Systemic Misuse of Scenarios in Climate Research and Assessment

Roger Pielke, Jr.[1], Justin Ritchie[2]

[1]University of Colorado Boulder, [2]University of British Columbia

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ABSTRACT

Climate science research and assessments have misused scenarios for more than a decade. Symptoms of this misuse include the treatment of an unrealistic, extreme scenario as the world's most likely future in the absence of climate policy and the illogical comparison of climate projections across inconsistent global development trajectories. Reasons why this misuse arose include (a) competing demands for scenarios from users in diverse academic disciplines that ultimately conflated exploratory and policy relevant pathways, (b) the evolving role of the Intergovernmental Panel on Climate Change – which effectively extended its mandate from literature assessment to literature coordination, (c) unforeseen consequences of employing a nuanced temporary approach to scenario development, (d) maintaining research practices that normalize careless use of scenarios in a vacuum of plausibility, and (e) the inherent complexity and technicality of scenarios in model-based research and in support of policy. As a consequence, the climate research community is presently off-track. Attempts to address scenario misuse within the community have thus far not worked. The result has been the widespread production of myopic or misleading perspectives on future climate change and climate policy. Until reform is implemented, we can expect the production of such perspectives to continue. However, because many aspects of climate change discourse are contingent on scenarios, there is considerable momentum that will make such a course correction difficult and contested - even as efforts to improve scenarios have informed research that will be included in the IPCC 6th Assessment.

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Introduction: What is the Problem?

Today, many areas of science face challenges related to research integrity. For instance, the so-called "replication crisis" has focused on the irreproducibility of published studies. Stagge et al. (2019) find that less than 7% of articles published in six hydrology and water resources journals in 2017 are reproducible. Similarly, Klein et al. (2018) found that just over half of 28 classic and contemporary studies in psychology could be replicated. Similar issues associated with reproducibility of published research have been found in economics (Cammerer et al. 2016), medicine (Begley and Ellis 2012), and in other fields (NAS, 2019).

Challenges related to research integrity are not limited to the reproducibility of published research. Other issues involved the continued citation of retracted research, such as in the case of fabricated research on pain management (Bornemann-Cimenti et al. 2016),[1] and similarly Sanz-Martín et al. (2016) argue that flawed citation practices have contributed to a false perception of increasing jellyfish populations. Such issues are argued to be at least partially a consequence of perverse incentives in academic research (Edwards and Roy, 2017). Challenges related to research integrity suggest problems within science, but the identification of integrity shortfalls may also reinforce the self-correcting nature of the research enterprise (Jamieson 2018).

Perhaps predictably, issues surrounding challenges to research integrity have become deeply politicized (Saltelli 2018). Some, often on the political right, have used integrity issues in science to undercut the legitimacy of science in political debates (e.g., Randall and Welser 2018). Others, often on the political left, argue that integrity issues in science have been overemphasized, and that a focus putatively on matters of scientific integrity is merely a stalking horse used to delegitimize certain areas of science important for policy (e.g., Oreskes 2018).

If the ensuing debate on research integrity is not fraught enough, this paper enters even more challenging territory: issues of research integrity associated with the practice and culture of

[1] See also, https://retractionwatch.com/the-retraction-watch-leaderboard/top-10-most-highly-cited-retracted-papers/

climate research and assessment. It is thus important and essential to state explicitly and unequivocally up front that human-caused climate change is real, poses significant risks to society and the environment, and various policy responses in the form of mitigation and adaptation are necessary and make good sense (see Pielke 2010). However, the reality and importance of climate change does not provide a rationale or excuse for avoiding questions of research integrity in climate science. To the contrary, it makes them that much more important.

The central problem at the focus this paper is that the misuse of scenarios in climate research has become pervasive and consequential. Scenario misuse has persisted because dynamics of self-correction in many areas of science have not to date resulted in identifying and correcting the misuse. A result has been the unchecked diffusion of climate scenario misuse, a topic which has only begun to receive high-level recognition in the academic literature (e.g., Hausfather and Peters 2020). The misuse of scenarios in climate research means that much of what we think we know about our collective climate future may be incomplete, myopic or even misleading or wrong, and as such, "uncomfortable knowledge" (Rayner 2012).

This paper proceeds in 6 parts. Part 1 explains why the problem matters. Part 2 overviews the role of scenarios in climate research and policy. Part 3 documents in detail scenario misuse and its pervasiveness. Part 4 explores factors underlying scenario misuse. Part 5 examines efforts by the climate science community to improve scenarios and address their misuse, finding such efforts to be so far unsuccessful. Part 6, the conclusion, offers recommendations for how climate science can get back on-track. Ultimately, the misuse of scenarios in climate research offers broader lessons for reinforcing standards of research integrity in the context of highly politicized and contested areas of science.

1. Why does this problem matter?

For decades, climate policy discussions have been grounded in methodologies of scenario planning (Nakicenovic et al. 2000). Anticipating changes in Earth's climate and assessing alternative response options fundamentally requires a multi-decade outlook, necessitating the production and use of long-term scenarios. Twenty years ago scenarios were used in climate research and assessment as plausible alternative futures, but without associated likelihoods

(Nakicenovic et al. 2000). Since that time, scenarios in climate research and assessment have been increasingly used as projections or even predictions of the future. In much of climate research today, scenarios provide a baseline expectation for projecting or predicting the future impacts of climate change as well as impacts potentially avoided, and other benefits of mitigation and adaptation policies. To the extent that scenarios are misused, they offer a restricted or misleading perspective on possible futures, and potentially influence the scope, substance and evaluation of alternative policy options. Since scenarios can be critical for near-term engineering and economic decisions, there can be tangible consequences of scenario misuse.

The issue of climate has been deeply politicized, with advocates for and against aggressive action seeking to wield science as authority in public debates (Pielke 2010). While large majorities of the public support action on climate and trust the scientific community,[2] the climate issue has become increasingly partisan in the United States.[3] To the extent that climate scenarios are misused in research and assessment, this could provide opponents to action with legitimate critiques of climate science, potentially affecting its legitimacy among the public or policy makers.[4] Scientific integrity issues aside, as a matter of political expediency, correcting scenario misuse should be a priority of climate advocates.

Beyond the issue of climate, claims of scientific authority in policy and politics depend in no small part upon its ability to self-correct when evidence warrants. However, such course corrections have proven challenging in some areas. As Sarewitz (2016) argues, "science, pride of modernity, our one source of objective knowledge, is in deep trouble." While the depth and significance of any broad crisis in scientific integrity has been debated, it is uncontestable that flawed research should be correctable and ultimately corrected. To the extent that scenarios are misused in the culture of climate research, it provides an important test of the self-correcting capacity of science in the context of one of the world's most important policy contexts.

Issues related to scientific integrity have already been weaponized in political debates, including climate science. More than a decade ago hacked or leaked emails of climate scientists at the

[2] https://www.pewresearch.org/fact-tank/2019/04/18/a-look-at-how-people-around-the-world-view-climate-change/
[3] https://www.pewresearch.org/science/2019/11/25/u-s-public-views-on-climate-and-energy/
[4] https://www.nytimes.com/2019/05/27/us/politics/trump-climate-science.html

University of East Anglia revealed practices at odds with fundamental norms of science, but did not challenge the fundamental scientific basis of climate change (see Grundmann 2013). The so-called "Climategate" scandal foreshadowed a subsequent decade of intense attacks on and defenses of climate science. It is not clear if these dynamics pose obstacles to course corrections in climate science, but to the extent that scenarios are misused in climate science, it provides a key test of whether the political context within which climate science operates over-rides the self-correcting aspirations of the scientific enterprise more generally.

Here we argue that scenario misuse in climate science offers one of the most significant and underappreciated examples of the current crisis in scientific integrity. The Manichean politics of the climate debate may pose obstacles to course correction. However, as matters of climate policy and politics, as well as science policy and politics, course correction is imperative.

2. Scenarios in climate research and policy

Scenarios are ubiquitous in environmental research, and particularly so in climate research (see, e.g., van Vuuren et al. 2012, Pulver and VanDeveer 2009, Girod et al. 2009, Nakicenovic et al. 2000). The climate research community uses scenarios to "provide plausible descriptions of how the future might unfold in several key areas—socioeconomic, technological and environmental conditions, emissions of greenhouse gases and aerosols, and climate" (Moss et al. 2010). Such scenarios are not just of academic interest, they "play a fundamental role in improving understanding of the climate system as well as characterizing societal risks and response options" (O'Neill et al. 2016). Climate scenarios thus make important contributions to the consideration and evaluation of climate policy options.

The following sub-sections introduce the technical and specialized scenario jargon necessary to describe the Representative Concentration Pathway (RCP) scenario framework that has been central to climate research and assessment for over a decade. The role of scenarios in climate research and assessment is incredibly complex, and demystifying its associated intricate vocabulary is a necessary first step to an evaluation of the use and ultimately misuse of scenarios.

Scenario Nomenclature

Scenarios in climate research are accompanied by a significant amount of specialized jargon. Such jargon creates obstacles for non-specialists to understand scenarios, but this specialized jargon is necessary for understanding the creation, use and misuse of scenarios. This section characterizes the following terms, as employed in RCP scenario development and implementation under the guidance of the Intergovernmental Panel on Climate Change (IPCC):

- Scenario
- Pathway
- Radiative forcing
- Exploratory scenarios
- Normative scenarios
    - Baseline (or reference, no-policy, business-as-usual) scenarios
    - Policy (or intervention, mitigation) scenarios
- Climate Models
- Integrated Assessment Models

Since 2005, those working to support the IPCC assessment process have ultimately sought to organize scenarios under a three-dimensional matrix architecture structure (Moss et al. 2005, Moss et al. 2008, Moss et al. 2010). The three dimensions of this architecture are policy, socio-economics and radiative forcing. The architecture began with two dimensions – radiative forcing and socio-economic assumptions (van Vuuren et al. 2013, O'Neill et al. 2014) -- and a third dimension, "shared climate policy assumptions" was introduced later (Kreigler et al. 2014). Full implementation of the integrated three-dimensional framework across climate research and assessment remains largely aspirational. In much of the literature, scenarios have been employed using only partial elements of this architecture, most commonly the radiative forcing and socio-economic dimensions (and at times, only the radiative forcing element), with shared policy assumptions introduced inconsistently or not at all.

The three-dimensional matrix architecture uses the term *scenario* to refer to "a plausible, comprehensive, integrated and consistent description of how the future might unfold (Nakicenovic et al. 2000) while refraining from a concrete statement on probability" and "specifically refers to integration of socio-economic, climate change, and climate change policy assumptions within the cells of the matrix [architecture]" (van Vuuren et al. 2014).

A climate scenario is comprised of several distinct components, with the term *pathway* used to refer to "the conditions describing the rows and columns of the [scenario] matrix… the term pathway emphasizes that these conditions are not comprehensive scenarios, but are focused on a specific component of the future (climate change or socio-economic circumstances). Only when combined can they provide the basis of an integrated scenario" (van Vuuren et al. 2014). In practice, the use of the term "scenario," even in IPCC publications, often departs from the idealized descriptions, and is commonly used imprecisely to refer to pathways.

Radiative forcing refers to changes in the energy balance of the global Earth system. More precisely and technically, according to the IPCC, radiative forcing is "the change in the net, downward minus upward, radiative flux (expressed in Watts per square meter; W/m^2) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide (CO_2) or the output of the Sun." In less technical terms, increasing greenhouse gases in the atmosphere (like CO_2) alter the planetary energy balance in a way that can be measured by radiative forcing. For its Fifth Assessment report the IPCC notes, "radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value."[5]

Scenarios can be *exploratory* or *normative* (cf. Pielke 2003). *Exploratory* scenarios "are meant to explore a wide range of possible futures, often to widen the scope of options considered by users… usually a set of widely contrasting scenarios is used to explore a range of possible future developments as a function of diverging assumptions for population, income growth and technology development" (van Vuuren et al. 2012). In contrast, *normative* scenarios "focus on the impacts of implementing a more narrowly defined set of goals or policy options… typically based on a central projection in which the current trends continue (assuming no new policies will be implemented), which is contrasted with a set of variants that evaluates the impact of specific policy interventions" (van Vuuren et al. 2012).

[5] https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html

Normative scenarios include *baseline* scenarios (also called “reference,” “no policy” or “business as usual”), which refer to integrated assessment models employed in their ‘free-running’ state, without explicitly included climate or energy policies.[6] Normative scenarios also include *policy* scenarios (also called mitigation or intervention) that involve the introduction of specific policy actions to integrated assessment models. When policies are introduced to the models, this allows for an experimental design that enables researchers to clearly identify – in the modeling results – the independent influence of the introduced policies by measuring changes in results from the baseline.

Baseline scenarios are central to climate research and assessment. Ho et al. (2019) explain that,

> “Baseline emission scenarios are the thread connecting the three working groups composing the Intergovernmental Panel on Climate Change (IPCC) Reports: integrated assessment models produce such scenarios (Working Group III; WGIII), which are fed to climate models producing climate change projections (WGI) which, in turn, are used, together with the socio-economic implications underpinning baseline emissions, to assess the impacts of climate change (WGII).”

Baseline scenarios thus play an important role in much of climate research and its application to policy.

The IPCC Second Assessment Report was extremely careful in its description of baseline and policy scenarios and their idealized nature for exploring mitigation costs and intervention options:

> The function of baseline scenarios in cost studies is to provide a basis of comparison for calculating mitigation costs. It is important to bear in mind that such baselines pose a somewhat artificial distinction between a notional "business-as-usual" case (i.e., what would happen if no mitigation policies were instituted) and a "policy intervention" case (what would happen if they were). Although such a procedure is required to obtain a basis of comparison and thus an estimate of the costs of intervention, in principle it does

[6] van Vuuren et al. (2012) further note that “The central projection is often called a reference, baseline or business-as-usual scenario.”

> not imply anything about the likelihood or relative economic efficiency of the baseline compared to the intervention case (Weyant et al. 1996).

Some scholars reject the entire notion of "baseline scenarios." For instance, Rosen and Guenther (2015) argue, "Because forecasting the future of the energy economy for the next 50–100 years is impossible (not just difficult), there is no valid baseline emissions scenario to which the costs of a mitigation scenario can be compared." Indeed, for much of the decade prior to 2005 the IPCC eschewed the use of baseline-versus-policy scenarios (Nakicenovic et al. 2000).[7]

The IPCC Fourth Assessment Report warned of potential confusion in the use and interpretation of baseline scenarios, due to inherent ambiguities in the definition of what constitutes an energy or climate policy intervention:

> "The root cause of this potential confusion is that, in practice, many policies can both reduce GHG emissions and achieve other goals (so-called multiple benefits). Whether such policies are assumed to be adopted for climate or non-climate policy-related reasons is determined by the scenario developer, based on the underlying scenario narrative" (Metz et al. 2007).[8]

Despite such caveats and concerns baseline and policy scenarios have come to dominate climate research and assessment for more than the past decade, setting the stage for their profound misuse.

Two additional terms of art are necessary to introduce in the context of this paper to describe scenarios and their roles in climate research and assessment.

Climate models are a type of earth system model, which "simulate physical, chemical, and biological processes that underlie climate" (Bonan and Doney 2018). In particular, "climate models focus on the physical climate system, as represented by atmosphere, ocean, and sea ice physics and dynamics and land surface hydrometeorology" (Bonan and Doney 2018). Climate models often emphasize the atmosphere, oceans and land. They are also called "general

[7] De Vries and Peterson (2009) argue that while the the four SRES scenarios were not associated with likelihoods, they did map onto distinctive worldviews.

[8] Compare N. Nakicenovic quoted in Moss et al. (2005): "The concept of "non-intervention" reference scenarios is increasingly becoming elusive and hypothetical as climate policies are becoming a reality in many parts of the world. Much of the Post-SRES literature still includes reference, non-intervention scenarios however."

circulation models" (GCMs) and Atmosphere-Ocean GCMs (AOGCMs). More sophisticated earth system models include additional elements such as the carbon cycle, ecosystem processes, and human influences, among other factors (Bonan and Doney 2018). A central objective of climate modeling (and earth system modeling more generally) is to produce projections or predictions of the future Earth system response to greenhouse gases and other climate forcings in support of both research and decision making (Bonan and Doney 2018).

Integrated Assessment Models (IAMs) "combine representations of human energy use, industrial development, agriculture, land-use/land-cover changes and scenarios of the future development of human societies in order to make projections about the future of anthropogenic and natural ecosystems" (Harfoot et al. 2014). IAMs utilize scenarios as inputs to produce projections as outputs. Weyant (2017) explains, "The objective of these models is to project alternative future climates with and without various types of climate change policies in place in order to give policymakers at all levels of government and industry an idea of the stakes involved in deciding whether or not to implement various policies." The goal of IAMs in many contexts is ultimately useful information to inform policy making.[9]

Climate models do not include representations of social or policy systems, while IAMs do not include detailed representations of the physical climate system. However, climate model experiments typically require the types of inputs that are generated as outputs from IAMs – in particular, trajectories of greenhouse gas emissions, aerosols, land use changes, etc. – which are essential for projecting changes in radiative forcing and thus impacts on the climate system.

Under the IPCC SRES, there was a straightforward conceptual link between recognizable socioeconomic assumptions, IAMs and the IPCC's SRES climate model scenarios (Figure 1 – upper). However, the logic connecting IAMs and climate models became more elaborate under the RCPs. The RCPs were originally selected from specific IAM scenarios but also later interpreted by many users to be IAM-agnostic: the RCP radiative forcing pathways were produced from individual IAMs and in principle were expected to subsequently link to a range of diverse IAMs and emission scenarios (Figure 1 – lower). Under the RCPs, the research emphasis for IAMs was shifted from creating an *a priori* library of fully quantified socioeconomic

[9] For a recent review of critiques of IAMs, see Gambhir et al. (2019).

scenarios that climate modelers could use, to creating a *post hoc* reconciliation of climate model results and socioeconomic possibilities. Therefore, a highly complex (and eventually problematic) relationship was created between socioeconomic assumptions, IAMs and climate models. How the IPCC sought to oversee this complex and problematic relationship over the past 15 years or so is the subject of the next section.

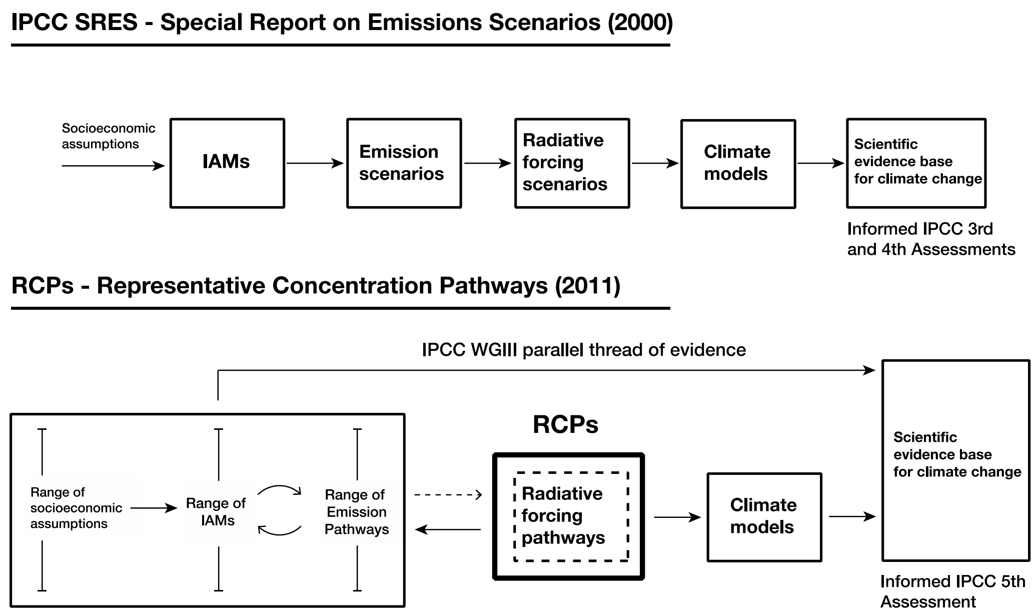

Figure 1. The IPCC Special Report on Emissions Scenarios (2000) scenario development process flow chart (upper) demonstrates a clear link between the explicit socioeconomic assumptions quantified by an IAM and the scenarios used by climate models to produce our scientific evidence base for climate change. The Representative Concentration Pathway (RCP) scenario development process flow chart (lower) illustrates how RCPs were to some degree independent of IAM scenarios, under and expectation that various possible combinations of emission scenarios, IAMs and socioeconomic assumptions could be consistent with individual RCPs.

The Representative Concentration Pathways

The scenario misuse documented in this paper focuses on the role the four RCP scenarios played in the climate research community. The RCPs were initially published in 2011 in a special issue of *Climatic Change* which established the foundation for more than a decade of climate science (van Vuuren et al. 2011). In 2005, a new scenario development exercise that would result in the

RCPs was begun under the auspices and at the request of the IPCC (Moss et al. 2005, Moss et al. 2008). The new exercise employed the "matrix architecture" in order – again, in principle -- to separate radiative forcing from socio-economic assumptions (van Vuuren et al. 2013). After the initial separation, it was intended that radiative forcing and socio-economic assumptions would be later reconciled (van Vuuren et al. 2013). Under the matrix architecture, with four levels of radiative forcing and four sets of socio-economic assumptions, this would result in 16 different scenarios.

However, under the RCP process it was decided to focus on only four scenarios at different radiative forcing levels – a baseline scenario from one integrated assessment modeling team, and three different policy scenarios from three other integrated assessment modeling teams. Four scenarios were preferred because it was a small number that would facilitate computationally intensive climate modeling, the set of four included a high and a low forcing scenario to enable comparisons. The choice of four scenarios was to address the cognitive biases of the scenario users because an even number, "avoids the natural inclination to select the intermediate case as the 'best estimate' " (Moss et al. 2008).

Three fateful decisions were made here. First, a focus on four scenarios, rather than the entire set of 16 (four radiative forcing levels times four integrated assessment models) set the stage for misinterpretation and misuse of the scenarios. Second, renaming the four scenarios as RCPs, rather than carrying forward the names of the actual IAMs that produced the scenarios – IMAGE, MiniCAM, AIM and MESSAGE – helped set the stage for their misuse as an intercomparable set, despite frequent warnings against this practice (Moss et al. 2008, Moss et al. 2010). Third, basing the four RCPs on the existing contemporary range of IAM scenarios carried forward the outcomes of previous comprehensive scenario exercises (like SRES), which inevitably adopted dated socioeconomic assumptions and data, much of which had not been updated since the 1990s (van Vuuren et al. 2011, Ritchie and Dowlatabadi 2017).

A primary motivation for the creation of RCP scenarios was a desire expressed by the IPCC to provide more detailed information on elements of radiative forcing as inputs for climate models, to allow for the evaluation of the costs and benefits of long-term climate policies and to explore the role of adaptation in more detail (Moss et al. 2008, van Vuuren et al. 2011). Moss et al. (2008) explain of the four RCP scenarios that their "primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations." In principle -- but crucially, not in practice – new socio-economic pathways were expected to be developed later following the creation of radiative forcing pathways.

The four scenarios chosen were renamed from their original integrated assessment modeling team names as RCPs based on their ultimate radiative forcing level in 2100: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. With respect to physical climate modeling, the IPCC ultimately prioritized the highest and lowest radiative forcing levels (RCP8.5 and RCP2.6), with RCP4.5 a second priority and RCP6.0 the lowest priority (Moss et al. 2008). Such prioritization was needed due to "scientific and computing limitations" (Moss et al. 2008).

Typically, scenarios and climate projections had been connected in a sequential process, "with socioeconomic and emissions scenarios developed first and climate change projections based on those scenarios carried out next" (Moss et al. 2008, compare upper panel of Figure 1). The development of the RCP scenarios was intended to re-order the scenario development timeline such that the characteristics of radiative forcing would be made available first to climate modelers, in the absence of underlying socio-economic and emissions scenarios which would follow later, as illustrated in Figure 2 from Moss et al. (2008).

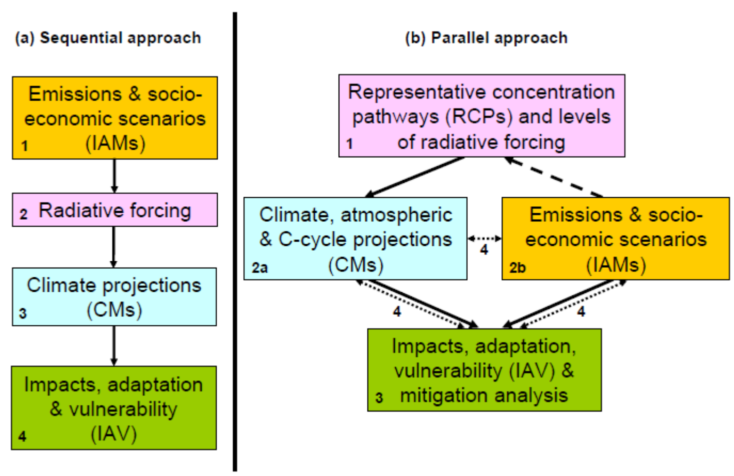

Figure 2. How Moss et al. (2008) characterized the intended new "parallel approach" to scenario development for the RCP scenarios under the IPCC. The caption accompanying this figure reads (emphasis in original): "Approaches to the development of global scenarios: (a) previous *sequential* approach; (b) proposed *parallel* approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Arrows indicate transfers of information (solid), selection of RCPs (dashed), and integration of information and feedbacks (dotted)."

The availability of information on the characteristics of radiative forcing "partially decouples climate science from the issues of socioeconomic projections because a given concentration trajectory can result from different socioeconomic projections" (Moss et al. 2008). The underlying idea was that climate models could be run based on the characteristics of radiative forcing, while in parallel integrated assessment modelers could explore what variety of socio-economic pathways might produce the specified radiative-forcing characteristics.

At the time, it was not well understood how alternative socio-economic pathways might actually result in the prescribed levels of radiative forcing: "It is an open research question as to how wide a range of socioeconomic conditions could be consistent with a given pathway of forcing, including its ultimate level, its pathway over time, and its spatial pattern. The RCPs will facilitate exploration of alternative development futures that may be consistent with each of the four RCPs" (Moss et al. 2008). The RCP development process expressed a preference that, "The group of four RCPs is intended to be representative of the full range of scenarios currently available" (Moss et al. 2008).

Crucially, the "representative" in RCP thus referred to a prior academic literature. The RCPs were not intended to represent real-world plausibilities or the consistency of socio-economic and radiative forcing pathways, which could only be explored through subsequent research addressing the "open research question." As we shall see, such subsequent research revealed some surprises indicating that the RCPs were not in fact representative of a literature or the real world (e.g., Ritchie and Dowlatabadi 2017, Riahi et al. 2017).

In practice, the development of the RCPs did not follow the parallel approach that was envisioned by the IPCC in 2008. The selection of four scenarios from the existing literature on integrated assessment model scenarios to represent each of the selected RCP forcing levels meant that "the RCPs are intended primarily to serve as concentration pathways to drive climate modeling, *but are based on fully articulated scenarios in the literature*" (Moss et al. 2008, emphasis added). In other words, the radiative forcing characteristics of the RCPs were the result of a prior sequential process of scenario development, fully based on socioeconomic and emissions characteristics of the relevant integrated assessment model.

The RCP process thus actually followed the "sequential process" of Figure 2 above, and it was only years later that something approximating the "parallel process" resulted in what are called

Shared Socioeconomic Pathways (SSPs) which were then associated with a new generation of radiative forcing pathways (Riahi et al. 2017). The heritage of the RCPs in existing, fully articulated IAMs was largely lost upon most of the community.

Because a parallel scenario development process took more than a decade to realize, the RCPs filled the gap, which fueled misperceptions of the RCPs in the climate research community. When the original RCP designers wrote "the socio-economic scenario underlying each RCP is just one of many possible scenarios that could be consistent with the concentration pathway" in practice this was interpreted as meaning climate model experiments based on concentration pathways could ignore explicit tangible links to plausible socioeconomic scenarios. This perception is reflected in the sustained misuse of RCPs throughout the literature. Yet, representativeness was a premature conclusion reached prior to an independent of rigorous interdisciplinary explorations of the socioeconomic and policy characteristics that may have been consistent with each RCP trajectory.

Decoupling the RCPs from relevant socioeconomic characteristics therefore served to create a *plausibility vacuum* which failed the original scenario architecture goals established to ensure plausibility and consistency. The initially selected IAM scenarios were directly intended to "provide useful information on the internal logic and plausibility of each of the individual RCPs" so they could be "judged as plausible story of the future by experts" (van Vuuren et al. 2011). As climate model experiments broke away from these archetypal IAM scenarios, there was no longer a definitive means to assess the plausibility of specific RCPs - they quickly became central to climate research and assessment without an accompanying mechanism to evaluate plausibility and consistency.

In the next section we document two major misuses of the RCP scenarios during their use at the basis of more than a decade of research and assessment in climate science.

3. Misuse of the RCPs in Climate Research and Assessment

There is a large literature on the use and misuse of scenarios in policy and politics. The focus of this critique is narrowly on two inter-related symptomatic misuses of the RCPs in climate research and assessment. One involves the role that the most extreme RCP has played as a reference or a plausible "business as usual" scenario. The second misuse involves the frequent comparison of other RCPs to the most extreme scenario in order to generate estimates of the future climate impacts avoided through mitigation, or as the basis for cost effectiveness or cost benefit analyses. These two misuses are pervasive in the scientific literature and in scientific assessments.

RCP8.5 as a Reference Scenario (aka Business as Usual)

For more than a decade, climate research and assessment has emphasized an extreme and implausible representation of the future under RCP8.5. The misuse of RCP8.5 often conflates its concentration pathway with its associated integrated assessment model-based scenario, or perpetuates the idea that RCP8.5 should only be viewed as a scenario of greenhouse gas concentrations. Misuse also commonly includes the characterization of either the pathway and/or the scenario as the world's most likely future in the absence of climate policies, often expressed as "business as usual." As a result, RCP8.5 has been used extensively as a baseline for projecting future climate impacts and evaluating policy options.[10] The misuse of this particular scenario has been consequential, as it has been emphasized by the IPCC, the U.S. National Climate Assessment and is pervasive in the underlying literature that these assessments rely upon. A Google Scholar search indicates almost 4,500 articles referring to RCP8.5 and "business as usual."[11]

Accordingly, there is a "sizeable portion of the literature" that has used RCP8.5 as a baseline or reference scenario, indicating that it is the world's most likely future in the absence of mitigation policies (Hausfather and Peters 2020). Such characterizations should not be surprising because the original paper introducing RCP8.5 to the research community characterized it as: "Compared

[10] We refer to RCP8.5 as a scenario in the context of its use to represent a plausible description of a business-as-usual future, following the nomenclature of the original Riahi et al. (2011) paper that introduced RCP8.5 to the literature.

[11] Specifically, the search was conducted 6 March 2020 in the following format: "[RCP8.5 OR "RCP 8.5"] AND "business as usual"." Not all papers that combine these terms characterize RCP8.5 as "business as usual" but an inspection of the papers indicates that almost all of them do. Similarly, some papers do not use the phrase "business as usual" but nonetheless employ RCP8.5 as a baseline or reference scenario. In contrast, the same search with RCPs 2.6, 4.5 and 6.0 results in 2,240, 2,710 and 1,090 articles, as these RCPs are typically presented in combination with RCP8.5.

to the scenario literature RCP8.5 depicts thus a relatively conservative business as usual case with low income, high population and high energy demand due to only modest improvements in energy intensity" (Riahi et al. 2011).[12]

RCP8.5 originates in a revised version the IPCC SRES A2 scenario (labelled A2r) using the MESSAGE integrated assessment model (Riahi et al. 2011, Riahi et al. 2007). The MESSAGE A2r scenario was one of three baseline scenarios presented in Riahi et al. (2007). The other two baseline scenarios were based on the SRES B2 scenario, with a baseline radiative forcing level of 6.6 W/m^2 and the SRES B1 with a baseline radiative forcing level of 5.5 W/m^2.[13] Riahi et al. (2007) issued a caution on its high and low baseline scenarios: "Readers should exercise their own judgment on the plausibility of above scenario 'storylines' that contain, particularly in the two more extreme scenarios A2r and B1, a number of normative scenario elements."

Issues associated with RCP8.5 and its use as "business as usual" were explored systematically by Ritchie and Dowlatabadi (2017), who argue that normative, dated and incorrect assumptions of possibilities for future coal consumption, in particular, render obsolete high radiative forcing pathways that are based on very high fossil fuel emissions trajectories. Their critique focuses on the theory of "learning by extracting" – which posits simply that the more fossils fuels that we extract, the more we learn, thus costs go down and then we continue to extract more and more independent of other relevant cost and technology factors. This particular theory of fossil fuel exploitation has proven to provide an incorrect guide to real-world patterns of energy consumption because it reflected normative assumptions that energy technologies would emerge to meet scenario requirements of, "drastic specific … improvements with implicit improvement rates several times the historically observed average" (Rogner 1997). Ritchie and Dowlatabadi (2017) concluded, "RCP8.5 does not provide a physically consistent worst case BAU trajectory that warrants continued emphasis in scientific research. Accordingly, it does not provide a useful benchmark for policy studies."[14]

Each of the IAMs underlying the four RCPs utilized a unique baseline level of radiative forcing in order to generate the policy scenarios resulting in the prescribed, lower radiative forcing

[12] In contrast van Vuuren et al. (2012) identified IPCC SRES B2 (comparable to RCP6.0) as a "business as usual" scenario.
[13] MESSAGE A2r has a radiative forcing level of 9.3 W/m^2.
[14] Others also have questioned the appropriateness of RCP8.5 (e.g., Capellán-Pérez et al. 2016, Mohr et al. 2015).

levels. The decision to utilize MESSAGE A2r as the sole baseline scenario included in the four RCPs conveyed the impression that it was *the* appropriate baseline scenario to use in climate research and assessment and that the other three RCP scenarios were only associated with globally coordinated climate policy. Such an impression was reinforced by the complex requirements of the RCPs in order to enable their output to be appropriate as input to climate models (van Vuuren et al. 2008). This created an availability bias – RCP8.5 was the only baseline scenario available under the RCP framework, and therefore for research employing the RCPs, it was the only possible scenario to be considered as "business as usual."[15]

It is important to note that since the IPCC's First Assessment Report, the climate research community sought to move away from officially designating a single scenario as 'the' business as usual scenario, and instead sought to create a wide range of no-policy baselines, such as with SRES (2000). Yet, by explicitly positioning the extreme RCP8.5 scenario as the only clearly defined baseline, the scenario user community of downstream scientists and policy researchers would therefore naturally see RCP8.5 as 'the BAU' scenario. The availability bias resulting from providing only one reference scenario thus inevitably placed this scenario into a central role in research and assessment.

Beyond specific problems with RCP8.5, the treatment of any scenario as a "business as usual" scenario has long been contested and debated. For instance, the IPCC SRES report eschewed the use of "business as usual" or equivalent scenarios as well as the distinction between reference and policy scenarios: "The broad consensus among the SRES writing team is that the current literature analysis suggests the future is inherently unpredictable and so views will differ as to which of the storylines and representative scenarios could be more or less likely. Therefore, the development of a single "best guess" or "business-as-usual" scenario is neither desirable nor possible." (Nakicenovic 2000. p. 169). Ritchie and Dowlatabaldi (2017) observe that selection of a scenario as "business as usual" necessarily conveys a likelihood estimate: "there is an implicit suggestion of high probability when a scenario is labeled as "baseline", "business-as-usual"…" – in other words, a business as usual scenario is readily interpreted as our most likely future in the absence of intentionally introducing new policies. Often lost is that a baseline scenario of an

[15] This availability bias was reinforced by the IPCC's direct association of RCP8.5 with the range of reference scenarios in the full AR5 scenario database, as shown in IPCC AR5 WG3 Figure 6.7 and AR5 Synthesis Report SPM.11

IAM says something about a model's internal workings or a hypothetical world represented by a model, but not necessarily anything about the real world.

Even among those who view "business as usual" scenarios as appropriate, some (including the developers of the RCPs) expressed a perspective that extreme scenarios, such as RCP8.5, are not appropriate as "business as usual."[16] For example, Van Vuuren et al. (2012) explained that "business as usual" scenarios "are not derived from a storyline that deliberately emphasizes a specific 'extreme' position, but from a storyline that assumes that historical dynamics will also be guiding the future. In quantitative terms, this often translates into 'intermediate' value." In addition, Van Vuuren et al. (2012) warned that the use of a single baseline scenario could lead to a conflation of scenarios and predictions: "only using the single baseline/variant approach does constitute an important risk: by not identifying some of the major fundamental uncertainties society is facing, the scenario results may only be true under a limited set of assumptions and falsely suggest that we know the future." Such misplaced certainties could result from ignoring or displacing scenario uncertainty, which may be more important than "environmental policy" uncertainties (van Vuuren et al. 2012, cf. Robinson 2003).

In addition, the selection of a single baseline or "business as usual" scenario means that perspectives arising from the use of multiple plausible baselines are lost: "While the method provides simplification and focus, this comes at a cost in case the policy-actions studied are smaller than the range of possible outcomes due to uncertainties in baseline assumptions, or if the effectiveness of the policy interventions is itself to a large extent dependent upon the very baseline assumptions" (van Vuuren et al. 2012). The selective use of business-as-usual scenarios requires the utilization of "implicit assumptions" which van Vuuren et al. (2012) argues creates "a risk of ''stealth advocacy'' (Pielke, 2007) if these implicit assumptions (e.g. preference for financial instruments) influence the results."

The original basis for the scenarios supporting RCP8.5 are extreme: they project a future that is characterized by high population, little technological advancement, extremely high carbon dioxide emissions and apocalyptic levels of climate change. Via RCP8.5, this outlook on the future was subsequently adopted for thousands of academic studies that predict or project future

[16] The IPCC in its First and Second assessments used extreme scenarios as "business as usual" – See IPCC (2013).

climate impacts on people and the environment, evaluate the costs and benefits of adaptation and mitigation policies, as well as estimate the cost effectiveness of policies designed to meet mitigation targets. The influence of this implausible scenario on public and policy discussion of climate change is pervasive and consequential.

Methodologically Illogical RCP Comparisons

Across the literature and within major assessments it is common to compare model outputs from RCP8.5, positioned as a baseline scenario, with model outputs from another RCP (typically RCP4.5 or RCP2.6) represented as a world with the successful implementation of climate policy. In these cases, RCP8.5 may not always be explicitly labeled BAU, but as a ‘high emission’ scenario that is valid to compare as a baseline or reference with ‘low emission’ scenarios. The difference in observed outcomes in such comparisons is intended to convey the benefits of mitigation policy, that is, the moving of the real word from its RCP8.5 trajectory to an alternative path represented by another of the lower-forcing RCPs based solely on climate policy.

However, such a comparison is methodologically incorrect and illogical. Moss et al. (2010) explained: “The RCPs cannot be treated as a set with consistent internal logic. For example, RCP8.5 cannot be used as a no-climate-policy reference scenario for the other RCPs because RCP8.5’s socioeconomic, technology and biophysical assumptions differ from those of the other RCPs.” The RCP Scenario Database explains in more detail: “the RCPs with lower radiative forcing (RCP 6.0, RCP 4.5 and RCP 2.6) are not derived from those with higher radiative forcing (RCP 8.5, or even RCP 6.0). The differences between the RCPs can therefore not directly be interpreted as a result of climate policy or particular socioeconomic developments.”[17] This means that any comparison of RCPs involving their socio-economic characteristics or values derived from those characteristics – with RCP8.5 used as a baseline and another used as a policy scenario – is invalid.

Despite the warnings on proper use of the RCPs, differences between the RCPs have been commonly interpreted as a projected consequence of climate policy implementation in the real world. For instance, the IPCC AR5 Working Group 1 Summary for Policymakers stated: “four

[17] https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome#descript

RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5). The RCPs can thus represent a range of 21st century climate policies…"[18] This stands in stark contrast to the cautions expressed for proper interpretations of differences between RCPs, which "may very well result from differences between models" (van Vuuren et al. 2011).

Similarly, the IPCC AR5 Working Group 2 Summary for Policymakers characterized differences between RCP8.5 and RCP2.6 as the result of climate policy: "The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the assessed scenario with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century."[19] However, van Vuuren et al. (2011) warned that it is not possible in many models to reach a radiative forcing level or 2.6 W/m^2 from an emissions trajectory "as high as in RCP8.5." Thus, if the world were indeed really headed to RCP8.5, then RCP2.6 would not be an appropriate mitigation scenario to use as a comparison.

Of course – to be absolutely clear -- one does not need the RCPs, or climate scenarios for that matter, to understand that higher levels of radiative forcing resulting from human activities, notably the burning of fossil fuels, are accompanied by higher levels of risk (Pielke 2010). However, the IPCC AR5 WG1 and WG2 each went well beyond high-level characterizations of risk to summarize detailed comparisons between RCP studies as indicative of the consequences of mitigation policies on projected societal and ecological impacts of climate change. At best such comparisons are methodologically flawed, at worst they are fundamentally misleading.

If, in such comparisons, RCP8.5 is intended to be utilized simply as an extremely high radiative forcing trajectory without any associated socio-economic context, then in this case the concentration trajectory is a "pathway" and not a scenario, which integrates pathways of radiative forcing and socio-economic assumptions (van Vuuren et al. 2014). As such, the results of such a comparison of radiative forcing pathways on physical climate outcomes (such as sea level rise) would properly be called a sensitivity analysis (of a climate outcome to different

[18] http://www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf
[19] https://www.ipcc.ch/site/assets/uploads/2018/03/ar5_wgII_spm_en-1.pdf

radiative forcing pathways, all else equal). The IPCC AR5 (2013) makes no such distinction, "RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models."

Using or referring to RCP8.5 as a *scenario* by definition invokes its socioeconomic assumptions. Specifically, if a comparison across RCPs involves vulnerability, impacts, adaptation or policy related to social or biological systems, then that comparison is misleading, as the RCPs represent vastly different worlds, within which projected changes in vulnerability, impacts, adaptation and policy will depend upon far more than just different radiative forcing levels. The use of RCP8.5 in such comparisons between high and low emission scenarios is further fundamentally misleading because it represents an implausible future and thus is inappropriately used as a baseline scenario when it its only used appropriately as an exploratory scenario.

For example, the IPCC 5th Assessment and the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate each include a plethora of images contrasting RCP8.5 to RCP2.6. This lends itself to being misinterpreted as a misleading binary choice between a world without climate policy on track for RCP8.5 and a world with effective climate policy on track for RCP2.6.

Comparisons across RCPs have largely ignored the fact that the plausibility of each RCP end-point in 2100 is the product of a unique integrated assessment model, and each such model has its own unique reference scenario, in addition to three additional scenarios associated with the four RCP forcing levels. The RCPs are thus actually four families totaling 16 scenarios.[20] The creators of RCP4.5 explain, "Each of the RCPs was produced by a different integrated assessment model; therefore, each has its own reference scenario… Thus, the reference scenario for RCP4.5 is not RCP8.5…" (Thomson et al. 2011). Similarly, van Vuuren et al. (2008) warned that regional information produced under the different RCPs "is intended for purposes of validation and to facilitate climate modeling. This information should not be used to infer regional differences across RCP stabilization levels because regional details and modeling approaches differ between the four IAM modeling groups."

[20] Van Vuuren et al. (2012) observe: A "*scenario family* denotes a set of scenarios in the literature that seem to share a very similar scenario storyline or logic."

Table 1 shows characteristics of the baseline scenarios associated with each RCP. RCPs 4.5 and 6.0 represent the results of model runs with climate policy interventions applied to a baseline scenario of 7.0 W/m^2 while RCP2.6 represents climate policy applied to a baseline of 7.2 W/m^2. Similarly, RCP8.5 represents a baseline scenario, but is accompanied by model runs with climate policy interventions leading to other, lower forcing levels. A proper comparison would be between different model runs utilizing the same integrated assessment model with consistent socioeconomic assumptions, such as between the IMAGE 2.4 B2 baseline with its climate intervention scenario resulting in a forcing level of 2.6 W/m^2 or MESSAGE V.2 SRES A2r with its climate intervention scenario resulting in a forcing level of 4.5 W/m^2. Of course, these four baselines are not unique (cf. Riahi et al. 2007) – the IPCC AR5 scenario database includes more than 250 baseline scenarios. Thus comparisons between a baseline and a policy scenario within the context of a single IAM would only represent a single example of many possible such comparisons across the scenario literature.

Scenario	Baseline IAM	Baseline radiative forcing	Reference
RCP2.6	IMAGE 2.4 B2	7.2 W/m^2	Van Vuuren et al. 2011b
RCP4.5	GCAM 2.0	7.0 W/m^2	Thomson et al. 2011
RCP6.0	AIM SRES B2	7.0 W/m^2	Masui et al. 2011
RCP8.5	MESSAGE V.2 SRES A2r	8.5 W/m^2	Riahi et al. 2011

Table 1. Characteristics of baseline scenarios for each RCP.

Figure 3 shows the actual matrix architecture underlying the RCPs as employed. Across the four independent integrated assessment models there were four different baseline scenarios. Each baseline was modified by the introduction of policies within the models to arrive at three different prescribed forcing levels. A proper comparison of baseline scenarios to policy scenarios (irrespective of the plausibility of either with respect to the real world) would take place *within* the columns of the matrix. Any comparison across different columns is methodologically inappropriate, and this was emphasized by the scenario architects: “The socioeconomic and technology assumptions are not consistent between the RCPs and thus the socioeconomic scenario underlying one RCP should not be used in conjunction with that of another RCP. For instance, the high RCP cannot be considered a baseline against which lower RCPs can be directly compared" (Moss et al. 2008). It is thus methodologically inappropriate to compare the individual RCP scenarios with each other in any way that depends upon socioeconomic or technological assumptions.

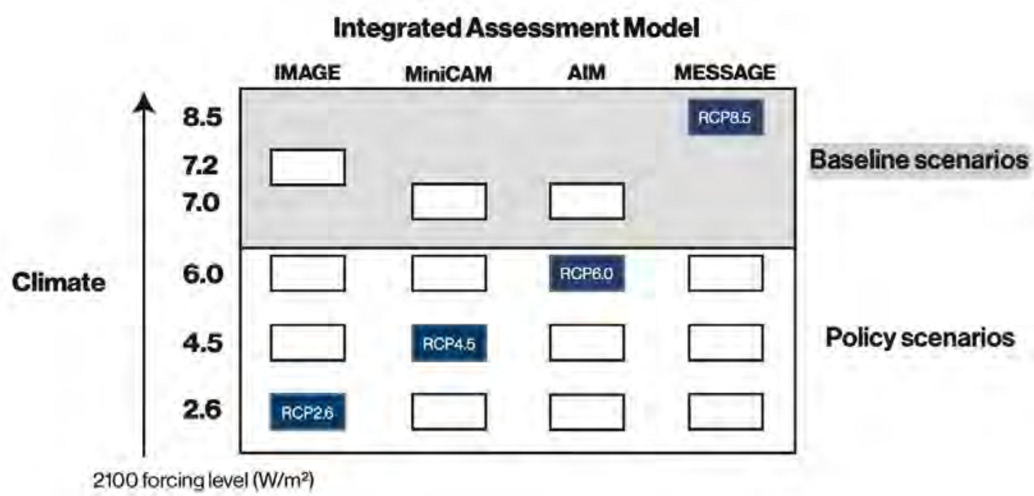

Figure 3. The actual matrix architecture of the RCP scenarios as implemented. The blue boxes indicate the four scenarios chosen from the set of 16 to serve as the RCPs.

Several complexities are immediately apparent upon recognizing appropriate comparisons of baselines and intervention scenarios. First, Table 2 shows differences in RCP baseline scenarios for assumed population and GDP in 2100, just two of many potential differences in socio-economic assumptions. These baselines represent vastly different envisioned future worlds, and thus comparing model outputs that depend upon different socio-economic pathways – such as policy or impacts – is methodologically inappropriate. A methodologically appropriate comparison of baselines with, for instance, a radiative forcing level in 2100 of 2.6 W/m^2 resulting from interventions introduced into the models would involve four paired comparisons within each RCP family, that is, within each of the columns of Figure 3.

Such comparisons would involve more than simply differences in radiative forcing, but also differences in assumptions of the socioeconomic pathways of the difference scenarios. As Robinson (2003) observed, differences between scenario pathways may be more significant than differences within scenarios due only to alternative projections of greenhouse gas emissions: “The difference between the different pathways may swamp the differences between any one pathway and its variants. For example, in the greenhouse gas emission scenarios prepared for the IPCC, it turns out that the differences among the four [SRES] underlying socio-economic and technological development pathways are as great as the difference between different scenarios of energy supply or demand within any of these pathways” (cf. Nicholls and Tol 2006, Pielke et al. 2000). Or as Hulme (2019) argues, “there are some futures beyond 1.5°C (or even 2°C) that are *more* desirable than other futures which do not exceed these warming thresholds.”

Scenario	Population in 2100	GDP in 2100	Reference
RCP2.6	9.1 billion	$329 trillion (1995$)	Van Vuuren et al. (2010)
RCP4.5	8.7 billion	$340 trillion (2005$)	Thomson et al. (2011)
RCP6.0	9.8 billion	$225 trillion (2005$)	Masui et al. (2011)
RCP8.5	12 billion	$250 trillion (2005$)	Riahi et al. (2011)

TABLE 2. Population and GDP assumptions of the baseline scenarios of the RCPs.

Second, the meaningfulness of even these comparisons is limited because all four RCPs utilized high baseline forcings: three RCPs utilize a baseline of 7.0 W/m^2 (or slightly above, in the case of RCP2.6) and one a baseline of 8.5 W/m^2. Yet, in its overview and presentation of the RCP scenarios, van Vuuren et al. (2011a) identify three of the four scenarios of the RCPs to be consistent with baseline scenarios of other integrated assessment models in the literature, with radiative forcing levels in 2100 ranging from 4.5 W/m^2 to 8.5 W/m^2:

- RCP4.5 is characterized as representing both “medium-low mitigation” and a “very low baseline;”
- RCP6.0 as representing both “high mitigation” and a “medium baseline;”
- RCP8.5 as representing a “high baseline.”

In principle, in the absence of assigned likelihoods to reference scenarios, then a comparison of baselines to other forcing levels that would be truly representative of the broader literature would have involved not just high baselines of 7.0 W/m^2 and above, but also lower baselines, including those in the range of 4.5 to 6.0 W/m^2.[21] The selective use of high baseline scenarios in the RCPs thus represented a bias with respect to the broader literature as represented by van Vuuren et al. (2011a). The RCPs were not, in fact, representative.

Third, complexities increase exponentially upon realization that the IPCC Fifth Assessment report scenario database includes 257 reference scenarios, representing a wider range of envisioned futures, across more than 50 different models. These reference scenarios are associated with 927 policy scenarios. The space of envisioned futures under these 1,174 scenarios is far greater than that mapped by the policy and no policy baselines that originally supported the four RCPs, or even the complete RCP scenario matrix of 16 scenarios. Ritchie and Dowlatabadi (2018) find that there are actually very few specific socioeconomic pathways that reach the radiative forcing level of RCP8.5, and of these all are associated with a severe course change from past energy use trends – a divergence from what would be recognizable as a credible baseline trajectory.

Therefore, not only is it methodologically incorrect to use RCP8.5 as a baseline, against which the other RCPs are compared as policy scenarios, but even the proper use of baseline scenarios within each RCP integrated assessment model set would result in a set of four paired comparisons that is an extremely small subset of the relevant scenario literature. Of course, because the RCP scenarios were developed before most of the scenarios of the IPCC AR5 scenario database, it is logical that they would not necessarily be "representative" of the 1,174 scenarios in that database.[22] Indeed, subsequent research has indicated that a forcing level of 8.5 W/m^2 "can only emerge under a relatively narrow range of circumstances" (Riahi et al. 2017). But by this time this was discovered, RCP8.5 had already become a centerpiece of climate research.

[21] About a third of the baseline scenarios of the more recent Shared Socioeconomic Pathways fall below 6.0 W/m^2, with the lowest at 5.0 W/m^2 (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10 and Riahi et al. 2017).

[22] As Moss et al. (2008) noted: "Most new IAM scenarios will not have any relationship to the RCPs, given that an RCP is only one scenario created by a single modeling team."

One outcome of the creation of the RCPs was to make socioeconomic pathways largely irrelevant to associated research on the physical climate system. This allowed physical science research to focus on pathways of greenhouse gases that may presumably arise from many different possible future developments in a plausibility vacuum: “A parallel approach using RCPs partially decouples climate science from the issues of socioeconomics because a given concentration trajectory can result from different socioeconomic projections and IAM model outcomes” (Moss et al. 2008). However, as Figure 4 shows, radiative forcings and temperature changes to 2100 for three 2.6 W/m^2 stabilization scenarios to 2100 associated with the RCP IAMs vary by more than 0.5 W/m^2 - reflecting major differences across models.[23] While exploration of the significance of different trajectories of radiative forcing and temperature change for projected climate impacts and evaluation of policy responses goes well beyond the scope of this paper, it is not unreasonable to suggest that such differences would be relevant to the timing and magnitude of future climate change, and thus also to impacts and policy, independent of any differences in socioeconomic pathways within integrated assessment models.

[23] https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about

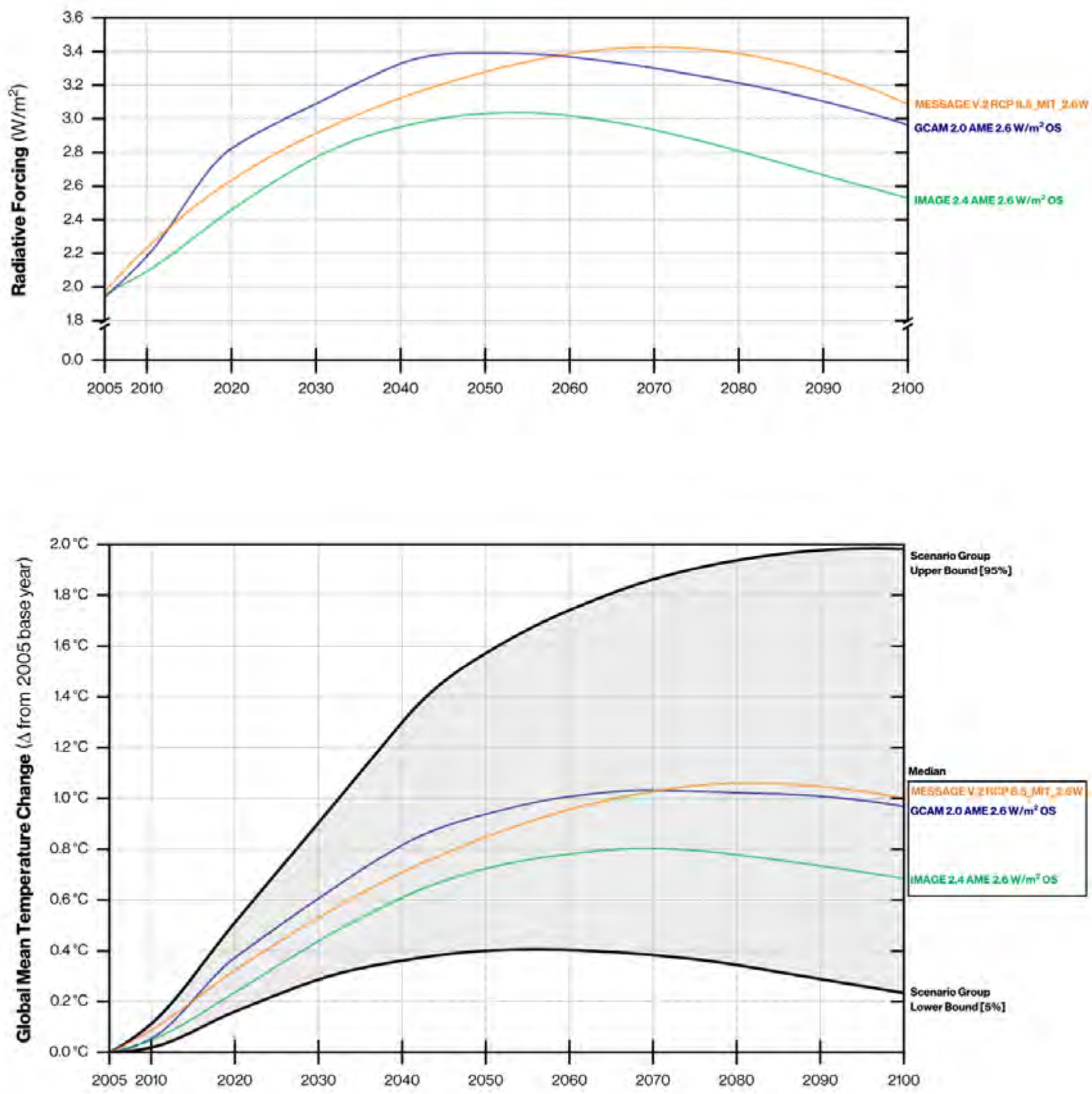

Figure 4. Different trajectories of radiative forcing (upper) and global mean temperature change (lower) to 2100 for three 2.6 W/m^2 stabilization scenarios of the RCP scenario family IAMs.

Perhaps ironically, the creation of the RCPs exacerbated (while simultaneously masking) a fundamental challenge to the use of scenarios in climate research. Prior to the development of the RCPs, Riahi et al. (2008) observed that "the climate policy analysis literature has, to date, been 'plagued' by significant problems of incomparability of results because different models and analyses continue to use widely different projections and scenarios as their analytical basis." Because they are based on four different IAMs, the use of the RCPs has also been plagued by these significant problems, which were easy to overlook by non-experts due to the common naming convention and the bifurcated purposes of the RCPs as pathways for use as input to climate models and RCPs as full scenarios for use in interpreting and integrating climate model results with analysis of climate impacts and policy.

Examples of RCP Scenario Misuse

Examples of RCP scenario misuse – both RCP8.5 as business-as-usual and methodologically inappropriate RCP comparisons – are commonly found throughout the literature. So too are appropriate uses of RCP pathways as inputs to climate models (e.g., Taylor at al. 2012). This section documents instances of RCP scenario misuse, in the U.S. National Climate Assessment, by the IPCC, and presents data on RCP prevalence in the broader underlying literature. These examples are both representative and indicative of systemic instances of misuse found across climate research and assessment.

US National Climate Assessment

The Fourth U.S. National Climate Assessment (USNCA) was published in two parts in 2017 and 2018 (USGCRP 2017, 2018). Throughout, the report uses RCP8.5 as a baseline scenario and the other three RCPs – in particular RCP4.5 – as policy scenarios. USNCA (2017) states: "RCP8.5 implies a future with continued high emissions growth, whereas the other RCPs represent different pathways of mitigating emissions... all of the three lower RCP scenarios (2.6, 4.5, and 6.0) are climate-policy scenarios." The USNCA (2018) explicitly used RCP8.5 as a baseline to evaluate the benefits of mitigation by comparing it to RCP4.5: "Comparing outcomes under RCP8.5 with those of RCP4.5 (and RCP2.6 in some cases) not only captures a range of uncertainties and plausible futures but also provides information about the potential benefits of mitigation." The report also characterizes (incorrectly) sea level rise associated with RCP8.5 as "intermediate."[24]

The misuse occurred despite USNCA (2017) warning against the use of RCP8.5 as a baseline scenario: "RCP8.5 reflects the upper range of the open literature on emissions, but is not intended to serve as an upper limit on possible emissions nor as a business-as-usual or reference scenario for the other three scenarios." The report (USNCA 2018) justified its use of RCP8.5 as a baseline by incorrectly claiming that it accurately represented recent emissions trends: "Current trends in annual greenhouse gas emissions, globally, are consistent with RCP8.5." This rationalization ignores the fact that scenarios such as the RCPs are defined by their long-term targets, and that short-term convergences of any one RCP with observations does not indicate it is more likely in the long-term future than another long-term scenario (van Vuuren et al. 2010). Further, data available at the time clearly contradicted this statement (Le Quéré et al. 2017).[25] The claims by the USNCA (2017, 2018) followed the publication of papers critiquing RCP8.5 such as of Ritchie and Dowlatabadi (2017) which were uncited by USNCA (2017, 2018).

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front page story, the *New York Times* promoted the report's misuse of RCP8.5 as a baseline scenario:

> "A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century's end."[26]

Of the RCPs, Table 3 (below) shows that RCP8.5 was more than 50% of scenario references in both parts of the USNCA report (specifically, 54% in part 1 and 58% in part 2). To the extent that RCP8.5 is misused as baseline scenario for evaluation of impacts avoided and benefits of

[24] See Table A3.1 in USNCA (2018).
[25] In fact, similar data can be found in a table on p. 152 of USNCA (2017).
[26] The 10% value comes from the most extreme estimate based on RCP8.5 utilized as "business as usual" found in a study referenced by the USNCA (Hsiang et al. 2017).

mitigation, the parts of the USNCA that employ RCP8.5 in this manner are not relevant to real-world policy discussions and even misleading.

IPCC Special Report on Ocean and Cryosphere in a Changing Climate

The IPCC Special Report on Ocean and Cryosphere in a Changing Climate (SROCC, IPCC 2019) also used RCP8.5 as a baseline against which it compared RCP2.6 as a policy scenario:

> "This report uses mainly RCP2.6 and RCP8.5 in its assessment, reflecting the available literature. RCP2.6 represents a low greenhouse gas emissions, high mitigation future, that in CMIP5 simulations gives a two in three chance of limiting global warming to below 2ºC by 2100. By contrast, RCP8.5 is a high greenhouse gas emissions scenario in the absence of policies to combat climate change, leading to continued and sustained growth in atmospheric greenhouse gas concentrations."

As with the USNCA (2017, 2018), the IPCC SROCC justified its use of RCP8.5 as a baseline with a claim that current emissions trajectories were following RCP8.5:

> "Current emissions continue to grow at a rate consistent with a high emission future without effective climate change mitigation policies (referred to as RCP8.5). The SROCC assessment contrasts this high greenhouse gas emission future with a low greenhouse gas emission, high mitigation future (referred to as RCP2.6)…"

There was even further evidence by 2019 that emissions trajectories were not continuing to grow consistent with RCP8.5 (e.g., Le Quéré et al. 2018). And even if short-term trends were judged consistent with a trajectory of emissions to 2100, it would be methodologically improper to simply project a continuation of such trends 80-plus years into the future using a simple extrapolation, rather than consider fundamental understandings of energy system theories, evidence and dynamics (cf. van Vuuren and Riahi 2008, Ritchie and Dowlatabadi 2017).

Of the 1,037 mentions of RCP scenarios in the IPCC SROCC, almost 60% (specifically, 596 or 56.3%) refer to RCP8.5. RCP2.6 is used throughout the report as a comparison to RCP8.5 and it makes up more than 30% of references (specifically, 388 or 32.4%). RCPs 6.0 and 4.5 together make up about 11% of mentions. Again, to the extent that the use of RCP8.5 as a baseline scenario and employed in comparisons with other RCPs characterized as policy scenarios, the resulting information is not relevant to real-world policy discussions and is even misleading.

RCP prevalence in research and assessment

Table 3 shows that of the four RCP scenarios, RCP8.5 was the most commonly referred to in the IPCC AR5 and the U.S. National Climate Assessment. A search of Google Scholar for RCP8.5 finds 16,800 articles for the period since 2010.[27] For RCP6.0, RCP4.5 and RCP2.6 the numbers are respectively: 4,720, 16,000 and 9,850. These data suggest that recent scientific assessments accurately reflect the prevalence of the various RCPs in the literature. It is unclear whether the increasing prevalence of RCP8.5 in the USNCA and SROCC as compared to the AR5 reflects a growing emphasis of RCP8.5 in the literature or decisions by assessment authors to emphasize RCP8.5.

Scenario	AR5 WG1	AR5 WG2a	AR5 WG2b	AR5 WG3	SUM
RCP2.6	629 (24.1%)	111 (28.6%)	62 (23.5%0	18 (30.5%)	820 (24.7%)
RCP4.5	715 (27.4%)	62 (16.0%)	52 (19.7%)	14 (23.7%)	843 (25.4%)
RCP6.0	446 (17.1%)	56 (14.4%)	15 (5.7%)	12 (20.3%)	529 (15.9%)
RCP8.5	821 (31.4%)	159 (41.0%)	135 (51.1%)	15 (25.4%)	1130 (34.0%)
TOTAL	2,611	388	264	59	3,322

Scenario	USNCA (2017, part 1)	USNCA (2018, part 2)	SUM
RCP2.6	47 (15.4%)	35 (6.6%)	82 (9.8%)
RCP4.5	82 (26.8%)	182 (34.4%)	264 (31.6%)
RCP6.0	11 (3.6%)	6 (1.1%)	17 (2.0%)
RCP8.5	166 (54.2%)	306 (57.8%)	472 (56.5%)
TOTAL	306	529	835

Table 3. Prevalence of mentions of the RCPs in the IPCC Fifth Assessment Report and the U.S. National Climate Assessment.

[27] Search conducted 8 March 2020.

The proliferation of RCP8.5 in the academic literature is set to continue. Through the first two months of 2020, according to Google Scholar, more than 1,300 studies were published mentioning RCP8.5, a rate of about 20 per day. Of these, studies mentioning RCP8.5 and "business as usual" were being published at a rate of more than two per day.[28] A search of abstracts (an indicator of future published research) submitted to the 2019 annual meeting of the American Geophysical Union for mentions of the RCP scenarios finds RCP8.5 in almost 60% of these abstracts, with RCP4.5 next most common at ~25%.[29] A full exploration of the prevalence and impact of the RCP scenarios in academic research and assessment goes well beyond the scope of this paper, but is a topic ripe for investigation.

Consequences of Scenario Misuse

The consequences of RCP scenario misuse include a myopic perspective on alternative futures and a correspondingly limited view on policy alternatives, the creation of a vast academic literature with little to no connection to the real world, and an unwarranted emphasis on apocalyptic climate futures that influences public and policy maker perspectives and the climate policy discourse in broader society.

Future Myopia

At the very minimum, the overwhelming prevalence of the RCP scenarios in climate research and assessment means that the resulting overall perspective on the future is incredibly myopic (cf. Pielke 2018). The RCPs are suitable for use as radiative forcing pathways to answer narrow questions related to the influence of different levels of radiative forcing on physical climate variables within models, such as sea level rise or global average temperature change (e.g., Taylor et al. 2012). Even in those cases where the RCPs are used appropriately as integrated scenarios of radiative forcing and socio-economic pathways, the four RCPs are far from representative of the broader scenario literature and do not reflect correspondence with the real-world. This is obvious from the fact that the four RCPs uniformly employ high radiative forcing baselines.

[28] Specifically, a search of ([RCP8.5 OR "RCP 8.5"] AND "business as usual") for studies published in 2020 resulted in 168 results on day 68 of 2020, a rate of ~2.5 per day.
[29] Specifically, 228 total mentions, RCP8.5 = 134 (58.8%), RCP6.0 = 11 (4.8%), RCP4.5 = 58 (25.4%) and RCP2.6 = 25 (11.0%). Search conducted 4 January 2020.

Such intellectual myopia is exacerbated to the extent that RCP8.5 is employed as a "business as usual" scenario.

Committing Scientific Resources to Science Fiction

The heavy reliance on RCP8.5 in climate research and assessment means, bluntly, that much of the limited scientific resources available to improve our understanding of the global climate are committed to what might be most charitably characterized as an extreme radiative forcing pathway suitable only for exploratory studies of implausible climate futures. Ritchie and Dowlatabadi (2017) argue that, "Scenarios of extreme outcomes can be useful for assessments of risk, but they are explicitly different from [business as usual]." Hausfather and Peters (2020) argue,

> "A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature."

A result of this confusion has been a large literature and leading scientific assessments that emphasize a scenario that – at least in its socio-economic pathways dimensions – is implausible and unrealistic. As such, derived estimates from RCP8.5 as "business as usual" such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real-world meaning. They are technical, sophisticated and employ methodologies of science, but in the end, they lack a meaningful connection to the real world.

Apocalypse Now

The overwhelming emphasis of climate research and assessment on the extreme RCP8.5 scenario means that the corresponding perspective of this literature is also extreme. The scientific literature has become imbalanced in an apocalyptic direction. Upon learning of the implausibility of RCP8.5 as a business as usual scenario, David Wallace-Wells, the author of *The Uninhabitable Earth* – which relied heavily on studies that employed RCP8.5 to describe an apocalyptic future – wrote:

> [A]nyone, including me, who has built their understanding on what level of warming is likely this century on that RCP8.5 scenario should probably revise that understanding in a less alarmist direction. Scientists who are studying particular impacts should probably stop using RCP8.5 as a stand-in for "no policy" or "business as usual" climate trajectories, and certainly stop describing research that does use it as reflecting a "business as usual" world. We could still get to an RCP8.5-like situation, theoretically, but it is pretty unlikely, and would probably require a departure from the blithe stumbling-down-our-current-path-blindly pattern of the last few decades. This is all, absolutely, cause for optimism, even if it is optimism in the face of great uncertainty.[30]

The is little doubt that the central role of RCP8.5 and the fact that it, and the other RCPs, have been misused in research and assessment could easily lead to debates over its plausibility, likelihood and continued role as a centerpiece of climate research, challenging the credibility of the studies and assessments that have misused it. Such debates aside, it is clear that to the degree that the RCP scenarios have been misused, as alleged here, the world had developed a perspective on climate change that is out-of-step with reality, and this bias is in the direction of apocalyptic futures.

4. How Climate Scenarios Went Off-Track

This section explores in some depth three factors that help to explain how the scenario misuse occurred. Misuse has arguably been an emergent property of a complex system, rather than a result of active decisions. The three factors are a divergence between the original intent for the RCPs versus their actual implementation, the orchestrating role played by the IPCC in the creation of the RCPs and trade-offs between the role of scenarios in climate modeling research and other domains, which increasingly favored climate modeling applications. Several other relevant factors are mentioned, but not explored in depth.

[30] https://nymag.com/intelligencer/2019/12/climate-change-worst-case-scenario-now-looks-unrealistic.html

The Intent for Integrated Scenarios versus Their Actual Implementation

The RCPs were originally intended to serve as an intermediate placeholder in the evolution of scenarios until the fully developed "matrix architecture" of scenario development could be completed (Moss et al. 2010). As originally envisioned, the RCPs provided concentration pathways intended to be more independent of socio-economic pathways, in order to set climate modeling and integrated assessment modeling on parallel paths. In practice however, the RCP scenario process highlighted the tighter interconnection of climate forcing agents and socio-economic pathways:

> "the prescription of regional-scale evolution of land use/land cover, aerosol emissions, tropospheric ozone precursors, and other factors influencing climate now introduces potentially tighter linkages to socioeconomic and technological factors than has been the case when only global-scale long-lived GHG emissions were used for climate modeling" (Moss et al. 2008).

Similarly, Moss et al. (2008) recognized that,

> "The emergence of new dependencies between what is required by [earth system model] simulations and the underlying socioeconomic assumptions means that we cannot assume that significantly different socioeconomic pathways could produce effectively equal climate scenarios, particularly at the regional scale that is important for [impacts, adaptation and vulnerability] studies."

This meant that it would be inappropriate to consider some climate system processes separately from associated socio-economic pathways.

In another example of a gap between the intended role for the RCPs and their actual use in practice can be found in the choice of a single baseline scenario to include in the original four RCP scenario publications. An approach based on evaluating policy interventions off of a prescribed baseline scenario was viewed as advantageous because it "significantly simplifies the analysis and is directly policy-relevant" (van Vuuren et al. 2012).[31] A "discussion note" prepared

[31] But at the same time, "the approach often pretends that options can be objectively evaluated on the basis of a single set of criteria (often cost-effectiveness) without communicating that these criteria themselves are worldview dependent" (van Vuuren et al. 2012).

for the IPCC 2007 expert meeting on new scenarios endorsed by 29 leading climate researchers perfectly anticipated the misuse of RCP8.5 as "business as usual" and the corresponding misinterpretation of the true scope of plausible baseline scenarios (Moss et al. 2008):

> "A terminology of one 'reference' and three 'stabilization' scenarios would mislead other parts of the scientific community into believing that all three stabilization scenarios 3.0, 4.5 and 6.0 W/m2 would represent scenarios that imply mitigation, i.e. emission reduction policies. Clearly, some medium scenarios could represent both non-mitigation or mitigation scenarios, depending on the assumed hypothetical "baseline". However, labeling a scenario a "stabilization" scenario, which is equivalent to the medium SRES non-mitigation scenario A1B, implies that recent research regards only A1FI, A2 or similarly high scenarios as credible baselines."[32]

Of note, the list of endorsers of this warning included a future co-chair of IPCC AR5 Working Group 3.

Differences between the intended role for the RCPs to fulfill a stopgap role until the full matrix architecture of scenarios could be developed helps set the stage for the misuse of the RCPs over more than a decade.

The Orchestrating Role of the IPCC

The IPCC has continued to play a leading role in developing and legitimizing scenarios for use in scientific research and then also in coordinating assessment of that same research. Its 24th Session, held in Montreal in 2005, the IPCC established a "task group" to establish a process for the development of new scenarios – these would replace the SRES scenarios which were formally published by the IPCC.[33] This decision was made based on guidance resulting from an IPCC workshop held earlier that year in Laxenburg, Austria to consider the substance of and process for the development of new scenarios for climate research and assessment (IPCC, 2005).

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[32] Note that 3.0 is used here rather than 2.6 because at the time that this was written, the final radiative forcing levels of the RCPs had not yet been determined.

[33] https://www.ipcc.ch/site/assets/uploads/2018/05/final-report-4.pdf

The consensus view expressed by the IPCC workshop participants was that the IPCC should play a leading role in the "facilitation or coordination" of the development of new scenarios.

The following year, at the 25th Session of the IPCC in Mauritius, such a leading role was called into question: "Different views were expressed about the IPCC role in scenario development, including the view that the IPCC should no longer itself commission or direct scenario development."[34] Sensitive to such concerns, the IPCC at its 25th Session used the inscrutable word "catalyze" to describe its role in new scenario development.[35] The IPCC (Moss 2008) later characterized itself (misleadingly) to be somewhat distant from the creation of new scenarios: "the IPCC decided that rather than directly coordinating and approving new scenarios itself, the process of scenario development should now be coordinated by the research community."

This statement was not entirely accurate. The new scenario development process included participants beyond the IPCC, but it was also led by the chair of the IPCC's Task Group on Data and Scenario Support for Impacts and Climate Analysis, funded by the IPCC and implemented a process developed by the IPCC resulting in the RCPs (Moss 2008, 2010). Specifically, Figure 5 shows the version of the process for new scenario developed first proposed in the 2005 Laxenburg workshop and ultimately employed by the IPCC. The "assessment" and "declare" elements of the process are the subject of Moss et al. (2008) and Moss et al. (2010). The IPCC played a lead role in the new RCP scenario development from start to finish.

[34] https://www.ipcc.ch/site/assets/uploads/2018/05/final-report-3.pdf
[35] https://www.ipcc.ch/site/assets/uploads/2018/05/final-report-3.pdf

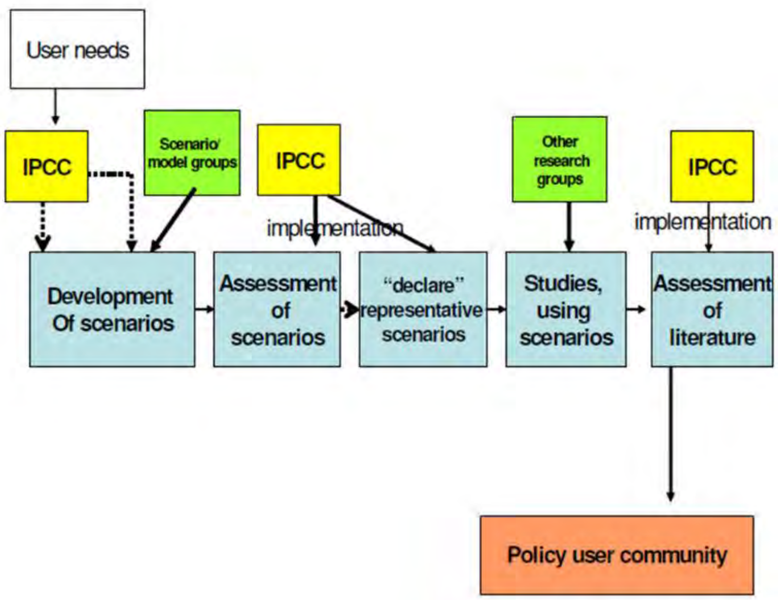

Figure 5. The approach to RCP scenario development employed by the IPCC, first proposed in IPCC (2005), showing the central role played by the IPCC from start to finish.

The 2005 IPCC workshop highlighted a potential conflict of interest: "A key trade-off identified is that a stronger IPCC coordination is more likely to produce a common and consistent set of scenarios that can be used in assessments across IPCC working groups, but a dominant coordination role of IPCC could be perceived as a potential conflict of interest with IPCC both generating and assessing scenarios" (IPCC, 2005). Individual countries expressed different views as to what role the IPCC should play in new scenario development:

- Canada: "the IPCC should lead the development of scenarios;"
- China: "IPCC could organize a process with the scientific community in developing new scenarios;"
- Germany: "experience in the past shows that it is useful for the IPCC to develop new scenarios;"

- Netherlands: "One could argue that IPCC has no active role to play in developing emission scenarios… However, from a practical viewpoint it is helpful if IPCC stimulates the development of sets of high quality scenarios so as to facilitate comparability of different model runs needs of climate research vs needs of policy making;"
- New Zealand: "We do not see benefit in the IPCC either becoming involved in a prescriptive approach to developing new non-mitigation scenario literature by external groups, or to develop new scenarios itself;"
- United States: "IPCC should have no specific role in commissioning or directing scenario development."

The IPCC ultimately placed itself into the unique position of not just assessing the broad scientific literature on climate change, but it also has played a central role in orchestrating the focus of that literature. The IPCC (2005) anticipated that this "would probably lead to more homogeneity in the literature that is to be assessed later." Indeed, that is what has happened. Since 2015 (post-AR5), of those studies that discuss climate change to 2100, almost 60% also reference the RCPs.[36] IPCC (2005) saw such homogeneity as an aid to the task of assessment: "IPCC working group reports can be made consistent if they use the same scenarios to organise the assessments."

Arguably, the IPCC decision to rely on four RCP scenarios, but to select them from four different integrated assessment modeling groups was the result of its attempt to at once coordinate the development of common scenarios while also enabling the participation in the process of the broader modeling community beyond the IPCC. This approach served the climate community poorly, because it ultimately encouraged and facilitated the misuse of scenarios. The IPCC would have been better served either by overseeing the creation of common, comparable scenarios (as it did under SRES, Nacinovic et al. 2000) or stepping back altogether from scenario development coordination, and simply assessing a literature produced independently of the IPCC.

[36] Specifically, a search of Google Scholar for ["climate change" 2100] returned 28,600 studies for the period 2015 to 7 March 2020. A search of ["climate change" 2100 RCP] returned 15,900, or about 56% of the total.

Trade-offs Between the Roles of Scenarios in Climate Research and Climate Policy

With hindsight, it is clear that different roles for scenarios in climate research and in support of climate policy led to trade-offs in the RCP development process. The IPCC (2005) workshop on new scenarios recognized demands for "multiple baselines" which would be "important to capture more of the socio-economic range and wide range of futures" and so that "uncertainty can be better represented." But IPCC (2005) also noted that for climate models there are "no variations in results" if the range of baselines is not large. Similarly, IPCC (2005), presciently, also recognized that the use of a single baseline "Does not reflect the range of possible futures in the long term and therefore may be misleading."

In submissions to the IPCC (2005) workshop, several countries requested an approach focused on baseline scenarios versus policy scenarios, including the United Kingdom and the United States (IPCC 2005). Governments also expressed a desire for scenarios to reflect "a wide range" (UK), "the full range" (Austria), "the possible future range of emissions, climate change, and impacts from both a probabilistic and a deterministic or "storyline" perspective" (United States) as well as being "as realistic as possible" (Netherlands). The policy making community expressed a clear desire for a wide range of scenarios to result from the IPCC scenario development process.

Apparently rejecting these concerns and requests, the RCP process ultimately resulted in the presentation of a single baseline scenario, which contributed to its common misuse as *the* "business as usual" scenario. One reason for this outcome is that the RCP process was primarily to meet the needs of the climate modeling community. The main objective of the new scenario development process was explained explicitly by van Vuuren et al. (2008): "Given that the primary goal of this exercise is to provide input data for climate models, the core products will be global emissions and concentrations of long-lived greenhouse gases, gridded emissions of shorter-lived species, and gridded land-use and land-use change information."[37] Moss et al.

[37] D. van Vuuren echoed this view in early 2020 in an interview with *de Volkskrant* on the origin of the RCPs: "We were in the run-up to the fifth report from the UN climate panel IPCC. The research community had a great need for data on the course of the greenhouse gases in order to be able to run climate models. We understood that it would take a lot of time to design an extensive system for that. So we opted for a faster route: we take four scenarios from the literature. One high, one low, and two in the middle." Via Google Translate: https://www.volkskrant.nl/wetenschap/zo-erg-wordt-het-ook-weer-niet-met-het-klimaat-hoe-het-rampscenario-de-bovenhand-krijgt~ba7b2e35/

(2008) also explain the primacy of climate modeling, "RCPs are mainly intended to facilitate the development of integrated scenarios by jump-starting the [climate modeling] process through the provision of data on emissions, concentrations, and land use/land cover needed by [climate models]."

One of the needs of the climate modeling community was a high-forcing scenario (like RCP8.5) in order to facilitate the identification of a forced-climate signal in climate modeling runs. Moss et al. (2008) explains, "A high [radiative forcing] pathway would allow the [climate modeling] community to explore climate system dynamics at high radiative forcing levels, and allow the [impacts, adaptation and vulnerability] community to explore high-impact scenarios (and associated adaptation strategies and possible limits to adaptation." Moss et al. (2008) further explain, "The difference between a pathway of this type and a low pathway (e.g., [RCP2.6]) also has a good signal-to-noise ratio for evaluating the climate response in [atmosphere-ocean general circulation model] simulations." The desire for a "good signal-to-noise ratio" explains why the IPCC prioritized RCP8.5 and RCP2.6 for use in research (Moss et al. 2008). The computational requirement of climate modeling, not potential policy relevance, was the driving factor.

In addition to helping to explain the primacy of RCP8.5 in climate research, it is also important to understand that the broader scenario literature is also influenced by research needs of the climate modeling community which is in turn, shaped by the intensive computational requirements necessary for realizing this mode of scientific investigation. The scenario literature is not independent of the climate modeling literature, nor separate from the technical resource constraints of climate models. Moss et al. (2008) observe: "The set of scenarios in this literature has been strongly influenced by specifications of [climate model] intercomparison exercises and continuity with earlier experiments, so it should not be considered a frequency distribution of independent analyses from which relative robustness, likelihood, or feasibility can be deduced." The scenario literature is thus in unknown (and perhaps unknowable) ways influenced by adjacent academic community interests. In no way can the broad scenario literature thus be used to characterize the future based on the statistical properties of distributions of characteristics of models within that literature.

The pedigree of the scenario literature is easily lost. For instance, the IPCC AR5 WG3 risked conveying an interpretation of its scenario database as a frequency distribution by reporting the statistical properties of the distribution of certain scenario inputs (e.g., annual carbon dioxide emissions in its Figure 6.7), the statistical properties of the distribution of certain scenario outputs (e.g., such as 2000-2100 temperature increase in is Figure 6.13) and finally the statistical distribution of mitigation costs derived from the scenario literature (e.g., regional mitigation costs relative to global average in its Figure 6.27). An appropriate interpretation of these statistical properties is impossible because it is unknown why the IPCC AR5 scenario database of 1,174 scenarios has the distribution of inputs that it does. Indeed, given such unknowables it may even be inappropriate to present the scenario inputs, outputs and derived estimates as a distribution at all.

Other Factors

There are no doubt other factors which help to explain the misuse of scenarios in climate research beyond those discussed in the previous subsections. A full exploration goes well beyond the scope of this paper, however, the following factors are likely to have some importance.

- Political dynamics. Scenarios are not neutral. As van Vuuren et al. (2012) observed, an environmentally friendly scenario of the SRES "was strongly criticized by some environmental NGOs as it would suggest that autonomous developments could also lead to a (modest) reduction of emissions." Scenarios are politically favored and contested, van Vuuren et al. (2008) continue: "societal actors often respond to specific scenarios and not to the set as a whole and that the responses often coincide with the political and/or economic interests of these actors." Foreshadowing future apocalyptic climate change, RCP8.5 offers imagery some might see as useful in climate advocacy, reinforcing its stature in research prioritization.
- Media dynamics. An analysis by the Dutch newspaper *de Volkskrant* in early 2020 found that 80% of its references in news stories to climate change projections to 2100 of the previous five years were ultimately based on studies relying on RCP8.5, with two-thirds of the news stories presenting RCP8.5 as a prediction of the future.[38] While a full analysis

[38] https://www.volkskrant.nl/wetenschap/zo-erg-wordt-het-ook-weer-niet-met-het-klimaat-hoe-het-rampscenario-de-bovenhand-krijgt~ba7b2e35/

of the role of RCP8.5 as business as usual in the media goes well beyond the scope of this paper, a leading hypothesis is that with ~60% of the focus on the USNCA, IPCC SROCC and underlying literature focused on RCP8.5, it would not be surprising to find a similar emphasis in the media.

- Professional dynamics. To the extent that studies based on RCP8.5 are favored in the IPCC review process and in the media, it would create incentives for academics to focus on such studies. Academia rewards publication and citation, as well as institutional publicity via media appearances. Thus, there are inter-related incentives among the IPCC, researchers, journals, university press offices, reporters and editors to reinforce the emphasis on RCP8.5 as business as usual and RCP comparisons. Correspondingly, there are few incentives to identify scenario misuse. The leadership role of the IPCC arguably has succeeded in making the literature "more homogeneous" and these dynamics have arguably been reinforced by the incentives shaping incentives in the ecosystem of research.
- Science dynamics. Beyond climate, there are obstacles to self-correcting science. Rayner (2012) explores the dynamics of the "social construction of ignorance," and Golman et al. (2017) survey dynamics of "information avoidance." Within climate science Boykoff and Boykoff (2004) argued that media norms of "balanced reporting" leads to a "bias" in media representations of climate change. This argument has widely been interpreted as supporting the suppression of views deemed to be critical of climate science. For instance, Kloor (2017) documents efforts within the climate science community to "police" views deemed "unhelpful." As issues associated with the misuse of climate scenarios is only beginning to emerge it remains to be seen how the climate research community might respond to claims of scientific integrity issues associated with the RCPs.

The bottom line is that scenario misuse involving the RCPs resulted from myriad factors coming together and reinforcing each other. They range from the ridiculously simple – the common naming scheme for the RCPs, to the incredibly complicated – the collapsing of complexity involved with the notion of baseline scenarios in methodologies of scenario planning, to institutional dynamics – the IPCC assuming the role of orchestrating the very literature that its main function was simply to assess. As such the objective of understanding scenario misuse is not to apportion or assign blame, but to understand how such a pervasive and consequential failure of scientific integrity came to be on such an important topic, how it can be corrected and how it can be avoided in the future.

5. **Not a pathway toward course correction: SSPs exacerbate forms of scenario misuse**

Some of the issues that we document from the last decade of RCP-based research arose alongside the motivation to conduct climate model experiments independent of an explicit connection to socioeconomics. Therefore, it would be reasonable to assume that once socioeconomic scenarios were finally issued to accompany a new set of concentration pathways the scientific community would be on a path toward course correcting. The following section argues that the introduction of socioeconomic narratives into the scenario mix has not addressed scenario misuse, but has introduced an additional set of problems that climate research must grapple with over the coming decade.

Introducing the Shared Socioeconomic Pathways (SSPs)

With publication of the Shared Socioeconomic Pathways (SSPs) in a special issue of *Global Environmental Change* (2017) after seventeen years the climate research community finally completed the process of creating successors to the SRES scenarios (Nacienovic et al. 2000). The SSPs fulfilled the new climate scenario architecture as originally designed (detailed in Section 4), linking a new set of RCPs with fully articulated IAM scenarios based on socioeconomic assumptions. The IPCC now had a full set of SSP-RCP climate scenarios.

The Shared Socioeconomic Pathways (SSPs) reconcile the climate forcing pathways of the RCPs with a standardized set of five socioeconomic narratives for possible 21st-century global developments in the absence of climate change or climate policy. Riahi et al. (2017) describe the narratives as:

- **SSP1 Sustainability:** the world shifts gradually toward a more sustainable path (low challenges to mitigation and adaptation).

- **SSP2 Middle of the Road**: the world follows a path which does not shift markedly from historical patterns (medium challenges to mitigation and adaptation).
- **SSP3 Regional Rivalry:** resurgent nationalism push countries to focus on domestic or regional issues (high challenges to mitigation and adaptation).
- **SSP4 Inequality**: highly unequal investments and increasing disparities lead to inequalities and stratification across and within countries (low challenges to mitigation, high challenges to adaptation).
- **SSP5 Fossil-fueled development**: the push for economic and social development is coupled with exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world (high challenges to mitigation and low challenges to adaptation).

Each of the five SSP narratives is intended to guide IAMs in developing the complete projections of radiative forcing needed to produce a RCP. Combinations of SSP-RCPs are described by the two-dimensional matrix shown in Figure 6 which is adapted from O'Neill et al. (2016), where each SSP (horizontal axis) connects to one or more RCPs (vertical axis).

The previous set of four RCP pathways were only a single dimension of this matrix since they lacked an explicit socioeconomic component, and therefore are shown as a single column of green rectangles on the right of Figure 6. The full suite of 5 SSPs and 7 RCPs would imply 35 different climate possible climate scenarios. However, some SSPs do not produce specific RCPs so there are only 25 published combinations. Notably it was found during the SSP development process that SSP5 is the only narrative able to produce scenarios consistent with a radiative forcing level of 8.5 W/m^2 (Kriegler et al. 2017). Four of these scenarios were chosen for emphasis as the most important scenarios in the climate experiments informing the IPCC 6th Assessment, the SSP5-8.5 (baseline), SSP3-7.0 (baseline), SSP2-4.5 and SSP1-2.6 scenarios – in Figure 6 these are shown in blue.

Despite 17 years since publication of SRES, the SSP scenario narratives are largely repeating the original SRES scenario storylines of A1, A2, B1 and B2 (van Vuuren and Carter 2014):

- SSP5 is equivalent to the fossil intensive global development of SRES A1F1.
- SSP3 follows the regional economic growth of SRES A2.

- SSP2 corresponds to the balanced economic growth of SRES B2.
- SSP1 mirrors the sustainability focused global development of SRES B1.

The SSPs have departed from SRES in two important ways. One is with the addition of the SSP4 Inequality narrative, described as creating parallel sets of contrasting high and low optimistic (SSP5/ SSP1) versus pessimistic scenarios (SSP3/SSP4) with SSP2 in the middle (O'Neill et al. 2016). A second is that two baselines have been assigned priority for climate model experiments – SSP3-7.0 and SSP5-8.5 – implying that these scenarios best represent the world's trajectory in the absence of climate policies.

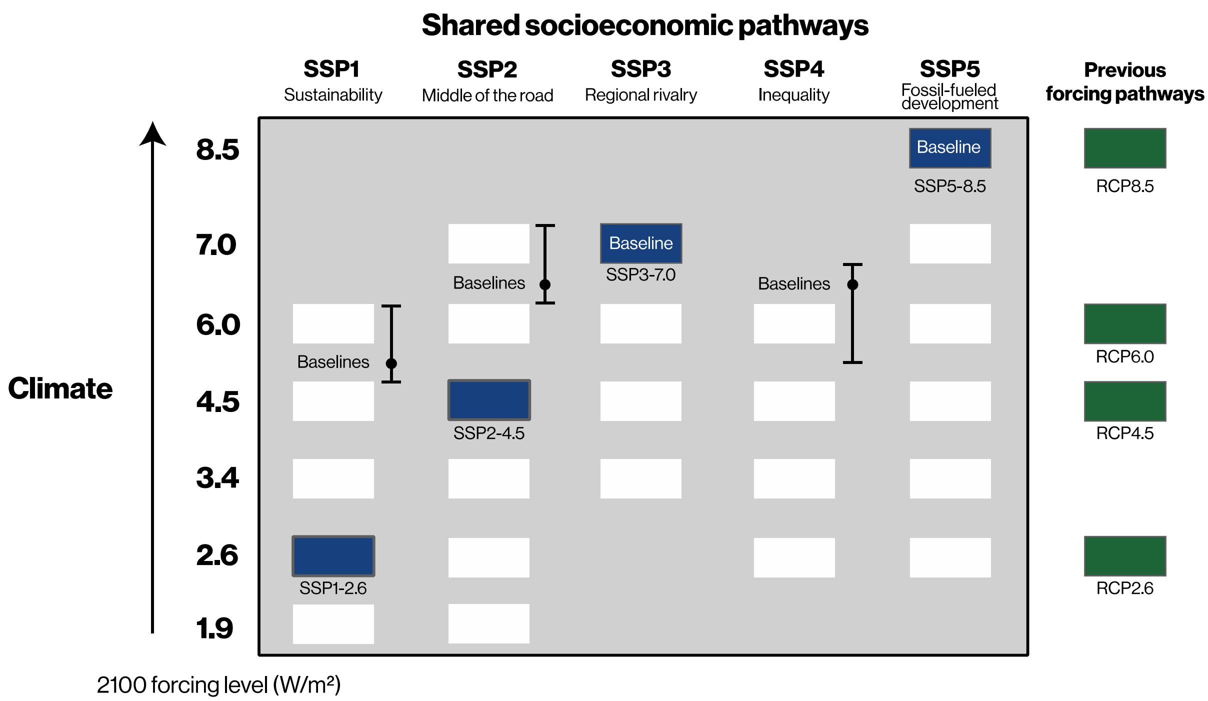

Figure 6. Matrix of scenarios for climate model experiments to inform the IPCC 6th Assessment. The SSP-RCP scenario matrix illustrates intersections between the five SSP global development narratives (horizontal axis) and the climate forcing pathways (vertical axis). Range of baselines for the SSP 1, 2 and 4 scenarios are shown with black lines. Blue rectangles denote the primary (Tier 1) scenarios selected for emphasis in climate model experiments. The previously used 'one-dimensional' RCPs shown on the right in green (author adaptation of a version from O'Neill et al. 2016).

Though the SSPs do ultimately fulfill their intended goal of providing a socioeconomic foundation for climate model experiments using RCPs, they introduce a new set of problems for scenarios in climate research: (a) forced continuity with experiments in the probability vacuum, (b) resurrecting issues with bias in narrative based scenarios, and (c) chimeras arise from an ever more complex architecture. The remainder of this section addresses each of these issues.

(a): Forced continuity with experiments in the probability vacuum

As the RCP8.5 scenario came to dominate climate research, a type of cultural inertia has created a situation of “doubling down.” Specifically, even as the multi-year SSP development process found that “8.5 W/m^2 can only emerge under a relatively narrow range of circumstances” a desire for continuity with past research has motivated the new SSP5-8.5 scenario to “be considered the highest priority” for the CMIP6 climate model experiments producing the IPCC 6th Assessment evidence base (O’Neill et al. 2016, Riahi et al. 2017). This contrast means that the research community has once again positioned an extremely unlikely, perhaps implausible, socioeconomic scenario as the most important scenario for climate model research.

Although it was originally intended that the SSPs would support the RCPs in a way which enhanced their plausibility and credibility, the prioritization of continuity created a situation where SSP scenarios needed to ultimately de-emphasize the role of plausibility as it was explicitly described in earlier publications (e.g. van Vuuren et al. 2011, and Riahi et al. 2011). Instead, under SSPs the relevance of a socioeconomic pathway is defined by its ability to link with one or more RCPs, and to span the range of conceptualized challenges to mitigation and adaptation (O’Neill et al. 2017). Therefore, the momentum of RCP8.5 in the work of physical system modelers became a self-fulfilling rationale that has supported the primacy of SSP5-8.5, even as its socioeconomic assumptions increasingly strain credibility.

Because the SSPs were designed as ‘backcasted’ scenarios based on envisioned end-points for global society in 2100 framed by radiative forcing levels selected prior to evaluations of the plausibility of socioeconomic pathways, it was no longer necessary for IAMs to create plausible connections between the actual economic and energy systems aspects of today’s world and those of 2100. For instance, the baseline SSP5-8.5 and SSP3-7.0 scenarios far exceed observed fossil fuel use in their year of publication (Figure 7).[39] Just a year after publication SSP5-8.5 oil production, and SSP3-7.0 coal consumption were projected to be more than 20% higher than the world actually experienced in 2018. Without a reasonable connection to contemporary development trends, these scenarios are thus accurately interpreted as exploratory or hypothetical rather than as the basis for real-world policy analysis. Such discrepancies between scenarios and the real world have become necessary to produce socioeconomic projections that maintain coherence with associated concentration pathways. This sets the stage for a continued misinterpretation of baseline scenarios of the SSPs as relevant to policy analyses and projections of future climate impacts. The plausibility of socioeconomic pathways has arguably become ancillary to the methodological requirements of physical science modeling.

[39] Figure 7 shows several SSP marker scenarios – a *marker scenario* is the version of a scenario selected as representative of an SSP. Because any single SSP can be illustrated by more than one IAM, the scenario developers select specific IAM implementations of an SSP to emphasize how it reflects the intended characteristics of the narrative pathway.

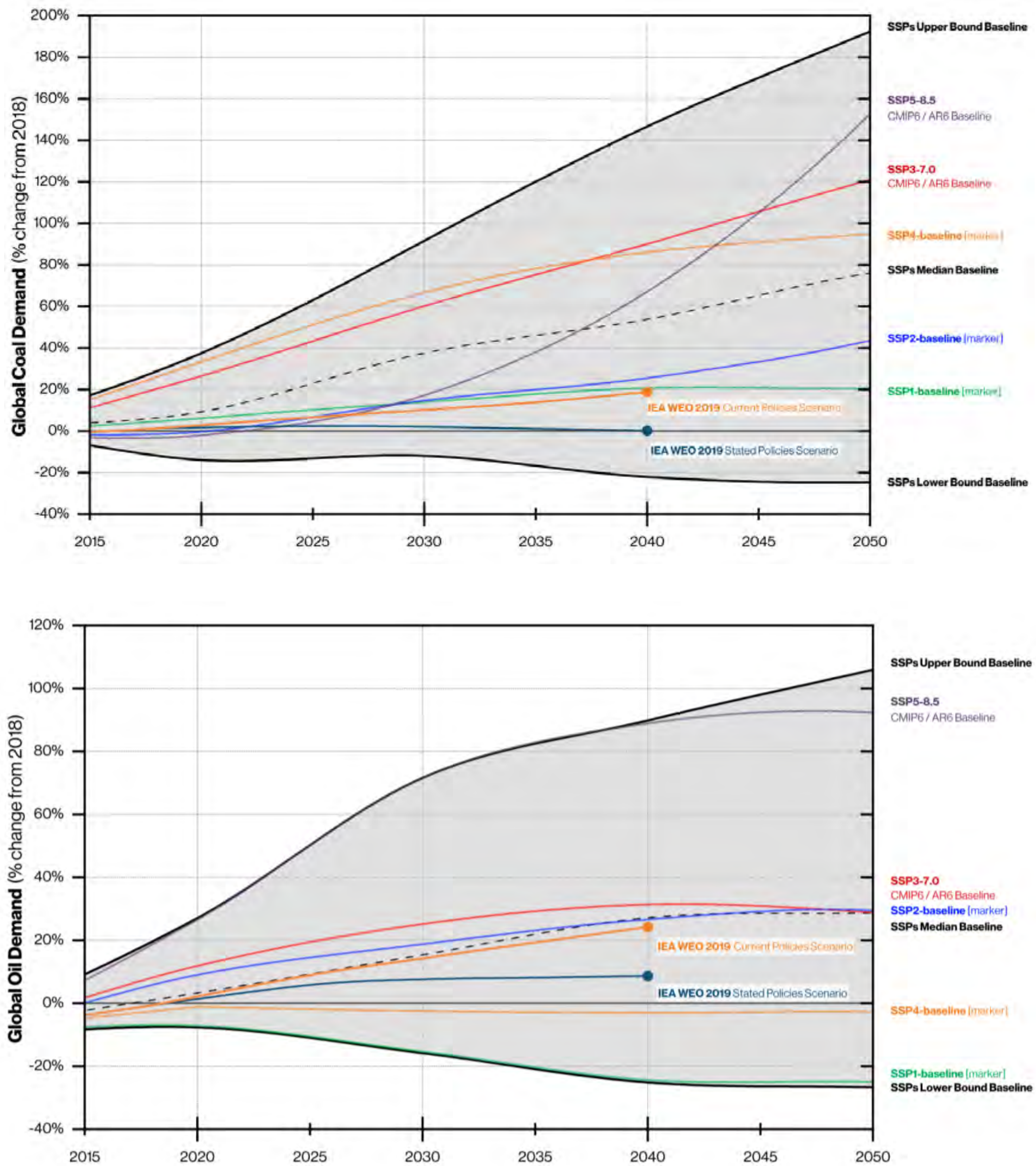

Figure 7. The range of SSP baseline scenarios through mid-century for global coal demand (upper) and global oil demand (lower) with emphasis on SSP marker scenarios, and trajectories of likely demand from the International Energy Agency under current policies and currently stated policies referenced to their relative change from 2018 (Riahi et al. 2017). Scenario primary energy harmonized to IEA WEO base year of 2010 (IEA 2019).

(b): Resurrecting issues with bias in narrative based scenarios

The SRES scenarios prompted valid critiques of narrative-driven scenario exercises for climate research which were not notably acknowledged by the SSP process. Most relevant to the context of this paper are the contentions from Morgan and Keith (2008) that elaborate storylines in the absence of likelihood assessments potentially mislead scenario users by encouraging the filling of a probability vacuum with their own subjective understandings or conclusions shaped by cognitive biases. In their assessment of SRES, Morgan and Keith (2008) highlight that even though narratives are proposed to expand thinking, consistent with the broader tradition of scenario planning, or in the case of the SSPs to expand the types of scenarios explored by IAMs, they can often have the opposite effect of enforcing *myopia* because they are, "cognitively compelling…causing users to overlook a wide variety of alternate developments that could lead to similar outcomes for key variables such as energy use."

The SSPs illustrate this dynamic with the example in Figure 7, where the International Energy Agency scenarios based on its interpretation of 'business-as-usual' result in similar energy use projections to the SSP1 sustainability narrative, despite the SSP1 pathway describing a globally coordinated sustainability transition. Similarly, Burgess et al. (2020) find that the SSP baselines narrowly replicated the uncertainty range of the previous IPCC AR5 WGIII scenarios, despite the SSP scenarios intending to draw from narratives to expand the range of scenario considerations.

Another cognitive bias in scenario interpretation highlighted by Morgan and Keith (2008) is *suppression*, in which specific plausible global developments are excluded by narratives because they are "constructed in a public setting in which future outcomes that include developments such as negative economic development in some regions, pandemics, or regional nuclear war, are excluded because they are politically unacceptable." Because the SSPs were issued without detailed notes on the alternative narratives and pathways considered and excluded, it is unclear to what degree the narratives are considered by experts to be comprehensive of plausible global developments in the coming years.

As history has repeatedly shown, negative shocks can and do regularly happen in the real world, including wars, economic crises, pandemics and so on. Yet, because such possibilities are excluded from the baseline trajectories in scenario exercises like the SSPs, such scenarios can become rapidly outdated in the context of a significant regional or global crisis. Consider that Burgess et al. (2020) find fossil carbon emission outlooks from major energy agencies are already at or outside the lower bound of the SSPs, meaning that there is little room for negative global shocks. This implies that the range of CO_2 emission trajectories under consideration for IPCC AR6 are likely to be overstated, as compared to scenarios that would realistically include the possibility of such negative shocks.

Morgan and Keith (2008) further describe how rich narrative details create the context for an availability bias which leads people to "overestimate the probability of a scenario or storyline when the detail with which it is specified is increased". This bias is suggested based on evidence from experiments by Tversky and Kahneman (1983) where participants demonstrate a conjunction fallacy: interpreting the more likely scenario as the one with more available details. Notably, the original article describing SSP5 has a higher word count than all other SSP articles, and 30-60% higher word counts than the lower SSP1 and SSP4 scenarios (Kriegler et al. 2017, Fujimori et al. 2017, van Vuuren et al. 2017, Fricko et al. 2017, Calvin et al. 2017). Similar discrepancies are replicated in the high-level summaries of the SSPs in Riahi et al. (2017) where the SSP5 pathway receives the most detailed summary of all the SSPs and a 60% greater discussion than the low SSP1 pathway (Riahi et al. 2017).

The late Stephen Schneider (2001) noted in the context of the SRES scenarios that, "If judgments about likelihood are not supplied with the scenarios, they will be assumed by the users either explicitly or implicitly. The convention of not communicating information about the relative likelihood of scenarios therefore muddies communication between analysts and users." In other words, the probability vacuum that accompanies SSP and RCP scenarios leaves scenario users particularly susceptible to these biases – they have no way to gauge the probability of climate scenarios other than through their own priors, known cognitive biases and the frequency with which particular scenarios are used over others. As a result, the identification of SSP3-7.0 and SSP5-8.5 as prioritized baselines for climate modeling research fills the probability vacuum, repeating the misplaced primacy associated with RCP8.5.

(c): Chimeras arise from an ever more complex architecture

The de-linking of the RCPs from socioeconomic scenarios across a decade of climate research created a motivation for scenario users to pick and choose the elements they want – creating chimera scenarios that break the goals of internal consistency, and creating more incoherent studies in the research community. This issue is demonstrated by the SSP3-8.5 scenario which is increasingly used in a range of studies (e.g. Jones et al. 2018, Wang et al 2018).

The combination of SSP3 and RCP8.5 was considered implausible by the SSP developers (see Figure 6), yet it is now employed by studies aiming to illustrate 'worst-case' continuity with RCP8.5. Since the RCP8.5 scenario was the worst-case for greenhouse gas concentrations among the RCPs, there is sustained motivation to study the climate impacts of such a high level of greenhouse gases. Yet now the socioeconomics of the updated SSP5-8.5 indicate this climate forcing pathway is no longer truly a worst-case, because under the characteristics of the scenario the incredibly wealthy society which produces it could conceivably have ample resources to readily adapt to resulting changes in climate. Thus, a growing body of research utilizes the implausible SSP3-8.5 chimera which projects a poor and vulnerable society in a high climate impact environment.

When chimera scenarios like SSP3-8.5 are employed in a culture of scenarios that eschews statements on the likelihood of socioeconomic developments, this creates a series of foreseeable issues. Scenario users are once again left with a probability vacuum which neglects assessment of which SSP-RCP combinations are consistent with evidence and theory available today. Further, there remain important empirical (and metaphysical) question about how to interpret the results of a comparison of, for example, modeling results using the SSP5-8.5 baseline scenario with those that use the radically different socioeconomics of a SSP2-4.5 scenario. The SSP process has not made the asking or answering of such questions straightforward, contributing to conditions that will lead to more illogical comparisons across scenarios that will only exacerbate the issues of scenario misuse covered in Section 3 of this paper.

6. Conclusion: How Can Climate Research Get Back On-Track?

"You simply do not realize that the RCPs can start a life of their own."[40]

The misuse of scenarios in climate research and assessment documented in this paper includes the inappropriate identification of an extreme, implausible scenario as a reference or "business as usual" baseline and the improper comparison of scenarios generated from different integrated assessment models. Neither type of scenario misuse is novel or surprising in the context of integrated assessment modeling. As complicated and jargon-laden as it may be, there should be absolutely nothing controversial about the misuse documented in this paper – these are not fine points of methodological debate, but rather, clear and unambiguous cases of scenario misuse of the sort documented in the IAM community for decades. Indeed, both types of misuse were identified on multiple occasions over many years as possibilities by those involved in the creation of the original RCPs (IPCC 2005, Moss et al. 2008, Moss et al. 2010, van Vuuren et al. 2012). The pedestrian nature of the misuse makes it that much more troubling.

Also troubling is the fact that the Sixth Assessment Report of the IPCC has positioned itself to continue the exact same types of scenario misuse documented in this paper with the SSP scenarios as detailed in Section 5. For instance, for the next generation of climate model studies, O'Neill et al. (2016) prioritizes high radiative baseline forcing scenarios (8.5 and 7.0 W/m^2), despite these scenarios diverging from contemporary trends, Even so, O'Neill et al. (2016) explain, "Baseline scenarios will be very important to [impact, adaptation and vulnerability] studies interested in quantifying "avoided impacts," which requires comparing impacts in a mitigation scenario with those occurring in an unmitigated baseline scenario." The updated trajectory of the new 8.5 W/m^2 pathway is even more extreme in its projected carbon dioxide emissions than RCP8.5 (Riahi et al. 2017). The IPCC continues to orchestrate scenario creation and assessment of the literature that utilizes those scenarios. Introducing the SSP scenarios has clearly not initiated the process of course correction, and has introduced a new set of problems.

Correcting course will not be easy. There are several options that might be considered:

[40] Anonymous Dutch climate scientist quoted in https://www.volkskrant.nl/wetenschap/zo-erg-wordt-het-ook-weer-niet-met-het-klimaat-hoe-het-rampscenario-de-bovenhand-krijgt~ba7b2e35/

- First, and obviously, the climate community could recognize the misuse of scenarios, its pervasiveness, and take steps to immediately address it to avoid a growing credibility crisis. As common sense as this may seem, there are countless academic papers, research grants, the scenario architecture developed over 17+ years, and the ongoing Sixth Assessment of the IPCC – all of which has created an enormous momentum with incentives that work against such a common sense response;
- Serious consideration should be given to either (a) terminating the role of the IPCC in orchestrating the content of climate science, or (b) transferring the mandate of the IPCC to assess climate science research to an independent organization that plays no role in shaping how that research is produced. With respect to scenarios of the future, the hegemony of the IPCC has become a source of myopia, rather than enlightenment;
- Despite the presence of thousands of IAM scenarios in the community, and the motivation to proceed with 'one model one vote' dynamics where all models are assessed equally with no explicit probability statements, more regular attention needs to be given to a much simplified set of near-term, policy relevant scenarios, similar to how IEA issues three scenarios on an annual basis: a Current Policies Scenario (high), a Stated Policies Scenario (baseline) and a Sustainable Development (policy) scenario.
- More work is needed to reconcile long-term narrative pathways based on an idealized year 2100 end-point with what policy makers need to know about the next few years and decades. While there are an increasing number of scenarios focused on the role of Paris Agreement NDCs through 2030, there is a significant gap in the literature for scenarios that address developments before 2050 in the context of today's policy environment. This gap is created by an excessive focus on long-run, full century scenarios, driven in large part by the needs of the physical science modeling community.
- Climate research and assessment would benefit from a more ecumenical and expansive view on relevant knowledge. The IPCC scenario process has been led by a small group of academics for more than a decade, and decisions made by this small community have profoundly shaped the scientific literature and correspondingly, how the media and policy communities interpret the issue of climate change. The dominant role of this small

community might be challenged in order to legitimize a broader perspective of views, approaches and methods.

Ultimately, the issues associated with the misuse of scenarios in climate research and assessment are a matter of scientific integrity. Climate change will remain an important issue, worthy of serious policy responses, irrespective of whether or not such misuse is addressed in the near term. However, if scientific integrity is to be deemed important, then when shortfalls are identified, remedies should be implemented, especially when the subject is politically contested. Both science and policy will be better for it.

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