How high is high enough? A multi-million-member ensemble analysis of future climate scenarios and their relevance

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Abstract:

Assessments of high-forcing climate scenarios provide unique insight into possible high-risk climate change impacts in the 21st century and beyond. Given rapid and ongoing societal changes (e.g., population growth, energy demand, technology, etc.), debates are increasing on the continued relevance of these 'high-forcing' scenarios, such as those designed to reach 8.5 W/m^2 by the end of the century (e.g., RCP8.5 and SSP5-8.5). Here, we determine an updated probability of exceeding 8.5 W/m^2 by 2100 by generating a multi-million-member ensemble from a newly developed database of probabilistic greenhouse gas (GHG) emissions scenarios, augmented here with improved characterization of aerosols and minor GHGs, coupled with the newest version of a reduced complexity climate model, with parameter distributions calibrated to match the IPCC 6th Assessment Report. The probability of exceeding 8.5 W/m^2 this century is estimated to be less than 1%, however, we discuss important rationales for the continued use of 8.5 W/m^2 scenarios, including for generating high temperature scenarios for use in calibrating damage functions, characterizing climate in the 22nd century (probability of exceeding 8.5 W/m^2 increases to ~7% by 2150), and assessing low-probability/high-impact futures..

Significance Statement:

Controversy exists regarding the relevance of 8.5 W/m^2 high-end climate scenarios. We calculate the likelihood of these scenarios. We show a less than 1% probability of exceeding 8.5 W/m^2 by the end of the century but also discuss why these scenarios are still useful for anchoring the high end of damage functions, for providing analogues for climates after the year 2100, and for investigating the outcomes of low probability but high impact futures.

Introduction:

Representation Concentration Pathway (or RCP) 8.5 was the highest of four concentration scenarios (RCP2.6, 4.5, 6.0, and 8.5) developed as inputs for the CMIP5 modeling exercise (Moss et al. 2010, van Vuuren et al. 2011). The numerical component of the scenario name refers to the increase in radiative forcing between pre-industrial times and 2100 in the scenario in units of watts per square meter (W/m^2). The RCP scenarios were used in climate models to inform the IPCC Fifth Assessment Report (AR5) and the US National Climate Assessment (NCA4), as well as innumerable research papers. While NCA4 used the full range of RCP scenarios, the assessment focused most closely on RCP4.5 and RCP8.5, which they considered as low-end and high-end scenarios, to be consistent with the range of scenarios used in previous assessments (USGCRP, 2015). These two scenarios were also the most heavily represented in the existing literature at the time. More recently, a new set of Shared Socioeconomic Pathway (SSP) scenarios were developed for the CMIP6 modeling exercise (O'Neill et al. 2016, Riahi et al. 2017), which were intended to more fully integrate changes in socioeconomics with changes in radiative forcing, and included new radiative forcing endpoints of 1.9, 3.4, and 7.0 W/m^2, peak and decline scenarios, and alternate socioeconomic assumptions (SSP1 through 5) for many of the scenarios. The SSP2-4.5 and SSP5-8.5 scenarios are considered the closest analogues to RCP4.5 and 8.5, which may account for why these two scenarios are similarly highly represented in the literature.

RCP8.5 has been characterized as a scenario that assumes high population growth, low income growth, and modest improvements in energy intensity over the next century, leading to high energy demand and GHG emissions (Riahi et al. 2011, Moss et al. 2010). The research community originally developed the four scenarios as “plausible futures”, with RCP8.5 roughly representing the upper 10th percentile of radiative forcing from scenarios in the published literature at the time of development in 2007 (Moss et al. 2010). However, this is not a rigorous method for determining probability of exceedance of a scenario. Because no probabilities were assigned to these scenarios from the literature, this 10% statistic may bear little resemblance to an actual probability of exceedance: the distribution includes both policy and non-policy scenarios leading to an underestimate of BAU emissions; the majority of the scenarios are likely to be designed as “best-estimates” which will underweight the tails; and carbon cycle uncertainties may not have been included in all the studies, again underweighting tails.

Due in part to the use of RCP8.5 in the NCA4 and other assessments, as well as the continued use and interest in SSP5-8.5, questions regarding the plausibility (e.g., Christensen et al. 2018, Schwalm et al. 2020, or Kemp et al. 2022) or implausibility (e.g., Hausfather and Peters, 2020, Burgess et al. 2020, Skea et al. 2021, Srikrishnan et al. 2022, or Pielke et al. 2022) of 8.5 W/m^2 scenarios have steadily increased. Additionally, the recent IPCC AR6 report stated that “the likelihood of high-emissions scenarios such as RCP8.5 or SSP5-8.5 is considered low in light of recent developments in the energy sector” (Chen et al. 2021). Importantly, while most of these evaluations of RCP8.5 or SSP5-8.5 have focused on the plausibility or implausibility of the fossil fuel usage and/or emissions pathways in the scenario, it is important to recognize that when these scenarios are used as input to global climate models (GCMs), they are primarily used as concentration pathways rather than emission scenarios (several of the studies previously referenced do discuss the potential importance of carbon cycle uncertainties, though without analyzing the implications of including those uncertainties – e.g., Hausfather and Peters 2020, Chen et al. 2021, and Srikrishnan et al. 2022). Huard et al. 2022 has also highlighted this issue of evaluating scenarios based on their emissions versus their concentrations. Radiative forcing is a simplifying aggregate metric to consider rather than comparing individual greenhouse gas concentrations. This then leads to two related questions: 1) given the latest available societal projections, what is the likelihood of exceeding 8.5 W/m^2 by the end of the century, and 2) what is the appropriate likelihood for the high-end scenario to include in scientific assessments? This paper addresses those questions.

To answer these questions, this paper has several primary aims. First, we leverage recent advances in probabilistic emission projections (RFF-SPs, Rennert et al. 2022a, Rennert et al. 2022b), and coupled these with a state-of-the-art simple climate model (FaIR version 2.1, Leach et al. 2021), augmented with improved methods to account for emissions of aerosols and minor GHGs (based on Lamboll et al. 2020), to generate a multi-million-member ensemble to derive an updated probability density function for end of century radiative forcing. Second, we use the forcing probability density function from this ensemble of equally probable emissions scenarios and climate parameter combinations to determine the likelihood of exceeding 8.5 W/m^2 in 2100 (or 2150). Lastly, we discuss considerations for the appropriate choice of likelihood for an upper bound, high forcing, scenario depending on the relevant application.

Results:

We first compare emission levels across the RFF-SP scenarios to those in the SSP scenarios (Figure 1) by calculating the number of RFF-SP scenarios where CO_2 emissions in 2100 exceed those in six SSP scenarios, and then divide by the 10,000 total scenarios to come up with a probability of exceedance. We also repeat this calculation with GWP-weighted emissions to account for the role of non-CO_2 GHGs. Table 1 shows the results of these calculations, with the 2100 emissions from each SSP scenario included in the left column for comparison.

Figure 1: Mean and the 95% and 5% bounds for CO_2 emissions from the RFF-SP scenarios, as well as CO_2 emissions from six SSP-RCPs, from 2000-2300

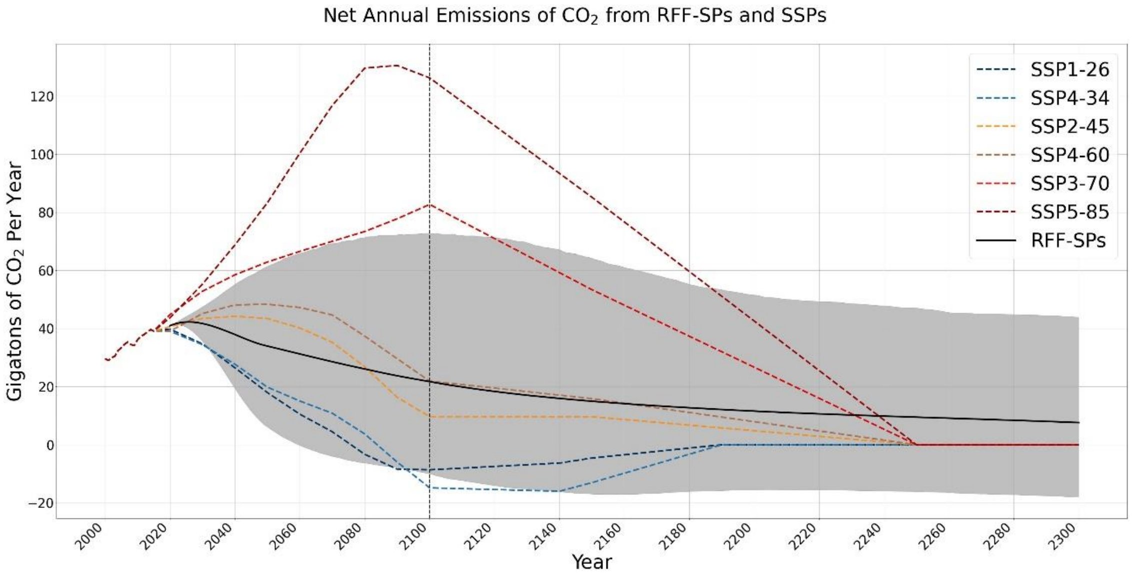


Table 1: Probability that CO_2 emissions in 2100 (absolute & GWP-weighted) in the 10,000 RFF-SP scenarios exceed those in six of the SSP scenarios. Global warming potentials (GWPs) are from IPCC AR4.

Comparison scenario End-of-century emissions	CO_2-only	GWP weighted	Cumulative CO_2 by 2100 (GtC)
SSP5-8.5 126 GtCO_2 142 GtCO_2e	0.030%	0.020%	3078
SSP3-7.0 82.7 GtCO_2 108 GtCO_2e	1.1%	0.46%	2813
SSP4-6.0 21.9 GtCO_2 39.0 GtCO_2e	41.8%	36.3%	2585
SSP2-4.5 9.68 GtCO_2 19.7 GtCO_2e	66.3%	71.8%	2523
SSP4-3.4 -14.8 GtCO_2 -0.921 GtCO_2e	100%	100%	2353
SSP1-2.6 -8.62 GtCO_2	100%	100%	2337

-3.07 GtCO$_2$e			

The RFF-SP emissions are then used as inputs to the FaIR model. Each of the emissions scenarios is run with all 1001 FaIR parameter combinations, for 10,010,000 total output scenarios. Figure 2 shows the radiative forcing from the SSP scenarios (run in FaIR with the same calibration) overlayed on top of the 90% bounds of this analysis. Table 1 shows the percentage of the runs from this analysis that exceed each forcing threshold in 2100 and then again in 2150.

Figure 2: Mean and the 95% and 5% bounds for total radiative forcing from the RFF-SPs scenarios run through FaIR 2.1 with the 1001 parameter sets, as well as total radiative forcing from six SSP-RCP emission scenarios run through FaIR 2.1.

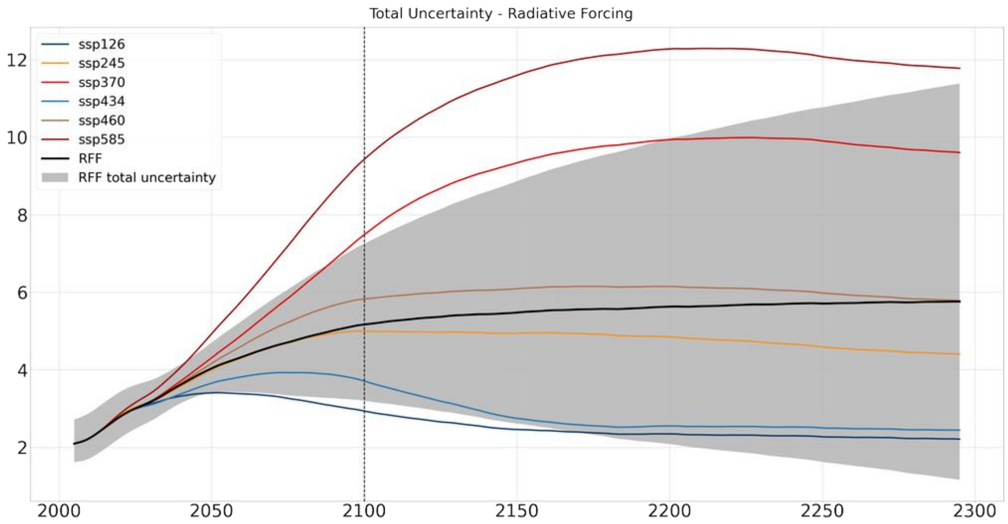
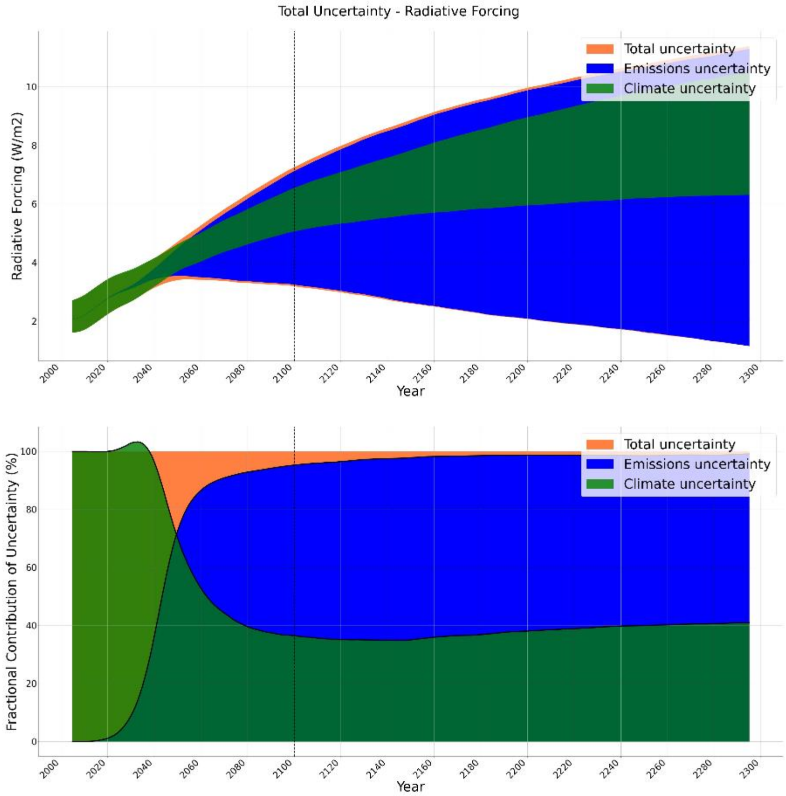


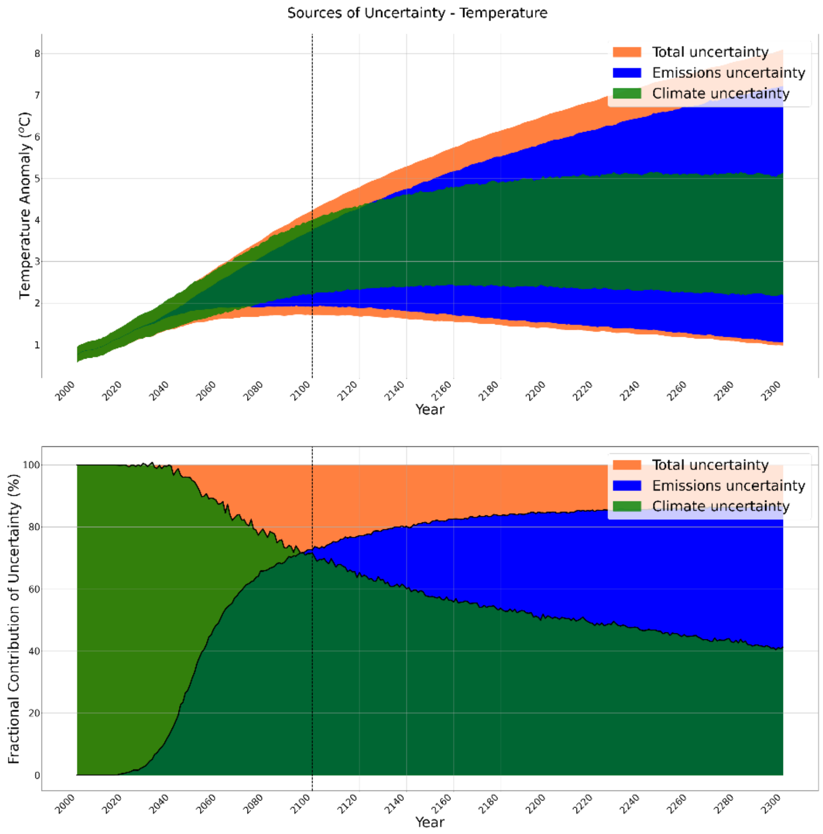
Table 2: Probability that total radiative forcing from the RFF-SP scenarios combined with FaIR climate uncertainty exceeds each SSP radiative forcing threshold in 2100, 2150, or 2300

Radiative forcing threshold (W/m^2)	Year: 2100	Year: 2150	Year: 2300
8.5	0.53%	6.9%	20%
7.0	7.2%	22%	32%
6.0	25%	37%	43%
4.5	68%	65%	62%
3.4	92%	85%	77%
2.6	99%	95%	86%

To assess the relative contributions of emissions uncertainty and climate parameter uncertainty, we also produce Figure 3, in the tradition of Hawkins and Sutton (2009) and Lehner et al. (2020). Figure 3 shows a timeseries of the range of radiative forcing and temperatures (an output from FaIR) resulting from the 1001 FaIR runs around the emissions scenario with median forcing (climate uncertainty), the 10,000 RFF-SP runs with a single FaIR parameter set (chosen as having the median climate sensitivity; emissions uncertainty), and the combination of the two (total uncertainty), along with the fractional contribution of each. Note that climate variability is included in all analyses, such that summing the individual uncertainty contributions is expected to exceed the actual total uncertainty.

Figure 3: Annual radiative forcing (a,b) and temperature (c,d) projections, showing the 5th to 95th % bounds from emissions uncertainty, climate parameter uncertainty, and total combined uncertainty. Note that internal climate variability contributes to all three uncertainty distributions.





Discussion

The relevance of a particular future scenario depends on the application, purpose, and audience of a particular analysis or assessment. However, the relevance also depends on the probability of exceeding the metric of interest, whether it be a given quantity of emissions, concentration of CO_2 or CO_2-equivalent, total radiative forcing, global temperature, or some other metric. Despite the low probability of exceeding 8.5W/m^2 by the end of the century (Table 2), there are at least three applications where it remains crucial to consider these high-forcing, low-probability scenarios: 1) development of damage functions or “by-degree” climate impact analyses, 2) as an analogue for post-2100 climate change, and 3) consideration of low probability but high impact possibilities.

For the first application, “by-degree” climate impact analyses are mostly scenario agnostic (Sarofim et al. 2021). However, the higher the emissions driving the analysis, the larger a temperature (or other climate parameter) range that will be covered, making a high-end, but plausible, future desirable. As damage functions are essentially a mathematical fit to a “by-degree” approach, the anchor for the high end of the damage function should be a low probability scenario (note that it can also be important to have a similar anchor for the low-end in order to explore marginal benefits of additional mitigation even when a stringent policy future is used as the reference). For example, Hartin et al. (2023) uses piecewise linear extrapolation between data points to assess climate change damages across a given range of temperature scenarios.

The second application regarding post-2100 analogues is relevant because most GCM scenario projections end in 2100 (O'Neill et al. 2016), except for a few GCMs which were run with extended scenarios. Therefore, the majority of the impacts literature is based on scenarios that end in 2100. However, the real world will continue past that date. For this reason, we argue that climate projections for 2100 under high forcing scenarios can be used as analogues for climates that may not be seen until much later. This use of climate projections for one year as an analogue for climate impacts in a different year is the fundamental concept behind the "temperature slice" or "global warming level" approach (e.g., Sarofim et al. 2021, Schleussner et al. 2016). Given this application, we have calculated the probability density function of radiative forcing in 2150 to show that the probability of exceeding 8.5 W/m2 reaches almost 7% due to a combination of potential continued emissions as well as climate feedbacks. While the 0.5% probability of exceeding 8.5 W/m2 is below the 1% relevance threshold we discuss below, it is difficult to argue policy irrelevance with a probability of exceedance of greater than 5%, even if the date is further in the future. While we have chosen 2150 to illustrate this point, we will note that projections developed for the social cost of greenhouse gas extend through 2300 (Rennert et al. 2022), and the exceedance probability of 8.5 W/m2 is 20% by the end of this period.

For the third application, low probability but high impact events are often of relevance to policymakers. As discussed further in the following paragraphs, the precise probability of exceedance becomes relevant in assessing risk in these contexts. This discussion of probability is also relevant to the choice of the high-end anchor for damage functions or by-degree analyses and for deciding the hottest post-2100 potential climate for which to simulate an analogue. The question then becomes how likely does a scenario have to be to be relevant? On the small end, Ansolabehere et al. (2003) recommended an annual risk of 1 in a million for a large, early release of radioactivity from a nuclear plant. On the larger end, few people would carry an umbrella with them if the probability of rain was less than 10%. However, these examples do not provide good context for the appropriate choice of likelihood for a high-end climate scenario. Many potential examples involve repeated probabilities for individual events that can happen at multiple locations (e.g., the nuclear example, or the choice of the 1 in 100 year flooding event for floodplain analysis). In contrast, climate change involves a global, accumulating problem where the probability of a high-end scenario is a function of socioeconomic assumptions and uncertainty in basic scientific parameters. We choose 1% as a policy relevant probability for a high-end scenario for generalized climate analysis purposes, though recognizing that others could choose a different threshold.

Several considerations are relevant for these three applications. There is the choice to focus on probability of exceeding radiative forcing rather than emissions. There are challenges involved in characterizing uncertainty, particularly for low probability tails of distributions. And there is the recognition that even if there are good reasons to include a high scenario in an analysis, that scenario is not necessarily the most relevant scenario.

Because CMIP GCMs and ESMs are generally driven by concentration scenarios, not emission scenarios, it is the probability of exceeding those concentrations which is most relevant. Radiative forcing is the best available metric to use to represent the aggregate climate impact of a concentration pathway, though it has some drawbacks. For example, different GCMs can have different radiative physics, such that different GCMs run with the same set of GHG and aerosol concentrations may result in different levels of forcing and two emission scenarios with the same forcing in one GCM may diverge when run in a second. Relevantly, while the IIASA database for scenarios suggests that RCP8.5 reaches 8.4 W/m2 in 2100 and SSP5-8.5 reaches 8.7 W/m2, more recent simple climate models incorporating updated knowledge in Earth system processes yield higher radiative forcings from the same set of concentrations (Byers et al. 2022). The most relevant forcing is the one embodied within the GCM calculations. Fredriksen et al. (2023) show that GCM-derived forcing is markedly higher for SSP5-8.5 in CMIP6 models than for RCP8.5 in CMIP5 models. Tebaldi et al (2021) estimate that most GCMs reach 8.9 W/m^2 by 2100 for SSP5-8.5. Wyser et al. estimated 9.2 W/m^2 in the EC-Earth3-Veg GCM for SSP5-8.5, but only 7.8 W/m^2 for RCP8.5. However, here we focus on radiative forcing as the best available metric, even while recognizing its imperfections.

In addition, when looking at low probability outcomes, considerations of additional sources of unbiased (no more likely to be above the reference parameters than below) uncertainty will always increase the probability of exceeding those outcomes. For example, while the chance of the world having higher forcing than the SSP5-8.5 scenario in 2100 is a low probability outcome, it is more likely than the chance of exceeding SSP5-8.5 emissions. In this case, the probability of exceeding the emissions in the SSP5-8.5 scenario in 2100 when taking the RFF-SP distribution as truth is substantially lower than 1%. Even the probability of exceeding SSP3-7.0 emissions by 2100 is on the order of 1%. However, when we move to radiative forcing, the probabilities become substantially larger: 0.5% for exceeding 8.5 W/m^2, and 7% for exceeding 7 W/m^2. A key contributor to this increase in the probability of exceedance is the inclusion of additional uncertainties, in particular carbon cycle and methane feedbacks, and methane chemistry uncertainties. Because there are more emissions scenarios that are just short of SSP5-8.5 than just larger than SSP5-8.5, changing parameter draws would be more likely to push a concentration pathway over the SSP5-8.5 threshold than to pull a pathway under it.

Figure 3 shows that climate parameter uncertainty is the driver of near-term uncertainty in both radiative forcing and temperature. Our analysis shows that while climate parameter uncertainty and emissions uncertainty become equal contributors to total forcing uncertainty by 2050, climate parameter uncertainty exceeds emissions uncertainty almost through 2100 for temperature uncertainty. This is a result of there being a more limited set of uncertain climate parameters that impact forcing (aerosol forcing, carbon cycle, and methane feedback uncertainties being some of the more important), and a more expansive set of climate parameters that impact temperature (climate sensitivity and ocean heat uptake being key). While most of this paper discusses radiative forcing as it is the key input to climate models, the presentation of temperature uncertainty is important as it is the actual driver of impacts that are relevant to human and ecological experiences. Two key advances over the previous Hawkins and Sutton (2009) and Lehner et el. (2020) are the use of fully probabilistic emission and climate parameter uncertainty inputs for this analysis (rather than, for example, assuming that the RCPs are all equally likely).

Of course, projecting even to 2100, less than 80 years into the future, is a challenging task, particularly for socioeconomic conditions that are key factors in determining future emissions. Barron (2018) discusses some of the challenges in projecting future penetration of low-carbon technologies using climate policy models. While the RFF-SP scenarios may be the best probabilistic emissions forecast available, these probabilities must be taken with some skepticism, particularly in the tails (such as the 1% threshold that we focus on). The RFF-SPs rely primarily on expert elicitation, but there are other approaches. Liu and Raftery (2021) use a Bayesian approach to drive a Markov chain Monte Carlo for developing emission scenarios. Morris et al. (2022) apply a complex computable general equilibrium model driven with uncertain input parameters whose distributions are defined by a combination of expert elicitation and statistical analysis of historical data. All these projections seem to be reasonably well aligned. The definition of "business as usual" can also be a challenging one – for the RFF-SP scenarios, the experts were instructed to provide economic growth estimates absent the effects of future climate change or additional policy efforts to reduce emissions, but several of the experts acknowledged that their final probability distributions did include some internalization of future climate policies and impacts. Moreover, experts were instructed to include views about the evolution of future policy for projecting changes in technology, fuel use, and other socioeconomic conditions relevant to emission factors.

While there is more confidence in the climate uncertainty probabilities as expressed in the 1001 FaIR ensemble members compared with the socioeconomic uncertainties driving emission projections, there are also some limitations regarding these physical parameter definitions. In particular, any feedbacks that don't exist in either the historical record or the climate models against which FaIR was calibrated will not be captured by this analysis. Prior distributions for FaIR parameters were informed by CMIP6 GCMs, and the potential for the uncertainty space to be under-sampled exists. Furthermore, the permafrost feedback is not included in FaIR, which has the potential to contribute substantially to radiative forcing and warming through release of additional CO_2 and CH_4.

While our analysis shows that 8.5 W/m^2 scenarios are appropriate for use in creating damage functions, and important to include in the next round of CMIP analyses, it is important to reiterate that 8.5 W/m^2 is still an unlikely future outcome – even through the 22nd century. We are arguing here for the inclusion of 8.5 W/m^2 scenarios to anchor the high end of possible outcomes or to develop damage functions, but not necessarily as the most relevant future. One pertinent example is the use of a future scenario for use in adaptation decisions. There are often non-negligible costs associated with over-adaptation: e.g., for sea level rise, there are expenses involved in building higher sea walls than would be optimal from a cost-benefit analysis, and in some cases, there could be unnecessary abandonment of properties based on over-reliance on pessimistic forecasts. While it may be appropriate to use a scenario that is higher than the median or mean scenario, something like the 25% likely 6 W/m^2 scenario might be better suited than the 1% likely 8.5 W/m^2 scenario. However, this does not mean an 8.5 W/m^2 scenario can't be relevant: the use of a by-degree approach allows for the GCM output of such a scenario to be used as analogues for lower temperatures whose probabilities are calculated by the use of reduced complexity models (such as FaIR and the RFF-SPs).

One noteworthy issue is that the estimated likelihood of high forcing scenarios has declined over time. While, as discussed in the introduction, there was no formal probability assigned to the 8.5 W/m^2 scenario though it was chosen to represent the upper 10% of existing scenarios (Moss et al., 2010), Webster et al. (2009) combined probabilistic estimates of emissions and climate parameters to estimate a 90% upper bound of 9.8 W/m^2 relative to 1990 (or about 11.6 W/m^2 relative to pre-industrial). Therefore, over the past 14 years, the probability of exceeding 8.5 W/m2 by the end of the century has dropped from double digits to below one percent. While some of this reduction of the high end of possible forcing futures may be due to better information about climate uncertainty, it is likely that the majority is due to reductions in estimated future emissions, due to a combination of technological progress and policy action. This is good news, and the trend towards lower probability of high forcing scenarios will hopefully continue in the future.

Conclusions

Here we use a 10 million-member-ensemble to analyze the probability of exceeding 8.5 W/m^2 in 2100, 2150, and 2300. Our results show that while the probability of exceeding this threshold in 2100 is less than 1%, it reaches 7% by 2150, and 20% by 2300. Because many climate analyses to date have focused on the current century, a scenario that reaches 8.5 W/m^2 in 2100 continues to have substantial relevance for serving as an analogue for post-2100 climates, as well as for driving impacts models to develop damage functions that can be useful through the year 2300.

Therefore, it is important that the CMIP community continue to include an 8.5 W/m^2 scenario in the family of scenarios for CMIP7. In addition, if an impact modeler is only going to use a single scenario, 8.5 W/m^2 is the appropriate scenario to use – not because it is the most likely, but because it can serve to inform a by-degree approach which can be coupled with a reduced complexity model to estimate the timing and probability of reaching future forcing and temperature thresholds, enabling the discussion of almost any possible future including years past 2100 (with a possible exception of peak-and-decline scenarios). However, if it becomes standard in the future to run impacts analyses through later years (such as 2150), it might be more appropriate to choose a high-end scenario which reaches 8.5 W/m2 in that later year (rather than 2100).

While our analysis suggests that 8.5 W/m2 continues to be sufficiently likely to be relevant based on projections founded on today's best estimates, we hope that as zero carbon technologies continue to become more competitive, and mitigation efforts continue to increase, that soon the 8.5 W/m2 scenario might drop enough in likelihood that our arguments for continuing to include it would no longer hold.

Methods

We quantify the likelihood of exceeding 8.5 W/m^2 by the end of the century by developing a probability density function, based on two components: 1) probabilistic projections of greenhouse gas (GHG) and aerosol emissions and 2) coupling these with a simple climate model that accounts for additional uncertainty in climate parameters. To derive emission projections, we start with the 10,000 global GHG emission scenarios from the Resources for the Future Socioeconomic Projections (RFF-SP) dataset, which provides global CO_2, CH_4 and N_2O emissions from 2020 through 2300 (Rennert et al. 2022a). While the original RFF-SP scenarios assumed that additional short-lived climate forcers (tropospheric ozone and aerosol precursors) and other greenhouse gases followed the SSP2-4.5 scenario, here we infill the RFF-SP GHG scenarios using the *silicone* tool (Lamboll et al. 2020). Infilling uses a database of existing integrated assessment model (IAM) GHG and air pollutant emissions scenarios and uses relationships between a lead species (in our case CO_2 emissions from fossil fuels and industry) and those that are not present in the RFF-SPs. The logic behind this is that emissions of CO_2 tend to be well-correlated with emissions of non-CO_2 species over time (Rogelj et al. 2014) as many species are co-emitted with $CO_{2.}$ Where they are not, high emissions scenarios tend to be indicative of high economic activity, low levels of climate and air quality policy, or both (and vice versa for low emissions scenarios). In this analysis, we use the IPCC Sixth Assessment Report (AR6) Working Group 3 (WG3) infiller database (Kikstra et al. 2022; Byers et al. 2022). The emissions in this database have been harmonized (Gidden et al. 2018) to ensure a smooth transition from historically reported emissions values to future scenario projections. As the RFF-SP dataset only provides total CO_2 emissions this contribution needs to be split into fossil fuel and industrial (FFI) emissions and land use (AFOLU) emissions to run FaIR and perform the infilling. This was performed using the silicone toolbox with the “time-dependent ratio” method, mapping FFI and AFOLU emissions to total CO_2 emissions from the AR6 infiller database using the average ratio of AFOLU and FFI to total CO_2 across the database (Lamboll et al. 2020).

We replicate the infilling methods of the IPCC Working Group 3 report (Kikstra et al. 2022; Riahi et al. 2022) as closely as possible. For example, short-lived climate forcers (SO_2, BC, OC, NH_3, NO_x, CO and VOCs) are infilled using the “quantile rolling windows” (QRW) method of silicone. We use CO_2 FFI as the lead species and the AR6 infiller database. QRW maps the lead specie (CO_2 FFI) to a specified quantile of emissions of the desired pollutant from the infiller database over time. We use the 50th percentile for each short-lived forcer. This preserves relationships of co-emittance between high and low emissions scenarios (e.g. high CO_2 FFI likely implies high SO_2 emissions in the absence of air quality improvements) but does not further differentiate between scenarios (e.g. high CO_2 FFI emissions could occur with low SO_2 emissions if air quality improvements occur but emissions mitigation does not).

All halogenated GHG emissions are infilled using the “RMS Closest” method of silicone. As suggested, this selects the emissions of the desired greenhouse gas from the AR6 scenario based on the scenario that minimizes the root-mean-square error between the time series of (reconstructed) CO_2 FFI emissions from the RFF-SP scenario and the AR6 scenario. For some of the more major hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) that are individually modelled by several IAM groups, the AR6 infiller database is used. In contrast, emissions for more minor gases and all ozone-depleting substances are not generally available in IAMs and therefore the set of eight SSP scenarios that drive the CMIP6 Earth System models and were prepared on global annual mean emissions timeseries for the Reduced Model Intercomparison Project (RCMIP; Nicholls et al. 2020, 2021) are used. FaIR uses NOx emissions from the aviation sector as a proxy for radiative forcing from contrails and contrail-induced cirrus, and this data is also infilled from the SSP scenarios using the RMS Closest method.

In addition, the AR6 and SSP scenarios only run to 2100, whereas we require emissions to 2300. We follow the logic discussed in Meinshausen et al. (2020) to extend SSP emissions beyond 2100. If CO_2 FFI emissions are positive in 2100, they are linearly ramped down to zero by 2250; if they are negative, they are ramped up to zero by 2150. CO_2 AFOLU emissions are ramped to zero by 2150 whether negative or positive in 2100. For CH_4, N_2O and short-lived forcers, the FFI component (always positive) is ramped down to zero by 2250, and the AFOLU component is held constant at 2100 emissions. As IAM scenario data does not provide the FFI/AFOLU split for non-CO_2 emissions, we estimate this from the average of the 2100 ratios in SSP scenarios that do have this granularity. Finally, minor greenhouse gases with no assumed AFOLU source are ramped down to their pre-industrial emissions level by 2250. Historical emissions from 1750-2014 are provided from RCMIP and for the period 2015-2020 we follow RFF-SP and use SSP2-4.5.

The final set of 10,000 infilled, complete RFF-SP emissions scenarios are then run using a 1001-member probabilistic ensemble of a state-of-the-art simple climate model: the Finite amplitude Impulse Response model (FaIR v2.1) (Leach et al. 2021). The FaIR calibration we use (v1.0; Smith 2023) is consistent with the IPCC AR6 Working Group 1 assessment of present-day warming, equilibrium climate sensitivity, transient climate response, present-day aerosol radiative forcing, present-day CO_2 concentrations, and recent-past ocean heat content change, including the uncertainties in these distributions (Forster et al. 2021; Smith et al. 2021), maintains a root-mean-square error between modelled and observed global mean surface temperature of less than 0.16°C in each ensemble member, and is consistent with historical emissions from RCMIP. We use stochastic, auto-correlated internal variability in temperature and forcing following Cummins et al. (2020). For comparison to the RFF-SP dataset, we also run the SSP scenarios under the same calibration for comparison. RCP scenarios also use this calibration but are additionally redrawn to historical emissions of short-lived forcers (Skeie et al. 2011).

The coupled combination of 10,000 RFF-SP emissions scenarios, run with a 1001-member climate parameter ensemble, creates 10,010,000 total outcomes (https://zenodo.org/record/7759089#.ZGI7kqXMK3C). Result data for each emissions scenario are saved as a netCDF file and includes ensemble-level information about global mean surface temperature, effective radiative forcing, ocean-heat content, and concentrations of CO_2, CH_4 and N_2O. Uncertainty ranges are produced for temperature and radiative forcing and are defined by the following 3 classifications: "total uncertainty" represents the uncertainty range of all 10,010,000 outcomes, "emissions uncertainty" represents the uncertainty range of median values for each climate parameter ensemble member, and "climate uncertainty" represents the uncertainty range associated with a single central emissions scenario. Uncertainty ranges are constrained by the 5th and 95th percentiles for the years 2020 through 2300.

Code and data availability

RFF-SP emissions scenarios are available from https://doi.org/10.5281/zenodo.5898729.

The AR6 Working Group 3 infilling database is available from https://doi.org/10.5281/zenodo.6390768 (registration required).

RCMIP emissions prepared for the SSP scenarios are available from https://doi.org/10.5281/zenodo.4589756.

FaIR v2.1 is available from https://doi.org/10.5281/zenodo.7459702 and v1.0 of the calibration is available from (https://doi.org/10.5281/zenodo.7545157).

The probabilistic FaIR output is available from https://zenodo.org/record/7838148 and code at https://github.com/chrisroadmap/rff-fair2.1.

The code for FaIR/Figure processing scripts is at https://github.com/erysimumcap/RCM_RCP8.5_Probability

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