Ocean Sciences Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

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Abstract

This article is composed of three independent commentaries of how Integrated, Coordinated, Open, and Networked (ICON), as well as Findable, Accessible, Interoperable, and Reusable (FAIR; under the umbrella of I from ICON), principles are currently embedded in ocean sciences, and what are the opportunities and challenges by adopting them. Each commentary focuses on a different perspective as follows: (i) field sampling and experimentation to remote-sensing and autonomous observations (Section 1); (ii) global collaboration, technology transfer and application, reproducibility, and data sharing and infrastructure (Section 2); (iii) increasing diversity and broadening participation in ocean sciences (Section 3). Overall, there is a consensus that ocean sciences is well-advanced in adopting many of the ICON-FAIR principles regarding (i) and (ii), although there are still plenty of opportunities to develop further by, for instance, making broader use of data-of-opportunity and citizen science, improving efforts towards standardized data organization and avoiding data fragmentation, and increasing training activities to implement good practices. On the other hand, fostering diversity and broadening participation in ocean sciences is still in its infancy. Actions are needed to overcome under-representation of women and other marginalized groups, create opportunities for early-career scientists, and build bridges to support scientists from low-income countries. We recognize that adopting ICON-FAIR principles come with high costs and efforts, but it has strong potential to develop ocean sciences in many aspects.

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Key Points:

- ICON-FAIR principles are broadly adopted in many observational- and experimentation-based initiatives within Ocean Sciences
- ICON-FAIR is a common practice in terms of global collaboration, technology transfer and application, reproducibility, and data sharing
- Amplifying the use of ICON-FAIR will contribute to fostering diversity and widening participation in ocean sciences

Abstract

This article is composed of three independent commentaries of how “Integrated, Coordinated, Open, and Networked” (ICON), as well as “Findable, Accessible, Interoperable, and Reusable” (FAIR; under the umbrella of ‘Open’ from ICON), principles are currently embedded in ocean sciences, and what are the opportunities and challenges by adopting them. Each commentary focuses on a different perspective as follows: **(i)** field sampling and experimentation to remote-sensing and autonomous observations (Section 1); **(ii)** global collaboration, technology transfer and application, reproducibility, and data sharing and infrastructure (Section 2); **(iii)** increasing diversity and broadening participation in ocean sciences (Section 3). Overall, there is a consensus that ocean sciences is well-advanced in adopting many of the ICON-FAIR principles regarding (i) and (ii), although there are still plenty of opportunities to develop further by, for instance, making broader use of data-of-opportunity and citizen

science, improving efforts towards standardized data organization and avoiding data fragmentation, and increasing training activities to implement good practices. On the other hand, fostering diversity and broadening participation in ocean sciences is still in its infancy. Actions are needed to overcome under-representation of women and other marginalized groups, create opportunities for early-career scientists, and build bridges to support scientists from low-income countries. We recognize that adopting ICON-FAIR principles come with high costs and efforts, but it has strong potential to develop ocean sciences in many aspects.

1 **Field sampling and experimentation to remote-sensing and autonomous observations**

This section provides a brief assessment of how ocean sciences adopt the "ICON-FAIR concepts in terms of "field, experimental, remote sensing, and real-time data research and application". The commentary is expectedly influenced in part by the authors' perspectives and experience and constrained by space limitation, but we have attempted to cover all aspects of ICON-FAIR in all of these major types of ocean science activities.

1.1 Current State

Ocean Science is the ultimate environmental science, multi- and interdisciplinary by definition, whereby oceanographic phenomena can rarely be described by drawing from a single core discipline (Powell, 2008). The need for multidisciplinarity is well-characterized during oceanographic cruises which, due to the high investment required, recruit researchers from diverse fields and institutes who ensure that observing and experimental strategies and high-quality data collection serve, on the one hand, their respective fields and, on the other hand, allow for integrated interpretation (I-integrated; e.g. Sloyan et al., 2019).

Many oceanographic parameters are quantified using detailed, well-established and widely accepted protocols, thus facilitating coordination and interoperability (C-coordinated), for instance, the Intergovernmental Oceanographic Commission (IOC) of UNESCO's international thermodynamic equation of seawater (IOC, SCOR and IAPSO, 2010). Another more recent global coordination initiative is the Ocean Best Practices System (OBPS, 2021). However, there are discipline-specific differences that manifest themselves prominently in the time needed to collect and analyze samples but also in the availability of advanced technologies, such as sensors, for the autonomous and/or remote collection of acceptable data. Physical parameter technologies are typically more mature than chemical ones and even more so than biological ones (Whitt et al., 2020), and this difference may result in lower integration and coordination of data-gathering efforts. As a consequence, 20th century biogeochemical and biological data (for instance) are less findable, accessible, interoperable, and reusable (O-open, FAIR) than physical data, since they are often produced later, after sample collection, analysis and elaborate quality control. A notable 20th-century exception is the observation of surface-ocean chlorophyll from space, initially by the Coastal Zone Color Scanner and then by SeaWIFS, an enterprise that required intense calibration and intercomparison to become acceptable (Hu et al., 2012).

Since then, transformative 21st-century advancements include the diversification of cutting-edge in-situ sensor technologies, the platforms that carry them, and (N-)networked data delivery systems (e.g. the Argo float programme; see Argo, 2021; Johnson et al., 2021), resulting in more data gathered and transmitted annually than for the whole 20th century (Tanhua et al., 2019). Because of the continuous consolidation of observing systems (e.g. IOOS, 2021) and the integration of databases (e.g. Copernicus, 2021), data flows are more interdisciplinary, integrated, coordinated, open and networked than ever before. And this strategy is also influencing more traditional ship-board efforts such as GEOTRACES (2021) and GO-SHIP (2021) through explicit investment in data centers for these global multi-year projects.

1.2 Challenges and opportunities

The plethora of near-real-time data becoming available in publicly accessible databases (O-open) may resolve some of the FAIR criteria, but not all. Quality assurance and control (QA-QC) remain key issues for less mature methodologies (such as some sensor technologies) that, if not addressed by the collection protocols and metadata files (i.e., greater coordination/interoperability), may render voluminous datasets unusable, less open and less FAIR. Where QA-QC is performed and extra resources and time are needed (for instance, in laboratory work), there is a real risk that datasets become fragmented and therefore neither integrated nor interoperable. Continuous and expert curation of databases which is needed to overcome these issues requires investment in training, development of expertise and infrastructure to reach a FAIR standard.

Citizen-science initiatives are an example of (N-)network efforts that may help gather and process large data streams (C-coordinated), under curated open database initiatives, and thus assist with the data-processing backlog that is currently observed. Two well-known examples that involve images include the collection of sea-surface images used in the estimation of ocean-color properties (e.g. Ceccaroni et al., 2020) and the identification of notable objects in underwater images (e.g. Langenkämper et al., 2019).

Similarly, we recommend taking advantage of the many possibilities for broader use of data-of-opportunity. This approach has already contributed to advance ocean science research towards the (O-)open and (N-)networked aspects of ICON on many fronts as, for example, during the global World Ocean Circulation Experiment (WOCE) program (e.g. Chapman, 1998), for characterizing water mass properties (Joyce and Robbins, 1996) and ocean circulation (Gay and Chereskin, 2009), and detecting zooplancton and fish in remote regions such as below the ice pack in the Arctic (Snoeijs-Leijonmalm et al., 2021).

1.3 Summary

Overall, we consider that Ocean Science is already well-advanced in many ICON-FAIR aspects in terms of ”field, experimental, remote sensing, and real-time data research and application”. Ocean Sciences are **I**ntegrated and multidisciplinary by nature, while the **C**oordinated use of consistent protocols is a widespread practice adopted for decades through intergovernmental recommendations - if not for all oceanographic variables, at least for the essential ones. Similarly, there are countless examples of **N**etworked efforts, although there are still plenty of opportunities to develop further in that direction. For example, by making broader use of data-of-opportunity and citizen science. We consider that the **O**penly and **FAIR** aspects are also broadly incorporated into Ocean Sciences, mainly for physical variables and satellite data. Collected data that requires further processing and analyses (e.g. chemical and biological variables) seems to have a more sinuous path to (eventually) become available for the community. Finally, the goals of the newly launched "United Nations Decade of Ocean Sciences for Sustainable Development (2021-2030)", by the United Nations (UN), resemble some of the ICON-FAIR principles and, therefore, it is a once-in-a-lifetime opportunity for Ocean Sciences to move towards a fully implemented ICON-FAIR approach.

2 Global collaboration, technology transfer and application, reproducibility, and data sharing and infrastructure

2.1 Current state

Oceanography and ocean observing are benefiting from incorporating innovations in sensor and communication technology to increase observational capacity. This is probably most impactful in the advent and now widespread use of autonomous vehicles and satellite communications which have the promise of driving the cost and accessibility of basic oceanographic data towards an asymptotic minimum relative to previous generations. For example, the Argo and Biogeochemical Argo (Bio-Argo) programs are worldwide efforts to collect and deliver physical and biogeochemical profiles from the entire world ocean on a sustainable basis in near real-time, implicitly if not expressly addressing ICON (O)pen and (N)etwork principles.

By its very nature as a worldwide effort, the Argo Bio-Argo programs have been incorporating ICON and FAIR principles essentially by default. One example of integration and networked relationships inherent in the oceanographic global nature of the system is SOCAT (Surface Ocean CO2 Atlas) and Bio-Argo, where the SOCAT project will benefit from Bio-Argo measurements in producing further data products and extending the dataset while researchers using Bio-Argo datasets can set those datasets into the context of the wider SOCAT dataset (SOCAT, 2021).

The Global Ocean Observing System (GOOS) is oceanography's well-established organization that exists to facilitate the creation of a global scale ocean observing system (GOOS, 2019). Its mission is to "grow an integrated, responsive and sustained observing system" which fundamentally includes the ICON principles of (I)ntegration across disciplines, (C)oordination of protocols, data collection and modelling, (O)pen data access and system level best practices, and development of global (N)etworks to drive capacity development through stakeholders to generate sustainable local to global-scale impacts. While GOOS does not specifically incorporate the ICON nomenclature, the organization does specifically refer to FAIR principles with respect to data.

Many other oceanographic data groups have adopted ICON and FAIR from their very nature as cooperative efforts oriented to large datasets, data collection methods and phenomenological observing systems (Pangeo, OceanGliders, SAMOC, TRIATLAS, among others). On the smaller scale scientists are now making datasets accessible as part of the publication process where journals encourage permanent accessible storage. For example, Frontiers in Marine Science requires data availability statements from authors prior to review and requires that at the least a 'minimal dataset' within FAIR guidelines is available to any qualified researcher.

There are many scientists that need the data of other people to conduct their own research. The value and opportunity that increasing accessibility of oceanographic data brings to all research, monitoring and management are that what has traditionally been extremely sparse under sampled systems will increasingly become data-rich. This will improve all data-based oceanographic activities as boundary conditions and variability assumptions become increasingly constrained. However, storage formats are not standardized, and metadata and processing methodology may be incomplete so other people cannot reproduce the results. Without standardization and structured storage with clear metadata it is likely that data will become inaccessible, or at the least is not available to the widest group of stakeholders (Benway et al., 2020; Trice et al., 2021).

UNESCO's International Oceanographic Data and Information Exchange (IODE) is developing an Ocean Data and Information System (ODIS) to provide a single-entry point for users to all oceanographic data systems (N), (C). The system is designed to be inclusive (O) and training is available to increase participation and expand the data network (IOC Workshop Report No. 290, 2020). Specific datasets, for example the World Ocean Database (Boyer et al., 2018), for oceanographic profiles, are currently accessible with a web browser.

2.2 Challenges

Given the collaborative nature and open access of many oceanographic datasets the central challenge for the uptake and use of ICON principles is promulgating awareness. We suspect, but have no real data, that many oceanographers are already developing some of the aspects of ICON science, however they aren't aware of this, and if you ask them about ICON principles, most of them would answer that they have only a little knowledge.

The oceanographic community has been building accessibility into data handling and best practices for many years as programs and funding expanded.

However, while it is increasingly common for researchers and programs to share software and methods with a new researcher or outside observer, one of the main challenges is that there are many sources available but structural and cohesive methods are not globally standardized.

2.3 Solutions

Fundamental to building awareness and use of ICON principles is to provide resources (time and funding) to the community so that utilization of ICON principles helps to facilitate science rather than become a burden.

The ICON and FAIR principles should be incorporated throughout the oceanographic community, especially within education, funding, and communication frameworks. Scientific societies in their role as facilitators of communication should adapt meetings and journals to ICON principles (I), (O). Education and training programs should incorporate ICON principles and build off current open science data and tools: training materials and methods should be as open and accessible as possible to foster worldwide use to overcome any hesitation to learn new tools by new users (C), (O), (N). Clear protocols and complete methodologies that avoid jargon and have been demonstrated to be repeatable by new users should be the long-term goal (C).

Funding providers and peer reviewer systems should develop structures that give credit for use of best practices in data sharing and methodology descriptions in evaluations and reviews. Funding agencies should consider data and methodology accessibility and sharing as part of the evaluation of proposals and provide budgetary support for ICON and FAIR implementation.

3 **Increasing diversity and broadening participation in ocean sciences**

Like many other disciplines, ocean science focuses on the achievements of established scientists (Nash et al., 2019), is male-dominated (Orcutt and Cetinić, 2014), and lacks diversity in cultural backgrounds. Early career researchers (ECRs), in general, are often not acknowledged as intellectual sources to improve the scientific knowledge base (IOC-UNESCO, 2020). Nevertheless, it is *the people*, especially ECRs, that bring new skills and diverse perspectives to ICON research.

3.1 Current state

The scientific community includes people from different nationalities and languages, however the primary language for science is English. This limits *integration* of non-English speaking researchers, which restricts the *open* exchange of local knowledge from oral history or cultural practices. ECRs from different parts of the world lack mentors or close collaborations resulting in unequal opportunities to do *networked* science and reduce opportunities to expand ocean science into new areas. For example, students from Europe and North America account for 69% of student participation in ocean science conferences globally (IOC-UNESCO, 2020), likely because socio-economic barriers restrict the global south to travel abroad. Additionally, researchers from non-English speaking countries may face cultural biases at work, on voyages, and during the publication process.

Ocean science has made progress on the gender gap, with 38.6% average of female researchers in ocean science (~10% higher than average across all scientific disciplines, IOC-UNESCO, 2020). However, female scientists make up $< 25\%$ of leadership positions (Orcutt and Cetinić, 2014), and for women and people of color in the mid to senior-level positions, the time allocated for ICON science must be balanced with increased participation on advisory boards and committees compared to male colleagues (Kamm et al., 2020).

3.2 Challenges and solutions

Creating a more accessible ocean science field is critical because a significant portion of the ocean remains underexplored and understudied. One major reason for this is that certain areas, or even entire countries, remain unexamined because those areas lack the resources to study their coastal and marine communities. These communities are greatly impacted by policies made in response to ocean science and may rely heavily on the ecosystem services offered by the surrounding marine environments, but have very little say in how their resources and ecosystems are managed. It is critical that, when scientists use the principles of ICON, they *integrate* not only traditional STEM disciplines, but local knowledge and oral histories. And that *networked* science be done intentionally, to the benefit of everyone (e.g., protocols are developed in *coordination* with local communities). When possible, protocols should be accessible enough for community leaders to be involved in the data collection process, which may require an expansion of the *coordination* principle to include proper training and instruction. Similarly, the *open* exchange of information gathered must take into account increasing data accessibility for the affected communities. Building *networks* between institutions across different communities allows for resources to be pulled together to support the use of technology that might otherwise be unavailable to single institutions. It is important to ensure, however, that in building this infrastructure there is an equitable distribution of power. The communities most affected by changes in coastal ecosystems should be the drivers of what and how data are being collected, and these data should be made *open* and accessible. For example, if a community doesn't have internet or computational resources, we should find alternative ways to share data or provide a data hub. Currently many data sources are difficult to find, poorly advertised, and rely heavily on supercomputers to access, but with increased efforts to build computer networks and less computationally-intensive data sharing networks, the field has the opportunity to find new and more accessible ways to share data and resources.

That being said, the vastness of the internet and overwhelming number of social media platforms makes it challenging for novice members of the community, or communities that are not as well integrated into existing networks, to navigate. Other than reading publications, which are in English and may be behind a paywall, information about data, tools, conferences, webinars, training, and networking opportunities require individuals to already be connected and informed, or already have a professional network that supports them. As the ocean community is truly global and diverse in research topics, it is important that everyone amplify opportunities. If we all take the time to amplify relevant resources, we can encourage discovery.

Once ECRs find ways to *integrate* with ocean science research, they still need to feel welcome. Many ocean science organizations have established Code of Conduct resources (AGU, OCB, ASLO, etc.), as well as programs that encourage underrepresented groups to develop cohorts and support networks (e.g., ASLO Multicultural Program) or centers to drive change in diversity, equity, inclusion, and integrity, like the AGU Ethics and Equity Center (AGU, 2021). ICON science requires *the people* to be part of a supportive community to be successful.

Once ECRs are aware of the openly available resources, informed on how to use coordinated data and protocols, and feel supported by their network, they should be given opportunities and encouraged to complete the cycle and communicate about their research and their experience. Creating speaking opportunities or social media highlights enables them to act as representatives to their local communities. These networks provide a connection to currently underserved communities, and creates a positive feedback loop to support ICON science.

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Author Contributions

AH and LP designed and wrote Section 1. IW and LS designed and wrote Section 2. JG, NM, and EWC designed and wrote Section 3. LP wrote the abstract and coordinated the team.

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