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### A New Toolkit for Developing Scenarios for Climate Change Research and Policy Analysis

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# A New Toolkit for Developing Scenarios for CLIMATE CHANGE RESEARCH AND POLICY ANALYSIS

*by Kristie L. Ebi, Tom Kram, Detlef P. van Vuuren, Brian C. O'Neill, and Elmar Kriegler*

**Y**ogi Berra succinctly captured how economic growth, technology change, demographic change, and climate change are altering visions of what the future could bring: “the future ain’t what it used to be.”<sup>1</sup> Understanding the range and character of possible futures is critical to furthering assessment of climate change, including the potential risks to physical, natural, and human systems in the context of different development pathways, and mitigation and adaptation options to avoid, prepare for, and manage those risks. Because concerns about climate change span the current to the far future, the field has a long history of using scenarios to explore and evaluate the extensive uncertainties associated with future climate change and development pathways. Projecting possible impacts under different futures and identifying the trade-offs and synergies of adaptation and mitigation policies require scenarios

that include (1) the drivers of greenhouse gas emissions, (2) the resulting emissions, (3) assumptions about other drivers of socioeconomic development that will affect the magnitude and pattern of impacts, and/or the ability to avoid, prepare for, cope with, and recover from climate change, and (4) the adaptation and mitigation policy environment.

*A scenario is a comprehensive and plausible description of the future of the human–environment system, including a narrative with qualitative trends and quantitative projections about development patterns.<sup>2</sup>*

Over the past decade, projections of the possible impacts of climate change were primarily based on scenarios developed in the Intergovernmental Panel on Climate Change (IPCC) Special Report

on Emission Scenarios (SRES).<sup>3</sup> The SRES scenarios were developed to represent the range of driving forces (including demographics, economic growth, and technology development) and emissions in the scenario literature, including underlying uncertainties. By design, the scenarios assumed no specific mitigation or adaptation policies and measures, and therefore describe how future greenhouse gas emissions could develop in the absence of specific climate policies. Descriptions of the four main storylines (A1, A2, B1, and B2) were developed using a forward-looking logic that started by describing possible internally consistent future development pathways, including demographic, social, economic, technological, and environmental dimensions.<sup>4</sup> Quantification of the storylines yielded estimated emissions of greenhouse gases over the course of the century that have been used by earth system models to project changes in temperature, precipitation, other weather variables, and sea



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level rise to 2100. Several scenarios were developed for each storyline (total = 40) to examine the range of possible future emission pathways associated with similar assumptions about driving forces.

Climatic changes projected under the SRES scenarios have been used over the last decade to provide critical insights into the possible consequences of climate change for human and natural systems, and on the effectiveness of policy options to manage risks. At the same time, advances in scientific understanding and in models mean the SRES scenarios are becoming dated. For example, earth system models now need a wider set of input data than greenhouse gases alone, such as detailed data on air pollutants and land use; demographic projections for mid to late century differ from the projections used in the SRES scenarios; and there is better understanding of the potential for a range of technology options to reduce greenhouse gas emissions. Further, policymakers and decision makers are

asking questions not just about the magnitude and pattern of climate change, but also about how development pathways could ameliorate or exacerbate the risks of climate change and the options for managing these risks. Answering these types of questions requires new variables not included in the SRES scenarios, such as how inequality and governance could evolve over coming decades. Further, new scenarios are needed to cover a wider range of greenhouse gas concentrations (not only scenarios without climate policy, but also covering concentration levels that can be reached by implementing mitigation measures) and to facilitate improved integration of mitigation, adaptation, and impact analyses.

After completion of the SRES process, it was decided that the scientific community rather than the IPCC would lead further scenario development because of the greater scientific credibility of scenarios that would result; the potential for broader participation of

researchers across a range of disciplines and geographic regions; and the growing ability of the climate research communities to self-organize.<sup>5</sup> Accordingly, the scientific community is now developing the next generation of scenarios for use by the climate change science community. The community is organized by several organizations including the Integrated Assessment Modeling Consortium (IAMC) and the International Committee On New Integrated Climate change assessment Scenarios (ICONICS).<sup>6</sup> This article describes the process being followed and the state of development of these new scenarios.

## Methods

Extensive discussions of approaches to and the process for developing new scenarios took place over many meetings and workshops, starting by 2006.<sup>7,8</sup> Discussions have involved members of





Kristie L. Ebi

*Different development pathways will influence children's health, well-being, and future prospects.*

the three main research communities working on aspects of climate change science: earth system modeling (ESM); impacts, adaptation, and vulnerability (IAV; alternatively VIA) researchers; and integrated assessment modeling (IAM). It was decided to take a new approach to developing scenarios. The following sections describe the logic of the process and the scenario architecture being used.

### **Parallel Process**

Participants at the Expert Meeting on Scenarios organized by the IPCC at Noordwijkerhout, the Netherlands, in 2007 formalized a roadmap to develop new scenarios, following a three-step, so-called parallel process.<sup>9,10</sup> Instead of replicating the process used for the SRES that started with driving forces and their resulting emissions, the scientific communities agreed to first choose four pathways of atmospheric concentrations (and their associated radiative

forcing) and land use over the 21st century; these pathways were picked to represent the range of concentrations in the scenarios literature and to meet other criteria. The pathways were then used as input to earth system models to project climate change over this century and beyond.<sup>11</sup> In parallel, social scientists began work on new scenarios describing alternative societal development pathways over the same time period. The plan calls for these development pathways to then be reconciled with the greenhouse gas emissions pathways that could produce the concentration pathways mentioned above. Finally, impacts researchers could use both the societal futures and the climate change projections to evaluate consequences for society and ecosystems.

The new scenario process includes three phases:

- A preparatory phase designed to serve the needs of the earth system modeling community. In this phase, four concentration pathways

(Representative Concentration Pathways or RCPs) were chosen. Because the RCPs incorporate carbon dioxide and other greenhouse gases, they are described in terms of their radiative forcing in watts per square meter in 2100 and their trajectory of change. The four RCPs reach 2.6, 4.5, 6.0, and 8.5 W/m<sup>2</sup> in 2100, corresponding to carbon dioxide equivalent concentrations of approximately 490 ppm, 650 ppm, 850 ppm, and 1370 ppm, respectively. The development of the four RCPs is documented in a special issue of *Climatic Change*.<sup>12</sup>

- A parallel phase (current focus of activity) in which the earth system models are using the RCPs to project climate change, and the IAV and IAM communities would develop alternative societal development pathways that could eventually be combined with the climate change outcomes. The RCPs are being used in simulations by earth





Kirstie L. Ebi

*A wide range of choices will influence future agricultural production, including investment in research and development to develop new cultivars, the rate of diffusion of new technological development, land use, and water availability.*

system models as part of the Climate Model Intercomparison Project (CMIP-5), producing projections of the magnitude and pattern of climate change over this century and, in some cases, to 2300.<sup>13</sup> They are the basis of some of the climate projections assessed in the Working Group I contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis.<sup>14</sup> At the same time, the IAM and IAV communities are developing new descriptions of future socioeconomic conditions, the Shared Socioeconomic Pathways (SSPs).<sup>15</sup>

- An integration phase where scenarios for use in climate change science research and assessment will be developed that integrate the socioeconomic development pathways with the climate change projections and with assumptions about climate mitigation and adaptation policies.<sup>16</sup> Meetings of researchers from the IAM and IAV communities convened

over the past two to three years facilitated development of a framework for socioeconomic development pathways<sup>17–19</sup> (plus a workshop co-sponsored by the IPCC and the government of the Netherlands in The Hague in May 2012). Proposed frameworks informed discussions that led the agreement to use a matrix architecture in developing new scenarios.<sup>20–22</sup>

### Scenario Matrix Architecture

The matrix architecture provides a toolkit for the scientific community to develop scenarios. Using a matrix architecture provides significant flexibility to develop scenarios to address a wide range of policy- and decision-relevant questions. Researchers and analysts can tailor-make scenarios to address specific decisions and policies.<sup>23</sup> In addition, marker scenarios are being developed to facilitate integration across disciplines and comparison within and across research communities.

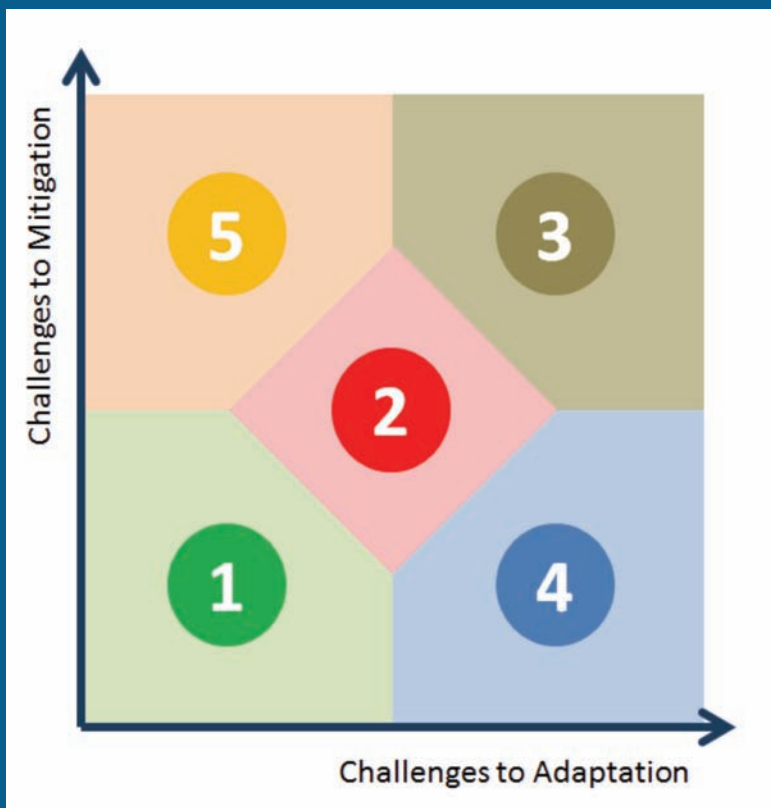
Three building blocks provide qualitative and quantitative elements for the new scenarios:

- Radiative forcing as described in the RCPs, and resulting climate change;
- Socioeconomic development pathways; and
- Climate (mitigation and adaptation) policies.

The socioeconomic development pathways under development are termed Shared Socioeconomic Pathways (SSPs) and can be combined with all or several RCPs when developing a scenario. The climate (adaptation and mitigation) policies are termed Shared climate Policy Assumptions (SPAs).

The rows of the matrix are the level of forcing (as represented by the RCPs) and the columns are the SSPs (described in the next section).<sup>24</sup> Scenarios will be developed within the cells of the matrix—although not all cells will be populated (e.g., it is hard to imagine a scenario where the world is striving for sustainable development, as in SSP1,

Figure 1.



while simultaneously emitting high concentrations of greenhouse gases, as in RCP8.5). When creating a scenario, additional assumptions may be needed about adaptation and mitigation policies to derive a scenario consistent with a given combination of an RCP and SSP; these are the SPAs (described later).

### Shared Socioeconomic Pathways (SSPs)

SSPs define plausible alternative states of human and natural societies at a macro scale. They include a narrative and quantified measures that define the state of societies and ecosystems as they evolve over the 21st century.<sup>25</sup> The SSPs describe reference pathways that assume no new climate policies and no significant climate feedbacks on development. While these are unlikely to be plausible assumptions, they are a useful

first step towards developing scenarios that include climate change projections, impacts, and climate policy responses. As noted previously, the SSP assumptions and quantifications may need to be modified when crafting integrated scenarios.

SSPs are defined along axes describing increasing socioeconomic challenges to adaptation and to mitigation, to encompass a wide range of possible development pathways of relevance for climate change research.<sup>26</sup> Socioeconomic factors considered in the SSPs include aspects of socio-ecological systems, such as demographic, political, social, cultural, institutional, lifestyle, economic, and technological variables and trends. Also included are the human impacts on ecosystems and ecosystem services, such as air and water quality and biodiversity.

Challenges to mitigation include factors and trends that generate high

greenhouse gas emissions in the absence of climate policy and that reduce the social capacity to mitigate those emissions. These include insufficient technologies, inadequate national and international policymaking institutions, and lack of financial and other resources to support mitigation policies, such as political will and human and social capital.<sup>27–29</sup> High reference emissions could result from various combinations of high population growth rates, rapid (conventionally defined) economic growth, energy-intensive economic systems, carbon-intensive energy supplies, and the like. Not all factors need to operate in the same direction to result in high (or low) emissions.

Socioeconomic challenges to adaptation increase the risks associated with any given level of climate change by making adaptation more difficult.<sup>30</sup> Challenges to adaptation include factors such as poverty and how wealth is distributed, ineffective national and international organizations and institutions, limited water and food security, low levels of educational attainment, and high levels of poorly managed urbanization.

The challenges space can be divided into five domains (Figure 1). Along the diagonal axis are (1) low challenges to adaptation and mitigation, (2) medium challenges, and (3) high challenges. Off-axis are (4) low challenges to mitigation and high challenges to adaptation and (5) high challenges to mitigation and low challenges to adaptation. Multiple socioeconomic pathways can lead to each domain. The pathways evolve over time, describing challenges that change over time rather than referencing a particular time period. The adaptation and mitigation challenges are relative to the middle-of-the-road development pathway described in the second domain, which itself evolves over time.

Defining the SSPs by challenges to adaptation and mitigation is very different from earlier scenarios, such as the SRES and the Millennium Ecosystem Assessment scenarios.<sup>31,32</sup> Those scenarios defined their axes by key socioeconomic driving forces assumed to be the principal uncertainties determining



the outcomes of interest (e.g. global vs. regional focus; economic vs. environmental focus). Instead, the SSPs use the outcomes of interest to define the axes. These outcomes are not intended to indicate which combination of socioeconomic elements would produce a given set of challenges, nor which elements are the key uncertainties in those outcomes.<sup>33</sup> Taking this approach allows characterization of uncertainty in the implications of mitigating climate change to a certain level of radiative forcing and of adapting to that level.

Key characteristics of the SSPs include:

- A focus on socioeconomic and environmental (except climate change) trends globally and in large world regions over the 21st century, sufficient to distinguish the SSPs.
- Qualitative narratives describing broad patterns of development.
- Quantifications typically used as input for integrated assessment models of the global energy–economy–land use system or for global-scale

impact models, such as assumptions about future demographics, economic development, and degree of global integration.

- The exclusion of assumptions about new climate adaptation and mitigation policies and decisions on how to most effectively manage the risks associated with climate change.
- Sufficient information for the global narratives to be extended in regional and sectoral scenarios. The SSPs create the boundary conditions within which such extensions can be created.

Based on these characteristics, elements already included in preliminary SSPs or will be included at a later stage include:<sup>34</sup>

- Demographics, including population total and age structure, and urban versus rural populations.
- Economic development, including global and regional gross domestic product, trends in productivity, and proportion of population in extreme poverty.

- Human development, educational attainment, and health.
- Environmental and ecological factors, including air, water, and soil quality.
- Resources, including fossil fuels and renewable energy potentials.
- Institutions and governance, including existence, type, and effectiveness of national/regional/global institutions.
- Technological development, including type and rate of technological progress and diffusion of innovation.
- Broader societal factors, including attitudes to the environment and sustainability, and life styles.
- Nonclimate policies, such as policies on development, technology, urban planning, transportation, energy, and environment.

Based on their placement within the challenges domain, short summaries of the SSPs are (provisional names in italics):<sup>35,36</sup>

- *Sustainability* (SSP 1) describes worlds making relatively good

*The patterns of rural development will differ across the shared socioeconomic pathways.*



Kristie L. Ebi





Floodwater in Srinagar, Kashmir, India.

progress toward achieving development goals. Characteristics include global cooperation, facilitated through effective international organizations and institutions, and low levels of resource intensity and fossil fuel dependency. Low-income countries would rapidly develop, with fewer people below the poverty line, reductions in inequality within and across countries, higher rates of female education, slower population growth, improved population health, increases in planned urbanization, rapid development of clean energy technologies, and a high level of awareness regarding environmental degradation.

- *Middle of the road* (SSP 2) describes worlds where trends typical of recent decades continue, with some progress toward achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Most economies would be politically stable, with partially functioning and globally connected markets. Some international cooperation and technology investments would exist. Uneven development of low-income countries would be a consequence of the limited number of comparatively weak global institutions, with some countries making relatively good progress and others left behind. Urbanization would follow a similar pattern. Educational investments would not be high enough to rapidly slow population growth, particularly in low-income countries.
- *Fragmentation* (SSP 3) describes worlds separated into regional blocks with little coordination between them. These worlds fail to achieve global development goals, with little progress in reducing resource intensity and fossil fuel dependency. Governance and institutions would show weakness and a lack of cooperation and consensus. The regions would be characterized by extreme poverty and pockets of moderate wealth, with the bulk of





Kirstie L. Ebi

*Development patterns will make it easier or more difficult to prepare for and manage the consequences of extreme weather and climate events, such as drought.*

countries struggling to maintain living standards for their strongly growing populations. Mortality rates would be high, with many children dying from preventable diseases (malnutrition, diarrheal disease, malaria). Countries would focus on achieving regional energy and food security goals with little international cooperation and low investments in technology development and education. Most urban growth in low-income countries would be in unplanned settlements.

- *Inequality* (SSP 4) describes highly unequal worlds within and across countries, with regular social conflict and unrest. A relatively

small, rich global elite would be responsible for much of the emissions, which they would be able to mitigate at low cost, while a larger, poorer group would contribute little to emissions. Access to high-quality education, health services, and family planning would be limited, leading to high population growth in low-income countries. Rural areas and mega-cities would house a large fraction of relatively poor and less educated people. Economic uncertainty in industrialized countries would lead to relatively low fertility and low population growth. Global energy corporations would invest in research and development to hedge

against potential resource scarcity or climate policy, developing (and applying) low-cost alternative technologies.

- *Conventional development* (SSP5) describes worlds focusing on self-interested market-driven development oriented toward economic growth to solve social and economic problems. Characteristics of these worlds include attainment of human development goals, robust economic growth, rapid urbanization, highly engineered infrastructure, and highly managed ecosystems. There also would be strong investments in health, education, and institutions to enhance human



Thinstock/Stockholm

and social capital. There would be faith in the ability to manage social and ecological systems, with relatively little specific proactive effort to avoid potential global environmental impacts. The preference for rapid conventional development would lead to an energy system continuing to be dominated by fossil fuels, resulting in high emissions. There would be a strong push for developing countries to follow the fossil fuel- and resource-intensive development model of industrialized countries, focusing on economic growth aided by consumerism and resource-intensive status consumptions.

### **Shared Climate Policy Assumptions (SPAs)**

When combining a particular SSP with a level of radiative forcing to create a scenario, the analyst may need to specify the mitigation and adaptation policies required to reduce emissions to achieve the RCP and to cope with resulting climate change.<sup>37</sup> Because there is a wide variety of such policies, Shared Climate Policy Assumptions (SPAs)

provide a means to employ common assumptions across a wide variety of studies. SPAs capture key climate policy dimensions not specified in the SSPs, describing features of policy such as global and sectoral coverage of greenhouse gas reduction regimes and/or adaptation effectiveness in different world regions. Note that because gross domestic product (GDP) and other elements within an SSP could be affected by climate policies and by climate change impacts, scenarios that include SPAs may need to modify some of the reference SSP assumptions.

### **Discussion**

The new scenarios are beginning to underpin research to provide insights into different possible approaches for more effectively managing the risks of climate change, and can help focus research efforts in reducing key uncertainties in projected impacts and risk management options.

As described in Van Vuuren et al.,<sup>38</sup> it will now be possible to explore what difference development pathways would make in terms of impacts and ease of

managing climate change-related risks in a world on a particular emission pathway, or the possible consequences of different emission pathways in a world on a particular development pathway.<sup>39</sup> For example, if the world is making progress toward sustainable development (SSP1), then what might be the magnitude of water insecurity attributable to climate change under different RCPs? Or, if the world is on track for  $4.5 \text{ W/m}^2$  in 2100, then what might be the magnitude of water insecurity attributable to climate change under different development pathways?

Another key policy-relevant area where the new scenarios can contribute is in facilitating analyses of the possible effectiveness of adaptation and mitigation policies under common assumptions.<sup>40</sup> One challenge with such analyses has been that adaptation assessments typically consider worlds that incorporate the realities of market imperfections, institutional and informational constraints, delayed policy implementation, and other issues, and focus on implementation in the very near term. Mitigation assessments, on the other hand, have often been evaluated with the assumption of full and



Kristie L. Ebi



*Development patterns will influence the extent to which future societies value preserving and maintaining forests and other ecosystems.*

immediate policy implementation. The new scenarios provide an opportunity for science and policy to understand the benefits, trade-offs, human and financial resource requirements, and residual damages under first- and second-best assumptions about the rate, extent, and timing of implementation of adaptation and mitigation policies.

Research is just beginning using the RCPs, SSPs, and new scenarios. At least two modeling intercomparison projects used a preliminary version of the SSPs, along with RCP-based climate simulations, in their experiments (the Agricultural Model Intercomparison and Improvement Project [AgMIP], <http://www.agmip.org/>; and the Inter-Sectoral Impact Model Intercomparison Project [ISI-MIP], <http://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip>). The ISI-MIP project was specifically undertaken to provide modeling results in time for the Working Group II contribution to the IPCC fifth assessment report, scheduled to be released in March 2014.

Research and development on the new scenarios will continue over the coming months and years, evaluating the usefulness of the approach for

climate science research. While undoubtedly complex, the new scenario process offers a flexible approach to addressing research questions relevant for policy- and decision-making on the magnitude and pattern of impacts and on the trade-offs between adaptation and mitigation, and for facilitating national and international assessments.

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tween socioeconomic development pathways, emissions, and climate change impacts, and scenario analyses linking long-term climate change goals to shorter-term actions. **Elmar Kriegler** is vice chair of the research domain Sustainable Solutions at the Potsdam Institute for Climate Impact Research. His research focuses on the integrated assessment of climate change, in particular on mitigation pathways in the context of climate change.

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Traffic in China is a contributing factor to its smog problem.