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

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Key Points:

- ICON-FAIR is common practice in observational and modelling data research and application among many cryosphere studies
- Strengthening ICON-FAIR principles in cryosphere research may increase opportunities for young researchers and students entering the field
- Increased opportunities for undergraduate involvement in cryosphere sciences is one approach to diversifying participation in our field

Abstract

This article is composed of two independent commentaries about the state of ICON principles (Goldman et al. 2021) in cryosphere science and discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: (Section 2) Observational and modelling data research and application in cryosphere sciences and (Section 3) Expanding undergraduate research experiences in cryosphere science. We found that many cryosphere-related research projects and data sharing initiatives engage in integrated, coordinated, open, and networked research. These efforts should be continued and improved. Specifically, we recommend standardizing methodologies and data, and removing existing barriers to data access and participation in our field. We acknowledge that such ICON-FAIR-aligned efforts are cost- and labor-intensive. They require leadership and accountability but they also have the potential to increase the diversity and knowledge of the cryosphere research community in the future.

Plain Language Summary

We explored the benefits of integrated, coordinated, open, and networked (ICON) principles in cryosphere research, which is the study of snow, ice, and other frozen water features. We found that some cryosphere research already uses ICON principles, but defining and using the same methodologies across research projects would help scientists understand frozen water environments better. ICON scientific research would also allow more diverse groups of researchers, particularly undergraduate students, to participate in the study of the cryosphere.

1 Introduction

Integrated, Coordinated, Open, Networked (ICON) science aims to enhance synthesis, increase resource efficiency, and create transferable knowledge (Goldman et al., 2021). This article belongs to a collection of commentaries spanning geoscience on the state and future of ICON science. For a deeper understanding of the ICON principles, see the introductory article for the collection. ICON-FAIR expands upon 'Open' to explicitly point to the Findable, Accessible, Interoperable, Reusable (FAIR) data principles (Wilkinson et al., 2016).

The cryosphere is one of the five major components of the global climate system along with the atmosphere, hydrosphere, lithosphere, and biosphere (IPCC, 2019). Its terminology originates from the Greek word "krios" (κρύος) meaning cold, while in science it encompasses any discipline related to water in a frozen state, whether seasonal or perennial (NOAA, 2021). These include sea ice, lake ice, river ice, snow, ice sheets, ice shelves, glaciers, freshwater ice, and frozen ground (IPCC, 2019; AGU, 2021a). Hence, cryosphere research is a field built around a common archive (ice) that embraces a variety of different research questions across spatial scales, time frames from modern to deep time, and is integrated (I-integrated) between traditional disciplines (i.e., physical, chemical, and biological). For example, in collected ice cores a variety of measurements from physical properties, chemical species, biological specimens, as well as atmospheric and ice flow modelling branch into other subdisciplines and require an assessment through integrated multidisciplinary approach including natural and social sciences (e.g., Richter-Menge et al., 2019; McConnell et al., 2021).

Due to recent climate change-forced phenomena, such as glacier retreats (e.g., Milner et al., 2017), sea ice depletion (e.g., Crawford et al., 2021), sea-level rise (e.g., Hugonnet et al., 2021), and polar amplification (e.g., Bindoff et al., 2013; Collins et al., 2013; Hartmann et al., 2019), the cryosphere is receiving increasing attention from the scientific community and policymakers (e.g., Vergara et al., 2017). At the same time, although data are extremely limited, publications suggest that the cryosphere research community is not a diverse field (e.g., Carey et al., 2016; Koenig et al., 2016; Hulbe et al., 2010). We use the American Geophysical Union's (AGU) definition of diversity "as the full spectrum of personal attributes, cultural affiliations, and professional or socioeconomic statuses that characterize individuals within society," and inclusion "as valuing the contributions of diversity to the Earth and space sciences and respecting the individual identities of participants engaged in executing AGU's vision, mission, and strategic priorities," both published in AGU's Diversity and Inclusion Strategic Plan (AGU, 2018).

Through two lenses we aim to discuss how the ICON-FAIR principles are currently implemented in cryosphere sciences and what opportunities and challenges arise by doing so. The first focuses on observational and modelling data research and application (Section 2), and the second focuses on undergraduate students opportunities for increasing diversity (Section 3). In this latter section, we focus on undergraduate research opportunities as a mechanism to increase diversity, as these experiences have been shown to increase the retention and post-graduation potential of underrepresented students (Hernandez et al., 2018). We acknowledge that cryosphere science is a broad field and we cannot fully explore all ICON-FAIR items here. Instead, this commentary is based on the authors' perspectives and personal experiences, as well as a few selected case studies. However, this approach presents numerous limitations in providing a comprehensive assessment for such a complex topic.

2 Observational and modelling data research and application in cryosphere sciences

Several well-established community initiatives indicate that cryosphere science is substantially aligned with ICON-FAIR principles. Below, we refer to just a few of those, while a comprehensive list would be much longer. Regarding cross-disciplinary integration, many cryosphere studies have a history of international collaborations not only across traditional disciplines but also across spatial and/or temporal scales. For example, early polar drilling campaigns leading to the famous Dansgaard-Oeschger Cycles, in which different aspects of traditional disciplines were covered, were conducted through networked efforts by researchers from Denmark, Switzerland, and the United States (Jouzel, 2013). The recent Year of Polar Prediction and European Union Horizon 2020 project APPLICATE brought together the efforts from several international partners to, among other goals, improve the prediction capability of polar regions including their cryosphere components (sea ice and snow), from weather to climate scales (Jung et al., 2016), by making better use of observational (in situ and satellite) datasets and model outputs (Ponsoni et al., 2020).

Cryosphere researchers can benefit from world-wide coordinated efforts related to the adoption of consistent protocols. The EPICA project in Antarctica and the EastGRIP project in Greenland are classical examples that coordinate ice core drilling campaigns, ice core sampling and analysis, resulting in high impact publications (e.g., Barbante et al., 2006; Erhardt et al., 2019; Spahni et al., 2005) . Other examples are the three CMIP6-endorsed projects (Eyring et al., 2016), ISMIP6 (Nowicki et al., 2016), PAMIP (Smith et al., 2019), and SIMIP (Notz et al., 2016); all three designed to perform a common set of experiments to assess the impact of cryosphere components on the climate system. Similarly, the ESMValTool is a large effort towards coordinated approaches for model evaluation, including cryosphere variables and phenomena (Eyring et al., 2020). In short, ESMValTool provides a handful of scripts for calculating cryosphere-related metrics and diagnostics that allow for a consistent model evaluation by making use of observational datasets.

These integrated efforts between disciplines reveal regional to global impacts within and beyond the cryosphere field. Examples span many frozen archives: Recent polar and high-alpine ice core studies integrate past climate, land use, and pollution (e.g., Hartmann et al., 2019; McConnell et al., 2018; Brugger et al., 2021). Ice caves were successfully used to reconstruct Holocene treelines in the Pyrenees (Spain) thus bridging the cryosphere to the biosphere (Leunda et al., 2019), while the investigation of ice patches enables scientists to link past climate to archeology (e.g., Chellman et al., 2021; Pilø et al., 2021). A modern example of how cryosphere science is connected to societal and environmental events, are the devastating Portugal fires in 2017 and the associated smoke plume that was traced to snow in the Swiss Alps using a combination of remote sensing, atmospheric trajectories, and traditional black carbon measurements in a snow pit (Osmont et al., 2020). The depletion of sea ice and earlier snowmelt has been reported to have an impact both on native communities and ecosystems. Due to these recent cryosphere changes, native communities are experiencing negative effects in subsistence activities (fishing and hunting; e.g., Grah and Beaulieu, 2013), while high-trophic predators are adapting their foraging behaviour and dietary preferences (e.g., Brown et al., 2016; Grémillet et al., 2015; Laidre et al., 2008; Lydersen et. al, 2017; Pagano et al., 2018). A case of bird body shrinkage due to earlier snowmelt has been identified (van Gils et al., 2016).

2.1 Opportunities and challenges in conducting cryosphere research

The implementation of the ICON-FAIR principles comes along with both opportunities and challenges. The first straightforward opportunity is likely the possibility for multidisciplinary and multi-institutional collaborations (C-coordinated) that are already in place to some extent for many projects. Cryosphere sampling efforts are often founded on costly, high-risk, time-intensive efforts to reach sampling locations and to transport the frozen material to the laboratory destination. Often, these challenges make cryosphere research feasible only through collaboration. While consistency of methods is an important principle for research in general, it becomes even more important for collaborative studies. As an example for lack of coordination (C), different ice core labs often have different methods to establish chronologies or proxies in ice cores which hampers comparisons of their data when working on the same ice core record as well as when comparing different ice cores (e.g., Svensson et al., 2006).

Following ICON-FAIR principles in networked efforts to generate datasets that are openly available and interoperable across systems and researchers (O-open, N-networked), allows for follow-up studies by different researchers and may contribute to model improvements. For sea-ice modelling, for instance, interoperable data facilitates the development, implementation, and evaluation of sea ice features parameterization such as melt ponds, form drag, landfast ice, snow scheme, or albedo (Ponsoni et al., 2021). Apart from many open access satellite products, initiatives such as the NOAA and NSIDC cryosphere databases collect a range of datasets sampled by different methods and spatiotemporal scales. In a few cases, the dataset is already organized in a consistent (C-coordinated) format (e.g., Unified Sea Ice Thickness

Climate Data Record, Lindsay and Schweiger, 2013). While there are plenty of opportunities by making use of those available datasets, it is not always straightforward to get access to many other datasets for a range of reasons that include national interests, contractual agreements, or personal research interests.

We identify a large potential in cryosphere science for making a broader use of data of opportunity and citizen science. For example, Schweiger et al. (2019) used historical ship log-books spanning from 1844 to 1970, transcribed by citizen scientists (www.oldweather.org), to identify whether a certain region was covered or not by sea ice when evaluating the PIOMAS-20C reanalyses. We recognize that organizing such information in concise datasets (C-coordinated) is a laborious task and represents a challenge for broad application.

Lastly, even by fully adopting the (N-)network principle of ICON-FAIR, high costs with training and knowledge transfer, and lack of infrastructure (e.g., computational capabilities), might still impose a barrier for disadvantaged contributors to accommodate resources (e.g., instruments, models, large datasets). We emphasize that alternatives to overcome such limitations should be prioritized. For example, research efforts from researchers with diverse backgrounds add more views on a research gap and thus increase chances for alternative out-of-the-box solutions.

2.2. Implications for observational and modelling data research and application in cryosphere sciences

The presented cases are a few of many examples in which ICON-FAIR efforts are already common practices in observational and modelling data research and application among cryosphere studies. We identified that such integrated and interdisciplinary (I-integrated) approaches to research questions bring new and powerful results with direct impacts on society. However, challenges are to continue developing standardized field and lab protocols (C-coordinated) that allow comparison of data, benefit science of opportunities, and facilitate knowledge transfer (N-networked). Additionally, we identify that open access of datasets and publications to share knowledge among the research community and society should be further developed (O-open). Implementing these addressed challenges for conducting cryosphere research may also benefit opportunities for young cryosphere researchers and students entering the field.

3. Expanding undergraduate research experiences in cryosphere sciences

There are limited opportunities for undergraduates to get involved in cryosphere sciences, and those that are available may be difficult to identify without guidance from someone in the field. A comprehensive catalog of available opportunities is beyond the scope of this commentary; instead, we searched for opportunities through basic internet searches, as an undergraduate might. Due to the algorithms that search engines employ, our outcomes will also be inherently biased based on IP address, location, and personal browser data. Our search efforts yielded few clearly defined cryosphere research opportunities for undergraduates. As one example, searching the US National Science Foundation's (NSF) Research Experiences for Undergraduates (REU) using cryospheric terms produces no results. There are only three programs available for students to get involved in polar research, two of which appear to offer experience in cryosphere research.

3.1. Challenges for undergraduate students in cryosphere sciences

Undergraduate students underrepresented in STEM fields may face challenges to involvement in cryosphere research, and by extension it is difficult for the career workforce of cryosphere scientists to represent a diverse collection of individuals.

Cryosphere research often requires costly travel, equipment, and a significant dedication of time. These requirements create a barrier to participation for low-income and/or disabled students, two demographics which may overlap with other underrepresented identities. These barriers faced by low-income and disabled students are a vital consideration for the development and improvement of undergraduate research experiences (UREs) in the cryospheric sciences.

Data regarding diversity in cryosphere sciences is limited (Koenig et al., 2016), making it challenging to identify barriers to participation in our field and to establish which groups are most excluded from our work. Recent efforts, such as AGU's DEI Dashboard, may improve our ability to assess progress, but only if Cryosphere Section-specific data and resources are made available. Improved data collection would help in the design and advertisement of more inclusive undergraduate research opportunities.

Working toward a more diverse cryosphere research community through undergraduate research aligns most closely with the 'Open...' and 'Networked...' ICON-FAIR principles:

O: **Findable, accessible, interoperable, and reusable (FAIR) data, software, and models**, when combined with mentorship, provide an excellent basis for undergraduate research opportunities, which in turn **enables more researchers to contribute and leverage resources**. Removing barriers to undergraduate involvement at different phases of the research process, from study design to sample analysis for example, will also promote open contribution in cryospheric sciences.

N: **Networked efforts** increase the opportunity for and impact of undergraduate contributions by connecting undergraduate data generation and/or sample collection with shared research goals, and by providing resources to potential undergraduate contributors that would otherwise be impossible for them to access. Field experiences for students are particularly difficult to obtain, due to the inherent cost of missions in remote regions; networked efforts between institutions and organizations and existing computing networks could help to provide more accessible experiences for low-income or resource-limited students.

3.2. Opportunities for undergraduate students in cryosphere sciences

We are well-positioned in cryosphere sciences to increase the number of UREs available to students. Advantages include the wide availability of remote-sensing datasets, existing data sharing initiatives, and the widespread development during the pandemic of virtual work resources such as the refinement of virtual meeting softwares, availability of faculty training for remote research mentoring, and the creation of virtual research communities (e.g., Corson et al., 2020). These resources together provide an opportunity to increase access to cryosphere research for a more diverse population of students. In particular, structures for virtual research experiences have the potential to broaden the reach of UREs by expanding accessibility to low-income and disabled students.

Expanding the availability of UREs is consistent with recent momentum toward a more diverse cryosphere research community. Examples include the Diversity in UK Polar Sciences Initiative, the Interagency Arctic Research Policy Committee's Diversity and Inclusion Working Group, and statements calling for continued action in support of a more inclusive field, such as that posted by the International Glaciological Society. We hope some of this momentum can be applied to the active recruitment and mentoring of a diverse generation of cryosphere scientists through more numerous and inclusive UREs.

To this end, we recommend clarifying the leadership and responsibility within cryosphere sciences for supporting and tracking progress toward expanding UREs in our field. AGU's Cryosphere Sciences section leadership (AGU, 2021b) and the Diversity and Inclusion Advisory Committee (AGU, 2021c) may provide a starting point from which a cryosphere-focused team can be assembled. Established research programs such as the Juneau Icefield Research Program (JIRP, 2021) could be identified, consulted, and included. Collaborations with established secondary education programs such as the Inspiring Girls Expeditions (Inspiring Girls Expeditions, 2020) could help establish clear pathways for more diverse participants to participate in UREs in cryosphere sciences; the AGU Bridge Program (AGU, 2021d) could be consulted to strengthen connections between URE participants and graduate opportunities. Once assembled, this group should establish (or continue) regular data collection about the diversity of participants in cryosphere sciences and make these data readily available to our community.

Several steps could increase the accessibility of existing UREs in cryosphere sciences. A searchable online listing of UREs in cryosphere sciences would make it easier for applicants to identify which UREs are right for them, and could increase the diversity of applicants. The same website could include resources to help students build competitive applications, including virtual mentorship opportunities; as well as resources to help URE mentors advertise more widely, and create inclusive professional development experiences for students. Many resources for creating inclusive UREs already exist, including scholarly articles (e.g., Hanauer et al., 2017).

We also recommend expanding resources for the creation of new UREs in cryosphere sciences. The development of a wide range of undergraduate research opportunities may reduce barriers for participation, and create a wider net for recruiting undergraduates at many different levels. Existing and publicly available remote sensing datasets such as those available through NSIDC (NSIDC, 2021) could support the creation of new undergraduate research opportunities, both in-person and virtual. Virtual collaborative tools could be employed in the development of non-traditional undergraduate research programs that would allow for more international collaboration and participation. The online resource described above could provide a centralized location for advertising supplemental or dedicated funding sources to incorporate undergraduate research into cryosphere research initiatives.

The creation and support of a wide range of UREs in cryosphere sciences would help to diversify participation in our field. Cryosphere sciences is well-positioned to achieve this goal given a renewed commitment to diversity, readily-available cryosphere datasets such as remote-sensing datasets, and virtual collaboration resources developed during the COVID-19 pandemic. Efforts to expand the availability of and participation in UREs would benefit from clear leadership and a centralized online resource for URE applicants and mentors. We recommend the creation of a group dedicated to leading and tracking this effort.

4 Conclusions

Cryosphere sciences has a long history of employing elements of ICON-FAIR Science. International, interdisciplinary projects and established data sharing initiatives have demonstrated the field's ability to engage in integrated, coordinated, open, and networked research. Recent initiatives also highlight the field's commitment to a more open, inclusive research community. We recommend expanding efforts to standardize methodologies and data formats, and to remove barriers to data access and to participation in our field. These ICON-aligned efforts will be cost- and labor-intensive, and require leadership and accountability - but will improve the diversity and knowledge of our field in the long term.

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Author Contributions

SOB and LP authored Section 2. CT and AAJ authored Section 3. All authors contributed equally to the entire manuscript. The authors declare no conflict of interests. LP acted as a facilitator and point of contact with the special collection organizing team.

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