SPECIAL FEATURE: INTRODUCTION

The elephant, the blind, and the intersectoral intercomparison of climate impacts

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It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind).

John Godfrey Saxe, "The Blind Men and the Elephant"

When decision makers discuss anthropogenic climate change, they often ignore the mighty elephant in the room, namely the question of what global warming really means on the ground. By all accounts, the impacts on our physical environment and society would be starkly different if our planet warmed by "just" 2 °C (1, 2), by a "dangerous" 4 °C (3), or by a "mind-boggling" 6–8 °C (4). However, the pictures of those sweltering worlds that are emerging from scientific research are still regrettably vague, blurred, and fragmentary (see, for example, refs. 5–7). The main reason for this vagueness is as obvious as it is tantalizing: the sheer diversity and complexity of potential climate-change effects on the existing multitude of regions, sectors, and cultures make the swift advancement of robust knowledge in this field extremely challenging.

Paradoxically, but entirely rational from the individual researcher's point of view, the scientific community tends to skip over the messy and multifaceted issue of impacts to focus on better-defined lines of investigation, such as the relationship between greenhouse gas emissions and global mean surface-temperature rise, or the economic costs of limiting warming to specific levels. This focus has enabled the respective communities of scholars to make impressive quantitative progress in the last two decades and to attain a high degree of coordination, as evidenced by important model intercomparison initiatives. More precisely, we are now seeing the results of the fifth phase of the Coupled Model Intercomparison Project (8), representing the backbone of the Intergovernmental Panel on Climate Change (IPCC) Working Group I (WG I) assessments. In addition, there have been major model intercomparison efforts regarding the quantification of mitigation costs in the framework of the Stanford Energy Modeling Forum and the Integrated Assessment Modeling Consortium, providing essential inputs to the IPCC WGIII reporting (e.g., refs. 9 and 10).

The climate impact research community is not there yet, but despite the more challenging task, is on its way. The community needs to continue to rise to this challenge because the elephant will not disappear. Quite to the contrary, understanding and dealing with climate-change effects through preparedness, adaptation, resilience, and so forth will become increasingly urgent with each passing year of unabated global greenhouse gas emissions. So the question remains, how can we paint robust and consistent pictures of possible impacts futures as defined, for example, by the representative concentration pathways (11)? Previous attempts, not only by the IPCC but also by a number of reports and articles, should be acknowledged in this context (12–16). All these contributions are highly valuable stepping stones, but none of them was based on a systemic comparison strategy guided by a unique modeling protocol and a common data pool, as is best practice in the climate modeling and Integrated Assessment Modeling communities, respectively. Furthermore, none of the former analyses aspired to explore the impact cascades arising from cross-sectoral and transregional dynamics.

A Parable and Its Lessons

The crucial challenges involved can be epitomized by an elephant metaphor again. A well-known parable from ancient India describes the dilemma of assembling fragments of knowledge based on individual perception into a meaningful whole. It is the story of six blind men who touch different parts of an elephant and try to identify their overall object. When eventually exchanging conclusions, the men find themselves in complete disagreement: the one fumbling with the animal's trunk thinks that he is grasping a snake; the other one feeling the sharp, smooth tusk presumes to touch a spear; and those who come across a leg, an ear, or the tail are reminded of a tree, a fan, and a rope, respectively.

It is no surprise that the attempts of the blind men end up in confusion. However, they could have done a lot better! A bit of reflection reveals two major errors. The first error is the false interpretation of the different parts of the elephant. If a tusk is mistaken as a spear, then there is no way to recognize an elephant, irrespective of the ensuing deliberations. This problem could be solved, however, if an entire group of blind individuals examined a given part of the animal and shared their experiences. The chances of correctly identifying the element should rise sharply with group size. The second error consists of drawing conclusions about the whole after examining only single components of the beast. This approach would be wrong even if the various parts were correctly recognized. For example, a moderately straight tusk could also belong to a walrus. However, the latter animal needs to be excluded if another true part—the huge ear, for example—is taken into account as well.

In summary, it is a two-stage comparison process, enabled only by communication at each level, which reveals the character of the complex object in question. Let us now come back to our starting point, namely the investigation of climate-change impacts.

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, www.isi-mip.org) is intended to provide a framework for the enormous challenge of comprehensively examining the impacts elephant, especially by establishing a forum, in which researchers from key impact sectors bring their knowledge together. The core product of the ISI-MIP is an open archive of impact model simulations from different sectors and different scales, driven by common

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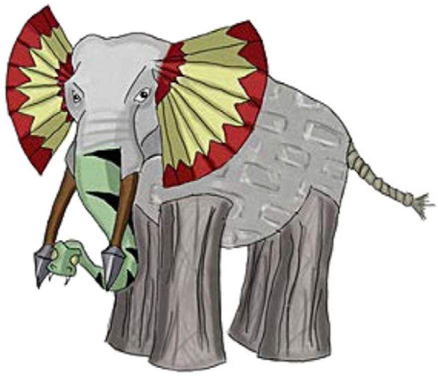

Fig. 1. What do we know of the whole problem, when we only have access to information about its parts? (Drawing from www.getwords.com, with kind permission of John Robertson.)

climate and socio-economic input data (https://esg.pik-potsdam.de). In this way, the ISI-MIP allows for: (*i*) multimodel assessment of sector-specific impacts at different levels of global warming, (*ii*) model improvement through a better understanding of model discrepancies, and (*iii*) cross-sectoral integration of impacts in a multimodel context. This PNAS Special Feature comprises main results of the initial fast-track phase of the project (see ref. 17 for the design of the framework and the substudies).

Better Recognition of Individual Parts

Multimodel assessments are crucial for lending substance to impact assessments; they bundle the current knowledge of expected impacts and capture, at least to some extent, the uncertainty in process representation, underlying empirical data, and modeling concepts. Climate-change impact uncertainties are often quantified only in terms of the spread of climate-model projections, but not in terms of variations between impact model projections. Among the exceptions are the biomes model intercomparisons that have a relatively long tradition, in part because biomes models are most closely connected to the carbon-cycle modeling embedded in climate projections (18, 19). More recently, similar initiatives in the water (20) and agriculture (21) sectors have been undertaken. However, in many sectors, model intercomparison exercises have never taken place. For example, this Special Features reports on the first intercomparison of Global Gridded Crop Models (22), and ISI-MIP also provided the framework for the first comparative analysis of malaria models. In addition, the Special Features issue includes multi-impact-model assessments of global flood hazard (23), human influences on global water resources (24), and water scarcity under climate change (25). Furthermore, the water model simulations have been used to quantify the change in irrigation water demand under global warming (26), and the biomes model simulations have been used to estimate the areas at risk for severe ecosystem changes (27). Although only based on one individual model, the uncertainty of the impacts of sea level rise on coastal infrastructure was assessed within the ISI-MIP framework by a systematic variation in model parameters, input data, and adaptation options.

The study by Dankers et al. (23) directly addresses the statement made in the IPCC Special Report on Extreme Events (28) that "overall there is low confidence in projections of changes in fluvial floods," partly because of the lack of multimodel assessments. Together with other contributions (e.g., ref. 29), the studies conducted within the ISI-MIP help to significantly advance our understanding of this important issue.

Sharpening Our Diagnostic Tools

One crucial finding of the initial ISI-MIP analyses is that interimpact-model spread of the projections is often comparable to, or even larger than, the spread introduced by the different climate models considered. Multimodel studies offer the opportunity to analyze the origin of the discrepancies between models as a basis for model improvements. In this Special Features issue, Friend et al. (30) show that the discrepancy in projected changes in the vegetation carbon stocks across the biomes models is dominated by often ignored differences in the simulated residence times (i.e., the lifetime of carbon in the ecosystem) rather than by the well-studied differences in net primary production. Similarly, Rosenzweig et al. (22) identify the representation of nitrogen stress as an important source of differences in projected crop production. Nelson et al. (31) present a pioneering analysis of the responses of the food system to climate-change impacts in a multicrop, multieconomic model setting. The authors quantify the model spread regarding the responses to climate-induced yield changes, such as intensification of management, expansion of agricultural land, changes in international trade, prices, and consumption. Based on these analyses, all three papers offer a clear perspective on where investment in further model development is required.

Understanding the Whole System

ISI-MIP is unique in facilitating an assessment of cross-sectoral climate change impacts in a multimodel context. Three papers in this issue make particular use of this unique framework. Piontek et al. (32) identify multisectoral hotspots of climate change: regions where climate change is expected to lead to severe changes or risks of changes in multiple sectors. Eleven water, seven crop, seven biomes, and four malaria models allow for an explicit assessment of the robustness of the projections. Elliott et al. (33) provide an assessment of the irrigation potential based on projected crop production increases using six global gridded crop models and irrigation water constraints based on 10 water models. The authors' analysis shows that there is a significant difference between the irrigation water consumption projected by the water models and the crop models. In addition to these multi- or cross-sectoral papers, there are two other studies using model simulations from different sectors to identify important differences in projections because of the inclusion of individual processes. Thus, the analysis of Prudhomme et al. (34) in this issue shows that the pure water-model–based projections of drought severity significantly differ from similar projections accounting for dynamic vegetation composition changes. Similarly, Davie et al. (35) have taken a cross-sectoral view of the projected changes in runoff using both hydrological and biomes models.

The results presented in this Special Features issue are essential building blocks of our quantitative understanding of the impacts of climate change on our natural and built environment, but the story does not stop there. The impacts picture remains far from complete, in particular with regard to socio-economic consequences. The human costs of climate change are often caused by the biophysical impacts, but are not at all identical to the biophysical impacts themselves. For example, food and water shortages may drive large-scale migration, and floods and storms may cause damages, including loss of life and economic costs. The multimodel studies reported here provide essential input to more aggregated approaches to modeling the lived impacts of climate change.

Furthermore, real-world decisions are more often than not tradeoffs between different response options. For example, there is a tradeoff between reaching a certain climate mitigation target, in part through expansion of land used for bio-fuel production, and reserving sufficient agricultural land to ensure food security. In this case, without an honest and comprehensive estimate of the distribution of probable crop-production responses to climate change, a prudent decision is impossible. Researchers in the field of climate-change impacts are faced with a formidable and urgent challenge. The impressive body of expertise in the response of individual biophysical systems, and in turn of society, to the pressures of climate change must now be amalgamated to understand how our Earth and human system as a whole will respond.

It is time to put our knowledge of the legs, tusks, tail, and ears of the elephant together to comprehend the true nature of the beast.

1 Schellnhuber HJ, Cramer W, Nakicenovic N, Wigley T, Yohe G, eds (2006) *Avoiding Dangerous Climate Change* (Cambridge Univ Press, Cambridge, UK).
2 Schellnhuber HJ (2010) Tragic triumph. *Clim Change* 100(1): 229–238.
3 New M, Liverman D, Schroeder H, Anderson K (2011) Four degrees and beyond: The potential for a global temperature increase of four degrees and its implications. *Philos Trans A Math Phys Eng Sci* 369(1934):6–19.
4 Meinshausen M, et al. (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim Change* 109(1-2):213–241.
5 Rosenzweig C, Wilbanks TJ (2010) The state of climate change vulnerability, impacts, and adaptation research: strengthening knowledge base and community. *Clim Change* 100(1):103–106.
6 McCarthy JJ, Canziani OF, Leary NA, Dokken DJ (2001) in *IPCC 2001, Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability*, ed White KS (Cambridge Univ Press, Cambridge, UK).
7 IPCC (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (Cambridge Univ Press, Cambridge, UK), pp 976.
8 Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. *Bull Amer Meteor Soc* 93(4):485–498.
9 Clarke L, Böhringer C, Rutherford TF, eds (2009) International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22. *Energy Economics* 31(Suppl 2):S63–S305.
10 Edenhofer O, et al. (2010) The economics of low stabilization: Model comparison of mitigation strategies and costs. *Energy J (Camb Mass)* 31(1):11–48.
11 Moss RH, et al. (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463(7282): 747–756.
12 Stern N (2007) *The Economics of Climate Change: The Stern Review* (Cambridge Univ Press, Cambridge, UK).
13 Smith JB, et al. (2009) Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proc Natl Acad Sci USA* 106(11):4133–4137.
14 Warren R, et al. (2013) Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change* 3:678–682.
15 Schellnhuber HJ, et al. (2012) *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided* (World Bank, Washington, DC).
16 Schellnhuber HJ, et al. (2013) *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience* (World Bank, Washington, DC).
17 Warszawski L, et al. (2013) The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. *Proc Natl Acad Sci USA*, 10.1073/pnas.1312330110.
18 Cramer W, et al. (2001) Global response of terrestrial ecosystem structure and function to CO 2 and climate change: Results from six dynamic global vegetation models. *Glob Change Biol* 7(4):357–373.
19 Sitch S, et al. (2008) Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Glob Change Biol* 14(9):2015–2039.
20 Haddeland I, et al. (2011) Multimodel estimate of the global terrestrial water balance: Setup and first results. *J Hydrometeorol* 12(5):869–884.
21 Rosenzweig C, et al. (2012) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric For Meteorol* 170:166–182.
22 Rosenzweig C, et al. (2013) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222463110.
23 Dankers R, et al. (2013) First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proc Natl Acad Sci USA*, 10.1073/pnas.1302078110.
24 Haddeland I, et al. (2013) Global water resources affected by human interventions and climate change. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222475110.
25 Schewe J, et al. (2013) Multimodel assessment of water scarcity under climate change. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222460110.
26 Wada Y, et al. (2013) Multi-model projections and uncertainties of irrigation water demand under climate change. *Geophys Res Lett* 40(17):4626–4632.
27 Warszawski L, et al. (2013) A multi-model analysis of risk of ecosystem shift under climate change. *Environ Res Lett* 8(4):044018.
28 IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, eds Field C.B., Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, and Midgley PM (Cambridge University Press, Cambridge, UK), pp 582.
29 Hirabayashi Y, et al. (2013) Global flood risk under climate change. *Nature Climate Change* 3:816–821.
30 Friend AD, et al. (2013) Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO_2. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222477110.
31 Nelson GC, et al. (2013) Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222465110.
32 Piontek F, et al. (2013) Multisectoral climate impact hotspots in a warming world. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222471110.
33 Elliott J, et al. (2013) Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222474110.
34 Prudhomme C, et al. (2013) Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proc Natl Acad Sci USA*, 10.1073/pnas.1222473110.
35 Davie JCS, et al. (2013) Comparing projections of future changes in runoff from hydrological and biome models in ISI-MIP. *Earth System Dynamics* 4(2):359–374.