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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

Key Points:

- Studying global environmental change can benefit from application of Integrated, Coordinated, Open, Networked (ICON) principles
- ICON principles provide guidance for innovations in field measurement strategies and remote sensing techniques
- Enhanced usability of climate models poses challenges and opportunities for ICON science

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Global Environmental Change Perspectives on Integrated, Coordinated, Open, and 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/10.1029/2021eo153180) in Global Environmental Change and discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: (Section 2) Field, experimental, remote sensing, and real-time data research and application; (Section 3) Earth system modeling. In Section 2 we stress the inherently integrated nature of global environmental change, which necessitates an integrated approach for the planning, execution and analysis of measurement campaigns, while highlighting opportunities for wider adoption of the other ICON principles. In Section 3 the highly integrated and networked nature of Earth system model development is discussed, with suggestions for how to increase openness and coordination to enhance model application by end-user and stakeholder communities.

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 (Goldman et al., 2022). In this commentary, we look at the current status, challenges, and opportunities related to ICON science in field, experimental, remote sensing, and real-time data research and application, and multiscale modeling (Earth system modeling) in Global Environmental Change sciences. As in the other commentaries of the collection of ICON articles (e.g., Belem et al., 2022; Dwivedi et al., 2022), we have kept these sections largely independent, but we end the commentary with a brief overall concluding section.

2. Field, Experimental, Remote Sensing, and Real-Time Data Research and Application

2.1. Current Status

Studying global environmental change requires a multidisciplinary approach, because of the feedback mechanisms between atmosphere, biosphere, soils and oceans that we need to understand (e.g., Heimann & Reichstein, 2008). In addition, there are entanglements between nature and human dimensions. Hence, feedback mechanisms are not only present at the natural level, but at the nature-human complex system level (Sinclair et al., 2017). Acknowledging these complex interactions, we conclude that studying global environmental change requires an integrated approach (the "I" in ICON). Better understanding these feedbacks and interlinks will allow the community to address "big questions" which have the potential for wider societal significance.

More specifically, in the context of field experiments and remote sensing, integration is of great importance. When it comes to remote sensing, cross-validation through field work is a very sensitive and important topic. For instance, in humanities and social sciences (above all in historical ecology, human geography, and archeology), methods are combined for a better investigation of long-term environmental dynamics. In these disciplines field work plays a crucial role for validating the evidence coming from computer-based analysis and to further propose improvements to analysis techniques and methods (Gillings et al., 2020; National Research Council, 1997; Swetnam et al., 1999). This translates to other fields within the domain of global environmental change. For instance, the use of satellite data for studying changes in ecosystems or soils requires validation against local measurements

(Buitink et al., 2020; Koren et al., 2018; Mengistu et al., 2021). We see integration of remotely sensed data and field data as a necessity, and consider these data streams with varying spatial scales as complementary to each other.

So far, we have put most emphasis on the integration, as this is a fundamental characteristic for global environmental change. We now consider the remaining aspects of ICON related to field measurements and remote sensing observations. Coordination (the "C" in ICON) is essential, as studying global environmental change requires data from different groups and synthesizing these data streams is most effective when these data are collected, processed, analyzed, and shared in a standardized way. Examples of coordination of measurements in the field of global environmental change are the standardized way of reporting fluxes and meteorological observations for eddy covariance sites in the FLUXNET network (Pastorello et al., 2020) and the concentration of atmospheric trace gases in ObsPack format (Masarie et al., 2014). In addition, models are important tools for supporting measurements in the context of global environmental change, and the coordination of model code is supported by the use of conventions (e.g., the PEP-8 Style Guide for Python Code), the use of version control software such as git and svn for referencing model code (e.g., Koren et al., 2019; Vilà-Guerau de Arellano et al., 2019) and coordination of model output can be achieved by the use of netCDF file architecture and implementation of Climate and Forecast (CF) metadata conventions (https://cfconventions.org/).

Open data sharing (the "O" in ICON), is becoming increasingly important and is facilitated by dedicated data platforms (e.g., https://www.pangaea.de/, which offers long-term data storage and provides doi's for easy access and referencing) and scientific data journals. Finally, we note that research in global environmental change is evolving toward the networked approach (the "N" in ICON). Examples are preprint servers (e.g., the Earth and Space Science Open Archive (ESSOAr), which is supported by AGU and several other societies in the field of global environmental change science, and the EarthArXiv platform, i.e., supported by academic institutions and not affiliated with societies or publishers.) that support discussion between researchers before studies are formally closed by a publication. Taken together, the ICON principles allow the community to perform detailed studies that go beyond a single measurement site or instrument, and potentially increase the impact of their research.

2.2. Challenges

ICON implementation brings some challenges as well, when it comes to field, experimental, remote sensing, and real-time data research and their applications in global environmental change.

A first limitation is represented by the difficulties to develop approaches that allow to bridge and integrate different spatial and temporal scales, which could lead to a more integrated and holistic understanding of environmental change. Many scholars remain stuck in their disciplinary boundaries, by focusing only on the study of specific aspects of certain phenomena or dynamics, while missing to see them as embedded in more complex systems. Nonetheless, the study of global environmental change requires a more integrated approach and long-term observational records, in order to identify significant trends compared to both variability and persistence dynamics. These long-term changes cannot be totally understood if contextualized only in the short term (Lane, 2019), whereas a multi-scalar approach allows us to look at both long and shorter term time scales. The same is true for spatial scales: we need to be able to switch between different spatial scales which coexist at the same time (Crumley, 2019). This could be possible if we interpret the evidence coming from remote sensing with cross-disciplinary conceptual frameworks brought by the Integration of spatial thinking into the social sciences and humanities (Goodchild & Janelle, 2010).

Another challenge is the development of more Integrated approaches at the science-society interface, co-developed with the wider community (Networked) which is going to benefit from their implementation (as, for instance, in the case of remote sensing applications for site management and/or policy development) (Mauser et al., 2013; Pricope et al., 2019). The main challenge in that direction is represented by the difficulty to fully integrate other worldviews and knowledge into (Western) scientific perspectives. In other words, how different epistemologies (ways of knowing) could coexist and be integrated, in order to formulate adequate research questions addressing real needs (Wright et al., 2019).

2.3. Opportunities

More fully implementing ICON approaches would provide ample exciting opportunities in the study of global environmental change using field, experimental, and remote sensing techniques. First, the developments that are made in different sub-disciplines (e.g., atmospheric sciences or oceanic sciences) can result in new insights into the Earth system when these are combined in an integrated manner. Evidently this is most likely to be achieved through interdisciplinary environmental change research, as well as communication and networked collaboration between specialists in different disciplines. Further, using coordinated methodological approaches during developments in field and experimental data collection techniques will make data more consistent, and thus more likely to be reused if also openly available.

Second, the rapid development of satellites will drastically increase our capacity to monitor the state of the Earth and contribute to a better understanding of the relevant processes. More specifically, the launch of several geostationary satellites can revolutionize our understanding of different fields (e.g., air quality, Judd et al., 2018, and the carbon cycle, Moore et al., 2018) because of the ability to diagnose sub-diurnal variability for different regions on Earth. Developments in remote sensing clearly give us the ability to generate data at greater scales and at ever-increasing spatial resolution. Making remote sensing data findable, accessible, interoperable and reusable (FAIR) whenever possible, as included in the ICON framework, is an opportunity to get the most from these data through their contribution to multiple scientific projects.

Third, implementing the integrated aspect of ICON presents the opportunity to deepen our understanding of anthropogenic influence in shaping the environment. This is particularly relevant when considering those environments with a more explicit nature-society interface, for example, through using this improved understanding to inform policy decisions and environmental management strategies. This opportunity will be realized most effectively through efficient and open communication, between scientific teams of different disciplines and areas of expertise, but also between the scientific community and the public, including policymakers.

3. Earth System Modeling

3.1. Current Status

Constructing a model of the complex Earth system requires a highly collaborative, cross-disciplinary effort. An adequate representation of this complex system must describe the vast network of interacting processes and objects within the atmosphere, ocean, land surface, cryosphere, and biological and human systems. Contemporary coupled models are made up of multiple models, each of which captures processes from one of these key components of the complex Earth system. Each one of these components is itself vastly complex, requiring a diversity of disciplinary expertise to inform its development (Danabasoglu & Lamarque, 2021). For example, the land component of an Earth system model represents rivers, glaciers, permafrost, vegetation, land use, and even detailed elements of agricultural production (Gettelman & Rood, 2016). Representing these features of the land surface and their interactions requires the integration of knowledge from hydrologists, glaciologists, ecologists and physical and social geographers. The practice of contemporary model development, and its inherently collaborative interdisciplinarity makes it exemplary of the integrated nature of ICON science.

A particularly salient example of integrated model development can be seen in the case of the Community Earth System Model (CESM; Hurrell et al., 2013) which is based out of the National Center for Atmospheric Research (NCAR), with the first version being developed in 1983. Other community modeling efforts have recently been implemented, such as with EC-Earth out of European Centre for Medium-Range Weather Forecasts (ECMWF), which brings together institutions across a dozen European countries to collaborate on the construction of a complex model. Both these models are examples of open and networked model development, with the model code being open source for the wider community. The long-standing CESM modeling effort features input and research from individuals at the NCAR, universities, and both national and international institutions (Danabasoglu & Lamarque, 2021). The community is represented by a collection of working groups, each of which is involved in the development of a component of the coupled model, and each of which has the ability to make decisions about how the model is developed in terms of their collective research and representational priorities, within the emergent empirical constraints of the system (Hurrell et al., 2013). Inclusion of atypical disciplines in model development practices—such as paleoclimatology—have the benefits of leading to the identification of model errors that would go otherwise unnoticed if the model was not evaluated by disciplines requiring out of sample experiments (Zhu et al., 2021).

In the past two decades, model evaluation practices have advanced to become more integrated, coordinated, open and networked, as is evident in the case of the Coupled Model Intercomparison Project (CMIP; Meehl et al., 2014). CMIP is a collective, cross-institutional program aimed at developing an understanding of the climate through a multi-model context. Within CMIP there are the standard Diagnostic, Evaluation and Characterization of Klima (DECK) experiments, which recently involved over 40 different institutionally developed models (Eyring, Bony, et al., 2016). These standard experiments are run on each individual model, collected, and compared, with the multi-model output data made publicly available for community use. There are also more specific MIPs, such as the comparison project focused on evaluating the behavior of ocean models (Griffies et al., 2016), or the ScenarioMIP, the latter of which also included around 40 unique models in the Tier 1 experiments (Tebaldi et al., 2021). Designs for individual MIPs are responsive to a diversity of science objectives within the community including understanding climate processes and modeling for mitigation, impact, adaptation, and vulnerability (O'Neill et al., 2020). This requires, within individual MIPs, not only cross-institutional coordination, but integration and collaboration across disciplines during the design of experiments. This standardization of experiments and metrics across the modeling groups for these comparative purposes is a prime example of a highly coordinated and networked effort. This has the scientific benefits of allowing the collective modeling community opportunities to diagnose sources of model error and understand sources of model behavior and bias and the divergence of that behavior across individual models (Eyring, Gleckler, et al., 2016).

3.2. Challenges

The CMIP and more specific MIP efforts are impressive examples of ICON science within climate and Earth system modeling. However, there are certain practices that are in need of improvement to be more consistent with the principles of ICON science. Outside of this international effort, individual modeling centers are free to choose the data they use to constrain and validate their model, as well as metrics for tuning (Schmidt et al., 2017). So, for less significant processes and metrics, there can be a lack of coordination and synthesis in evaluations of individual model skill (Morrison, 2021).

While the researchers involved in the development of a unique model engage in a coordinated effort to construct a single representation of the target system, one area where development is somewhat inconsistent with ICON science is with respect to coordination during development across different modeling centers. While there a few efforts to collectively determine the future of model development—for example within Bretherton et al. (2012) and Arias et al. (2021)—and therefore better coordinate and synthesize how Earth system models are developed cross-institutionally, it is not clear how much coordination there should be, as there are negative consequences to too much coordination. Too much coordination and networking may limit the diversity of approaches that can be implemented for development, as well as place unnecessary constraints on prioritization of research questions and projects. When engaged in the modeling of a complex system it is not possible to adequately represent all the important components with the utmost fidelity—lack of knowledge and practical constraints like computing power force tradeoffs. However, diversification of research interests and priorities allows for different representations to be produced, and for the existence of a diversity of models of the same target system, each of which can be optimized for different purposes (Morrison, 2021).

3.3. Opportunities

Earth system model use is perhaps the main area where there are significant challenges, but also opportunities to improve practices to be more integrated, coordinated, open and networked. While products of CMIP and individual MIP runs are made available, as well as the data from institutionally specific simulations, there is little information on how to choose data from these resources to answer one's individual research question, and even less information about the limitations of certain simulations. There are efforts to inform modeling product users about how to engage with modeling simulations and data. For example, Phillips et al. (2020) developed a use sheet for researching climate variability with the CESM large ensemble, which provides guidelines for researchers on how to interpret data and best practices for using these modeling products.

Another significant example of efforts to increase openness through transparency and accessibility of modeling products is GLISA—the Great Lakes Integrated Science and Assessments project—which functions as a boundary organization between climate science and decision-making communities. A recent effort within GLISA has been an analysis of the usability of CMIP5 data for informing research concerning climate change and the Great Lakes region (Briley et al., 2021). The study found that CMIP5 models were deficient in their representation of the regional impacts of Great Lakes on the climate, creating questions for the credibility of using these modeling products for impacts and adaptation investigations. Insufficient representation of key processes and interactions needs to be communicated to the communities accessing climate model data, and efforts such as the one mentioned by GLISA can go a long way to increase the openness of data and its usage for stakeholder purposes. This can be achieved through greater networking (the "N" in ICON). However, many more efforts such as this one are needed, and greater transparency with respect to modeling deficiencies is required for optimal accessibility.

But, even if we are able to overcome challenges with making the modeling products and models themselves accessible, there are still questions of usability of models and modeling data for impacts and adaptation purposes. This is a worry that was initially brought up by Dilling and Lemos (2011) and Lemos et al. (2012), for which they called upon greater amounts of co-production with user communities to address problems with simulation and data usability (which requires practicing more "N" in ICON). Their concern was mainly the generation of modeling products that are accessible, relevant, and valuable to applied research communities. A recent example of a successful effort to enhance usability on these fronts is the Useful to Usable (U2U) project through the United States Department of Agriculture, which sought to make climate science knowledge more usable by agricultural decision-makers by involving stakeholders in knowledge generation process (Prokopy et al., 2017).

These efforts, however, are currently limited. Increasing the amounts of co-production in modeling practice will allow for the values, priorities, and needs of diverse collections of stakeholder communities to be integrated into modeling agendas and approaches. This in turn will facilitate the production of knowledge suitable for decision-making surrounding mitigation, adaptation, impacts and vulnerability at the regional and local scales. During model development, priority decisions are made about what to adequately represent for a particular set of purposes, with these purposes being determined by what is valued for the immediate research community. As a consequence, current climate models might provide better answers to questions, and represent future climate states, for those regions and communities that have development authority and can make priority decisions (Jebeile & Crucifix, 2021). If there are certain worldviews and value systems that are not represented in the model development practice, models might not be able to provide possible and adequate answers to questions for many communities and geographic regions.

Co-production (an activity that necessitates strong networking) with vulnerable and underrepresented communities and geographic regions requires greater amounts of interdisciplinarity that is non-reductive and capable of synthesizing and accepting multiple worldviews and narratives (Schipper et al., 2021). This interdisciplinarity in model development and use also requires coordination globally with adaptation and impacts researchers and the stakeholder communities they engage with. But, connecting with, and incorporating diversity of values in model development itself so that there is responsiveness to stakeholder communities remains a considerable challenge because of the institutionally insular nature of model development practices, and the embeddedness and lack of transparency with development decisions.

4. Conclusion

We described the current status, challenges, and opportunities of the ICON principles in the field of global environmental change from an experimental and modeling perspective. Overall, we conclude that a wider adoption of ICON can stimulate further scientific progress. Considering this, we call on scientific practitioners across different career stages to embrace the ICON principles and call on funding agencies, societies, publishers, and other stakeholders to facilitate this by incorporating ICON principles in their policies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this commentary.

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GK, VF, and MT authored Section 2 "Field, experimental, remote sensing, and real-time data research and application." MAM authored Section 3 "Earth system modeling."

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