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COMMENTARY
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Special Section:
The Power of Many: Opportunities and Challenges of Integrated, Coordinated, Open, and Networked (ICON) Science to Advance Geosciences

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Key Points:
- Integrated, Coordinated, Open, Networked (ICON)-Findable, Accessible, Interoperable, Reusable is common practice in observational and modeling data research and application among many cryosphere studies
- Strengthening ICON 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 the field

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

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Abstract This article is composed of two independent commentaries about the state of Integrated, Coordinated, Open, Networked (ICON) principles (Goldman et al., 2021, https://doi.org/10.1002/essoar.10508554.1) in cryosphere science and discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: (Section 2) observational and modeling 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 ICON 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-Findable, Accessible, Interoperable, Reusable-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, 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-Findable, Accessible, Interoperable, Reusable (FAIR) expands upon "Open" to explicitly point to the 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 (AGU, 2021b; IPCC, 2019). 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, and biological specimens, as well as atmospheric and ice flow modeling branch into other subdisciplines and require an assessment through integrated multidisciplinary approaches including natural and social sciences (e.g., McConnell et al., 2020; Richter-Menge et al., 2019).

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

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the scientific community and policymakers (e.g., Vergara et al., 2007). 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; Hulbe et al., 2010; Koenig et al., 2016). 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 principles are currently implemented in cryosphere sciences and what opportunities and challenges arise by doing so. The first focuses on observational and modeling 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 items here. Instead, this commentary is based on the authors' perspectives and personal experiences, as well as a few selected case studies with an inherent bias. However, this approach presents numerous limitations in providing a comprehensive assessment for such a complex topic.

2. Observational and Modeling Data Research and Application in Cryosphere Sciences

Numerous well-established community initiatives indicate that cryosphere science is substantially aligned with ICON 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 (I-integrated). For example, the recent Year of Polar Prediction (YOPP) and the 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) data sets and model outputs (C-coordinated) (Ponsoni et al., 2020). Furthermore, the YOPP-endorsed activities are making data openly accessible (O-open). Also, early polar drilling campaigns leading to the Dansgaard-Oeschger Cycles in which different aspects of traditional disciplines were covered, were conducted through (N-)networked efforts by researchers from Denmark, Switzerland, and the United States (Jouzel, 2013).

Cryosphere researchers can benefit from world-wide (C-)coordinated efforts related to the adoption of consistent protocols. The EPICA project in Antarctica and the EastGRIP project in Greenland are classic 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 toward (C-)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 data sets.

(I-)integrated efforts 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 several disciplines to study past climate, land use, and pollution (e.g., Brugger et al., 2021; Hartmann et al., 2019; McConnell et al., 2018). 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 environmental impacts on society, 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 satellite images, atmospheric trajectories, and traditional black carbon and microfossil measurements in a snow pit (Osmont et al., 2020).

The study included scientists from ice core science, paleoecology, atmospheric modeling, and remote sensing. 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 & Beaulieu, 2013), while high-trophic predators are adapting their foraging behavior 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).

2.1. Opportunities and Challenges in Conducting Cryosphere Research

The implementation of the ICON principles presents both, opportunities and challenges. The first straightforward opportunity is likely the possibility for multidisciplinary (I-integrated) and multi-institutional collaborations (N-networked) 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 (e.g., Figuerola et al., 2021). 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 (C-coordinated). As an example for lack of coordination, 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 principles in networked efforts to generate data sets that are openly available and interoperable across systems and researchers (O-open), allows for follow-up studies by different researchers and may contribute to model improvements.

For sea-ice modeling, for instance, interoperable (C-coordinated) 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 (O-)open access satellite products, initiatives such as the NOAA and NSIDC cryosphere databases collect a range of data sets sampled by different methods and spatiotemporal scales. In a few cases, the data set is already organized in a consistent (C-coordinated) format (e.g., Unified Sea Ice Thickness Climate Data Record, Lindsay & Schweiger, 2013). While there are plenty of opportunities by making use of those available data sets, it is not always straightforward to get (O-)open access to many other data sets for a range of reasons that include national or personal interests as well as contractual agreements (Pope et al., 2014).

We identify a large potential in cryosphere science for making a broader use of data of opportunity and engaging more people through citizen science approaches. For example, Schweiger et al. (2019) used historical ship log-books spanning from 1844 to 1970 CE (common era), 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 data sets (C-coordinated) is a laborious task and represents a challenge for broad application. Lastly, even by fully adopting the (N-)network principle, 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, and large data sets). However, we emphasize that alternatives to overcome such limitations should be prioritized (Settles et al., 2019). Indeed, researchers with diverse backgrounds could add more views on research gaps and thus increase chances for alternative out-of-the-box solutions (Harris et al., 2021).

2.2. Implications for Observational and Modeling Data Research and Application in Cryosphere Sciences

The presented cases are a few of many examples in which ICON efforts are already common practices in observational and modeling 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 (Harris et al., 2021). 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 data sets and publications to share knowledge among the research community and society should be further developed (O-open). Addressing these challenges for conducting cryosphere research will make cryosphere research more equitable, inclusive, and 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. Our search efforts yielded few clearly defined cryosphere research opportunities for undergraduates. For example, searching for "cryosphere internships" yields links to job boards that list later career opportunities such as tenure-track faculty positions. Narrowing search terms to focus on glaciology opportunities uncovers the Juneau Icefield Research Program (JIRP, 2021), but also links to institution-specific Research Experiences for Undergraduates (REU) sites, some of which are outdated. Students may be directed to the US National Science Foundation's REU database, but searching for cryosphere 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 (e.g., Figuerola et al., 2021; Hoag, 2018). These requirements create a barrier to participation for low-income and/or disabled students (Bangera & Brownell, 2014; Stokes et al., 2019), demographics which may overlap with other underrepresented identities. These barriers are a vital consideration for the development and improvement of undergraduate research experiences (UREs) in the cryosphere sciences.

While recent studies describe a lack of diversity in geosciences as a whole (e.g., Bernard & Cooperdock, 2018), 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-open: 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 in the research process may also promote more diverse participation in STEM fields (Pierszalowski et al., 2018).

N-networked: 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. Opportunities include the wide availability of remote-sensing data sets and existing data sharing initiatives such as those described in Section 2, and the widespread development during the pandemic of virtual work resources. These resources include the refinement of virtual meeting software, availability of training for remote research mentoring (e.g., Womack et al., 2020), 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 (Johnson et al., 2020).

Expanding the availability of UREs is consistent with recent activities to promote a more diverse cryosphere research community. Examples include the Diversity in UK Polar Sciences Initiative (British Antarctic Survey, 2022), the Interagency Arctic Research Policy Committee's (IARPC, 2018) 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 (IGS, 2022). 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.

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, 2021c) and the Diversity and Inclusion Advisory Committee (AGU, 2021d) 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, 2021a) 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 through professional organizations, affinity groups such as the Society for the Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS), historically Black colleges and universities, and Hispanic serving institutions. Resources for creating inclusive professional development experiences for students could be compiled; many resources for creating inclusive UREs already exist, including scholarly articles (e.g., Ahmad et al., 2019; Hanauer et al., 2017). We also encourage the compilation of resources for structural changes at the department and institutional level that could reduce barriers to participation in cryospheric research (e.g., Ali et al., 2021; Berhe et al., 2022; Dutt, 2021).

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 data sets 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 data sets such as remote-sensing data sets, 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 ICON research. Recent initiatives also highlight the field's commitment to a more open, inclusive research community.

We recommend to further 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. We call for research institutions as well as individual researchers to be open about and actively work toward changing systemic inequities and lack of inclusivity in cryosphere sciences to achieve this goal. Cryosphere will overall benefit from being even more inclusive in the future following the concept of "Power of many" researchers to address complex cryosphere topics. We further recommend that the cryosphere research community reflects on common values of our field and inherent biases when implementing ICON items.

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References

AGU. (2021a). *AGU Bridge Program*. Retrieved from https://www.agu.org/bridge-program

AGU. (2018). *AGU Diversity and Inclusion Strategic Plan*. Retrieved from https://www.agu.org/-/media/Files/Learn-About-AGU/AGU-Diversity-and-Inclusion-Strategic-Plan-2019.pdf

AGU. (2021b). *Cryosphere Sciences*. Retrieved from https://connect.agu.org/cryosphere/home

AGU. (2021c). *Cryosphere Sciences Leadership*. Retrieved from https://connect.agu.org/cryosphere/about/leadership

AGU. (2021d). *Diversity and Inclusion Advisory Committee*. Retrieved from https://www.agu.org/Learn-About-AGU/About-AGU/Governance/Committees/Diversity-Committee

Ahmad, A. S., Sabat, I., Trump-Steele, R., & King, E. (2019). Evidence-based strategies for improving diversity and inclusion in undergraduate research labs. *Frontiers in Psychology*, *10*, 1305. https://doi.org/10.3389/fpsyg.2019.01305

Ali, H. N., Sheffield, S. L., Bauer, J. E., Caballero-Gill, R. P., Gasparini, N. M., Libarkin, J., et al. (2021). An actionable anti-racism plan for geoscience organizations. *Nature Communications*, *12*(3794). https://doi.org/10.1038/s41467-021-23936-w

Bangera, G., & Brownell, S. E. (2014). Course-based undergraduate research experiences can make scientific research more inclusive. *CBE-Life Sciences Education*, *13*(4), 602–606. https://doi.org/10.1187/cbe.14-06-0099

Barbante, C., Barnola, J. M., Becagli, S., Beer, J., Bigler, M., Boutron, C., et al. (2006). One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, *444*(7116), 195–198. https://doi.org/10.1038/nature05301

Berhe, A. A., Barnes, R. T., Hastings, M. G., Mattheis, A., Schneider, B., Williams, B. M., & Marín-Spiotta, E. (2022). Scientists from historically excluded groups face a hostile obstacle course. *Nature Geoscience*, *15*, 2–4. https://doi.org/10.1038/s41561-021-00868-0

Bernard, R. E., & Cooperdock, E. H. (2018). No progress on diversity in 40 years. *Nature Geoscience*, *11*(5), 292–295. https://doi.org/10.1038/s41561-018-0116-6

Bindoff, N. L., Stott, P. A., Achuta Rao, K. M., Allen, M. R., Gillett, N., Gutzler, D., et al. (2013). Detection and attribution of climate change: From global to regional. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

British Antarctic Survey. (2022). *Diversity in UK Polar Science Initiative*. Retrieved from https://www.bas.ac.uk/project/diversity-in-uk-polar-science-initiative/

Brown, T. A., Galicia, M. P., Thiemann, G. W., Belt, S. T., Yurkowski, D. J., & Dyck, M. G. (2016). High contributions of sea ice derived carbon in polar bear (*Ursus maritimus*) tissue. *PLoS One*, *13*, e0191631. https://doi.org/10.1371/journal.pone.0191631

Brugger, S. O., Schwikowski, M., Gobet, E., Schwörer, C., Rohr, C., Sigl, M., et al. (2021). Alpine glacier reveals ecosystem impacts of Europe's prosperity and peril over the last millennium. *Geophysical Research Letters*, *48*, e2021GL095039. https://doi.org/10.1029/2021GL095039

Carey, M., Jackson, M., Antonello, A., & Rushing, J. (2016). Glaciers, gender, and science: A feminist glaciology framework for global environmental change research. *Progress in Human Geography*, *40*(6), 770–793. https://doi.org/10.1177/0309132515623368

Chellman, N. J., Pederson, G. T., Lee, C. M., McWethy, D. B., Puseman, K., Stone, J. R., et al. (2021). High elevation ice patch documents Holocene climate variability in the northern Rocky Mountains. *Quaternary Science Advances*, *3*, 100021. https://doi.org/10.1016/j.qsa.2020.100021

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., et al. (2013). Long-term climate change: Projections, commitments and irreversibility. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Corson, T. W., Hawkins, S. M., Sanders, E., Byram, J., Cruz, L., Olson, J., et al. (2020). Building a virtual summer research experience in cancer for high school and early undergraduate students: Lessons from the COVID-19 pandemic. *Preprint via bioRxiv*. https://doi.org/10.1101/2020.11.23.393967

Crawford, A., Stroeve, J., Smith, A., & Jahn, A. (2021). Arctic open-water periods are projected to lengthen dramatically by 2100. *Communications Earth & Environment*, *2*(1), 1–10. https://doi.org/10.1038/s43247-021-00183-x

Dutt, K. (2021). Addressing racism through ownership. *Nature Geoscience*, *14*, 58. https://doi.org/10.1038/s41561-021-00688-2

Erhardt, T., Jensen, C. M., Borovinskaya, O., & Fischer, H. (2019). Single particle characterization and total elemental concentration measurements in polar ice using continuous flow analysis-inductively coupled plasma time-of-flight mass spectrometry. *Environmental Science & Technology*, *53*(22), 13275–13283. https://doi.org/10.1021/acs.est.9b03886

Eyring, V., Bock, L., Lauer, A., Righi, M., Schlund, M., Andela, B., et al. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – An extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP. *Geoscientific Model Development*, *13*(7), 3383–3438. https://doi.org/10.5194/gmd-13-3383-2020

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Figuerola, B., Valiente, N., Barbosa, A., Brasier, M. J., Colominas-Ciuró, R., Convey, P., et al. (2021). Shifting perspectives in polar research: Global lessons on the barriers and drivers for securing academic careers in natural sciences. *Frontiers in Ecology and Evolution*, *9*, 815. https://doi.org/10.3389/fevo.2021.777009

Goldman, A. E., Emani, S. R., Pérez-Angel, L. C., Rodríguez-Ramos, J. A., & Stegen, J. C. (2021). Integrated, Coordinated, Open, and Networked (ICON) science to advance the geosciences: Introduction and synthesis of a special collection of commentary articles. *Earth and Space Science*. https://doi.org/10.1002/essoar.10508554.1

Grah, O., & Beaulieu, J. (2013). The effect of climate change on glacier ablation and baseflow support in the Nooksack River basin and implications on Pacific salmonid species protection and recovery. *Climatic Change*, *120*, 657–670. https://doi.org/10.1007/s10584-013-0747-y

Grémillet, D., Fort, J., Amélineau, F., Zakharova, E., Le Bot, T., Sala, E., & Gavrilo, M. (2015). Arctic warming: Nonlinear impacts of sea-ice and glacier melt on seabird foraging. *Global Change Biology*, *21*, 1116–1123. https://doi.org/10.1111/gcb.12811

Hanauer, D. I., Graham, M. J., Betancur, L., Bobrownicki, A., Cresawn, S. G., Garlena, R. A., et al. (2017). An inclusive Research Education Community (iREC): Impact of the SEA-PHAGES program on research outcomes and student learning. *Proceedings of the National Academy of Sciences*, *114*(51), 13531–13536. https://doi.org/10.1073/pnas.1718188115

Harris, L. A., Garza, C., Hatch, M., Parrish, J., Posselt, J., Alvarez Rosario, J. P., et al. (2021). Equitable exchange: A framework for diversity and inclusion in the geosciences. *AGU Advances*, *2*(2), e2020AV000359. https://doi.org/10.1029/2020AV000359

Hartmann, M., Blunier, T., Brügger, S. O., Schmale, J., Schwikowski, M., Vogel, A., et al. (2019). Variation of ice nucleating particles in the European Arctic over the last centuries. *Geophysical Research Letters*, *46*(7), 4007–4016. https://doi.org/10.1029/2019GL082311

Hernandez, P. R., Woodcock, A., Estrada, M., & Schultz, P. W. (2018). Undergraduate research experiences broaden diversity in the scientific workforce. *BioScience*, *68*(3), 204–211. https://doi.org/10.1093/biosci/bix163

Hoag, H. (2018). *Fieldwork in the Arctic is surprisingly costly, limiting the research done there*. Scienceinsider, news article of 18 June 2018. https://doi.org/10.1126/science.aau4941

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., et al. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), 726–731. https://doi.org/10.1038/s41586-021-03436-z

Hulbe, C. L., Wang, W., & Ommanney, S. (2010). Women in glaciology, a historical perspective. *Journal of Glaciology*, *56*(200), 944–964. https://doi.org/10.3189/002214311796406202

IGS. (2022). *The Core Values of the International Glaciological Society*. Retrieved from https://www.igsoc.org/about/corevalues.pdf

Inspiring Girls Expeditions. (2020). *Inspiring Girls Expeditions*. Retrieved from https://www.inspiringgirls.org/

Interagency Arctic Research Policy Committee (IARPC). (2018). *Principles for Conducting Research in the Arctic*. Retrieved from https://www.iarpccollaborations.org/uploads/cms/documents/principles_for_conducting_research_in_the_arctic_final_2018.pdf

IPCC. (2019). Annex I: Glossary [Weyer, N.M. (ed.)]. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P.Tignor, M. Zhai, E. Poloczanska, et al. (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge Press.

JIRP. (2021). *Juneau Icefield Research Program*. Retrieved from https://juneauicefield.org/

Johnson, M. D., Baltrus, D. A., & Gardy, J. (2020). Crowdsourcing virtual summer research opportunities to support minorities in microbiology. *Nature Microbiology*, *5*(11), 1311–1313. https://doi.org/10.1038/s41564-020-00807-6

Jouzel, J. (2013). A brief history of ice core science over the last 50 yr. *Climate of the Past*, *9*(6), 2525–2547. https://doi.org/10.5194/cp-9-2525-2013

Jung, T., Gordon, N. D., Bauer, P., Bromwich, D. H., Chevallier, M., Day, J. J., et al. (2016). Advancing polar prediction capabilities on daily to seasonal time scales. *Bulletin of the American Meteorological Society*, *97*(9), 1631–1647. https://doi.org/10.1175/BAMS-D-14-00246.1

Koenig, L., Hulbe, C., Bell, R., & Lampkin, D. (2016). Gender diversity in cryosphere science and awards. *Eos*, *97*. https://doi.org/10.1029/2016EO049577

Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, Ø., Heide-Jørgensen, M. P., & Ferguson, S. H. (2008). Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*, *18*(sp2), S97–S125. https://doi.org/10.1890/06-0546.1

Leunda, M., González-Sampériz, P., Gil-Romera, G., Bartolomé, M., Belmonte-Ribas, Á., Gómez-García, D., et al. (2019). Ice cave reveals environmental forcing of long-term Pyrenean tree line dynamics. *Journal of Ecology*, *107*(2), 814–828. https://doi.org/10.1111/1365-2745.13077

Lindsay, R., & Schweiger, A. J. (2013). *Unified Sea Ice Thickness Climate Data Record, 1947 Onward, Version 1*. NSIDC: National Snow and Ice Data Center.

Lydersen, C., Vaquie-Garcia, J., Lydersen, E., Christensen, G. N., & Kovacs, K. M. (2017). Novel terrestrial haul-out behaviour by ringed seals (*Pusa hispida*) in Svalbard, in association with harbour seals (*Phoca vitulina*). *Polar Research*, *36*(1), 1374124. https://doi.org/10.1080/17518369.2017.1374124

McConnell, J. R., Sigl, M., Plunkett, G., Burke, A., Kim, W. M., Raible, C. C., et al. (2020). Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom. *Proceedings of the National Academy of Sciences*, *117*(27), 15443–15449. https://doi.org/10.1073/pnas.2002722117

McConnell, J. R., Wilson, A. I., Stohl, A., Arienzo, M. M., Chellman, N. J., Eckhardt, S., et al. (2018). Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion during antiquity. *Proceedings of the National Academy of Sciences*, *115*(22), 5726–5731. https://doi.org/10.1073/pnas.1721818115

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., et al. (2017). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, *114*(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114

NOAA. (2021). *What is the cryosphere?* National Ocean Service Website. Retrieved from https://oceanservice.noaa.gov/facts/cryosphere.html

Notz, D., Jahn, A., Holland, M., Hunke, E., Massonnet, F., Stroeve, J., et al. (2016). The CMIP6 Sea-Ice Model Intercomparison Project (SIMIP): Understanding sea ice through climate-model simulations. *Geoscientific Model Development*, *9*(9), 3427–3446. https://doi.org/10.5194/gmd-9-3427-2016

Nowicki, S. M. J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., et al. (2016). Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. *Geoscientific Model Development*, *9*, 4521–4545. https://doi.org/10.5194/gmd-9-4521-2016

NSIDC. (2021). *Data at NSIDC*. National Snow and Ice Center. Retrieved from https://nsidc.org/data

Osmont, D., Brugger, S. O., Gilgen, A., Weber, H., Sigl, M., Modini, R. L., et al. (2020). Tracing devastating fires in Portugal to a snow archive in the Swiss Alps: A case study. *The Cryosphere*, *14*(11), 3731–3745. https://doi.org/10.5194/tc-14-3731-2020

Pagano, A. M., Durner, G. M., Rode, K. D., Atwood, T. C., Atkinson, S. N., Peacock, E., et al. (2018). High-energy, high-fat lifestyle challenges an Arctic apex predator, the polar bear. *Science*, *359*(6375), 568–572. https://doi.org/10.1126/science.aan8677

Pierszalowski, S., Vue, R., & Bouwma-Gearhart, J. (2018). Overcoming barriers in access to high quality education after matriculation: Promoting strategies and tactics for engagement of underrepresented groups in undergraduate research via institutional diversity action plans. *Journal of STEM Education*, *19*(1). Retrieved from https://www.learntechlib.org/p/182980/

Pilø, L. H., Barrett, J. H., Eiken, T., Finstad, E., Grønning, S., Post-Melbye, J. R., et al. (2021). Interpreting archaeological site-formation processes at a mountain ice patch: A case study from Langfonne, Norway. *The Holocene*, *31*(3), 469–482. https://doi.org/10.1177/0959683620972775

Ponsoni, L., Gupta, M., Sterlin, J., Massonnet, F., Fichefet, T., Hinrichs, C., et al. (2021). Deliverable no. 2.5 final report on model developments and their evaluation in coupled mode. *Zenodo*. https://doi.org/10.5281/zenodo.4916934

10.1029/2021EA002111

Ponsoni, L., Massonnet, F., Docquier, D., VanAchter, G., & Fichefet, T. (2020). Statistical predictability of the Arctic sea ice volume anomaly: Identifying predictors and optimal sampling locations. *The Cryosphere*, *14*, 2409–2428. https://doi.org/10.5194/tc-14-2409-2020

Pope, A., Rees, W. G., Fox, A. J., & Fleming, A. (2014). Open access data in polar and cryospheric remote sensing. *Remote Sensing*, *6*(7), 6183–6220. https://doi.org/10.3390/rs6076183

Richter-Menge, J., Druckenmiller, M. L., & Jeffries, M. (2019). *Arctic Report Card 2019*. NOAA Arctic Program. Retrieved from https://www.arctic.noaa.gov/Report-Card

Schweiger, A. J., Wood, K. R., & Zhang, J. (2019). Arctic Sea Ice volume variability over 1901–2010: A model-based reconstruction. *Journal of Climate*, *32*(15), 4731–4752. https://doi.org/10.1175/JCLI-D-19-0008.1

Settles, I. H., Brassel, S. T., Soranno, P. A., Cheruvelil, K. S., Montgomery, G. M., & Elliott, K. C. (2019). Team climate mediates the effect of diversity on environmental science team satisfaction and data sharing. *PLoS One*, *14*(7), e0219196. https://doi.org/10.1371/journal.pone.0219196

Smith, D. M., Screen, J. A., Deser, C., Cohen, J., Fyfe, J. C., García-Serrano, J., et al. (2019). The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: Investigating the causes and consequences of polar amplification. *Geoscientific Model Development*, *12*(3), 1139–1164. https://doi.org/10.5194/gmd-12-1139-2019

Spahni, R., Chappellaz, J., Stocker, T. F., Loulergue, L., Hausammann, G., Kawamura, K., et al. (2005). Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science*, *310*(5752), 1317–1321. https://doi.org/10.1126/science.1120132

Stokes, A., Feig, A. D., Atchison, C. L., & Gilley, B. (2019). Making geoscience fieldwork inclusive and accessible for students with disabilities. *Geosphere*, *15*(6), 1809–1825. https://doi.org/10.1130/GES02006.1

Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., et al. (2006). The Greenland ice core chronology 2005, 15–42 ka. Part 2: Comparison to other records. *Quaternary Science Reviews*, *25*(23–24), 3258–3267. https://doi.org/10.1016/j.quascirev.2006.08.003

Vergara, W., Deeb, A., Valencia, A., Bradley, R., Francou, B., Zarzar, A., et al. (2007). Economic impacts of rapid glacier retreat in the Andes. *Eos, Transactions American Geophysical Union*, *88*(25), 261–264. https://doi.org/10.1029/2007EO250001

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 1–9. https://doi.org/10.1038/sdata.2016.18

Womack, V. Y., Thakore, B. K., Wood, C. V., Jewett, D. C., Jones, R. F., Ingram, S. L., et al. (2020). The aspet mentoring network: Enhancing diversity and inclusion through career coaching groups within a scientific society. *CBE-Life Sciences Education*, *19*(3), ar29. https://doi.org/10.1187/cbe.19-10-0195