EARTH SYSTEM SCIENCE FRONTIERS

An Early Career Perspective

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We, the Young Earth System Scientists community, describe our long-term vision for developing a holistic understanding of the Earth system.

The future of Earth system science is bright and exciting, with exponentially increasing computational power available to Earth system research (e.g., O'Neill and Steenman-Clark 2002; Ramamurthy 2006; Nativi et al. 2015; Pianosi 2014) and ever more well-educated Earth system scientists around the world.[1] This technical and social capability comes at a time when society is increasingly realizing that global change is one of the greatest challenges it faces, both now and for future generations. To adapt to this changing world, we must deepen our understanding of natural systems and how we are impacting them. Current grand scientific questions in Earth system science revolve around identified knowledge gaps that are mapped onto well-coordinated research programs within existing World Meteorological Organization (WMO) research programs (Brasseur and Carlson 2015). They are also reflected in the ambitious targets of the integrative Future Earth network (as outlined in Future Earth 2014). To make good policy decisions, there must be a continuous conversation between scientists and stakeholders (Mitchell et al. 2006; Jones et al. 2008; Kamelarczyk and Gamborg 2014). This insight is well illustrated by the interconnectedness of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC), as well as the ongoing evaluation thereof (IPCC 2014). To what extent fundamental research can be balanced with user-driven agendas is a key issue for questions regarding the long-term financial sustainability of Earth system science as a whole. A global, unified long-term vision is required to adequately guide the long-term development of Earth system research and to shift from a Group of Seven (G7)-centered research world to a more distributed and equal use and creation of scientific information. An increased

[1] The difficulty of—mostly Western—scientific systems to provide an increasing number of doctoral students with long-term perspectives in academia is one problematic aspect of that increase as well. This problem is discussed elsewhere (e.g., Larson et al. 2014) and does not contradict our diagnosis: that there are more well-educated Earth system scientists around the world right now than ever before. The challenge for Earth system science is to use this potential to its fullest.

focus on capacity building should become an inherent part of this journey.

We, the Young Earth System Scientists (YESS) community, are a global, integrated, bottom-up-established network of early-career researchers. We have worked with support of the World Climate Research Programme (WCRP), the World Weather Research Programme (WWRP), and the Global Atmosphere Watch (GAW) program to create this white paper on Earth system science frontiers, based on results from a WMO-funded workshop in October 2015 in Offenbach, Germany. It presents our vision and serves to guide the discussion around the future of Earth system science. We chose the concept of frontiers as a guiding theme for the workshop and this essay explicitly to indicate that we do not expect the topics we mention below to be "solved" in the next years; instead, we envision them to be a guideline for the scientific community in the decades to come. Some of the frontiers already have known challenges, but for others the frontier represents only a general direction in which we believe Earth system science should move. We identify both frontiers in our understanding of the Earth system itself and frontiers in the way we handle and define Earth system science. Despite them being conceptually different, we believe that true progress in Earth system science will be possible only if we push all frontiers simultaneously.

We believe that a vision of Earth system science must start from continuity, that is, sustaining the long-term development of infrastructure that is required by the global research community to answer the questions that society will be raising in the future. At the same time, the overall long-term goal of the Earth system science research community should be to provide globally available, seamless, robust, and instructive environmental prediction on all time scales, as well as an improved ability of societies to make use of this information. What we exactly mean by some of these terms will be outlined throughout this essay. To reach this long-term goal, our science has to push multiple frontiers, which can be visualized in three dimensions: scales (both temporal and spatial), disciplines, and users (see Fig. 1). Earth system science has to push all frontiers at the same time while acknowledging that the interpretation of questions and corresponding research priorities shift between different scales, disciplines, and users. This is where we have perceived the need to deviate from the status quo and break with continuity: to approach and cross these frontiers, we have to ask questions that exceed boundaries of scale, discipline, and user communities, making synergetic use of the interdisciplinary intellectual wealth available in the global Earth system science community instead of following disciplinary-based funding and organization structures. How we think this goal can be achieved is the core of this essay, including our view on how to improve equal global capacity development in the Earth system sciences.

THE SCALE FRONTIER: SEAMLESS ENVIRONMENTAL PREDICTION. Potentially, the clearest scientific frontier of our research community

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is going beyond what is currently available in modeling technology to develop a comprehensive understanding of the most relevant Earth system processes and their interactions at all scales—scales currently thought to be predictable and those that may only become predictable in coming decades. The goal is to integrate all facets of Earth system understanding and modeling to create seamless environmental prediction frameworks that provide information from minutes to centuries and from meter to global spatial scales (e.g., Brasseur and Carlson 2015; WMO 2015). These frameworks will most certainly still include different models or model configurations, but they will give a consistent description of processes on all scales that are missing from today's array of models.

Multiple components and features, including biogeochemical cycles, chemistry, and multidirectional coupling, are important at certain scales and need to be further integrated into Earth system models and data assimilation systems. Modeling systems with flexible and interchangeable model components and grids are required to tackle and predict regional and local scales in a global context. The development of an interchangeable modeling environment would require collaborative guidance and build on existing infrastructure, such as the Earth System Modeling Framework and WCRP's Coupled Model Intercomparison Project (CMIP). Sustainable development of models, big data concepts, and evaluation approaches via online model diagnostics will need to be developed and improved in a future of high-resolution simulations. The range of aspects that seamless environmental prediction systems will need to address extends from near-real-time warnings for extreme events (regional pollution effects, tropical cyclones, floods, etc.) to long-term effects, such as ocean acidification and consequent impacts on fisheries. The user groups of these seamless environmental prediction systems will be similarly diverse: from farmers who require short-term thunderstorm forecasts to policy makers who may have to weigh the risk of global sea level rise against the cost of global energy system change and possible corresponding disruptions of historical growth processes, either for their country or on a global scale. The design of seamless environmental prediction systems must therefore be coproduced, including the capabilities and requirements of end users from the beginning. To develop seamless environmental prediction systems effectively and to take advantage of the growth in computational capacity, a strong, sustained focus on basic model development is required.

Seamless environmental prediction frameworks will also require ever more observations, and as

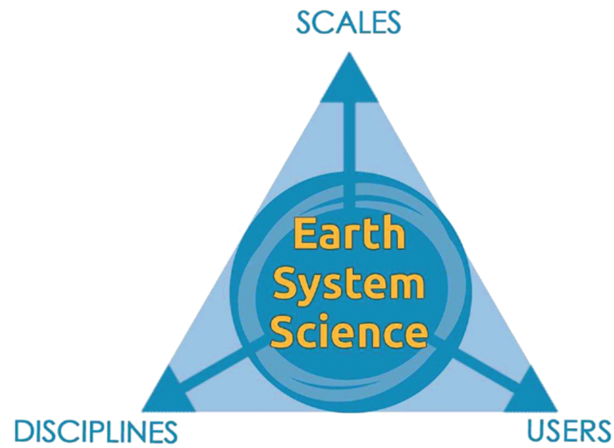

Fig. 1. The solution space of an integrated science community that must bring together disciplines, knowledge about different scales, and use cases. True progress for Earth system science can be accomplished only by pushing all frontiers at the same time.

model resolution increases to focus on the representation of smaller-scale processes, so will the limits of observational capabilities be pushed to ever finer scales. The global observing network must be made sustainable and—where justifiable—extended. This is especially true for satellite observations, where funding decisions today determine the observation capabilities 20 years from now. Observations must be made available to the entire global scientific community, which requires unified data formats and descriptions, as well as harmonized quality control and documentation. While the available observations also need to be more efficiently incorporated into data assimilation schemes, innovative methodologies have to be developed to use new observations, ranging from the global (e.g., satellite) to local scale (e.g., smartphones, cars, planes, drones, citizen-science projects). The integration of such extensive datasets will require exceptional technical expertise and presents a challenge to the capacity of today's Earth system science community. Responding to these needs will require Earth system scientists to be comfortable working with flexible and innovative modeling systems, combined with increased usage of supercomputers, familiarity with methods from machine learning and big data, and a highly accurate global observing network.

Many of these issues and novel demands require technical work that starts today, and a few of them particularly stand out to us as early-career scientists. We acknowledge the many scientists within various research programs already working on these issues; we acknowledge their struggle by voicing this support. To enable the technical and intellectual revolution leading to global, robust, and seamless environmental prediction, we need to have the best models and observational data available to as many researchers around the globe as possible. This means, when coordinating international research programs, the participating institutions should keep the following points in mind and work to convince governing bodies of their necessity:

- Continued emphasis on open access that extends to all aspects of scientific work, including the recent progress of open access publications.
- A strong focus on documentation of the construction and tuning processes of Earth system models from all modeling centers (as proposed, e.g., by Hourdin et al. 2017). Models should be made open source, where possible, and a well-coordinated, potentially modular model development structure is recommended to allow communities from around the world to work on improving key components of Earth system models.
- Datasets and observations should always be made accessible to the global community. This requires a massive rethinking and considerable effort in terms of data harmonization and documentation. Higher-resolution observations and model data will create archiving and sharing challenges, as well as raise the question of appropriate processing to ensure the required availability of results (Overpeck et al. 2011). As part of the ever-evolving big data challenge, the current system of "run, then analyze" will have to be changed in many cases to a research system, where the key outputs have to be determined before the model simulation, similar to the design of observation systems.

THE USER FRONTIER: GOING BEYOND THE IVORY TOWER. To work on the aforementioned fundamental research, sustained and—where possible—increased funding for Earth system science will be required. One aspect of fundamental research is, who pays for it and why? The struggle for a sustainable balance between short-term user-driven agendas and long-term problem-based research is an inherent challenge to all fundamental research, and one that will likely remain a crucial point of contention in Earth system science in the coming years. Should the end user—that is, the public or its representatives—decide how Earth system science funding is distributed? This approach enhances justification for overall science expenses and automatically directs science toward user needs. But, at the same time, creates the risk of focusing only on short-term problems, ignoring long-term risks, and missing relevant perspectives. The other extreme would be if the scientific community autonomously decides how to distribute its own funding. This approach could be seen as beneficial, since scientists might know better where to put research priorities, but it carries the danger of distancing science from the public. A well-constructed balance would have scientists consistently reporting and defending their fundamental science to the public in a format that aligns users and scientific communities iteratively. Any well-constructed balance must naturally be region specific and topic dependent. Strategies to find those balances will remain highly relevant in the coming years as the public perceives problems to be solved and the risk of decreasing Earth system science funding remains.

Some key research issues in Earth system science, such as long-term observational consistency or persistent modeling problems, suffer from the short-term "attention span" of public funding. The balance between societal pressures to focus on urgent regional problems (e.g., droughts) and the necessity to focus on long-term global issues (e.g., shift of monsoon) so that we are ready for future urgent regional problems must be created carefully. Transparent communication of why we do the science we do is a crucial aspect. We believe that Earth system science—as a relatively new field—should try to adapt to best practices in this field from other fields that have existed in a similar balance of societal needs and fundamental research priorities, specifically long-term medical research. The current practice of large-scale short-term funding certainly also contributes to our ability—or lack thereof—to deal with unexpected, long-term, and large-scale dangers that are not on today's research agenda. User-driven, locally anchored research priorities must be used to overcome one of the sources of this problem, which was also mentioned by Brasseur and Carlson (2015), namely, that some implications of Earth system research clash with societal trends, such as consumerism and permanent economic growth. To increase long-term public funding effectively and to warrant sustained funding, the Earth system science community has to persistently communicate its research priorities in a clear way to the public.

A second key aspect of fundamental research similar to the question of fundamental or user-driven research is, who uses the results? Specifically for Earth system science, this means how best to comprehensibly communicate our knowledge of the Earth system, as well as the limitations of this knowledge, to society. A proper communication of scientific outcomes is a prerequisite for establishing a rational discourse with society about the implications of our knowledge and emerging priorities for future research. Furthermore, it has to be assured that user needs are communicated regularly and explicitly enough to the scientific community in order to guide our research priorities adequately. Cultural and socioeconomic factors, as well as contexts of both communicators and users (e.g., level of knowledge, skills, incomes, ability for adaptation), influence the communication and understanding of science and its application. Hence, the challenge lies in communicating scientific results in an understandable language to policy makers and end users globally (e.g., Brewer and Stern 2005) so as to trigger mechanisms to protect against and adapt to disasters or other, longer-term environmental changes. One aspect of this communication problem is the insufficient training of many scientists to communicate outside of their discipline, with either scientists from other disciplines or the public. As scientists, we have an obligation to create efficient communication channels that a) allow users to engage with scientists to improve communication from the science side and b) train users how to manage scientific information for their needs.

Another challenge in disseminating our knowledge of the Earth system is different perceptions of uncertainty. The research community is well aware of the uncertainty related to scientific results and has established numerous ways of assessing and quantifying this uncertainty. In all aspects of Earth system prediction systems, uncertainty is inherent and can be multiplied from one step in the prediction chain to another (Webster et al. 2002; Stainforth et al. 2005; Maslin and Austin 2012). This uncertainty stems, for example, from an inevitably incomplete observation of the Earth system, approximations and assumptions that are part of forecast models, and an uncertain contribution of external forcings, such as anthropogenic emissions. To be able to produce robust and instructive predictions, these uncertainties need not only be understood on each level but also taken into account throughout the prediction framework in an appropriate manner. When relevant for decision processes, uncertainties need to be communicated to users in an understandable manner, adapted to their needs. Failure to communicate both certain facts and their associated uncertainty effectively limits the transfer of knowledge. But, even if done correctly, uncertainties often oppose society's request for concrete and certain statements, and thus may be seen as a "deficiency in research" (Sense about Science 2013). This issue is further complicated by the fact that even different communities in Earth system science utilize different vocabularies (e.g., Rauser et al. 2014). Continuous work is required to homogenize language among disciplines while further communication channels with end users should be explored and established. We acknowledge that the goal of a "best practice" will most likely not be a fixed optimum solution but change in time. However, sustained focus on this issue will hopefully lead to more robust communication and better understanding of the largest difficulties on the way to effective communication. Knowledge and understanding of uncertainty inherent to particular scientific results go hand in hand with the general level of understanding—a better understanding of Earth system uncertainties will also help society grasp why predictions might diverge (e.g., differing forecasts for next week's temperatures).

To sustainably address the challenges of fundamental research funding and effective communication represents a substantial frontier to work toward: only if science manages to fulfill this effectively—and better than today—will all that follows make sense. In a politicized and highly relevant science like Earth system science, which combines fundamental with applied research, the scientific community cannot stay disconnected from the public but also cannot yield completely to the public's demands. This balance can be found only through iterative interaction with society. To enable sustainable use of its results, Earth system science has to cross the user frontier and leave the ivory tower for good.

THE HUMAN FRONTIER: A NEW, INTERDISCIPLINARY EARTH SYSTEM SCIENCE IN THE ANTHROPOCENE. Earth system science aims to observe and to enhance the understanding of the Earth System processes and their interactions. Over the last decades, the human component and its interactions with the natural Earth system have gained prominence (IPCC 2014). Human activities are now so prevalent and dominant that they rival the large forces of nature (Crutzen 2006; Steffen et al. 2007), and scientists have therefore suggested that a new epoch "the Anthropocene" has begun.[2] A definition of the Earth system and its interconnections is incomplete without addressing this large and influential human component, requiring that we overcome the disciplinary boundaries between natural sciences, social sciences, and the humanities

[2] The British-led Working Group on the Anthropocene (WGA) reported at the 35th International Geological Congress in Cape Town, South Africa, in August 2016 that, in its considered opinion, the Anthropocene epoch began in 1950.

(Boucher et al. 2016). To facilitate this change, we need a consistent focus on interdisciplinary and transdisciplinary Earth system science by a multidisciplinary scientific community. Only by doing this will we be able to fully understand the governance of Earth's limited resources and humanity's physical footprint on the planet, including planned and unplanned attempts to control the Earth system (van der Hel 2016). We recommend a larger focus of educational and institutional resources on questions integrating natural and social sciences within the broad field of Earth system science.

We acknowledge the challenges of transdisciplinary cooperation and coproduction of science, and we look forward to a future where the boundaries between sciences become increasingly fluid. At the same time, we acknowledge that for specific scientific questions—for example, atmospheric composition, geological sediment processes, or deep ocean circulation patterns—there probably is no permanent need to consult, for example, a political analyst, while for other questions there might be. One way forward would be to formulate and address scientific questions starting from a real-world perspective, instead of a disciplinary scientific question. The main challenges in coproduction and transdisciplinary science in the Anthropocene are to find valuable entry points among disciplines, to develop just the right level of interdisciplinary interaction and to identify the roles of coproducers and stakeholders (Boucher et al. 2016; van der Hel 2016). The only truly promising way of organizing, guiding, and integrating Earth system science in the Anthropocene is to find an organizational framework that allows us to explore these questions and to find a common way forward involving transdisciplinary interactions. One relevant aspect of the human frontier is therefore to overcome historical disciplinary limitations and develop our science to be naturally inclusive of social and political processes and effects, going far beyond already ongoing efforts to reconcile communication difficulties between different disciplines as mentioned in the paragraphs above.

Another aspect of the human frontier is the way we treat human interactions with the Earth system. In the coming decades, even more attention should be given to how we manage Earth's natural resources and how to take into account the importance of sustainability as the human population continues to grow in a changing climate. Questions about, for example, water availability and food security, as well as waste management, might impose the greatest direct risks for more vulnerable, developing countries,[3] but they need to be answered as part of a global quest to create a new, global governance regime for the Anthropocene (e.g., Messner and Nuscheler 1996; United Nations 2015). As an example, global decarbonization implies a huge societal transformation in all sectors: energy, transport, industrial, and housing. Such a decarbonization strategy will require massive sustainable development in all countries to cope with growing demand for materials, energy, and water (Wiedmann et al. 2015). For Earth system science, it is a major future task to investigate the effective management of natural resources and environmental risks on time scales of decades to centuries. Our community must increase efforts to address the global problems of pollution, food, and water availability, and the transfer of best practices across regional boundaries.

The twentieth century can be seen as the single largest experiment in exerting unregulated and reckless climate engineering, that is, attempts to control the Earth system. Humanity has been changing global atmospheric composition through anthropogenic greenhouse gas emissions and will continue to do so for some time, despite recent agreements to globally reduce them (UNFCCC 2015). Additionally, humanity has massively influenced land use on a global scale, mostly lacking any sort of coordination. The slow-moving process of humanity to massively influence our environment in the past requires more research about the motives and social drivers behind these actions and decisions, leading to a clearer understanding of what Anthropocene really means. The study of how humans influence Earth system processes has a long history, but it has gained additional visibility in recent years, particularly when confronted with the question of legal responsibility for changes in the Earth system (Sanderson et al. 2002). Providing a scientific base for these types of societal discussions is an enormous challenge and simultaneously a huge motivation. We believe that the opportunities and limits of anthropogenic control of the Earth system must be tackled with large, interdisciplinary, and global approaches. This represents the largest aspect of the human frontier: we have to think of the Earth system as an inclusive system, including social systems; anthropogenic influences no longer provide external input to the Earth system but are a fundamental part of this system. There

[3] We refer here to an undefined group of countries, sometimes referred to as "Global South." Some of these countries are represented at climate conferences by the coalitions of the least developed countries (LDCs), landlocked developing countries (LLDCs), and small island developing (SID) countries.

is still a long way to go to fully develop technical, legal, social, and economic models or concepts for this type of Earth system science, and it will be truly possible only if the other frontiers and dimensions of Earth system science are tackled at the same time.

GOING FORWARD: GLOBAL KNOWLEDGE TRANSFER AND SKILL DEVELOPMENT. As early-career scientists, we will play a critical role in shaping Earth system science in the coming decades, recognizing that the role of scientists in society may change in the future. The fast pace of change, which is brought about by scientific and technical progress and new understanding in Earth system science, necessitates new ways and means for knowledge transfer and skill development. It is imperative that the scientific community continues to push knowledge transfer to complement ongoing efforts and to nurture a new generation of scientists for the tasks that lie ahead. The transfer of knowledge and continued development of skills are needed not only from one generation to the next but also across disciplines and across regions to advance the field of Earth system science as a whole.

To better address the communication challenge, we need to encourage interdisciplinary science and develop a common language to facilitate a good understanding and application of science. A well-integrated community of interdisciplinary Earth system scientists will provide multiple perspectives when considering a particular societal problem. It is vital to build this common language within the interdisciplinary field of Earth system science, for example, by defining terms, clarifying concepts, and explaining uncertainties. Interdisciplinary education of early-career researchers is one way to improve this situation. This has been addressed by interdisciplinary graduate schools around the world, but it has yet to be transferred into an interdisciplinary reality of global Earth system science. A global network for early-career researchers in Earth system science provides the opportunity to cross boundaries between disciplines and to establish cooperation among scientists worldwide. It can thus support the development of a new generation of interdisciplinary scientists, preparing them for the challenges that lie ahead while facilitating effective skill development and knowledge transfer.

To further integrate this global community, a long-term funding framework supporting scientific exchange between early-career Earth system researchers and their integration into global research initiatives should be developed. This framework should complement and unify existing approaches around the world. The funding framework should be deliberate in its efforts to support early-career researchers in regions where Earth system science research remains less well represented, thus enhancing local research capacity. An additional focus of our early-career community will be to complement support for scientific exchange through continuous experimentation with carbon-friendly virtual meetings; Earth system science should take the lead in the decarbonizing it suggests as necessary.

We envisage the establishment of a truly global and interdisciplinary Young Earth System Scientists community to organize and enhance interactions among early-career researchers around the world (Rauser et al. 2015). This community will connect with existing networking efforts not only from within WCRP, WWRP, and GAW, but also with other global Earth system science–related research initiatives, such as Future Earth. We believe a sustainable organizational structure will allow the next generation of Earth system science leaders to work in an integrative and collaborative way to effectively tackle the challenges of Earth system science without the disciplinary boundaries of the past—and to push our science beyond the frontiers outlined in this essay on the way. We believe that increased awareness of funding agencies around the world is required to support an early-career researcher network in Earth system science (see Fig. 2). The network we suggest specifically has been developed from the bottom up, is interdisciplinary in nature, and aims to become well

Fig. 2. The structure of the YESS community.

connected with stakeholders and decision-makers around the world. We want to start creating the unified globally integrated science community of the future—right now.

CONCLUSIONS. The goals outlined above are a vision. They may be idealistic, but we believe them to be complementary to existing research programs, and particularly, to help to initiate a discussion of what Earth system science wants to achieve in the long term. While the process of identifying knowledge gaps has been extremely helpful in focusing scientific ideas and questions (e.g., Bony et al. 2015), a discussion of the overall vision of what Earth system science can—and will—offer to humanity is needed to meet societal demands and to overcome funding issues. As mentioned above, the funding situation will be improved only if communities around the world recognize the need for increased awareness and understanding of the Earth system as a whole, as well as the capacity to be able to predict relevant aspects of this system. The envisioned targets are long term in nature and can be fully achieved only if we successfully assemble the global Earth system science community and coordinate research plans and activities across academia, government, industry, and society. Unification at the early-career level will be beneficial not only to existing global research coordination programs but also to laying the necessary foundation for future Earth system science and the challenges that need to be addressed by our research community.

The goals of our early-career network are to strengthen interdisciplinarity and to improve exchanges between all regions of the globe, right from the beginning of researchers' careers. Most importantly, we must work hard to communicate to the world that the Earth system science community has accepted the challenge of creating tangible products for the benefit of society. A coordinated, interdisciplinary, and truly global approach to Earth system science is the best means to foster understanding of the complex interplay of Earth's processes and to develop applicable tools to confront the challenges facing society both now and in the future.

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REFERENCES

Bony, S., and Coauthors, 2015: Clouds, circulation and climate sensitivity. *Nat. Geosci.*, **8**, 261–268, doi:10.1038/ngeo2398.

Boucher, O., V. Bellassen, H. Benveniste, P. Ciais, P. Criqui, and C. Guivarch, 2016: In the wake of Paris Agreement, scientists must embrace new directions for climate change research. *Proc. Natl. Acad. Sci. USA*, **113**, 7287–7290, doi:10.1073/pnas.1607739113.

Brasseur, G., and D. Carlson, 2015: Future directions for the World Climate Research Programme. *Eos*, **96**, 9–11, doi:10.1029/2015EO033577.

Brewer, G. D., and P. C. Stern, Eds., 2005: *Decision Making for the Environment: Social and Behavioral Science Research Priorities*. National Academies Press, 296 pp., doi:10.17226/11186.

Crutzen, P. J., 2006: The "anthropocene." *Earth System Science in the Anthropocene: Emerging Issues and Problems*, E. Ehlers and T. Krafft, Eds., Springer, 13–18.

Future Earth, 2014: Future Earth 2025 vision. [Available online at www.futureearth.org/sites/default/files/files/Future-Earth_10-year-vision_web.pdf.]

Hourdin, F., and Coauthors, 2017: The art and science of climate model tuning. *Bull. Amer. Meteor. Soc.*, **98**, 589–602, doi:10.1175/BAMS-D-15-00135.1.

IPCC, 2014: *Climate Change 2014: Synthesis Report*. Cambridge University Press, 151 pp. [Available online at www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf.]

Jones, N., H. Jones, and C. Walsh, 2008: Political science? Strengthening science–policy dialogue in developing countries. Overseas Development Institute Working Paper 294, 57 pp.

Kamelarczyk, K. B. F., and C. Gamborg, 2014: Spanning boundaries: Science–policy interaction in developing countries—The Zambian REDD+ process case. *Environ. Dev.*, **10**, 1–15, doi:10.1016/j.envdev.2014.01.001.

Larson, R. C., N. Ghaffarzadegan, and Y. Xue, 2014: Too many PhD graduates or too few academic job openings: The basic reproductive number *R0* in academia. *Syst. Res. Behav. Sci.*, **31**, 745–750, doi:10.1002/sres.2210.

Maslin, M., and P. Austin, 2012: Uncertainty: Climate models at their limit? *Nature*, **486**, 183–184, doi:10.1038/486183a.

Messner, D., and F. Nuscheler, 1996: Global governance: Challenges to German politics on the threshold of the twenty-first century. Development and Peace Foundation (SEF) Policy Paper 2, 12 pp.

Mitchell, R. B., W. C. Clark, D. W. Cash, and N. M. Dickson, 2006: *Global Environmental Assessments: Information and Influence*, MIT Press, 352 pp.

Nativi, S., P. Mazzetti, M. Santoro, F. Papeschi, M. Craglia, and O. Ochiai, 2015: Big Data challenges in building the Global Earth Observation System of Systems. *Environ. Modell. Software*, **68**, 1–26, doi:10.1016/j.envsoft.2015.01.017.

O'Neill, A., and L. Steenman–Clark, 2002: The computational challenges of Earth-system science. *Philos. Trans. Roy. Soc. London*, **360**, 1267–1275, doi:10.1098/rsta.2002.1000.

Overpeck, J. T., G. A. Meehl, S. Bony, and D. R. Easterling, 2011: Climate data challenges in the 21st century. *Science*, **331**, 700–702, doi:10.1126/science.1197869.

Pianosi, F., 2014: Computational models for environmental systems. *Methods and Experimental Techniques in Computer Engineering*, F. Amigoni and V. Schiaffonati, Eds., Springer International, 3–13.

Ramamurthy, M. K., 2006: A new generation of cyberinfrastructure and data services for earth system science education and research. *Adv. Geosci.*, **8**, 69–78, doi:10.5194/adgeo-8-69-2006.

Rauser, F., A. Schmidt, S. Sonntag, and D. Süsser, 2014: ICYESS2013: Uncertainty as an example of interdisciplinary language problems. *Bull. Amer. Meteor. Soc.*, **95**, ES106–ES108, doi:10.1175/BAMS-D-13-00271.1.

——, V. Schemann, and S. Sonntag, 2015: Sustainable early-career networks. *Nat. Geosci.*, **8**, 745–746, doi:10.1038/ngeo2541.

Sanderson, E. W., M. Jaiteh, M. A. Levy, K. H. Redford, A. V. Wannebo, and G. Woolmer, 2002: The human footprint and the last of the wild. *Bioscience*, **52**, 891–904, doi:10.1641/0006-3568(2002)052[0891:THFATL]2.0.CO;2.

Sense about Science, 2013: Making sense of uncertainty: Why uncertainty is part of science. Sense about Science, 26 pp. [Available online at www.senseaboutscience.org/data/files/resources/127/SAS012_MSU_reprint_compressed.pdf.]

Stainforth, D. A., and Coauthors, 2005: Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature*, **433**, 403–406, doi:10.1038/nature03301.

Steffen, W., P. J. Crutzen, and J. R. McNeill, 2007: The Anthropocene: Are humans now overwhelming the great forces of nature. *Ambio*, **36**, 614–621, doi:10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2.

UNFCCC, 2015: Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1, 32 pp.

United Nations, 2015: Transforming our world: The 2030 agenda for sustainable development. Agenda for Resolution 70/1, A/RES/70/1, 35 pp. [Available online at www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.]

van der Hel, S., 2016: New science for global sustainability? The institutionalisation of knowledge co-production in Future Earth. *Environ. Sci. Policy*, **61**, 165–175, doi:10.1016/j.envsci.2016.03.012.

Webster, M. D., M. Babiker, M. Mayer, J. M. Reilly, J. Harnisch, M. C. Sarofim, and C. Wang, 2002: Uncertainty in emissions projections for climate models. *Atmos. Environ.*, **36**, 3659–3670, doi:10.1016/S1352-2310(02)00245-5.

Wiedmann, T. O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, and K. Kanemoto, 2015: The material footprint of nations. *Proc. Natl. Acad. Sci. USA*, **112**, 6271–6276, doi:10.1073/pnas.1220362110.

WMO, 2015: *Seamless Prediction of the Earth System: From Minutes to Months*. G. Brunet, S. Jones, and P. M. Ruti, Eds., WMO-1156, 471 pp.

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