BAMS Article

Best Practice Strategies for Process Studies Designed to Improve Climate Modeling

Janet Sprintall, Victoria J. Coles, Kevin A. Reed, Amy H. Butler, Gregory R. Foltz, Stephen G. Penny, and Hyodae Seo

ABSTRACT: Process studies are designed to improve our understanding of poorly described physical processes that are central to the behavior of the climate system. They typically include coordinated efforts of intensive field campaigns in the atmosphere and/or ocean to collect a carefully planned set of in situ observations. Ideally the observational portion of a process study is paired with numerical modeling efforts that lead to better representation of a poorly simulated or previously neglected physical process in operational and research models. This article provides a framework of best practices to help guide scientists in carrying out more productive, collaborative, and successful process studies. Topics include the planning and implementation of a process study and the associated web of logistical challenges; the development of focused science goals and testable hypotheses; and the importance of assembling an integrated and compatible team with a diversity of social identity, gender, career stage, and scientific background. Guidelines are also provided for scientific data management, dissemination, and stewardship. Above all, developing trust and continual communication within the science team during the field campaign and analysis phase are key for process studies. We consider a successful process study as one that ultimately will improve our quantitative understanding of the mechanisms responsible for climate variability and enhance our ability to represent them in climate models.

https://doi.org/10.1175/BAMS-D-19-0263.1
Corresponding authors: Janet Sprintall, jsprintall@ucsd.edu; Victoria J. Coles, vcoles@umces.edu; Kevin A. Reed, kevin.a.reed@stonybrook.edu; Amy H. Butler, amy.butler@noaa.gov; Gregory R. Foltz, gregory.foltz@noaa.gov; Stephen G. Penny, steve.penny@noaa.gov; Hyodae Seo, hseo@whoi.edu
In final form 8 April 2020

AFFILIATIONS: Sprintall—Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California; **Coles**—Horn Point Laboratory, University of Maryland Center for Environmental Science, Cambridge, Maryland; **Reed**—School of Marine and Atmospheric Sciences, Stony Brook University, State University of New York, Stony Brook, New York; **Butler**—NOAA Chemical Sciences Laboratory, Boulder, Colorado; **Foltz**—NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida; **Penny**—Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Physical Sciences Laboratory, Boulder, Colorado; **Seo**—Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Since the first computerized regional forecasts (Charney et al. 1950), there have been great advances in understanding crucial atmospheric and oceanic processes that improve our ability as scientists to model these interactions and their effects on the climate system. However, given the complexity of the climate system, many challenges remain. This is evidenced by lingering limitations of state-of-the-art climate models, such as systematic errors that lead to the accumulation of model biases and long-term model drift (e.g., Fox-Kemper et al. 2019). Much of the recent progress in climate model improvements has come as a direct result of concentrated "process studies" aimed at understanding the key processes in the climate system. These process studies typically include coordinated efforts between intensive field campaigns collecting a carefully planned set of in situ observations paired with modeling studies aimed at better representing either a new physical process or a poorly modeled process. Ideally, the expansion of knowledge that results from process studies improves our quantitative understanding of the mechanisms responsible for climate variability and enhances our ability to represent them in both climate and prediction models, leading to improved predictive and projection skills.

Part of the mission of the Process Study and Model Improvement (PSMI) panel of the U.S. CLIVAR program is to provide guidance on the coordination and assessment of process-oriented research (Cronin et al. 2009). This includes the development of observational campaigns that lead to improved model parameterizations of critical climate processes and better quantification of climate model uncertainties to improve climate variability prediction (https://usclivar.org/panels/psmi). As such, the PSMI panel has reviewed and provided feedback to a broad array of process studies to help foster effective strategies for implementation and coordination of those projects. This article provides a framework of best practices that have arisen from that effort to help guide scientists in carrying out more productive and collaborative process studies. A summary of the steps involved in implementing the best practices is given in Fig. 1. The primary goal of U.S. CLIVAR is to "understand the role of the ocean in observed climate variability on different time scales" (U.S. CLIVAR Scientific Steering Committee 2013). Hence, the PSMI panel is more focused on assessing oceanic and coupled atmosphere–ocean process studies, although many of the same principles outlined here may apply to atmospheric process studies. The hope is that this guide will enable the community to go beyond simply improving mechanistic understanding toward also helping develop next-generation scientists with the skills to lead process campaigns in the future and to translate process level understanding into applied climate models.

Initial steps toward fostering successful process studies

The development of focused science goals and testable hypotheses are essential to the planning and implementation of a process study. Analogous to a successful scientific proposal, a strategy for achieving these goals must be well planned prior to embarking on a proposed

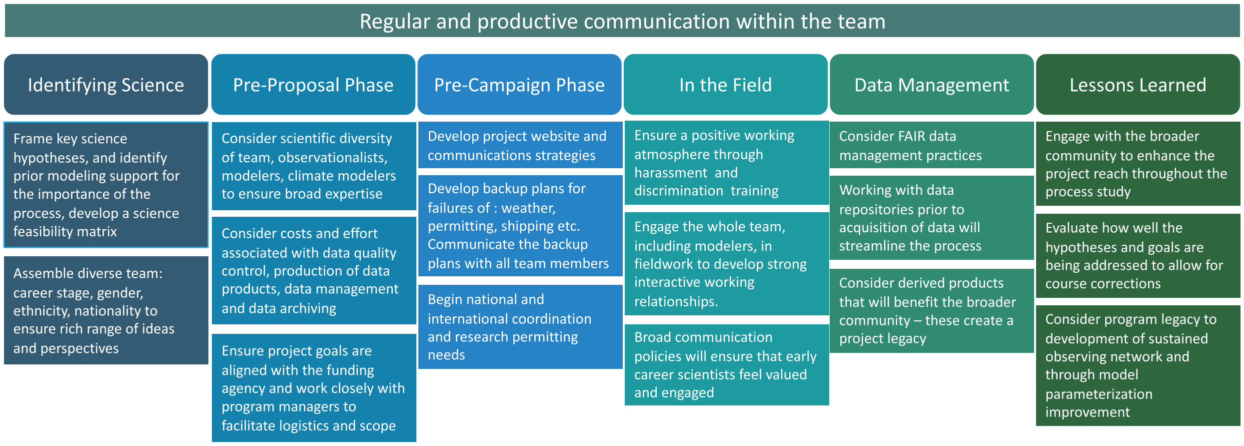

Fig. 1. Outline of steps toward the successful implementation of process studies.

process study to ensure the measurements will be sufficient to derive greater physical understanding of the process. This can be aided by the development of a science traceability matrix detailing the type of observations, as well as their required density, time scale, and accuracy, in order to meet the project goals and to determine how these goals might be implemented (Weiss et al. 2005). This step is also important for identifying whether the available technology and measurement platforms are capable of achieving the scientific objectives.

Another early planning step is focused on building an integrated and compatible participant group that should include observationalists, modelers, and theoreticians, as well as experts in data assimilation who are typically tasked with reconciling observations and numerical models in downstream applications such as operational forecasts. To enhance the success of the study, it is critical to ensure that the collaborative team is represented by diversity of social identity, gender, career stage, and scientific background. A diverse and inclusive team will foster more creative and innovative teamwork by incorporating a wider range of ideas, perspectives, and approaches needed to maximize success of the process study (e.g., McLeod et al. 1996; Smith-Doerr et al. 2017). Numerical model developers, theoreticians, and users are obvious but often overlooked groups to include in the process study team. Indeed, observational process scientists can lack the skills or knowledge to carry a parameterization from the underlying theory to its operational stage. Inclusion of a broader range of participants and their relevant skill sets can better deliver the necessary team expertise to successfully accomplish that goal.

Climate models are typically used to test and build scientific understanding of the Earth system, and it is through these models that scientists project future climate variability and change. As climate models become more comprehensive and incorporate more components of the integrated Earth system, end users of this climate knowledge will extend beyond conventional climate scientists to other scientific fields as well as government stakeholders and the general public (e.g., Motesharrei et al. 2016). Consideration of end-user groups typically comes with the assessment of which governmental or intergovernmental agencies are most aligned with the goals of the full process study participant group.

Dealing with logistical challenges

Preproposal phase. A process study requires a complex web of logistical details that can include lengthy interactions to attain permissions from government agencies. This degree of complexity often surprises scientists unfamiliar with the development and implementation of field projects. Hence it is never too soon to begin coordination of the science plan and construction of the research team. Early coordination is even more critical for international or multidisciplinary projects that might bring an additional level of complexity.

Fundamental information to help improve the observational strategy, sampling plans, and needs can be gained by integrating modelers in the fieldwork experimental design phase. This can be achieved through the use of pre–field campaign modeling and observing system simulation experiments (OSSEs) (Hoffman and Atlas 2016). Modelers could also prepare to assemble forecasts and update data assimilating models to help guide sampling during field campaigns. Incorporating modelers into the decision-making process can further cultivate an integrated awareness of the abilities and limitations of both the measurement systems and the models.

It is important that the initial team communicate and meet frequently, either in person or virtually. The objective of the meetings should be to identify gaps in the experimental design. Such concerns include consideration of timing and location in terms of logistical feasibility and science preferences, as well as pursuing additional information that might be obtained through data and/or model analysis. It is also important to identify any additional key personnel needed to accomplish the project. An initial workshop of interested parties might be useful to work through some of these issues.

There are many factors that require consideration when packaging your process study for prospective funding. Cost estimates for data quality control, production of data products, and data management should be prepared in the early stages. It may be that such associated costs need to be budgeted in the proposal. The requisite data repository should be contacted early so as to understand what data formats and metadata might be required (see "Data management practices" section). Determine which funding agencies might be most interested in your science project and work with them to understand how best to tune your proposal to better meet their requirements and the agency's mission. If a project includes international partnerships, work with funding agency managers at very early stages to ensure that international funding is coordinated within the time scale of the proposed project. An engaged funding agency representative has frequently been highlighted as key to project success in our PSMI panel reviews.

Congratulations—Your process study has been funded. What now? Once you have gotten over the initial thrill of having a process study funded it is time to get to work organizing and finalizing the field program. This phase often includes a revisit of much of what was undertaken in the preproposal phase ("Dealing with logistical challenges" section), and similarly requires frequent communication via remote and in-person meetings and workshops to better synthesize the proposed research plan. It is often useful to allocate small task teams to assume responsibility for the various tasks that need to be achieved at this stage with respect to the field campaign. This is also a good time to initiate a project website to share information and publications among the team and to help elevate the visibility of the project among the broader community.

The pre–field work phase is also a good time to develop trust and communication within the science team, which will help ensure a successful field campaign. Inevitably, delays may require reevaluation of the process study. Such delays can be caused by practical concerns such as shipping schedules, bad weather, or geopolitical issues affecting permits or safety. Delays can also be caused by scientific issues, such as the absence of the central process that is the focus of the observational field work. Ideally, these potential complications will have been considered prior to the field campaign. Backup plans should be developed in the early phases in order to leverage the available resources effectively should such delays occur. These backup plans should also include strategies for communicating the delays or changes within the project team. The plans should be coordinated and communicated in advance with all team members to ensure clarity concerning which and whose science goals will be affected in the event of such inevitable changes in experimental design.

Field work can include ship time and/or aircraft usage, so it is important to be cognizant of additional funding opportunities and application deadlines to use these facilities. Often, the schedules for these resources can be set a year or more in advance. Fieldwork and cruises in the exclusive economic zones (EEZs) of foreign nations typically involve applying for research permits and marine science research (MSR) clearances that can take an exceptional amount of time and effort. Each country has different individual requirements, and it is often the lead scientific principal investigator's job to be aware of what visas and permits are needed to conduct research within foreign EEZs. It is advantageous to identify international partners to help provide local guidance and scientific collaborations that link the team with the right local government agencies that approve MSRs within that country. A recent article (Doyle et al. 2019) describes an online white paper (Brenner et al. 2019) that provides a thorough overview of the issues, responsibilities, and key topics in planning cruises to foreign countries. The paper was produced by University–National Oceanographic Laboratory System (UNOLS) for the U.S. Academic Research Fleet, although it contains useful information to help guide any scientist in the protocols and best practices of this complex endeavor.

Task teams can be a good mechanism for achieving many of these matters. Small teams or point persons might be designated to assist in acquiring research permits, to obtain documents from cruise personnel needed by research vessels, website development, etc. At this stage, it is often also useful to discuss and form data-sharing agreements so that all participants are aware of obligations and the timetable for making both the raw and quality-controlled data available within the project and to the broader community. It is also a good idea to discuss potential paper authorship in advance so that students and early career scientists have the freedom and ability to develop their research topics without significant restriction.

Working in the field

Creating a diverse team and welcoming atmosphere. A compatible and diverse team working together in the fieldwork stage of a process study is central to carry out productive research. For the overall project team, we stress the importance of considering diversity and encouraging participation by students and early career scientists. The comradery and community that develops from the collaborative effort of collecting observations, as well as, in some cases, the shared experience of physical isolation on your "island" ship or field station, are not so easily replicated in our home office environments. Frequent scientific conversations necessarily occur among the students, technicians, and senior personnel about the experimental design of the fieldwork or interpretation of the measurements being collected. This creates a natural environment for the mentoring of young scientists, enabling them to form professional relationships that often continue long after the field phase has finished.

For many of the younger scientists it may be their first time participating in a field campaign. This can naturally be an exciting experience but also daunting, as there are many new unique situations. For example, at sea, everyone lives and works in very close quarters. It is essential that everyone who participates in the field project understands the need for a working environment that is free of harassment and discrimination. Due to inherent power structures, this is an especially important standard to be set by the project leaders. In many cases, national facilities that operate ship or aircraft have well-defined policies and procedures that have been put in place in order to prevent and respond to harassment during field work [e.g., see the UNOLS Maintaining An Environment Of Respect Aboard Ships (MERAS) Program website: https://www.unols.org/committee/special-committee-maintaining-environment-respect-aboard-ships-meras]. However, research shows that these policies are not always communicated effectively (Clancy et al. 2014). Research conducted in foreign countries, or aboard foreign vessels or aircraft may be subject to differing cultural norms. Scientists and scientific staff associated with the project, facilities, and research vessels should discuss expectations for behavior prior to the field campaign, and clearly communicate them in advance to all participants. Equity in the application of these expectations is important to a successful scientific mission. To ensure the most successful field campaign possible, all team members should be well informed of these policies through specific training sessions to actively avoid creating hostile work environments. Any occurrence of witnessed harassment should be reported for immediate resolution. Response to a harrassment issue should be carefully considered to ensure that the scientific mission of the harrassed individual is not impaired or limited. Senior investigators play a critical role in creating a productive work environment by actively calling out the importance of the training and their intention to follow up on reported incidents. Recent studies have shown that significant efforts to address these issues, such as through sexual harassment avoidance training both prior to and during field campaigns, can lead to a more welcoming and inclusive atmosphere for all who participate, not just for the early career scientists.

While it is rarer to engage the participation of modelers (including numerical and theoretical) and data assimilation experts directly in field campaigns, there are a number of direct benefits that accrue by engaging them in fieldwork. Modelers and data assimilation researchers can be enlisted to provide forecasts (either remotely or on-site/onshore) throughout the field campaign, which helps both to optimize sampling strategy in real-time and to incorporate modelers into the decision-making process. If the modelers and data assimilation experts understand the details and uncertainties inherent in the collection of observations they can provide valuable feedback on potential gaps in the experimental design. Modelers and data assimilation experts have a good understanding of which measurements might help to improve models. Perhaps most importantly, inclusion at this stage also helps to strengthen relationships and team building that can pay off in the later stages of data analysis and model implementation.

Another key advantage of directly engaging modelers and data assimilation experts in field work lies in informing them of the challenges associated with the data collection process, the limitations and assumptions that go into the data collection process, and the precision of the data itself. Without first-hand experience with data collection, there may be a disconnect between the expectations of the modeling group and the realities of measurement uncertainties and data gaps. The reverse is also true. Modelers involved with the field campaigns can inform observationalists about the strengths and weaknesses associated with the models, such as turbulent closure parameterizations (e.g., Li et al. 2019), or constraints on the vertical resolution. Observationalists may acquire a better appreciation for the importance of specific measurements that best constrain the model parameters, the inability to constrain model solutions in the absence of sufficient reliable data, and the need to adapt entire frameworks of parameterizations as new processes are better understood (e.g., Plougonven et al. 2020).

Keep talking! While team building is a somewhat intangible outcome, in the PSMI panel assessment of multiple process studies, we find it is often central to high-quality communication between observationalists and modelers. Observationalists must feel confident that their unpublished and unvalidated data will not be misused or misattributed if provided early to modelers. Modelers must know about ancillary measurements that were perhaps not listed in the initial proposal discussions or team meetings but were collected opportunistically. These data can often be of great value to the modeling component, but only if there is a close interaction and communication between the team. Both sides must develop trust in order to be comfortable describing the inadequacies in the data collection process, unexpected features in the data, or limitations, and biases of the models. These challenges can often be the key elements that lead to breakthroughs in our understanding of a process.

Communication must remain a priority during the field campaign. Particularly when observations are ongoing around the clock, it is important that the strategies for sharing changes, problems, concerns, or key science results are widely disseminated. This dissemination may occur through the project website, an e-mail listserv, and/or cloud-based collaboration software. All team members must be aware of the communications strategy and be encouraged to engage routinely with the shared information. While it is often tempting to avoid broadcasting specific information to the entire team, it is important to recognize that all team members bring unique insights that may help in resolving an issue. Understanding and analyzing unanticipated features of the observations during key points of the field campaign may require identifying and involving different team members. One approach for avoiding gaps in resources is to maintain and perhaps expand (or reorganize) the task teams and the go-to point people identified prior to the field program (see "Congratulations—Your process study has been funded. What now?" section). Early career scientists make good co-leaders of these task teams. The process of resolving a challenge is a genuine training opportunity for junior scientists, helping them to develop management skills and reputation.

Frequent communication with junior scientists regarding strategies for response to various problems will provide a valuable learning experience. This experience can accelerate their transition into future principal investigators with the competence to organize a field program by giving them the tools necessary to reduce the risk of failure in future field campaigns. This is particularly important in an era of scarce resources.

Finally, there can be enormous value in creating cruise reports that provide a narrative of what was undertaken during the cruise, where and why. Cruise reports are often useful for providing details of unusual or unexpected events, and for understanding why cruise plans might have deviated from original sampling plans. Ideally, these should be completed by the end of the cruise and widely distributed to the whole team.

Data management practices

Data management has become a fundamental aspect of process studies, and the integration and synthesis of datasets made available to the community should be considered a priority. Most recently, guidelines for scientific data management and stewardship have been promoted as part of the "findable, accessible, interoperable, reusable" (FAIR) data principles (e.g., Wilkinson et al. 2016).

For process studies, data should be made publicly available as soon as possible at a recognized data repository in a unified and easy-to-use format, including the metadata needed to understand the measurements. Common data repositories can provide digital object identifiers (DOIs) for datasets, allowing improved citing and tracking of the data (for lists of commonly recommended repositories, see www.nature.com/sdata/policies/repositories or https://copdessdirectory.osf.io/). Contact data repositories early in the project and work with them to ensure the data meet format requirements and includes proper metadata. In addition, very large datasets could require additional funding for data management; contacting a data repository early on could allow researchers to anticipate these costs from the beginning.

Besides making the raw data available, researchers should consider what additional products the community would find most useful for assessing and validating models (e.g., gridded fields and derived variables). Such products make the data more accessible for study by many researchers and students. Additionally, efforts should be made to develop process-based metrics or diagnostics for model intercomparison and to provide open-source code to calculate these metrics (e.g., Gille et al. 2018). Although it is important that the original data and metadata are submitted to recognized public data repositories, making these additional data products available through the project website might also be useful. A website can track data usage, for example, through site registration, and can provide acknowledgment sources for the data and a list of publications using the data.

Engaging the broader community and lessons learned

As the process study begins to collect data and preliminary analyses are conducted, we recommend considering outreach efforts to the broader scientific community. Engage experts that were not part of the original research plan to add value through new analyses and so contribute to the legacy of the project and its impact over time. The broader community includes national centers for climate science and modeling as well as individual scientific users of climate models. If field campaigns were conducted in foreign EEZs, consider capacity building workshops to more closely entrain international collaborators and their students in the scientific analysis phase.

In general, the processes under study are key aspects of the climate system that may contribute to biases in global models. Communicate early results of the process study with the broader modeling community as they might add resources to evaluate or improve the representations of the specific process in their models. A successful process study will ripple out from the original team, providing useful long-term datasets and improved parameterizations that fuel advances over a much broader community.

As the process study nears the end, it is essential to recapitulate and critically reassess the initial hypotheses or goals in light of the newly acquired observations and to identify specifically what new information was gained in relation to the process of interest. This should be undertaken not only within the project team but also with the broader community. It is also important to demonstrate how these outcomes facilitated model–observation integration, improved representation of the process in numerical models or led to the novel identification of model biases. Field work can often lead to the unexpected recording of exceptional "events," but it is crucial that the observations of the more "typical" expected conditions are evaluated; otherwise, there is a risk of introducing inherent bias in the models and their parameterizations.

While a process study is typically limited in time and space, one can also consider how the outcomes of the particular study could possibly contribute to the sustained observing network. Consider the "legacy" elements of a process study for which there is a compelling case for continuity in support of the observing system beyond the field campaign. Demonstration of the lasting impact of the process study may also occur through parameterization efforts and the resulting improvements in the predictive capabilities of numerical models. These could be tangible ways not only to gauge the benefits and success of the project but also to help the community consider the need for the continued observing capability. Indeed, the principal investigators are encouraged to actively engage in communication and dialogue within the community to share their experiences, lessons learned, and challenges overcome (or not) in developing and conducting the field experiments. This dissemination of information could be in the form of webinars through U.S. CLIVAR, in-person presentations at scientific meetings, and/or short articles in popular, multidisciplinary journals. It is the PSMI panel's goal to facilitate the exchange of these insights and ideas gained from process studies within the community so that new process studies can more effectively achieve their goals and maximize their impacts.

Acknowledgments. We gratefully acknowledge U.S. CLIVAR for supporting the PSMI panel, as well as all the principal investigators that contributed to our PSMI panel webinars. JS was inspired by participation in the process studies funded by NASA NNH18ZDA001N-OSFC and NOAA NA17OAR4310257; GF was supported by base funds to NOAA/AOML's Physical Oceanography Division; and HS was supported by NOAA NA19OAR4310376 and NA17OAR4310255.

References

Brenner, L., and Coauthors, 2019: Proposing, planning and executing logistics involved in oceanographic field operations in foreign waters and ports. UNOLS Rep., 3 pp., www.unols.org/sites/default/files/White%20Paper_Operations%20Foreign%20Ports%20and%20Foreign%20Waters.pdf.

Charney, J. G., R. Fjörtoft, and J. von Neumann, 1950: Numerical integration of the barotropic vorticity equation. *Tellus*, **2**, 237–254, https://doi.org/10.3402/tellusa.v2i4.8607.

Clancy, K. B. H., R. G. Nelson, J. N. Rutherford, and K. Hinde, 2014: Survey of academic field experiences (SAFE): Trainees report harassment and assault. *PLOS ONE*, **9**, e102172, https://doi.org/10.1371/journal.pone.0102172.

Cronin, M. F., S. Legg, and P. Zuidema, 2009: Best practices for process studies. *Bull. Amer. Meteor. Soc.*, **90**, 917–918, http://doi.org/10.1175/2009BAMS2622.1.

Doyle, A., D. J. Fornari, E. Brenner, and A. P. Teske, 2019: Strategies for conducting 21st century oceanographic research. *Eos, Trans. Amer. Geophys. Union*, **100**, https://doi.org/10.1029/2019EO115729.

Fox-Kemper, B., and Coauthors, 2019: Challenges and prospects in ocean circulation models. *Front. Mar. Sci.*, **6**, 65, https://doi.org/10.3389/fmars.2019.00065.

Gille, S., and Coauthors, 2018: Open code policy for NASA space science: A perspective from NASA-supported ocean modeling and ocean data analysis. National Academies of Sciences, Engineering, and Medicine White Paper, 5 pp., www.nap.edu/resource/25217/whitepapers/pdf/41_GilleSarahT.pdf.

Hoffman, R. N., and R. Atlas, 2016: Future observing system simulation experiments. *Bull. Amer. Meteor. Soc.*, **97**, 1601–1616, https://doi.org/10.1175/BAMS-D-15-00200.1.

Li, Q., and Coauthors, 2019: Comparing ocean surface boundary vertical mixing schemes including Langmuir turbulence. *J. Adv. Model. Earth Syst.*, **11**, 3545–3592, https://doi.org/10.1029/2019MS001810.

McLeod, P. L., S. A. Lobel, and T. H. Cox Jr., 1996: Ethnic diversity and creativity in small groups. *Small Group Res.*, **27**, 248–264, https://doi.org/10.1177/1046496496272003.

Motesharrei, S., and Coauthors, 2016: Modeling sustainability: Population, inequality, consumption, and bidirectional coupling of the Earth and human systems. *Nat. Sci. Rev.*, **3**, 470–494, https://doi.org/10.1093/nsr/nww081.

Plougonven, R., A. de la Cámara, A. Hertzog, and F. Lott, 2020: How does knowledge of atmospheric gravity waves guide their parameterizations? *Quart. J. Roy. Meteor. Soc.*, **146**, 1529–1543, https://doi.org/10.1002/qj.3732.

Smith-Doerr, L., S. N. Alegria, and T. Sacco, 2017: How diversity matters in the US science and engineering workforce: A critical review considering integration in teams, fields, and organizational contexts. *Engaging Sci. Technol. Soc.*, **3**, 139–153, https://doi.org/10.17351/ests2017.142.

U.S. CLIVAR Scientific Steering Committee, 2013: US Climate Variability & Predictability Program science plan. U.S. CLIVAR Rep. 2013-7, 82 pp.

Weiss, J. R., W. D. Smythe, and W. Lu, 2005: Science traceability. *2005 Aerospace Conf.*, Big Sky, MT, IEEE, 292–299, https://doi.org/10.1109/AERO.2005.1559323.

Wilkinson, M. D., and Coauthors, 2016: 2019: The FAIR guiding principles for scientific data management and stewardship. *Sci. Data*, **3**, 160018, https://doi.org/10.1038/sdata.2016.18.