than those of satellite images.

Understanding Algal Blooms Data Sources for Predictive Modeling Modeling Techniques and Algorithms Impact of Predictive Models on Management

Future research will be needed to provide high-resolution validation data for modeling predictions, particularly for unexplained or unique blooms, using in situ measurements at time of satellite overpasses to the fullest extent possible. By processing and validating a significant number of coincident event images versus in situ data, more predictive accuracy may be achieved. In addition, HAB specialists must agree on a nomenclature of algal bloom definitions that enables researchers to communicate clearly as opposed to being species-specific. Moreover, models must also incorporate future projections such as a climate model's effects on local physics, particularly nutrient loading, temperature, salinity, wind-driven currents, precipitation, and water column mixing. This inclusion will enhance predictive capabilities, especially for projections that indicate increases in temperature, nitrogen loading, and reduced salinity, conditions favorable to promoting bloom proliferation.

5.1. Understanding Algal Blooms

One of the more visually striking and threatening phenomena of the coastal ocean and large lakes are harmful algal blooms. These events can kill fish and marine mammals and injure or kill people who swim, eat shellfish, or breathe air tainted by toxins. Certain algae produce domoic acid, which is dangerous to marine mammals. Although humans have reported disease from algal blooms for centuries, it is only in the last few decades that these blooms have caused human morbidity and mortality. Increased fertilizer runoff, especially phosphorus, from farming and urbanites living in coastal regions and changes in nutrient delivery from freshwater river and stream flow, especially during flooding and drought, have made blooms of microcystin producing cyanobacteria more frequent, longer, and widely distributed.

In addition to surface blooms of cyanobacteria, algal blooms of dinoflagellates make many of our oceans and lakes famous during summer for their beauty. Other toxic, but non-HAB, diatom and archaeomonad blooms or dispensers of ichthyotoxins also cause problems to marine and lake life. Within America’s waterways some localized areas, influenced by semi-enclosed land masses, are naturally enriched and predisposed to bloom more frequently through processes of circulation, high nutrient concentrations, light attenuation, salinity, and temperature. Potential nutrient pollutants have become much more biogenic. Again, an increase in phosphorus and nitrogen from animal and human waste, fertilizer runoff, wastewater treatment plants, and urbanization are rich sources of inputs.

5.2. Data Sources for Predictive Modeling

To develop a predictive model, it is critical to have the right data and choose the correct algorithm. Predictive analysis is based on historical data of past events, which is then used to determine the future events based on the algorithm chosen. However, to create accurate predictive models using data, large amounts of quality, heterogeneous satellite data are essential. Satellite data provides better temporal and spatial coverage and consistency than local in-situ sampling. Level 2 products are the most commonly used source for developing HAB models on the water quality and algal bloom dynamics. Level 2 data are available from various sources. These products contain quality assurance flags, which help to filter out bad data, such as cloud covers over data. However, the products are not a complete solution to data collection. To create a full picture of algal blooms and water quality, multiple satellites need to be combined. Additionally, to incorporate the water quality prediction model into a decision support tool, archival data spanning decades for historical validation would be needed.

Different satellite missions and data products over the years have been synthesized to investigate and analyze algal blooms in the Black Sea. There is a unique opportunity to have archived data products from various satellites over time for the same locations. The synergistic use of all these satellite missions and data products can provide valuable information for the validation of forecasting models for HAB satellite detections.

5.3. Modeling Techniques and Algorithms

While early models for predicting algal blooms were based on statistical comparisons among in situ and satellite data, most of the current models rely on a combination of physical/biogeochemical models and artificial intelligence models. In the last few decades, a diverse family of modeling approaches and associated algorithms have been developed for predicting algal blooms based on a multitude of inputs and scales. A current challenge is modeling algal bloom species which often go beyond the methods typically used in ecological forecasting, such as the standard output from NPZD or any of the derivative models for phytoplankton, notably dynamical systems or statistical models driven by observations on varied scales.

The first groups of regression algorithms are based on either generalized linear regression models or further generalizations like hybrid models. These methods estimate how the temporal dynamics of phytoplankton concentrations depend on a set of explanatory variables. Random forest or boosted regression tree models are closely related, but they perform more complex tasks of data adaptation, searching the best way to combine trees in ensembles. Advanced data mining methods like classification-regression approaches lead to a very efficient tool for data complexity reduction and handling, which is then easily upgradable to a different configuration. Recently, machine-learning approaches using recurrent artificial neural networks or Long Short-Term Memory RNNs have been applied successfully to the emulation of various geophysical tasks, probably due to their intrinsic capability to deal efficiently with the complexity of temporal dynamics.

5.4. Impact of Predictive Models on Management

Finally, predictive models for algal blooms could also help bolster outreach efforts for citizen science programs and the use of mobile apps that might increase early detection of blooms through user-generated data. Few predictive models have been used to develop or inform decision support tools for management authorities. Predictive tools are available for freshwater systems, but are rarely used for coastal marine waters and seldom for open ocean locations. A potential barrier to the use of predictive models is that they use output from numerical model simulations that require a steep learning curve for many end users and the models might not include important physical and biogeochemical processes known to trigger blooms or modulate bloom dynamics.

The current decision support tools that have included any model output as a component primarily address freshwater systems. Difficulties associated with monitoring sensors in the open ocean may have contributed to the lack of predictive tools for open oceans. Alternatives for using the coastal shoreline-seeking sensors are constrained to specific nearshore locations without the need for accurate prediction of the actual site of bloom initiation. Feedback from managers of coastal and ocean properties should be incorporated into the development of any predictive models to ensure that the necessary information is included in the models. The predictive capabilities of existing bloom models should be carefully validated for a variety of bloom conditions and for the required time and space scales.

6. Data Integration with Environmental Protection Platforms

In order to make the best use of the data and products generated by a monitoring or modelling system, it is crucial to integrate it with platforms that have been developed for the specific purpose of tracking, analysing and reporting on pollutant information streams. Environmental Protection Platforms have been developed as part of the continuing evolution of environmental reporting at both the national and transnational levels. Although they have evolved independently, these platforms have similar structures and goals, and would benefit from coordination and sharing of data and services. By integrating citizen science monitoring and modelling efforts with these established platforms, the data becomes part of a trusted system at the primary quality assurance level that is already integrated, at higher levels, with transnational and national data management systems.

Environmental Protection Platforms have been developed to track a variety of water quality indicators. To ensure a common consistency in monitoring and communicate with the integrated platforms, monitoring efforts must provide data that obeys the data standards for the specific indicators. Partnerships with established agencies and groups are key to developing this national and local monitoring capacity. Three become involved generally. First, monitoring and research institutions must align their protocols with the Water Information Systems to integrate on the same data reporting structure. Second, established organizations are needed to encourage people to get involved in the monitoring. Third, the community needs to gain experience, and receive support and training to build the local capacity.

6.1. Overview of Environmental Protection Platforms

Environmental issues like air and water pollution or global warming need sustainable technical and social systems solutions. Governments, municipal authorities, and scientists are working hard to protect the environment against human activity, from international treaties to legislation to prevent harmful substances from being emitted. Information and Communication Technologies play a crucial role in ensuring the connection and coordination of the different players involved in these solutions. Environmental Protection Platforms are such solutions, which combine sensor networks, sensor data, and other information sources, with the purpose of tracking, and helping mitigate, environmental degradation impacts.

The emergence of Relational Database Management Systems, Cloud Computing, and Web 2.0 brought a shift from proprietary expensive solutions for Disaster Management and Environmental Monitoring for research institutions, to low-cost solutions available to anyone. Modern, flexible, and cheap solutions to build Environmental Protection Platforms available to environmental research scientists and enthusiasts, while allowing the secure integration of remote environmental monitoring and satellite data with other knowledge sources, such as high-resolution meteorological and climate predictions, are scarce. Governments need channels to guarantee an informed society involved in environmentally related issues, and help technology developers innovate under a sustainability perspective.

6.2. Data Integration Techniques

Various environmental protection approaches and techniques involve a significant number of management information systems, environmental and pollution control databases, knowledge-based systems, and sensor networks. The adoption and transition to environmental decision-making depend on the availability of existing reported data from globally-distributed environmental resources, the level of standardization of their formats and procedures, the level of integration among the tools specified, and their user-friendliness. Several organizations exist that collect environmental data. However, there is no single organization that is the owner of the entire life cycle for all data. Furthermore, they usually do not share their data, as there are no commonly agreed protocols or data standards regarding shared data and there are ownership issues.

Data inconsistency is another issue. In any field, we expect that different data sources provide us with some varying reports of a certain event. However, it is not uncommon for different data sources to supply contradictory information regarding the occurrence of some events. This overwhelming amount of inconsistent statistical data formed the context in which researchers birthed the area of information fusion. Information fusion may be defined as a process that combines or fuses information from different sources in order to create a more accurate and consistent report on a certain event. Some researchers define data fusion as an integration of those multiple sources of information that takes into some shared knowledge and produces data of higher heritage quality than was available from the individual data sources.

6.3. Collaboration with Stakeholders

The platforms discussed in this chapter were developed without any research team or organization collaboration. The main goal is to share their expertise and expand their use by scientists and managers for marine pollution monitoring. The projects are open for collaboration. Users may offer their customized sensors that could be adopted on the platforms. In this option, each user may have its own sensors in the field to collect the exact data which may be necessary for the discussed monitoring. Data can be shared in common time slots, with some frequency adapted to the event. The idea is to sign a contract specifying each partner's obligations in terms of data sharing or sensors sharing during the whole project or in specific time windows.

The most feasible option is to develop additional data processing chains on the platform. These processing chains will probably remain closed for security issues. However, the final data products can be shared and used by many users on long time scales. This approach will be feasible if the interested party has a larger database of missions covering the time slot of the satellites. For such a use case, the interested party may fund the implementation of the dedicated processing chains to develop expertise in specific fields.

With the collaborations established for oil slick monitoring applications, the provided algorithms were implemented on the platform. These collaborations were all focused on oily slick detection through a transfer from the uses on ships to the use of the platform in satellites. It consisted mostly of insuring that the database provided its performances, and that some data filtering was easy to achieve. These collaborations have been really convincing. This is how the team managed to implement the platform. The database could be shared and protected with authorized practices.

6.4. Case Studies of Successful Integrations

Data integration is a necessary step for checking and responding to alarm events from EPPs. We explored several different case studies of systems providing a successful realization of integrating seafloor and seawater information from autonomous observatories and buoys into several different EPPs.

Plone is a proven open-source, web-based content management system that has a robust set of online site management tools organized to facilitate ease of use. The Cyprus Institute hosts a Plone EPP, with information on beach cleanliness and water quality at several swimming areas along the southern coastline of Cyprus, measure reports are regularly made available on the system. The automated EPPs (seafloor and buoy platforms) data integration into the Plone application is achieved in two steps. The first reads the data from the private database at the Cyprus Institute at pre-defined intervals and automatically inserts it into an XML file, and the Transforma module transforms it into an

RDF document with a proper ontology. In Poland, in 2009 the Research and Academic Computer Network established the Coastal Research Centre. The EPP is developed on a smaller scale to present values coming from sensors considered for the sea water suspicious states but is based on similar ideas as the ones from the above project. The integration of data from the autonomous EPPs and buoys with the main home page of the Marine and Coastal Research Center is achieved on the base of web services.

Critical data has been provided to respond to a large scale of oil spills for decades. The Environmental Response Management Application is a mapping tool used by agencies and partners to aid in response planning and real-time response operations for oil discharges into navigable waters. The present aim is to speed up and facilitate data intake into the application for use during the response for a possible suspicious state by adding integration of the key parameters from EPPs and buoys. Data are obtained from autonomous monitoring at its coastal waters. The addition to the application is realized by using the existing data service.

7. Challenges and Limitations in Marine Pollution Monitoring

Monitoring marine pollution is essential to understanding the impact of human activity or natural phenomena on the marine environment. The vastness of the oceans and the diversity of the pollutants excluded the possibility of exhaustive analyses. Thus, over the last decades, sensor technology and wireless sensor networks have been developed and started to be applied to marine pollution monitoring. This is a relatively new topic that raises many challenges and limitations. This chapter is meant to be a starting point for students interested in Marine Traffic Monitoring. There are several deep technical limitations and challenges, such as quality of sensor data and cost of deployment. This chapter only briefly discusses these issues, focusing on the more general societal aspects of marine pollution monitoring.

The study of Marine Pollution covers a wide range of topics. The development of Sensor Island technology, a distributed sensor network deployed in remote locations, has started to produce new and relatively inexpensive information sources about the physical, chemical, and biological features of seawater. These Sensor Islands are remotely controlled and monitored and allow the exchange of data in near real time. New types of self-organizing Wireless Sensor Networks have also started to be deployed. These WSNs allow more inexpensive measurements with heterogeneous sensor nodes but face several reliability and quality issues.

8. Future Directions in Marine Pollution Monitoring

True progress in marine pollution monitoring will only occur when it is coordinated nationally and internationally. In the current paradigm of marine pollution monitoring, where national interests and commercial motives drive individual activities, contradictions and unfulfilled objectives arise. Priority-setting and resource allocation are currently the prerogatives of individual countries and agencies. While many marine pollution problems are common to several countries, coordinated multinational efforts are rare. Yet such efforts would be more efficient than separate, uncoordinated efforts. However, such multinational efforts are subject to jurisdictional problems and varying country priorities. To aid in international agreements for pollution monitoring, we propose a protocol for marine pollution monitoring. The protocol specifies standards for quality assurance/quality control, data submission to internationally accessible databases, procedures for data access, minimum periods for data access exclusivity, and re-analysis. The protocol will provide guidance to ensure compatibility in measurement procedures, reduce data discrepancies, and ensure data quality to maximize the usefulness of the data generated.

Research on emerging pollutants, microplastics or nanoplastics, including their effects in tissues and cells, biogeochemical cycling, and vectors for transfer is increasing rapidly. Directed research needs to be more systematically implemented in marine pollution monitoring programs. Host animal and sample collection programs must be designed creatively to include these. Such knowledge will be particularly important for marine animals and the general public, who face exposure and risk via contact and consumption. Thus, the collection of biomarkers of exposure and effects in host animals and development of exposure characterization and risk assessment procedures will be needed. More extensive integration of biological measures, such as who, what, when, and where of exposure, will help link contaminants in tissues and fluids with effects. Using biological measures of pollution exposure and effects along with chemical measures will help more fully characterize both the temporal and spatial distribution of exposure.

9. Conclusion

Monitoring marine pollution is a major challenge for all present and future generations. Exploration of the sea and the ocean, essential for our security and protective sustainable strategies against pollution and climate change, requires a huge effort on a blatant multi-disciplinal research, ground in the knowledge of nature, reactions on the ecosystems, circulation of the atmosphere and oceans, the knowledge of the thermodynamic windows transcending transports of energy and matter and transfers from the marine systems to our atmosphere. Development of new detection tools combined to high frequency analysis over long durations require a lot of investments. While several pollutants are measured constantly at coastal marine stations, alas, more fragile pollutants remain to be measured. Development of new tools able to measure emerging pollutants automatically in the open ocean or the coastal sea is a vital objective for the coming decades. And the long chain of pollution impacts and consequences could not be possible without the access and the massification of new techniques being developed inside the information technology. These techniques created by humans can also destroy and pollute our environment, so we must develop automatically, inside this long chain of pollution impacts and consequences, the same machine learning approaches to estimate the good balance between our development and our pollution.

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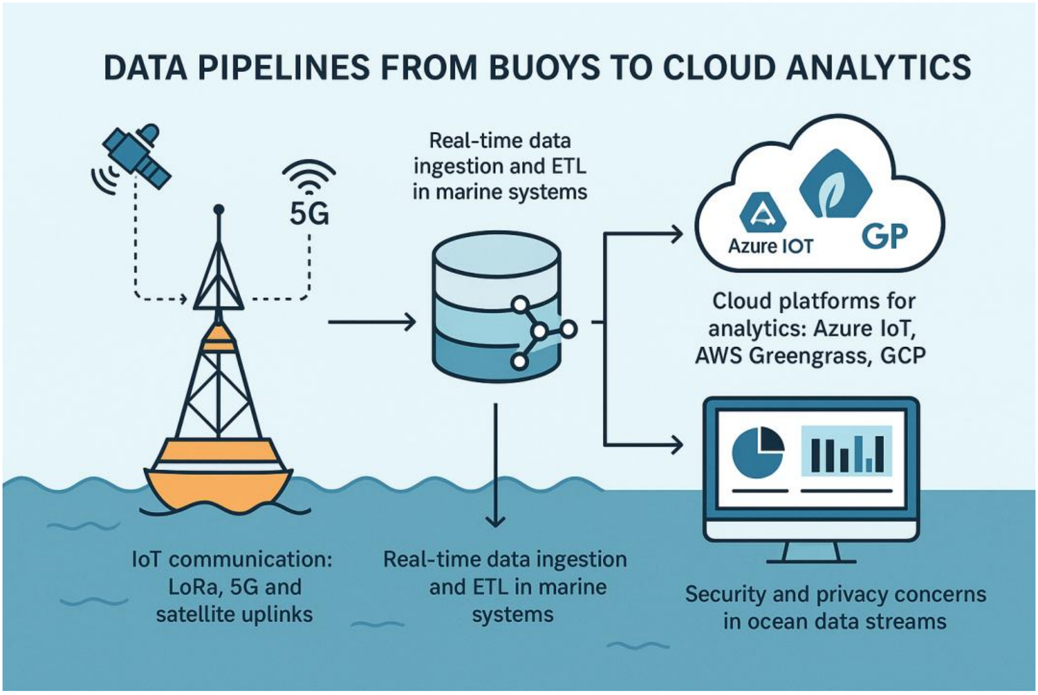
Chapter 6: Data Pipelines from Buoys to Cloud Analytics

1. Introduction to IoT Communication

Over the last decade, the Internet of Things (IoT) has matured into a broad array of technologies and applications. These systems often contain unique aspects of design when considered at the edge, but still are generally responsive to protocols designed for the unique needs of the IoT realm. Much progress has been made in the development of IoT systems in marine environments, as they are well-suited for the construction of IoT devices that are long-lasting, autonomous, resource management, and enabling collaborative frameworks, as well as the efficient assessment of common pool resources such as fisheries or the seabed, and the provision of data for scientific research. In this chapter, we focus on the aspect of IoT communication through the construction of sensor buoys that relay data over long-distances to cloud architectures through cellular data networks. However, IoT devices configured for short-distance transmission to a local relay, and local relays configured to forward data to a cloud architecture through WiFi, can also easily be utilized for marine applications as needed. (Agrawal, 2016) (Zehnder et al., 2020) (Lorenz et al., 2020)

Wireless communication is critical to the utility of IoT devices for data collection without an intrusive physical presence or constant maintenance needs. Perhaps unsurprisingly, basic wireless principles of the last century are still relevant in the appraisal of currently available communication devices for IoT applications, as new radio technologies are coupled to advanced information technology infrastructure. There are many decisions to make when developing a communication system, from the low-level protocols constructing raw data into understandable packets, to the coordination of many devices relaying and querying packets over shared frequencies, to the management of long-range packets carried to the cloud by cellular data networks, or satellite communications. Here, we describe the primary devices available for relaying data from buoy-based IoT data collection efforts to cloud architectures.



1.1. Overview of IoT in Marine Systems

Marine systems are at the same time the protection and the target of an increasing number of human activities, and this is putting a burden on our oceans and seas that is difficult to manage. The seas contain about 70% of the surface of our planet and they are being increasingly exploited for purposes such as aquatic resources like fish, oil, and new sources of renewable energy like offshore wind farms, marine transport, coastal and offshore tourism, but they are also susceptible to threats caused by anthropogenic activities, such as shipping accidents with oil pollution or more complex geo-political scenarios based on armed confrontations. Protection from these threats involves using a combination of traditional and non-traditional sensing and surveillance means, such as surveillance radars, coastal surveillance systems to monitor commercial traffic and possible illegal traffic, the use of AUVs and USVs for local detection, as well as the use of satellites or aircraft, which have a much larger coverage area, to characterize what is happening at higher altitudes.

Traditionally, Information and Communication Technology has been mainly terrestrial, but more recently it has extended to include marine and aerial domains as well. Interconnected devices and sensors are no longer limited to traditional terrestrial applications in fields such as commercial and industrial automation, but address other sectors such as health, energy, transport, or logistics to mention just a few. The paradigm of the Internet of Things should also allow us to transform a difficult environment such as the marine from a sensory-poor environment to a sensory-rich one. As with any difficult environment, in order to apply the Internet of Things paradigm in the marine domain, it is necessary to address the implementation of efficient means for data ingestion, transport, and processing with the aim of achieving real-time and continuous monitoring of the targeted events of interest. In particular, researchers in the field of marine ICT have focused on the challenges posed in the phase of enabling the ingestion and transport of IoT data, mainly referred to as Delay and disruption Tolerant Networking.

1.2. Importance of Communication Technologies

Communication technologies are a pivotal element of IoT systems, where data is sensed, captured, transmitted, processed, and acted upon. Challenges commonly arise due to the need for long-range communication with severe bandwidth restrictions, low power availability and budget considerations, and the need for increased node system density. In addition, the harsh and sometimes unpredictable environments found in marine systems pose additional operational challenges. Every link in the setup — from buoy to cloud — must be carefully designed and tested to provide reliable, cost-effective operation over long periods, even under adverse conditions. This section describes some of the main communication technology considerations associated with data-driven marine systems.

The choice of protocol stack is a major decision. Several IoT-specific lower-level protocols have been developed to meet the requirements of low power, mobility, and scalable heterogeneous networks with many or all nodes sharing radio spectrum, including various protocols. Lower layers include MAC protocols for dealing with multiple concurrent users, and at the network layer, path selection and network configuration protocols, network hosting capabilities, and support for Quality of Service guarantees are important in ensuring good performance. Higher layers serve a variety of purposes, from presentation transformation to multipoint communication, and from network agent and supporting services — timing, naming, discovery, and localization — to application and middleware support. Further layers allow new capabilities such as security and low power modes to be attached as needed, and the satellite lower layers address the problem of significant delays and errors associated with interconnecting low earth orbit satellite networks for IoT traffic.

2. LoRa Technology in Marine Applications

2.1. Technical Overview of LoRa

LoRa is a low-power wide-area network (LPWAN) technology designed for long-range, low-rate data applications. Proprietary LoRa modulation is a spread-spectrum technique based on CSS (Chirp Spread Spectrum), which optimizes link budget relative to competing solutions, enabling better range, capacity, and battery requirements. Today, LoRa networks are commonly used in single-channel gateway (LoRaWAN) mode but can also support star-daisy chain architectures, with TSMP gateways, which enable real-time, bidirectional, low-latency communications and are easy to integrate with existing cloud systems. A power-sensitivity study confirmed that the best optimization condition for the LoRa wireless system for underwater monitoring applications, which demand low power and a long range, is a spreading factor (SF) of 10, a bandwidth of 125 kHz, a transmitter power of 14 dBm, and an omni-directional antenna at both ends: both the communicator and the receivers.

LoRa technology allows for simple, single-channel gateways capable of receiving data from multiple sensors and transmitting it to the cloud through an Internet connection. In recent years, LoRaWAN technology has emerged as a standardized protocol widely used for sensor networks in several fields, including medical, agricultural, transport, and industrial applications. In the domain of marine environments, it has recently been proposed for use on ships for cargo location tracking. In these initial works, the complete LoRaWAN reference stack was used. These works have described maritime-constraint ships, used LoRaWAN nodes, and developed LoRaWAN end-to-end testing using LoRaWAN packet forwarders, gateways, and network servers. They also used low-cost commercial off-the-shelf LoRaWAN components, such as Raspberry Pi configured as LoRaWAN gateways, as well as commercial LoRaWAN transceivers and a LoRaWAN packet forwarder. Some previous works developed a prototype, in non-LPWAN mode, consisting of a sensor connected to an Arduino microcontroller and an integrated LoRa IC but did not evaluate the radiosensitive sensor underwater.

2.2. Use Cases in Marine Environments

Marine environments are considered extreme for many human activities; nevertheless, a big amount of buoyancy devices are deployed in the sea, and for a wide range of applications. The needs for increasing the coverage, security, and reliability of wireless communication networks have the effect of raising the costs of offshore investing. Until today, the most widely used communication technology for buoys is satellite data link, through the mechanisms and systems that store data collected at the buoy until a satellite pass that allow battery recharge and data transfer or, in the best situation, using satellite modem or router that provide a constant data link between buoy and shore stations. The extreme amount of costs related with the implementation of satellite data link buoy systems pushed some researchers to propose and implement the use of short range RF mesh networks; these systems manage to remove from the buoy the costs of satellite modem, but have the inclusion that only very close buoys can communicate with each other, use local networks that are in some sites of no feasible utility, due to tower and buoy locations, and at the end use relaying points that are usually ais stations, which cost less than satellite but not much less. Other possible alternative are the many gateways installed in shore, and the use of the buoys as end nodes for reporting to these shore gateways their condition, the relaying of some environmental parameter like chlorophyll a or kok value at some close buoy to base station use, or monitoring conditions at the end of the deployment using communication. Many researches are dedicated to different aspects of buoys talking with shore gateways. Some tests were performed to evaluate flow, direction, air temperature, and ambient pressure during some time in the deployment corridor of the buoy in order to determine what exists as flow and correction of errors like time misalignment between the devices and bad radio link condition.

3. 5G Communication for Marine Data Transfer

This chapter focuses on 5G telecommunication supporting mobile marine data applications. Collecting ocean data at scale is hampered by communications. Current satellite systems are slow and expensive. 5G is being deployed globally on land, supporting phones, IoT devices, remote sensors, and more. 5G was designed for land features and is not yet available over oceans for buoy and ship Internet-of-Things sensor communications. 5G networks are expensive to build out, so communication over non-populated areas will be slower for longer - delayed until satellites can be deployed to cover oceans - but each coastal area will see increased speed of service sooner as user density increases. Speed of service for coastal and on-vessel communications is also likely to be delayed as rules are developed to include 5G communications on or near vessels at sea.

For buoys, the advantages of 5G include data upload rates faster than for traditional satellite solutions and download rates faster than can be managed using legacy systems. These speedy data transfers are critical not just for necessitating live, user-facing data applications but also for enabling more complex models to be developed which require more data to be transferred for training, development, and calibration. In addition, the short messaging intervals of 5G technology are of interest in transient sample contexts where sensors risk missing time-sensitive events like tsunami swells or microburst winds.

3.1. Benefits of 5G in Marine Systems

Mobile internet access is ubiquitous in onshore settings but, traditionally, difficult in offshore locations. Satellite communications have been the standard for transmitting numeric data, with 2G-4G communications emerging since the late 2010s as a viable alternative for buoys and some marine vehicles. These systems were limited in capacity, range, and data speeds. Untethered, mobile areas of the environment have relied on its own published set of communications capability based on Wi-Fi and similar protocols. The advent of 5G-Advanced, a more technically diversified technological framework than typical in mobile telecommunications, is set to change both commercial and non-commercial placement of data loggers in the ocean environment, especially the “blue water” that is the largest untapped reservoir of climate data on Earth.

Data flows to shore may be improved and more anonymous; the 5G principle of excess capacity allows an 8Gbps connection to a cloud service or NOC; ubiquitous TCP/IP networking allows any entity to create an unmanned or manned shore-to-buoy communications relay and share that capacity with the operator of interest. Flexible frequency use; more lower-bandwidth devices; more-specific beam steering from satellites; several beams directed toward a moving platform, at least some of which are pointing toward the satellite;

constellation-level globe-ranging; and mobility management all help 5G-A improve remote connectivity. The operational costs of sending and processing sensor data on and near the water are drastically reduced, though data transmission costs still outweigh traditional time-series storage. Companies are making waves in commercial network systems in marine remotes; as more ships are placed in the waters, costs will fall and commercial logging will finally become commonplace.

3.2. Challenges and Limitations

Recent developments in wireless communication technologies have progressed at a staggering pace. The ongoing rollout of fifth generation (5G) wireless communication has claimed to meet the ever-demanding connectivity requirements of society in tandem with the continuous exponential increase in consumption of data. More specifically, 5G systems will support a new generation of wireless maritime operations due to their lower cost, reduced high delay time, and increased data rate capacity. 5G marine use cases correlated with the maritime economy include digital twins and avatars for container and ship tracking, ship remote monitoring by real-time and high-definition video transfer, and augmented/virtual reality access for remote expert console-based support to crew.

Despite its utility, the adoption of 5G technologies in maritime use cases faces a number of challenges. Indeed, the use of marine wetware currently operates on private satellite connectivity, high-cost data transfer, and multi-day or weeks delays for input data access, thereby reinforcing a choke hold. It is important to reframe marine specific communication requirements for remote areas that spatially approximate the marine infrastructure services and submerged assets to both terrestrial and space-based infrastructure. Furthermore, Terrestrial 5G architecture may have limited performance, either due to lack of terrestrial base stations or interference due to non-communication specific equipment operating on similar electromagnetic frequencies. Hence, it is critical that elevated mobile network structures on buoys, ships, or undersea communication cables be utilized to augment 5G terrestrial capacity at targeted areas that operate during peak infrastructure use.

4. Satellite Uplinks for Remote Monitoring

4.1. Overview of Satellite Communication

The number of marine buoys transmitting real-time environmental data exceeds 1,500 globally, with many deployed in ocean waters. The utility of real-time data, transmitted directly from the buoy, is clear in research, industry, and public safety. Data from geophysical buoys are used in trending and in modeling efforts, used by agencies for marine and weather monitoring, and of course for fishing, sailing, and recreational diving. The cost of data transmission by satellite continues to decrease, and the service has become ubiquitous. Reliable, low-power uplinks are enabling the deployment of increasingly diverse sensors in remote areas, and in tracking and mobility of both corporate and government services.

Satellite uplinks enable two-way service for monitoring, deployment, and transmission of information on demand, with redundancy and recovery, and for periodic updates sent in the event of an alert condition. In the first case, operators can update the microcontroller firmware by restoring the buoy to a known state, or adding telemetry logging and processing more sophisticated data. Recovery without a wet-well or monitor switch for switches is possible using vibrational sensors for boats or other large vehicles, and using auxiliary logging and processing to trip a monitor switch. In the second case, the buoy can be instructed to periodically log additional data, e.g., from a fluorescence sensor or nutrient chemistry pump that cannot be powered continuously, with ease for the new generation.

Through either case, remote buoy monitoring is critical for maximizing operating life and vessel safety. The buoy can track hurricane path, inform the buoy owner for predictive deployment or fuel needs, and be instructed to collect additional information when it is hardest to deploy the buoy. Sufficient monitoring capacity enables adiabatic, autonomous predictive deposition of buoys, data loggers, and monitoring resources, without the need to have vessels on site.

4.1. Overview of Satellite Communication

While commercially available satellite communications systems have been in use for more than half a century, there have been major innovations in recent years that continue to change and enrich applications that are practical on a global basis. The story begins in 1962 with a satellite launched into a low elliptical orbit. From that time forward numerous satellites have been placed into geostationary orbits, appearing fixed in space above the surface of the Earth. Because of the directionality of microwave communication, well designed and properly applied, these satellites have provided nearly unlimited coverage for telephone conversations and video broadcast. Unlike the numerous direct-to-home television satellites, the space segment of these satellites is usually designed for multi-channel operation, serving different communications companies around the world. The large fixed dishes that are conventional on the receiving ends of such services are not suitable for mobile station use, but travel-in-motion antennas have been built and used successfully on ships and trucks.

The technology has matured to the point that high-data-rate services via these satellites can be provided at moderate cost. To which data system will be applied the capabilities of the satellite systems in the near future? Certainly the burden is on the ground system design. Any communication channel has its unique characteristics which must be matched by the requirements of the signals being transmitted, to achieve the most efficient performance. In the case of the geostationary satellite, its particularly long channel delay imposes restrictions on the type of modulation that can be used. Error correcting and other signal structure details must match the available errors. Satellite channels may have a relatively large variation in carrier-to-noise ratio, which may be minimized at the expense of a reduced overall capacity.

4.2. Integration with Marine Data Systems

A wide variety of satellite providers now supply many forms of remote connectivity to install marine sensors. The choice of satellite system to use depends on many factors: data volume, timing, structure, and cost; location, power consumption requirements; logging system, device or functionality to be integrated with the satellite service; provisioning process and duration, contractual requirements and duration; SLA requirements, maintenance, and service support. Deployment costs and order size will also influence the choice of satellite service, and in many cases multiple diverse sources of satellite uplink could fit well within a data pipeline’s distribution workflow.

The design, architecture, and capabilities of the satellite system and its protocol greatly affect data timeliness, latency, redundancy, and costs. Gaps in availability for stored retrievals can occur if callbacks are not possible, if wide bandwidth reset requests are not tracked by a local timer, if the commands become discontinued, or if server-packet processing is delayed. Limitations on data gathering capability can also occur from hiccups in sensor sampling or logging device comms, and adjustments could be incorporated within the sensor sampling and operator logging file transfer strategy, or the backplane return window of the satellite store-and-forward callback. In some cases, external factors could prevent utilization of callbacks and wide-bandwidth requests through the satellite relay, leading to long gaps in data recovery from the sensor. Some architectures can have long intervals on resets, and should be avoided for timely satellite scenarios.

5. Real-time Data Ingestion Techniques

In the Marine Web we find high volumes of real-time heterogeneous datasets collected over disparate Earth System Observing Systems and their nodes. Although the open Web allows the free access of these datasets, their discovery and query involve high technical overheads. As a result, observation science and marine research communities tend to use proprietary systems that limit scientific collaboration and repeatability of research work. In particular, ingestion and processing of real-time data from sensor nodes deployed at sea and in oceans are important steps of marine observatory open Data Pipelines. On the one hand, open Data Pipelines should provide and maintain continuously real-time Ocean data services. On the other hand, such Data Pipelines should at least facilitate but also automate the collection of custom, hybrid, and historical data services offered through a variety of distributed Data Providers. In the practice of marine systems, there exist several tools based on ETL processes performing regular intervals batch updates. In particular, facilities periodically produce gridded fields and other dataset representations from point-based data and provide Data Services APIs for customizing the variable options. Stream processing frameworks can accommodate dynamic event data units build, filter, and process operations needed to create real-time high-frequency parameters series using data from proprietary and public open data APIs. This type of implementations of the Ingest/Process primitives of the Marine Data Pipeline model are used for Data Providers embedded in the Service-oriented Architecture. The uses stream processing frameworks for building prediction models, and to provide transformation algorithms to be embedded in Sensor-Driven Workflows through Web Services.

5.1. ETL Processes in Marine Systems

Marine life study or monitoring systems are traditionally organized in Long Term Observatory Programs, although new types of services are starting to be offered based on the needs expressed by niche types of Researches. These systems collect and store data and have a long time persistence, while newer ones are instead based on a more task-oriented approach, allowing a higher balance and optimization among costs and quality of the service. For what concerns the data pipeline processes we can identify different kind of designs. Very often a set of distributed buoys are deployed to acquire different data streams; these data streams are then periodically retrieved, organized and stored in a dedicated repository. If we consider a more advanced configuration, where each buoy is equipped with more powerful computational resources and capabilities, we may have a more complex type of processing, based not only on data retrieval from those nodes, but also involving data analysis and mining strategies in extreme edge conditions; these more sophisticated frameworks result in buoys that implement a more efficient role of data pre-processing and basic analysis in a distributed way, with a certain level of independent intelligence.

In the last decades, several challenges in the management of the marine data pipelines have been addressed, attracting the interest of the scientific community, focusing their attention both on the optimization of specific components of the pipeline architecture - staging, buffering, transfer - and on the definition of the architecture itself, mainly with reference to the complexity and engineering of the edge nodes performing storage and/or processing. Solutions have been proposed with reference to resource constrained networks as those that connect the sensor nodes, through the terrestrial transport. Oriented to satisfy specific requirements of the marine domain or information other than the data, as for example techniques or Metadata. Present also different categories of sensors' data in terms of format type for which resources and solutions have to be added or design. Adaptation to specific conditions or events either at network level or node level have been also addressed.

5.2. Stream Processing Frameworks

One of the oldest and most frequently used ETL technologies in analytics, whether in the cloud or on-premise, is the Extract-Transform-Load (ETL) process that transforms the source data prior to ingestion and loads it together.

It sits in contrast with ELT processes that load the data into the destination store first before transformation. As the volume and velocity of the datasets continue to increase, streaming analytics has gained ground over traditional batch processes in both the cloud and in big data technologies such as Spark. However, in addition to the real-time aspect of scraping the web for fresh datasets and frequently loading them onto cloud services, streaming analytics differs in the cloud from those offered in on-premise and hybrid environments because of cloud geographic specialization and the need for streaming localizations. In comparison to traditional ETMs with structured operations, often referred to as traditional ETL operations, streaming analytics also allows for complex event processing, or CEP.

Streaming data pipelines can be built to issue alerts on events as they are streamed through the pipeline and before they are accessible in the cloud, on conditions specified as event patterns by the user. A pattern that is detected to have occurred real-time, such as excess phosphorous or dissolved oxygen in the case of an algae bloom, can be passed before saved onto storage into a CEP machine. In addition to being passed on, which could take up considerable resources, it could also simply use the alert to trigger a script, such as post on social media or execute an action website, monitoring a position, or even transfer to load clouds suitable after further processing.

6. Cloud Platforms for Analytics

In this section we discuss three cloud infrastructures that marine researchers can quickly get started with to collect, exchange, and analyze buoy data. In addition to these core infrastructures, all three cloud providers have a variety of tools for developing, deploying, and maintaining applications. These toolsets form an ecosystem with strong support for artificial intelligence (AI) and data analytics applications. Data service capabilities on the three platforms have a lot of overlaps. The strengths of each service differ based on the specific use case and costs. We recommend doing a cost benefit analysis comparing the approaches in this document and the semester to make the right decision.

Microsoft Azure offers tools for data collection and analysis that are ready for deployment at each stage of the data flow, from buoys to visualization. Azure IoT Hub is the deployment on the cloud for connecting to devices sending messages, and the time series data is added with an Analytics worker that is polling messages from the IoT Hub queue. Azure Event Hubs can also be used for the aggregation of incoming message streams, and it is used in applications that need very fast ingestion speed. The time series data is then moved to Azure Data Lake Storage, which is optimized for storing large amounts of unstructured data on the cloud. The data travels over to data explorers and application developers through Azure Search Indexer over a plugin to the data lake link, where users can annotate the data with tags. Workers for the Analytics are locally deployed in each buoy using Azure IoT Edge that is used to route messages among modules and update images in the pipeline from the cloud image repository. Modules can be developed on a development setup running on a local IoT device emulator using the same underlying Linux container architecture.

6.1. Overview of Azure IoT

The design of the Azure IoT Hub is a service within Microsoft Azure that connects, monitors, and manages Internet of Things (IoT) assets. We utilize many associated Azure services to quickly and efficiently process stream data from our assets, which are geared toward real-time analytics for visual appearance, location, and performance. Stores such as Azure SQL Database and Blob Storage hold back-end data in a manner that makes it easily retrievable for further data analysis. Our goal is to conduct forensic analysis on Pipeline Data after a completion event in order to extract valuable information from this large data set. We adapt other vehicle-related cloud templates for both Pipeline Data and forensic analysis. The Azure portal offers a graphical and easy solution for setting up stores such as Blob Storage, SQL, and Geospatial. Part of the work we are doing is to provide reference architecture for other teams executing Cloud Pipeline Data with Compression onboard the Buoy Vessels, and these are templates that we would reproduce for these teams.

Temperature, pressure, and other buoy measurements are efficiently streamed to Data Lakes with continuous Data Factory transfers. At the same time, they are moving to SQL Databases for real-time analytics of the data just received. The CLI for Azure Data provides efficient transfer. The Microsoft Azure Services make sense for our work for several reasons, even considering support for other Cloud Platforms. Azure allows us the flexibility to measure what we need at lower Power until we need larger Data. There are less complex setups available from Azure that also allow a full-fledged monitoring of our devices with a Real–Time view, along with easy transfers, while C2 offers limited direct capabilities. Sharing the same Azure services minimizes cloud interconnect fees, while its regional reach minimizes latency with a close-by Data Center.

6.2. AWS Greengrass for Marine Applications

In AWS IoT Greengrass, some of the AWS Lambda programs run on IoT devices instead of the cloud. AWS provides a module to put the AWS Lambda runtime on IoT devices, including Amazon's Snowball Edge, which is used for physically transported bulk data processing and transfer, as well as Raspberry Pi systems. An AWS service called Greengrass Device Management can help deploy and manage the Greengrass module on these devices. You can imagine a small computing structure with Snowball Edge at a port for a bulk data transmission ship and AWS IoT Greengrass modules running on Raspberry Pi systems on the bulk carriers or fishing boats. The AWS Greengrass IoT system registers the Raspberry Pi sensors/actuators and indicates the runtime AWS Lambda programs and the schedule of which processing should be executed when and where.

A distributed IoT system like this is useful for the marine environment. But it would also have some severe drawbacks related to the cloud services of AWS IoT Greengrass and Edge AI. For example, the marine hardware would not get updated automatically because IoT Greengrass does not support a package manager, so enrolled devices need a custom solution that uses the Linux command line. AWS IoT Greengrass is offered in public clouds, but facilities that want to use this service have to request general access to these IoT edge management services. These would probably take a month or two to be available, which is a bottleneck to the deployment time of a new IoT module in a new working location. Security is another big issue because access to core functions would need to be restricted with firewalls. AWS Greengrass can also be difficult to use in harsh marine environments that are very different from land settings.

6.3. Google Cloud Platform Solutions

Google Cloud has several components that can be used to create analytics pipelines for buoys and other marine systems. While there are common tools across cloud platforms, the way they work together is often specific to the cloud provider.

The primary components are listed below.

• Google Cloud IoT Core: Secure device connection and management.

• Google Cloud Pub/Sub: Global messaging service for event-driven systems.

• Google Cloud Dataflow: Process data in any combination of batch and streaming modes.

• Google Cloud Storage: Durable, highly available object storage with strong consistency. Suitable for storing raw data.

• Google BigQuery: Fully managed fast SQL analytics to analyze large datasets.

• Google Cloud Functions: Function as a Service serverless code execution that can process Cloud Pub/Sub messages and customize an application.

• Google Kubernetes Engine: Managed scalable container environment that can run a microservices architecture application.

• Google Cloud Data Studio: Productivity tool for fast dashboard creation.

• Google Cloud Vision: Image and video recognition for analyzing photographs and video.

• Google Cloud Build: Fast build pipelines for compiling applications so that they can be deployed.

The IoT Core is a central part of the overall solution to securely connect buoys to the cloud, where Pub/Sub is the central event bus between all of the services. An inexpensive, low-power processor on the buoy sends messages from the sensors and to Bleed CPU at an appropriate polling interval. Messages from the buoy are sent via Pub/Sub to a Dataflow pipeline that writes the raw messages to Cloud Storage. Ingested images and videos are processed by Cloud Functions and use Cloud Vision for analysis. The resulting messages are sent on to Pub/Sub for further processing and storage as needed.

7. Data Visualization for Marine Stakeholders

7.1. Importance of Data Visualization

Marine stakeholders need to be able to visualize buoy-sensed data in an accessible manner so that they can learn from and utilize insights contained in the data. For example, fishermen may want to identify when surface waters are at stable temperatures, stable salinities, and low chlorophyll abundances, and at what depths these conditions occur, as an indicator of stability in the euphotic zone where fish want to eat and where they are easy to locate. Fishermen may also turn to sea surface salinity and chlorophyll trends north of the Gulf Stream for answers to questions about supply and demand on the Mid-Atlantic fishing banks. Forest service scientists may want to see more complex relationships between buoy data and land fast ice conditions or review model results that are fused with buoy data to seek ways to improve models. Modeling scientists may want to visualize buoy data that they have assimilated to improve model output.

Academic researchers publishing papers on buoy data or results of machine learning with buoy data may want to visualize machine learning thresholds for classification of buoy data or where machine learning methods could have been improved. Environmental watchdogs may want to compare mini-buoy or mooring data with satellite or model MET data from the same years to assess correlations and differences.

7.2. Tools and Technologies for Dashboarding

Many software technologies allow the presentation of sensitive geolocated data in open-source dashboards. The computational and visualization framework of choice for this work is a scripting language used for building interactive web applications. It is integrated with R code embedded with visualization packages, including Leaflet, Highchart, and ggplot2. It can clean or reshape data in local text and CSV files or access data at a distance from a web API. It offers both client-side and server-side processing, enabling it to deal with heavy processing tasks such as creating a graph or customizing a map background with ggplot2 that typically might be too processor-intensive for web clients. Its reactivity allows for clear organization and coherence between UI and server design elements that any developer with minimal coding experience can handle, and it’s possible to build complicated applications purely using this framework. While many platforms require long-term financial support from user groups, apps can be free as long as they’re hosted in the cloud on the open-source server.

8. Security and Privacy Concerns

As data pipelines become more ubiquitous, security and privacy issues will increasingly become important factors in deciding which systems and assets to deploy to the cloud or allow accessible from the cloud. Uses of ocean buoy data pipelines can be co-opted for malicious things either instead of or in addition to scientific research, ocean observing system management, and engineering resource design and safety. Counterintuitively, malicious usage could stem from good intentions by some perpetrator utilizing buoy data toward research with good intentions and without the racial, ethnic, socio-economic, or political divisions that polarize people working toward a common goal. But the immense potential for both good and harm from the data pipeline automatically implies an urgency to ensure that the data pipeline has a sufficient security system in place to prevent navigational hazards, other ocean users inadvertently acting without appropriate coordination through lack of timely distrust monitoring, and waves, currents, seas, coasts, and everything else in the oceans remaining healthy. While we envision security systems to minimize conduct risk, enforceability risk, and external risk with the data pipeline will be a decentralized autonomous organization, decentralized finance, or some combination of the two, technology creates challenges as well as resolutions. Buoys could either be hacked and the data invalidated or hacked and data streams altered, and having complete faith and trust in the security systems in play would seem an unsustainable fantasy. While the best approach may vary depending on circumstances, best practices include least privilege, defense in depth, assume breach, monitoring and logging everything, web application firewall, and distributed denial of service remediation. These best practices would need to start with onboard processing and deployment security cameras on buoys dedicated to these two functions, and the onboard processing and deployment security camera data along with vehicular data would be validated off-buoy and archived onto a permanent storage medium whenever the buoy boat came within range of telecommunication.

8.1. Risks in Ocean Data Streams

In this short section, we will explore the possible risks of manipulating ocean data streams. The primary details of our deployment and configuration are based on a project developed to expose filtering modules and aggregation methods for a data-centric IoT platform architecture. In particular, we will focus on the presentation methods and the authentication across the layers of the IoT systems.

The data collected by intelligent buoys has different types of signals containing information that is interesting for data scientists. When this data is ingested in the cloud, it is manipulated and prepared for research. The ocean data streams contain some sections that are composed with empty and useless data. This empty section time is detected in real time and sent to the researchers. Moreover, there are time sections where the anchor in the ocean bottom by the buoy was on and it is not interesting since it does not contain data for research (the signals are always zero), but other signals, such as sea surface temperature, are not zero. These specific situations have to be monitored and filtered according to the awaiting for the inferred research. These particularities will be highlighted along the chapter.

The buoys, based on the control architecture that transports the digital signals, can also be exposed to various kinds of attacks, including replay attacks, spoofing attacks, remote scanning, and so on. These attack types could make the sensors compromised to deceive the forum system. Falsified data can have different nasty implications ranging from a loss of safety through potential privacy breach. The Operating System for sensor nodes must provide cost-effective data protection mechanisms to fight against compromised data by using control channel traffic monitor strategies.

8.2. Best Practices for Data Security

Adopt a layered intruder defense strategy. Perimeter security includes firewalls and protection against distributed denial of service attacks. Intrusion detection systems raise alarms when intruders are detected trying to penetrate the system from the outside or to move around the system from within. Payload security prevents other system users from reading or modifying each other's data. Multiple solutions have been used successfully, including access control lists and certificates. Detection of pipeline-level faults, such as loss of data quality, is necessary. Preventative approaches include monitoring for availability, integrity, and authenticity as data travels through pipelines. The use of hashed passwords, cryptographic data-signing tools, and cryptographic hash algorithms is encouraged.

Researchers should employ a data protection plan with court-ready documentation. Data producers must create formal usage agreements with data consumers that specify security requirements, data protection plans, data sharing plans, and data backup requirements. The guidelines differ depending on the type of data: forcing focus on both how the data pipeline is built and how the security capabilities are implemented; open data and net benefit make cyber security caveats more complex; and final archiving is specified as a minimum basis for data protection plans.

Most importantly, researchers should try to create deterrence by legally demanding the consequences of inappropriate actions through well-crafted agreements that effectively support trust but verify. For the principal investigator, this means acquiring the consent of the data providers, particularly for private data like tracking information. The responsibility of the private entity that provides the data to the principal investigator needs to be assessed, and the extent of the data security should be determined as well.

9. Case Studies of Successful Implementations

In this section we provide two case studies from real project implementations. These cover applications that either relied on realtime data or collect either live data from buoys or download data to run post-processing analysis with DTM software. The reasons triggering those choices are indicated.

9.1. Case Study 1: Real-time Monitoring

The real-time monitoring of the bay of La Paz uses a buoy named S-1, which started operating in October 2003 with a sampling period of 15 minutes for sea surface and water column temperature (from 1 to 35 meter depth). The buoy downloads regularly the data after each sampling period. The installation of data pipelines from buoy-to-a local server and data-to-the-cloud followed the original guidelines on the use of DTM software. Those provided data, about 9500 days long, are continuously used for real-time monitoring, and have also been reliable for post-processing of extreme event analysis, climate variability, and atmospheric–ocean models' calibration.

The buoy has been operating mostly in real-time since 2008, including the full support of the data pipeline. The buoy uses an Aanderaa data logger to measure wind speed/direction, air and water (at 1 meter depth) temperature, barometric pressure, and a RDI ADCP for currents and temperature in the water column. The real-time data pipeline runs continuously and recover any possible erroneous value and message generated by the buoy. For that, the DTM software is responsible for daily and per-sensor validation of the data from the channels being studied. Using the original work recommendations, additional statistical and temporal validation procedures have been implemented, as well as a set of external trained engineers that take care of local procedures (e.g., float calibration, urgent buoy recovery). A backup buoy using only wind and air temperature remembers errors either locally or via satellite, so other local partners could be supporting the buoy during strong winds or any other adverse environmental scenarios.

9.1. Case Study 2: Real-time Monitoring

In the following two sections on "Case Studies of Successful Implementations", we present some of our historic work and learnings in setting up reliable, low-latency data pipelines and in building out monitoring dashboards to visualize timely, useful information from the data. These projects, gathered and initiated over many years, helped in guiding development for the eurus pipeline and dashboard design. Based on our previous recommendations to collaborators and clients and our early experiences with the Data Pipeline and Visual-Monitoring Pipeline, we initially focused on getting simple monitoring dashboards up and running and then built in additional complexities, including more cameras and data sources, labels based on data-driven approaches, database storage of findings, and custom APIs offering limited accessibility.

As one of the first, simplest examples, we describe here a project we did to follow a local initiative to gather data on climate change and its effects on the fragile conservation region around Garibaldi Provincial Park. The framework consists of four critical buoys anchored just outside of the Garibaldi Park area. They are outfitted with sensors that measure the speed, direction, temperature, and humidity of the air above the water, amongst other components. Weather station sensors deliver important local research data as poor data from inaccurate far-away stations that do not factor local microclimates. The delivery of local microclimate data is important for ensuring the sensitivity of our region’s fragile ecosystems and the health of the lichen growing on Blackcomb Mountain, where researchers are trying to learn more about climate change and its effects.

9.2. Case Study 1: Data Analytics in Action

The implementation of Data Pipelines from Buoys to Cloud Analytics was conceived first to answer the question “What happened?” at a very broad scale. IPv6 addressing allowed rapid promotion of hundreds of analysis simulation output files stored in facilities to hundreds more rent and governed nationally, and their relationship to tidal currents in populated estuarine regions occupying most of the New England’s shores. Undertaking the task of unifying and extending these probative datasets, it was determined to publish the resulting available data products widely, freely, and openly, where appropriate and to anticipated individualized discovery and download through special projects.

As the offshoot of Real-Time Monitoring, and as it anticipated analysts' further efforts, Data Analytics in Action took input from data monthly, looking back no further than the past few weeks, and reviewed presence, duration, intensity, and frequency of conditions. For each of two sensors at the base of two strategic buoys – Woodstock and Underhill – variable sigma-I thresholds determined the total integrated bands on vertical emission. A lot coded according to band isolation determined when conditions appropriately revealed fine structure or whitecap transitions on 0.67 and 0.78 µm radiation. Rainbow-banding in 670nm light while insisted on the Moon on 755nm radiation, both bands considered on a 0.09µm scale, enabled response type discriminations as surf cap or fine transit, respectively. Cored in ten-minute intervals, bytecoded images were sent to commodity storage while remaindering the data-rich PNGs.

10. Future Trends in Marine Data Pipelines

In the future, intelligent data pipelines will emerge and become interactive "conversational data pipelines," enabled in part through the adoption of new machine learning techniques and capabilities. Adaptive sampling from marine sensors will continue to increase, inferring data needs for different phenomena on shorter time scales and trigger sampling on demand. For example, for water quality management at an embayment, a predictive model will drive the sampling rates at the buoy. The buoy will sample more frequently if a storm-generated flow into the embayment is predicted and on a lower sampling rate at other times. Systems will also work better with less frequent and lower quality remote sensing, determining areas in need of groundtruthing through sensor measurements at nearby buoys or coastal stations. Innovations in drones, autonomous surface craft, fixed platforms, and marine vehicles will enable measurements of processes that are poorly resolved at the patch-scale of floating buoy data but are critical for models of how, for example, fronts and eddies break down and impact exchange of heat, carbon, and momentum.

Different marine and coastal environments place different demands on sensor components, data transmission, processing pipelines, and analysis. Data pipelines will adapt to these differing conditions and requirements as the sensors evolve. Cloud business models will provide the incentive for ecosystem innovations and for solutions that actively reduce the cost of hosting and delivering broadband service such that the needs of the country for climate and weather monitoring are met in an equitable manner, alongside business and recreational requirements. The next decade will also see transitions to new observables and new platforms: new conditions call for different measurements to optimize for their effects; new issues call for the infrastructure to optimize for observations.

10.1. Emerging Technologies

Planning for the future of any endeavor requires understanding of the trends in emerging technology. For marine science, technology in general has enabled more automation, smaller sensors, and the gathering and analysis of more data than was ever possible before. Here, we review several important trends in technology that are of interest for the development of future marine data pipelines.

Increasingly autonomous decisions can be made by sensors deployed in the environment. Edge processing allows for more intelligent decisions to be made in near real-time at the sensor: for example, an underwater acoustic recorder can make a decision about whether any cetacean vocalizations were present in a given time slice and only transmit the most relevant data across the all-too-narrow bandwidth of satellite communications, instead of sending a huge volume of audio data that has to be transmitted and then processed. On another augmentation of this concept, machine learning models can be executed on floating platforms collecting near-surface data, thus reducing the amount of near-real-time data to be transmitted to cloud compute resources for more comprehensive processing.

More modular and smaller sensors are changing the types of deployments possible for collecting in situ observations, as well as the amounts of data that are able to be collected. Innovations in energy harvesting technology, low-power wireless communications, and energy-efficient microcontrollers and sensors are revolutionizing the field of environmental monitoring. Data collected from custom sensor modules deployed in less sensor-friendly locations, like the deep sea, are enabling new scientific discoveries. Data collected from diverse modular networks that are connected by low-power wireless communications, receive regular firmware and configuration updates, and share computing resources are revolutionizing the field of environmental monitoring. The availability of more low-cost modular sensors only increases the flexibility for deploying sensor networks in other more diverse areas, such as coastal and estuarine marine environments.

10.2. Predictions for the Next Decade

Participation across marine data collection efforts should lead to dramatic increases in the variety and volume of data. The amount of data is expected to follow a significant growth pattern, increasing the amount of available high quality marine data by a factor of 100 every 10 years. Autonomous vessels are likely to become common, as will low-cost autonomous underwater vehicles (AUVs) and modular sensor suites that facilitate a wide variety of missions. Additional sensing capabilities, such as blue-green or hyperspectral optical sensors, sonar systems with increased capabilities for bathymetric, target detection, and classification, or detection of specific underwater features, such as marine mammal detection, incorporated into these AUVs need to be specified to ensure we are building the sensor capabilities required for widespread, cost-effective data collection. Many river and coastal systems, as well as major lakes and estuaries, remain poorly understood; should missions be designed to close these data gaps, and what would that mission design process look like?

These factors will result in abundant marine data, with far less effort expended to make it available and usable than is the case today. These abundant high-quality datasets should truly prove transformative; predictive skill in many areas, such as modeling coastal flooding and predicting harmful algal blooms and other marine disasters, should result in significant reductions in societal costs and disruption. Do these opportunities and predictions provide enough motivation for all the current players supporting the effort for Marine Data Pipelines? The impact of distributed networks and working groups needs to be evaluated, to what extent can their functionality be significantly enhanced or already ephemeral tasks simplified?

11. Conclusion

extracting raw data, whether from scraping web pages or querying relational databases, typically takes less time and resources than filtering, normalizing, and cleaning that for analysis or machine learning. Due to very different designs, issues, semantics, and efficiencies, building an end-to-end system for domain-specific, built-in data, and statistical methods is not trivial, and usually done only by teams of expert engineers. However, those engineers rely heavily on library routines to do the heavy lifting. We explored in detail several common machine learning tasks in a domain rich with production-quality routines and critical mass of expert domain knowledge: oceanography.

In this essay, we have presented a complete and full-cycle data system and various automated and semi-automated routines from data ingestion through exploratory data analysis augmented by supervised machine learning for building convergence maps to a few more specific applications such as noise estimation. The ocean optics problem of how water absorbs and scatters light is of fundamental interest because it characterizes natural water bodies and modulates both atmospheric and oceanic optics after mixing or stirring oceans to add foam, bubbles, and particulates. It is also of applied interest because it enables concurrent inference of new data from already-existing models or concurrent estimation of new data from already-existing models. To help perpetuate the circular economy of ocean optics data, we hope that this essay serves both as an inspiration and a foundation upon which future protocols can develop and build new synergistic connections to the data plumbing and automatic modeling-cycle systems presented here.

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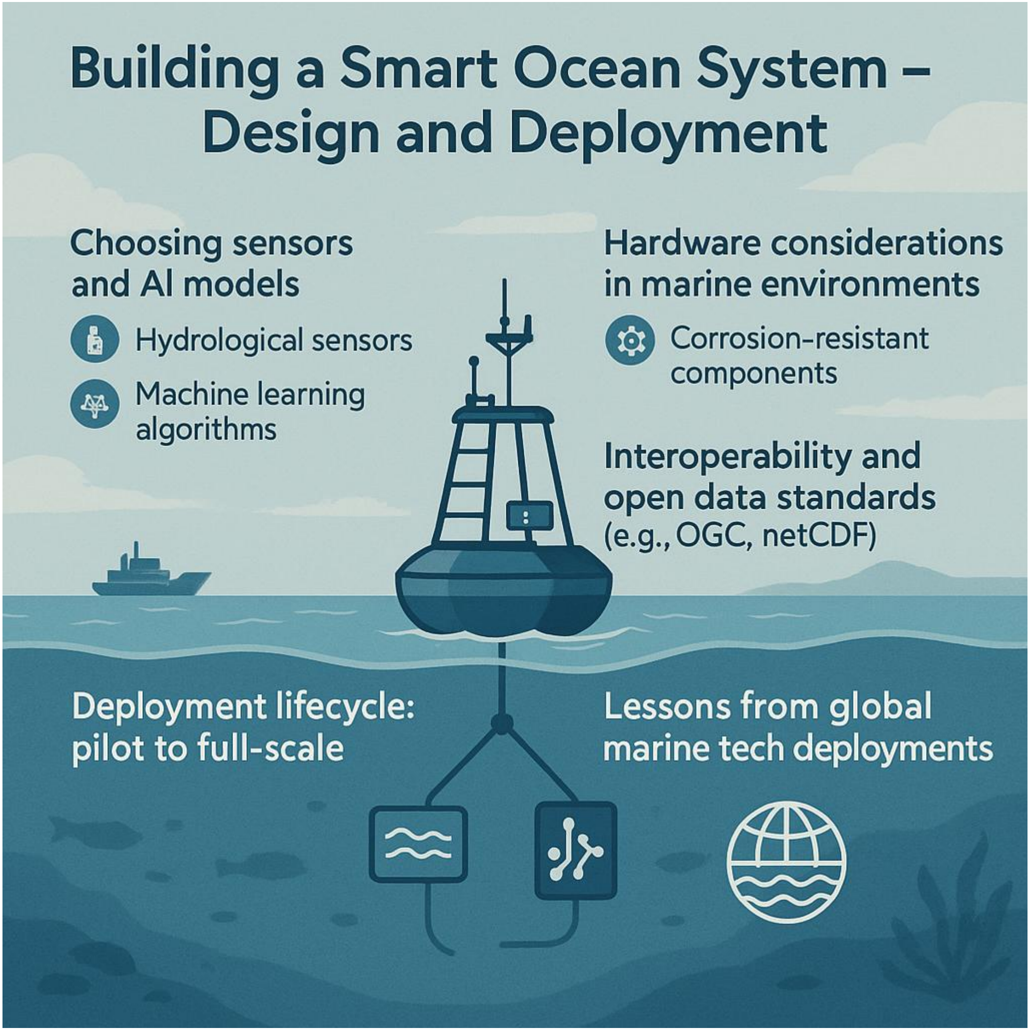
Chapter 7: Building a Smart Ocean System: Design and Deployment

1. Introduction to Smart Ocean Systems

Because of its broad impact on climate, commerce, and communication, the oceans serve as a commons for our planet's inhabitants, and therefore demand our attention as we navigate the challenges of the Anthropocene. As such, the oceans and the ecosystems they support act as the foundation for varied aspects of life on Earth, from early human settlements to the complex web of trade today. Consequently, understanding the ocean environment, including its physical/chemical properties and biological inhabitants, is essential to sustaining ocean health and maintaining a balance for life above sea level. Data obtained from the ocean guide and enhance many functions that benefit populated coastal areas as well as passengers transiting through. These functions encompass weather prediction, seismic monitoring, climate change mitigation, natural resource harvesting and management, and marine transportation. (Viegas et al., 2018) (Trevathan et al., 2012) (R. Teixeira et al., 2021) (Geryes Aoun et al., 2024)

Execution of these functions is currently limited due to a lack of universal autonomous sensing and awareness systems that can both observe and communicate with varying types of targets – from AUVs and submarines to whales and seabirds – within the uncertainty intrinsic to the ocean environment. Such ocean system network management and tasking operations are crucial for addressing the needs of the existing global ocean observation system, require the capabilities of smart ocean systems to interact with these data-hosting agents to schedule and direct their data-delivery tasks, control their motion, and selectively incentivize deployment of energy-harvesting nodes and buoys.

Smart ocean systems provide a foundation for the decentralized management of a diverse set of remotely tuned, adaptable mobile and static nodes that together compose accelerated ocean data collection efforts on behalf of science and society, driven by agency and responsibility. These smart systems motivate our unified design and deployment effort.



2. Choosing Sensors and AI Models

Ocean monitoring and actuation may involve a diverse array of specific objectives and scales, requiring a variety of sensors and complementary AI models for critical observable quantities. Satellite imaging is essential for ocean color, ocean and surface temperature, and both observation and recovery of ocean optical properties. Specifically, sea-surface salinity and winds, phytoplankton bloom development, and interaction of ocean-surface currents with atmospheric cyclones for hurricane forecasting have been addressed with dedicated sensors and appropriately-timed missions deployed for specific conditions or events, and this domain is a legitimate focus of the long-standing concept of constellation of small satellites. A convenience of such pre-packaged sensor packages is that they are well-prepared for processing, saving significant effort for selecting and tuning appropriate AI algorithms.

As we select, calibrate, and deploy sensors, however, our focus inevitably broadens to a wider range of sensors and particularly to the coupling of sensors and AI models. The close coupling of sensors and AI models is typically neutral: some are sensors-first and AI models rely on special solution routes to provide numerical description of relevant state quantities such as wind velocity and sea surface height, or coastal quantities such as erosion or short-duration inundation zones; others are models-first and require training data from sensors to allow supervised learning. For procedures such as data assimilation to be feasible, models-first approaches demand that the observed quantities are reasonably captured by the AI model and that they are not significantly divergent during the forecast or modeled period. Both approaches are enhanced by high observation-frequency capabilities, and AI models are increasingly embedded elsewhere in the solution. For example, trained AI models are now able to predict Lagrangian trajectories and surface- and interior currents at longer time scales, as well as inter-sensor differences in ocean column properties being determined by other physical models.

2.1. Types of Sensors for Marine Environments

Sensors play a crucial role in the Smart Ocean System by measuring quantities of interest in the ocean. Sensor data inform AI models, which generate outputs to enable novel capabilities, such as evaluation of marine health. Here, we consider the types of sensors that are applicable to the Smart Ocean. Sensors measuring physical properties of the ocean serve as foundational sensors as they create basemaps through which all marine life interacts with the physical environment. Optical sensors may be complementary and add important information about chemical components, biological organisms, or incident light.

Physical data related to the movement of water, the state of the water, and the manner in which heat is absorbed strongly influence how marine life interacts with the physical environment. The nutrient flow, algae bloom, primary organic production, ocean stratification, hurricane forecasting, or guessing when an eco-catastrophe will occur are examples of physical data that can be gathered with these sensors. Information on the last two examples, ocean stratification and eco-catastrophes, can also be gathered and could potentially be enhanced by other optical and chemical sensors mentioned below.

Different measurement techniques can be used to measure the physical properties of water. Sensors built based on sonar pieces of equipment, which are referred to as Acoustic Doppler Current Profilers, measure the current speed and direction on different water column levels via high-frequency echoes. Thermistors can measure temperature. CTDs sensors can measure temperature, salinity, and depth. These types of oceanographic sensors can only measure these parameters when mounted on a moving platform that goes from the surface to the bottom and back. These indeed require being physically deployed through the water column, and they create sparse but high-quality data.

2.2. Selection Criteria for AI Models

The advancement of machine learning (ML) and computer vision (CV) methodologies has greatly facilitated understanding and pattern recognition in most data types. There are thousands of papers and open-source software libraries available that can be employed for a wide variety of different problems. Therefore, a sensible next question is: given that we have data from any position in the oceans, what are the “magic keys” that we can deploy in order to unlock the secrets hidden in this data? The answer lies in the application of the correct CV and ML methodologies.

Sequential feature selection helps in selecting the most significant features that can make a prediction and compressing the amount of data that need to be sent back from the sensor. Combined with labels that indicate which objects from the classes categories are present in each sample, a spatial model can be trained and deployed at each sensor, to localize these three-dimensional features that indicate the presence of a given class. The alternative is to develop a purely supervised ML model. However, the latter comes with the risk of suffering from domain shift and the absence of training data. Both approaches require human intervention to one degree or another. The work described in this chapter seeks to propose a methodology that balances the need for supervision with the availability of data. The goal is to maximize prediction accuracy while minimizing the amount of effort required for the data gathering and labeling steps. Once the correct models are validated, they can be deployed at scale at each sensor, to begin observing, exploring, and understanding how the dynamics of the ocean produce the community structure we see on a day-to-day basis.

2.3. Integration of Sensors with AI

When integrating sensors with AI, the most common approach is to connect different types of sensors with an AI model running on a device capable of receiving large amounts of data from all different types of sensors, performing the AI function and sending relevant information to the output. However, this approach has limited usage in a smart ocean system where the goal is to monitor a diverse and dispersed ocean environment for possible climate changes or for monitoring the ocean ecosystem. Spatially distributed AI is an emerging application of AI for edge computing environments where the data from local sensors is first processed by AI algorithms running on the local devices and only extreme data is sent to a central device for additional processing. We first describe this approach for integrating sensors with AI and then provide the possible variations in sensor types and device types being used for edge computing environments. In distributed AI applications such as in a smart ocean ecosystem, the goal is to conserve bandwidth, storage, and processing requirements in the smart ocean system. The latter requirements can be obtained by deploying spatially distributed AI applications with the different types of physical devices. The types of edges performing the function of local processing and extraction of relevant data pertinent to the AI algorithms depend on their capability for operating the different AI tasks and types of pre-processing devices such as cameras or low-cost smart phones not being capable of processing heavy AI tasks cannot be used as edges. Supporting low power devices as the edge nodes also depends on the types of networks available in the ocean ecosystem environment and these are not universally available making general solutions for the problem of configuring edge nodes difficult.

3. Hardware Considerations in Marine Environments

Collectively, the contributions of the various technologies described in the previous sections constitute the intelligence that makes the Smart Ocean system "smart". New underwater, surface, and above-water hardware, specifically designed for reliability and autonomy, are required in order to network and synthesize the data that is necessary to understand and resolve questions regarding ocean processes. In this section, we highlight some of the considerations and requirements for constructing these intelligences, with specific examples from the hardware developed in our own laboratory.

3.1. Durability and Environmental Resistance. To be programmable ecosystem scales and resolving complex multi-variable ecosystem dynamics in space and time, a truly “smart”, i.e., autonomous and adaptable, ocean observatory must sample with sufficient spatial and temporal fidelity at time-scales relevant to the ecosystem processes being probed. Such systems can be deployed in the ocean environment for days, months, or even years, for the purpose of interrogating some of the underlying physics. The data required can only come from responsively outfitted surface, underwater, and sub-seabed platforms. These platforms must be able to withstand the environmental conditions of the specific deployments, otherwise the collected data, or lack thereof, will be suspect. The sensor systems require appropriate coverings for safety against the environment.

3.2. Power Supply Solutions. Most of the oceanic measurements currently in operational use are made by systems on buoys or deployment ships that return to solar recharge or refuel for battery-powered sensor operation, usually every week to month, such that the sensor data return is highly erratic and limited in scale and novelty. Power consumption and management have been the principal impediment to operational use of many smaller sensors for continuous monitoring of the ocean environment from autonomous submerged and advancing platforms. These systems include buoys and vehicles that travel and or drift with the internal waves or currents while taking ocean water measurements that are relayed sporadically back to the shore. Thus, existing practices tagging and following predators is limited to only a few tagged animals at a time and is not practical for implementing more ambitious and broader scientific questions.

3.1. Durability and Environmental Resistance

Marine environments are dynamic and often extreme. Sensors deployed at sea must endure multi-month or multi-year deployments where they experience a steady barrage of sunlight and humidity as well as predictable seasonal swings in seawater temperature and pressure, the latter increasing by 1 atmosphere for every 10m in depth. In turbulent locations, such as the coast, turbulence and breaking waves also result in additional pressure cycles for devices attached to the sea bottom. For underwater hardware, biofouling becomes an increasingly important issue with organisms colonizing equipment having been observed propagating within weeks of deployment. While it is possible to meet some of these requirements, such as sealing all hardware using industry-standard methods, or to coat hardware with antifoulant chemicals, doing so is often an expensive enterprise in both time and money that significantly drives up the price and complexity of all components. Furthermore, national and military applications may set further requirements. It is often difficult to strike a balance between satisfied operating time and the sensor's ability to survive in the environment, both in terms of physical property design and reliability.

Thus, researchers must perform detailed physics-based modeling on various aspects of environmental resistance before they can settle on a design. These models can then inform the design by predicting the level of reliability as a function of design inputs. Often, the most effective design technique for underwater electronics is to follow existing design guidelines from the aerospace community where space and weight use is critical and systems undergo severe entropy kneading while operating above their design temperature between deployments. Such guidelines help improve reliability during critical design phases. In addition, the accelerators required for acceleration factors are often conservative functions from vendor data for these stressful use cases and more accurate use-case specific models must also be used once designs mature for specific applications.

3.2. Power Supply Solutions

The infrastructure cost of deploying a Smart Ocean System can be at a billion-dollar cost level, yet the cost of the electronics contained within the system is on the order of a few million dollars. The task of keeping the system operational for long periods of time is non-trivial. Powering a small computing system continuously on at the bottom of the ocean for years on end is a tall order. The Smart Ocean System integrates solenoids, cameras, sensors, data acquisition, data processing, filtering, and communicating with the world above. The crucially important assumption is that the underwater electronics required for the system propose no more than a few hundred watts of power which allow powering the entire system. It is commonplace to power all of the electronics from a battery for which the empirical design point used here is a 48-V DC lead-acid battery.

The system design restricts currents to less than 10 Amperes. This is about the maximum that can be drawn without the resulting voltage drop harming the operation of electronics, the majority of which run off of 3.3 V, and which would place excessive burdens on switches and connectors. Connecting all of the electronics on to a bus running off of a single battery representation to determine the total power may well attempt to switch off when the current drawn is on the order of 4 Amperes, so this capability needs to be kept in mind at all times. Any question concerning why 48 V and not 12 volts is because the supply is two series lead-acid cells and one needs to compensate for battery voltage drops. Circuit components also need to be kept at rated voltages. While this is being designed for a specific set of component voltages, utilizing a battery that consists of three series Li-ion cells is a more practical design, since the individual cell voltages are about 3.7 V at maximum, and may go to about 2.4 V or 0.7 V charge/discharge at minimum levels.

3.3. Communication Technologies

Communication technology is a crucial consideration for Smart Ocean deployments. We need to address how nodes in the network share data, and the latency, speed, reliability, and distance requirements of the applications and use cases. We often focus on long range data transfer, from the ocean floor to cloud data centers. However, other communication needs may be just as important, such as communication between sensors that trigger local responses, communication from buoy-based mobile sensors to shore, or new local computing algorithms that only send the results of a calculation to the cloud. Many types of sensors currently deployed in the ocean utilize Acoustic modems to transmit data to buoys for access via satellite technology. Acoustic communication depends on the pressure and temperature profiling of the project site, data security requirements, and data transfer rate and latency. Current commercial products offer bandwidth of 100s kbs but with significant limitation on distance and depth, and 100s bps over long distance and depth, as much as 120 km!!!

While advances in Acoustic communication may help us extend the range and reliability of some chemical sensors in deep water, it still requires frequent access to maintain them. Similarly, some optical sensors may be more reliable than chemical sensors but will require less frequent visits and eventually need to be replaced. New optical and pressure/temperature sensors combined with new optical acoustic communication capability may allow significant advancement in ocean monitoring by allowing for simultaneous measurements across different time scales as well as increased acoustical communication bandwidth for data transfer from deeper water columns without requiring buoy based mobile communication nodes.

4. Interoperability and Open Data Standards

Developing a smart ocean system will require the collaboration of many organizations and the integration of multiple data sets. To achieve this, we must design common data models ensuring data interoperability and reduce barriers to data sharing. Moreover, ocean data, like many other types of data, become exponentially more useful when combined with other datasets, yet because of differing data models, developers often struggle to integrate data produced by different organizations or instruments. Creating common data standards puts the power of building on shared data in the hands of more developers. These issues were long recognized by the geospatial community; in response, a series of open standards designed to promote discoverability and interoperability of terrestrial and marine geospatial data were developed. Those standards are now available for the benefit of other scientific domains, including sensor data.

The netCDF format is the dominant data format for meteorological and oceanographic data, providing a common model and allowing a diverse set of sensors to produce files easily readable by any programmer, no matter the programming language they prefer. The netCDF software library gives programmers high-level programming commands that abstract the complex implementation details of the underlying file format and network protocols. As a result of these well-maintained open-source libraries and the dual standard of netCDF4 Classic and netCDF4 Enhanced Model formats, the netCDF format is supported by nearly every important math and science programming environment.

4.1. Overview of OGC Standards

The standards provide a set of rules and protocols that allow any computer to talk to any other computer on the Internet and exchange spatial data. The exchange of data following these standards allows different software components to each do what they do best. These standards are often called "specifications" because they define the requirements for developing geospatial services and their clients. Specifications are similar to other technical standards in use for Internet and Web services. Organizations and vendors develop compliant services and clients that intentionally match these specifications. Data collected with a particular sensor, for example, can be processed by one vendor's software and published as a potential data layer on a map created by a different vendor's software. The viewer can select and control different data layers even though each comes from a different data catalog.

A basic premise is that data can be better managed when it is served in its native format using a Web service, not simply put into another format and made available for download and manual transformation. In this scenario, the standard service interfaces are used to share or integrate spatial information across communities and organizations without sharing the actual data. Furthermore, the existence of standard digital service interfaces makes it possible for individuals, communities, and enterprises to select from many available service providers. Standards ensure that the serviced data will continue to be available and properly formatted.

4.2. Understanding netCDF Format

The Network Common Data Form (netCDF) is a data format originally developed to allow for the sharing of scientific data, including climate and forecast data. The primary focus of the netCDF format is to create a structure for sharing large amounts of multidimensional data that can include a variety of dimensions of different sizes. The end goals of the netCDF project are to provide self-describing and portable data, with a platform-neutral file format that works with both large and small datasets, and thus enabling cross-discipline data sharing.

The standards established by the netCDF developers can be utilized through libraries to create netCDF-formatted files in other programming languages, including Python and C. Although it creates the least amount of overhead to process in the C programming language, there are netCDF libraries that ease processing with Python using wrapper functions. The netCDF file format has also been integrated into the commonly used Hierarchical Data Format (HDF5), which has the same goals as netCDF.

The primary way to determine how to structure the metadata is to look at actual netCDF files and their accompanying documentation. There are many resources that have netCDF data files and provide additional field descriptions. There are also the established best practices from the Climate and Forecast (CF) metadata conventions that go into greater detail about how to construct and represent variable values. These practices are the accepted de facto standard for how to create netCDF files that enhance their usability across diverse datasets in practice. However, as previously mentioned, there are no formal certification mechanisms for either netCDF files or the CF conventions.

4.3. Data Sharing and Interoperability Challenges

Ocean science has always benefited from the open sharing of data and collaboration among scientists. Due to shipping, plus the need for detailed precision mapping of coastlines in a variety of wavelengths, various agencies and their respective contractors have maintained an extensive collection of bathymetry and seafloor maps. However, detailed sea floor samples are rare, and getting samples of the same area at the scale of a cruise is expensive. Even so, valuable information is available from historic photographs, magnetometry, and sediment slides for archaeological and geological coring. Technology now allows for high-resolution maps with more datapoints than a manned submersible can collect, and at a lower cost than what a detailed coring or submarine sampling expedition would incur.

The same is true of underwater systems that are not historically surveyed. Efforts have been made to encourage the open exchange of data, but this requires a reliable and flexible pipeline and storage structure. When the time comes for a question to be asked and an answer prepared, few scientists are willing to work on the request when the only alternative would be to work their way through an arcane archiving structure, with confusing filenames, or query each individual scientist, slowly awaiting replies accompanied by files in a wide variety of proprietary formats. Providing data in standard formats, using clear naming conventions that break the files into manageable components, and placing it in a single location for retrieval will enable that future realization.

5. Deployment Lifecycle: Pilot to Full-Scale

The primary goal of a Smart Ocean System is to transform the state-of-the-art in ocean services and research into a scalable system that integrates intelligent, sensor-based sea-water processes, cyber-informed shore-based infrastructures and citizen-driven data collection. To achieve this goal, Smart Ocean will leverage both its existing system and ongoing blue economy activities in the region of Puerto Rico and the U.S. Virgin Islands. While the existing system has demonstrated unique data accessibility, the goal of Scalable WISE is an easily expanded and sustained operational readiness so that Strategic WISE focuses on special events and Static WISE freely collected data supports the research community. Both system adaptations will create persistent, smart-ocean service that turns ocean data into knowledge derived products.

In support of S-WISE, here we discuss several components of the S-WISE development pipeline. These components include pilot deployment planning and feasibility studies, pilot deployment strategies, and scaling up considerations that address various aspects associated with the transition from pilot- to full-scale deployment. Technical discussions and development based lessons from a S-WISE pilot deployment on a migrating humpback whale route off the coast of the United States from Massachusetts to Florida are used to highlight and inform the S-WISE deployment discussion since many of the science and technology elements described were ported from the existing project.

5.1. Planning and Feasibility Studies

While the technological development of SMART-Ocean components is fundamental to enable this framework, deployment in the real world poses additional challenges. Unlike terrestrial environments, where human needs result in the modification of vast tracts of land, ocean deployment must take into account the natural dynamics of a sensitive area in order to avoid unintended and possibly catastrophic interactions. These interactions are not restricted to the deployment of actual devices. Support vessels can also cause unintended interactions with the environment and its inhabitants. This is particularly important if we wish to deploy multiple sensor or action networks, or support the resupply of such a network over time. For these reasons, it is important to initiate the design process with a comprehensive planning phase, followed by pilot deployments that explore spatial and temporal scale issues. The planning phase will identify suitable deployment locations, as well as a scientific rationale for actual deployments, so that beyond collection of proof-of-concept data, the sensors deployed can answer larger scientific questions. The planning phase can also identify needs for infrastructure that will lessen the cost of actual deployment activities. Pilot deployment scoping then develops the plan into an actionable field deployment plan.

5.2. Pilot Deployment Strategies

It is impractical, if not impossible, to deploy a smart ocean system at full scale on the first try. A phased approach is warranted where a pilot system is deployed, tested, and iterated many times until it scales to the desired size and scope. The first version of the pilot system may be very simple but must be able to test key performance scenarios, lessons learned from these deployments will drive designs of future pilots. The scope of the first pilot may depend a lot on the project team's expertise and the research partner's willingness to support infrastructure costs and any possible raised eyebrows from the research community. If the incumbents push back or there is a lack of interest from the local stakeholders, it is not necessarily predestined that you choose the same pilot location forever. Dependent on the learning outcomes of the location switch, it may be worth temporarily clustering near incumbent or local expert led deployments to accelerate experience and technology exchange.

The area that requires active discussion is the transition from small pilots that shift into bigger pilots and finally into the full SMART-Ocean system. This transition requires careful design, as it needs to reflect both scientific considerations, but also some form of expectation management on the industrial side that wants – in various guises – to see monetization opportunities and is not prepared to wait. What should additionally be factored into the design of deployment strategy is the consideration for initial system fragility and the limited capabilities of early sizes and shapes of the system. Consequently, any scaling-up strategy should carefully consider how to transition from a small dysfunctional system, to a first pilot and then scaling from there towards the size and capabilities that can credibly be considered a SMART-Ocean System.

5.3. Scaling Up: Challenges and Solutions

Having demonstrated that a Smart Ocean System can deliver useful capabilities at the pilot scale, researchers will be motivated to expand the installation towards full system scaling. This will involve challenges at many levels. Ocean elements are not evenly distributed in space or time. How can we manage observability gaps in time and space during expansion? In a pilot, operators are well known players, often residing at the site for the duration of the mission. What happens when we scale up and more users from outside the mission are asking questions of the system? Security is also a concern. Our work has operated under an expectation of insider threat as the pool of capable operators has been relatively small. A large, expanded, external user base will expose the system to a greater threat of outsiders taking control of elements, likely on a temporary basis, in ways which disrupt. Trusted operation under large-scale distributed control over an extended, remote system requires capability-based trust for operation and also security to ensure that capabilities cannot be used to disrupt deployed sensors.

The physical upscaling task also presents challenges. Deployments must be repeated, and increased size brings both equipment and personnel scaling issues. Previous work has been limited to small installations, seeking to prototype hardware and software designed for lower cost access, but the system demonstrated at small scale will not be cost-effective for global implementation and expansion. A nanosatellite or nanosat constellation can provide low-cost delivery of systems with minimal launch disruptions, but won't deliver the resolution or revisit of larger systems. Creative partnerships will be required to provide many of the extended monitoring and in situ sampling functions. For passive across a range of wavelengths, the capability of existing commercial systems is being rapidly improved, yet the demand is greater than the capacity.

6. Lessons from Global Marine Tech Deployments

In this section, we will compile the various general deployment requirements discussed and apply them to some successful deployments of smart ocean systems, their enabling technologies and subsystems, to derive some general conclusions and guidelines for future deployments.

We start out this section by presenting case studies of successful deployments of ontogenetic and ecosystemic MTS and smart ocean systems, in an attempt to provide a template for future deployment efforts. We also discuss what particular deployment aspects of these case studies are relevant to global deployments. We then list additional successful deployments of various enabling marine technologies in order to synthesize general recommendations from these mini case studies. Lastly, we address some additional general deployment issues such as the manners in which these deployments could be funded and how future deployments of such systems would change as technology becomes cheaper and broadband network capabilities become more ubiquitously available in open oceans.

The many ships, equipment, and services used to operate in oceans are an underutilized asset for a plethora of benefits and services that need to be provided to society and are difficult to be provided from land. State-of-the-art ship vessel and underwater vehicle capacities can be inexpensively made available to augment various capabilities in the oceans. The shipping companies and other organizations and institutions that can provide this underutilized equipment, with their enacted deployments, have demonstrated that if these resources are appropriately coordinated and coupled with geographically and temporally sustained sensing and actuation capabilities, the capabilities of oceans can be enhanced for executing many ocean-centric tasks and missions that generate locale-based additive economic and societal value, while costing and impacting the ocean-as-ecosystem less.

6.1. Case Studies of Successful Deployments

While there have been innumerable marine research missions executed by virtually all oceanographic institutions for decades, the longstanding history of ocean drifters, buoys, tethered or robotic platforms, AUVs and other types of mobile and located instruments and vehicles for remotely collecting marine data has emerged from multiple focused initiatives. Public and academic institutions, private companies, and non-profit organizations have developed and utilized such systems and associated radio- and satellite-based communications networks, already paving the way for the next generation of expanded capabilities. Here, we summarize a limited number of examples, spaced around the world, that illustrate relevant aspects of either macro- or micro-scale initiatives that have proven successful. The lessons learned, however are transdisciplinary in relevance. They are not intended to provide a detailed description of every such effort, but rather, high-level pointers to more detailed information.

Collaborative and co-production science and engineering design of sensors deployed for the purposes of environmental monitoring, disaster mitigation associated with wildfires to seismic events, coastal management, safe aquatic recreational use, and tourism has proliferated over the past decade through the work of many principled and affected stakeholders. From coastal towns to neighborhoods, to ocean coastal regions and waters, it is now apparent that the balance of work that must be performed, and the monitoring of conditions, both exceedingly low-cost and seemingly simple, can be incredibly informative to those who need timely access to this data most. While being involved in such work, whether leading or participating, is inherently gratifying, maintaining the health and sustainability of such efforts must wrestle with the underlying citizen fatigue, which often leads to apathetic conditions following such efforts.

6.2. Common Pitfalls and How to Avoid Them

Our work to date has focused on consulting marine technology developers on prototype testing and on-demand, large-scale deployment. A clear pitfall of prototyping is the danger of over-designing a device for a few specific expected applications. A mutually beneficial relationship between developers and end-users can ideally encourage multiple device iterations prior to deployment. During early testing phases, with devices designed for specific jobs, operation and maintenance costs are borne by the developer until the device is ready for revenue generation. Sometimes, in such instances, it makes sense for developers to work closely with commercial users who have particular use cases whose needs differ from those anticipated by the developer. This can help inform the design as the market moves closer to revenue generation.

Developers must also listen carefully to early users of the technology and make ready the ability to address the feedback they receive or risk losing business opportunities while they figure it out. More generally, a pitfall of commercial deployments is setting up deployments too large to fail. Commercial developers of marine devices must sometimes test out the marine tech waters carefully and be equally careful to ensure that the initial successes are real rather than a product of good market timing. Marine technology does not always work as engineers expect and we see many instances of system failure when devices are launched in ever-greater numbers and used in ever-wider application areas. The ocean is death to electronics that rely for success on assumptions of hardware function that are well supported on land or even in many other sea areas. However, ocean conditions vary considerably, and it is essential that deployments through which marine technology expects to commercialize assure operational function through an expected number of cycles.

6.3. Future Trends in Marine Technology

We have shown that the current rules for designing and deploying tools to manage our human impact on the ocean are still being written. Our Worldwide Ocean employs nearly 500 million people, using the ocean as a source of food, shelter, raw materials, commerce, transportation, and leisure. Consequently, the new tools of Ocean Tech, from whale acoustic detection to enforcement vessel reconnaissance, hold an enormous market potential. Ocean Tech applies the wide array of tools and trends that have brought great benefits to our lives on land to our Infrastructure of the Ocean, including Fusing the Subsea and Land-based Internet Infrastructures, Autonomous Surface and Underwater Vehicles, Oceanic Data and Application Clouds, and the Geo-Localization Infrastructure for the Global Ocean. Ocean Tech focuses these powerful resource management and transportation infrastructure tools on very focused problems in the resource-rich but poorly populated territory of the Global Ocean, such as boat monitoring for Search and Rescue, pollution detection for resource management, and bottom fishing monitoring for commerce, revenue, and pollution reduction.

Many of the tools that minimize our impact, monitor compliance, and provide effective rebuttals rely on accuracy and low costs. In the future we can expect to see the better integration of AI methods in visual and other recognition tasks, improving the potential and ability to train ad hoc classifiers for marine and atmospheric tasks. However, deploying these new approaches in marine environments will still face many challenges, regarding the ad hoc ability to handle real-time requirements, low power consumption, and the need to process huge volumes of data with low cost for the system budget. Moreover, extreme environmental conditions such as storms, snow, fog, or high humidity usually affect the performances of the deployed technology and the trade-offs with some current approaches, especially for AI-enabled approaches and computer vision systems, will have to be properly evaluated in order to avoid failures on the detection and classification tasks.

7. Conclusion

Over the last two decades, we have gathered unprecedented data on the biology, ecology, and biogeochemistry of open ocean ecosystems. Today, we are faced with an even greater challenge: how to manage ongoing human activities that continue to impact these global commons. With the establishment of management structures for ocean activities similar to those provided by national states for their Exclusive Economic Zones, we have begun to address these challenges. New satellite-based sensors are being developed that will make it possible to conduct regular audits of global commons activities. The ocean has long been viewed as a vast expanse of empty water, devoid of life outside of a few pockets of actively engaged humans. But now, with new sensors, new cyberinfrastructure, and a growing network of land-based and mobile robots, we can watch and analyze the environments of the global commons in near real time.

The Sensing Capital of a nation grows with both new sensors and with novel uses of already decommissioned and soon-to-be-superannuated sensors. Additive remote sensing enriches the content of monitored information and opens the design space for closed loop uses of in-water mobile robots. The Smart Ocean System focuses on guiding the global commons toward sustainability, resilience, and biodiversity. Community-based Citizen Ocean Observatories based on freely accessible sensor data not only assist scientists and decision-makers, but also engage citizens in the learning and discovery processes essential for future generations.

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Chapter 8: Ethical, Legal, and Societal Considerations in Marine Environments

1. Introduction to Marine Ethical and Legal Frameworks

Marine issues are often framed as common property resource dilemmas, captured in the tragedy of the commons literature, based on the depletion of resources that all can access, and highlighted by examples of communities self-organising to prevent tragedy. What trophic levels are regulated, and how? Where does one draw lines regarding human access, landing and by-catch? Issues at the law and ethics nexus are complex, given the patchwork of different and differing global regulatory regimes, especially in the high seas, or outside of Exclusive Economic Zones. Marine ecosystems are intrinsically international, challenging traditional terrestrial notions of sovereignty, although these challenges are increasingly salient in other terrestrial domains with respect to surveillance, piracy, shipping and security issues. However, the pragmatic and policy approaches governments and other stakeholders have taken have inherited a terrestrial, anthropocentric perspective. Managing maritime domains for human use alone rarely addresses the needs for the ecosystems involved. Management for marine ecosystems, therefore, requires a necessarily different lens if we are to successfully implement the policies needed for effective ocean governance. (CILIBERTI et al., 2024) (W. Barr, 2016) (Katona et al., 2022) (Strain et al., 2019) (Gustavsson, 2018)

Necessary actions require international cooperation and commons based policies, which in turn require a re-thinking of ethics and law, a remediation of the anthropocentric perspective that dominates to create new frameworks for marine use and development, including issues such as marine resource allocation, the ethics of marine knowledge generation and transfer, marine safety, security, autonomy and cleanness, all framed within the context of sea and ocean law. This text adopts a tripartite focus on counternarratives to traditional human-focused anthropology - relational ontologies, indigenous knowledge and other-than-human agency - as the foundation for goal agreements. The focus on ethos, rather than strict loss and gain calculations, allows for the possibility of having something other than personal happiness at the centre of analysis.

2. Data Ownership and Sovereignty in Marine Environments

The oceans and their development require investments in terms of time and resources. The technologies developed for these investments are increasingly being developed outside the oceanic environment. It is thus difficult to divest data from its source, but for the scientist, these data are a commodity that provides scientific knowledge. Further, the public data produced by such research are used as validation data for commercial organizations to develop commercial infrastructures, sensors, and tools, that eventually are commercialized at very high prices. Moreover, the combination of these multiple, commercial-off-the-shelf, lower-cost sensors can be used to collect data at lower prices compared to any funded agency as well as commercial organization with only a single source of acquisition. This places the entities interested in acquiring data from the ocean at a very advantageous position.

Increasingly, government policies are focused on mutual concern for national economic well-being. Underlying many ocean governance efforts are differences in wealth and access that result from levels of development achieved, and levels of investment in ocean policy and management established. Regaining full jurisdiction over national territorial seas is often important to a developing nation, and there are significant range of trade-offs regarding the benefits that will accrue to and responsibilities that will be incurred by the developed and developing nations through ocean investments. New technologies can assist nations in their attempts to maximize both the benefits accrued and the costs incurred, both individually and jointly through cooperative efforts with trade-off agreements. Data sovereignty addresses issues associated with the use of data collected within a country, usually within its territorial waters, exclusive economic zone, or a more broadly defined marine region. Emerging challenges to data sovereignty arise in response to technology-enabled data collection that is pervasive and inexpensive as well as in consideration of private sector investments in oceans which increasingly are greater than those investments made by governments.

2.1. Concept of Data Ownership

Data sharing has gained prominence with the advent of the Internet, with the declaration that now “information wants to be free” - data is seen as free good that should be openly and freely exchanged and without attribution. In contrast, the Data use License relieves the data producer from liability concerning the consequences of the use of the data and the data user from the obligation to mark the products made with the data as based on the producer's data. It is because of this reason, the move to share freely acquired, using taxpayer money, environmental data, has been the point of contention between producers and users of the data. Although policy demands the sharing of data, providing clear guidelines and fair compensation in a business model that incentivizes the producers while providing low-cost access to the user will create a win-win situation for both parties.

Policies, such as the location privacy policy highlight where the issue of privacy become a point of friction, distinguishing personal from non-personal data and claiming that it is unlawful to collect or use personal data without consent, regardless whether such data has been made publicly available by the owner. In the maritime domain, ship data is generated from two sources. AIS is controlled and is a regulation by the government, and VMS is controlled by the ship owner, who may not consent to its public release. IMB is a private entity that charges money to supply data on piracy that is freely available otherwise. Who controls piracy data in the public domain from IMB and what is ethical and unlawful about charging fees to access what is otherwise free data? These questions that have significant business implications in ensuring that resources are not wasted are both about data ownership and its associated costs.

2.2. Sovereignty Issues in Marine Data

Vast stretches of our planet's surface lie underwater and remain unexplored and unseen. While new ways of observing these areas are maturing, a question lingers: Who owns the data collected? Many companies and academic institutions around the world have turned to remote sensing systems for a plethora of observations, from bathymetry, benthic mapping, and seagrass, to temperature, salinity, and other water properties, revealing a rich set of applications. Startups offer services derived from the collected data, charging for access. Meanwhile, which path should amateur researchers take? From a legal perspective, it is not clear who products derived from these underwater observations belong to.

Considering the history of mapping the Earth's surface, a clear distinction can be made when this process occurred above or below sea level. Upper-world mapping began with explorers walking on territory and naming it for their governments and sovereign naturalists detailing it in richly illustrated books. Spaceborne sensors later supplanted Earth's explorers for the purposes of topographic and landcover mapping; a few projects are seizing on the tremendous progress that has been made in recently generating high-resolution topographic DEMs and landcover maps from satellite stereo towed- and low-cost drone aerials, offering free access to these products. How can in-water EUV sensors compete while satisfying sovereignty and, by extension, data ownership challenges?

2.3. Case Studies on Data Sovereignty

Two examples illustrate, in different ways, the political considerations involved in the idea of sovereignty in scientific data products in the marine realm. The first, a dispute between the United States and Canada over whether the Canada Department of Fisheries and Oceans could, without permission, acquire sonar seabed mapping data collected by the U.S. Navy, and the second, a decision by the British Antarctic Survey to remove the base data from its publicly available digital elevation model of Antarctica because other scientists misused the Survey's grant-funded work.

The Canada-United States dispute illustrates the importance of the physical presence of vessels or other means engaged in mapping or observing marine environments in the political consideration of sovereignty. A shallow seabed extends into the marine realm under the territorial sea of a coastal state—up to 12 nautical miles from a state's baseline—but only a coastal state can impose special permissions to enter this part of the public sea. In the latter part of the 1980s, the Canada Department of Fisheries and Oceans began to acquire mapping sonar data about the southern portion of the Canada-U.S. border seabed. The Department of Fisheries and Oceans processed the Navy data, filled gaps with extra data that had been provided in 1986, and extracted information such as the physiographic map of the seafloor, map of sediment classification, and map of sand deposit forecast for northern United States and Canada, and published the maps in 1990 and 1991, submitting them to the International Hydrographic Organization.

3. Ethics of Autonomous Marine Systems

This chapter addresses the ethical, legal, and societal factors associated with marine systems and the enabling technologies. Marine Autonomous Systems, and in particular Autonomous Marine Vehicle operations, are new to ocean science and exploration. Consequently, very few ethical, legal, or societal factors associated with these operations have been created or are known. We explore ethical implications and avenues for developing ethical policies for deployment in oceans across multiple sectors, and provide general recommendations for developing ethical guidance for deployment in the marine domain. Considerations for these guidelines also apply to any general autonomous technology but have a particularly strong impact on marine systems that have low human oversight.

Overview of Autonomous Marine Technologies

Robotic technologies such as AUVs, UUVs, and ROVs enable data collections through autonomously and semiautonomous unsupervised operations. Data are provided for a diverse array of services from scientific exploration, geotechnical data execution, SAR, oceanographic measurements, and exploration for minerals among many others. A specific robotic technology, the Autonomous Maritime Vehicle, enables maritime operations and associated maritime support activities. Several public and private organizations are developing, modifying, and operating their technologies. These vehicles are especially suited to perform remote and dangerous tasking. They can conduct surveillance or monitoring for extended lengths of time without the accompanying risk to lives and costs associated with manned assets, and difficult air or maritime conditions. These include monitoring and data collection, supporting information operations, C4I activities, among other mission tasking. Very large high-speed semi-autonomous vessels have been designed to perform transport operations at low operational costs. Robotic cargo transport systems have been designed to support intra-theater and inter-theater logistics support missions.

3.1. Overview of Autonomous Marine Technologies

Advancements in engineering and computer science have led to the development of highly capable, and increasingly autonomous, systems for employment throughout the marine environment, including more immediate coastal regions and the deep ocean. Current examples of marine systems with low to moderate levels of autonomy include towed and anchored buoys with onboard sensors for remotely collecting physical, chemical, geological, and biological data; autonomous surface and underwater vehicles for mapping, monitoring, and inspecting; and semi-autonomous craft for logistics and cargo transport. When deployed in small fleets, scientists can leverage swarms of simple, inexpensive sensor-laden buoys and vehicles to collect, process, and transmit high-frequency data streams while processing elements in the cloud perform filtering and anomaly detection. Technologies differing from vehicles and buoys for in situ data collection include offshore autonomous floating, hovering, submerging, and anchoring – some with cables and some without – nodes, small and large scale, with onboard intelligence and sensor payloads, for passive to fully autonomous and coordinated monitoring and inspection of oceanic physical, chemical, and biological processes, conditions, and events; autonomous gliders for deep ocean ballistic monitoring; and tele-operated and autonomous vehicles and buoys for discontinuous inspection of maritime infrastructure. Increasing artificial intelligence capabilities, platforms for assembling, launching, and recovering second generation offshore mobile and stationary disaggregated converged network nodes supporting edge computing, and enabling lighting-harshening solutions are leading researchers into all whether and some ideals-of-up-to-space corridors, some of them dual use, for building next-generation smart oceans with great computing control and resilience graduating from ocean sensors, and systems for resource exploitation and environmental remediation operating with high availability and reliability in persistently unaccompanied from days through months – graduating from present days and a few weeks.

3.2. Ethical Implications of Autonomy

Three general ethical considerations for autonomy are the obvious questions about what the role of autonomy should be for a task; whether we should even consider giving the authority of moral consideration to the agent; and how such systems could be held accountable for any activities they may engage in. Aside from the fact that there are general ethical questions about the deployment of autonomy, many marine-related applications have a specific culture within which they take place, i.e., they can be seen as applications within the broader branch of marine engineering. There are also some rather specific safety and security issues connected to marine robotics and some linked ethical questions that bear on the design stage of any of the constituent marine systems. Furthermore, it has to be acknowledged that the current deployment pace of marine robotics is rather fast; a timescale on which it is probably too late to redo major preparations for deployment even if it becomes evident that possible issues were completely neglected. All of this tends to suggest that the ethical issues of current robotic deployment may place different constraints on what types of deployment areas an autonomous underwater vehicle might be allowed to operate within noise in the underwater domain.

In this talk, we will be addressing the importance of continuing to have a role for human oversight, the associated consequences for speed of operational effectiveness, and the importance of the subsequent feedback to the development process itself. We will also be addressing the importance of continued involvement of the wider public, i.e., continued public engagement, and how that might affect final systems. It thus also should be a component of the timeline. Furthermore, we will be discussing technological requirements for a clear decision-making ability to be developed ahead of time; also at what timescale that ability be confirmed to work. This includes the developmental aspects and possible requirements on human – machine interfaces to allow such a decision-making ability to be successfully evaluated.

3.3. Regulatory Challenges and Solutions

Various regulatory agencies oversee the use of these marine technologies. For example, the Federal Aviation Administration manages the use of Unmanned Aerial Systems, the Coast Guard manages the use of Unmanned Surface Vehicles, the Navy manages the use of Unmanned Underwater Vehicles, and, to a certain extent, the Environmental Protection Agency manages all three technologies when they are used for data collection on commercial fishing. It is not uncommon for an agency overseeing certain air, land, or space use to exercise siloed control of certain marine substances. Such near exclusive control can create additional regulatory ambiguity, disincentivizing investment in these technologies and hindering technology advancement. This incongruency is different than air, land, and near space where different agencies have symmetry issues in exercising their mandates. The ease and openness of these other ecosystems contrasts with the comparative difficulty and obscurity of the marine regulatory ecosystem despite its commercially attractive features.

For larger commercial investors and collaborators, company lawyers can help streamline the process of regulatory navigation. However, for public sector mission achievement, the difficulty in regulation can harm operations, from supporting the inhabitants of remote islands in times of disaster to answering maritime search and rescue queries. Additional regulation burden exists for international voyages. Areas beyond nation control, such as micropollutant data collection over the Southern Ocean, are often under the jurisdiction of the agency responsible for international ship traffic regulation. Additionally, consultation of the commission is recommended to ensure finish legal compliance for maritime wildlife protection. Grounding approaches in multistep agreements can simplify the regulatory burden; however, this typically creates longer time frames and reduces flexibility in testing and missions.

4. International Maritime Law and Sensor Deployments

Between the conception of international maritime law and the adoption of the UN Convention on the Law of the Sea, the popular thought was that the oceans were essentially res nullius, completely free and free of ownership. However, with the population explosion, technical progress, and taking natural resources for granted, that position changed and intensified. The result of that change is that the oceans are “the common heritage of mankind.” Thus, the importance of their use is both individual and collective.

In the 20th century, maritime law was based on the right to free navigation; however, that principle was in conflict with the interest of coastal states that were beginning to accede to independence and sovereignty from foreign exploitation in favor of the riches of their geocentric position. The result was that UNCLOS imposed a counterweight, whose fundamental elements became a protection system based on the banning and repression of certain activities that could disturb the tranquility of coastal states, such as piracy and slave trafficking, and the harmonization of what is known as maritime delimitation between neighboring states. In other words, respecting nautical law is a duty of the coastal state and foreign users.

Under UNCLOS, maritime spaces are divided into three types: Those under national sovereignty; those reserved exclusively for the exercise of sovereign rights; and those predominantly in international traffic. Coastal states could unilaterally determine the extension of their territorial waters and apply their national laws for the exploration and exploitation of marine resources. To prevent the term “territorial sea” from becoming a synonym for enclosure, the coastal state could not impede the passage of vessels belonging to foreign states, which should be governed by the rules established by said coastal state. Outside the area of the territorial sea was the exclusive economic zone, which the coastal state had the power to economically exploit but not the sovereignty. The high seas would be the rest of the ocean, with free access for all to carry out their activities.

Deploying marine sensors should follow the framework established by UNCLOS: The Convention requires licensing or other forms of control over offshore oceanographic activities. Marine data collection must include advance consultation with coastal states and other states involved. Wherever feasible, the privately sponsored project should contribute to the costs incurred in the wake of the study.

UNCLOS establishes that the coastal state may adopt laws concerning the identification of foreign ships and their equipment. Absent indication of presumed malfeasance, the coastal state should contact the flag state before conducting, or allowing real-time monitoring of non-consensual activities. The state under whose registry the ship or aircraft operates shall be liable accordingly.

UNCLOS recognizes an interest in not being involved in military hostilities. However, the wording allows an intermediate interpretation: “The only protection is that instruction forbids military exercise, tests, or explanation of certain technologies. Also, studies can be carried out in coastal waters of states if there is information about imminent disasters”. Beyond that, military vessels have the right to carry out navigation whatever the purpose; Marine species respond with neutral Boucans. Any other ship making use of sensors or sonar, be it for tourism or commercial purposes.

4.1. Fundamentals of International Maritime Law

International law is a collection of rules and standards that has been created by treaties or customary practice to regulate the relations among States and, in some cases, other entities. The conduct of States, or more exactly the exercise of their sovereign powers, creates the basic structure of international law. In return, international law creates certain rights for States and other entities; when these rights are violated, international law statutes and procedure provide for international justice and remedies. International law must reflect the needs of the world community as it develops, and the increased interdependence and interaction among all nations increases the pressure for the creation of an international legal structure that can respond effectively and usefully to these demands. International Maritime Law is that part of international law that regulates those areas of State interactions, which can only be applied in and to the maritime areas. These areas can either be the area given to each State bordering the sea, namely the Internal Waters, Territorial Sea and Contiguous Zone, or the areas which are oceanic and to which no State has any specific jurisdiction, namely the High Seas, the Area, or the Atmosphere. The subject matter of international maritime law includes nationality of ships, classification, regulations and technical standards, jurisdiction of coastal States, jurisdiction of Flag States, nationality of crews, regulation of marine security, regulation of maritime usage, and regulation of the maritime environment.

4.2. Legal Framework for Sensor Deployments

Because sensing systems rely on both launching platforms and sensor deployments, these systems are affected by various layers of domestic and international laws. As private parties deploy and operate sensors with more layers, multiple jurisdictions affect more aspects of sensor deployments. These factors cumulatively influence the data generation cost and the utility of deployed sensors. Sensor deployments have data generation and profit-making effects; thus, the traffic signs for society's access and use of generated data through varying property-like rights determine the business models of sensor systems.

The geopolitical notion of sensor networks describes military-security, economic-trade, and ecological-environmental domains of social interest that rely on sensor deployments. The domains summarize the general interest of states since they stand for national security, trade leverage, and social responsibility. Sensor operation modes to explore these interests can be delineated by sensor types, durations, intensity, distances, and locations of data generation. Consequently, interest sentences govern sensor deployment regulations and are applied at various territorial facets: a State can regulate access to data generation according to its own interest in the territorial sea, the exclusive economic zone, and the continental shelf, whereas the use of data for political purposes can be restricted in the area of high seas.

As a general rule, only the territory of a State, where its sovereignty extends, is subject to its exclusive jurisdiction. The existing maritime law touch points when it comes to sensor deployment make deployments and use of the systems in coastal state jurisdiction straightforward. In contrast, sensor systems in foreign jurisdictional domains are legally more complex in nature.

4.3. Impact of Sensors on Marine Ecosystems

Marine programs that deploy sensors in the oceans typically strive to benefit science and humanity through better management of marine systems. While the goals are generally enviable, the impact of deployment on marine animals, assemblages, and environments needs to be considered very carefully. Damage can stem from misplaced sensor design and installation strategies even when the potential for negative impacts is known. Seafloor installations, for example, can survive for decades and thus cause a long-term alteration of delicate benthic assemblages. These can be important to fishery health, coastal water clarity, and the carbon cycle, especially near coral reefs and sea grass beds.

Sensors implanted in marine animals can cause pain and long-term suffering, particularly if the device cannot be removed, if it becomes infected, or if it alters the animal's natural behavior — e.g., by preventing feeding or movement. Any sensor that induces significant stress and/or alteration of migration and reproduction should be avoided at all costs, particularly for long-distance migratory species such as sea turtles or Atlantic salmon. Sensors designed to be deployed for years such as acoustic transmitters can be benign in some animals. However, if stress alteration is detrimental for regions of interest, motives for deployment should be questioned and techniques improved, as bioenergetics is already a major concern. Collectively working to minimize negative effects via innovative and sensitive ethical design, placement, and removal practices coupled with sensitivity to local needs and people involved is a wise decision that could improve the positive fate of long-term sensor programs. Fatigue avoidance practices, including those stemming from the new field of biomimicry, can provide additional benefits for animal-friendly marine monitoring approaches.

5. Engaging Local Communities and Ocean Stakeholders

Although we are a long way from achieving comprehensive ocean governance, it does not mean that the ocean is devoid of formalised systems, by laws and rules which, in many cases, are the result of negotiation processes with local communities and their needs. Knowledge of the local marine environment by fishing communities has been passed down and preactivated for an extremely long time. Abundant marine resources offer incentives to promote marine migrations, and complex marine resources exploitation strategies have been developed in many local communities. Close attention should be directed to these mechanisms when placing "Anthropocene" labels on marine environment processes and features, and stigmatizing local communities, particularly when it comes to conservation issues which could put restrictions on local traditional practices.

Since decision-making effectiveness is directly linked to the amateurs of the concerned stakeholders, the only way to guarantee support for future governance and decision-making for the ocean is to involve all layers of these societies (and not simply their leaders). The relationship between the decision-making actors of a given territory is, in fact, an essential step in the consideration of local populations who enjoy their full rights, and this is where all the similarities between what are normally considered terrestrial communities and maritime communities come from. Such dialogues should deal with more than purely conservation issues; they should make it possible to reflect on a broader framework for economic development which prioritizes providing local communities with better living conditions; it should use marine resources within an ecosystem services framework. The local knowledge produced through these dialogues, although heavily accused of being purely anecdotal, could also serve as a basis for the identification of sensitive areas, the establishment of marine protected areas or the restoration of fish stock levels.

5.1. Importance of Community Engagement

With over 70 percent of the world's population projected to live within 200 km of the coast by 2050, including some of the world's largest cities, the ocean provides livelihoods for more than 3 billion people and is critical to food security, income, and sustainable development. Yet, ocean and coastal ecosystems are under increasingly unsustainable use, and deteriorating environmental conditions jeopardize food security and livelihoods. Many ocean and coastal species are in decline, including the largest sharks and rays as well as many marine mammals and reptiles. Increases in both frequency and severity of climate hazard events such as hurricanes, inundations, and sea level rise pose additional challenges, especially for coastal communities already confronting existing inequities and vulnerabilities. Ensuring a healthy and productive ocean for the future will require decisive action by communities and local governments as well as international cooperation. Strengthening community resilience promises to be among the most effective methods for limiting damages and accelerating recovery from catastrophic storms. Building a more sustainable relationship between ocean coastal systems that favors inclusion and equity will require a profound transformation in the way many coastal and marine ecosystems are managed. Integrated ocean and coastal management with a focus on involvement of local communities in management is considered to be the foundation for ensuring both sustainable coastal development and effective ocean and coastal ecosystem stewardship. Creating a more sustainable relationship between coastal systems and the communities which depend upon them will undoubtedly be challenging, requiring as it does a melding of a wide host of disciplines, but the inspiration offered by nature's resilience makes it a challenge worth undertaking.

5.2. Strategies for Effective Stakeholder Engagement

Particularly, when managing or dealing with a range of stakeholders - values, beliefs and priorities should be acknowledged. In order to ensure that stakeholders are meaningfully included in decision-making or in government-led marine management initiatives, it is important to consider how the assortment of different groups and people could impact on the outcome of the initiative and also how they would react to the outcome. Prior stakeholder engagement is therefore a must in any marine initiative or activity. The development of an engagement plan (who to engage, how to engage them, when to engage them, how often to engage them, why to engage them, what resources will be needed) is a logical first step. Enquiry should also be made into pre-existing guidelines for stakeholder engagement and/or expertise that can be made use of. An understanding of community structures and implementation of appropriate incentives for participation is key. Resources that provide tangible support for communities can help generate and sustain interest in stakeholder activities or even help motivate communities to collaborate and share suggestions for the implementation of engagement mechanisms or techniques. Using non-legally binding measures that support small-scale social structures and factor in the notion of care can also be considered.

When engaged and given sufficient responsibility and liberty, communities can also typically provide significant insight and recommendations regarding stewardship of their unique ecosystems. Sensitive and actor-oriented participatory governance and the establishment of multi-stakeholder management bodies have proven especially effective for small-scale environments. Long-term management efforts of thematic and spatial relevance are important enablers for sustained cooperation and cross-sectoral linkages.

5.3. Case Studies of Successful Engagement

Case studies provide concrete examples of effective and impactful community engagement in ocean policy processes. Generally, most case studies identified through our review are external, describing a single effort with limited contextualization and reflection. As a complement, we identified some internal case studies explaining their approach to engagement in specific projects or programs.

The Gulf of Maine Research Institute works to support an integrated, collaborative approach to fisheries management through the Fishermen Feed Us! program, which engages fishers and their families in discussions about the future of our fisheries and our food. The Fishermen Feed Us! program brings together commercial fishers and their families to discuss the challenges and opportunities of providing seafood to the US lifestyle. In this program, a venue is provided for fishermen to speak directly to the needs of consumers, inspire awareness about seafood sourcing, and educate the public on topics ranging from seafood fraud to what is plucked from the sea on any given day. Those involved in this program recognize that fishers need to better communicate the value, both economically and ecologically, of a well-managed access system. The current situation is steeped in the "if it bleeds, it leads" syndrome; therefore, trade groups, fisheries management councils, and agencies must innovate a way to present the story of the industry and its sustainability in a media-friendly package that becomes immune to sensationalistic reporting.

6. Interdisciplinary Approaches to Marine Ethics

As concerns for the oceans, marine ecosystems, and their inhabitants increase, an interdisciplinary approach to marine ethics is critical. As a relatively new area of study, marine ethics can benefit greatly from the perspectives and methods of other fields. Additionally, research tools from other areas can often enhance marine ethical explorations. Marine ethics can benefit from literature, art, and religious studies in particular by enhancing the emotional and cultural connectiveness of marine ethics topics. The humanities, through the perspective of history or literature, can facilitate understanding how diverse populations and cultures have conceptualized the ocean and our relation to it. The arts, likewise, can deepen the emotional connection we have with the ocean. Finally, the study of religion can clarify the difference in ethical standing of the ocean's inhabitants, or lack thereof, by various groups.

The social and natural sciences can also bring different but equally necessary perspectives to marine ethical concerns. Geography can aid in understanding the global disparities between the developed and developing worlds and their influence on marine issues such as overfishing and pollution. These disparities are deeply embedded in social theory. Furthermore, the involvement of the different community groups affected by decisions about the ocean, such as fishing, tourism, and oil, needs to be addressed in some manner as well, perhaps by political theory. In this way, the impact of culture on marine issues, such as the cultural importance of cetaceans to indigenous peoples against their hunting, can be analyzed. Finally, the natural sciences, by clarifying how marine ecosystems operate and the importance of balance and biodiversity within them, can show how human activity can impact the seas and their inhabitants.

7. Technological Innovations and Ethical Considerations

For centuries, people have harnessed the oceans for a variety of reasons, yet recent technological advances have encouraged a renewed interest in, and exploration of, marine environments. From mapping the seafloor and monitoring ongoing natural hazards to obtaining resources and storing climate-related carbon, the oceans are being leveraged in all corners of the globe. As we risk unsettling delicate balances in a third of Earth's surface, we find ourselves again faced with questions of the ethics of what we do and how do we do it. At present, there is insufficient guidance among existing frameworks for broadly applied oversight for marine-based implementation of emerging technologies to allow consideration of the ethical implications before they are realized. To inform both those who work to change the planet—scientists, industrial entrepreneurs, policy makers, non-governmental organizations—and those who bear the risk and potentially suffer the consequences—a more intentional deliberation about ethical frameworks is needed.

Emerging technology works to change the course of human history by altering both the capabilities of the implementer and the natural world upon which all of humanity depends. Scientific and commercial interest in the oceans is further enabled by novel interactions or scale-up with existing techniques and by recent understanding of the risks imposed by both climate change and the ongoing pandemic. Particular considerations arise when the users are private corporations rather than governments, and national interests trump environmental protection. Areas of interest not within particular nations' economic zones remain relatively free of legal oversight. Furthermore, enhancement or alteration of an ecosystem for general benefit is an activity usually trumped unless particular special interest groups object.

8. Policy Recommendations for Ethical Marine Practices

Many marine-related legislations already exist, however, they are often disconnected, lack coherence across cultural contexts, or remove subjectivities from marine-related action spaces, where studies tend to be land-based centric. As a result, few practical guidelines exist to help marine practitioners act, apply for permits, or conduct research according to STEM ethics principles and values. For policymakers and other interested stakeholders to attempt creating marine-related legislation or addressing policy gaps in ocean ethics, we provide three accessible principles for ethical marine practices. The principles are contextual — they can serve as a start to inform researchers' decision-making processes no matter the socioecological context or scale of study.

First, ensure your study is driven by ethical motivation. Marine ecosystems provide abundant yet threatened resources. A study should focus on helping a community either plan for adaptation to the effect of climate change on marine resources, or increase the resilience of resources associated with marine ecosystems. Second, consider if the relevant stakeholders involved in the project truly reflect the wider marine environment. AI capability for the output of fine resolution solutions is driven by fine resolution data-collection capacity. These should both include within-community involvement, actual participation of the communities involved in the study site. Finally, ensure your study can benefit the marine environment to truly operationalize the ethical principle of beneficence. Your study should not simply increase efficiency, or determine a "go" or "no go" for implementing a certain recommendation. Instead, it should create a suite of solutions that allow room for decision-making that will address environmental, resource, or community concerns.

9. Future Trends in Marine Ethics and Law

Increasing knowledge of our changing environment is likely to increase the complexity and number of regulation attempts - most attempts to ensure fair access to resources as well as protect the shared resource of the ocean. Emerging challenges in marine ethics and law include:

- The ethical and legal implications of emerging, potentially disruptive marine technologies will demand broad consideration. Ethical concerns regarding autonomous vessels and drones - raising fundamental questions for ethics regarding degree of human control over technology - could relate to armed patrols for more aggressive marine surveillance, or autonomous vessels for research, travel, and cargo. Human supervision, oversight, orders, and liability for these autonomous vessels could be clearly delineated in laws to be developed, adapted, or changed. Law could govern the social liability of marine tech companies regarding transparency, accountability, accuracy, safety, harm prevention, error responsibility, and interoperability when developing such technologies. General ethical principles directly from relevant philosophies could guide the development of emerging marine technologies. The society-wide implications of options for marine applications of prevalent machine learning technology could also demand ethics consideration and technical engagement.

- The concept and law of the commons will undergo revitalization, modernization, and adaptation in response to efforts to resolve orphaned digital issues, in step with a revival and adaptation of philosophical interest in the commons. A leading effort in protecting existing, and creating new digital commons for our ocean has been initiated. It holds substantial promise to protect ocean resources of information, artwork, and writing, especially from threat of commodification and gating. The potential successes and failures of this influential future commons outside of our ocean could also guide development of approaches for protection of relevant domains.

10. Conclusion

Protecting underwater cultural heritage is beneficial for society. Underwater cultural heritage benefits society both through its public good nature, in terms of direct use or consumption, providing either scientific knowledge and public education or other intangible benefits supporting community identity, memory, and sense of place, and through indirect use, such as economic stimulation. The benefits provided from the societal perspective of underwater cultural heritage may outweigh the cost of disallowing the area to pursue profit maximization. Nevertheless, some of the most significant underwater cultural heritage is protected from the perspective of national laws, priorities, and limits. National laws, priorities, and limits deal not just with preservation and protection of underwater cultural heritage, but also with policies promoting development and utilization in society's interest, entering into potential conflicts of priority and determination. These conflicts are reflected in risks of either too little or too much protection or preservation of underwater cultural heritage. Insufficient protection or preservation can be physical in the sense of destruction, and its extent can be seen in the increase of underwater cultural heritage looting and private property rights claims. Such insufficient protection or preservation can also be financial, as when private claims disallowing or restricting public access to underwater cultural heritage result in significant or gross liabilities imposed upon society. Emphasizing the positive contribution marine spaces may experience from more systematic and academic knowledge from underwater cultural heritage helps to reduce the physical reasons for too little protection.

Conflicting powers seeking exclusive access to seas that subsume underwater cultural heritage push for too little physical protection of underwater cultural heritage, and conflicts may also trigger too great a destruction or diminishing physical protection of underwater cultural heritage. Traditional distinction between private rights motivated by capture, fixation and concentration supports regarding coastal zones and ports contrast with public goods functions regarding marine spaces necessitating public domain regulation regarding preservation of underwater cultural heritage influences economic forces requesting special treatment, too little protection or no protection.

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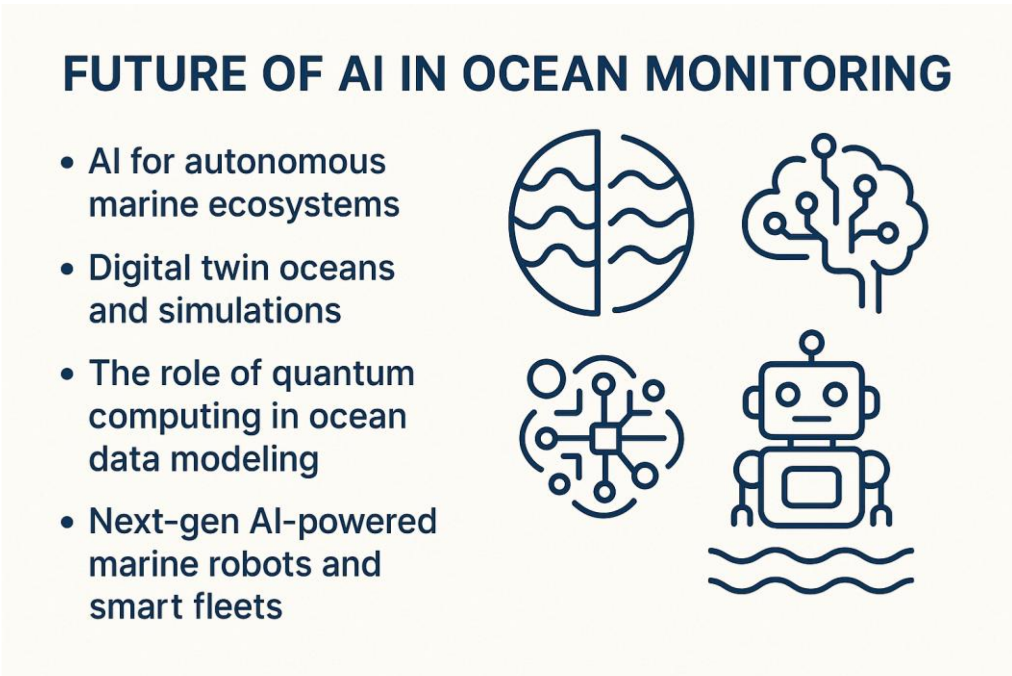
Chapter 9: Exploring the Future of Artificial Intelligence in Ocean Monitoring and Management

1. Introduction to AI in Ocean Monitoring

Artificial Intelligence (AI) is often described as the "new electricity". Similar to how electricity transformed numerous industries about a century ago, AI has started to create unprecedented disruptions in all domains, including technology, education, politics, and the economy. The technology-related developments in the industry, services, and economic sectors have created a constantly evolving environment. These developments cause rapid alterations in the oceans as well, with increasing effects on the ocean's health, biodiversity, marine ecosystems, and the economies and well-being of coastal communities. Thus, intelligence-enabled data processing and information management via AI algorithms will help us better monitor and understand the oceans. Implementing AI in ocean-monitoring systems can help ocean scientists better understand the oceanic mechanisms and their subsequent influence on the marine ecosystem, which, in turn, can help them provide more efficient solutions for dealing with the problems faced by the oceans and humans.

Similar to the diversity of disciplines or fields contributing to the innovation and improvements of AI technologies, the development of AI-driven techniques to support ocean monitoring and make ocean-related predictions requires contributions from all ocean-related and -interested stakeholders and communities. For example, climatology, physical oceanography, marine biology, ecotoxicology, and marine economies play important roles in this endeavor. In addition, as training AI techniques related to the ocean require ocean-related data of adequate volume, quality, and diversity, it is imperative to ensure sustained ocean observations via already available or new, advanced, innovative, robust, and networked ocean observation systems, from coastal to open oceans including shelf seas with varying spatiotemporal scales, to meet both the diverse nature of the ocean and the expected improvements in ocean monitoring and understanding. Fortunately, these oceans observing systems could be enhanced through new developments in the internet-of-things or the sensor web for real-time data acquisition, data fusion and blending, machine learning as well as AI-driven autonomous data processing, and advanced data and information archiving and management systems.



2. AI for Autonomous Marine Ecosystems

Abstract. Autonomous underwater robots are the result of decades of development in autonomous robotics and underwater sensors. At large scale and with sufficient funding support covering design to deployment, decentralized underwater robots could provide persistent, cheap, accurate monitoring of diversity, mapping, enumeration, and discussion of a range of ocean tasks. The future of AI in Ocean is an AI-enabling and AI-using decade of Applied AI in the Ocean, where Theory is put to practical work and

monitoring models are put to design verification and optimization through feedback learning control and training. Feedback learning control and training are unique for AI-supported autonomous robotics in the Ocean with located feedback in 4D with deep learning inference and feedback control. This enables only partial training and update be used to position optimize and stabilize up to highly nonlinear ocean models. Upon deployment, learned prediction may enable low-power, intermittent operation, with constantly optimized low-power system, sensor and data reduced interfaces.

I introduce the concept and tools of autonomous marine ecosystems enabled through new and applied AI for design, operations support, and training. Long summarize present theory and future vision roadmaps for AI in autonomous robotics. I describe AI tools, Autonomous Marine Ecosystems, and architectures, with enabling capabilities, operations, and ecosystem applications. My comment introduces some of the challenges that lie ahead.

The expanded interest in investing in monitoring of the Planet Ocean through Autonomous Marine Ecosystems is a positive turn and provides the foundations to transition further into the constant online economization of the Planet Ocean. With this monitoring comes the need to focus on generating actions counted with predictive and optimal decision making for understanding the global temperature crisis, and supporting global security and planetary economics in building sustainable blue economy jobs and growth. This action interactive capabilities in trees is modeled through Feedback AI enabling the AI over a system of systems of systems, both for design and for executable Hybrid Control Markov interfaces.

3. Digital Twin Oceans and Simulations

Simulations can improve predictions of extreme weather and other events or phenomena associated with the oceans. However, with inherent model simplifications and uncertainties, climate models struggle to reproduce certain aspects of context and especially fine spatial-temporal details. To overcome the limitations of existing models, a number of Information and Communications Technology (ICT)-driven approaches, which can vary in their levels of sophistication, can be applied to create digital twins of the oceans, including utilization of ocean models of varying spatial-temporal resolutions, statistical downscaling, physical machine learning techniques, and data-assimilative modeling. Digital twins can further use data realistically simulating future changes expected with global warming, knowledge about the functioning of a physical system that allows for credible estimation of important unobserved oceanic variables, and artificial intelligence or machine learning-driven techniques that can achieve closure for unresolved processes or improve physical representations of the system.

Detailed simulations that digitally recreate the past and present oceans can help validate and improve the predictive skill of different levels of digital twins. Digital environments of the present, recent past, and possibly the near future can also support decisions around operation and investment by businesses in various sectors reliant on the oceans. Such descriptions can involve high-dimensional information, including atmospheric state variables which are impacted by latent variables and in turn influence ocean dynamics, and the states of the marine fauna and flora including fish, marine mammals, plankton, and primary producers. By complementing efforts at monitoring to fill in the gaps of both in-situ and remotely sensed data and forecasts grounded in physical science, advanced digital twins can help inform various ocean monitoring and management decisions conducted in the present and near-future time horizons by providing further confidence regarding the current and near-future digital twin state of the oceans.

4. The Role of Quantum Computing in Ocean Data Modeling

Ocean modeling is the calculation or consideration of specific oceanic variables or physical properties of the ocean or ocean-atmosphere, by means of a mathematical formulation and/or by translating them into numerical discretization. In this way, the comprehensive description of the operation and variability of astrodynamics especially in the long-term prediction is produced. Generally, the sea monitoring data are characterized by high speed, high frequency, non-continuous intensity, and high uncertainty. These characteristics have brought great challenges to how to effectively extract information of marine environment change via computing. Computing plays a nonnegligible role in this issue.

For a long time, AI-assisted computing has been a potential solution to ocean data modeling, such as physical model-assisted AI seismic inversion, deep reinforcement learning for path planning of marine autonomous vehicles, and

ML for the prediction of coastal ocean currents. Sufficient labeled training samples are indispensable for the successful training and implementation of ML-assisted ocean data computation. However, the quantity of samples for ocean data is normally too scarce to train the ML models. Recently, quantum computing has been proposed as a new mode of computing and has been shown to have the capability of further improving the prediction efficiency and prediction accuracy when compared with its classical counterpart in dealing with a handful of supervised samples. Thus, quantum computing can be helpful for ocean modeling not only for the prediction of ocean dynamics but also for solving the uncertainty dilemma encountered by the data-hungry AI algorithms supported by the classic computing. Therefore, quantum computing may evolve into a new and promising paradigm for ocean data computation.

5. Next-Gen AI-Powered Marine Robots and Smart Fleets

Advancements in artificial intelligence (AI) have the potential to revolutionize the capabilities of ocean observing technologies. This transformation is enabled by several developments, including increasingly sophisticated robotic platforms for collecting ocean information, the application of AI techniques for data and sensor fusion, the widespread availability of AI-aided cloud-based analytical tools, and the existence of large datasets for training and evaluating AI systems. Moreover, AI can accelerate the mission performance of intelligent autonomous robots, such as autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASVs) equipped with various scientific sensors. As part of a sensor network, large fleets of autonomous robots may be guided by AI towards specific ocean regions of scientific interest to collect calibrated space-time data that can be confirmed or further analyzed by existing ship or satellite sensors. Next-generation marine robots equipped with AI will reshape how we monitor and manage the ocean. Intelligent marine robots will collect more ocean data, more efficiently and safely than conventional platform and sensor configurations. Fleet integration and intelligence will drive data products with higher resolution and better information content for scientists. New robotic concepts will be developed for non-traditional applications, some with AUVs that are small, low-cost, and specialized for a single mission. Robotic observers will be used in applications that are currently difficult, if not impossible, with traditional technologies. AI will expedite the volume of machine-measured data needed to achieve the societal ocean goals. Robust, flexible, all-weather, intelligent, autonomous systems will minimize the risks to ship-based science fleets. New risk models can predict the probability of conducting shipboard research safely while boats remain connected to support on-site scientists.

6. Data Collection Techniques

Several technologies for aerial, maritime, and underwater imaging are widely used to monitor the oceans, namely remote sensing, underwater drones and robotics, and traditional shipboard methods using acoustic sensors, cameras, and nets. In this section, we outline the data collection techniques that have been critical for observing jellyfish blooms and their interactions with marine ecosystems. New and existing data from multiple organizations can now be fused in real time or rapidly analyzed through cloud computing and artificial intelligence techniques.

6.1. Remote Sensing Technologies

Visible, infrared, and microwave remote sensing have become useful tools for observing the physical, biological, and chemical properties of ocean water from dedicated satellites or commercial satellite constellations and, most recently, from unmanned aerial vehicles equipped with high spatial resolution cameras. Remote sensing provides wide-area ocean coverage, high spatial resolution, and synoptic observations from different time perspectives. Short- and long-term monitoring of the ocean can thus be performed. Indeed, the same locations can be revisited on a daily basis by a constellation of commercial-path and small satellites and UAVs at different places. Measurements can be integrated into satellite-derived iconic products that inform about jellyfish abundance, distribution, and ecological interactions, including surface temperature, chlorophyll-a concentration, and bathymetric information.

6.2. Underwater Drones and Robotics

Autonomous underwater vehicles (AUVs) are instruments for collecting ocean data, which are either remotely controlled or autonomous. For controlling the missions of these vehicles in the oceans, the missions are usually preprogrammed, and marked by underwater GPS based on acoustic technologies to land so that they can be recovered. AUVs are useful and convenient tools for many coastal and onshore/offshore ocean activities, such as environmental monitoring, coastal zone evaluation, offshore structure monitoring and maintenance, slope design, underwater decommissioning, tideland maintenance, tidal current investigation, and so on, as well as the exploration/utilization of offshore renewable energy in, on, and under the waters. AUVs are also widely used in marine archaeology, finding, photographing, and filming shipwrecks and submerged sites, mapping the remain distributions, investigating protected sites, and recovering artifacts.

Merely providing ocean data is not adequate to manage ocean environments. Effective management of oceanic environments requires long-term monitoring of oceanic processes, which can be achieved with oceanbuoy or buoyancy-evading ocean drones or drifting buoys. These types of drones are invaluable for continuously measuring and describing ocean currents, meteorological parameters, wave heights, ocean temperatures, color, and salinity, or more generally, acting like robotic vessels on-site for marine and meteorological monitoring.

7. Machine Learning Algorithms in Ocean Data Analysis

The development of marine-based products has increased the need for the efficient processing of data collected from oceans. Today, oceanographic data collection has also been combined with advancements in sensor technologies and big data analysis techniques, including AI and machine learning algorithms. Descriptions of several recent works that utilize ML for ocean data analysis are summarized.

Using ML algorithms for large volumes of complex and diverse data minimizes dependence on domain knowledge in feature extraction and classification model design. The two classical ML algorithms, supervised and unsupervised learning, are commonly used in ocean data analysis based on objectives. Supervised ML learns the characteristics of labeled data with existing classifications and then predicts class labels for similar unlabeled datasets. Supervised ML alleviates the need for a broad ocean physics background as a feature design guideline while partially relying on expert knowledge for the labeling of training data. For core areas such as biological-activity forecasting and ocean-climate prediction, this necessity has driven researchers to explore supervised ML applications.

Essentially, the effectiveness of supervised ML relies on the quality of the labeled training dataset. Data labeling is often challenging due to the limitations in domain expertise and the long computation times associated with numerical models and expert-driven approaches. Most machine-generated simulated training data will not match real observed ocean data due to variations in setting conditions and sensor placements. Thus, the generalization ability, or overfitting issue, is a challenge for practical applications of supervised ML. Another alternative is the transfer-learning method using pre-trained models.

7.1. Supervised Learning Applications

Supervised learning presents the most straightforward machine learning procedure: users annotate models with ground truth data to train and build predictive models potentially usable in many contexts. The ocean realm has benefited from supervised learning research efforts and applied predictive modeling to many different types of datasets and observations. Applications range from species tracking and detection to developing species-environment relationships, removing errors or noise, and classifying images. Ocean remote sensing has one of the richest research outputs.

Due to the expensive and often sporadic nature of biological surveys, particularly within remote marine environments, monitoring of many marine species would be impossible without the availability of artificial intelligence for powered detection. Passive acoustic monitoring is one such field where machine learning has developed due to both the quantity of available data and a reliance on automated solutions to data processing. Species including whales, dolphins, and fish have benefitted from supervised computer vision and acoustic plugin services. Images captured using underwater cameras provide researchers with useful assessments of fish assemblage structure and dynamics, some fish species abundance, and habitat characterization. In these cases, the ability to monitor such parameters continuously and achieve high temporal resolution has, however, been limited by human search through, and manual labeling of, images, a costly, time-intensive, and often insensitive task. Supervised models for image analysis of underwater systems are designed to exploit data augmentation, parallelization of label-error reduction via worker crowdsourcing, recurrent convolutional structure, or majority-voting of bagged component classifiers to solve the issues of volume-associated biases.

7.2. Unsupervised Learning for Pattern Recognition

A wide variety of unsupervised techniques have been developed for ocean science applications, and they can be broadly classified into three main categories, which are established primarily according to the representation of the original data: (1) dimension reduction; (2) pattern discovery; and (3) cluster identification.

Dimension reduction techniques compress data to a lower-dimensional representation, potentially preserving some intrinsic structure that is present in the original high-dimensional data. Many new scientific discoveries have emerged from the application of dimension reduction methods to ocean observational data. The availability of high-dimensional oceanographic parameter datasets has facilitated the application of well-known Multidimensional Scaling (MDS) and its variants to the approximation of geophysical flow dynamics of complex, especially multiscale, high-dimensional systems. Specifically, MDS methods have been successfully applied to the structure approximations of ocean eddies based on measuring the geophysical distribution of the dynamically active angular momentum in the dynamical system of ocean temperature. Moreover, the more recent application of t-distributed Stochastic Neighbor Embedding (t-SNE) method to the high-dimensional observational temperature dataset showed the feasibility of using asymptotic posterior probability distributions of latent variables from Stochastic Dynamic Models for t-SNE-based geophysical flow modeling.

In addition to dimension reduction, unsupervised learning techniques have been shown to produce unique spatial and temporal patterns for enhanced scientific analyses of oceanographic phenomena from available complex observational data. These techniques have been successfully used in discovering new dynamical features in stratification, waves, mixing, and coherent structures on 2D surfaces using large high-dimensional ocean temperature datasets observed by sensor networks.

8. Artificial Intelligence in Predictive Analytics

Predictive modeling relies on algorithms combined with observed data on multiple determinants of a phenomenon in order to accurately predict that phenomenon based on the determinants. The common use of the term "predictive analytics" implies the development and application of predictive modeling techniques to large datasets, not only in training models and estimating their output levels at actual locations, but also in the model selections and monitoring process. As descriptions of determinants of phenomena become more spatial, and as spatial data infrastructures and the compiling of large, multi-variable datasets accelerate, predictive modeling of spatial analyses will increasingly be dominated by predictive analytics.

Recent research and development in applied machine learning has catalyzed the synthesis and implementation of predictive analytics in fields such as oceanography. This accelerated adoption suits the aims of predictive analytics, as ocean monitoring and management is challenged by not only the sheer spatial scale of the ocean ecosystems of interest, but also by the scale of the data demands associated with addressing many needs in a usable time frame. In reaching across the ocean surface and deep into its benthos, the need to accurately represent variability as a single time-series or space-filling representation is impossible, and the choices scientists and managers have available to them must be made carefully. In addition to the need for model output at close temporal intervals and balanced in the spatial dimensions that suit the intended application, the underlying models must be, to the extent possible, provided as a free product or service, statistically robust, predictive of aspects of the ocean environment of interest, and collaboratively developed or verified across sectors.

8.1. Forecasting Marine Conditions

Artificial intelligence (AI) is often described as a general-purpose technology. In this role, it provides a set of technologies to increase productivity of other technologies – production process machine learning, natural language processing, and robots, among others. AI in predictive products or services is another way in which AI can be classified, occasioning increased efficiencies and added value. It turns out that predictions are a very large subset of products and services, such that the impact of predictive AI systems on the direction of human behaviors and activities is likely been enormous.

In the oceans and along the coasts, AI and machine learning approaches are being used to predict marine conditions, and the ecological and economical activity that those conditions support, for times ranging from hours to several months. Short-term predictions of waves and currents enables vessel guidance to avoid dangerous conditions, usually created by waves but also by currents or a combination of both. Predictions from a few days to two or three weeks are useful for planning and conducting recreational and commercial activities supported by those marine conditions, depending on the season or the occurrence and intensity of nor'easters. Long-term seasonal forecasts are beneficial for certain aspects of economic activity, including fisheries management, shipping, and offshore energy development including wind and oil and gas. Seasonal and annual predictions of oxygen depletion are important not just for fish species sensitive to low or low/no oxygen levels, but also for those species that interact with them, such as those species that feed on or prey upon either fish.

8.2. Species Distribution Modeling

Many animals, including commercially and ecologically important fish stocks, migrate seasonally at large spatial scales in response to environmental variability. Fleet dynamics in marine fisheries can result from localized depletion due to high catch per unit effort. Consequently, understanding the migration of marine species is important for informed stock assessment and management activities. Historical modeling efforts for fish distributions have incorporated time series data on hypothesized environmental cues. Such models are, however, highly parametric and sample size can become an issue. Advances in statistics, process modeling, and machine learning make it timely to explore the full potential of a predictive modeling approach based on remotely sensed covariates and a wonderfully rich package of alternative statistical treatments.

Fish are poikilotherms, which makes temperature a primary cue in their search for prey. Ocean floor depth is also an important driving parameter. For some fish, temperature, depth, and salinity affect ammonium absorption in the gills. For others, salinity is the only major driving parameter due to rare absorption. However, incorporating a long-but-dense route highway into modeling has many benefits. First of all, it preserves the geographic features along the highway. Having density along the route helps to understand the reason for the colonies: a high colony density can be due to a spawning fish migrating back or a migratory fish mustering up strength for its journey. Besides, by following the maturity cycle, we know what period the specific colonies are at and this information can help fill data gaps. Both of these benefits build confidence in generalizing the model results.

9. Challenges in AI Implementation

Despite the numerous advantages of AI, there is a significant gap in the implementation of AI systems for ocean monitoring and management, likely due to the associated challenges in the realization of AI. Some of these challenges are discussed here. Although the Large Language Models considered here are trained on vast amounts of publicly available content that would be impossible for humans to read in the lifetime available to an individual, the handling of data that has not been publicly shared presents ethical and security challenges. While the training of machine learning models does not involve the storage of data in the traditional sense, data used for training is nevertheless discoverable, and this poses risks if sensitive data is inadvertently used. The implementation of machine learning systems in domains, such as healthcare or finance, where data privacy is paramount, typically involves some form of data scrubbing to remove sensitive information, a process that is complex and difficult. As AI finds increasing use in ocean monitoring, the data vacuum-cleaner approach to data collection may disadvantage those countries or regions with less manpower or financial resources, since these data may be disruptive to sensitive ecosystems or be used as a proxy by competitors during crunch times.

In most scientific fields, research is carried out within a loosely defined community, and data is collected and shared for the good of the community. Such is still not necessarily true for the ocean, although the creation of publicly accessible databases is becoming the norm. The sharing of data has still not produced the kind of dividends that might be expected on that investment, in part because data remains available in silos, but also due to issues of data quality and provenance. Much of the publicly accessible acoustic data relevant to marine bioacoustics has been collected by commercial companies or research groups from developed regions at varying levels of expense, and as a result, they are often produced for different ends, using different collection methods with varying success rates.

9.1. Data Privacy and Security

The utilization of AI presents opportunities for extraordinary enhancements in fieldwork operations and policy implementation efficiency and sloganing. While these transformations present enormous promise, the nature of digital transformation upon government agencies structures and institutional capacities, and upon measurable efforts in investing agency missions, creates a new set of needs for research and implementation. Moving towards a future where AI agents aid human decision-makers and data collection is curated in a proper manner is a shared goal. However, these emerging technologies face challenges with anecdotal experiences often being used to convince governments to adopt a technology afterwards experiencing operational failure as no foundational work had been completed.

Data privacy must be the leading consideration in development if agencies wish to be successful. Data privacy breaches can occur at any stage of the evidence synthesis pipeline from data collection and transfer, to the decision models used to analyze the results and their recommended actions, to the day-to-day enactment of those decisions. When trained on aggregated, individual accounts, hallucination can put private information at risk. Model parameters may also leak sensitive data. This poses a risk of exposing personal information if models are later run without careful anonymity guards. During the knowledge distillation process, secret data points may be discovered, which is a serious issue when developing mental model generators for utilizational systems. Users or agents are likely to send unique instances during general use of the AI, such as through social media channels.

9.2. Integration with Existing Systems

Integration of AI solutions with existing systems can be a challenge. For example, if fish aggregation devices are equipped with AUVs for monitoring, existing protocols for data linkage need to be reviewed and updated to include automated tagging and archival of data in secure databases. Furthermore, information technology restrictions might prevent AUV data access, slowing down decision-making processes. These shortcomings will need to be addressed for more robust use of AUVs equipped with AI solutions for ocean monitoring and management. AI-enabled Lagrangian observing systems deployed for ocean monitoring usually rely on passive tagging of particles or use of satellite data as a precursor, providing information on how long it may take a particle to reach a site of interest and guiding priority observations such as for oil spills. These limitations can delay decision making like assessment of near real-time information on whether it is authorized fishing or not for Subsurface Whirl Flux buoy, a system able to detect subsurface motion using machine learning and co-array processing techniques.

Some commercially available autonomous systems may be modified to allow for rapid data exchange. With the advent of miniaturized robotics, launching small autonomous systems from ocean-going vessels, while heading towards a target location based on available data in secure cloud platforms, can be achieved within short time frames. These incidents highlight the importance of investing in interoperability of autonomous vehicles with information sharing features to undertake public safety missions. To facilitate successful deployment of autonomous systems in adverse incidents such as oil spills, some form of centralized command structure may be used to facilitate discussions, determine responsibilities, and assist with integration.

10. Ethical Considerations in AI for Ocean Management

Acknowledging the rapid advancements in AI deployment for ocean monitoring and management, it remains crucial that these systems be designed, developed, and deployed in a responsible manner. There are many key ethical considerations to consult when designing AI systems to interact with marine life and ecosystems, and frequently the discussions surrounding it are troubling and unregulated. This raises the potential for harm, including violations of privacy, lack of accountability and transparency, and even deployment of systems for unwarranted oppressive behavior. The review of practical implementations of AI for ocean monitoring, and the continuously growing catalog of natural and anthropogenic issues in the oceans, expose various scientific, economic, technical, and ethical research fronts that will need to be filled to advance the field. Here, we explore two pertinent topics: (i) Impact on Marine Life: The consideration of some monitoring and management systems that interact directly with marine life may require to be operated or designed cautiously, in order to minimize unavoidable bycatch or animal disturbance during learning or fielding efforts, or other detrimental environmental impacts; (ii) Regulatory Frameworks: An effective regulatory framework remains to be discussed and implemented to address responsibility and bycatch and disturbance mitigation.

Marine organisms are sensitive to even small perturbations from human activities, especially during periods of high evolutionary and ecological significance, such as during feeding, breeding, brooding, and dispersal. Many monitoring and management missions necessitate disturbing marine life at some point, either through incidental bycatch or through temporarily placing individuals and the environments they reside in at risk of direct or indirect harm. It is essential to assess how systems will operate in realistic conditions, including the possibility of encountering sensitive species. These challenges are particularly acute for learning-based methods.

10.1. Impact on Marine Life

Ethical consideration in AI for ocean management has made researchers attentive for implementation of any AI solution without series questioning of hidden costs. Despite the fulfillment of great task by AI in devising effective plans for ocean management and resource sustainability, there are some real costs as well. These costs about directing attention from intrinsic interest in ocean study to their monetary use quantification. If these ethically questionable applied solutions become the prey of socio-economic advantages getting allure, the right course of ocean study may be diverted because of significant performance boost by AI. Uncertainty estimation which is one of the imbalance in model, may induce an ethical concern when it comes to using AI for decision making. Future result retraction after AI predictions for offshore activity boom utilization could be sensitive. If AI could be fully reliable then no human intervention would be needed, but since it relies on machine interfaces and learning data which at times go wrong, this becomes a question of ethical use. Such issues become of greater importance for marine species and habitats that are already vulnerable, threatened or at risk. Marketing sensitivity, environmental stress and harm to species have all been cited as potential issues in relation to the new AI techniques. Such reactions could potentially influence negative response to these innovations.

The back-and-forth nature of the interactions also raises concerns about misleading information being put into circulation without caution or context, particularly when regarding sensitive or critical topics related to the environment. Although the keywords set approach relied on known keywords for most snow crab developmental stages or early life processes, the AI model has the potential to explore other, less well-known keywords. Ultimately, awareness of the advantages and risks that come with the promotion of this novel technology and its algorithm functions should ensure that it is enhancing what is already being done, helping to fill gaps in study or knowledge and ensuring the risk of management or species threat are not increased.

10.2. Regulatory Frameworks

The governance of AI and ML on an international and national level is still often patchy and underdeveloped. However, some obligations and other conventions, treaties, and guidelines have relevance for the means by which AI and ML will be deployed. Therefore, it is evermore essential to clarify guidance and develop more comprehensive legal, policy, and regulatory frameworks to facilitate international cooperation and the positive contribution of international law to the development and deployment of AI and ML with respect to the marine environment.

There exists an abundance of AI guidelines and AI ethical values, but many of them are vague and overly suggestive. With respect to AI's impact on the ocean, relatively few sections that connect to specific international policy frameworks, guidelines, or ethical codes exist. As such, marine science development and ocean management decisions in favor or against the use of AI or preference or priority for certain AI methods cannot create appropriate incentives or regulatory frameworks nor substantially reduce the likelihood that potentially harmful uses of AI and ML will be misapplied to the ocean in question. A focus exclusively on AI-code approaches would neglect the benefits of regulatory initiatives as a driver for general adherence to ethical considerations for the use of AI within a specific domain, which could take the shape of marine and ocean laws, policies, or area-specific guidelines or constraints operating within the testimonial conduits listed.

11. Case Studies of AI Applications in Ocean Monitoring

This paper describes some of the case studies found about Artificial Intelligence (AI) applications in ocean monitoring. The implementation of these cases benefited with the usage of AI methodologies in order to conduct the research or achieve a goal. More specifically, the cases refer to some advancements in areas of ocean monitoring, like whale or fish detection, marine geographic identification, climate or marine environment predictions, extraction of information from satellite, buoys, or floats data, visual recognition of non-science-related underwater images, and the quality control of non-event data. Many AI and Machine Learning (ML) algorithms have learned with the use of supervised, semi-supervised, or unsupervised approaches, in order to bring revolutionary solutions to these ocean monitoring areas. These areas have undergone advances due to the availability of methods for these existing monitoring problems, along with the increase in the availability of different data and amounts of monitoring data, computing resources, and investments in the AI area.

AI's increasing impact on society, and also on science, brings many advances to scientific fields through its successful implementations during the last decades. For autonomous and operational ocean monitoring, AI is bringing many solutions to recognized problems and increasing our monitoring capabilities to problems that have not been demonstrated until today. The autonomous operational ocean monitoring of predicting what marine events will happen and when is probably the field with the greatest technological advancement in relation to ocean monitoring. There is a very dynamic activity bringing together many research projects composed of strong consortiums individuals from several countries, exploring concepts over the last decade and showing promising results, but yet to be published for widespread use. Many of those cases were achieved with AI but are not labeled as AI to facilitate the applicability of the advances described herein.

11.1. Successful Implementations

In this section, we highlight eight different case studies of AI successfully deployed for ocean monitoring. Each of these examples illustrates the lessons that can be learned from how bias and error are balanced in real-world examples and illustrate some of the different ways that AI can be applied for ocean monitoring. We end this chapter with thoughts on how to more broadly enable AI deployment to ensure the lessons learned from these examples are available widely to others, enabling the next generation of AI solutions to spur progress towards more sustainable management of ocean health. The examples are listed alongside stage in the AI development cycle at which they operate, and stage of ocean monitoring process enabled.

We assume the first question readers might ask is, "Why these examples?" The eight examples showcased here were chosen not because we felt they were the best applications of AI, but rather because they illustrate a variety of the different ways in which these technologies can be used for ocean monitoring. Taken as a whole, they explore a variety of technological applications, some demonstrating different stages in the AI developmental cycle: from prototype implementations to system deployments. They additionally cover a number of different processes within the larger ocean monitoring workflow, focusing on two main steps: data collection and data extraction. Finally, we also emphasize a diverse number of communities submitting the material and applications to different ocean domains, either focused on discrete questions on environmental health or using AI as part of an integrated observation system.

11.2. Lessons Learned

Book-ending our discussion here are lessons learned from the previous projects. Almost all AI applications discussed here share an important insight from multiple stakeholders interviewed: AI is a tool and, as with all tools, it should not be applied indiscriminately for any problem. In general terms, AI will not solve problems that are not properly defined or, more importantly, for which data does not exist. Furthermore, AI should not be a substitute for the best available domain knowledge but rather a complement or a boost to it. In gift detection research, domain experts can create sound detection algorithms that do not require that training datasets be labelled, thus allowing global bias reduction; however, training data is the key concept for all machine learning techniques, as its quality and the way it was collected will directly impact the quality of AI models. The best solution, as pointed out, is creating models based on both domain experts' knowledge and AI.

Moreover, model explainability is also an important issue that stakeholders highlighted. Simply using AI techniques to label species is not sufficient. Science is based on reproducibility, and AI models need to be able to provide natural explanation and influencing factors for their decisions to be considered. Such explanations also help model taming, a task that most AI-based models require when applied to a problem outside the training data distribution. In fact, the AI techniques described work by inferring correlations from multimodal datasets, an often-disregarded fact. This means it is important to consider the multimodality of the data when creating the technique or to apply it to similar problems; otherwise it can be unsuitable for problems that deviate from their training data.

12. Future Trends in AI and Ocean Management

Artificial intelligence has the potential to drive disruptive innovation in a variety of ocean-related sectors, including tourism, energy, marine biology, habitat restoration, exploration, shipping, and management. Priorities for the deployment of data scientist work must focus on the needs of these sectors. Simple to implement decision-support tools can help drive the successful deployment of AI tools by non-technical investigators, and standardizing well-tested predictive models will allow federation of predictive systems that work across the many borders that oceans represent. Nevertheless, the recent evidence of an AI winter suggests that, while early adoption is accelerating in some areas, user confidence in AI may need to be earned. Cross-disciplinary teams of representatives of end-user domains partnering with AI and computer vision experts allow for accurate definition of problems but also sophisticated understanding of modeling uncertainties which may affect the predictions years after they were made. So-called “embodied models”, designed to mimic human reasoning but containing multi-disciplinary knowledge are likely required for the complex ocean problems we want to address. Interdisciplinary engagement, including ocean modeling and ground-truthing expertise, is essential for effective use of AI and machine learning by the diverse stakeholders in ocean policy. Governments keen to accelerate the rapid and broad application of AI to ocean management in support of the Sustainable Development Goals may consider developing tax incentives and research funding programs to enable public-private partnerships to focus efforts on answering the complex questions facing the future of oceans at a time when major drivers of change challenge marine ecosystems.

12.1. Emerging Technologies

In fact, apart from funding, which in many cases is still modest, the majority of enabling technologies are rather more advanced. Various sets of UxVs are available. From sensor to decision support systems, a variety of technological building blocks are available. They are exploitable either directly from the computer science community or via a quick integration with more domain-specific technology. Such co-designs are needed to provide satisfactory performances because environmental conditions in Oceanographic applications are particularly harsh, from high altitude and solar storm interference to underwater pressure or corrosive saltiness, even more when buried in sediments. We see two classes of enablers that are quite in an advanced state of maturity and will require dedicated efforts to be directly exploitable in real missions.

Due to the extreme hostile environments both for electronics and human mounted sensors, with the proper exception to satellite-based monitoring, we should approach the next decade with a combination of Smart and Big Data approaches. With Smart Data, we intend to encode domain-specific knowledge in more or less ad-hoc modeling tools, reducing the search-space complexity. Big Data approaches exploit the increasing computer power available and the number of sensors distributed that provides data and decide to take the ultimate choice by evaluating thousands of generated options.

We expect that within the upcoming decade the number of missions able to provide raw data will really explode combining and integrating UxVs with very advanced onboard automatic interpretative capabilities and drastically lower their exploitation costs, while still being able to discover anomalies, changes, or specific events.

12.2. Collaborative Efforts in Research

A key challenge in the adoption of AI for ocean management is the interdisciplinary nature of much of the ocean economy, and technology development customs for technical disciplines do not fit neatly with those for social sciences or humanities. The involvement of industry partners and non-profit ocean management stakeholders—which are not accustomed to undertaking technology development—are important. For example, it can be challenging to obtain access to the data and field sites required, there is often little or no funding at the proposal phase, and the results of such research can take years to bear fruit. However, perhaps more importantly, industry and non-profits have much more limited experience or resources to manage long-term research projects in an academic-like structure nor do they have experience collaborating with one another or deepening the collaboration with academic researchers throughout the project.

There are numerous examples of successful current collaborative efforts. One project saw a developed optical processor detect excavation sites on the ocean floor months after the event, and multiple groups have proposed or executed AI-enhanced acoustic and optical planning and exploration. Another initiative has funded several successful "Testbed" initiatives focused on the use of AI for unmanned aerial systems or marine autonomous surface and underwater vehicles for marine science. More broadly, a branch is developing custom computing capabilities for marine vehicles, and its partners have been executing an at sea research agenda with AUVs and docked vessels for various years. Funders are also supporting research in future military or missions. These are all examples of particularly tangible future pathways for collaborative research into the implementation of AI for ocean management.

13. Conclusion

The ocean remains a poorly understood environment, primarily due to its vastness, inaccessibility, and unique conditions. However, the ocean also plays a crucial role in maintaining the Earth's energy balance, global climate, and the ecosystem's functioning. As a result, various oceanic processes, such as currents, tides, and heat content, are increasingly being investigated in relation to the long-term climate variability, seasonal climate prediction, and extreme climate phenomena. Furthermore, the ocean is an important natural resource providing food, fuels, raw materials, and fresh water; it supports economic expansion and development. As a result, the ocean is being increasingly exploited, and climate change, pollution, and over-exploitation seriously threaten its health. However, maintaining the ocean health is a necessary condition for ensuring the ecosystem health and the proper functioning of the entire Earth system. Thus, a strong and sustainable investment is necessary to promote the understanding, monitoring, and responsible management of the ocean system.

Technological developments in Artificial Intelligence are revolutionizing the ocean monitoring and management. The AI-assisted implementation of innovative equipment and techniques such as autonomous unmanned surface vehicles, autonomous water sampling, water chemistry-corrected bio-optical measurements, and fixed and mobile platforms with optical sensors have resulted in dense monitoring of various oceanic features. Furthermore, AI-aided real-time, or close to real-time, satellite observations are crucial for proper ocean monitoring and management. They facilitate tracking of various ocean properties driving primary production, heat, gas, and pollutant exchange, as well as climate variability and predictability. They also support daily and fine-scale forecasting of the oceanic features that are difficult to model. As a result, dense monitoring and an appropriate level of model skill would promote the implementation of AI tools such as machine learning, neural networks, and deep learning for solving various assimilation and prediction problems in ocean monitoring. Integrating deep learning with numerical ocean models results in hybrid models, which are often superior to the numerical models, generating accurate forecasts and estimations for various satellite and in situ measurements.

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