Paleoclimatology and Paleoceanography Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

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Key Points:

Open science and global collaboration increase networking opportunities, data availability, and quality of scientific outcomes.

ICON principles support inclusivity and diversity ultimately resulting in increased and quicker uptake of scientific outcomes.

ICON practices are well established in large-scale international collaborations, but coordinated data and sampling standards are needed.

Abstract

This article is composed of three independent commentaries about the state of ICON principles (Goldman et al., 2021) in the AGU section Paleoclimatology and Paleoceanography (P&P), and a discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: (Section 2) Global collaboration, technology transfer and application, reproducibility, and data sharing and infrastructure; (Section 3) Local knowledge, global gain: improving interactions within the scientific community and with locals, indigenous communities, stakeholders, and the public; (Section 4) Field, experimental, remote sensing, and real-time data research and application. P&P projects can better include ICON principles by directly incorporating them into research proposals. A promising way to overcome the challenges of interdisciplinarity and integration is to foster networking, which will advance our research discipline through the application of ICON.

Plain Language Summary

Paleoceanography and Paleoclimatology seeks to reveal past changes in the oceans and the climate, to help us better understand how Earth systems work.

Traditionally, it has a strong focus on international networks and cooperation and we have accomplished many international projects. However, we are still facing some major challenges to achieve equity among researchers and science questions. In this article we discuss the current state, issues and solutions from three different perspectives: (1) data structure problems and data sharing issues, (2) relationships between research groups with different levels of knowledge, cultural aspects and their interaction with local communities in fieldwork, and (3) utilization of data, instrument sharing, promotion of networking, and effective communication with the public to make our research as inclusive and visible as possible. Actions aimed at ICON could be further promoted by research programs, governments, and scientists via integration of cooperation strategies into research projects.

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.

Paleoceanography and Paleoclimatology (P&P) is driven by global collaboration in interdisciplinary and multicultural networks. Integration of diverse expertise in climate physics, oceanography, statistics, biology, ecology, numerical modeling, and many other subjects is important for the comprehensive development, analysis, and interpretation of paleorecords. In comparison to other fields, P&P is particularly multidisciplinary and is often conducted through far-reaching multinational research cooperation. Although ICON practices are usually well established in P&P, they depend on the scale and collaborative effort of research projects and their leaders. In this article, we examine the current state of ICON from three different perspectives.

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

A prevailing strategy to overcome the challenges of interdisciplinarity and *Integration* is to foster networking among career levels. Improving feedback mechanisms whereby early-career researchers (ECRs) add strength and perspective together with the experience of more established scientists may also enhance self-sustainability of ICON principles in the long term. Global coverage of this practice is partly hindered by geopolitical imbalance, emphasizing the need for community efforts to engage in ICON science internationally. Further, the number of ECRs open to travel and work internationally far exceeds the number of opportunities available, but full mobility potential has not yet been achieved, and such opportunities are simply not possible for everyone. Challenges here include limited training investments, funding constraints, political barriers and, most recently, travel and laboratory restrictions associated with the COVID-19 pandemic. For some sub-areas of P&P (e.g. modelling and big data analysis), these exchanges can often be carried out remotely. This presents an opportunity to improve *Networked* approaches, whereby individuals or groups strategically contribute products and data keeping in mind goals of integration and synthesis among the community.

Community, institutional, and personal benefits to embracing an *Open* research culture are clear, but global inequities in terms of infrastructure and investment remain. These inequities limit our community's capacity to fully realize its intellectual and impact potential. There are various ways of achieving this, with an aim of rebalancing known inequity, including establishing requirements for data and sample accessibility for publication acceptance, global-scale support for collaborative networking and technology transfer, and cross-disciplinary collaboration. This would ensure researchers, especially ECRs, are able to access, for example, modern analytical equipment without financial or personal barriers. Such an initiative would require strong C*oordination*, but the benefits to paleo-science would be significant.

The long-term stability of many paleo archives enables future reuse as new technologies develop. Physical samples collected decades or even centuries ago can have potentially significant resource value (Amand et al, 2020). Here, challenges associated with sample discovery and access are a primary concern, further confounded by potential incompatibility in sample preparation between measurements (e.g., destructive analyses), at times preventing state-of-the-art analyses and limiting the full potential for scientific advances. This highlights the importance of detailed metadata for physical samples, and the usefulness of standardized guidelines to allow between-sample comparisons. Allowing for flexibility in best practice approaches will help ensure they are able to respond to, and keep pace with, technological innovation. Archiving libraries and cataloging physical samples in online databases, such as the International Geo Sample Number (IGSN) database, provides another avenue to strengthen the *Coordinated, Open*, and *Networked* qualities of P&P science.

Many paleo records created before the advent of online databases, for example, have not been digitized ("dark data"). Today, numerous data repositories and database communities are available, such as PANGAEA (https://www.pangaea.de), Neotoma Paleoecology Database (NEOTOMA; https://www.neotomadb.org), National Centers for Environmental Information (NCEI; https://www.ncei.noaa.gov), Past Global Changes Databases (PAGES; https://www.pastglobalchanges.org/), and other institutional repositories. These are endeavors undertaken by multiple researchers in the field, often driven by ECRs, to increase findability and accessibility of data (Kaushal et al., 2021).

A significant challenge for P&P data *Integration* and *Coordination*, lies with the fact that paleorecords represent unique materials (e.g., corals, ice, sediments), measurements (e.g., elemental ratios, density, layer width), geographic ranges (e.g., local, regional, global), temporal resolutions (e.g., annual, decadal, millennial), and temporal spans (e.g., geologic periods, epochs, ages). While it has become common practice to make newly produced paleoclimate datasets publicly available, researchers seeking to interpret and synthesize such data frequently encounter inconsistent use of terminology, data formats, and other details (Emile-Geay and Eshleman, 2013). Evolving a common and standard language among paleodata producers and users has been a central goal of recent community-wide efforts (Khider et al., 2019, Hollis et al., 2019). Many projects are already underway to improve paleo data production, preservation, and interoperability that complement the ICON approach. For example, the Linked Earth project pursues ICON principles through its goals to "enable the curation of publicly-accessible databases by paleoclimate experts "and foster the development of standards, so paleoclimate data are easier to analyze, share, and re-use." Many other initiatives also exist (e.g. EarthCube; C4P, ELC, ePANDDA, PBOT). The development of a clear and unified data dissemination format, such as GeoJSON or LiPD, can increase the efficiency of data use and collaboration between groups. Currently, while much of the numerical modeling community uses NetCDF and Zarr formats, observational data is often preserved in TAB-delimited text files. Even if a globally unified format is not possible, the development of more comprehensive tools and associated training opportunities would enhance collaboration and research efficiency among different groups.

Ideally, the community can move toward the following advancements to increase Integration and *Coordination* through (i) creation of standardized dataset formats, (ii) peer review of datasets, (iii) digital object identifiers (DOIs) that provide credit to data-contributors, data-reviewers, and database creators, (iv) nesting of multiple databases in database communities that engage in conversations on standardized terms and units across P & P datasets, and can further apply these progressive changes, and (v) further development of Google Dataset Search capability to track dataset citations. More joint efforts such as PAGES are helpful to develop and disseminate such advancements as best practices. This will enhance broader scientific progress and provide co-benefits on a personal level, such as wider professional networks and greater research exposure (Popkin, 2019). An increase in the use of preprint servers (e.g. ESSOAr, EarthArXiv) and open peer review for research, highlights another recent shift in the acceptance of open science. Such coordinated efforts can be considered one of the best examples of low risk/investment and high reward/benefit for the P&P community.

3. Local knowledge, global gain: improving interactions within the scientific community and with locals, indigenous communities, stakeholders, and the public

Research in P&P relies on fieldwork and incorporates the expertise of scientists from many disciplines. Although current fieldwork practices are well established with inclusive ICON science, in this section we focused on one of the issues that we need to address to improve *Integration* and *Coordination*. P&P fieldwork has historically excluded local communities and failed to integrate their knowledge through the practice of "parachute science," whereby international scientists generally from a country with higher economic level conduct field studies in another country without local engagement and without addressing local research needs (Stefanoudis et al., 2021).

However, the most effective P&P fieldwork benefits from and often relies on local and indigenous knowledge and expertise. Actively collaborating with local scientists and nonscientists to contribute to local, preferably urgent, research needs is critical. An example of such efforts that improve *Networked* science is described by Fukuyo et al. (2020; 2021). In this collaborative project, Japanese and Australian researchers conducted paleoclimate fieldwork in Tonga. While there, the research team met with local leaders and learned they did not have an effective system to secure groundwater for domestic use. After learning the communities' needs, the researchers surveyed the local freshwater distribution system and contacted the Japanese embassy to secure funding for future work. Research conducted in this manner is a promising first step towards a more inclusive and reciprocal model of fieldwork that respects and integrates indigenous and local knowledge and enriches communities. This example shows how including local communities as stakeholders in the project planning stage is an effective way to perform ICON principles in P&P science.

Building inclusive collaborations is an opportunity for P&P to *Integrate* across traditional disciplines and expand the *Network* of those that contribute to and benefit from research beyond the scientific community. However, these opportunities come with significant challenges. Developing the relationships necessary to avoid parachute science takes time, and requires the research team to adopt methodologies and pursue outcomes that may not fit the mold of conventional P&P research. Funding structures on one-to-three-year timelines are not set up to facilitate and recognize research conducted in this manner, nor are scientists typically trained to do this effectively. True collaboration requires researchers to co-develop mutually beneficial projects with the local community, aligning outcomes with both of their goals (e.g., working to develop a new record of sea level change and identifying a new groundwater source for the local community). Further, respecting a community's ownership of their data and their right to determine how and for what their data are used (i.e., Carroll et al., 2020), may come into conflict with the FAIR (findable, accessible, interoperable, reusable) principles of *Open* science. Accompanying these challenges, however, are exciting opportunities to integrate indigenous and local knowledge into P&P, ensuring research is responsive to societal needs.

Fortunately, regular media attention and publicity of climate change and human impact ensures public visibility of P&P research. Therefore, ICON principles represent critical efforts to raise awareness, convey the importance of science in tackling challenges, and interact with stakeholders and the wider scientific and public community. Social media is an increasingly important vehicle for disseminating such information. An example of accessible science in P&P is the International Ocean Discovery Program (IODP; https://www.iodp.org/), which has been facilitating better collaboration and connections worldwide, inclusiveness, diversity, sample and data sharing, scientific publication and outreach to the wider public. In doing so, IODP seeks to generate the most value and impact from the research undertaken. However, is this enough? IODP is an international effort of a few countries and research contributions and participation are relative to their financial contributions, which leads to a global participation imbalance. There therefore remains great potential to expand the IODP network to include more countries, and local or indigenous peoples.

Another example of ICON and public/stakeholder inclusion is the PAGES network, an open cooperation and inclusive environment where diversity is highly valued. Funding and investment of this successful initiative is provided by the Swiss Academy of Sciences, the Chinese Academy of Sciences, the University of Bern (Switzerland), and formerly the U.S. and Swiss National Science Foundations. PAGES facilitates inclusive and worldwide research cooperation, networking, and open science, with over 5,000 scientists from more than 125 countries independent of origin, nationality, background, research area, and career stage. Another PAGES initiative is the support of ECRs to actively contribute to working groups, with dedicated funding for ECRs and other underrepresented researchers to attend conferences and workshops. These actions help facilitate inclusiveness and diversity, improving *Networked* components of P&P. With interconnected, long-term networks such as PAGES, it also becomes possible to provide regional funding, allowing regional representatives to guide decisions on where the funding is most relevant in-line with the organization's mandate.

Traditional scientific literature is generally produced for the scientific community, necessitating outreach efforts to convey new scientific knowledge to the wider public, policy makers, and other stakeholders. However, even among public and private scientific institutions and stakeholder communities, publishing and access fees represent a common barrier to supporting *Open* science in P&P. Many established journals supported by the European Geoscience Union and American Geophysical Union are innovative leaders in open access publishing, including innovations such as open peer-review, important to scientists and other stakeholders including policy makers. Unfortunately, many high-impact and high-visibility journals charge what for some scientists may represent prohibitively high open access and article processing fees, contributing to scientific publications being placed behind paywalls. Collaboration between governments and academic institutions on a wider scale can help mitigate this through negotiations with publishers and promotion of supplementary open access channels (i.e., 'Green Open Access').

Activities promoting ICON often require some extra effort from scientists and institutions. Thus, enacting such principles can be a challenge for scientists and principal investigators due to insufficient support, whereby it is considered as a possible "distraction" from traditional metrics for core job duties or even perceived as threatening by giving away control of data, for example, prior to publication. The value of ICON principles to improving the P&P community, however, outweighs potential pitfalls and encourages a more productive scientific structure that is more useful in the long term. Better incorporation of ICON in project and program design and increased support of such efforts by governments and funding agencies is needed, so that aspects like data sharing, collaboration with local and or indigenous communities, and outreach can generate a much higher impact on society.

4. Field, experimental, remote sensing, and real-time data research and application

ICON practices are usually well established where large-scale international collaborations are a prerequisite for sampling, field/laboratory methods, and data sharing, such as the international Geotraces program that monitors biogeochemical parameters of modern ocean waters. Modern data are required for: (1) proxy development, (2) calibration, and (3) robust modern baselines to which paleo data are compared. Satellite and monitored data are made openly accessible and can be leveraged through platforms like the Global Network of Isotopes in Precipitation, National Centers for Environmental Information (NCEI), and the World Meteorological Organization's KNMI Climate Explorer. P&P data archives (e.g. NEOTOMA, PANGAEA) can be accessed by individual research groups, but ICON initiatives are typically led by the archive-specific community. The National Lacustrine Core Facility (LacCore), a U.S. NSF-supported facility, provides infrastructure and support for sedimentary coring projects.

Insufficient comparison between paleoproxies and modelling studies limits our ability to *Integrate* and draw conclusions from records of past changes because of issues of scale (both spatial and temporal), variation in local processes, sampling strategies and methodologies, and a paucity of FAIR data. Sample collection is often limited by the costs of instrumentation, equipment, and fieldwork, or prohibited by difficulty in site access. Establishing regional models and baselines, perhaps through modern day proxy (or "ground truthing") studies would be useful in comparing paleo studies across sites. This would require active *Networking* between the international scientific community, local scientific teams, and local communities. Collected samples are sometimes available to the P&P community in a limited way (e.g. LacCore), which helps address some of the issues around physical site access and costs of field sampling. *Networking* can also facilitate shared instrument usage for analyses, which further improves access to P&P science. Data storage in open digital repositories is often voluntary, only for final datasets, and not enforced. An open-access FAIR database of data and applied methodologies would facilitate *Integrated* analysis and synthesis of data while leveraging existing networks and expanding ICON practices to smaller or minimally funded projects and alternate interpretations.

The adoption of open science, FAIR, and ICON principles can be an important consideration at a project's onset, and it is summarized in Figure 1. While efforts are underway to develop publicly-available proxy-specific databases, many databases (e.g., Speleothem Isotope Synthesis and AnaLysis database) often require data stewards to perform time-intensive reformatting and reconfiguring to match database-specific standards, as submitted data can be inconsistent in submission format. While organizations may have consistent standards, these are rarely distributed beyond immediate collaborators or resource users. The P&P community would benefit from more *Coordination* to develop and distribute comprehensive "gold standards" for modern field collection, data processing, and data management schemes achievable by researchers on limited budgets. It would be helpful if these ICON standards could be implemented across sub-disciplines and irrespective of the region of work so that researchers can develop cross-proxy correlations. Data schemes can be developed by creating and working with a network of scientists in multiple disciplines and regions to identify FAIR data standards, while recognizing that one-size-fits-all does not fit all sub-disciplines or regions.

Figure 1. Open science, Findable, Accessible, Interoperable, Reusable

(FAIR) and Integrated, Coordinated, Open, Networked (ICON) principles that could be applied to the Paleoceanography and Paleoclimatology research approach.

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