SYMPOSIUM ON ADVANCES IN OCEAN OBSERVATION

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BACKGROUND AND MOTIVATION

Two technological revolutions have transformed our understanding of the oceans over the last 40 years. The first, in the 1980s and 1990s, was the advent of satellite based remote sensing that provided views of the global ocean surface at spatial and temporal scales previously unimaginable. The second, in the 2000s and 2010s, was the development in genomic methods that provided new knowledge about oceanic life forms from the smallest viruses to the largest whales covering habitats from the surface to the seafloor. Despite these advances, the oceans remain woefully under sampled and oceanographers have yet to fully leverage recent and rapid advances in technology, inclusive of the advent of microfluidics, compact sensors, and autonomous robotic platforms. In addition, more recent advances in Computer Science, Mathematics, Statistics, Software Engineering, Machine Learning (ML), and Artificial Intelligence (AI) have shown promise in data and pattern analysis and made an impact in embedded machine intelligence. Yet ML/AI have had a peripheral impact for gathering and analyzing data and/or making informed decisions in the ocean sciences. Equally, the diverse science and technology communities associated with the use of such techniques—which include sensors technology, engineering, and physical and bio-chemical oceanography—have not yet had meaningful in-depth dialogs on how to leverage such advances in the context of ocean observations, as a way to move the needle forward to make observations at the vast spatial and temporal scales the oceans present.

THE AZORES SYMPOSIUM

The Symposium on Advances in Ocean Observation was held in Terceira, Azores from 3–7 July 2022[1] to bridge the gap between computational and robotic sciences and ocean sciences by bringing together physical, biological, chemical oceanographers, ocean modelers, remote sensing experts, marine robotics and autonomous platform experts, sensor technologists, experts in AI, adaptive sampling, and spatial statistics. A total of 27 participants from 13 different countries across the Atlantic and representing diverse backgrounds and fields with near parity in gender were invited by the organizers. In addition, a competitive open call was used to select three early-stage researchers from India, Madagascar, and Brazil to attend the meeting.

The event was unique in two key ways. First, it brought together a transdisciplinary group of people to ensure a diverse set of opinions, approaches and concepts to critically look at the complexity of doing science in the ocean (Fig. 1).

Second, to strengthen participant engagement in this multidisciplinary setting, we developed and implemented a pairing methodology where a presenter and challenger exchanged ideas prior and during the meeting. The presenter and challenger were asked to meet online a priori, with the challenger's role to provide feedback as an outsider "looking in" with a fresh and differing perspective. The pairing order was made to bridge divergent topics and demography while maintaining some common scientific and technological interest(s) within each pair. Working prior to the meeting also helped break down some of the communication barriers between siloed fields.

OUTCOMES

The "tall poles" (or main outcomes) of understanding that were derived from the conversation over four intense days of interaction revolve around the following ideas:

- The oceans are vast and under sampled in space and time. Therefore, the use of cost-effective and improved sensing technologies and their deployment at scale is critical to our understanding of the global biogeochemistry that underpins the basis of oceanic and all planetary life. Discussions around this outcome emphasized that in addition to the measurements of concentrations across space and time, it is also critical to measure *rates of processes* and *rates of change* across a variety of spatial scales. The importance of cross/inter-calibration of instruments from multiple experiments across different regions and regimes was also emphasized.
- Coupling observations of biogeochemistry to modeling is important, both as a way to make predictions for situational awareness, as well as a means to "test" what-if scenarios in a digital representation of the ocean and its processes. Models could then enable stakeholders to make informed policy decisions with desk-top scenarios, allowing them to be responsive to sudden and emergent needs. Such coupling would also enhance model skill and improve sampling designs as a means to reduce uncertainty with techniques used in adaptive sensing.
- The importance of robotic platforms with sensing capabilities that can extend the "human senses" is typically centered around

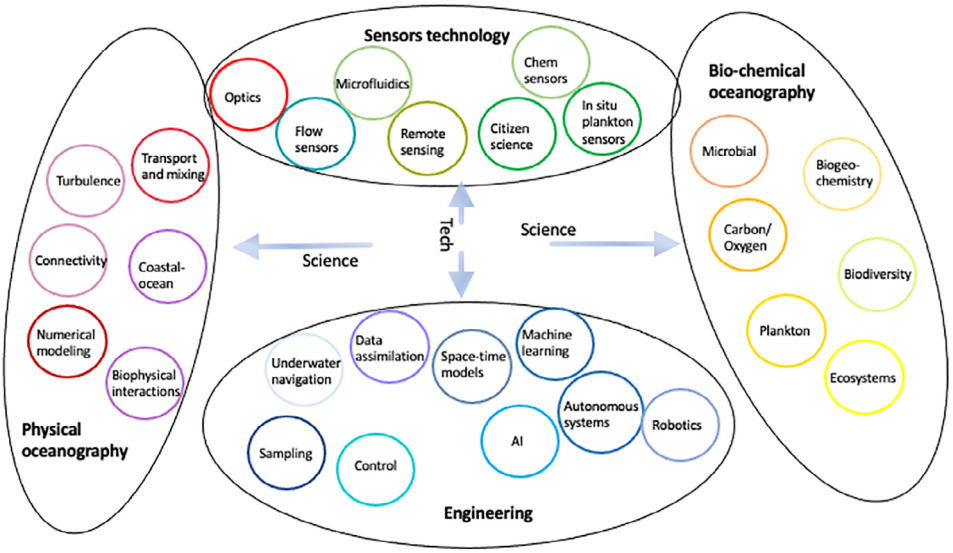

FIG. 1. At the Azores symposium, efforts were made to bridge gaps and spark collaborations across the multiple disciplines shown above.

[1] https://sites.google.com/view/oceanobs-advances/home?authuser=0.

their use with a research vessel. Advances in computation, algorithms, and hardware enable computational decision making and machine intelligence to be part of sustained observations, including "smart" approaches to sampling (at the "right place and time") given the large spatial and temporal scales to be addressed. Participants discussed ways to couple observations and models with intelligent decision-making to ensure the best use of these tools while maximizing the value of gathered data.

- Cost will play a role in the use of these technologies. Novel sensors can potentially be embedded at moderate cost on existing infrastructure, such as ARGO floats, gliders, autonomous underwater vehicles, unmanned aerial vehicles, and autonomous surface vehicles. The advent of low power sensors driven by commercially available smartphones has given a boost to sensor technology development which in turn has been leveraged for oceanographic needs.
- There is a need to overcome structural impediments that prevent deeper and "real" global stakeholder collaboration/utilization. Particular areas that need to be addressed include societal and economic limitations on access to and utilization of data, as well as support of international scientists. Participants were particularly enthused by the potential for collaboration in this UN Decade of the Oceans, but discouraged by the continuing barrier to cross-Atlantic collaborations even after the Galway, Belem, and Lisbon agreements on international collaborative research and data sharing. Funding and cross-nation collaborations continue to face significant barriers even if there are complex and convoluted ways that such efforts can and have been carried out in the recent past.

One specific outcome that the participants unanimously supported was the establishment of a Cross-Atlantic "Toolbox" of contributed sensors, platforms, and hydrodynamic and numerical models. Developing such a "Toolbox" would both build the basis for collaboration across the Atlantic (both the North and the South), while also fostering a shared understanding of common and standardized calibration of instruments, as well as continually contributed/maintained software infrastructure. Moreover, this would allow for the involvement of students so they can be trained as future leaders in transdisciplinary science/engineering. Starting out small with a field experiment where measurement of key bio-geochemical rate measurements and variables is undertaken by blending modeling, robotics and data analysis in real-time would be a viable way to demonstrate this drive to "move the needle" of ocean observation.

At the end of the symposium, participants were joined by a distinguished panel of program managers and scientists from the European Union and the United States who endorsed the "tall poles" and shared their perspective on how to achieve transdisciplinary work across geopolitical boundaries. Participants were encouraged to pool their ideas in ways that can be articulated in white papers that can be presented to funding agencies or to actually propose experiments and demonstrations.

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