Exhibit 1

Key Issues Facing California's GHG Cap-and-Trade System for 2021-2030

Todd Schatzki, Ph.D.

Analysis Group, Inc.

Robert N. Stavins

Harvard University

July 2018

Key Issues Facing California's GHG Cap-and-Trade System for 2021-2030

Executive Summary

Todd Schatzki and Robert N. Stavins[1]

July 2018

California's Greenhouse Gas (GHG) cap-and-trade program is a key element of the suite of policies the State has adopted to achieve its climate policy goals. The passage of AB 398 (California Global Warming Solutions Act of 2006: market-based compliance mechanisms) extended the use of the cap-and-trade program for the 2021-2030 period, while also specifying modifications of the program's "cost containment" structure and directing CARB to "[e]valuate and address concerns related to overallocation in [ARB's] determination of the allowances available for years 2021 to 2030." The changes being considered by CARB will not only affect the program's stringency, but also its performance by affecting the ability of the "cost containment" structure to mitigate allowance price volatility and the risk of suddenly escalating allowance prices.

This white paper addresses key design issues that were identified by the legislature in AB 398 and have been identified by CARB in its "Preliminary Concepts" white paper, including:

1. Price levels for the Price Ceiling and Price Containment Points;
2. Allocation of allowances between the auction budgets, Price Containment Points, and Price Ceiling;
3. "Overallocation" of GHG allowances; and
4. The program's administrative and operational rules, including: (1) procedures for distributing allowances to the market from the Price Ceiling or Price Containment Points; (2) procedures for using allowances once distributed; and (3) banking rules.

Price Levels for the Price Ceiling and Price Containment Points

CARB must establish specific price levels for the Price Ceiling and Price Containment Points. When setting the price for the Price Ceiling, there are a number of considerations that are relevant and useful from an economic perspective, including the estimated social cost of carbon, the risk of emission

[1] Dr. Schatzki is a Vice President at Analysis Group. Stavins is A. J. Meyer Professor of Energy and Economic Development, John F. Kennedy School of Government, Harvard University; University Fellow, Resources for the Future; and Research Associate, National Bureau of Economic Research. He is an elected Fellow of the Association of Environmental and Resource Economists, was Chairman of the U.S. Environmental Protection Agency's Environmental Economics Advisory Committee, and served as Lead Author of the Second, Third, and Sixth Assessment Reports and Coordinating Leading Author of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Institutions listed are for purposes of identification only, implying no endorsement of this work. Support was provided by the Western States Petroleum Association, but the opinions expressed are exclusively those of the authors. Research assistance was provided by Jonathan Baker and Tyler Farrell. To request further information or provide comments, Dr. Schatzki can be reached at: tschatzki@analysisgroup.com.

leakage, linkages with other cap-and-trade systems and/or other types of climate policy instruments in other jurisdictions, and continuity with prior market rules:

- **The social cost of carbon reflects the estimated damages that an additional ton of GHG emissions will have on society, and thus is a key economic consideration in setting the Price Ceiling.** Setting the Price Ceiling above the social cost of carbon creates incentives for covered sources to undertake abatement of GHG emissions that is more costly than the damages these emissions create. CARB should rely on reliable estimates of the social cost of carbon that are based on sound scientific methods. A widely respected benchmark was developed by the United States Government's Interagency Working Group ("IWG") on the Social Cost of Greenhouse Gases. The IWG estimated the social cost of carbon to be $25 to $115 per metric ton for the year 2030, with a central tendency of about $79 per metric ton.[2]
- **A lower Price Ceiling limits emission and economic leakage, all else equal.** Leakage will rise with higher allowance prices, as economic activity shifts outside of California to avoid GHG cap-and-trade compliance costs. With this shift in economic activity, environmental benefits are diminished and economic impacts are larger.
- **A high Price Ceiling may have positive or negative implications for linkage with other GHG cap-and-trade systems (or other types of climate policy instruments in other jurisdictions).** Linkage can lower the cost of achieving California's GHG goals. One risk of linkage, however, is that shocks to allowance demand or supply in one system will diffuse to linked systems. A Price Ceiling can mitigate this risk by limiting price spikes. However, the choice of Price Ceiling (and price floor) also needs to be consistent with policy objectives in other regions.
- **Continuity in market design is important for investor confidence needed for cost-effective investments in low-GHG technologies.** Thus, changes to program design should be minimized, and program design decisions, including Price Ceiling levels, should be chosen with long-term implications in mind. However, it will be unwise to defer rule changes that meaningfully improve program performance, unless absolutely necessary.

The costs of existing efforts to reduce emissions are not a useful guide for the Price Ceiling. The value of environmental policies reflects the benefits they create, not the cost of achieving those benefits. Thus, conceptually, the social cost of carbon provides a better benchmark for a limit on the price of carbon emissions. Further confounding matters, many (if not all) programs in CARB's Scoping Plan are pursued to achieve multiple benefits, not solely GHG emission reductions. Thus, any metric of cost that attributes costs to only GHG emission reductions will overstate the true cost of GHG abatement. More broadly, the fact that CARB has adopted a policy with high costs (potentially affecting only a small portion of California's economic activity) does not mean that it makes sense to impose this cost on the entire California economy (and might even imply that this policy should not be pursued in the first place.)

"Shadow prices" on carbon used by private corporations for internal decision-making are even more problematic as a basis for setting the Price Ceiling. Private corporations adopt these shadow

[2] This estimate varies with the choice of discount rate used to convert future damages into present value terms, as well as other factors.

prices for multiple reasons, many of which are unrelated to the true social cost of carbon. Moreover, the specific shadow prices chosen by private corporations vary widely, from less than $0 per MTCO$_2$e to more than $800 per MTCO$_2$e, and many other companies have adopted no shadow price at all.

When deciding on price levels for the Price Containment Points, it is important to keep in mind their underlying purpose. The Price Containment Points will contain allowances taken from the allowance budgets to help "contain costs" if there is a surge in demand for allowances. Under volatile market conditions, the Price Containment Points can mitigate allowance price volatility, provide the market with additional time for price discovery, and allow market participants more time to adjust investment and operational decisions. These benefits may be particularly important for California's system given the risk of volatile allowance prices identified by some research (Borenstein et al., 2017.)

All else equal, evenly distributing the Price Containment Points throughout the range between the price floor and Price Ceiling will most effectively mitigate price volatility, including the risk of large, sudden increases in price. To the extent that CARB is making decisions about the disposition of allowances (e.g., allowances already allocated for a 2021-2030 allowance reserve prior to recent legislation), adding these to the Price Containment Points would provide a greater buffer against volatile prices than placing these in the Price Ceiling.

"Overallocation" of Allowances

The "overallocation" issue has emerged due to a combination of factors including banked allowances from the 2013-2020 period that could be used to achieve compliance in 2021-2030. Some stakeholders have raised the concern that the bank of allowances could jeopardize achievement of the program's "intended" goals, while others have raised concerns about legal compliance with California's legislative statutes. We make several observations about this, setting aside issues related to GHG cap-and-trade's underlying stringency, which may be a central thrust of many stakeholder's focus.

First, no regulatory mechanism can "guarantee" compliance with a particular environmental target. While proposed remedies can increase the *likelihood* that total emissions are at or below a particular target in a particular year, they cannot enable CARB meet some bright line with certainty.

Second, the "overallocation" debate reflects, in part, a concern that actual emissions may exceed particular *annual* targets, rather than a concern about cumulative targets. A shift in focus away from cumulative emission targets and toward annual targets would be both costly and inconsistent with the underlying science of the climate problem. Climate impacts reflect cumulative rather than annual emissions, and GHG policies that are designed to reflect this flexibility lower costs by allowing emission reductions to occur when they are less costly and increase environmental benefits by allowing early reduction in emissions. Moreover, allowance banking does not imply that emissions will exceed certain annual targets, particularly because market participants are likely to maintain a bank of allowances to mitigate against economic risks (rather than expend the entire bank to achieve compliance in particular years).

Third, empirical analysis suggests that there is a meaningful possibility that market conditions will tighten substantially; Borenstein et al. find a 1-in-3 chance that allowance prices will rise to a value of $85 per MTCO$_2$e without any changes to allowance budgets. Proposals to eliminate allowances from allowance budgets (or other accounts and reserves) would increase the likelihood that this occurs. The risk of such price increases will remain as California's climate targets increase in stringency over time, thus providing an on-going incentive for market participants to maintain a sizable bank of allowances.

Allocation, Holding, and Use of Price Ceiling and Price Containment Point Allowances

CARB faces multiple administrative decisions related to the allocation, holding, and use of allowances from the Price Ceiling and Price Containment Points. Initial discussions propose many restrictions on the timing, holding, and use of these allowances.

When designing administrative rules for the Price Ceiling, some rules may simplify the program's operation without sacrificing performance. Because the Price Ceiling ensures a supply of allowances sufficient for companies to comply, the timing of sales and constraints on holding and use of allowances is less critical.

By contrast, restrictions on the timing, holding, and use of allowances from the Price Containment Points could be costly and diminish market performance. Given the potential for Price Containment Point allowances to be released during volatile market conditions, the timely availability of supply to the market will improve price discovery and mitigate price volatility. Sale of Price Containment Point allowances on an on-going basis (an "open window") or through frequent (e.g., monthly) sales will improve market performance. Similarly, CARB is contemplating limits on the use and holding of allowances, such as requirements that Price Containment Point allowances be used immediately for compliance. Such constraints would be costly by potentially constraining market participants' ability to bank allowances for future use. The fact that allowance prices rise to the Price Containment Points does not diminish the economic value of allowance banking.

Finally, changes to the program's banking rules have been proposed, including rules that would discount (devalue) allowances under certain circumstances. Devaluing of allowances should not be adopted, as it creates market risk that distorts banking decisions. However, CARB should consider modifying the current holding limits on allowances to avoid limiting flexibility to mitigate (hedge) the financial risks of compliance.

Key Issues Facing California's GHG Cap-and-Trade System for 2021-2030

Todd Schatzki and Robert N. Stavins[3]

July 2018

California's Greenhouse Gas (GHG) cap-and-trade program is a key element of the suite of policies the State has adopted to achieve its climate policy goals. With the passage of AB 398 ("California Global Warming Solutions Act of 2006: market-based compliance mechanisms…"), California's legislature extended the use of the cap-and-trade program and identified a set of modifications that should be made to the program. The most important of these modifications alters the program's "cost containment" structure to include a Price Ceiling and two Price Containment Points during the post-2020 program. AB 398 also directs CARB to "[e]valuate and address concerns related to ***overallocation*** in [ARB's] determination of the allowances available for years 2021 to 2030, inclusive, as appropriate" (emphasis added). While SB 32 ("California Global Warming Solutions Act of 2006: emissions limit…") and AB 398, together, set clear targets for the GHG cap-and-trade programs, these modifications will nonetheless affect the program's actual stringency by affecting allowance supply under various market conditions.

This white paper addresses key design issues that were identified by the legislature in AB 398 and have been identified by CARB in its "Preliminary Concepts" white paper, designed to "commence the public discussion" on these design issues.[4] Specifically, in this paper, we consider:

5. Price levels for the Price Ceiling and Price Containment Points;
6. Allocation of allowances between the auction budgets, Price Containment Points, and Price Ceiling;
7. "Overallocation" of GHG allowances; and
8. The program's administrative and operational rules, including: (1) procedures for distributing allowances to the market from the Price Ceiling or Price Containment Points; (2) procedures for using allowances once distributed; and (3) banking rules.

[3] Dr. Schatzki is a Vice President at Analysis Group. Stavins is Albert Pratt Professor of Business and Government, John F. Kennedy School of Government, Harvard University; University Fellow, Resources for the Future; and Research Associate, National Bureau of Economic Research. He is an elected Fellow of the Association of Environmental and Resource Economists, was Chairman of the U.S. Environmental Protection Agency's Environmental Economics Advisory Committee, and served as Lead Author of the Second and Third Assessment Reports and Coordinating Leading Author of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Institutions listed are for purposes of identification only, implying no endorsement of this work. Support was provided by the Western States Petroleum Association, but the opinions expressed are exclusively those of the authors. Research assistance was provided by Jonathan Baker and Tyler Farrell. To request further information or provide comments, Dr. Schatzki can be reached at: todd.schatzki@analysisgroup.com.

[4] CARB, "Preliminary Concepts" February 2018.

If prices remain at or close to the Auction Reserve price, the program's implicit price floor, then these decisions may not matter much. With CARB continuing to include many complementary policies in the State's suite of climate policies, demand for allowances may continue to be suppressed, and the current low prices may persist.[5] However, as the State's overall emission targets become increasingly stringent, demand for allowances may become tighter, which could cause an increase in allowance prices.

In the event that there is an increase in allowance prices, the market's performance under tight allowance market conditions will depend on the outcome of current decisions faced by CARB. A rapid increase in allowance prices or highly volatile allowance prices could have many adverse economic consequences, which in turn could lead to *ad hoc* regulatory efforts to contain prices that undermine market confidence. Problematic market outcomes due to poor design can also undermine political support for the cap-and-trade program and support for the State's climate change policies more broadly. Because continued – if not expanded – reliance on the cap-and-trade program to achieving GHG reductions at manageable costs is important for California's stated climate goals, such an outcome could undermine achievement of the State's climate policy objectives. Further, demonstrating effective climate policy design has positive spillover effects to other states and countries at various stages of climate policy development and implementation. Because the climate impacts of these spillovers may far exceed the direct effect of emission reductions undertaken in California, careful design of climate policies to demonstrate their efficacy can be one of the most effective approaches available to California to address the global climate problem.

We evaluate GHG cap-and-trade design decisions from an economic perspective, although we identify certain key legal issues that affect the design decisions we evaluate. One economic issue at the core of many design decisions currently under discussion is the program's stringency, as reflected in the tradeoff between GHG emission reductions and abatement costs. The legislature has set the stringency of the GHG cap-and-trade program by establishing a 2030 target of 40 percent below 1990 emissions. **However, the AB 398 cost containment structure effectively modifies the program's stringency over the range of prices between the price floor and Price Ceiling.** The price levels for the Price Containment Points determine the point at which the program's stringency adjusts to changing market demand. Similarly, decisions about allocating allowances between the auctions, Price Containment Points, and the Price Ceiling affect program stringency.

Our analysis *does not* consider the tradeoffs between environmental benefits and abatement costs in making the program more or less stringent. The choice made by the legislature in setting the program's aggregate cap presumably reflects its judgement regarding the balance of these tradeoffs. We do not attempt to re-open that question, while recognizing that the positions of many stakeholders may reflect preferences for either more or less stringent policies. Instead, we focus on how market design decisions affect other aspects of the program's performance, including the program's ability to moderate abatement costs and the various economic risks created by the program, including volatile (or suddenly escalating) allowance prices.

[5] Schatzki, Todd and Robert N. Stavins, "Implications of Policy Interactions for California's Climate Policy," Regulatory Policy Program, Mossavar-Rahmani Center for Business and Government, Harvard Kennedy School, August 27, 2012.

I. MARKET DESIGN DECISIONS RELATED TO THE PRICE LEVELS

A. Key GHG Cap-and-Trade Rulemaking Issues

AB 398 extends the GHG cap-and-trade program through the year 2030, keeping core elements of the system intact. Sources covered by the program are required to obtain allowances to cover their actual GHG emissions. The total quantity of allowances is capped at annual budgets to be set by CARB, with the annual budget for the year 2030 set at 40 percent below 1990 emission levels. Faced with the choice between using an allowance or reducing emissions, in principle, covered sources will opt for the less costly of the two, resulting in allowance prices that equal to the marginal cost of emission reduction. Through this mechanism, the GHG cap-and-trade system creates a price signal that encourages emission reductions that are less costly than the allowance price, but not those that are more costly than the allowance price.

1. The Price Ceiling

In passing AB 398, the legislature mandated several important changes to the GHG cap-and-trade program, and identified certain issues for CARB to consider. One important change is the addition of a **Price Ceiling**. With a Price Ceiling, allowance prices cannot rise above a specified level. Thus, a Price Ceiling is often referred to as a "hard" cap. AB 398 directs CARB to:

"Establish a price ceiling… consider[ing]… all of the following:

- (I) The need to avoid adverse impacts on resident households, businesses, and the state's economy.
- (II) The 2020 tier prices of the allowance price containment reserve.
- (III) The full social cost associated with emitting a metric ton of greenhouse gases.
- (IV) The auction reserve price.
- (V) The potential for environmental and economic leakage.
- (VI) The cost per metric ton of greenhouse gas emissions reductions to achieve the statewide emissions targets established in Sections 38550 and 38566."[6]

A Price Ceiling mitigates the risk that the allowance price rises to economically or politically unacceptable levels, which has several benefits.

First, the Price Ceiling mitigates the potential for sources to take excessively costly efforts to reduce GHG emissions.[7] In turn, the price ceiling also avoids excessive increases in the prices for energy (gasoline for fueling cars and natural gas for heating homes) and GHG-intensive goods and services. In both cases, the Price Ceiling avoids economic costs and consequences that are disproportionately large relative to the benefits created.

Second, the Price Ceiling creates clear *ex ante* rules specifying what happens if allowance prices rise unexpectedly. Absent such rules, decisions to mitigate excessively high allowance prices may be made through rushed, *ad hoc* regulatory processes that do not provide sufficient time for deliberative,

[6] Health & Safety Code § 38562(c)(2)(A)(i).

[7] AB 398 requires CARB to achieve GHG emission reductions through other means to offset any new allowances created through the Price Ceiling.

balanced decision-making. As a result, there is an increased likelihood that poor decisions are made that undermine the credibility of the system.

Third, because it reduces the need for *ad hoc* decisions, the price ceiling creates greater certainty for the market which, all else equal, is more conducive to investment in low-GHG technologies. Such technologies often require many years to recover upfront investment costs, making certainty about the durability of the cap-and-trade system important to financing such investments.

AB 398 also directs CARB to establish **Price Containment Points**:

> "Establish two price containment points at levels below the price ceiling. The state board shall offer to covered entities non-tradable allowances for sale at these price containment points. The price containment points shall be established using two-thirds, divided equally, of the allowances in the allowance price containment reserve as of December 31, 2017."[8]

The Price Containment Points are a pool of allowances available for purchase at predetermined prices. The Price Containment Points are referred to as "speed bumps" because they slow the rise in prices by providing additional allowances to the market to meet an increase in allowance demand. If the supply of allowances at the Price Containment Points is exhausted, however, allowance prices can rise above the Price Containment Point.

Figure 1 illustrates how the Price Containment Points and Price Ceiling affect the quantity of allowances available to the market. As prices rise to each Price Containment Point and then the Price Ceiling, additional supplies of allowances become available to the market. While AB 398 specifies criteria for setting the Price Ceiling, it does not identify criteria for setting the Price Containment Points.

The current GHG cap-and-trade system has an APCR comprising of three tiers. AB 398 specifies that two-thirds of the allowances from the APCR as of December 31, 2017 will be allocated to the Price Containments Points, and all allowances remaining in the APCR on December 31, 2020 will allocated to the Price Ceiling.

The new cost containment mechanisms legislated through AB 398 differ in some respects from the APCR's current structure. Lacking a "hard" Price Ceiling, the APCR currently operates like a "soft" price cap, raising stringency to increase emission reduction efforts, providing a buffer in the event that prices rise unexpectedly and providing regulators and legislators with additional time to make market changes in the event that prices rise to economically and politically unacceptable levels.

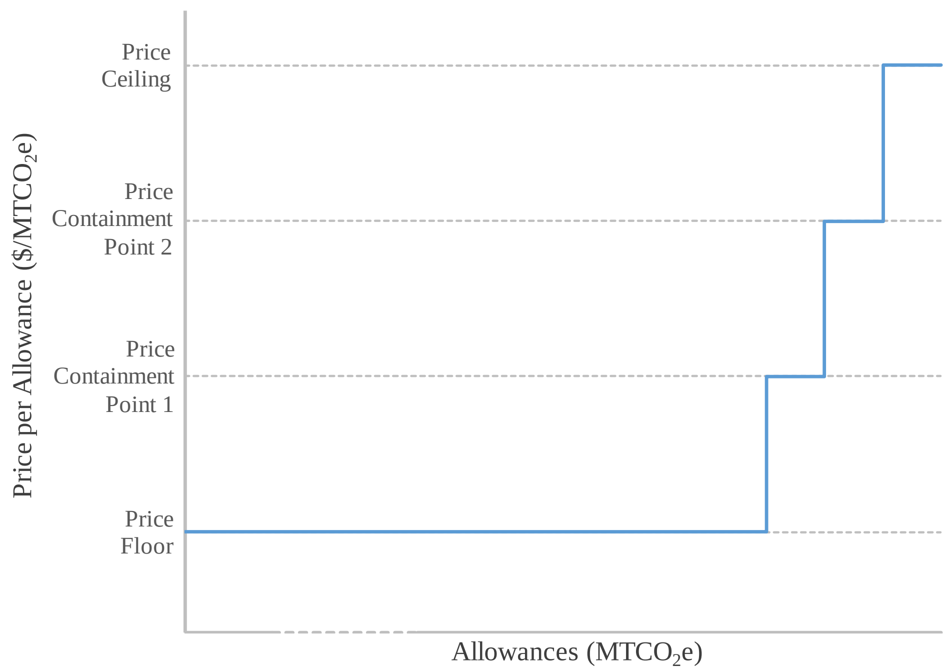
AB 398 adds a Price Ceiling that, among other things, mitigates the risk of ad hoc intervention. Thus, in principle, the Price Containment Points can take on a different role in cost containment than the APCR. Instead of providing a buffer "at the top" of the market, they can achieve other ends. As we describe below, other than the changes in cap stringency inherent in any decision related to the size of an allowance "reserve", such as the Price Containment Points or the APCR, the primary benefit of the price containment points is the mitigation of allowance price volatility.

AB 398 also creates an Independent Emissions Market Advisory Committee (the "Committee"). The Committee has no regulatory or enforcement authority, but is designed to provide guidance to the Board and legislature on the environmental and economic performance of the cap-and-trade system and

[8] Health & Safety Code § 38562(c)(2)(B).

other relevant climate policies. The Committee will be comprised of experts on emission trading market design that, in principle, can provide the Board and legislature with recommendations on changes to program rules and operations depending on the system's performance. The Committee will develop periodic reports (at least annually) on the program's performance for the Board and legislature, and is required to develop a report if two consecutive auctions exceed the lower of the two Price Containment Points.[9]

Figure 1. Illustration of Price Containment Points and Price Ceiling



B. Economic Factors Relevant to Establishing the Price Levels for the Price Ceiling and Price Containment Points

AB 398 does not specify the price levels for the Price Ceiling and Price Containment Points, leaving this task to CARB. For the Price Ceiling, AB 398 specifies certain criteria, listed above, whereas it provides no guidance for the Price Containment Points. In this section of the paper, we consider, from an economic

[9] AB 398 specifies that the report must assess "the potential for allowance prices to reach the price ceiling for multiple auctions." We consider this a less important objective for the Committee in comparison to its role in evaluating program performance and identifying potential rule modifications to improve market function. Forecasting market prices is inherently difficult, and policy decisions should not generally rely on the outcomes of such forecasts. Moreover, even if the Committee found that allowances were likely to remain above the price containment point, there is nothing *per se* problematic with this, and this fact should not be used as a rationale for modifying the program, unless the legislature deems the price levels adopted by CARB for the Price Ceiling or Price Containment Points to be either too high or too low. Health and Safety Code 38562 (c)(2)(J)(i).

perspective, the various factors that should be considered by CARB when setting these price levels, as well as factors that are less useful.

1. Price Ceiling Considerations

AB 398 identifies considerations that CARB should take into account when setting the Price Ceiling, and CARB elaborates on these criteria in its "Preliminary Concepts" paper. We consider these criteria for setting the Price Ceiling, and assess their relevance and usefulness from an economic perspective.

a) Social Cost of Carbon

The social cost of carbon is an important benchmark for the level of the price ceiling. The social cost of carbon is an estimate of the social cost (damages) of additional GHG emissions (represented in terms of CO_2 equivalents). Allowance prices send an economic signal to emissions sources that, in principle, determine the (marginal) costs they will incur to reduce GHG emissions. As a result, if allowance prices rise above the social cost of carbon, then sources may incur cost to reduce emissions that are greater than the benefits created.

The United States Government's Interagency Working Group ("IWG") on the Social Cost of Greenhouse Gases comprised twelve different federal agencies and endeavored to provide United States' regulatory bodies with a consistent estimate of the social cost of carbon for use in regulatory analyses.[10] The IWG published several sets of estimates of the social cost of carbon, with each set estimating the social cost of carbon annually from 2010 through 2030.[11] **The IWG's most recent estimates indicate that the social cost of carbon from emissions occurring in 2030 would range from $25 to $115 per metric ton (in nominal dollars), depending upon the choice of discount rate used to convert the future damages created by those emissions into present value terms.[12]** For example, the damages from 1 metric ton of

[10] *See* TSD 2010 at 1-4. There have been wide ranging estimates of the social cost of carbon; anywhere from a few dollars per ton of CO_2 to over one hundred dollars per ton of CO_2. *See e.g.* National Research Council, 2009, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, Washington, DC: The National Academies Press at 216-219 for a brief review.

[11] *See e.g.* Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12688, Interagency Working Group on Social Cost of Carbon, United States Government, February 2010 ("TSD 2010"); *see also* Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12688, Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, August 2016 ("TSD 2016"). Updated estimates were published in May 2013, November 2013, and July 2015. See TSD 2016 at 3 and Appendix B. Further discussion was added in 2016, with no changes to the estimates themselves. *See* TSD 2016 at 3-4. While the underlying method between the 2010 and 2016 document did not change, a recent publication by the National Academies has recommended an overhaul of how the IWG estimates the social cost of carbon. *See* National Academies of Sciences, Engineering, and Medicine, 2017, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*, Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24651.

[12] See TSD 2016 at 4. The IWG also presents a set of higher estimates reflecting more extreme assumptions regarding the underlying modeling inputs. This higher set of estimates places the 2030 social cost of carbon at $240 in 2030 (in $2030). The IWG reports the social cost of carbon in $2007. We convert $2007 to $2030 using historical annual

emissions in 2030 would be $79 in 2030 dollars when the future impact of those emissions are discounted back to 2030 at a 3% discount rate. These Social Cost of Carbon estimates represent the global damages to various sectors, including agriculture and energy dependent sectors, climate driven human health impacts, the damages of sea-level rise, and impacts to ecosystem services.[13]

The IWG's estimates have become a respected benchmark for the social cost of carbon. Several federal rules incorporated these estimates in determining the net benefits of proposed regulations. For example, the EPA Regulatory Impact Analysis for the Final Mercury and Air Toxics Standards utilized the IWG's 2010 estimates.[14] The EPA also employed the IWG's estimates in recent rulings regarding vehicle emissions standards.[15] The Trump administration now estimates the social cost of carbon to be $1 to $6 per $MTCO_2e$, using only the higher discount rate and counting only domestic, rather than global, damages.

IWG estimates have also informed state policy. CARB adopts the IWG's 2016 estimates in its 2017 Scoping Plan and references the estimates in its "Preliminary Concepts" paper. CARB's Scoping Plan assumes a social cost of carbon of $57 in 2030 (in $2015) based on IWG's 2016 estimates.[16]

Other studies have also developed estimates of the social cost of carbon. To the extent that CARB relies on estimates from other research, it should perform a thorough and careful evaluation of each estimate and come to its own sound conclusions through scientific methods such as meta-analysis. **CARB should not rely on estimates of the social cost of carbon from individual studies, particularly if those studies produce estimates substantially departing from the central tendency of other research.[17]**

average CPI values for all urban consumers provided by the BLS (https://www.bls.gov/cpi/tables/supplemental-files/home.htm) and forecasted CPI values that we derive from forecasted year to year (specifically Q4 to Q4) percent changes in the CPI presented by the 2018 Economic Report of the President, (https://www.whitehouse.gov/wp-content/uploads/2018/.../ERP_2018_Final-FINAL.pdf, Table 8-1, column 4).

[13] These values derive from three integrated assessment models ("IAM") that describe in reduced-form how changes in greenhouse gas driven temperatures impose costs and various impacts. All models also contain some description of adaptation, and in various ways capture catastrophic or extreme climate change driven impacts. *See* TSD 2010 § III.A for further detail regarding the models underlying the social cost of carbon estimates. *See also* TSD 2016 § II for further detail regarding updates to these models that underlie the most recent social cost of carbon estimates. For further details regarding the process IWG followed in estimating the social cost of carbon, see TSD 2010 § III, IV.

[14] United States Environmental Protection Agency, Regulator Impact Analysis for the Final Mercury and Air Toxics Standards (MATS RIA).

[15] *See* EPA, "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule," *Federal Register* Vol. 76 No. 179, 57106–513 at 126; *see also* EPA, "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule," *Federal Register* Vol. 77 No. 199, 62624–63200 at 2929.

[16] CARB relies on the IWG's estimate assuming a 3% discount rate. CARB also converts this value to 2015 dollars, accounting for inflation. *See* California Air Resources Board, California's 2017 Climate Change Scoping Plan, November 2017 ("2017 Scoping Plan") at 40 and fn. 97; *see also* Concepts at Table 5.

[17] For example, CARB's Preliminary Concepts paper cites one paper, Moore and Diaz (2015), that estimates the social cost of carbon could be approximately $220 per ton of CO_2. However, this is the only study cited by CARB other than the IWG study, and CARB provides no description of the methodology used to identify this study among the many estimating the social cost of carbon. Moore, F. and Diaz, D.B., 2015, "Temperature impacts on economic growth warrant stringent mitigation policy," *Nature Climate Change*, 5:127–131.

b) Leakage

Leakage occurs when the cost of complying with a new (or more stringent) regulation leads to a shift in economic activity from the region with the regulation to regions with less stringent regulations. Leakage can occur through many routes, including a shift in the level of production at in-state business, and actual relocation of in-state businesses. The shift in economic activity leads to apparent emission reductions in the region with the more stringent regulation, when in fact emissions may have simply shifted geographic location. As a result, leakage reduces the effectiveness of the regulation in achieving actual (rather than apparent) emission reductions.

Under cap-and-trade, compliance costs, and thus the incentive to shift production to avoid these costs, are directly proportional to the allowance price. As a result, limiting allowance prices through the price ceiling can limit the leakage that occurs due to the GHG cap-and-trade program. Leakage potential is a particular concern for California given its substantial trade and close economic ties with other states and countries.[18]

c) Linkage

Linkage between cap-and-trade systems allows covered entities under one program to use allowances from another system to comply with its cap-and-trade obligations.[19] With linkage, the two systems become integrated into one market. As entities buy and sell across programs, allowance prices converge, which lowers economic costs of reducing GHG emissions by harmonizing the GHG price signal across a broader economic area.

Linkage also has implications for the rules related to trading, compliance, and allocation of allowances in each of the linked systems. Decisions about the Price Ceiling (and other price containment mechanisms) in California can have consequences for the other systems to which it is linked. In effect, a Price Ceiling in California's cap-and-trade system would extend to all systems that are linked to California's system. For example, if the price ceiling was set at $90 per $MTCO_2e$, then allowances in any linked system would not rise above $90 per $MTCO_2e$, because market participants in the linked systems could always purchase allowances from California sources at $90 per $MTCO_2e$.

The level of the Price Ceiling has several potential implications for a region's willingness to link their cap-and-trade system to California's system. **First, a region may be less willing to link with another system if the Price Ceiling is set at a level that is inconsistent with the region's policy objectives.[20]** A price ceiling set too low may make it less desirable to link with that system, since price ceilings would

[18] *See* Fowlie, M., "California's Carbon Border Wall," *Energy Institute Blog*, May 22, 2017. Available at: https://energyathaas.wordpress.com/2017/05/22/californias-carbon-border-wall/. See also Cullenward, D., (2014) "Leakage in California's Carbon Market," The Electricity Journal, 27(9): 26-48.

[19] For background on linkage, *see* Jaffe, Judson and Robert Stavins, *Linking Tradable Permit Systems for Greenhouse Gas Emissions: Opportunities, Implications and Challenges*, prepared for the International Emissions Trading Association, November 2007.

[20] If a region objects to price ceilings, in principle, including a price ceiling could act as a barrier to linkage. However, regions that achieve cost containment through other means, such as *ad hoc* changes in allowance budgets and allocation, pose other economic risks to linked systems.

prevent allowance prices from reaching levels that the region may deem necessary to achieve its climate policy objectives. However, a price ceiling set too high may also make it less desirable to link with that system, because allowance prices could reach economically and politically unacceptable levels.

Second, while linkage can lower aggregate economic costs and risks, it also exposes each region to economic risks from events that originate in other regions. With linkages, a sudden shock in demand for allowances in one region would cause allowances prices to rise in all linked systems, with allowances flowing to the region that experienced the increase in demand. **A Price Ceiling can mitigate these economic (and political) risks by acting as a "brake" on allowance prices caused by unexpected events in other regions.**

d) Continuity

AB 398 requires CARB to consider the tier prices of the APCR when establishing the Price Ceiling. All else equal, continuity in market rules provides greater certainty to participants and thus reduces investment risks in low-GHG technologies. By contrast, changes in market rules send a signal to market participants that future rule changes might occur that could undermine the value of investments, which further increases these investments' financial risk. **Thus, when deciding where to set the Price Ceiling, it is reasonable to consider prior cost containment mechanisms. However, continuity should be balanced against the need to have a sound market design, which may require modifications of market rules.**

e) Costs of Abatement

AB 398 indicates that CARB should consider the cost of achieving GHG abatement under other California climate policies when setting the Price Ceiling.[21] **Several factors suggest caution in using GHG abatement costs as a benchmark for setting the Price Ceiling.**

In principle, from an economic perspective, the goal of any environmental policy is to achieve economic benefits through improvements in environmental conditions. **Thus, relying on measures of abatement costs to set the pricing ceiling would confuse benefits – the objective of environmental policy – with costs.** While the cost of achieving reductions under one policy might imply that society is "willing to pay" that amount to achieve environmental benefits, there are several reasons why this inference may be inappropriate.

Policies and programs in the Scoping Plan are undertaken to achieve multiple benefits in addition to reducing GHG emissions, including: reducing emissions of particulate matter, criteria air pollutants, and toxic air pollutants; health improvements from active transportation;[22] technology transformation; and other benefits. **When a policy achieves multiple benefits, attributing all costs to only one stream of benefits will overstate the cost of achieving that type of benefit.** In this context, relying on CARB's estimates of

[21] See, for example, comments of the Natural Resources Defense Council (NRDC), summarized in CARB, "Summary of Stakeholder Comments" April 2018, p. 6.

[22] Active transportation includes walking and biking. CARB, 2017 Scoping Plan, pp. ES7, 47-50.

the abatement cost per metric ton of GHG (from the Scoping Plan) to set the Price Ceiling may inappropriately attribute all costs incurred by the program to only a portion of the environmental benefit, reductions in GHG emissions. CARB notes this in the Scoping Plan:[23]

> The cost (or savings) per metric ton of CO_2e reduced for each of the measures is one metric for comparing the performance of the measures. Additional factors beyond the cost per metric ton that could be considered include continuity with existing laws and policies, implementation feasibility, contribution to fuel diversity and technology transformation goals, as well as health and other benefits to California. These considerations are not reflected in the cost per ton metric below.

Of course, it is also possible that non-GHG benefits are relatively small for certain policies. If this is the case and the estimated cost per $MTCO_2e$ is particularly high, it may raise questions about the efficacy of this particular policy in addressing climate change, rather than serve as a sensible benchmark for other policies.[24]

CARB might also be considering the cost to deploy a particular "backstop" technology as a benchmark for the Price Ceiling, particularly a technology at an early stage of development. There are several concerns with this approach. First, this approach also conflates costs with benefits. Simply because a technology exists to reduce GHGs does not mean it is sound policy to deploy at any cost. Second, the development of any particular technology faces many unknowns, making the timing of commercialization and eventual costs highly uncertain. Moreover, cap-and-trade is not well suited to promoting the development of particular technologies because it creates uniform incentives for innovation that are technology neutral, encouraging the least-cost means of achieving emission reductions, regardless of technology.

Finally, many policies in the CARB Scoping Plan may affect a limited scope of economic activity. **Simply because CARB has adopted a policy with a high (marginal) economic cost that affects a limited amount of economic activity does not imply that it is sensible to impose such a cost on all economic activity covered by the GHG cap-and-trade program.**

f) Carbon "Shadow Prices"

A few corporations have voluntarily adopted an internal social cost of carbon, or carbon "shadow price," for use in internal decision-making.[25] CARB indicates it intends to consider these shadow prices in its decision regarding where to set the price ceiling.[26] It should not do so for several reasons.

[23] CARB, 2017 Scoping Plan, p. 44.

[24] For example, one measure, increased utilization of renewable natural gas, has an estimated cost of $1,500 per $MTCO_2e$ in 2030, which appears to have extremely high costs compared to alternative approaches to abating GHG emissions *if* the only benefits derived are GHG reductions. CARB, 2017 Scoping Plan, p. 46.

[25] CDP, "Embedding a carbon price into business strategy," September 2016.

[26] CARB, Preliminary Concepts, p. 6.

First, unless the corporation has expressly tied its shadow price to the social cost of carbon, there is no reason to think that the selected shadow price truly reflects the benefits associated with reducing emissions. Instead, this price reflects the decisions of an unelected, unrepresentative group of individuals on behalf of a corporation reflecting a number of different considerations that may differ from the social benefits of GHG emission reductions.

Second, many factors affect actions taken for corporate social responsibility, including the value customer's place on a good or service, worker benefits, political influence and other factors unrelated to GHG emissions.[27] Because carbon shadow prices are adopted not for compliance with state or federal environmental laws, but as part of these corporate social responsibility objectives, the rationale for adopting a particular value of the shadow price reflects these other corporate benefits, in addition to the underlying social cost of carbon. Moreover, because the implementation of such shadow prices within the context of corporate operations and investment decisions is not monitored, there is no way to verify that the corporation actually incurs financial costs that correspond to these shadow prices.

Third, estimates of corporate carbon shadow prices vary widely. Some corporations use prices less than $1 per MTCO$_2$e, while others claim to use prices in excess of $800 per MTCO$_2$e.[28] Many, of course, adopt no shadow prices at all. Developing any inferences about the social cost of carbon from this wide range of values is scientifically challenging, particularly in light of the various incentives associated with the choice of shadow price.

In light of these factors, we recommend that CARB not consider corporate "shadow prices" when determining the level for the Price Ceiling.

2. Price Containment Point Considerations

Under the current GHG cap-and-trade design, the Price Containment Points, are developed largely as a tool for mitigating short-term fluctuations in prices, referred to as allowance price volatility. The structure of California's energy and allowance markets creates a potential risk that prices fluctuate between the price floor and the Price Ceiling over relatively short time periods. An element of this risk is that

[27] For example, some evidence suggests that consumers are willing to pay a higher price for goods and services that are produced in a socially responsible manner. For example, *see* Servaes, H., & Tamayo, A. (2013). The impact of corporate social responsibility on firm value: The role of customer awareness. Management Science, 59(5), 1045-1061; Elfenbein, D. W., Fisman, R., & Mcmanus, B. (2012). Charity as a substitute for reputation: Evidence from an online marketplace. Review of Economic Studies, 79(4), 1441-1468. Likewise, workers may show preferences for working for a socially responsible company, making them more willing to work hard or work for a lower wage. For example, *see* Turban, D. B., & Greening, D. W. (1997). Corporate Social Performance and Organizational Attractiveness To Prospective Employees. Academy of Management Journal, 40(3), 658- 672. For analysis of the impact on corporate social responsibility on employee misbehavior, *see* List, John, and Fatemeh Momeni, "When Corporate Social Responsibility Backfires: Theory and Evidence from a Natural Field Experiment," NBER Working Paper No. 24169, December 2017. Reinhardt, Forest L, and Robert N. Stavins. "Corporate Social Responsibility, Business Strategy, and the Environment." *Oxford Review of Economic Policy* 26.2 (June 2010): 164-181; Reinhardt, Forest, Robert Stavins, and Richard Vietor. "Corporate Social Responsibility Through An Economic Lens." *Review of Environmental Economics and Policy* 2(2008): 219-239.

[28] CDP, 2016.

allowance prices suddenly increase from the currently low prevailing market prices. By providing a supply of allowances at intermediate points between these extremes, the Price Containment Points reduce the likelihood that prices fluctuate or swing between these extremes.

Price volatility can have adverse consequences, including inefficient operations and investment (if abatement is undertaken in response to temporary high prices), uncertainty in investment and pricing of energy and energy-intensive goods and services, financial losses (and risks) for companies short on allowances, and challenges to the operation of a well-functioning allowance market. Price volatility, in turn, has consequences for the strategies used by companies to manage their compliance risks. The Price Containment Points reduce market volatility by increasing the supply of allowances as allowance prices increase. This additional supply of allowances can bound the range of price movements and provide additional time for price discovery.

In the context of California's GHG cap-and-trade program, empirical analysis indicates that allowance price volatility could be very high. Borenstein, Bushnell and Wolak (Borenstein et al., hereafter) find that there are limited options to reduce GHG emissions (at reasonable cost) if market conditions increase the demand for allowances.[29] The limited supply of abatement options is largely due to the many complementary climate policies that limit the incremental opportunities for covered sectors to reduce emissions under the cap-and-trade program. Due to the limited supply of abatement options, there is a risk that allowance prices fluctuate rapidly between the price floor and Price Ceiling in response to relatively small changes in allowance demand.

Specifically, Borenstein et al. find that 145 $MTCO_2e$ of emissions can be reduced at a cost less than \$85 per $MTCO_2e$. As result, if demand increases more than 145 $MTCO_2e$ (over the course of the 2021-2030 period) due to, for example, increased economic activity, then allowance prices could suddenly rise from the allowance price floor to the allowance price ceiling. Given allowance banking and the market's anticipation of future market conditions, the market could capture changes in allowance prices relatively quickly if underlying market conditions change to project future allowance scarcity. **Price Containment Points at intermediate points between the allowance price floor and Price Ceiling can mitigate such the large increase in allowance prices that could occur under these circumstances.**[30]

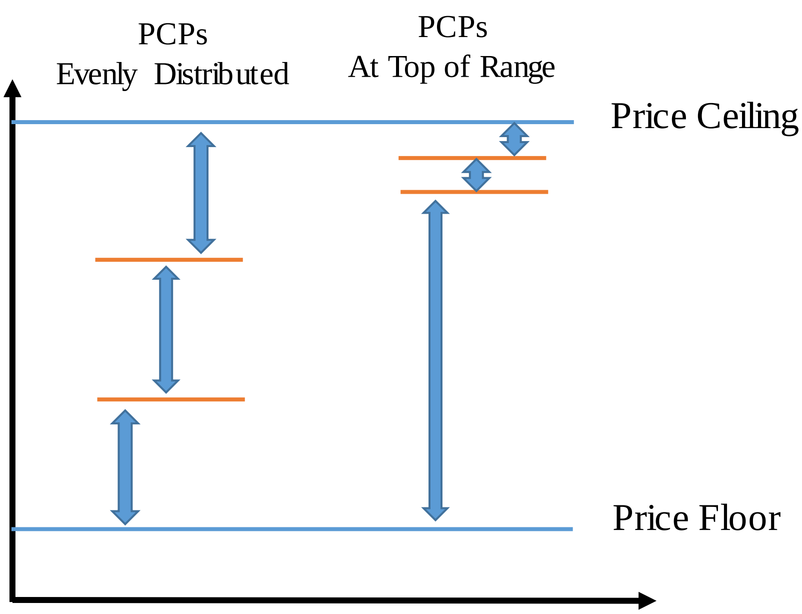
[29] Borenstein, Severin, et al., "California's Cap-and-Trade Market Through 2030: A Preliminary Supply/Demand Analysis", Energy Institute at Haas, Working Paper 281, July 2017, Table 1. For earlier analysis, *see* Borenstein, Severin, James Bushnell, Frank Wolak and Matthew Zaragoza-Watkins, "Report of the Market Simulation Group on Competitive Supply/Demand Balance in the California Allowance Market and the Potential for Market Manipulation," Energy Institute at Haas, Working Paper 251, July 2014; Borenstein, Severin, James Bushnell, Frank Wolak and Matthew Zaragoza-Watkins, "Expecting the Unexpected: Emission Uncertainty and Environmental Market Design," Energy Institute at Haas, Working Paper 274, August 2016.

[30] Volatile commodity prices can impose economic costs, although such costs may not (and typically do not) justify regulatory interventions given the costs such interventions impose, particularly when they introduce distortions of the commodity's true opportunity cost. However, allowance markets differ from commodity markets in at least two respects. First, economic volatility arising from the program can undermine the political consensus needed to support the underlying regulatory policy. Second, allowance markets arise from a regulatory design used to achieve certain environmental objectives, and the regulation's design reflects tradeoffs among many factors, including variability of environmental and economic outcomes. A tax and cap-and-trade differ in the tradeoff between variability of environmental and economic outcomes; and a cap-and-trade program with allowance reserves, such as the Price

Borenstein et al.'s analysis illustrates the potential benefit of the Price Containment Points in the context of California's market. Their analysis finds that, due to the limited supply of GHG abatement, prices are likely to be at one of the two extremes, the price floor or the Price Ceiling. With the addition of two Price Containment Points, the likelihood that prices in 2030 are between these two extremes increases from 20% to 39%.[31] Thus, the Price Containment Points substantially reduce the likelihood that allowance prices are not at the price floor and Price Ceiling, consistent with less volatile market outcomes.

To illustrate how placement of the Price Containment Points can affect market outcomes, **Figure 2** compares the range of allowance prices between two Price Containment Point configurations. On the left, the Price Containment Points are distributed evenly between the price floor and Price Ceiling. Under this configuration, a sudden increase in demand will cause prices to rise to the first Price Containment Point, allowing the market to readjust. On the right, the Price Containment Points are placed at the top of the range between the price floor and Price Ceiling. In this case, a sudden increase in demand leads to a larger price increase, because there is no influx of supply until the first Price Containment Point.

Figure 2. Illustration of Price Containment Point Placement



By adding allowance supply to the market, the Price Containment Points may also bound allowance price volatility. For example, if prices are near to the price floor, new events or information may lead to price volatility. When the Price Containment Points are distributed evenly, price fluctuation is bounded by the price floor and first Price Containment Point, since the additional supply in Price

Containment Points, is a hybrid of these two approaches. The choice among these regulatory mechanisms reflects, among other things, the extent to which marginal impacts vary over time. For GHG emissions, such variation is relatively small, suggesting less value to time-varying (or volatile) prices compared to other environmental impacts (or commodities).

[31] Borenstein et al., 2017, Table 2.

Containment Points tends to limit the range of short-run price increases. With the Price Containment Point at the top of the range, these price fluctuations could be much larger given the larger range between the price floor and the first Price Containment Point. Thus, even distribution of the Price Containment Points provides greater limits on short-term price fluctuation compared to a tight clustering of Price Containment Points.

Second, placing the Price Containment Points at the top of the range provides less opportunity for CARB and the Emissions Market Advisory Committee to assess the market's performance and function, and the need for modifications to market rules. Through evaluation of market outcomes, the Committee can assess the drivers of changes in market allowance prices to ensure that they reflect market fundamentals, identify limitations to market rules, and develop recommendations for changes to those rules, if any. A lower Price Containment Point can slow an otherwise rapid increase in prices, providing the Committee with more time to conduct its review.

In light of these factors, Price Containment Points equally distributed across the range between the price floor and Price Ceiling appear to offer positive net benefits, compared with placement at the upper end of this range.

3. Decisions Related to Additional Allowances

Prior to the passage of AB 398, CARB passed rules that would shift 52.4 million allowances from the 2021-2030 allowance budgets to the APCR.[32] CARB has sought comment regarding how it should allocate these allowances in the context of its rulemaking under AB 398.[33] In principle, these allowances could be allocated to: (1) annual budgets, (2) Price Containment Points, (3) the Price Ceiling, or (4) retirement accounts. Stakeholder comments vary widely, encompassing all of these options.

Each of these has implications in terms of the program's stringency. At one extreme, placing the allowances in the annual budget for sale through the auctions provides an additional supply at all price levels (above the auction reserve price). As a result, allowances prices are lower at all levels of demand.

At the other extreme, placing allowances in the Price Ceiling limits supply to the market, raising allowance prices and increasing likelihood that prices rise to the Price Ceiling (compared to placing allowances in the budget or Price Containment Points).

Placing allowances in the Price Containment Points not only affect program stringency, but the extent to which price volatility is mitigated. Given the risk that the quantity of GHG abatement possible at reasonable prices is limited, the Price Containment Points allowances can mitigate price volatility and provide the market with time to adjust to sudden increases in price. Supplying allowances to the Price Containment Points tends to support this end, although, in principle, marginal benefits may diminish (or even become negative) with additional allowances. We are not aware of analysis to determine how market

[32] Cap-and-trade regulation, Table 8-2.

[33] CARB, Preliminary Concepts Paper, p. 8.

outcomes (e.g., distribution of market prices or price volatility) would likely vary with the quantity of allowances placed in the Price Containment Points.[34]

Retiring these allowances altogether makes little sense. Under AB 398, if allowances at the Price Ceiling are exhausted, CARB is required to achieve additional GHG abatement through some means. Thus, if CARB retires allowances rather than placing them in the Price Ceiling, it might inadvertently increase the quantity of additional "out of market" abatement required to make up for a lack of allowances at the Price Ceiling.

II. DECISIONS RELATED TO "OVERALLOCATION"

A. Background on "Overallocation"

In designing the new cap-and-trade program regulations, AB 398 directs CARB to "[e]valuate and address concerns related to *overallocation* in the state board's determination of the number of available allowances for years 2021 to 2030, inclusive, as appropriate."[35] The discussion around "overallocation", while often not well-defined, relates to concern that the supply of banked allowances may threaten compliance with statutory requirements in California's climate legislation or the achievement of California's climate policy objectives. For example, one commentator states: "Unaddressed, oversupply and expected banking is large enough to allow for significantly more emissions than intended under the 2017 Scoping Plan, cutting into cumulative emissions and possibly leaving 2030 emissions above the SB 32 target."[36] Another states: "But we want to emphasize that ultimately AB 32 and SB 32 charge ARB with the responsibility of meeting annual targets in 2020 and 2030, not a cumulative target expressed over a period of time."[37]

The "overallocation" concern stems from the fear that an "overallocation" of allowances will cause actual emissions to be above "intended" emission levels or statutory targets. This concern is most salient for the 2030 target of 40% below 1990 emissions. To mitigate this threat, some stakeholders propose that CARB eliminate (or reduce the value of) some portion of unused allowances, including allowances not yet auctioned (particularly unsold allowances from prior auctions), allowances in the APCR, and even allowances held in covered entities' accounts (i.e., banked allowances). In effect, these options would increase the stringency of the GHG cap to achieve additional environmental benefits.

We do not consider any legal issues raised regarding statutory compliance, **but it is important to appreciate that none of the regulatory mechanisms available to CARB can "guarantee" compliance**

[34] Borenstein et al.'s analysis does not test the sensitivity of market outcomes to different quantities of allowances in the Price Containment Points. Their analysis assumes 174 $MMTCO_2e$ for the Price Ceiling and Price Containment Points, including both the current APCR (121 $MMTCO_2e$) and the 52.4 million allowances from the 2021-2030 allowance budgets. They find there is a 60% likelihood that prices are at the price floor or Price Ceiling.

[35] Emphasis added. Health & Safety Code § 38562(c)(2)(D). *See also* Health & Safety Code § 38562(c).

[36] Busch, Chris. "Oversupply Grows in the Western Climate Initiative Carbon Market," December 2017.

[37] Cullenward, Danny, et al., "Removing excess cap-and-trade allowances will reduce greenhouse gas emissions", January 11, 2018, p. 4.

with a GHG target for 2030 (or any other year). For example, the Low Carbon Fuel Standard affects the rate of emissions (i.e., GHG emissions per mile traveled), but does not affect the number of number of miles traveled. Thus, total emissions may exceed any fixed target. In fact, among all the available regulatory mechanisms, cap-and-trade provides the most effective option for achieving particular targets because cumulative emissions are constrained to the cap by design. But, even with cap-and-trade, the state could only guarantee achievement of an annual target by *eliminating allowance banking*, which would impose undue economic costs and risks. Absent this change, reductions in the current allowance budget at most increase the *likelihood* that total emissions are at or below a particular target in a particular year. **But, these proposed remedies do not help CARB meet some bright line with respect to its "responsibility" to meet particular emission targets.**

Below, we address several questions related to "overallocation" concerns. First, the concerns regarding "overallocation" reflect, in part, a focus on short-run (even annual) climate targets rather than long-run, cumulative targets. This is inconsistent with the underlying science and can raise the cost of achieving climate objectives. Second, we consider factors affecting the likelihood that 2030 emissions are not 40% or more below 1990 emissions.

B. The Importance of Cumulative Emission Targets and Allowance Banking

Concerns raised regarding "overallocation" reflect, in part, the concern that actual emissions exceed particular annual targets, rather than cumulative emission targets. **A shift in focus away from cumulative emission targets and toward annual targets would be both costly and inconsistent with the underlying science of the climate problem.** To understand why this is so, it is important to understand first the underlying economics of the climate problem. Like many air emission problems, climate impacts reflect the total concentration of GHGs in the atmosphere. However, unlike typical pollutants, such as criteria air pollutants, the impact of GHG emissions are much less sensitive to the timing of emissions.[38]

With many other air pollutants, health impacts reflect emission levels over short a period of time, requiring regulations to ensure that annual (or even daily) emissions do not exceed levels that would lead to health impacts. However, with GHGs, impacts reflect cumulative emissions.

The fact that GHG emissions impacts reflect cumulative rather than annual emissions has many important implications. **First, establishing a cap-and-trade system that limits emissions to a cumulative cap without requiring specific reductions in any given year will ultimately provide the same environmental benefit as requiring specific reductions in each compliance period year.**

Second, given that environmental impacts reflect cumulative rather than annual emissions, regulation that can provide emission sources with flexibility to achieve cumulative emission targets will lower economic costs. California's GHG cap-and-trade system is designed to take advantage of this flexibility through allowance banking. Rather than emit GHGs, sources can carry out additional emissions reductions, and hold and "bank" unused allowances for future use. Through banking, sources

[38] This arises due to a combination of factors, including the lifetime of various emissions and the relationship between physical changes in the atmosphere and impacts. In particular, many GHGs, including CO_2, remain in the atmosphere for a very long time, on the order of decades to centuries.

can achieve emission reductions in lieu of using allowances if the future cost of abating GHG emissions is expected to be higher, which lowers the costs of achieving cumulative emissions.

Along with reducing aggregate economic costs, banking can help manage the financial risks of complying with the GHG cap-and-trade program given uncertainty in allowance prices. Banking reduces allowance price volatility by providing a supply of allowances to buffer against short-term fluctuations in allowance demand and supply. The absence of effective banking provisions was one of the primary causes of the dramatic price spikes observed in the year 2000 in the RECLAIM program in Southern California. Without banking, covered sources would face more volatile allowance prices, which would raise financial and operational risks due to the potential for restricted allowance supply in later years, and reduce incentives to make early emission reductions.

A requirement that annual emissions be at or below annual allowance budgets effectively eliminates the value of allowance banking. If, in total, actual emissions can *never* exceed the annual budget, banked allowances would have no value.

However, *the use of banking does not imply that at some point in time actual emissions will exceed annual allowance budgets*. In a system where market participants anticipate that the program will extend (indefinitely) into the future, the market may hold a bank of allowances to address the *possibility* that banked allowances are needed to achieve compliance. Given this possibility, actual emissions paths may remain below the budgets to allow the market to maintain an ongoing bank of allowances needed to mitigate against economic and financial risks.

C. The Need to Take Action to Lower Emission Caps

We do not assess the likelihood that actual emissions in 2030 are above the 2030 target of 40% below 1990 emissions, but we make several observations about the potential for this to occur. **First, given uncertainties in the drivers of future emissions, it would seem premature to begin eliminating allowances to address a compliance concern 12 years in the future.** Borenstein et al. find that there is a 34% likelihood that allowances prices hit a price ceiling of $85 per $MTCO_2e$ (in 2030).[39] Thus, they find that there is a 1-in-3 chance that the allowances will be so scarce that prices rise more than 6 times compared to their current level. Under such scenarios, banking plays a critical role in mitigating environmental goals while achieving long-run climate objectives. Their analysis accounts for the many factors that drive the demand for GHG allowances, most of which are virtually impossible to predict with certainty, including:

1. <u>Macro-economic trends</u>: Macro-economic growth will drive the future demand for allowances. Just as the recession in 2008-2009 reduced California's total emissions, expansion of the State's economy puts upward pressure on emissions. Uncertainty in macro-economic growth is a key driver of future variation in GHG emissions.

2. <u>Complementary Policies</u>: Complementary policies, such as the Low Carbon Fuel Standard (LCFS) and Renewable Portfolio Standards (RPS), lower demand for allowances[40] by requiring

[39] Borenstein, Severin, et al., "California's Cap-and-Trade Market Through 2030: A Preliminary Supply/Demand Analysis", Working Paper, July 2017, p.12.

[40] Schatzki and Stavins, 2012.

that covered entities reduce emissions outside the program. However, the effectiveness of these programs in reducing emissions is uncertain, which in turn creates uncertainty about these programs' impacts on the GHG cap-and-trade program.

3. Technological Change: The effectiveness of many of the state's complementary policies and the future cost of GHG abatement depends on the availability of new low-GHG technologies and the ability of California's energy systems, such as its electricity grid, to reliably and cost-effectively deploy expanded shares of low-GHG technologies.

4. Consumer decisions: Reducing GHG emissions in many sectors depends on consumer decisions. However, there is uncertainty about the extent to which consumers will deploy certain low-GHG technologies or will curtail activities that lead to GHG emissions. For example, consumers' decisions regarding vehicle purchases and miles driven (and energy consumption more generally) will have a large impact on emissions levels and subsequent demand for allowances.

5. Linkages: With linkage between systems, market events that increase or decrease demand for allowances in linked systems would flow through to California. For example, substantial operational or legal problems with Quebec's hydropower resources could increase demand for allowances in Quebec, which would diminish available supply in California.

Second, the concern that an allowance "over-supply" would create a non-compliance risk for California implicitly makes the unlikely assumption that the cap-and-trade program ends in 2030, covered sources remit their banked allowances to achieve compliance, and revert back to pre-cap-and-trade program emissions rates.[41] Such a fear is unwarranted for several reasons. First, once implemented, abatement technologies, such as low-carbon electric power generation, alternative fuel vehicles, and more efficiency equipment and buildings, remain in place and generally have lower variable operational costs than fossil fuel technologies. For example, if a firm operating delivery service vehicles switches to electric vehicles, it would not suddenly switch back to gasoline powered vehicles in 2030 simply because it has additional allowances. Second, it is reasonable to assume that the cap-and-trade program will continue beyond 2030 and, more importantly, market participants are likely to assume the program will continue in making their investment decisions. In fact, if CARB and the California legislature fail to convey a strong signal that the program will continue beyond 2030, this will substantially dampen investment incentives because the market benefits gained from investment in low-GHG technologies would be reduced once the program is terminated. In fact, the potential for higher abatement costs beyond 2030, given the increased cost of achieving more stringent targets, will incentivize covered entities to hold onto, rather than remit, banked allowances. This risk of higher allowance costs creates continued incentives for banking, which would lead to emissions below the 2030 cap.

Third, the current cap-and-trade program already has measures that implicitly address concerns about "overallocation". The cap-and-trade program has an auction reserve price that sets a floor on allowance prices, thus limiting the creation of new allowances when there is very low demand for

[41] Busch, Chris, "Oversupply Grows in the Western Climate Initiative Carbon Market", Energy Innovation Report, December 2017; Cullenward, Danny, (2014) "Leakage in California's Carbon Market", The Electricity Journal, 27(9): 26-48; Cullenward, Danny, "Removing excess cap-and-trade allowances will reduce greenhouse gas emissions", Research Note, January 11, 2018.

allowances. The cap-and-trade program also has a mechanism that further tightens the cap when demand for allowances remains low for extended period. AB 398 creates a new requirement that any allowances that remain unsold in the auction for 24 months be transferred to the APCR, which would raise the price at which these allowances could be accessed. Further, any allowances shifted to the APCR would then be moved into the Price Ceiling reserve as of 2021, making it even more costly to access this allowance supply.

III. DECISIONS RELATED TO ALLOCATION, HOLDING, AND USE OF PRICE CEILING AND PRICE CONTAINMENT POINT ALLOWANCES

Operation of the cap-and-trade system requires rules and procedures for determining how allowances are allocated to market participants, and how they can be traded, held, and used. These rules are important because they can affect market participants' abilities to trade allowances, which in turn affects market volatility, allowance price discovery, and the market's ability to equalize (marginal) costs across sources. By affecting trading and holding of allowances, these rules also affect companies' abilities to manage the financial risks of compliance with the GHG cap-and-trade program. These rules can also affect the risk of market manipulation or exercise of market power.

CARB has explicitly sought input on certain administrative rules related to the Price Ceiling and Price Containment Points. Effective market design decisions will differ for the Price Ceiling and the Price Containment Points due to differences in the supply of allowances available through each mechanism. Because the Price Ceiling ensures a supply of allowances sufficient for companies to comply with cap-and-trade, the Price Ceiling is like a carbon tax (for any allowances that an emission source is short). As a result, the timing of sales and flexibility of allowance use is less critical.

By contrast, because the supply of allowances at each Price Containment Point is finite, it is important that liquidity be supplied in a timely way and that sources can flexibly use and hold these allowances. Below, we discuss how rules can support this objective.

A. Frequency of Sale of Allowances

California's GHG cap-and-trade system allocates allowances through a combination of free allocations and quarterly allowance auctions. The quarterly allowance auctions provide a regular flow of allowances to the market that approximately corresponds to the system's aggregate compliance obligations.

CARB must decide how frequently (and through what mechanism) to allocate allowances from the Price Containment Points and Price Ceiling. CARB has several options, including periodic, regular sales and an "open window", where allowances can be purchased at any time at the price containment point.

Frequent allowance sales for the Price Ceiling is not critical to a well-functioning market. Because compliance entities know that they can purchase any allowances needed for compliance at the price ceiling, there is no need to have periodic sales. Allowances can be sold at the end of the compliance period so that entities that are short on allowances can come into compliance.[42]

Offering Price Containment Point allowances on a more frequent basis, through either an open window or frequent (e.g., monthly) sales offer greater benefits compared to infrequent (e.g., annual) sales. Several basic considerations lead to this conclusion.

More frequent sales can increase market liquidity. Liquidity is the volume of a commodity traded in the market. Liquidity is important to a well-functioning market. A higher volume of trading leads to more reliable price discovery, reduces the risk of market manipulation, and lowers risk management costs for market participants.

More frequent sales also provide more timely mitigation of price volatility and improved price discovery. More-frequent allowance sales will ensure that the increase in allowance supplies in the Price Containment Points are available to the market in a timely way when market prices rise to the Price Containment Points. If the release of allowances from the Price Containment Point reserves is delayed, market participants would need to trade "as though" these allowances were available, even if the actual supply of allowances available in the market was less than this quantity. While commodity markets often operate with uncertainty about commodity supplies, price discovery is improved with more trading of the physical product (i.e., allowances) as opposed to financial products (e.g., forward allowance purchases). Because the Price Containment Points are likely to occur during periods of higher price volatility, when efficient price discovery is particularly important, timely availability of allowances could be particularly valuable to supporting a well-functioning allowance market.

With either an open window or periodic sales, institutional infrastructure and procedures must be developed, which entail administrative costs. All else equal, more frequent sales would likely impose higher costs than less frequent sales, although any difference is likely to be modest.

B. Constraints in Use and Sale of Price Containment Points or Ceiling Allowances

CARB has asked for comments on certain potential administrative rules related to use of allowances from the Price Containment Points or Price Ceiling, including:

1. Timing Price Containment Points and Price Ceiling sales to occur between the end of a compliance period and the time when compliance is determined;
2. A limitation that Price Containment Point or Price Ceiling allowances can be used only to achieve compliance in the current compliance period; and
3. A requirement that each firm's holding account be empty before purchasing Price Containment Point or Price Ceiling allowances.

For the Price Ceiling, as discussed above, it is sensible to have Price Ceiling sales at the end of the compliance period, consistent with the first rule. The second and third rules would effectively ensure

[42] In fact, there is little reason for compliance entities to purchase allowances at the price ceiling prior to the end of the compliance period, because market prices may fall, which would allow the compliance entity to purchase allowances at a lower price.

that market participants do not purchase allowances at the Price Ceiling and bank them for use in the future compliance period. These limitations would not meaningfully impact market function because sources know that supplies are available for compliance at the Price Ceiling. Moreover, assuming the Price Ceiling is available in the future, it would make little sense for market participants to buy and hold (i.e. bank) allowances, since these could only depreciate in value (i.e., prices can only decline below the Price Ceiling). Nonetheless, if CARB wants to minimize the likelihood that actual emissions exceed allowance budgets, these limitations would support this goal.[43]

By contrast, these rules would be highly problematic for the Price Containment Points, exacerbating market volatility, raising financial risk and limiting banking, which in turn would raise costs. As described above, failure to make Price Containment Point allowances available to the market in a timely way could have many adverse consequences, including increased market volatility and weaker price discovery. While it is sensible to structure the Price Ceiling as a mechanism that allows sources to "true up" deficiencies between allowance holdings and actual emissions at the end of the current compliance period, this is not the purpose of the Price Containment Points. The Price Containment Points are intended as a mechanism to mitigate price volatility, and thus allowances need to be made available in a timely way to achieve this objective.

The second and third rules would effectively eliminate the banking of allowances when allowances prices rise to the Price Containment Point levels. This would be highly problematic. **Simply because allowance prices have risen to the Price Containment Points does not mean that banking is not economically efficient given potential future escalation in abatement costs (and allowance prices), nor does it mean that banked allowances are not valuable in mitigating price volatility.** Elimination of banking would raise economic costs and increase financial risks to companies requiring allowances for compliance. Further, from an environmental perspective, elimination of banking removes incentives for covered sources to undertake "early" emission reductions. There is simply no rationale for eliminating banking (or reducing firms' abilities to bank) simply because the market prices for allowances rise above the Price Containment Point prices.

C. Decisions Related to Allowance Banking

The economic benefits of allowance banking are well understood and demonstrated. As described above, allowance banking gives flexibility about when emission reductions can occur, thus lowering the cost of achieving emission reductions, and can help mitigate volatility in allowance prices, thus lowering financial risk. California's existing cap-and-trade program allows banking, and banking is a standard element of cap-and-trade systems for GHG emissions and other pollutants (e.g., SO_2).

Some stakeholders have proposed to modify the rules for allowance banking, including proposals that would discount any allowances held (banked) in individual allowance accounts. **CARB should avoid any discounting of banked allowances, which would distort market participants' future banking**

[43] Increases in emissions could occur if allowances were purchased at the Price Ceiling and banked for future use, allowance prices then fell below the Price Ceiling in the next compliance period, and banked allowances from the prior period were used for compliance. In this case, total emissions would increase if CARB were unable to take actions that reduced GHG emissions for all allowances sold at the Price Ceiling, as required by AB 398. The proposed rules mitigate this risk.

decisions due to the risk of allowance devaluation. CARB should preserve the current banking rules with one exception: it should consider modifying the current limits on the quantity of allowances that can be held in allowance accounts ("holding limits"). Holding limits were imposed to address the concern that a market participant could accumulate a large share of allowances and manipulate allowance prices through the exercise of market power. These limits, however, are imposed uniformly across all market participants irrespective of the difference in the costs they impose on different types of market participants. These limits could constrain the ability of firms subject to cap-and-trade to hedge the financial risks of compliance by banking allowances for use in future periods. Other markets with similar holding limits (e.g., derivative markets regulated by the Commodity Futures Exchange Commission) provide exemptions for legitimate business activities, such as hedging. ARB should modify these holding limits to account for legitimate hedging and banking activities through exemptions or increases in holding limits that reflect the size of market participant's compliance obligations.[44]

IV. CONCLUSION

California's GHG cap-and-trade system is well designed, serving as a template for systems in other parts of the world. However, its performance has not to date been seriously tested, because of a combination of factors, including the existence of complementary policies that achieve emission reductions (albeit at higher cost). As it moves into the 2021-2030, CARB must address a number of rules and considerations that will affect the likelihood that more scarce market conditions occur, and will affect the market's performance. Decisions aimed at mitigating economic risks while achieving environmental objectives will provide the greatest net benefits for California's citizens, while also maintaining political support for the program (and California's climate policies more broadly) and providing leadership on effective climate policy design that can inform other regions contemplating similar initiatives.

[44] For further discussion, *see* Schatzki, Todd and Robert N. Stavins, "Three Lingering Design Issues Affecting Performance in California's GHG Cap-and-Trade Program," November 19, 2012.

Exhibit 2

Understanding, Improving, and Using the Social Cost of Carbon

Steven Rose

Energy & Environmental Analysis Group

Climate Forum on California's Cap-And-Trade Program

September 19, 2018

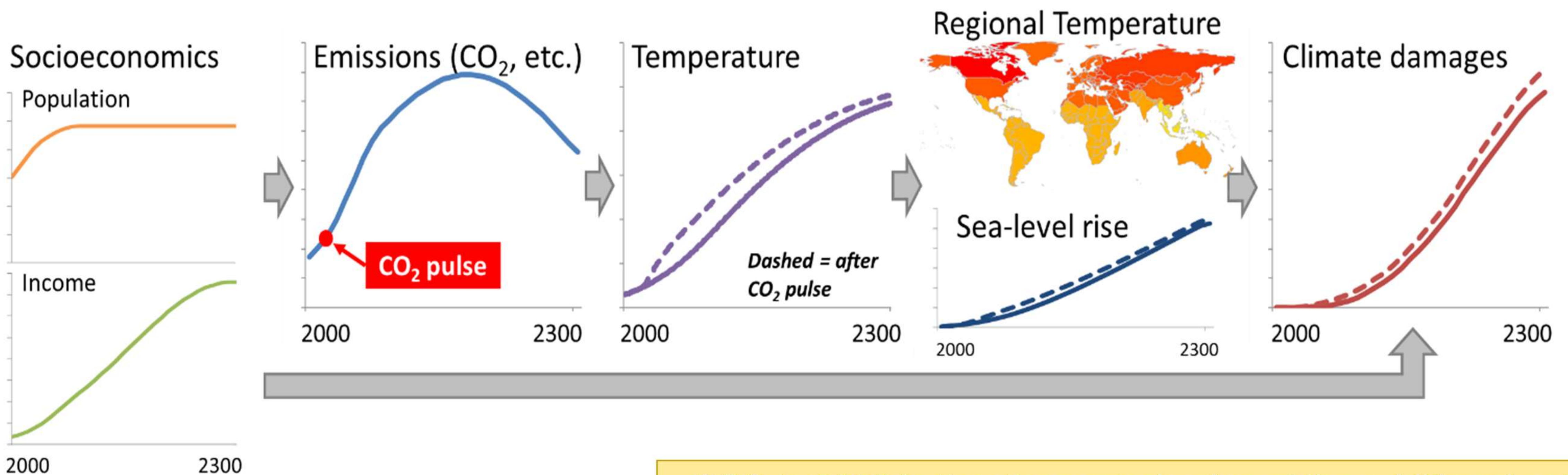
Outline

- Social cost of carbon (SCC) basics
- US Government SCC estimates
- Assessing SCC modeling
- Improvement opportunities
- Are current estimates too low?
- Using the SCC
- Key messages

Social Cost of Carbon (SCC) Basics

Social Cost of Carbon (SCC) Modeling

Definition: The net present value of future global climate change impacts from one additional net global metric ton of carbon dioxide emitted to the atmosphere at a particular point in time



SCC in 2020 is the discounted value of the additional net damages from the marginal emissions increase in 2020

Source: Rose et al (2017)

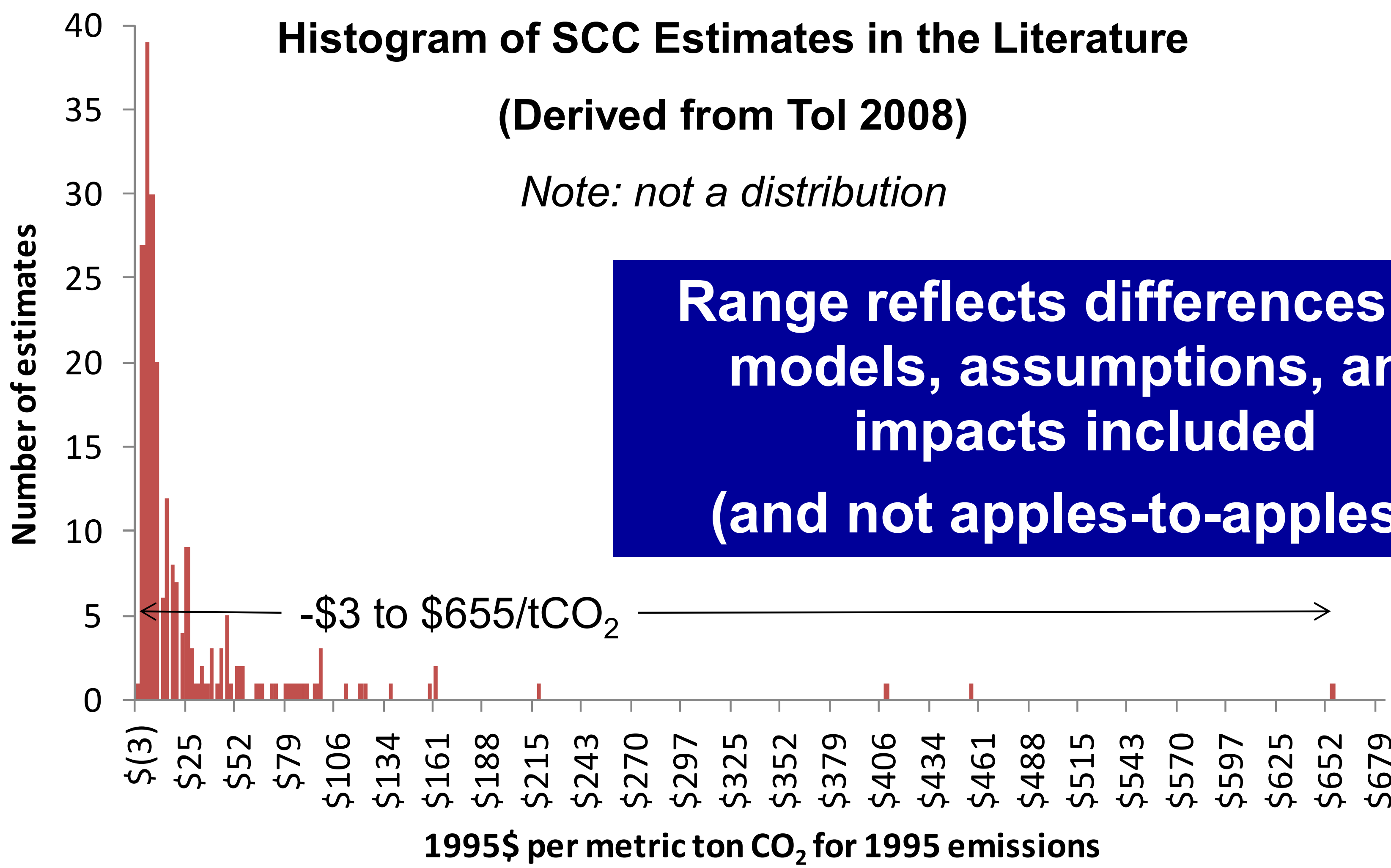
Types of Impacts Being Monetized

- Health
- Agriculture
- Forestry
- Sea level
- Water resources
- Energy consumption (space cooling & heating)
- Migration
- Extreme weather (e.g., hurricanes)
- Ecosystems
- Catastrophic

Estimates based on sector specific impacts studies in the literature (incomplete & evolving)

Impact types included and formulations vary by model

Vast Range of SCC Estimates Have Been Produced



Range reflects differences in models, assumptions, and impacts included

(and not apples-to-apples)

Developed from Tol (2008) meta analysis of SCC estimates

ELECTRIC POWER RESEARCH INSTITUTE

SCC Sensitive to Key Assumptions

Example Using One Prominent Model

Global Annual Marginal Benefits for an Emissions Reduction in 2005 (2006$/t$CO_2$)

		CS = 1.5°C			2°C			3°C			4.5°C			6°C		
	Baseline	DR = ~2%	~3%	~7%	~2%	~3%	~7%	~2%	~3%	~7%	~2%	~3%	~7%	~2%	~3%	~7%
Global	FUND	−$2	−$5	−$3	$9	−$2	−$3	$43	$9	−$1	$140	$35	$1	$365	$81	$5
	A1b	−$6	−$5	−$3	$0	−$3	−$2	$16	$3	−$2	$54	$16	$0	$114	$37	$3
	A2	−$2	−$6	−$3	$15	−$1	−$3	$68	$13	−$2	$240	$51	$1	$655	$125	$5
	B2	−$4	−$5	−$3	$8	−$2	−$3	$43	$8	−$2	$145	$34	$1	$409	$83	$4

Discount rate (DR): -$1 to $43

Climate responsiveness (CS): -$5 to $81

Socioeconomics/emissions: $54 to $240

All: -$6 to $655

Characterizing uncertainty a key issue. Need to be careful, transparent, and critical!

Source: USEPA (2009) Draft RIA, Table 5.3-2 produced with an earlier version of FUND (as presented in Rose, 2012)

Why is the Social Cost of Carbon (SCC) Important?

- It is an estimate of damages to society
- US Government (USG) legally obligated to value CO_2 (9th Circuit Court, 2007)
  - SCC modeling (of some kind) an option
- USG generated SCC values to estimate benefits of CO_2 reductions for federal rules
- SCCs increasingly being considered and used – rulemakings, states, other countries, other applications
- However, general lack of understanding and technical information about the modeling and climate risks represented ➔ motivated EPRI work

Application type	Examples	Global emissions implications	SCCs used
Federal regulatory	DOT (NHTSA) vehicle efficiency standards, EPA Clean Power Plan, DOE small motor efficiency standard, DOE microwave efficiency standard (1, 2, 3, 4)	Incremental	USG
Federal non-regulatory	CEQ NEPA reviews, BLM coal mine permitting (5, 6)	Incremental	USG
State	Minnesota, Maine (7, 8)	Incremental	USG considered
Local (e.g., city)	Austin, TX (9)	Incremental	Custom
Value of technology	Technology SCC pricing (10)	Incremental	USG and other
Non-U.S. regulatory	Canada, United Kingdom (U.K.) (11, 12)	Incremental	Canada – USG UK – Custom
Federal climate goal evaluation	U.S. proposed legislative GHG cap and trade policy (12)	Non-incremental	USG
Global climate goal evaluation	Tol (2009) (13)	Non-incremental	Custom

Rose and Bistline (2016)

US Government SCC Estimates

USG SCC Estimates – Default Values to Many

Obama Administration

Table ES-1: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

US Government (2015, 2016)

Trump Administration (proposed values)

Table 3-7. Interim Domestic Social Cost of CO_2, 2015-2050 (in 2011$ per metric ton)*

Year	Discount Rate and Statistic: 3% Average	7% Average
2015	$5	$1
2020	6	1
2025	7	1
2030	7	1
2035	8	1
2040	9	2
2045	9	2
2050	10	2

EPA Proposed CPP Repeal (2017)

Same modeling machinery used – thus, fundamental issues for both

Major differences in Obama vs. Trump estimates: global vs. US only damages, discounting, distribution statistics used

USG SCC Modeling Approach

Feature	Detail
Multiple SCC models	Three models — DICE, FUND, PAGE
Standardized uncertainties	• Five reference socioeconomic and emissions scenarios (each extended from 2100 to 2300) • One distribution for the climate sensitivity parameter
Model specific parametric uncertainties	In FUND and PAGE climate and damage components
Standardized discounting	three constant discount rates — 2.5%, 3%, and 5%
Thousands of SCC results	150,000 SCC estimates for a given discount rate and year (3 models × 5 socioeconomic scenarios × 10,000 runs each)
Aggregation of results	• Average of 150,000 results for each discount rate and year • "3% (95th percentile)" value is 95th percentile from distribution of 150,000 results with 3% discounting

- USG SCCs the result of significant aggregation
  - Over models, time, world regions, impact categories, and many scenarios
  - $42 derived from 150,000 SCC estimates
- Making sense of, & assessing, the estimates requires delving into these details

ELECTRIC POWER RESEARCH INSTITUTE

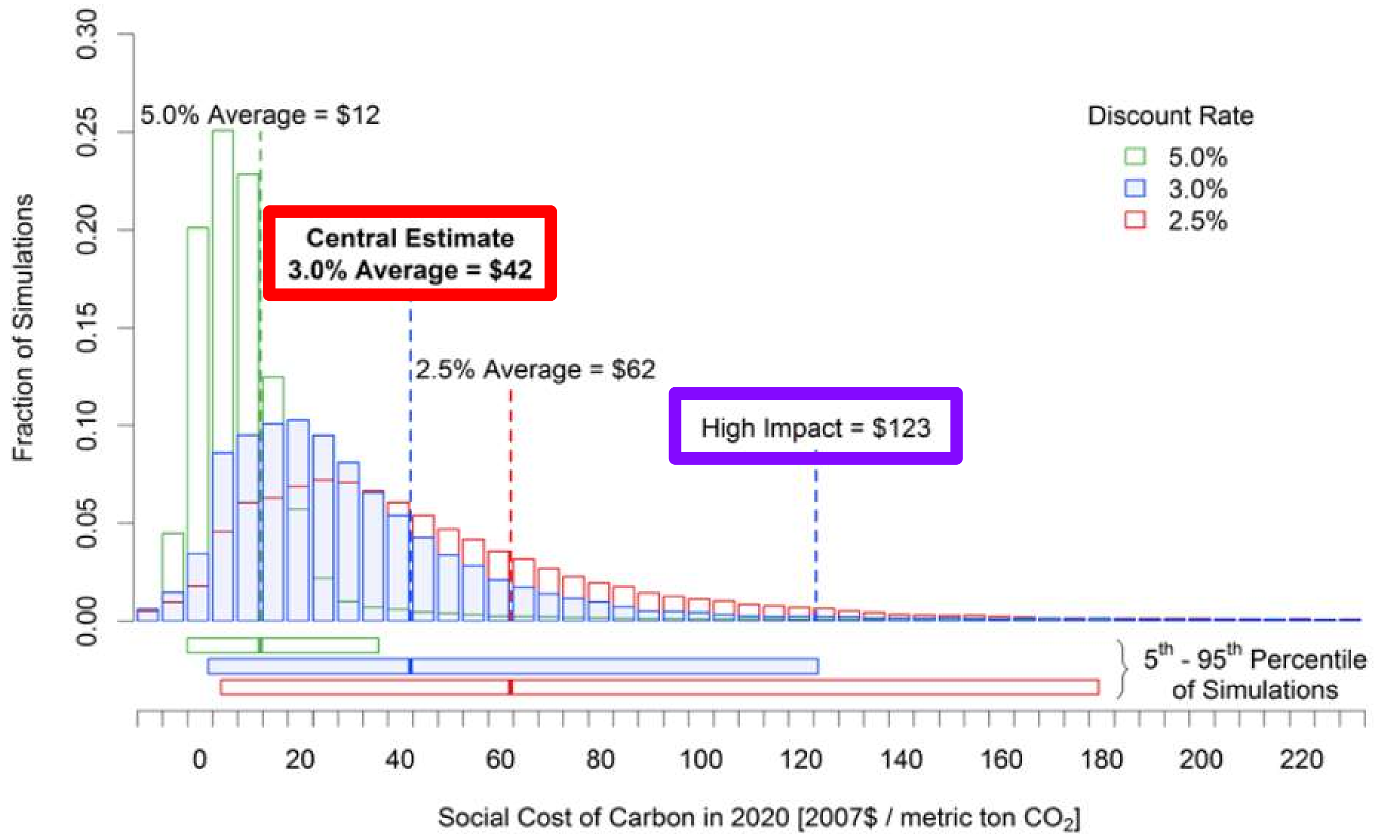
150,000 Estimates Underlie Each USG SCC Value

Table ES-1: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

USG (2015, 2016)

Figure ES-1: Frequency Distribution of SC-CO_2 Estimates for 2020[3]



USG (2016)

ELECTRIC POWER RESEARCH INSTITUTE

Assessing SCC Modeling

EPRI Study Assessing SCC Modeling

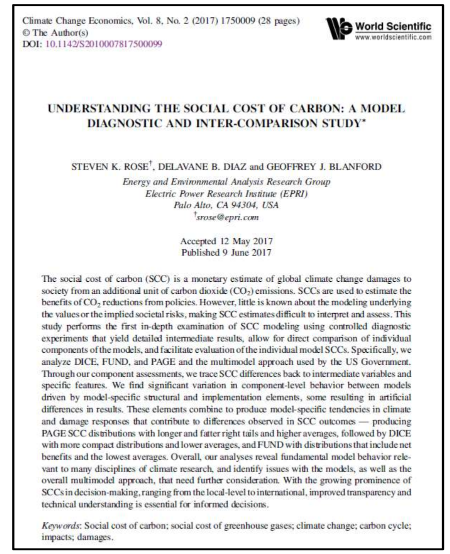
Motivation: What does $42 mean?

$42 of damages to the world from a ton of CO_2

Difficult to interpret and assess – little is known about the modeling underlying the values or the implied societal risks.

Understanding the Social Cost of Carbon: A Model Diagnostic and Inter-Comparison Study

(*Climate Change Economics* Vol. 8, No. 2, 2017)



Climate Change Economics, Vol. 8, No. 2 (2017) 1750009 (28 pages)

DOI: 10.1142/S2010007817500099

World Scientific
www.worldscientific.com

UNDERSTANDING THE SOCIAL COST OF CARBON: A MODEL DIAGNOSTIC AND INTER-COMPARISON STUDY*

STEVEN K. ROSE†, DELAVANE B. DIAZ and GEOFFREY J. BLANFORD
Energy and Environmental Analysis Research Group
Electric Power Research Institute (EPRI)
Palo Alto, CA 94304, USA
†*srose@epri.com*

Accepted 12 May 2017
Published 9 June 2017

The social cost of carbon (SCC) is a monetary estimate of global climate change damages to society from an additional unit of carbon dioxide (CO_2) emissions. SCCs are used to estimate the benefits of CO_2 reductions from policies. However, little is known about the modeling underlying the values or the implied societal risks, making SCC estimates difficult to interpret and assess. This study performs the first in-depth examination of SCC modeling using controlled diagnostic experiments that yield detailed intermediate results, allow for direct comparison of individual components of the models, and facilitate evaluation of the individual model SCCs. Specifically, we analyze DICE, FUND, and PAGE and the multimodel approach used by the US Government. Through our component assessments, we trace SCC differences back to intermediate variables and specific features. We find significant variation in component-level behavior between models driven by model-specific structural and implementation elements, some resulting in artificial differences in results. These elements combine to produce model-specific tendencies in climate and damage responses that contribute to differences observed in SCC outcomes — producing PAGE SCC distributions with longer and fatter right tails and higher averages, followed by DICE with more compact distributions and lower averages, and FUND with distributions that include net benefits and the lowest averages. Overall, our analyses reveal fundamental model behavior relevant to many disciplines of climate research, and identify issues with the models, as well as the overall multimodel approach, that need further consideration. With the growing prominence of SCCs in decision-making, ranging from the local-level to international, improved transparency and technical understanding is essential for informed decisions.

Keywords: Social cost of carbon; social cost of greenhouse gases; climate change; carbon cycle; impacts; damages.

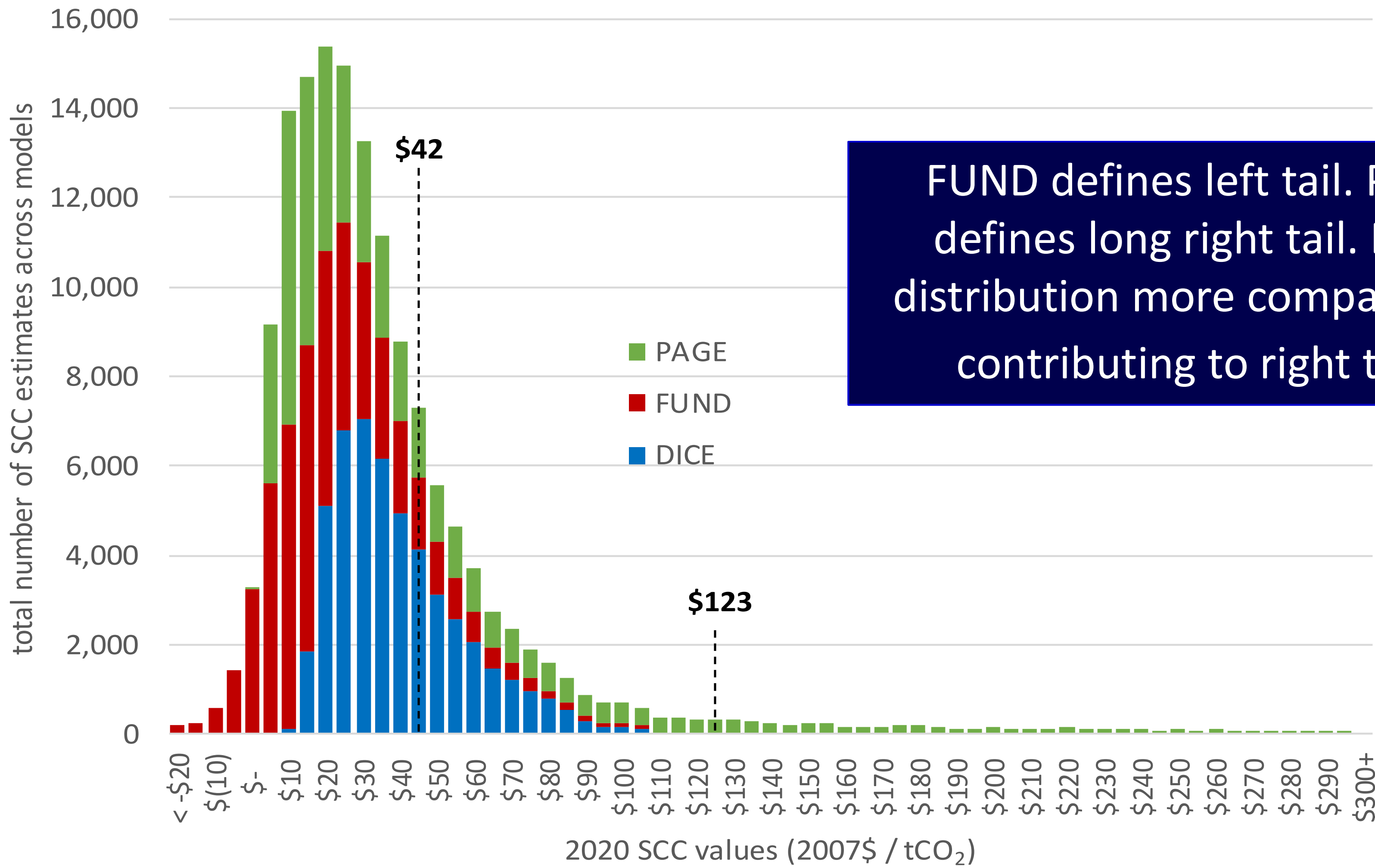
Rose et al (2017)

* $42 is the US Government's most recent "central" social cost of carbon (SCC) estimate of the future global damages to society from a metric ton of CO_2 emissions in 2020. Used as an estimate of the benefit of reducing a ton of CO_2 in 2020.

ELECTRIC POWER RESEARCH INSTITUTE

The Role of Individual Models in USG SCC Estimates

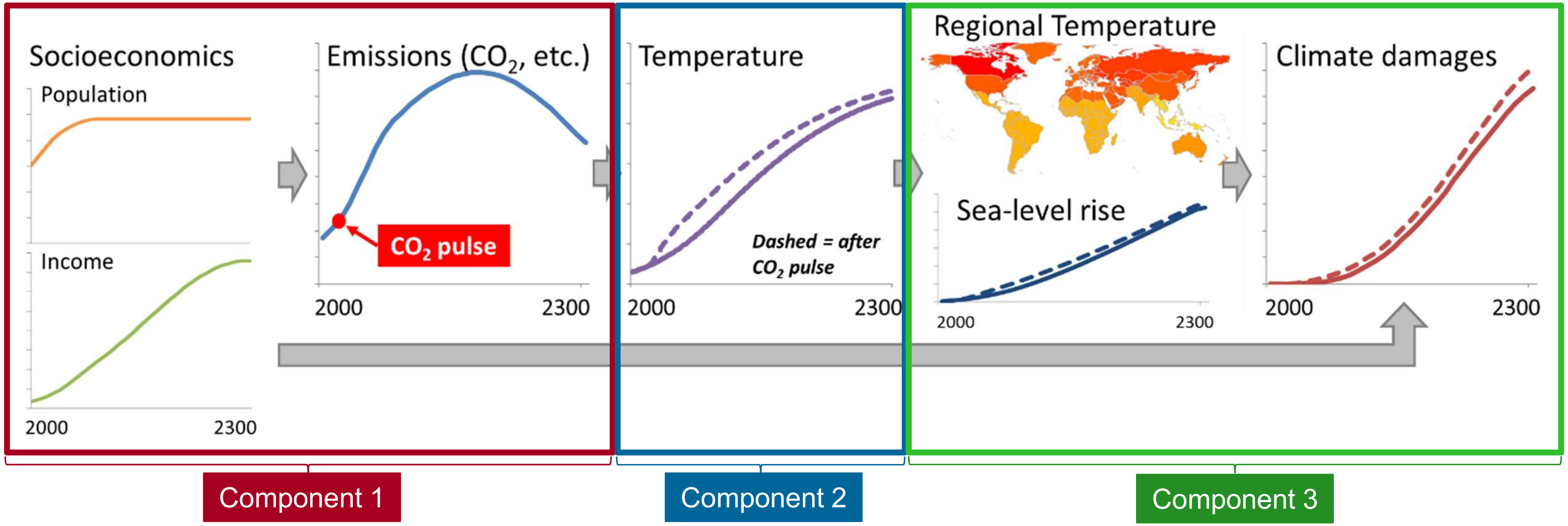
Histogram of the 150,000 SCC estimates behind the USG SCCs for 2020 with a 3% discount rate



FUND defines left tail. PAGE defines long right tail. DICE distribution more compact and contributing to right tail.

Source: Rose et al (2017). Developed from USG data available at https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.

Assessing SCC Modeling Component-by-Component & Overall



Reviewing modeling & code, programming components, running diagnostic scenarios, comparing, exploring multiple perspectives

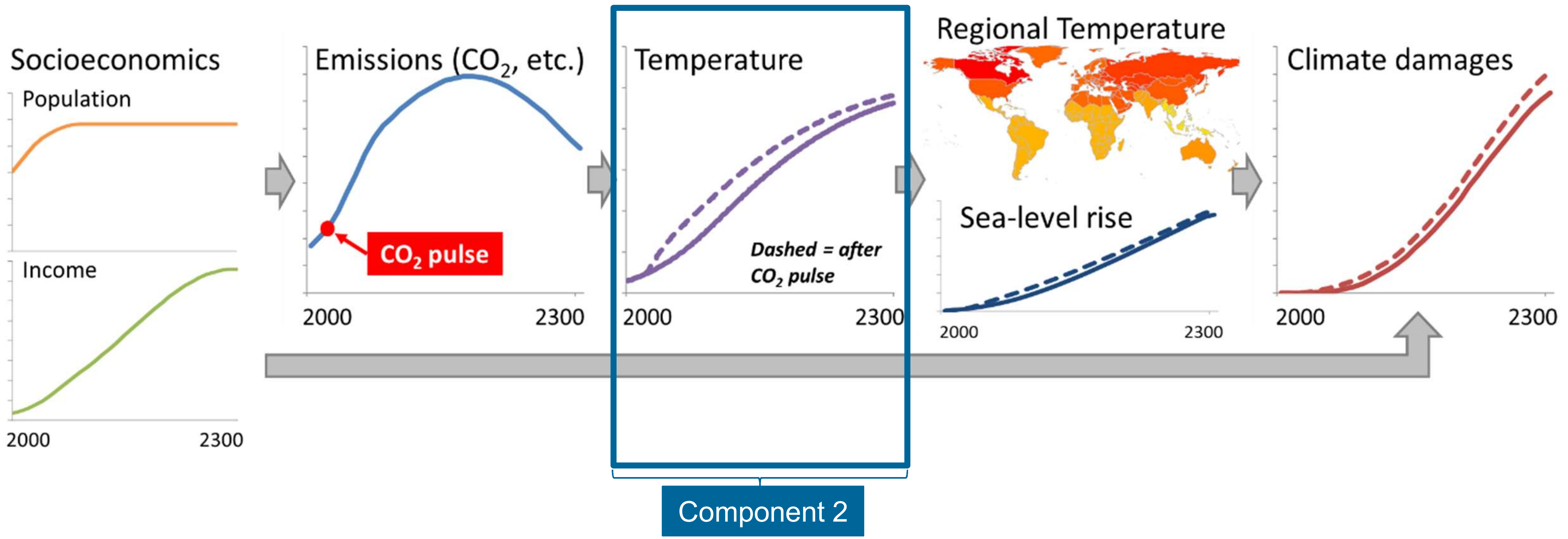
- Examining the **inner workings** of the modeling
- **4 separate technical assessments** – elucidating & assessing individual modeling components & overall USG experimental design
- Learning about **the raw intermediate modeling and behavior** – undiscounted & disaggregated

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Study Overview

- **Objective = improve understanding of SCC estimation**
  - Essential to understand and assess the state-of-the-art
  - For anyone wanting/needing to value greenhouse gas emissions
  - To facilitate informed dialogue, assessment, decision making, and scientific advances
- **The study offers perspectives on models & differences not previously available**
  - First detailed SCC model diagnostic and inter-comparison – comparable insights into modeling structures, implementation, and intermediate results
  - We trace significant differences in SCC distributions to component-level behavior, implementation, specific features, and model tendencies
  - Important to communicate, evaluate, and justify differences and address those with insufficient scientific rationale, improve representation of uncertainty and resulting robustness, and enhance documentation for components and models
- **The study observes fundamental scientific issues with current modeling**
  - Opportunities for immediate and longer-term improvement
- **The study is an enhancement and refinement of the earlier EPRI report that was a key input to the NAS SCC study on updating estimation (NAS, 2017)**

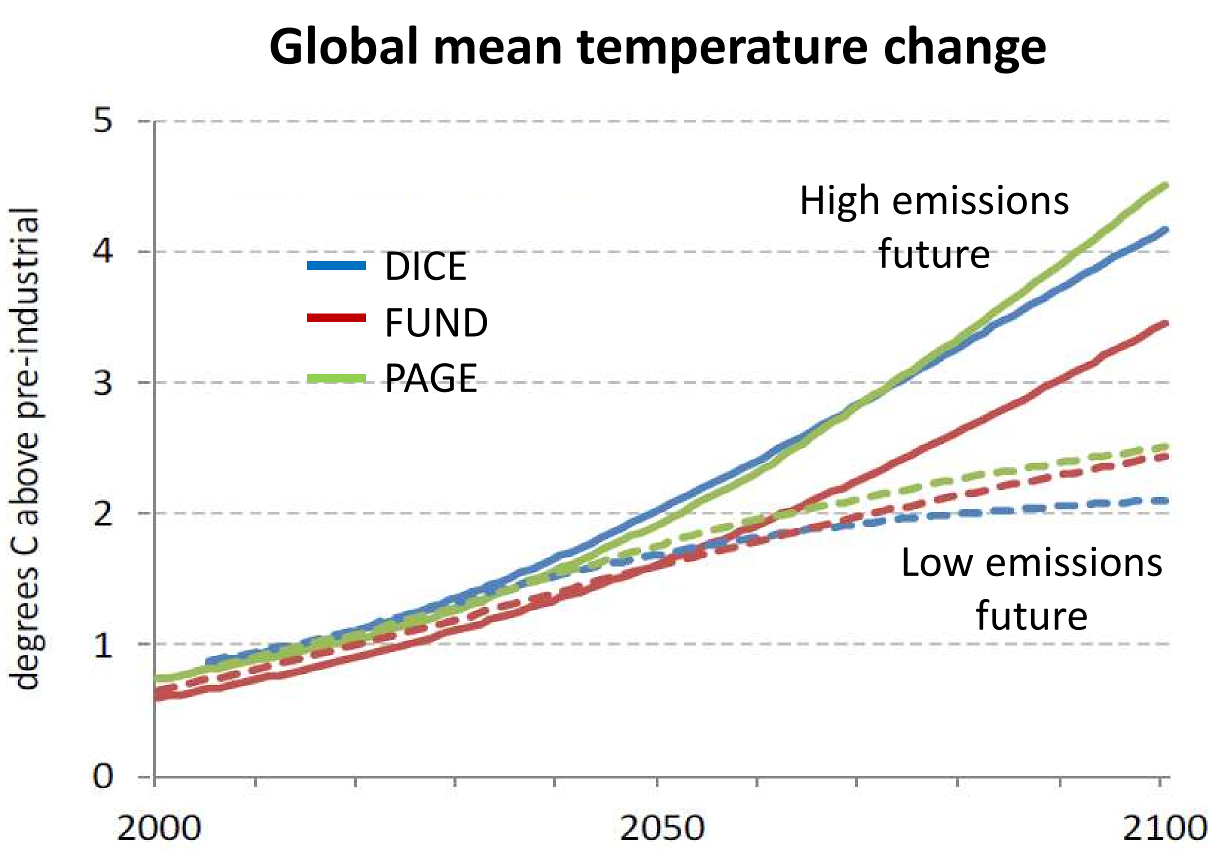
Climate Modeling Component Assessment – Sample Results

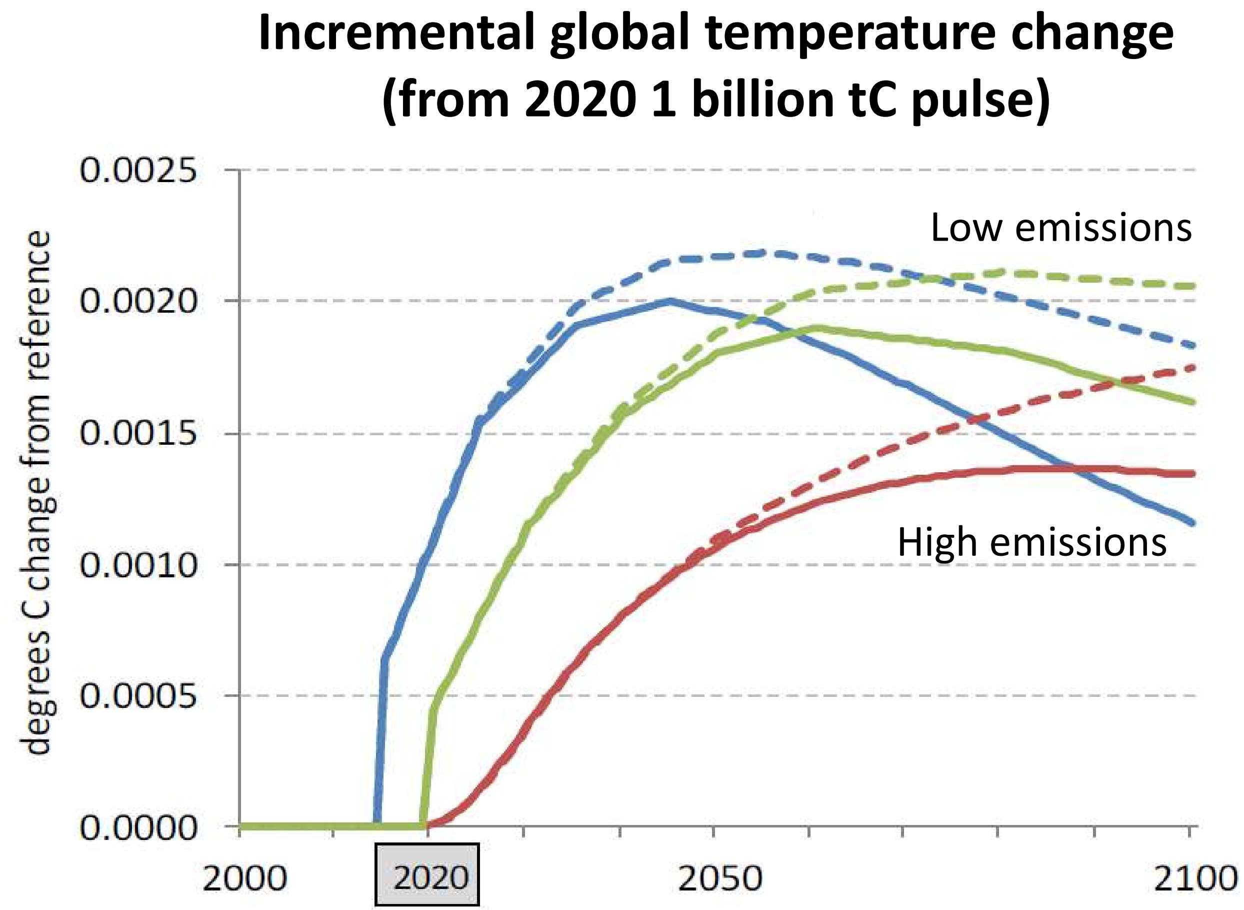


Evaluate climate component structure, code each model's component, and run diagnostics with standardized emissions & radiative forcing inputs

Global Temperature Responses to 2100

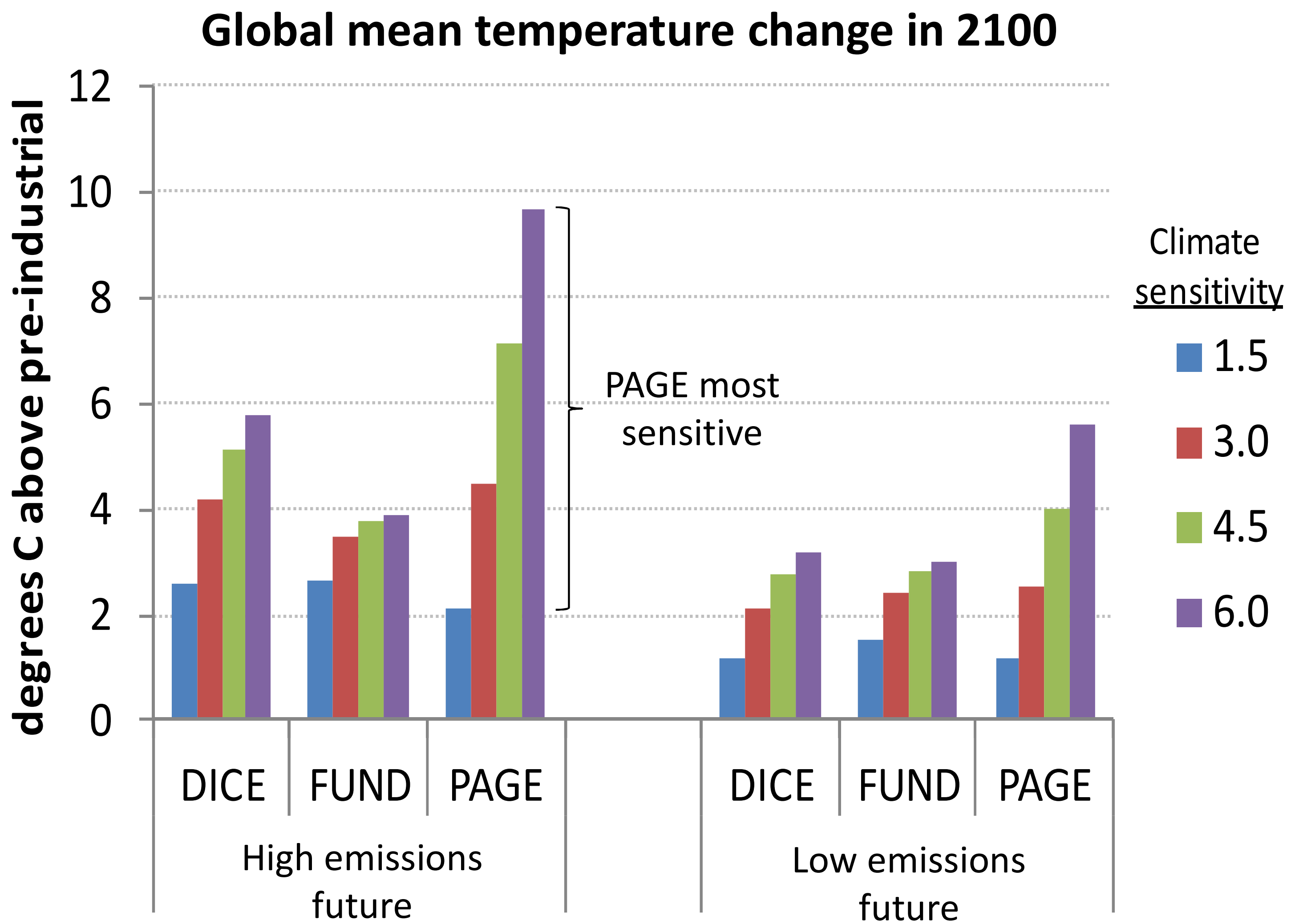
(with equilibrium climate sensitivity 3˚C)





Meaningful differences in outcomes and sensitivity for the same inputs. Trace to modeling & implementation features (e.g., carbon cycle, non-CO_2, forcing translation, pulse implementation).

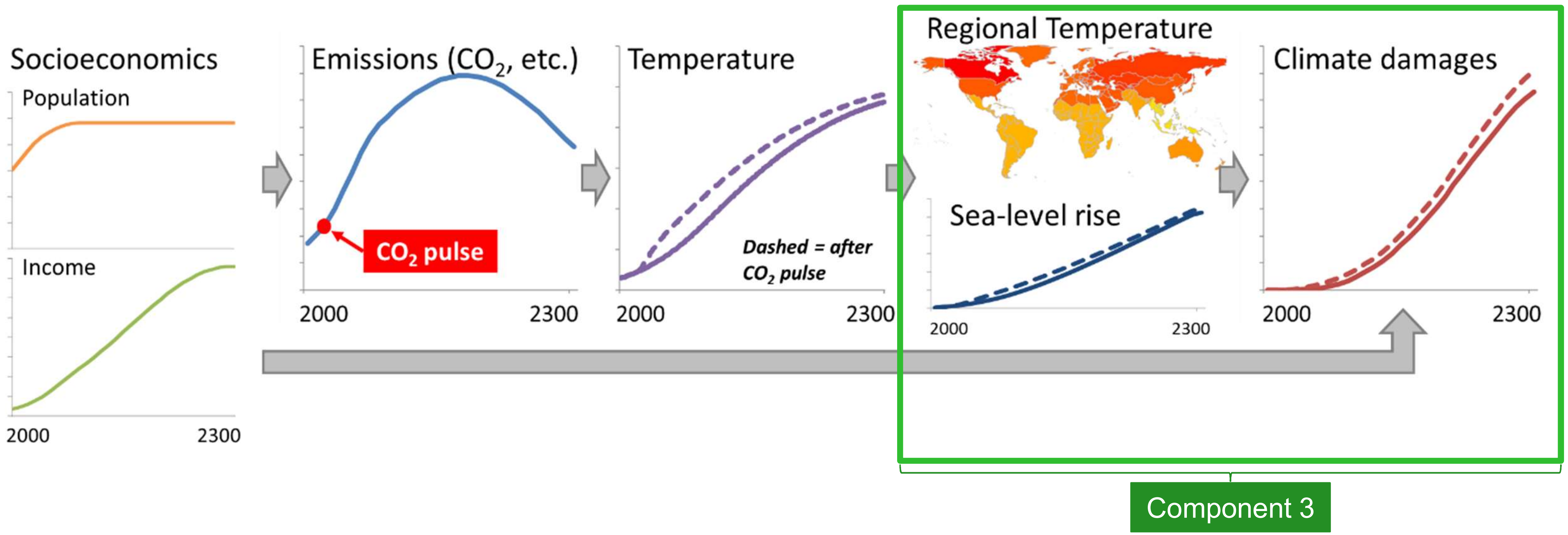
Sensitivity of Temperature Response to Climate Sensitivity



PAGE most sensitive, FUND least sensitive.

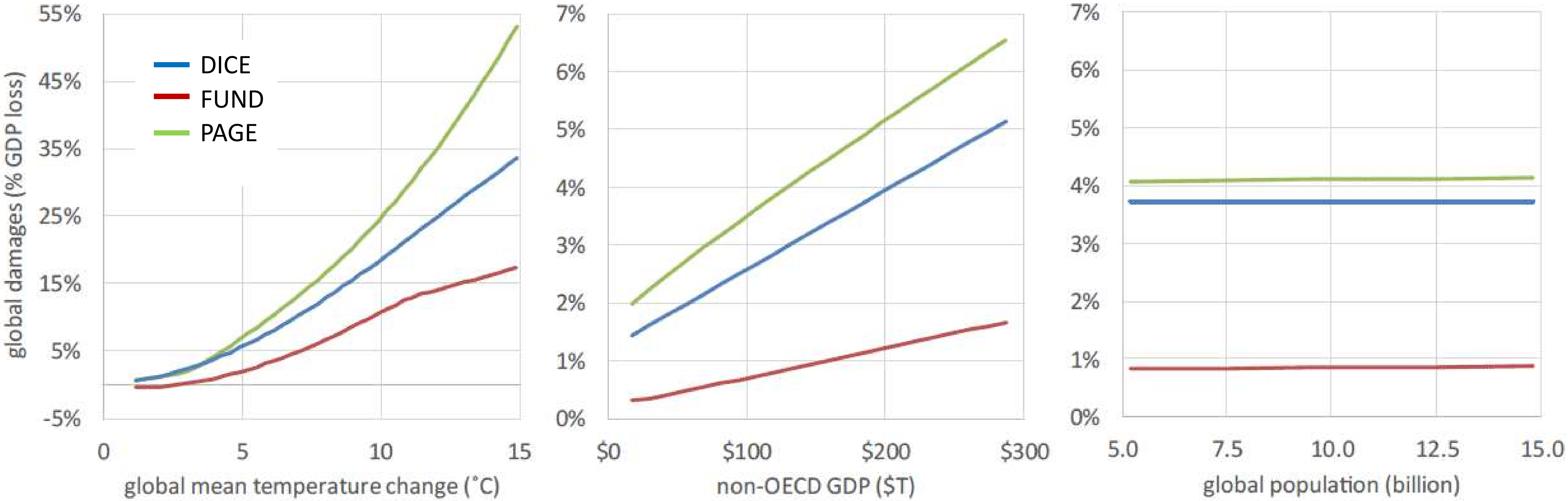
PAGE not adjusting rate of temperature response.

Climate Damages Modeling Component Assessment – Sample Results



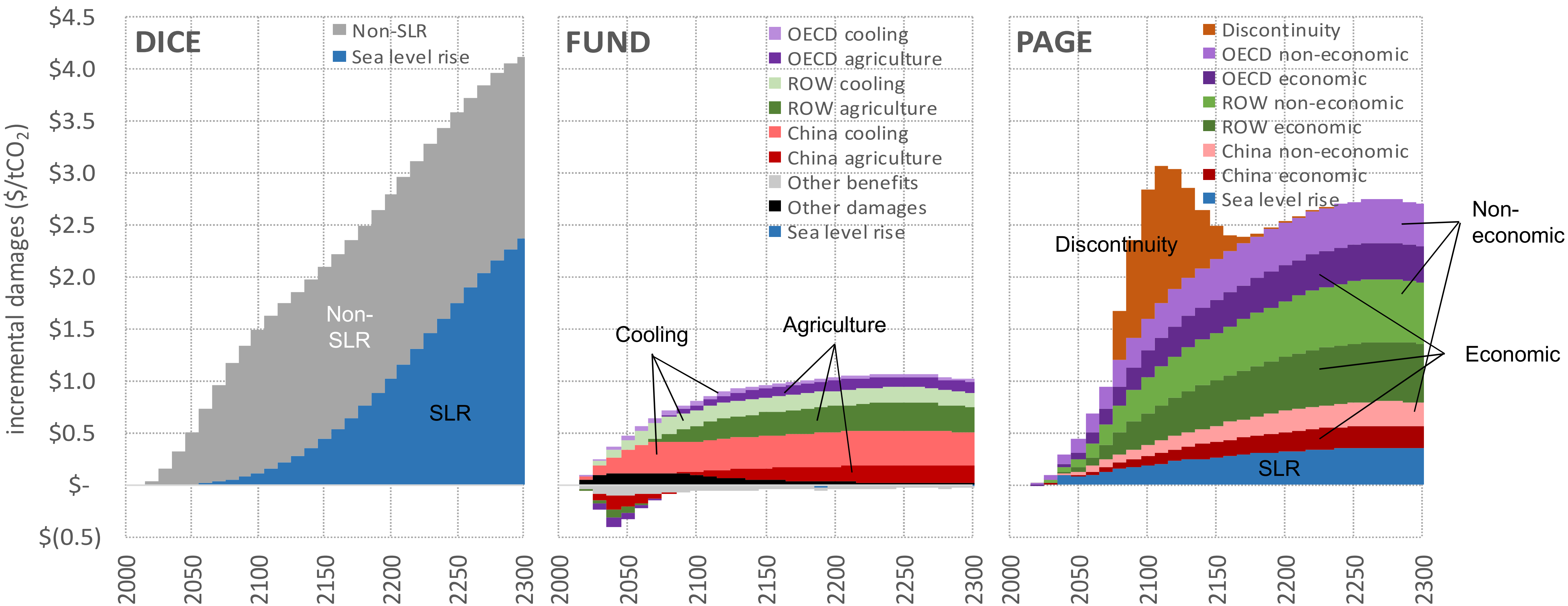
Evaluate damage component structure, code each model's component, and run diagnostics with standardized climate & socioeconomic inputs

Implied Damage-Driver Relationships from Sensitivity Analyses



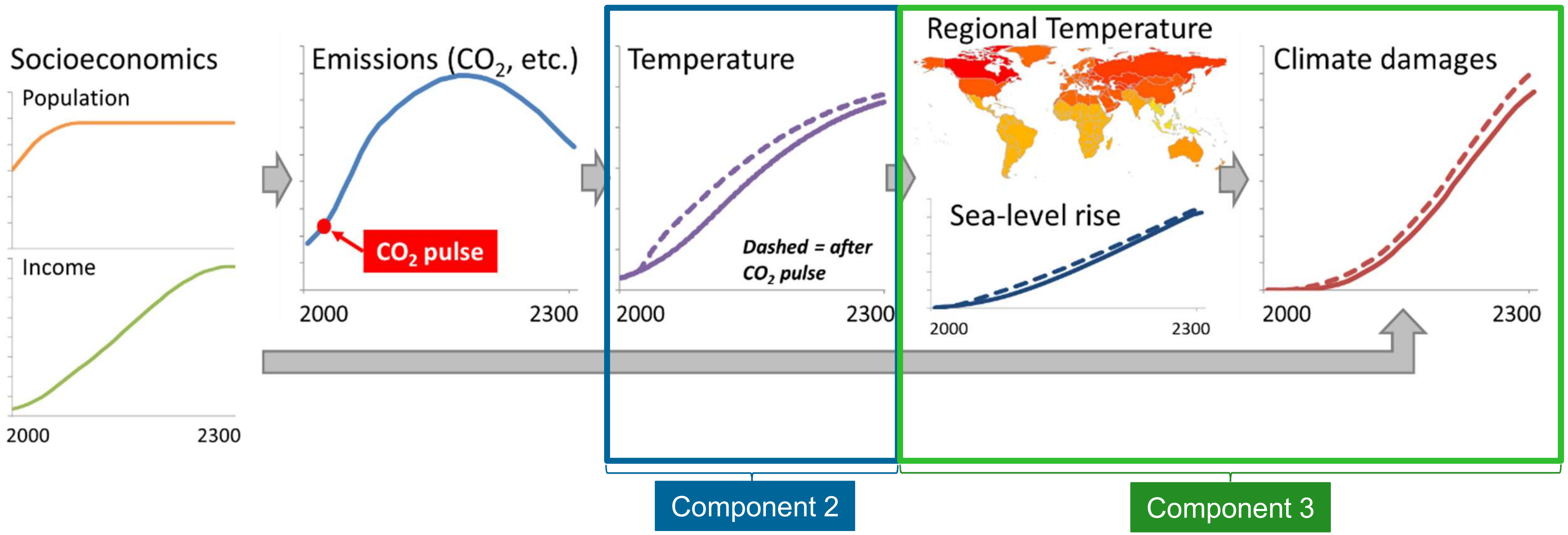
PAGE damages systematically more sensitive to key drivers. FUND systematically less sensitive. Trace to modeling features (e.g., sea-level rise, regional temperatures, functional forms and drivers, specific categories, adaptation).

Annual Incremental Damages to 2300 – Decomposition and Differences



Model specific features dominate incremental damages

Climate and Damages Probabilistic Specification Assessments – Sample Results



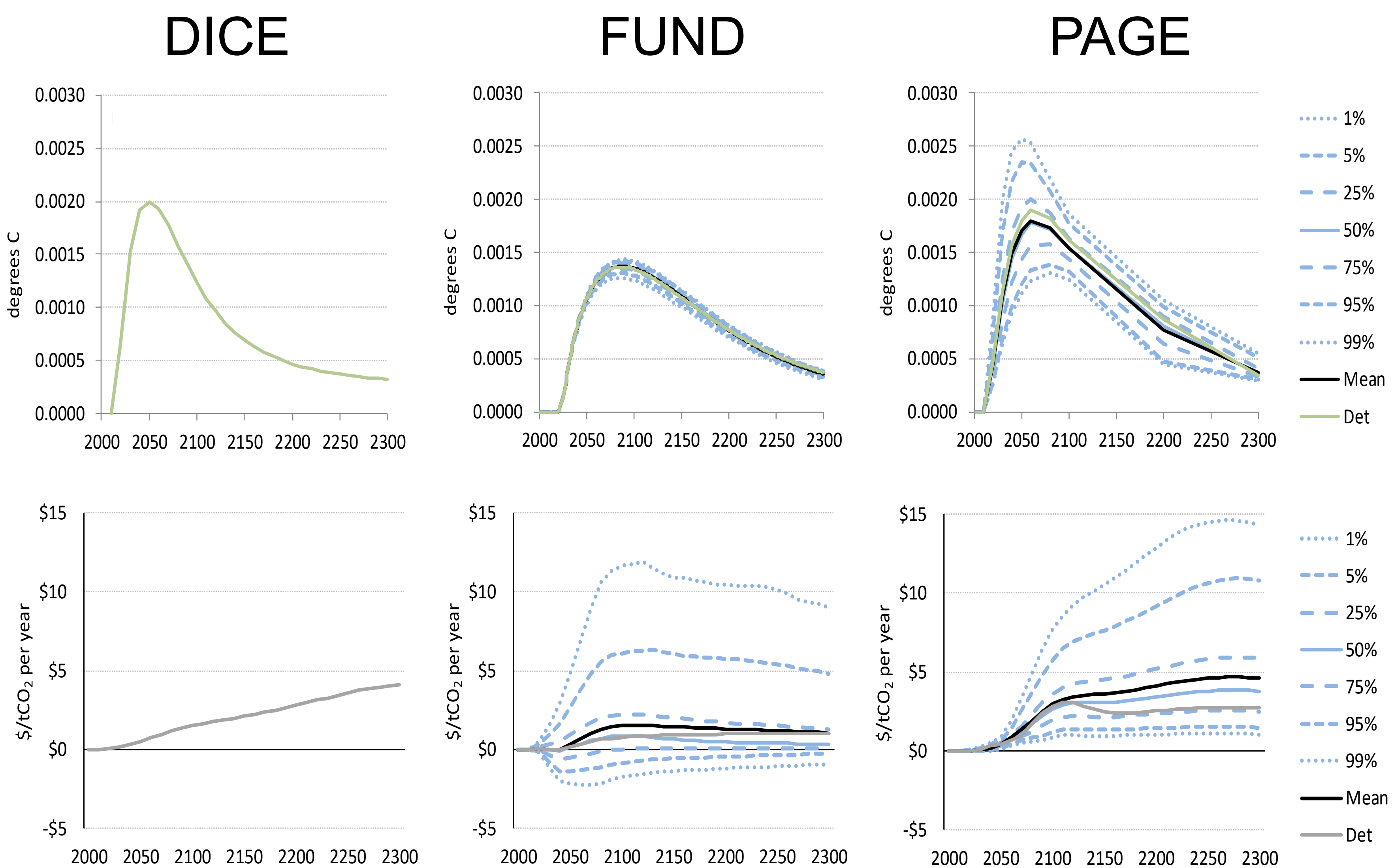
Assess probabilistic specifications and behavior by coding probabilistic versions of components and running with standardized inputs and random draws over model-specific uncertain parameters

Probabilistic Incremental Climate and Damage Responses

Different uncertainty considered across models contributing to SCC distribution outcomes

Incremental temperatures to 2300*

Incremental damages to 2300#



* With high emissions reference, climate sensitivity 3˚C

\# With high temperature reference, USG2 socioeconomics

Fundamental Issues with SCC Models and USG Framework

The study offers perspectives on models & differences not previously available

We observe fundamental scientific issues, and improvement opportunities for greater confidence in results

Fundamental Individual Model Issues

- **Model-specific issues**
  - **DICE** – no climate feedback, CO_2 pulse, quadratic damages, implied adaptation, limited parametric uncertainty, damages dependent on other models
  - **FUND** – partial radiative forcing, long temperature lag, potential for climate benefits and adaptation
  - **PAGE** – non-CO_2 forcing, ECS implementation, slow carbon cycle, CO_2 pulse, regional damage scaling, undefined damages, fixed adaptation, damages dependent on other models
- **Transparency and justification** for individual model structure and behavior
- **Damage representations** dated and dependent

Fundamental Multi-Model Framework Issues

- **Transparency and justification**
- **Structural uncertainty** representation
- **Input and parametric uncertainty** representation
- **Comparability and independence** of results
- **Robustness** of results unlikely
- **Multi-model approach** – reconsider.
  - Challenges (transparency, justification, comparability, and independence)
  - Consider developing a model component-by-component

NAS SCC Committee agreed that a new approach and model components were needed (NAS, 2017)

Improvement Opportunities

Preliminary analysis and results

Improving from USG Values

- We know a great deal more than we used to about the modeling
- What we know doesn't instill confidence
- There are clear opportunities to improve
  - Especially immediate opportunities given decision-maker willingness to entertain current modeling and estimates

Preliminary

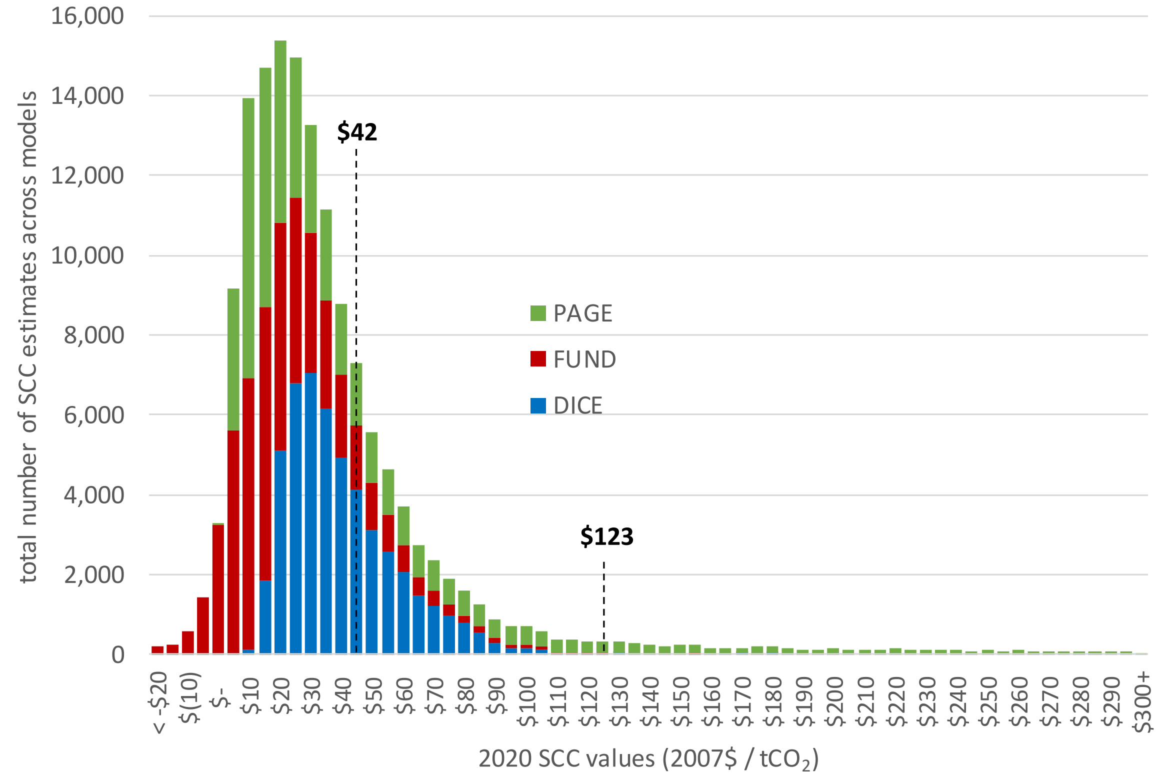
Immediate Option: Filtering USG SCC Values

- Recall that 150,000 estimates underlie every USG estimate (e.g., $42)

- Thus, there is an estimates database that can be filtered by model or scenario

- Can use scientific criteria to identify the better underlying estimates and produce improved aggregate estimates
  - Apply to individual models and input assumptions

Histogram of the 150,000 SCC estimates behind the global USG SCCs for 2020 with a 3% discount rate



Source: Rose et al (2017)

Preliminary

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Evaluate Modeling According to a Minimum Scientific Standard

- **Having a minimum scientific standard seems reasonable**
  - Model peer review journal publication insufficient, especially for regulatory models

A proposed approach

- **Apply NAS SCC Committee requirements for modeling** (NAS, 2017)
  - Transparency, Scientific basis (justification, consistency with state of knowledge), Characterization of uncertainty
- **Apply a conservative minimum scientific standard for models and inputs:**
  - Transparency – enough documentation to know what's there
  - Scientific basis – there is some sort of justification & minimum necessary functionality
  - Plausibility – assumptions and modeling reasonable

Preliminary

Model Evaluation According to a Minimum Scientific Standard

Scientific Criteria	DICE	FUND	PAGE
Transparency	e.g., damages calibration	Most things described	e.g., unspecified discontinuity damages
Minimum scientific justification	e.g., quadratic damages	e.g., probabilistic parameters	e.g., unsubstantiated discontinuity damage, regional damages scaling, & probabilistic parameters
Minimum scientific functionality	e.g., no climate feedback	e.g., partial radiative forcing	e.g., climate modeling missing structural element
Plausibility	Adequate	e.g., some probabilistic outcomes	e.g., some probabilistic outcomes

"Red" implies model does not meet minimum scientific standard

Green = adequate; Yellow = meets min but could be improved; Red = inadequate

Proposed conservative minimum scientific standard:

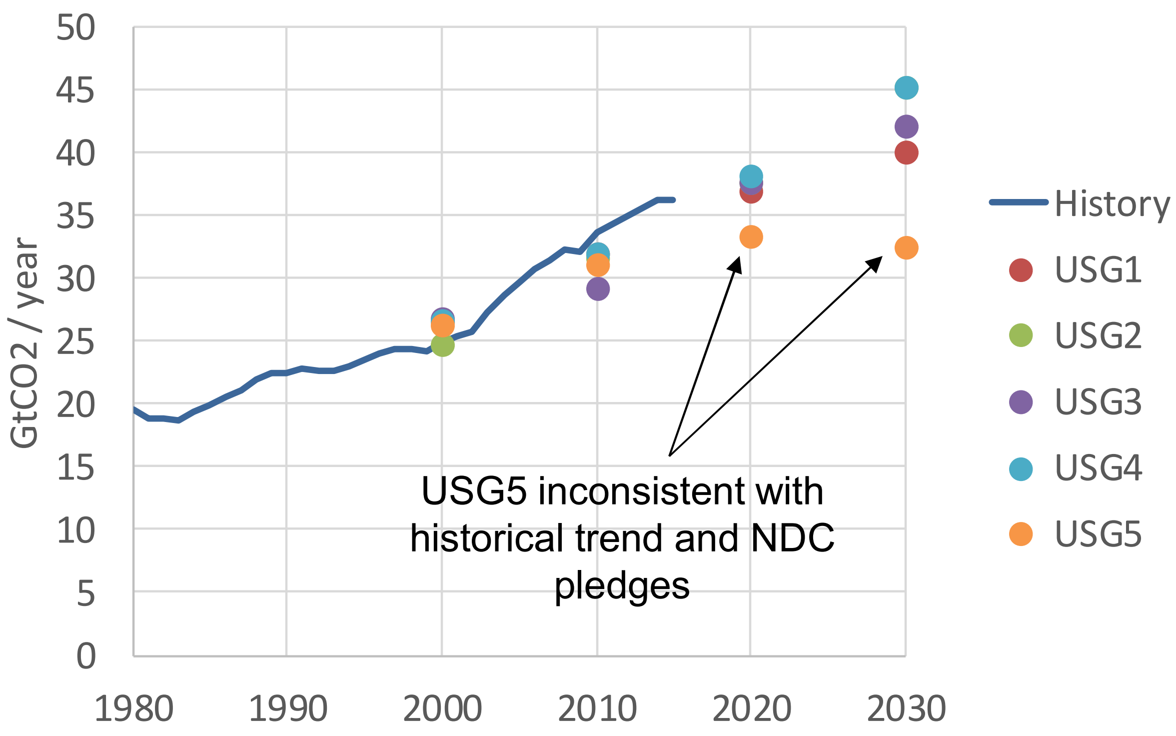
- Transparency – enough to know what's there
- Scientific basis – some sort of justification & minimum functionality
- Plausibility – assumptions and modeling reasonable

Preliminary

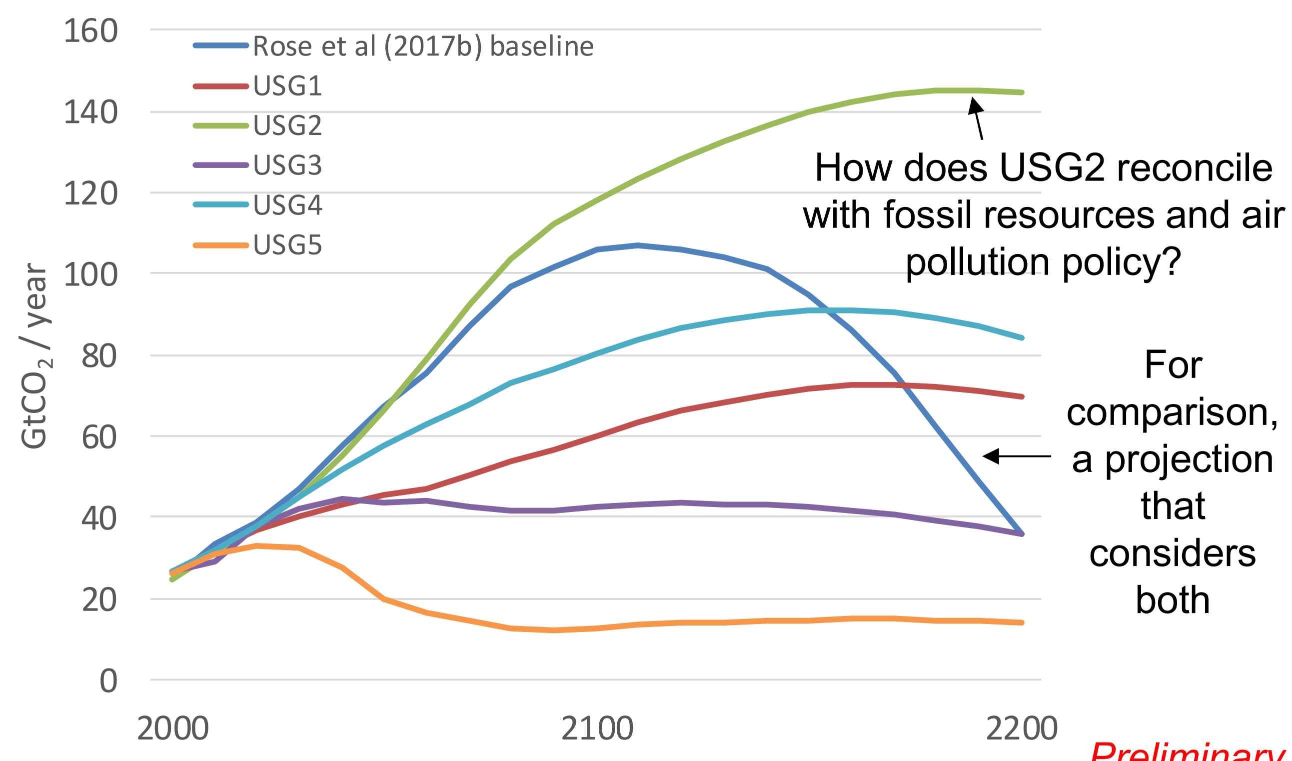
Input Evaluation According to a Minimum Scientific Standard

- **Are input emissions projections plausible in the near-term and long-run?**
  - In the near-term, reasonably consistent with historical trends?
  - In the long-run, reasonable given fossil resource constraints and air pollution?

Global fossil and industrial CO_2 1980-2030



Global fossil and industrial CO_2 2000-2200



Preliminary

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Results from Filtering According to Minimum Scientific Standard

		Current 2020 USG SCCs with a 3% DR	Filtered 2020 SCCs with a 3% DR
Domestic SCCs	**Average**	$5*	$1
	5th	$0	$(0)
	95th	$21	$3
Global SCCs	**Average**	$42	$30
	5th	$2	$1
	95th	$123	$71

DICE & FUND 1st-4th emissions scenario results (*could also justify dropping 2nd emissions scenario results)*

** $6 in Proposed CPP Repeal values. Appears to be a typo in the proposed rule's value.*

Developed using Rose et al. (2017) and Proposed CPP Repeal docket

Preliminary

Refinement and Replacement Options for Improving From USG Values

Immediate options (individual or combination) for improved estimates (< 1 year)

Option	Description
Filter USG SCC values	Select a subset of USG SCC values based on minimum scientific standard
Improve USG inputs	Refine modeling inputs to address known issues and incorporate best knowledge
Revise USG outputs	Refine modeling results based on scientific criteria
Refine USG elements	Revise model implementation and elements with issues
Replace USG components	Replace components with alternatives that better satisfy the scientific criteria
Replace USG approach	Develop approach and modeling different from that currently used by USG

Preliminary

Immediate Options to Improve USG Inputs, Elements, Components

- **If filtering insufficient for meeting a minimum scientific criteria, options to…**
- **Improve USG Inputs**
  - Update equilibrium climate sensitivity (ECS) distribution assumptions or use set of alternative distributions
  - Expand global CO_2 emissions range considered to improve uncertainty representation
- **Refine USG Elements**
  - Revise CO_2 pulse implementation (DICE and PAGE issue)
  - Revise non-CO_2 forcing representation (FUND and PAGE issue)
  - Revise ocean diffusivity parameterization (PAGE issue)
- **Replace USG Components**
  - Use components with strongest scientific basis (e.g., replace climate component)

Preliminary

Longer-Term Option: Replace USG Approach

- Longer term opportunities (3+ years)
  - **Develop new components and a new overall framework**
    - Not using the current multi-model framework or even USG models as is
    - See EPRI and NAS studies for recommendations
- However, **methodological challenges** need to be confronted along this path
  - Newer doesn't imply better – details matter, assessment required
  - Problems with comparability and aggregation of sectoral estimates
  - Considering drivers beyond temperature change
  - Reconciling methodological differences in literature damage estimates
  - Insufficient data for identifying the shape of damage gradients (vs. speculation)
  - Accounting for adaptation potential – micro (individual/firm), macro (economy)
  - Characterizing uncertainty

Preliminary

Are Current Estimates Too Low?

Are Current Estimates Too Low?

- **We can't tell until we address issues with current modeling**
  - **Need to understand current modeling to assess bias**
  - **Can't generalize given differences in models**

- **Potential biases in both directions**
  - Omitted damages – e.g., biodiversity, ocean acidification, extreme weather, arctic access
  - Current modeling of poorly understood risks (e.g., PAGE "discontinuity) and uncertainty specifications (e.g., some combinations produce 100% regional GDP losses)
  - Adaptation responses considered – micro and macroeconomic
  - Implied perpetual annual damages
  - Newer literature from empirical and structural modeling
  - Regional weighting and risk preferences

- **Potential "big" risks unlikely to be affected by a metric ton of CO_2 (e.g., acidification)**

- **Include things were we have sufficient scientific understanding**
  - Risk perceptions and preferences should drive policy stringency, not a measurement metric

Using the SCC

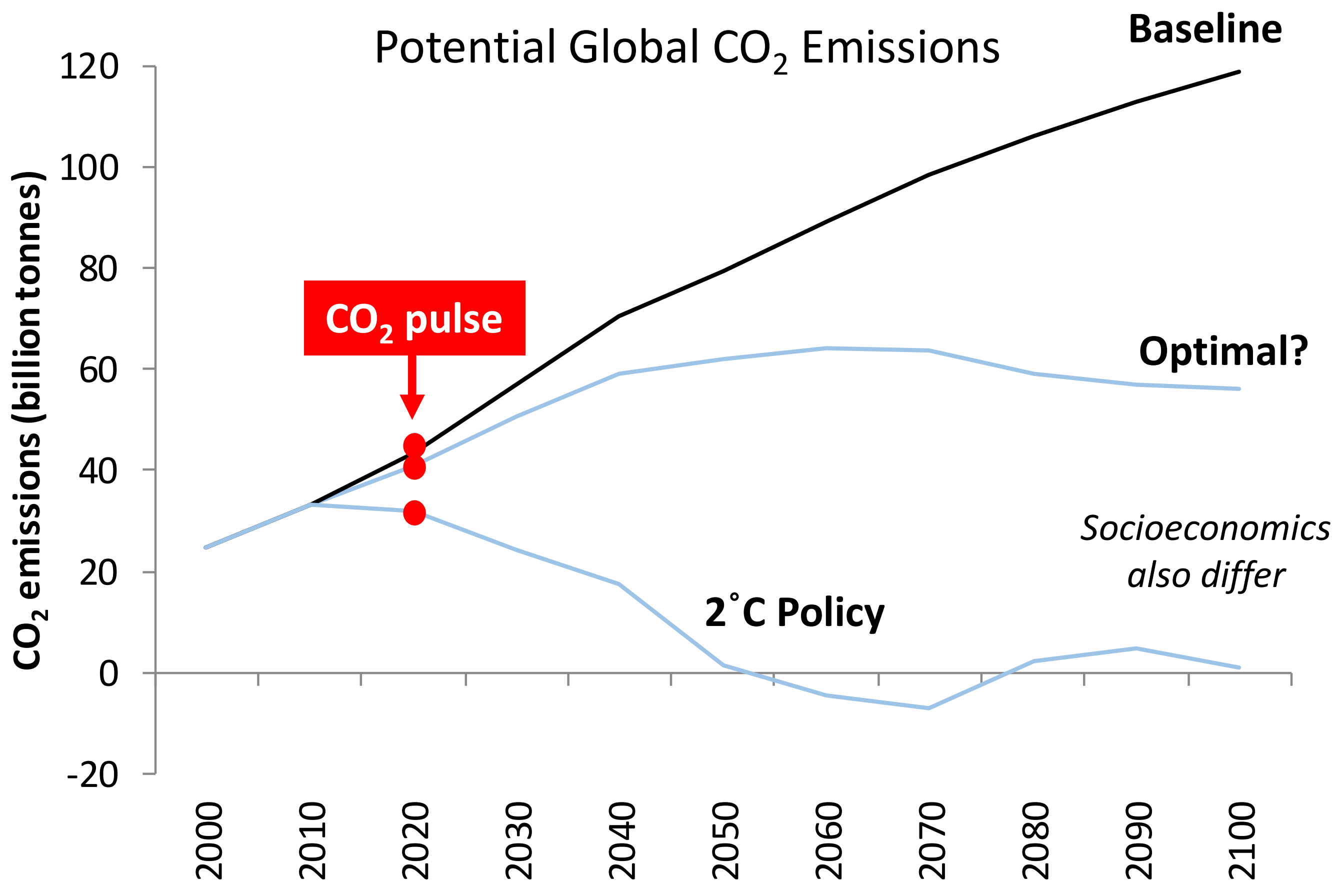
Using the SCC

- Most commentary (public & scientific) on SCC estimation, not its use
- Conceptual and methodological issues to consider
  - Different types of SCC estimates
  - How to use multiple SCC values
  - Consistency between benefits & cost calculations
  - Accounting for net global CO_2 changes (leakage = lower CO_2 benefits)
  - Valuing/pricing CO_2 more than once
  - Valuing non-CO_2 GHGs
- Some may be relevant in this context

Sources: Rose and Bistline (2016) and Rose (2017)

Different Flavors of the Social Cost of Carbon

- Baseline
- Optimal
- Policy



SCC varies across pathways with differences growing over time.

How much depends (e.g., damages shape, climate system, discounting, socioeconomics)

U-PAGE*	2020	2100
Baseline	$21	$123
2˚C Policy	$17	$79

U-FUND*	2020	2100
Baseline	$6	$64
2˚C Policy	$0	$6

** Modeling using the MERGE model with damage functions fitted to Rose et al. (2017a) USG SCC damage component deterministic assessment results and endogenous discounting.*

Key Messages

- We now understand the inner workings of modeling used by both the Trump & Obama Administrations
- There are fundamental issues with USG modeling that undermine confidence in estimates
- We should consider the issues and pursue immediate improvements given the need for estimates (e.g., filter-out the current best estimates)
- It is difficult to assess bias in current estimates given the issues
- Longer term improvements important, but challenges to overcome
- Conceptual and practical SCC use issues to consider as well

Resources

- Anthoff, D, S Rose, RSJ Tol, and S Waldhoff (2011), Regional and Sectoral Estimates of the Social Cost of Carbon: An Application of FUND, Discussion Paper, *Economics: The Open-Access, Open-Assessment E-Journal*.
- Bistline, J and SK Rose, 2018. Social Cost of Carbon Pricing of Power Sector CO_2: Accounting for Leakage and Other Social Implications from Subnational Policies, *Environmental Research Letters* 13 014027.
- National Academies of Sciences, Engineering, and Medicine (2017). *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Committee on Assessing Approaches to Updating the Social Cost of Carbon, Board on Environmental Change and Society, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. doi: 10.17226/24651.
- Rose, SK, 2012. The role of the social cost of carbon in policy. *WIREs Climate Change* 3:195–212. doi: 10.1002/wcc.163.
- Rose SK and J Bistline, 2016. *Applying the Social Cost of Carbon: Technical Considerations*. EPRI Report #3002004659 (Palo Alto, CA), http://epri.co/3002004659.
- Rose, SK, 2017. *Carbon Pricing and the Social Cost of Carbon.* Discussion Paper. EPRI, Palo Alto, CA. 3002011391.
- Rose, SK, DB Diaz, GJ Blanford, 2017. Understanding the Social Cost of Carbon: A Model Diagnostic and Inter-Comparison Study, *Climate Change Economics* 8 (2). doi: 10.1142/S2010007817500099.
- USG Interagency Working Group on Social Cost of Carbon, 2015. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, July.
- USG Interagency Working Group on Social Cost of Carbon, 2016. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, August.

ELECTRIC POWER RESEARCH INSTITUTE

Thank you!

Steven Rose, Senior Research Economist

Energy & Environmental Analysis Research Group

srose@epri.com, (202) 257-7053

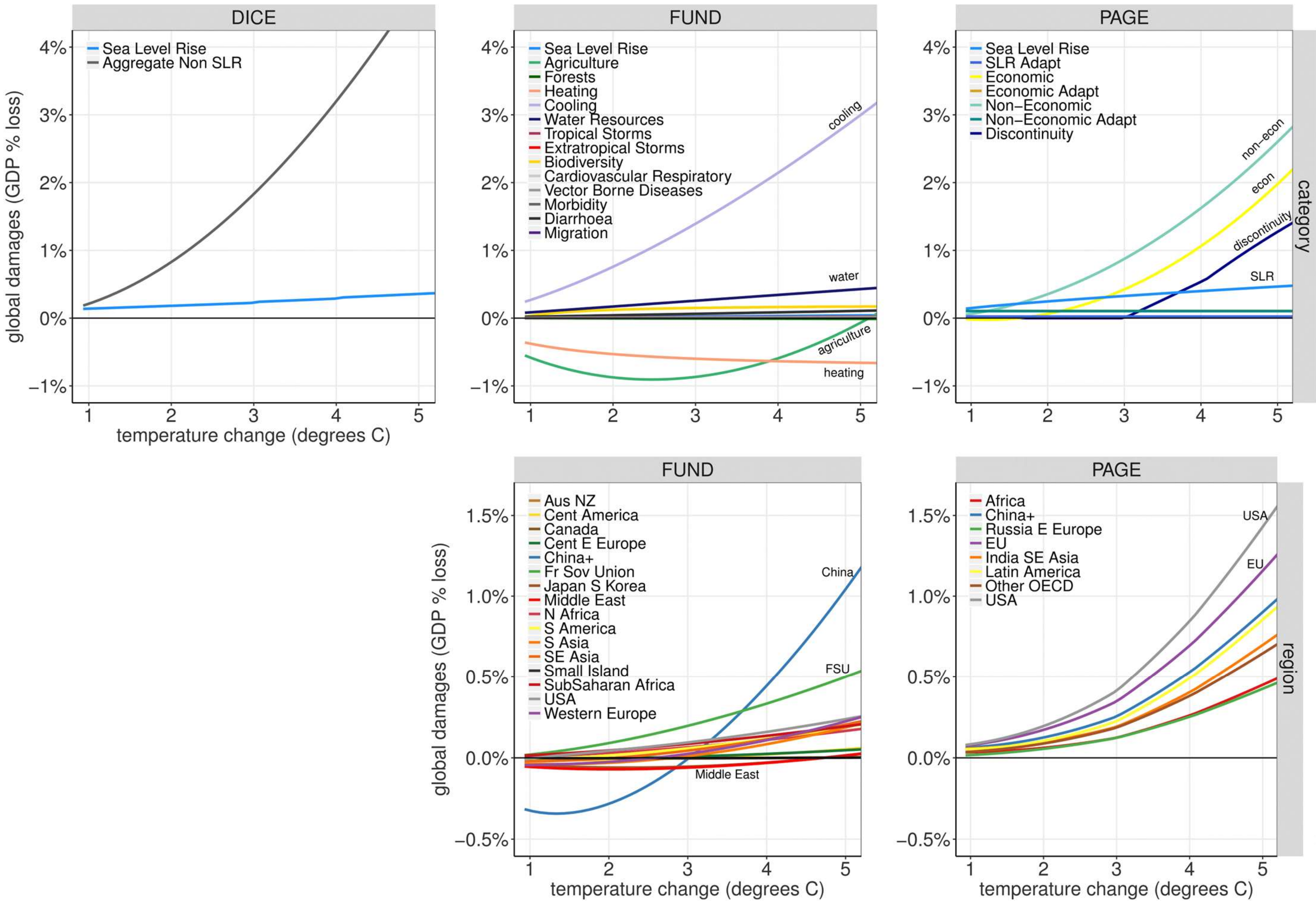
Damage Specifications Literature Basis

All formulations based on older climate impacts literature, with some formulations based on those from the other models

Model (version)	Damage category	Study	Basis	Links to SCC models
DICE (2010)[a]	Aggregate non-SLR	IPCC (2007), Tol (2009)[b]	Calibration	DICE, FUND, PAGE
	SLR coastal impacts	Undocumented		
FUND (v3.8)	Agriculture	Kane *et al.* (1992), Reilly *et al.* (1994), Morita *et al.* (1994), Fischer *et al.* (1996), Tsigas *et al.* (1996)	Calibration	
		Tol (2002b)	Income elasticity	
	Forestry	Perez-Garcia *et al.* (1995), Sohngen *et al.* (2001)	Calibration	
		Tol (2002b)	Income elasticity	
	Energy	Downing *et al.* (1995, 1996)	Calibration	
		Hodgson and Miller (1995)	Income elasticity	
	Water resources	Downing *et al.* (1995, 1996)	Calibration	
		Downing *et al.* (1995, 1996)	Income elasticity	
	Coastal impacts	Hoozemans *et al.* (1993), Bijlsma *et al.* (1995), Leatherman and Nicholls (1995), Nicholls and Leatherman (1995), Brander *et al.* (2006)	Calibration	
	Diarrhea	WHO Global Burden of Disease (2000)[c]	Calibration	
		WHO Global Burden of Disease (2000)	Income elasticity	
	Vector-borne diseases	Martin and Lefebvre (1995), Martens *et al.* (1995, 1997), Morita *et al.* (1994)	Calibration	
		Link and Tol (2004)	Income elasticity	
	Cardiovascular and respiratory mortality	Martens (1998)	Calibration	
	Storms	CRED EM-DAT database,[d] WMO (2006)	Calibration	
		Toya and Skidmore (2007)	Income elasticity	
	Ecosystems	Pearce and Moran, (1994), Tol (2002a)	Calibration	
PAGE (2009)	SLR	Anthoff *et al.* (2006)[e]	Calibration and income elasticity	FUND
	Economic	Warren *et al.* (2006)[f]	Calibration	DICE, FUND, PAGE
	Noneconomic	Warren *et al.* (2006)	Calibration	DICE, FUND, PAGE
	Discontinuity	Lenton *et al.* (2008), Nichols *et al.* (2008), Anthoff *et al.* (2006), Nordhaus (1994)[g]	Calibration	DICE, FUND
	Adaptation costs	Parry *et al.* (2009)	Calibration	

Rose et al (2017)

Implied Category & Region Damages with Warming



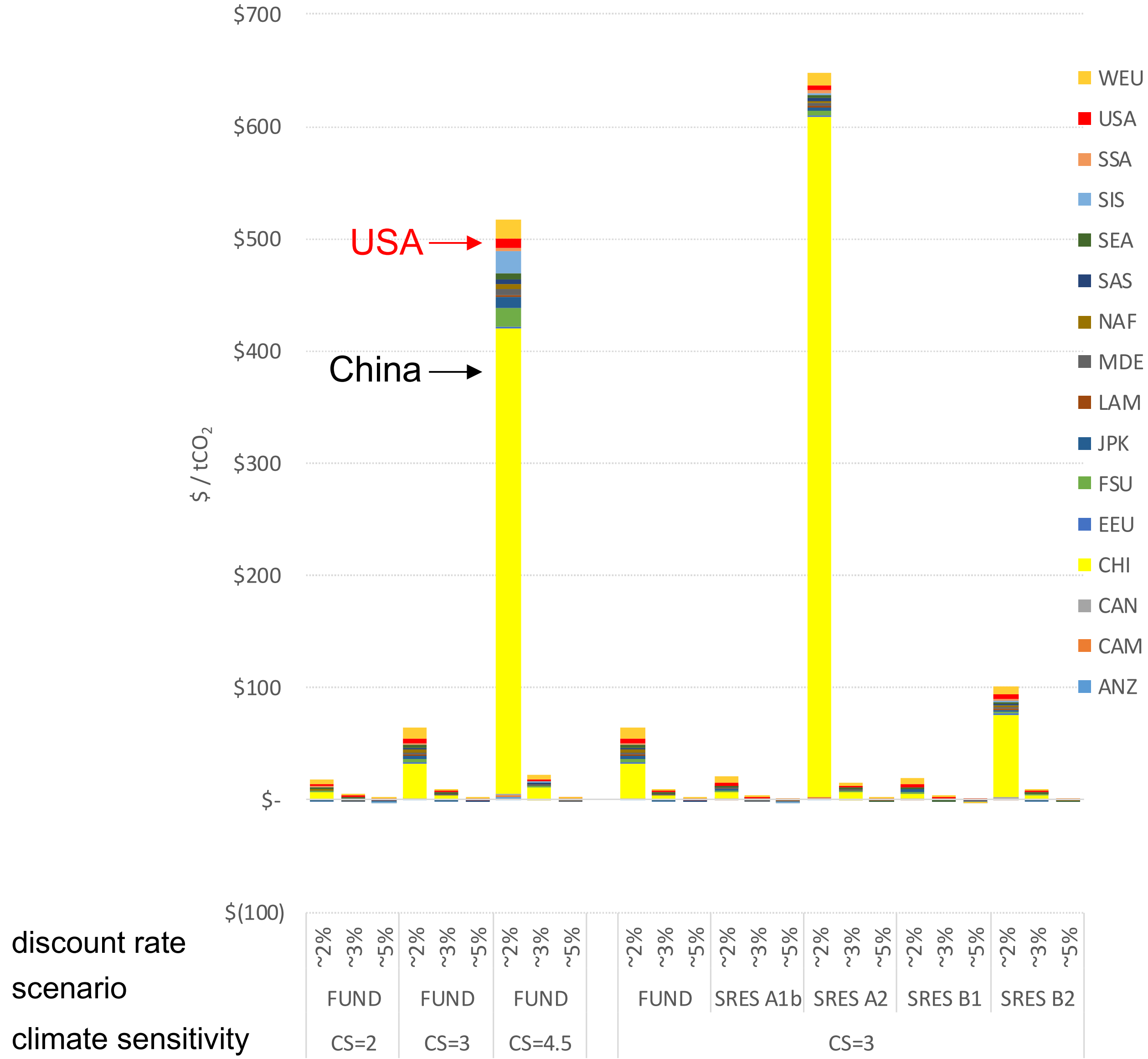
Damages driven by model-specific features (e.g., DICE quadratics; FUND benefits, cooling, China; PAGE noneconomic, discontinuity, regional scaling)

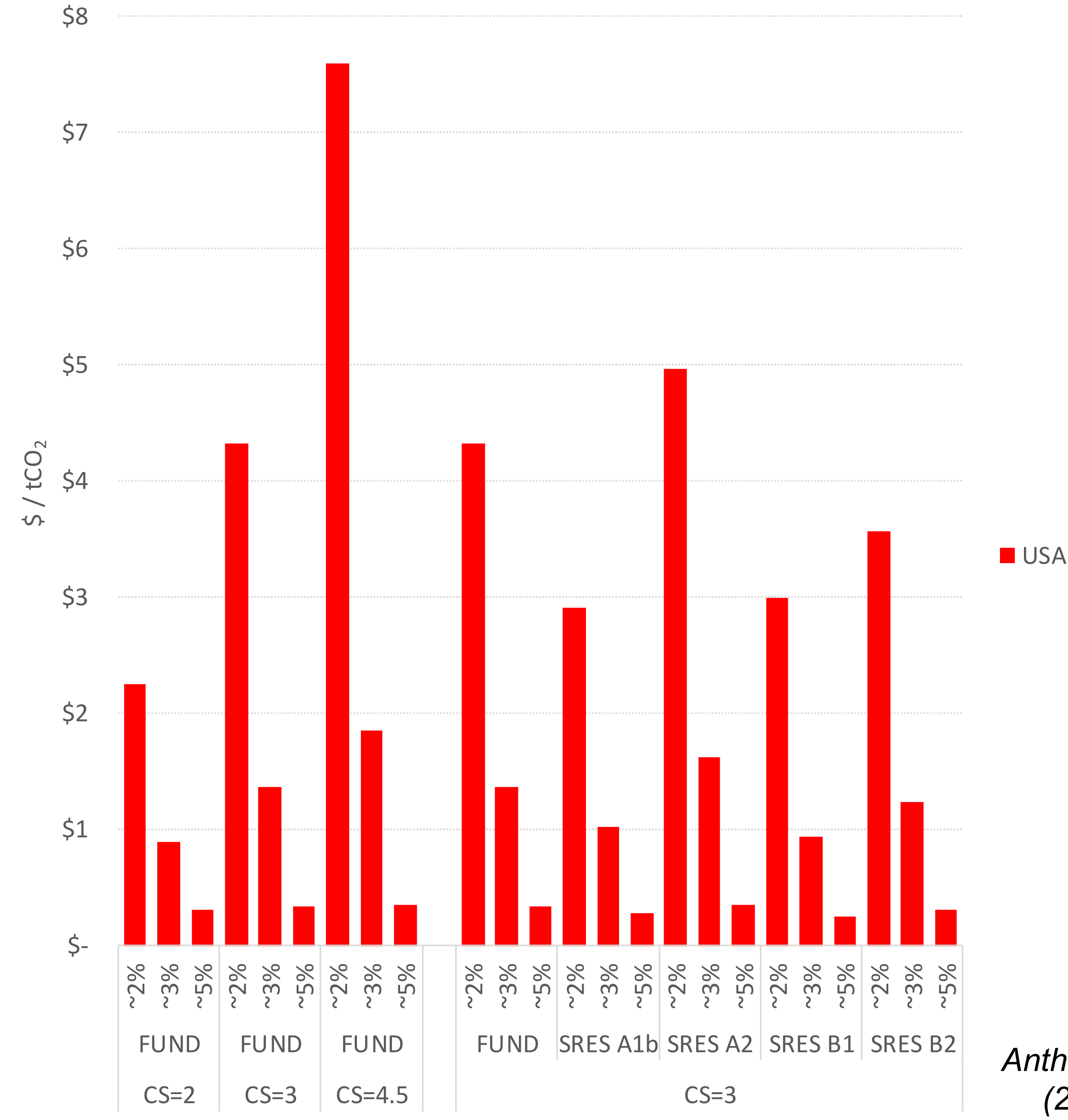
Rose et al (2017)

ELECTRIC POWER RESEARCH INSTITUTE

Estimates of the Social Cost of Carbon for the U.S.

Regional SCCs for 2010 with varying assumptions, 2006$ (derived from Anthoff et al, 2011 & FUNDv3.5)





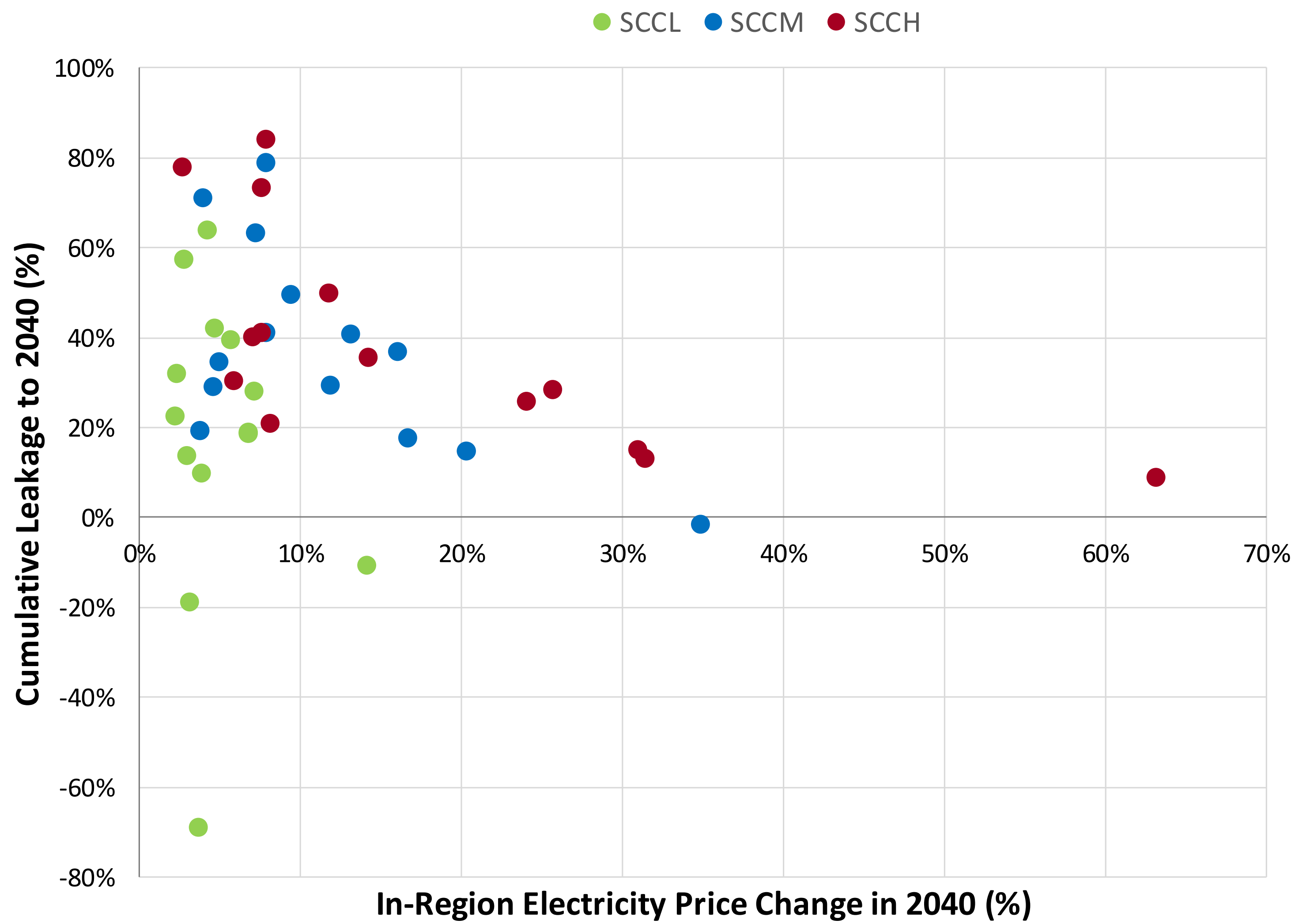
Anthoff et al (2011)

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Need to Estimate Net Global CO_2 Changes

- Do we need to revise CO_2 benefits estimates?
- Yes, if there is expected to be significant CO_2 leakage beyond the regulated segment
- X% leakage = X% lower CO_2 benefits!

E.g., Estimated CO_2 leakage and electricity prices changes with subnational SCC pricing of power sector CO_2



Bistline and Rose (2018)

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Which SCC Should be Used?

Example range of CO_2 reduction benefits using the four USG SCC trajectories (CPP)

	Rate-Based Approach		
	2020	2025	2030
Climate Benefits [b]			
5% discount rate	$0.80	$3.1	$6.4
3% discount rate	$2.8	$10	$20
2.5% discount rate	$4.1	$15	$29
95th percentile at 3% discount rate	$8.2	$31	$61

Order of magnitude difference in estimated climate benefits. Which one to use?

What do they represent? Current SCC range not a representation of uncertainty.

Guidance needed.

Table ES-1: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

US Government (2015, 2016)

NAS notional alternative for improved SCC uncertainty communication

	Discount Rate								
	5.0%			3.0%			2.5%		
Year	Low	Avg.	High	Low	Avg.	High	Low	Avg.	High
2020	–	–	–	–	–	–	–	–	–
2025	–	–	–	–	–	–	–	–	–
…									
2050	–	–	–	–	–	–	–	–	–

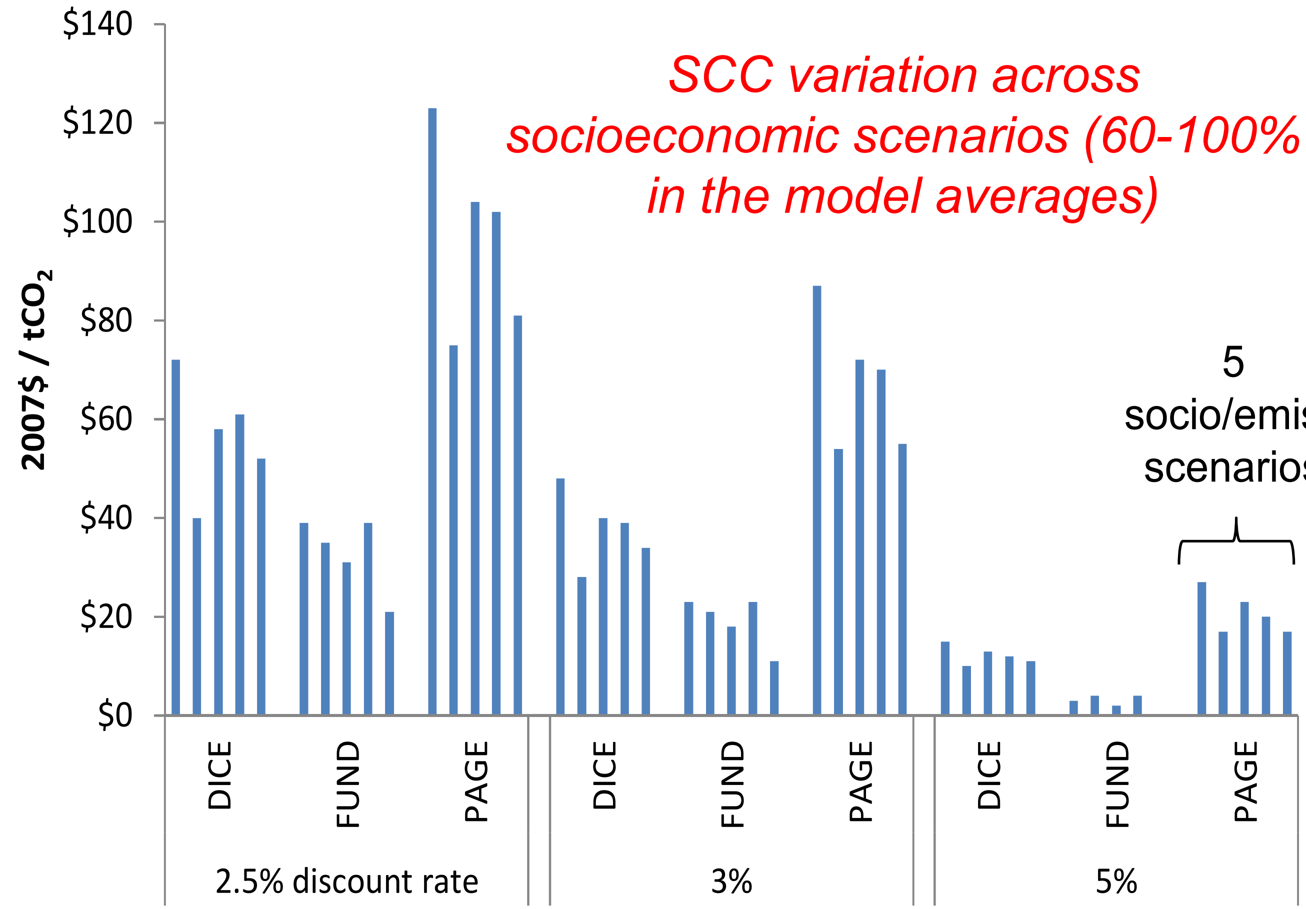
Source: National Academies of Sciences, Engineering, and Medicine. (2016)

Rose and Bistline (2016)

Inconsistency in Reference Assumptions & Uncertainty

Socioeconomic/emissions assumptions matter for the SCC. May matter for other cost-benefit calculations also.

Average 2020 USG SCCs by discount rate, model and socio/emissions scenario



Rose and Bistline (2016)

Exhibit 3

Climate Change Economics, Vol. 8, No. 2 (2017) 1750009 (28 pages)

DOI: 10.1142/S2010007817500099

UNDERSTANDING THE SOCIAL COST OF CARBON: A MODEL DIAGNOSTIC AND INTER-COMPARISON STUDY*

STEVEN K. ROSE†, DELAVANE B. DIAZ and GEOFFREY J. BLANFORD

Energy and Environmental Analysis Research Group
Electric Power Research Institute (EPRI)
Palo Alto, CA 94304, USA
†*srose@epri.com*

Accepted 12 May 2017
Published 9 June 2017

The social cost of carbon (SCC) is a monetary estimate of global climate change damages to society from an additional unit of carbon dioxide (CO_2) emissions. SCCs are used to estimate the benefits of CO_2 reductions from policies. However, little is known about the modeling underlying the values or the implied societal risks, making SCC estimates difficult to interpret and assess. This study performs the first in-depth examination of SCC modeling using controlled diagnostic experiments that yield detailed intermediate results, allow for direct comparison of individual components of the models, and facilitate evaluation of the individual model SCCs. Specifically, we analyze DICE, FUND, and PAGE and the multimodel approach used by the US Government. Through our component assessments, we trace SCC differences back to intermediate variables and specific features. We find significant variation in component-level behavior between models driven by model-specific structural and implementation elements, some resulting in artificial differences in results. These elements combine to produce model-specific tendencies in climate and damage responses that contribute to differences observed in SCC outcomes — producing PAGE SCC distributions with longer and fatter right tails and higher averages, followed by DICE with more compact distributions and lower averages, and FUND with distributions that include net benefits and the lowest averages. Overall, our analyses reveal fundamental model behavior relevant to many disciplines of climate research, and identify issues with the models, as well as the overall multimodel approach, that need further consideration. With the growing prominence of SCCs in decision-making, ranging from the local-level to international, improved transparency and technical understanding is essential for informed decisions.

Keywords: Social cost of carbon; social cost of greenhouse gases; climate change; carbon cycle; impacts; damages.

*This article contains supplementary material (SM) available on the journal website. The supplementary information includes a modeling overview for the US Government approach, structural details for individual models, standardized inputs for our diagnostic experiments, additional results from our analyses, and a summary of the literature underlying damages specifications.

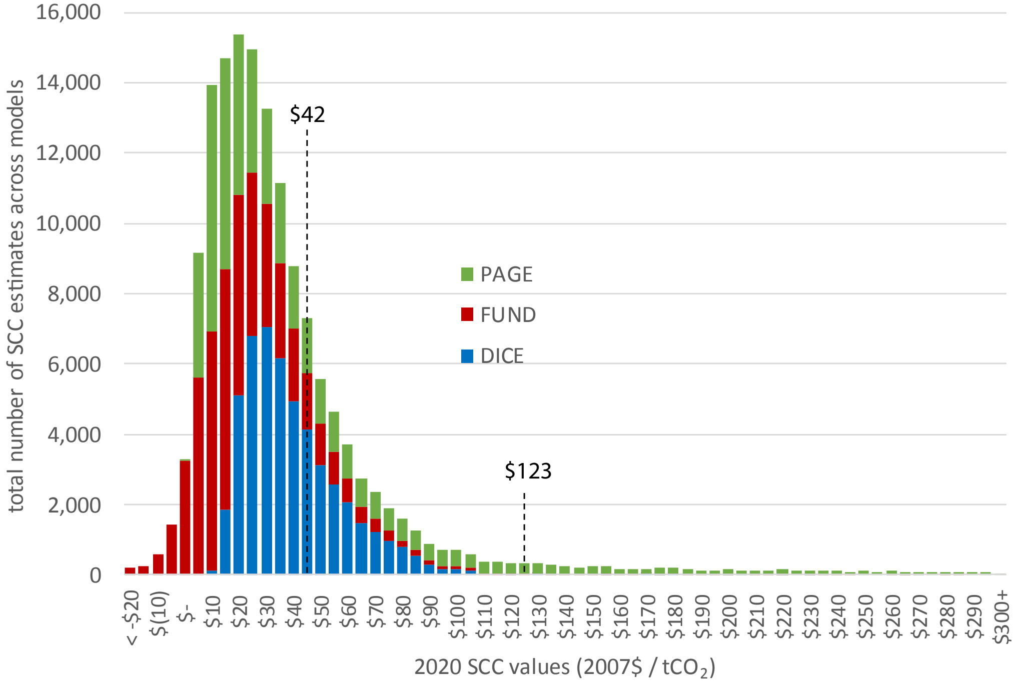
1. Introduction

The social cost of carbon (SCC) is defined as the incremental monetized global damages arising from an additional unit of CO_2 emitted to the atmosphere. It is also referred to as the social cost of CO_2. It is socially important as an estimate of the global damages of CO_2 emissions, and practically important for policy-making. For instance, United States Government (USG) agencies are now legally required to value CO_2 emissions in rulemakings to assess the potential benefits of CO_2 reductions from regulations, including rules affecting appliances, vehicles, and industry.[1] Furthermore, SCC estimates, frequently the USG estimates, are increasingly being applied or considered at state (e.g., Colorado, Maine, Minnesota, New York) and local levels, as well as by other countries (e.g., Canada). The USG developed its own SCC estimates for use in rulemakings, first in 2010 and then revised in 2013 and 2015 with significantly higher estimates (USG Interagency Working Group on Social Cost of Carbon, 2010, 2013, 2015, 2016). However, little is known or available about the modeling underlying current estimates, making them difficult to interpret or assess.

The SCC is typically estimated using an integrated assessment model (IAM) to simulate a "causal chain," starting with projected socioeconomic futures, and their greenhouse gas emissions, followed by projected resulting climate change and climate damages for both a reference and a CO_2 pulsed emissions trajectory (Fig. S1). The SCC associated with a CO_2 pulse in a particular year is the discounted value of the future annual incremental damages off of the reference trajectory. To date, only a few IAMs, those with more aggregate economic structures and damage components, have generated SCC estimates.

The USG estimates were derived from a complex approach using three IAMs well known in the SCC literature: DICE (Nordhaus, 2010), FUND (Anthoff and Tol, 2013), and PAGE (Hope, 2011). While each of these models has been applied individually to estimate the SCC — indeed, most published estimates are from versions of these models — the USG approach was novel in its experimental design, running multiple models tens of thousands of times each with standardized and model-specific uncertainties, standardized discounting, and a procedure for aggregating the results and selecting values. Through this approach, the USG produced SCC estimates to apply to the estimated emission changes in current and future years from 2010–2050. Underlying each official USG SCC is a wide range of estimates, with a frequency distribution of 150,000 estimates (50,000 from each model). For CO_2 emitted in 2020, for instance, the current USG estimates have a central value of \$42/tCO_2 (\$2007), with alternate estimates of \$12 to \$123/tCO_2 corresponding to different discount rates and likelihoods, and behind each are 150,000 estimates (USG Interagency Working Group on Social Cost of Carbon, 2015, 2016). For an overview of the USG experimental design, see Table S1 in the Supplementary Material (SM).

[1]Center for Biological Diversity versus National Highway Traffic Safety Administration, United States Court of Appeals for the Ninth Circuit, No. 06-71891, November 15, 2007.



Notes: The figure combines the 50,000 2020 3% discount rate estimates from each of the three USG models to illustrate their influence on the aggregate histogram that determines the official USG SCCs for 2020 at 3% — the average ($42) and 95th percentile ($123).

Figure 1. Histogram of the 150,000 USG SCC estimates for 2020 with a 3% discount rate with estimates from the individual models identified.

A USG estimate is the result of significant aggregation: aggregation within a model — over time, world regions, damage categories, and uncertain inputs and parameters — and aggregation across models. This aggregation obscures the underlying details and drivers of results within models, as well as variation and inconsistencies across models. For example, decomposing the 150,000 SCC results for a given discount rate and emissions year by model (Fig. 1), we immediately observe significant differences in the role each model is playing in the official USG SCC values (the 3% discount rate average and 95th percentile values of $42 and $123/$tCO_2$).[2] Estimates from FUND alone represent the left tail of the distribution, while PAGE's estimates define the long right tail, and DICE generates a more compact SCC distribution with no negative values and a right tail that contributes to a higher average.

Figure 1 provides a necessary, but insufficient, first step — a first order decomposition of the role of the models in the USG aggregation. To truly understand and assess the results, we need to know what is driving each model's distribution. Despite

[2]Figure 1 developed from USG data available at https://www.whitehouse.gov/omb/oira/social-cost-of-carbon. Also see USG Interagency Working Group on Social Cost of Carbon (2015, 2016).

the increasingly widespread use of the USG SCC estimates in policy, little is known or available regarding these details and intermediate results, making the values difficult to interpret and evaluate in terms of implied climate risks to society — types and locations over time. Moreover, no study to date has undertaken a direct comparison of the modeling underlying the SCC estimates. With SCC estimates based explicitly on this multimodel approach shaping US policy, and that of states and other countries, understanding the modeling and differences, and the opportunities for and implication of aggregating across models, is essential.

This study presents the first in-depth examination, comparison, and assessment of the three models underlying the USG estimates, as well as the overall multimodel approach. We conduct a model diagnostic and inter-comparison exercise with systematic, independent analyses of the major components of the modeling causal chain: socioeconomics and emissions, climate, and damages. We review model code, program and run components, and isolate and evaluate differences within each component with standardized inputs and diagnostic scenarios that reveal component behavior — undiscounted and disaggregated. These analyses elucidate model dynamics behind the SCC that are not reported — intermediate and disaggregated variables such as projected climate and damages over time, regions and categories, as well as characterizations of sensitivity. We generate and evaluate deterministic and probabilistic results for both reference outcomes and incremental responses. Our component assessment findings allow us to then reflect on the overall USG approach. We therefore conclude with a final assessment of the USG SCC experimental design.

The intent of this analysis is not to assess whether the USG estimates are accurate, nor is it to re-compute the SCC. Instead, the objective is to provide the community of policy-makers, stakeholders, and scientists greater technical clarity on the state-of-the-art for SCC and global climate damage estimation. Other issues, such as omitted impact categories and biases (e.g., Howard, 2014; Tol, 2009; IPCC, 2007), USG SCC development process (e.g., US GAO, 2014), equity weighting and low intergenerational discounting (e.g., Johnson and Hope, 2012) are beyond the scope of this study. Our focus is on understanding, evaluating, and improving the modeling currently in place, which is a requisite first step before many of these other issues can be broached. Furthermore, while we are analyzing particular versions of the models used for the most recent USG estimates, our perspectives and insights apply to other SCC modeling, other applications of these models (e.g., social cost of other greenhouse gases),[3] and discussions of aggregate climate risks and goals. With this analysis, we hope to establish a new common analytical ground for moving forward — improving public and scientific understanding, informing future estimation and use, and identifying climate impacts and climate damages research priorities.

[3]USG Interagency Working Group on Social Cost of Greenhouse Gases (2016).

2. Methods

Our analysis is based on versions of the three models as used by the USG, versions that have been modified in important ways from the standard versions found in the literature. See Rose *et al.* (2014) for details. We evaluate the socioeconomic and emissions, climate, and damage components of each model separately, reviewing model structure and input assumptions, recoding the component in a consistent programming language, running standardized diagnostic scenarios, and comparing the raw results. We run reference and CO_2 pulse experiments to reveal behavior. Incremental pulse responses are relevant because SCCs are an estimate of *additional* damages from an incremental climate response. Total responses are equally important, as they define the reference conditions for marginal damages and allow for direct comparison to other analyses. Across models, there is variation at each component step that would normally propagate through the causal chain. However, we standardize the inputs for each component assessment to isolate component behavior. We evaluate model behavior from numerous perspectives — total/incremental, deterministic/probabilistic, aggregated/disaggregated, reference and sensitivities, and to 2100 and 2300. Some perspectives are in the main paper, many are in the SM.

For the climate component, we evaluate reference paths for temperature and other intermediate climate variables for the USG experiments high and low emissions and non-CO_2 forcing scenarios (Table S3). We then re-evaluate each scenario with a CO_2 emissions pulse to calculate the incremental response in each climate variable. We use a standardized incremental emissions pulse of 1 billion metric tons of carbon in 2020. In the USG exercise, the emissions pulse in a given year *t* was implemented inconsistently by the three models in terms of shock size and how it was introduced over time. For our diagnostics, we standardize the pulse size, but retain the model-specific implementations with respect to time (Table S2 and Fig. S8).[4] We also run the USG climate components and a more sophisticated model, MAGICC6, with Representative Concentration Pathway (RCP) emissions projections (Meinshausen *et al.*, 2011; van Vuuren *et al.*, 2011). See Table S3 for RCP inputs. For the damage component in all three models, we use as inputs the DICE reference and incremental temperature projection results for both the high and low USG emissions from our climate component analysis, and the corresponding socioeconomic projections (Figs. S13 and S14).

We begin our component analyses running each component with central parameter values to understand the fundamental nature of each model and reveal differences in sensitivity and the shape of responses. To learn about the uncertainty being modeled, we also develop probabilistic versions of the climate and damage components of the models and run them with random draws over their model-specific parametric spaces. For the probabilistic analyses with FUND and PAGE, we sample independently over each model's uncertain climate and damage component parameters with 2500 Latin

[4]This is a large pulse (roughly 10% of current global emissions). The climate response appears to scale proportionally with the pulse size, but the many facets of a climate response to pulse size should be explicitly studied in the future.

Hypercube draws. The USG exercise used 10,000 random samples and Monte Carlo and Latin Hypercube sampling for FUND and PAGE, respectively; we use Latin Hypercube sampling for both models, which allows us to use fewer draws while still representing the full sample space. For comparison, using RCP emissions inputs, we also run MAGICC6 probabilistically, and the USG climate components with both model-specific and ECS uncertainties.[5]

3. Socioeconomics and Emissions Component

The marginal damages of emissions today are conditional on assumptions about the future evolution of natural and economic systems, beginning with the assumed future global populations, economies, and emissions over the next three centuries. With such a large scope, uncertainty clearly needs to be considered. Our assessment of this component explores the following questions: (1) What sort of socioeconomic and emissions uncertainty is currently represented in the USG exercise? (2) Is there additional uncertainty to consider? and (3) Are results sensitive to alternative assumptions? In this section, we consider the first two questions through comparison to the literature. The third question is discussed, but not explicitly explored until subsequent component assessments.

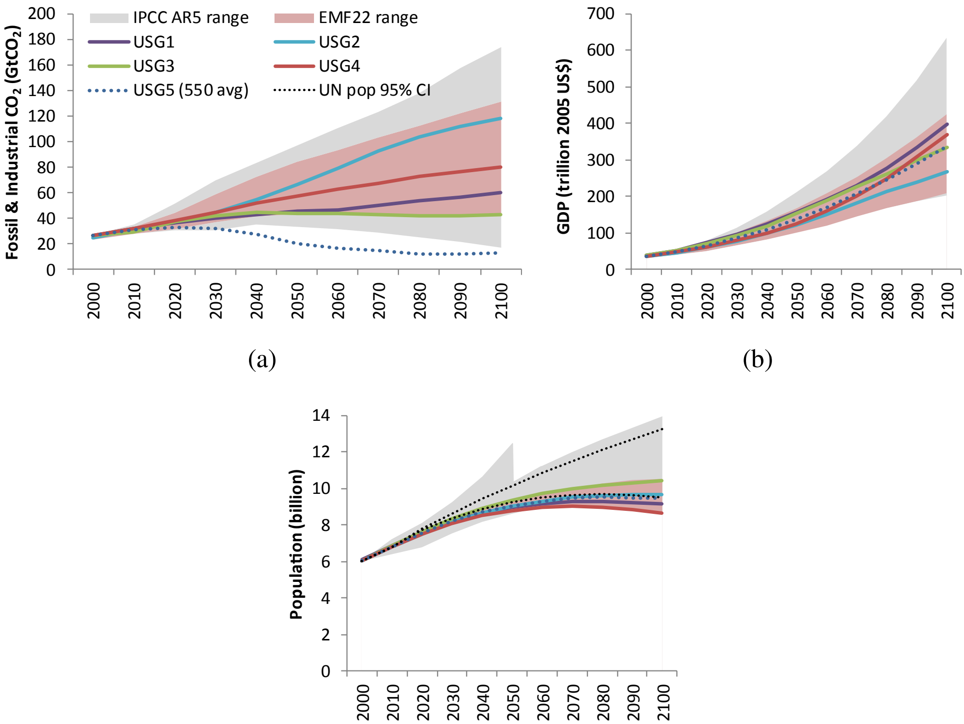
In the USG SCC calculations, socioeconomic and emissions uncertainty is represented via five alternative futures — four "baseline" with no assumed future climate policy (USG1-4) and one "policy" future (USG5) described as consistent with stabilizing atmospheric concentrations at 550 ppm CO_2e. Each future consists of a set of projections to 2100 for gross domestic product (GDP), population, fossil and industrial CO_2 emissions (F&I CO_2), land CO_2 emissions, and non-CO_2 emissions and/or radiative forcing (USG Interagency Working Group on Social Cost of Carbon, 2010). These are then extended in a very stylized way by the USG to 2300.

Through comparison to the literature and evaluation of the relationships between variables, we find opportunities for improving consideration of uncertainty. Overall, we find that some socioeconomic and emissions uncertainty are captured. However, it is not comprehensively or rigorously characterized, and some are artificial due to implementation inconsistencies.

Specifically, we find that the five scenarios span some uncertainty, but are narrowly focused on uncertainty in a single variable — global F&I CO_2 emissions — from one particular study (Clarke *et al.*, 2009). The four baseline scenarios span the F&I CO_2 emissions range in the selected study (Fig. 2). However, the range is broader when one fully considers the scenarios literature (Clarke *et al.*, 2009, 2014), and the policy scenario cannot alone represent uncertainty about policy pathways.[6] The five scenarios, therefore, are not reflective of the full range of uncertainty about future emissions.

[5]We ran MAGICC6 probabilistically from magicc.org using the default set-up (Meinshausen *et al.*, 2009).

[6]The policy scenario has an additional issue in that it is not internally consistent. It was constructed by averaging variables independently from four other scenarios.



(a) (b) (c)

Notes: Some projections run to 2050. The policy scenario (USG5) is shown for comparison. Literature ranges are from Clarke *et al.* (2009, 2014) and United Nations (2015).

Figure 2. Baseline global fossil and industrial CO_2, GDP, and population for USG SCC futures and literature ranges.

Consideration of uncertainty in the other variables is also essential, e.g., Clarke *et al.* (2014) for GDP and United Nations (2015) for population ("IPCC AR5" and "UN 95% CI" in Fig. 2 respectively), as is consideration of uncertainty in socioeconomic structure that determines emissions from a future society. For instance, the emissions–socioeconomic relationships in the current projections are arbitrary (e.g., USG2 exhibits high emissions with slow economic growth and USG3 exhibits low emissions with high growth). Uncertainty in socioeconomic structure, such as the energy intensity of economic growth and emissions intensity of that energy, is relevant for projecting emissions, but also for estimating damages, which are sensitive to socioeconomic levels. Finally, weighting of scenarios is important. The USG exercise implicitly assigns 20% likelihoods to each scenario. No formal process was undertaken to develop probabilities for the five futures. While it is, in general, difficult to assign such probabilities, it is possible to recognize unlikely or less likely futures (such as high emissions for centuries and emissions inconsistent with global trends), and there are methods for developing defensible distributions using historical ranges, parametric uncertainty, and expert elicitation. Note that, consistency, uncertainty, and likelihood are also issues for the USG extensions to 2300 (Rose *et al.*, 2014).

The representation of socioeconomic and emissions uncertainty is not only a function of the specification of the inputs, but also how the inputs enter the models. For instance, within the code, we find inconsistency in input implementation that results in differences in what is standardized, exogenous, and even included. For example, DICE and PAGE include more complete sets of non-CO_2 radiative forcing constituents than FUND. FUND excludes some elements of forcing, which drive temperature. In addition, the socioeconomic inputs are represented differently in each model. These implementation differences result in artificial differences in projected climate and damages. See Tables S2 and S3 for model implementation details and Rose *et al.* (2014) for additional discussion.

Overall, our component assessment provides perspectives for the enhanced representation of socioeconomic and emissions uncertainty. Our findings suggest that the USG consideration of uncertainty is incomplete and the distributional specification ad hoc, with additional uncertainty to consider, in both the projected variables currently included and the relationship between variables. With a more comprehensive and rigorous specification, we would expect different posterior distributions of SCC estimates from each model. Unfortunately, it is impossible to know the exact implications for SCC values without developing an improved specification and doing the modeling. Our findings also imply that some of the uncertainty represented in the current USG estimates derives from implementation inconsistency that is not indicative of scientific uncertainty. For example, the specific forcing constituents omitted from the FUND modeling generate an upward bias in FUND's climate projections and SCC estimates. Finally, as shown in the next two sections, each model's climate and damage projections are sensitive to alternative socioeconomic/emissions assumptions, with a more comprehensive consideration of uncertainty likely to have a larger impact on the distribution of SCC results from DICE and PAGE.

4. Climate Modeling Component

Each model includes its own reduced-form climate module for translating projected emissions into global mean temperature (GMT) change. Each module estimates CO_2 concentrations and radiative forcing, includes equations or assumptions for non-CO_2 concentrations and radiative forcing, and derives GMT from total radiative forcing and equilibrium climate sensitivity (ECS).

Our assessment of the climate component explores the questions: (1) How do the climate models underlying SCC calculations behave, and are they similar? (2) What do the incremental climate responses look like from each model, and are they similar? and, (3) How do the USG SCC model responses compare to more detailed climate models? Uncertainty in climate system dynamics is also important and we dedicate a later section to the modeling of climate and damage uncertainty.

First, from evaluating the code, we observe that the climate module structures and specifications vary substantially across models, as does their implementation in the USG approach (Table S2). As discussed below, we find that both are contributing to differences in projected levels of global warming. For instance, inconsistencies extend beyond the radiative forcings included, noted in the previous section, to climate feedbacks modeled, the relationship of ECS to other parameters, modeling of parametric uncertainty (discussed in uncertainty section), and the implementation of the incremental CO_2 pulse.

For our diagnostics, we begin by running the climate components with standardized inputs — the USG high and low emissions projections — to explore reference pathway responses. As shown in Fig. 3 and the SM, we find substantial variation across models in all aspects of projected climate: carbon cycle (Fig. 3(a)), translation of concentrations to forcing and the constituents of forcing (Figs. S4(a,b)–S6(a,b)), and temperature dynamics as a function of forcing (Fig. 3(c)). For example, by 2100, projected GMT results vary by 1°C in the higher emissions reference scenario, and by 0.5°C in the lower emissions reference. For SCC estimates, this matters, as the models are evaluating marginal damages relative to different reference warming levels.

For the high emissions scenario, DICE and PAGE project significantly greater warming than FUND. However, in deriving projected temperatures, it is PAGE that has the lowest projected CO_2 concentrations, CO_2 forcing, and total forcing. Behind this shift in ordinal ranking are pronounced differences between models in the translation of total forcing to temperature. In particular, a long temperature lag assumption in FUND results in a more gradual development of temperature, while PAGE's temperature responds more quickly to the ECS parameter than the other models (discussed below), resulting in a large temperature response to forcing. Importantly, some of the variation in results is driven by the differences in model structure and the USG implementation, differences that may be artificial.

From our sensitivity analysis, we gain insights into the responsiveness of the models to uncertain emissions and input assumptions, which helps us to further understand the distribution of SCC estimates from each model. Specifically, our sensitivity analysis reveals FUND to be the least sensitive to alternative projected emissions (Fig. 3(c)), as well as the ECS (Fig. S7). DICE's temperature projections are the most sensitive to alternative emissions projections, as are the DICE projected CO_2 and total forcings, while PAGE's temperature projections are significantly more sensitive to alternative ECS values than the other models.

ECS is a key uncertain parameter, and there are differences in how ECS affects the temperature transition in each model. To ensure consistency with historical temperature observations, an increase in ECS should be accompanied by both faster ocean heat uptake (or in simple models, a slower response rate of average surface temperature) and larger negative aerosol forcing (e.g., Urban *et al.*, 2014). DICE and FUND adjust the temperature response rate, and DICE further includes a moderating ocean feedback. PAGE, however, does not include any countervailing adjustments, and consequently its temperature results are significantly more sensitive than those from the

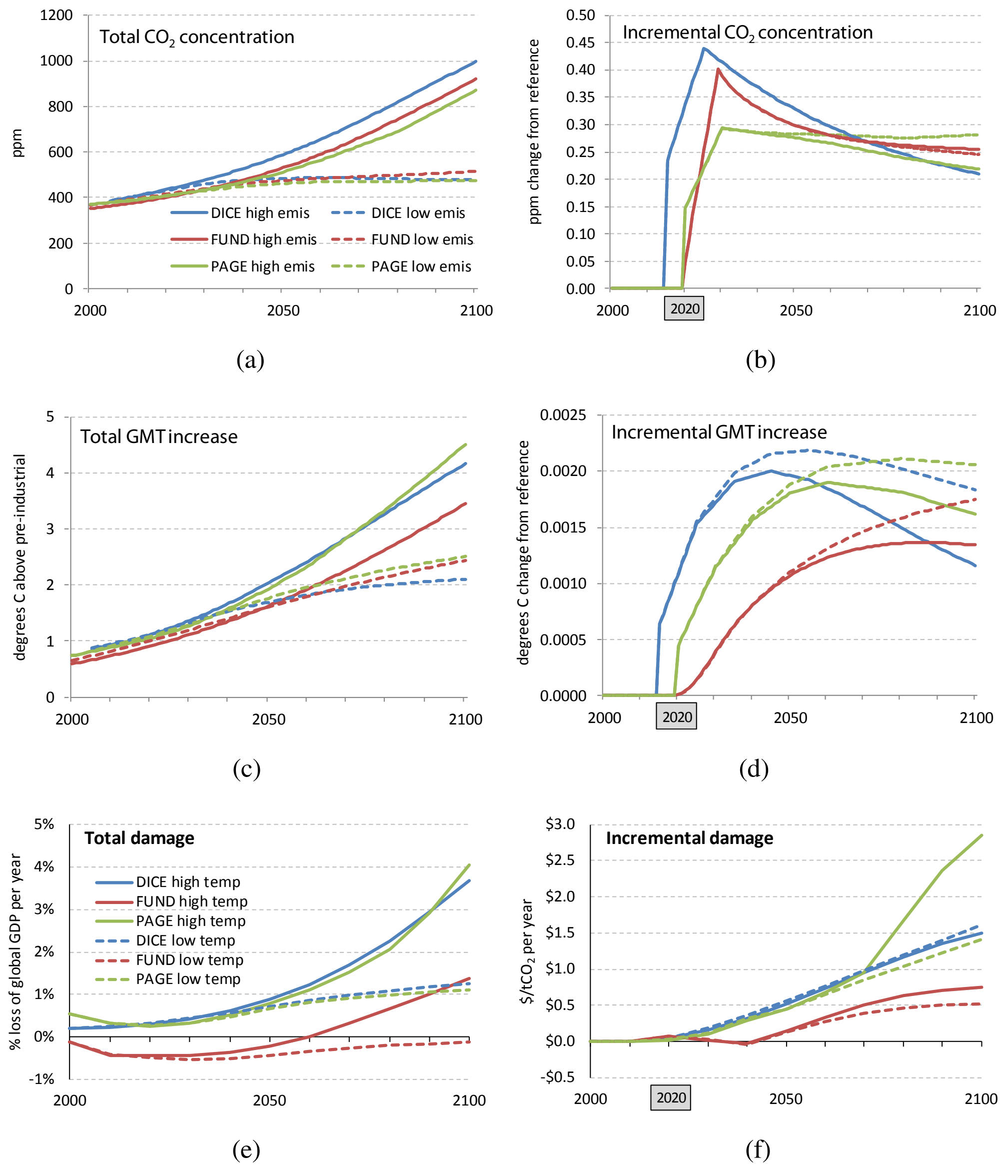


Figure 3. ((a), (b)) Total and incremental responses in CO_2 concentrations and ((c), (d)) GMT increase with standardized emissions inputs, and ((e), (f)) global damage responses with standardized temperature and socioeconomic inputs. See Figs. S2, S3, S9, S10, S17, and S22 for results through 2300.

other models (Fig. S7). Note that, none of the models currently adjust aerosol forcing for alternative ECS values.

Next, we evaluate incremental responses with our 2020 CO_2 pulse experiment (Methods). In general, we find incremental GMT responses that peak and decline with atmospheric decay of the pulse from all the models, but with significantly different timing, levels, and rates entering into damage and SCC calculations (Figs. 3(d) and S10 for results to 2300). Levels diverge by as much as a factor of two in 2050, with DICE producing an earlier and higher peak, followed by PAGE, and both well above the incremental GMT response from FUND. In Fig. 3(d), we also observe that all the models exhibit higher incremental temperature responses from scenarios with lower emissions due to the concavity of the logarithmic function for CO_2 forcing (see Fig. S11(a,b) for forcing responses).

The differences in the incremental pathways derive from differences in component structure, as well as pulse implementation. Inconsistency in the implementation of the pulse between models, with variation in how the pulse is spread over years (Fig. S8), results in DICE and PAGE producing incremental climate effects in 2020 higher than they would be otherwise (Figs. 3(b) and 3(d)).

We also observe carbon cycle response differences due to the treatment of feedbacks to terrestrial and ocean carbon uptake. DICE includes no feedbacks, making its incremental CO_2 concentration response insensitive to the emissions scenario, while FUND and PAGE include feedbacks, but with responses that exhibit different signs and absolute magnitudes (Figs. 3(b) and S9 for results to 2300). PAGE's slower carbon cycle is also evident in a significantly lower CO_2 concentration spike that is ultimately offset by the strength of its conversion of forcing to temperature. Meanwhile, FUND's higher concentration spike is offset by its slow temperature response. Finally, the sensitivity of incremental GMT responses to emissions and ECS assumptions is consistent with what we observed for total GMT.

For comparison, we conducted the same pulse experiment in MAGICC, a more sophisticated climate model designed to emulate complex earth system models. Using two alternative carbon cycle representations, we find similarities in the *reference* temperature projections between MAGICC and the USG models, but also notable differences in initial levels and rates of change (Fig. S12). Most relevant to the SCC, we find substantial differences in the *incremental* climate response (Fig. 4). In MAGICC, atmospheric decay begins immediately after the pulse, leading to a much earlier peak in incremental temperature than in the USG models (especially FUND), and the decline following the peak is slower, in particular when emulating models with stronger temperature feedbacks. Additional evaluation is merited, but the MAGICC pattern for the incremental response appears to be more consistent with complex models (Joos *et al.*, 2013).

From our component assessment, we conclude that the modeling and implementation of the climate system is very different across models. These are differences that affect results and need justification, with some not indicative of structural uncertainty (e.g., pulse implementation, carbon cycle feedback, forcing constituents). These differences impact projected incremental temperature responses and ultimately SCC estimates. FUND's more modest and less sensitive temperature responses are contributing to lower SCCs and a more compact SCC distribution; PAGE's higher, earlier, and more sensitive temperature responses contribute to higher SCCs and a wider range

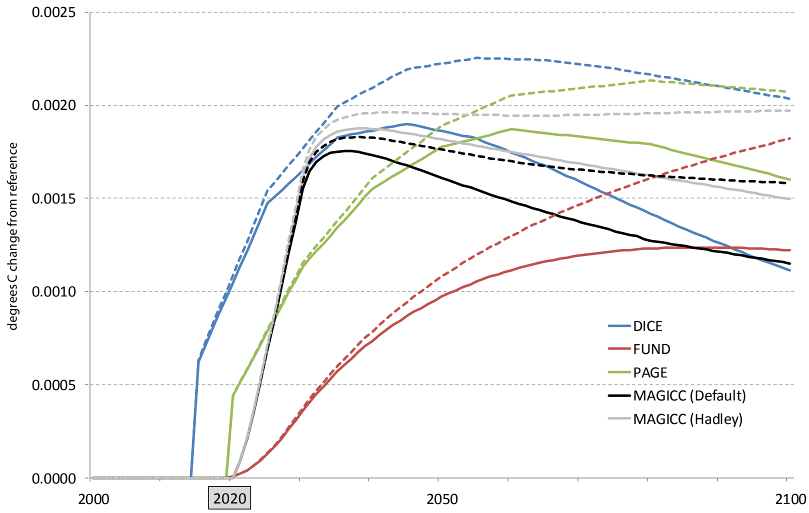


Figure 4. Incremental responses in GMT to 2100 for MAGICC versus the USG models with standardized RCP emissions inputs (RCP8.5 solid, RCP3-PD dashed).

of temperature projections and SCC values, including PAGE's prominence in the right tail of the SCC distribution (Fig. 1); and, DICE's higher and earlier temperature responses contribute to higher SCCs, but without a climate feedback, DICE's SCC distribution is more compact ceteris paribus. Finally, we note that the higher incremental temperature response off a lower emissions pathway contributes to a higher SCC, though it is a combination of factors, including damages, that determine whether the resulting SCC is higher or lower.

5. Climate Damages Modeling Component

These three IAMs are among the few available models for monetary valuation of global climate damages. As an aggregate metric, an SCC is not particularly intuitive or easily interpreted: it encapsulates damages projected to occur at different points in time, in different regions of the world, and for different types of impacts. The official USG SCCs are not only an aggregation of damages within models, but also across models and scenarios. Understanding, evaluating, and comparing SCC estimates requires the raw undiscounted and disaggregated damage outcomes over time from the individual models, and alternative model runs. These intermediate results, however, have not been made available until now. Our assessment of the damage component fills this gap and explores the following questions: (1) What are the detailed constituents of damages underlying SCC calculations? (2) How sensitive are the damage estimates to alternative assumptions and formulations? and (3) How do damage estimates respond incrementally to a marginal change in emissions?

We begin by evaluating the damage component formulation of the models. Each model estimates global damages by calculating some degree of disaggregated damages, with substantial variation across models in structure, specification, and implementation (Table S2). For example, DICE is globally aggregated with two categories of damages as a fraction of GDP increasing quadratically with GMT and sea level rise (SLR), respectively; while, FUND derives damages for 16 regions and 14 damage categories that respond to a broader set of drivers such as regional temperatures, temperature rate of change, CO_2 concentrations, population, income, and technological change; and, PAGE estimates damages for eight regions and four categories, including a generic discontinuity impact, with more drivers than DICE but fewer than FUND. While global damage results can be readily compared between the models, the differences in the region-category resolution of damages limit us to a few sub-global comparisons. It is worth noting that, even a highly aggregate damage structure, through its calibration, has implied patterns of damages in terms of damage locations and types for different levels of warming. This information, however, is not discernable from current documentation.[7] Going forward, these kinds of details are critical for transparency and evaluation.

Compiling and evaluating the literature basis for the damage specifications (Table S4), we find the models relying directly and indirectly on older studies that do not reflect current knowledge of climate impacts (e.g., Field *et al.*, 2014). This is, in part, because the more recent literature is not readily usable for this application. Moreover, we find interdependencies among the models, with DICE and PAGE specifications based on damage estimates from previous DICE, FUND, and PAGE results. This issue is discussed later.

For our diagnostics, we begin by running the damage components with standardized high and low GMT projections and socioeconomic inputs (Methods). Despite the major structural differences in damage components, DICE and PAGE project very similar global annual damages over the century, both substantially higher than those from FUND, which projects net benefits for much, or all, of the next century (Fig. 3(e)). By 2100, the models differ in annual damages by as much as a factor of three, with differences growing beyond 2100 due to more rapid growth in damages from DICE and PAGE (Fig. S17). Numerous factors contribute to the very different perspectives on the potential damages for a given climate and society, including intermediate projections, functional forms, individual damage categories, and other model idiosyncrasies. For instance, we find that for the same GMT projection, intermediate outputs of SLR and regional temperatures vary significantly, with FUND projecting up to twice the SLR by 2100 as DICE and PAGE, and PAGE's temperature pattern-scaling producing notably warmer regions than FUND's (Figs. S15 and S16(a,b)). Below, we disaggregate damages and discuss the contributions of other factors.

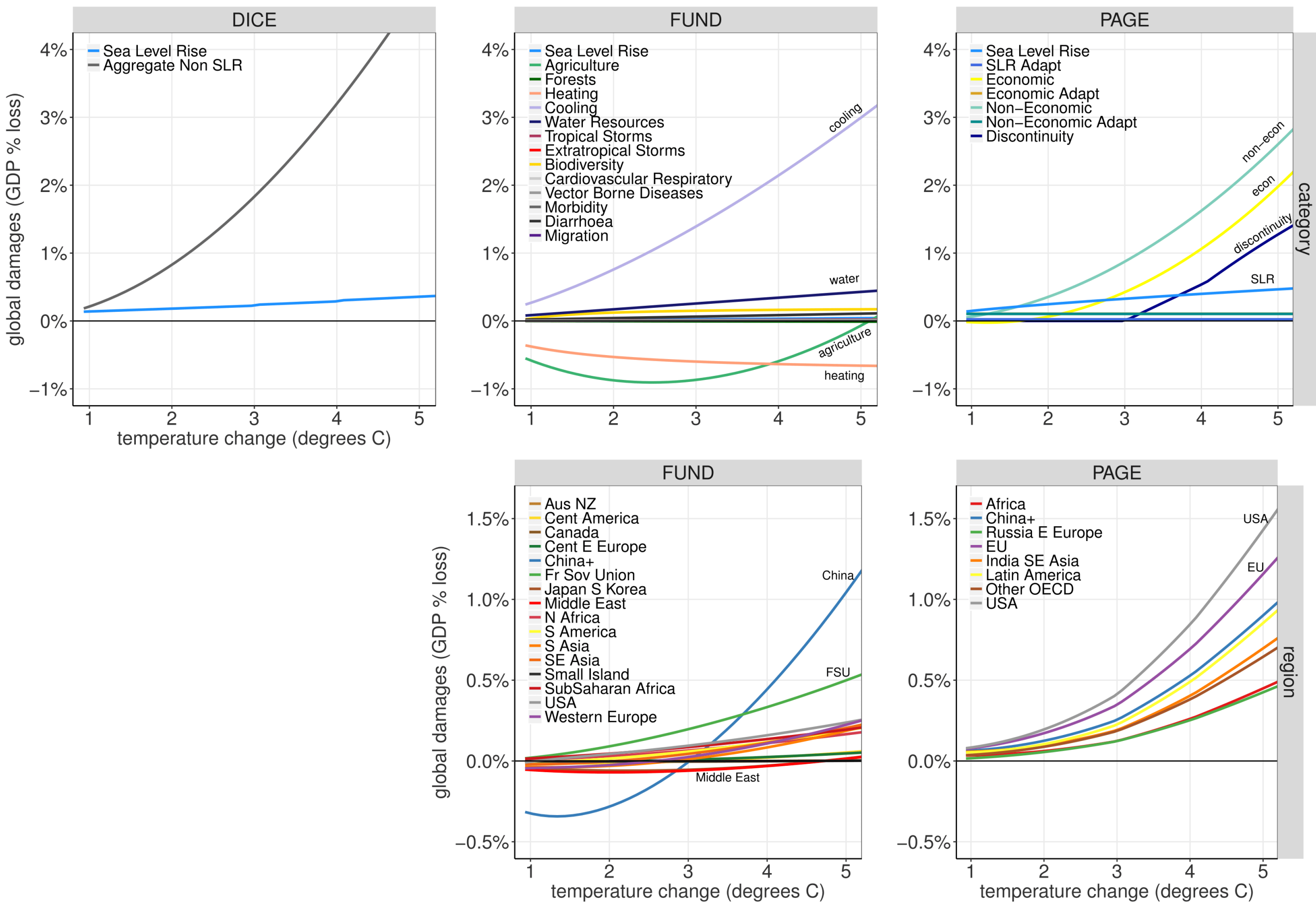
[7]For instance, National Academies of Sciences, Engineering, and Medicine (2017) noted that DICE damages at the global level have been updated and calibrated to meta analyses, but the assumed region and category structure of damages are still based on earlier work by Nordhaus and Boyer (2000).

The slopes of the implied damage functions of temperature are particularly relevant for the SCC, as they indicate the marginal damage response to incremental temperature change. We tease these out by scaling our GMT input projection. We find that across categories, regions, and models, damages differ in responsiveness to warming, including differences in sign (damage versus benefit). Figure 5 presents damages by category and region as a function of temperature with a fixed 2050 society. Overall, the models provide very different damage pictures in terms of potential benefits and costs, damage locations, and rate at which damages might increase with warming. For DICE, non-SLR damages accumulate most quickly (quadratically) with warming. For FUND, the dominant damage responses (positive and negative) are increased cooling costs, avoided heating costs, agriculture net benefits up to 5°C warming, and water resource damages. For PAGE, SLR and noneconomic damages are the most responsive at lower levels of warming, while noneconomic and economic damages are the most responsive at higher warming levels, with the expected damage from the discontinuity rising steeply beyond 3°C of warming. Interestingly, the cost of adaptation in PAGE is constant, small, and unresponsive to temperature. Note that damages that accumulate over time (e.g., SLR) are not captured by these experiments (more below).

The different model aggregations make direct comparison across models challenging. SLR damage is the only damage category present in all three models. In this case, FUND projects the least amount of SLR damage, despite projecting more SLR for a given temperature. Aggregating FUND and PAGE damage categories into harmonized economic and noneconomic groupings, we find that PAGE's economic and noneconomic damages dwarf FUND's, with the economic damages sometimes differing in sign (Fig. S19).

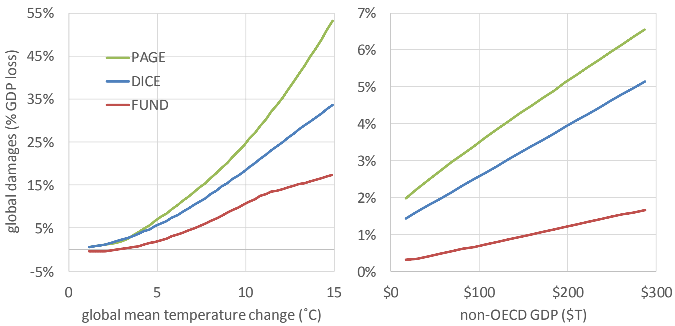
Regarding regional damages, the responses are fundamentally different in FUND and PAGE (Fig. 5). FUND projects net benefits for a few regions of the world, even up to 4.5°C GMT rise, while PAGE projects net damages for all regions and levels of warming. Developing regions dominate FUND's damages, while developed regions dominate PAGE's, especially at lower temperatures, and significantly exceed the developed region damages from FUND (Fig. S20(a)). In FUND, China dominates the overall response, switching from net benefits to net damages around 3°C, driven by the country's damage coefficients, elasticity parameters, and income and population growth. Note that regional damage responses in PAGE grow proportionally by construction, as regional damages (SLR and non-SLR) are scaled off EU damages based on relative coastline, with a small adjustment for per capita income (Hope, 2011). FUND, on the other hand, calibrates regional damage functions that respond uniquely to warming.

From additional sensitivity experiments, we find that damages are responsive to income, as well as temperature (Fig. 6), and that some models are systematically more or less sensitive. Damages increase with temperature and income in all the models; however, DICE and PAGE damages increase most quickly, with PAGE the most responsive to both drivers, and FUND the least responsive to both. Globally, damages are relatively unresponsive to population size, with FUND and PAGE



Notes: *y*-axis' ranges vary between top and bottom figures. USG2 socioeconomics in 2050 — global GDP $123 trillion, global population 9 billion.

Figure 5. Total climate damages by category (top) and region (bottom) as a function of GMT increase for 2050 with USG2 socioeconomics.



Notes: For each chart, only a single driver is varied from the standardized USG2 conditions in 2100 (2100 values: global GDP $268 trillion, non-OECD GDP $162 trillion, global population 9.6 billion, GMT above preindustrial 4°C).

Figure 6. Implied global damage functions with respect to GMT change, non-OECD income, and global population (y-axis' ranges vary).

exhibiting only slight positive correlations. This is, in part, because of how population enters each model, as well as smaller projected relative damages for categories with more direct population ties (e.g., health).[8] In all models, the absolute value of damages increases with income simply because there is more to affect (i.e., exposed society); however, FUND projects increasing net benefits when there are low levels of warming, and damages respond differently to income in rich versus poor countries, moderated by regional dynamic vulnerability (i.e., resiliency as a function of per capita income). See Figs. S18 and S21(a,b) for additional results.

Next, we examine incremental damages, the additional damages from a standardized pulsed temperature pathway versus a reference (Methods). We find that, despite a decaying incremental temperature input, annual incremental damages increase over time in all models due to income growth and rising reference temperatures (Figs. 3(f) and S22 for results to 2300). The differences in incremental annual damages are a reflection of the different damage gradients we observed above. Rising temperatures and incomes result in larger marginal increases in damages in DICE and PAGE. In addition, PAGE's incremental damages rise sharply with a marginal increase in expected discontinuity damages. Meanwhile, incremental annual damage growth declines notably over time in FUND as income growth reduces vulnerability.

To highlight prominent features in the pattern of incremental damages over time in each model, we develop a custom region-category disaggregation of incremental annual damages (Fig. 7). In DICE, incremental non-SLR damages dominate through 2100, but incremental SLR damages, which accumulate over time, become the primary

[8]Our population sensitivity analysis scales global population growth with the regional distribution fixed. Future analysis should consider sensitivities on the distribution of growth. In DICE, population enters as an input to total factor productivity, income, and the capital stock. In FUND, population defines per capita income and is an explicit input into the following damage categories: water resources, energy consumption, ecosystems, human health damage categories, and tropical storms. In PAGE, population defines per capita income, which is an input into each of the damage categories in the model.

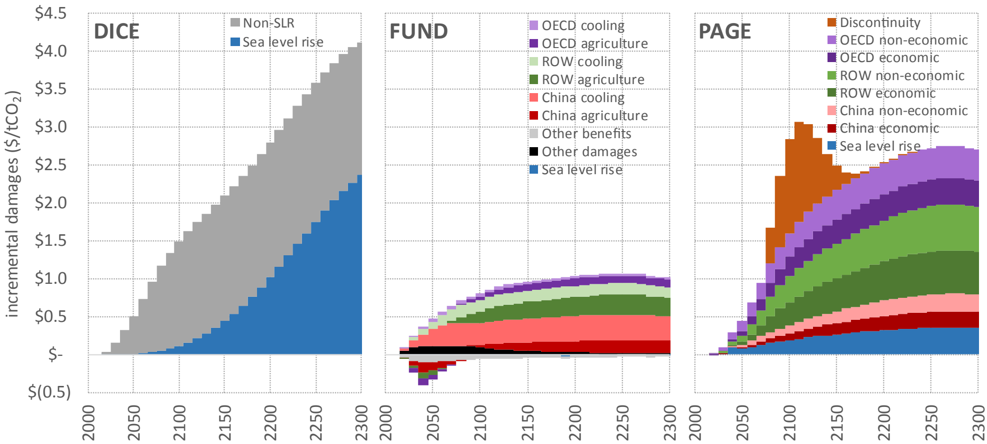


Figure 7. Key factors of annual incremental global climate damages to 2300 with the standardized high temperature and USG2 socioeconomic inputs.

annual damage by 2300. Yet in FUND, incremental SLR damages are almost nonexistent, while incremental cooling (damages) and agriculture (benefits then damages) dominate, with China accounting for approximately half of cumulative incremental damages. In PAGE, incremental noneconomic and economic damages are more consequential than SLR (with its sublinear functional form), and incremental discontinuity damage with its 3°C GMT threshold arrives slightly earlier due to the additional CO_2 from the emissions pulse. Incremental damages in developed countries (OECD) dominate PAGE's damages through 2050, but are eventually surpassed by annual developing country damages. To 2100, roughly half of PAGE's incremental damages occur in developing countries, compared to 80% in FUND, with incremental damages in China much larger in FUND than in PAGE. Cumulatively through 2300 (Fig. S20 (b)), the leading incremental damage category-region combinations in FUND are cooling in China (33% of incremental damages), followed by agriculture in China and South Asia (9%, 6%). In PAGE, they are noneconomic damages in Latin America, China, and the US (8%, 7%, 6%), followed by economic damages in Latin America, China, and India (all 6%).

From this component assessment, we conclude that damage component modeling varies substantial across models with key features contributing to higher or lower SCC values and different SCC distributions. For instance, damages in FUND are less responsive than in the other models to two primary drivers of damages — temperature and income — due in part to lower regional temperatures, agriculture and heating benefits, and adaptation responses. These elements contribute to lower SCCs and tighter SCC distributions. Damages in DICE and PAGE, on the other hand, are more responsive to the drivers due in part to assumed net damages for all levels of warming, income, and population, higher regional temperatures (PAGE), explicit or implicit functional forms with higher exponents, less prominent adaptation, unspecified discontinuity damages (PAGE), and regional scaling of damages (PAGE). These elements contribute to higher SCCs and broader SCC distributions.

6. Model-Specific Uncertainty

Results to this point in our study reflect calculations based on the models' central parameter values and sensitivity analysis with inputs and the ECS parameter. Recall, however, that the models were run probabilistically in the USG exercise. Our review of the probabilistic specifications of the models finds that parametric uncertainty is handled quite differently across models. Specifically, the USG experimental design specifies standardized ECS uncertainty for all models, but the FUND and PAGE climate and damage components are also run with their native parametric uncertainty. For FUND, there are 11 and over 400 independent general and regional uncertain parameters in the climate and damages components, respectively, for PAGE, 10 and 35, respectively, and for DICE, none. The specific uncertain parameters in FUND and PAGE differ, as does the assumed distributional specifications, with triangular distributions assumed for all PAGE parameters, and various distributional forms assumed in FUND (see Table S2 for details on the different types and specifications of parametric uncertainty). As discussed in Methods, we develop and run probabilistic versions of the climate and damage model components to learn about the uncertainty modeled.

In the climate component, we find substantially larger climate uncertainty and higher central tendencies being represented and projected through 2300 in PAGE than in FUND (Fig. 8). Indeed, the 90% confidence interval, 5th to 95th percentiles, for incremental GMT change in 2050 from PAGE is 30 times wider than FUND's, with PAGE producing higher annual mean increases in incremental temperature. Re-running the USG climate components with RCP inputs and model-specific and ECS uncertainties, we can compare to probabilistic results from MAGICC. MAGICC has an alternative characterization of parametric uncertainty with 82 uncertain parameters (Meinshausen *et al.*, 2009). Comparing to the resulting MAGICC temperature distribution for the high emissions scenario (RCP8.5), we find FUND suggesting significantly less uncertainty and risk, and PAGE significantly more (Fig. 9). Interestingly, the DICE distribution is the most closely aligned with MAGICC, however the DICE distribution represents only ECS uncertainty. Comparing results for the low emissions scenario (RCP3-PD), we find that all the USG models suggest very different temporal profiles and significantly more uncertainty than MAGICC. Note that in Fig. 9, we are comparing 66% confidence intervals, which is all that was available for the online version of MAGICC. The tails are clearly important to SCC calculations and should be further explored.

In the damage component, we find FUND representing and projecting more uncertainty than PAGE in annual incremental damages through 2100, and less beyond (Fig. 8). The broader first century distribution in FUND is driven by uncertainty in cooling, agriculture, and water resource damages in China, South Asia, and South America, while the primary uncertainty drivers in PAGE are noneconomic and

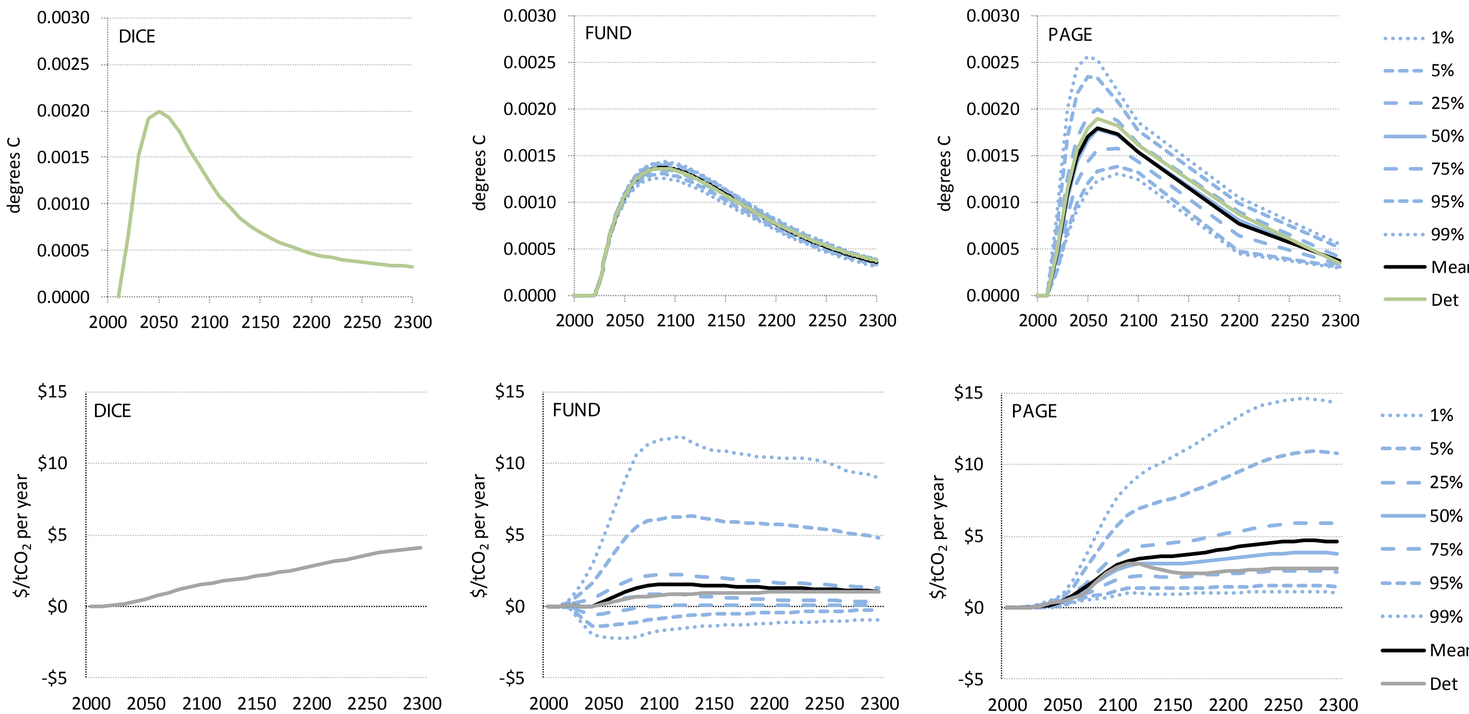


Figure 8. Probabilistic incremental annual GMT (top) and global damage (bottom) responses to 2300 (percentiles, mean, and deterministic result) for model specific uncertainties with respective standardized high inputs.

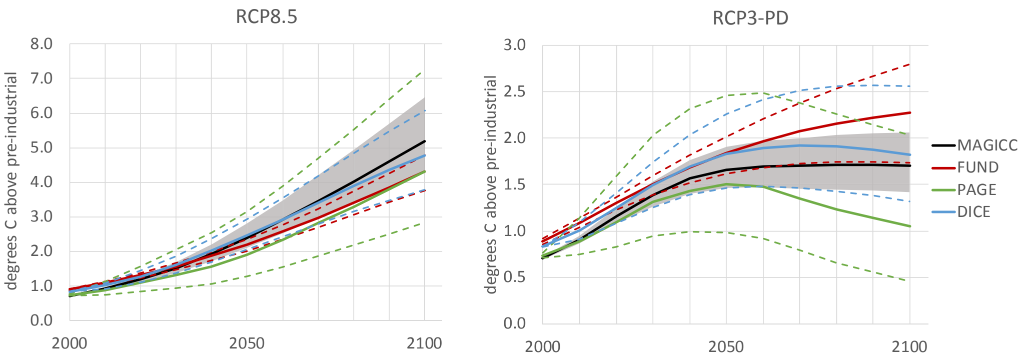


Figure 9. Probabilistic GMT to 2100 for MAGICC versus the USG models with standardized RCP emissions inputs (solid = median, dashed = USG model 17th–83rd percentile, shaded = MAGICC 17th–83rd percentile. *y*-axis' vary.)

economic damage in China, Latin America, and India (Rose *et al.*, 2014). We note that some FUND and PAGE parameter combinations lead to annual damages equal to or greater than 100% of the economy for some regions at higher levels of warming, which can mean a regional annual incremental damage effect of zero.[9] Whether the magnitudes of reference losses projected by the models make sense is a topic onto its own and beyond the scope of this study. Throughout the time horizon, PAGE produces higher annual mean incremental damages, a point germane because the USG aggregation approach emphasizes means. There are, unfortunately, few examples in the literature of uncertainty distributions over climate damages, for a given climate and society, to which the FUND and PAGE ranges can be benchmarked. A systematic study of damage uncertainty based on the current impacts literature is a key research need.

From our assessment of model specific uncertainties, we conclude that there is inconsistency across models in the representation of parametric uncertainty. Furthermore, the PAGE formulations yield both higher average incremental temperatures and damages. From Fig. 8, we also note that the average results differ from the deterministic results, with similar to slightly lower average annual incremental temperatures and clearly larger average annual incremental damages. However, average incremental temperature projections can exceed deterministic outcomes when we include ECS uncertainty, with the effect strongest in PAGE. These findings, in addition to the tendencies identified earlier from our deterministic experiments, contribute to wider PAGE SCC distributions with larger right tails, and higher average estimates.

[9]FUND enforces a 100% maximum on total economic damages, but not on the sum of economic and noneconomic damages. PAGE has separate saturation approaches for economic and noneconomic damages that does not explicitly limit total damages to less than 100% of the economy. One justification given for greater than 100% losses is that noneconomic damages can push total damages above income levels (Anthoff and Tol, 2013). In this case, noneconomic damages should not be interpreted as willingness to pay estimates, which are budget constrained.

7. Summary of Component Assessment

The component assessments above have identified differences in model structure and behavior, and revealed model tendencies that help us interpret SCC results. Our independent component assessments have isolated and elucidated differences across models in intermediate projections, sensitivity, and implementations — socio-economics, emissions, CO_2 concentrations, radiative forcing, temperature, regional temperatures, SLR, and the magnitude and composition of damages. We found that some differences are artificial, and all the differences need justification. Most importantly, we found tendencies in intermediate results due to component modeling elements that contribute to differences in the observed SCC outcomes between models. For instance, we found FUND producing the lowest incremental temperature and damage responses, and having more muted sensitivity than the other two models to uncertainties about emissions, ECS, and temperature, as well as responses to income that contribute to a lower average SCC. DICE and PAGE, on the other hand, generated higher and earlier incremental temperature and damage responses, with DICE the most sensitivity to emissions, while PAGE is the most sensitive to ECS and temperature, as well as income at higher levels of warming, and PAGE's parametric uncertainty further contributing to higher incremental temperatures and damages. Together, PAGE's responses combine to yield SCC distributions with longer and fatter right tails and higher averages than the other models. DICE's and FUND's distributions are more compact, and FUND, with the lowest averages, is the only model producing distributions that include the possibility of global net benefits.

8. USG Experimental Design and Discussion

Overall, our component assessments have allowed us to trace SCC differences back to component modeling, and even specific features, which accommodate the evaluation of individual model SCCs in terms of concrete underlying elements. The assessments have also provided comparable details about the models and modeling that allow us to reflect on the overall USG experimental design. To date, SCC estimates in the literature have only been generated by individual models with nonstandardized uncertainties (e.g., Tol, 2009). The USG experimental design, however, is novel — a multimodel, probabilistic approach with standardized and model-specific uncertainties, and an aggregation procedure. The USG experimental design is defined by a set of methodological choices, which we have itemized in Table 1.

Each of these choices can affect results (examples below), and as choices, there are alternatives. It is therefore important that the choices be clearly communicated and scientifically supported for peer and public evaluation. Without such information, it is difficult to interpret results and evaluate the approach. The kind of transparency our study is providing is an example of what would be useful, along with justification. The conceptual motivation behind many of the above choices is pragmatic. For instance, given the geographic and temporal scope of the modeling, uncertainty should be

Table 1. USG experimental design features and choices.

Experimental design feature	USG choices
Model	• Use multiple models • Use DICE, FUND, and PAGE • Modify models from native formulations
Projected socioeconomics and emissions/forcing	• Use partially standardized exogenous alternative socioeconomic and emissions/forcing projection inputs • Use five projection sets based on Clarke *et al.* (2009) • Extrapolate each projection variable from 2100 to 2300
ECS parameter	• Use a standardized ECS parameter value distribution and choose a random sampling procedure
Other input parameters	• Use model specific uncertainty distributions, make assumptions about correlations, and choose a random sampling procedure for various other FUND and PAGE climate and damage component parameters
Discounting	• Use constant discounting • Use three alternative discount rates • Use 2.5%, 3%, and 5%
Model runs and results	For each official USG SCC... • Run each model 50,000 times (with 10,000 random parameter draws for each socioeconomic/emissions projection) • Aggregate results across models into overall distributions by discount rate with equal weighting of models and socioeconomic/emissions projections • Select specific values from the overall distributions (averages for each discount rate, and one 95th percentile)

embraced and incorporated. Considering multiple models, uncertainty in socioeconomic futures, and uncertainty in climate dynamics and damage specifications are examples of doing so. Discounting is also appropriate for aggregating effects over time.

Our component assessments provide us with an intimate understanding of the modeling that allows us to reflect on the overall experimental design and identify opportunities for improvement. Using multiple models is a means for accounting for differences in expert opinion about the structure and dynamics of social, economic, and physical processes. Upfront consideration of different models is prudent, but it also creates challenges regarding transparency, justification, comparability, and independence that need to be considered in deciding whether to select one model, multiple models with a weighting scheme, or to develop a new model.

A multimodel approach in which results are averaged across models and assumptions (with an implicit equal weighting) should be used when each model is generating comparable and unique information. We find, however, fundamental structural, parametric, and implementation differences across the models, in all components, that are artificial rather than a reflection of differences in expert opinion or scientific uncertainty about an element. In addition, the models have significant dependencies, especially in the representation of damages. Review, and possibly modification, of component specification and implementation differences and dependency is an essential future activity for more comparable estimates, which might also provide a model weighting scheme rationale. Such an assessment should, among other things, include evaluation and justification of modeling differences in emissions and radiative forcing, carbon cycles, ECS implementation, climate feedbacks, pulse implementation, empirical bases for damage responses, and parametric uncertainty implementation.

In addition to improving the representation of structural uncertainty, our component assessments identify opportunities for improving the representation of other types of uncertainty. First, the current USG standardized uncertainties could be revised to capture the uncertainty available in the current literature for socioeconomics, emissions, and ECS. There are legitimate alternatives, as well as constraints on what is reasonable and comparable, to consider. Regarding ECS, see Bindoff *et al.* (2013) for updated ECS distribution assumptions, which includes alternative distributions that would allow for explicitly incorporating uncertainty about the distribution itself. Second, there are additional uncertainties that could be included (e.g., socioeconomic structure, 2300 extrapolations, climate modeling specifications). Finally, parametric uncertainty should be clearly characterized and considered across all models to the extent possible.

Our assessments also suggest that the USG estimates could be made more robust (insensitive to alternatives) to provide greater confidence in final SCC estimates. Our component analyses have shown the climate and damage outcomes to be sensitive to, among other things, emissions scenarios, ECS, income levels, parametric uncertainty, and model choice. We have also identified reasonable alternatives to the assumptions and modeling currently in use. As such, future analysis could expand the evaluation and consideration of alternatives consistent with the state of scientific knowledge to increase the robustness of results.

Given our interest in model behavior, we have said little about discounting up to this point. Discounting aggregates model responses over time. Economics can provide guidance given the type of investment and context, but selecting a discounting approach is complicated by many considerations (National Academies of Sciences Engineering and Medicine, 2017; Rose, 2012). One practical analytical issue is consistency with assumed economic growth, with lower (higher) economic growth implying a lower (higher) discount rate; and, uncertainty in economic growth implying uncertainty in the discount rate. The National Academy of Sciences identified this issue as well and recommended an approach to incorporate these elements (National Academies of Sciences Engineering and Medicine, 2017). Note that, while having alternative discounting schemes is practical, it creates a need for guidance on how the set of resulting SCCs should be utilized in regulatory analyses (Rose and Bistline, 2016).

There are many alternatives to the choices associated with the USG experimental design. We have identified some, including input assumptions, climate models, discounting, and model and scenario weighting. Properly evaluating alternatives and comprehensively incorporating uncertainties is a research program onto itself and should be a policy priority. Our analyses have also identified a set of issues (e.g., implementation inconsistencies, arbitrary structural differences, dependence, and specific features needing justification), as well as model tendencies that need further evaluation. Together, these items call into question equal weighting of models and scenarios, and could justify different weighting schemes and/or different modeling altogether. Table 2 illustrates the implications of simply doing the former, weighting the current results differently. Other issues associated with the models and experimental design are still present.

Specifically, for Table 2, we assembled alternative distributions from the 150,000 estimates underlying the 3% 2020 USG SCC values (Fig. 1) by first giving a zero weight to results based on the fifth socioeconomic/emissions projection, which is below current global emissions; and second, varying the weights given to results from individual models, from 100% to 0% weight for a single model with the remaining models weighted equally. The USG official estimates are also shown for comparison ("USG SCCs"). Table 2 includes 5th, as well as 95th, percentile values to provide symmetrical information about the tails of the distributions and better represent the uncertainty (National Academies of Sciences Engineering and Medicine, 2017). The table clearly illustrates the sensitivity of the current USG estimates to the weighting schemes. In particular, the individual models have pronounced roles, with PAGE pulling the multimodel average significantly higher, and DICE and FUND pulling it lower. This dichotomy demonstrates the importance of understanding, communicating, and justifying differences in models, as well as the individual model formulations and tendencies.

Finally, we note that consideration of alternatives to the multi-model approach would be practical. With multiple IAMs, it will always be challenging to ensure comparable and robust results that account for dependency. In the current SCC simulation context, where optimization or equilibrium is not required, one could design a framework component by component, choosing the best approach for each and

Table 2. SCC based on alternative weighting of 2020 3% discount rate USG values.

	USG SCCs	Without 5th socioeconomic/emissions results						
		All	DICE	FUND	PAGE	DICE/FUND	DICE/PAGE	FUND/PAGE
Average	\$42	\$44	\$39	\$21	\$71	\$30	\$55	\$46
5th percentile	—	\$3	\$16	\$3	\$5	\$1	\$7	\$1
95th percentile	\$123	\$130	\$76	\$59	\$297	\$71	\$183	\$183

entertaining uncertainty through a single structure within each component. Such an approach offers full experimental control, statistically comparable results, and greater transparency regarding modeling and uncertainty. Furthermore, the framework could evolve over time with improved understanding of damages and feedbacks.

9. Conclusion

This study elucidates and assesses the modeling and raw detailed results underlying USG SCC estimation. We conduct the first detailed diagnostic and inter-comparison of the models used by the USG and others, isolating the socioeconomic, climate, and damage components, elucidating model structure, and presenting intermediate and comparable outputs not previously available. Together they provide insights into differences in SCC distributions between models. The distribution and average of SCC results from an individual model reflect a combination of responses across the components of the causal chain (recall Fig. 1). Through decomposition and comparison, our analysis provides insights into each model's results and relative differences.

From our detailed results and understanding of model structure, we are able to go even further and identify the key modeling elements behind each model's behavior and results, thereby enhancing understanding and enabling further scientific assessment. Overall, across models, we find significant differences in structure, implementation, and model behavior, and identify fundamental scientific issues with the SCC models and the current USG approach and estimates. The issues point to several opportunities for improving SCC estimation and increasing transparency and scientific and public confidence in results.

Going forward, it is important to communicate, evaluate, and justify differences and address those with insufficient scientific rationale, improve the representation of uncertainty in its various forms and the resulting robustness of estimates, and enhance documentation, including providing intermediate and disaggregated reference and incremental results over time from individual components and models. Taken together, our observations also suggest that the current multimodel approach be reconsidered. Finally, peer review of existing and future frameworks (e.g., models, runs, aggregation), uncertainties (standardized, model specific, and specifications), and other elements would be pragmatic and valuable. The current USG approach has been in place for some time and the latest estimates and/or models may be as well at some jurisdictional level (US federal, state, non-US federal), thus it is important that the public have confidence in the methods and numbers.[10]

Regarding uncertainty, it is well known that the SCC is sensitive to assumptions, which simply means that it is essential to explicitly incorporate uncertainty for those factors to which the SCC is sensitive. A challenge however is defining distributions for

[10]Note that National Academies of Sciences Engineering and Medicine (2017) was not asked to formally review or critique the current approach, though it did consider the approach in making recommendations.

inputs and parameters. One must first identify potential values and then assign probabilities. In some cases, there is limited if any information to inform either, especially the latter. Even expert elicitation, which is sometimes used to develop distributions from expert judgement in lieu of gaps in observations and analysis, is simply a method for characterizing what is known and is therefore constrained by the state of knowledge (National Academies of Sciences Engineering and Medicine, 2017).

By providing a detailed technical foundation for better understanding estimation of the SCC, we hope this study encourages discussion and facilitates a new generation of SCC analyses and climate change research. In addition, it is important to look beyond the USG exercise and apply these findings more broadly to the representation of climate and damage components in IAMs for future research on climate risk management and global carbon policy. Damage estimation is an area particularly ripe for improvement given that current formulations are based on dated and dependent assumptions, and poorly understood calibrations. Finally, while this study focuses on SCC estimation, SCC application in calculating climate and net benefits is a separate, but important, topic, with guidance needed to avoid misapplication (Rose and Bistline, 2016).

References

Anthoff, D and RSJ Tol (2013). FUND v3.7 Scientific Documentation. Available at http://www.fund-model.org/.

Bindoff, NL *et al.* (2013). Detection and attribution of climate change: From global to regional. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Clarke, L *et al.* (2009). International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, 31, S64–S81.

Clarke, L *et al.* (2014). Assessing transformation pathways. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, O Edenhofer *et al.* (eds.) Cambridge, UK, New York, NY, USA: Cambridge University Press. Available at https://tntcat.iiasa.ac.at/AR5DB, pp. 413–510.

Field, C *et al.* (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Hope, C (2011). The PAGE09 integrated assessment model: A technical description. Working Paper 4, Cambridge Judge Business School.

Howard, P (2014). Omitted damages: What's missing from the social cost of carbon. The Cost of Carbon Project of the Environmental Defense Fund, the Institute for Policy Integrity, and the Natural Resources Defense Council. March. Available at: http://costofcarbon.org/reports (last accessed May 28, 2017).

IPCC (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. In Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on

Climate Change, ML Parry, OF Canziani, JP Palutikof, PJ van der Linden and CE Hanson (eds.). Cambridge, UK: Cambridge University Press.

Johnson, LT and C Hope (2012). The social cost of carbon in US regulatory impact analyses: An introduction and critique. *Journal of Environmental Studies and Sciences*, 2(3), 205–221 doi: 10.1007/s13412-012-0087-7.

Joos, E *et al.* (2013). Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmospheric Chemistry and Physics*, 13, 2793–2825.

Meinshausen, M *et al.* (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458, 1158–1163.

Meinshausen, M, S Raper and T Wigley (2011). Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6 — Part 1: Model description and calibration. *Atmospheric Chemistry Physics*, 11, 1417–1456.

National Academies of Sciences, Engineering, and Medicine (2017). *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Committee on assessing approaches to updating the Social Cost of Carbon, Board on Environmental Change and Society, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. doi: 10.17226/24651.

Nordhaus, W (2010). Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences*, 107(26), 11721–11726.

Nordhaus, WD and J Boyer (2000). *Warming the World: Economic Models of Global Warming*. Cambridge: MIT Press.

Rose, SK (2012). The role of the social cost of carbon in policy. *WIREs Climate Change*, 3, 195–212. doi:10.1002/wcc.163.

Rose, SK *et al.* (2014). Understanding the Social Cost of Carbon: A technical assessment. EPRI Report #3002004657. Palo Alto, CA.

Rose, SK and J Bistline (2016). Applying the Social Cost of Carbon: Technical considerations. EPRI Report #3002004659. Palo Alto, CA.

Tol, R (2009). The economic effects of climate change. *Journal of Economic Perspectives*, 23, 29–51.

United Nations (2015). Probabilistic population projections based on the world population prospects: The 2015 revision. Population Division, DESA. Available at http://esa.un.org/unpd/ppp/.

Urban, NM *et al.* (2014). Historical and future learning about climate sensitivity. *Geophysical Research Letters*, 41(7), 2543–2552.

United States Government Accountability Office (2014). *Regulatory Impact Analysis: Development of Social Cost of Carbon Estimates*, Report to Congressional Requesters, GAO-14-663, July 2014. Available at http://www.gao.gov/products/GAO-14-663 (last accessed May 29, 2017).

United States Government Interagency Working Group on Social Cost of Carbon (2010). *Appendix 15A. Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, March.

United States Government Interagency Working Group on Social Cost of Carbon (2013). *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, May.

United States Government Interagency Working Group on Social Cost of Carbon (2015). *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, July.

United States Government Interagency Working Group on Social Cost of Greenhouse Gases (2016). *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, August.

United States Government Interagency Working Group on Social Cost of Greenhouse Gases (2016). *Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*: *Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide*, August.

van Vuuren, DP *et al.* (2011). The representative concentration pathways: An overview. *Climatic Change*, 109, 5–31.

UNDERSTANDING THE SOCIAL COST OF CARBON: A MODEL DIAGNOSTIC AND INTER-COMPARISON STUDY

STEVEN K. ROSE, DELAVANE DIAZ and GEOFFREY BLANFORD

Energy and Environmental Analysis Research Group
Electric Power Research Institute (EPRI)
Palo Alto, CA 94304, USA

Published 15 June 2017

1. General: Additional Information

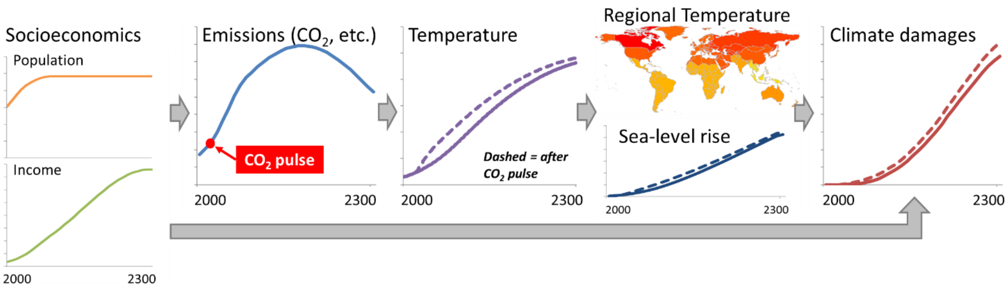


Figure S1. Modeling causal chain for computing the SCC.

Table S1. USG SCC experimental design features.

Feature	Detail
Multiple SCC models	Three models — DICE, FUND, PAGE
Standardized uncertainties	• Five reference socioeconomic and emissions scenarios (each extended from 2100 to 2300) • One distribution for the climate sensitivity parameter
Model specific parametric uncertainties	In FUND and PAGE climate and damage components
Standardized discounting	three constant discount rates — 2.5%, 3%, and 5%
Thousands of SCC results	150,000 SCC estimates for a given discount rate and year (3 models × 5 socioeconomic scenarios × 10,000 runs each)
Aggregation of results	• Average of 150,000 results for each discount rate and year • "3% (95th percentile)" value is 95th percentile from distribution of 150,000 results with 3% discounting

Table S2. Structural and implementation characteristics of USG SCC models.

Characteristic	DICE	FUND	PAGE
Socioeconomics and emissions			
GDP	Global levels	Regional per capita income growth	Regional growth rates
Population	Global levels	Regional population growth	Regional growth rates
F&I CO_2	Global emissions	Derived regional emissions based on regional per capita income and population growth and FUND emissions coefficients	Regional emissions
Land CO_2	Global emissions	Derived regional emissions based on regional per capita income and population growth and FUND emissions coefficients	Regional emissions
Kyoto non-CO_2	CH_4, N_2O, and fluorinated gas forcing[a]	CH_4, N_2O, and SF_6 emissions	CH_4, N_2O, and fluorinated gas forcing[a]
Other non-CO_2[b]	Aerosols and residual forcing	Global SO_2 emissions	Regional SO_2 emissions and other forcing
Climate modeling			
Atmospheric concentrations			
CO_2	3-box model (atmosphere, surface ocean, deep ocean)	5-timescale impulse response function	3-timescale impulse response function
Non-CO_2 Kyoto	Not modeled	CH_4, N_2O, SF_6	Not modeled
Non-CO_2 non-Kyoto	Not modeled	SO_2	SO_2
Radiative forcing			
CO_2 (per doubling)	3.80 W/m^2	3.71 W/m^2	3.81 W/m^2
Non-CO_2 Kyoto	Exogenous	CH_4, N_2O, SF_6	Exogenous
Non-CO_2 non-Kyoto	Exogenous	SO_2	SO_2, non-SO_2 exogenous[c]
GMT	Adjustment speed a function of climate sensitivity and surface temperature modulated by ocean heat uptake	Adjustment speed a function of climate sensitivity	Function of land and ocean temperatures

Table S2. (*Continued*)

Characteristic	DICE	FUND	PAGE
Ocean temperatures	2-box (upper and deep ocean)	1-box	1-box
Regional temperatures	n/a	Implicit with regional damage parameters calibrated to regional temperatures downscaled based on a linear pattern-scale average of 14 general circulation models	Explicit with regional temperatures downscaled according to latitude and landmass adjustment
Global mean SLR	Components (thermal expansion, glacier and small ice cap melt, Greenland Ice Sheet (GIS) melt, West Antarctic Ice Sheet (WAIS) melt) functions of temperature and lagged temperature	Function of temperature and lagged temperature	Function of temperature and lagged temperature
Climate feedback	None	Terrestrial carbon stock loss with warming (with central parameter values: ~0.14% of terrestrial carbon stock in a given period released per degree of warming relative to 2010)	Atmospheric CO_2 increase with warming (with central parameter values: 10% CO_2 concentration gain per period per °C, with maximum of 50%)
Time steps	10-year	1-year	Variable (10-year 2000–2060, 20-year 2060–2100, 100-year 2100–2300)
Implementation of CO_2 pulse in year t^d	Pulse spread equally over the decade straddling year t	Pulse spread equally over the decade from year t forward	Pulse distributed evenly over the two decades preceding and subsequent to year t
Model specific uncertainties (number of parameters; distribution types)	None	11 — normal, truncated normal, triangular, and gamma distributions	10 — triangular distributions
Climate damages			
Regions	1 region: World	16 regions: ANZ, CAM, CAN, CEE, CHI, FSU, JPK, MDE, NAF, SAM, SAS, SEA, SIS, SSA, USA, WEU	8 regions: Africa and Middle East, China and CP Asia, EU, FSU and ROE, India and SE Asia, Latin America, Other OECD, USA

Table S2. (*Continued*)

Characteristic	DICE	FUND	PAGE
Categories	2 categories: SLR, aggregate non-SLR	14 categories: SLR, agriculture, forests, heating, cooling, water resources, tropical storms, extratropical storms, biodiversity, cardiovascular respiratory, vector-borne diseases, morbidity, diarrhea, migration	4 categories: SLR, economic, noneconomic, discontinuity (e.g., abrupt change or catastrophe)
SLR damage specification	Quadratic function of global SLR (e.g., $DF = \alpha SLR^2$)	Additive functions for coastal protection costs, dryland loss, and wetland loss, based on an internal cost-benefit rule for optimal adaptation	Power function of global SLR (e.g., $DF = \alpha SLR^{0.7}$)
SLR damage drivers	Global mean SLR (driven by temperature), income	Global mean SLR, dryland value, wetland value, topography (elevation, coast length), protection cost, population density, income density, per capita income	Global mean SLR, regional coast length scaling factor relative to EU, adaptation capacity and costs, per capita income, income
Non-SLR damage specification	Quadratic function of global temperature (e.g., $DF = \alpha T^2$)	Uniquely formulated by category	Power function of regional temperature (e.g., $DF = \alpha T^2$)
Non-SLR damage drivers	GMT, income	GMT, CO_2 concentrations (for carbon fertilization and storms), population, income, per capita income, technological change	Regional temperature, regional scaling factor relative to EU, adaptation capacity and costs, per capita income, income
Adaptation	Implicit (damages net of adaptation)	Explicit for agriculture and SLR, implicit otherwise (econometric studies of net response to warming)	two types of exogenous fixed adaptation policy (i.e., fixed irrespective of level of climate change and socio-economics) that reduce impacts for a cost
Climate benefits	Implicit (damages net of benefits)	Explicit outcome of certain sectoral damage functions (e.g., avoided heating demand, agriculture benefits from CO_2 fertilization)	Assumes small economic benefits at low levels of warming

Table S2. (*Continued*)

Characteristic	DICE	FUND	PAGE
Catastrophe	Implicit (via calibration to an expected value of catastrophic loss)	Represented in probabilistic mode via extreme tails of parameter distributions	Unspecified 'discontinuity' impact occurs with a positive probability linked to temperatures over 3°C
Model specific uncertainties (number of parameters; distribution types)	None	442 (58 general, 384 region specific) — normal, truncated normal, triangular, and gamma distributions	35 (specific to damage formulation) — triangular distributions
Other features		"Dynamic vulnerability" (climate resiliency increases with per capita income)	

Notes: [a]Derived from EMF-22 reported total Kyoto radiative forcing and computed CO_2 radiative forcing.

[b]Model specific inclusion and implementation of non-Kyoto emissions and forcing. Non-Kyoto emissions and forcing not reported in EMF-22.

[c]PAGE SO_2 forcing projections are identical across USG socioeconomic and emissions scenarios because PAGE regional SO_2 emissions projections are identical across scenarios.

[d]In the USG exercise, the incremental emission shocks in a given year t were implemented differently by the three models. In DICE, a one GtC shock was added over the decade which straddles year t, in FUND, a one million metric ton carbon (1 MtC) shock was added to every year within a decade from year t forward, and in PAGE, 100 billion metric tons of CO_2 (100 $GtCO_2$, 27 GtC) was distributed evenly over the decades preceding and subsequent to year t. With PAGE, the emissions pulse is initially introduced as a uniform increase in average annual CO_2 emissions over the given period associated with year t. However, within PAGE's climate model, emissions for years $t - 1$ and t are averaged. Thus, the emissions pulse enters PAGE's carbon cycle as uniform (but half-sized) increases in average annual emissions in both the decades preceding and following year t. For our pulse diagnostics, we implemented the pulse as it appears to PAGE's carbon cycle. Also, for our diagnostics, we standardize the pulse size — a 1 GtC pulse — but retain the model specific implementations with respect to time periods. Thus, the additional CO_2 emissions associated with the 1 GtC pulse appear at different times and magnitudes across the models (Fig. S8).

Table S3. Standardized emissions inputs and model use for climate component diagnostics for the selected years.

Scenario	Variable	Units	USG model using	2000	2050	2100	2200	2300
USG2	FF& I CO_2	$GtCO_2$/yr	all	24.8	66.5	117.9	144.4	102.4
	Land CO_2	$GtCO_2$/yr	all	0.0	0.0	0.0	0.0	0.0
	CH_4	$MtCH_4$/yr	FUND	268.6	347.1	487.6	481.3	481.3
	N_2O	MtN/yr	FUND	5.9	7.7	7.7	5.3	5.3
	SF_6	$ktSF_6$/yr	FUND	8.2	24.1	32.6	32.1	24.4
	SO_2	$MtSO_2$/yr	FUND	39.9	36.0	35.3	34.4	34.4
USG5	FF& I CO_2	$GtCO_2$/yr	all	26.2	20.0	12.8	14.2	7.4
	Land CO_2	$GtCO_2$/yr	all	3.0	0.5	−2.1	0.0	0.0
	CH_4	$MtCH_4$/yr	FUND	268.6	289.3	285.9	285.4	285.4
	N_2O	MtN/yr	FUND	5.9	7.5	6.1	4.8	4.8
	SF_6	$ktSF_6$/yr	FUND	8.2	25.4	37.4	45.5	35.2
	SO_2	$MtSO_2$/yr	FUND	39.8	34.8	34.5	34.4	34.4
RCP8.5	FF& I CO_2	$GtCO_2$/yr	all	24.7	74.1	105.4	55.9	7.3
	Land CO_2	$GtCO_2$/yr	all	4.2	2.1	0.3	0.0	0.0
	CH_4	$MtCH_4$/yr	FUND	300.2	676.8	887.6	896.1	910.1
	N_2O	MtN/yr	FUND	7.5	12.8	15.8	14.5	13.3
	SF_6	$ktSF_6$/yr	FUND	5.5	12.0	16.9	8.8	0.9
	SO_2	$MtSO_2$/yr	FUND	107.7	52.2	25.7	25.7	25.7
RCP3-PD (RCP2.6)	FF& I CO_2	$GtCO_2$/yr	all	24.7	11.7	−3.4	−3.4	−3.4
	Land CO_2	$GtCO_2$/yr	all	4.2	0.7	1.9	0.0	0.0
	CH_4	$MtCH_4$/yr	FUND	300.2	189.3	142.1	142.1	142.1
	N_2O	MtN/yr	FUND	7.5	6.2	5.3	5.3	5.3
	SF_6	$ktSF_6$/yr	FUND	5.5	0.6	0.0	0.0	0.0
	SO_2	$MtSO_2$/yr	FUND	107.7	31.1	12.9	12.9	12.9

2. Climate Modeling Component: Additional Information

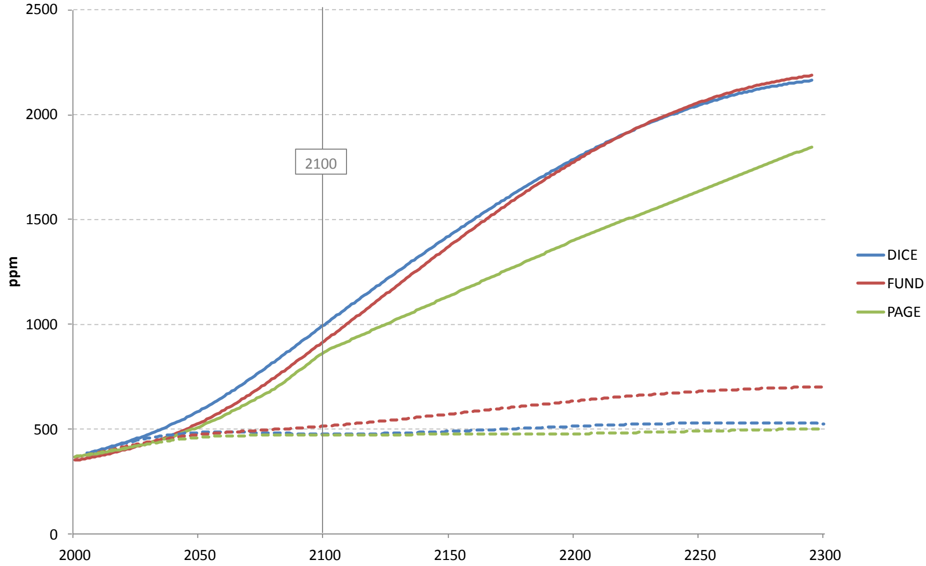


Figure S2. CO_2 concentrations to 2300 for USG2 (solid) and USG5 (dashed) scenarios (corresponds to Fig. 3(a)).

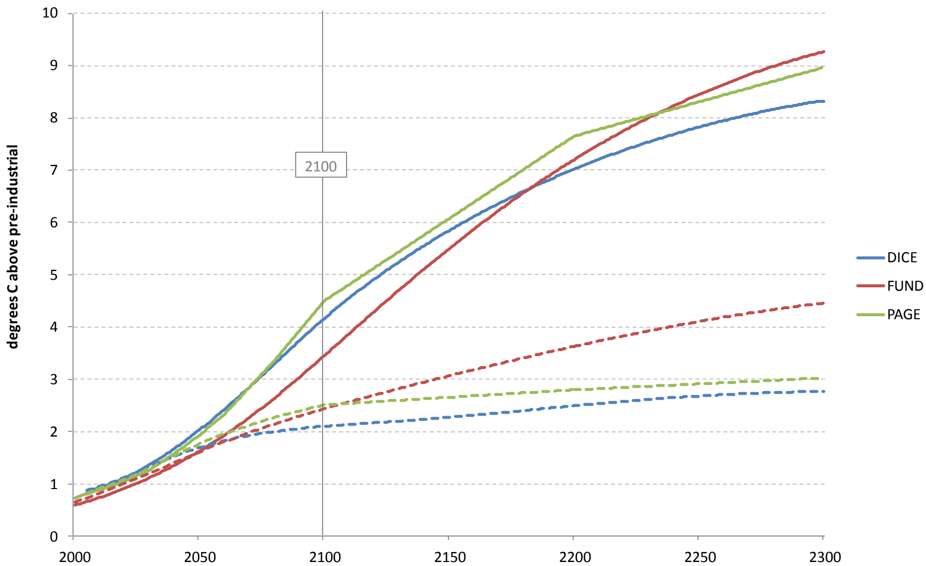


Figure S3. GMT to 2300 for USG2 (solid) and USG5 (dashed) scenarios (corresponds to Fig. 3(c)).

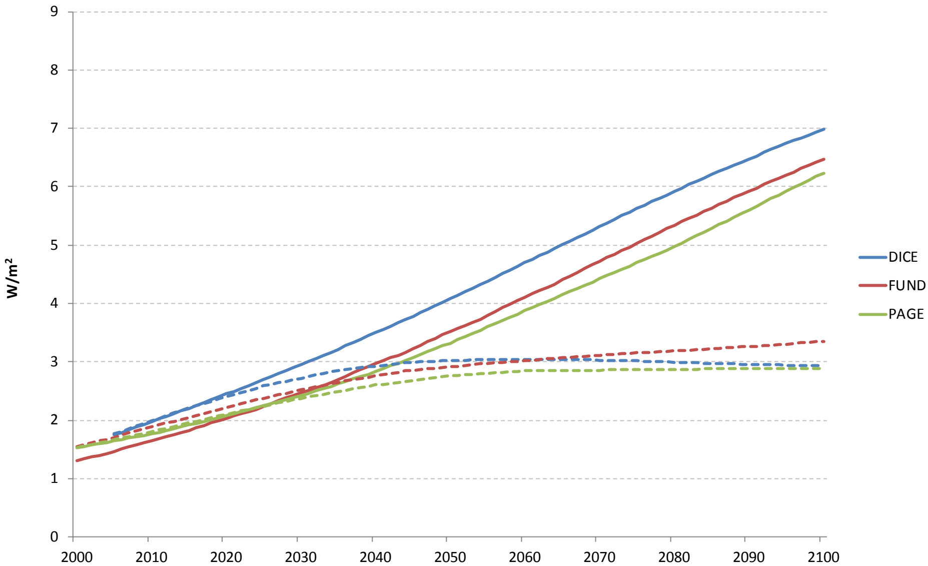


Figure S4(a). CO_2 forcing to 2100 for USG2 (solid) and USG5 (dashed) scenarios.

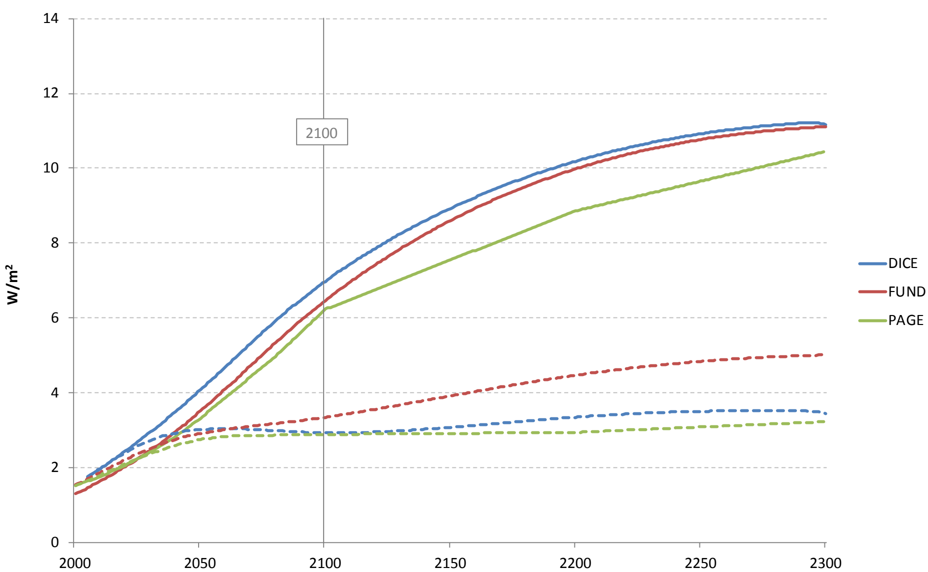


Figure S4(b). CO_2 forcing to 2300 for USG2 (solid) and USG5 (dashed) scenarios.

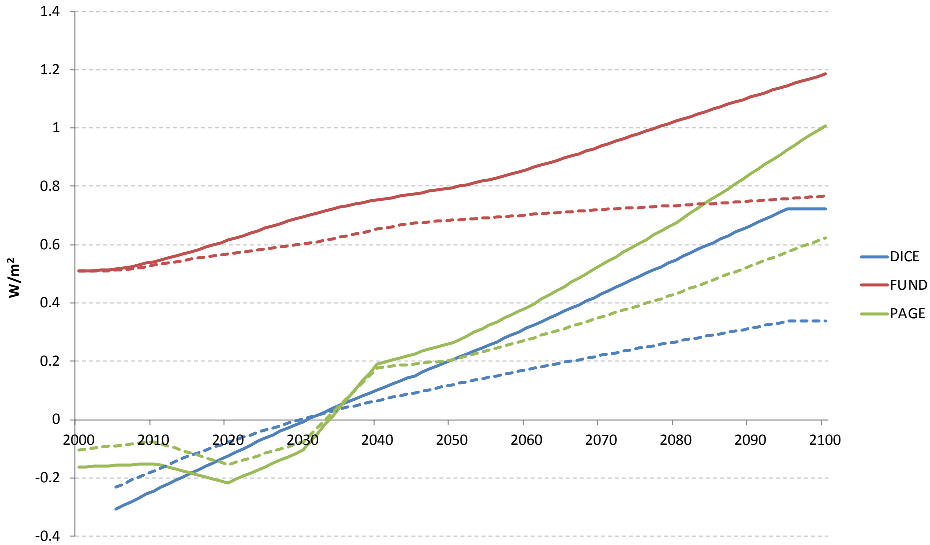


Figure S5(a). Non-CO_2 forcing to 2100 for USG2 (solid) and USG5 (dashed) scenarios.

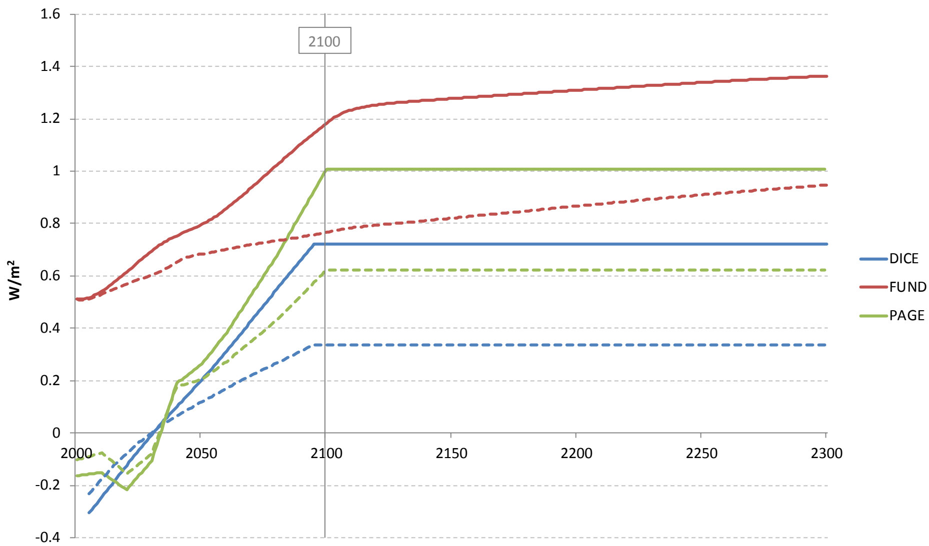


Figure S5(b). Non-CO_2 forcing to 2300 for USG2 (solid) and USG5 (dashed) scenarios.

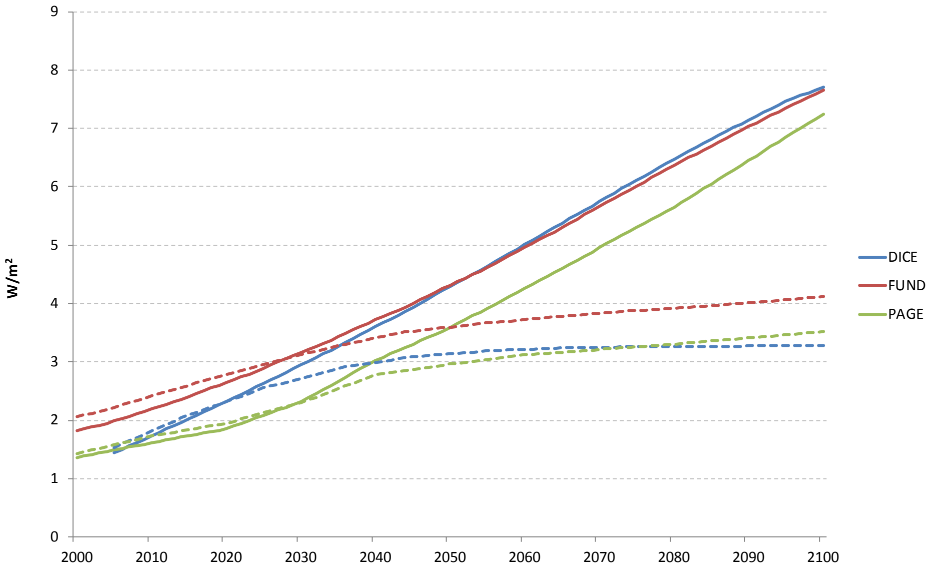


Figure S6(a). Total forcing to 2100 for USG2 (solid) and USG5 (dashed) scenarios.

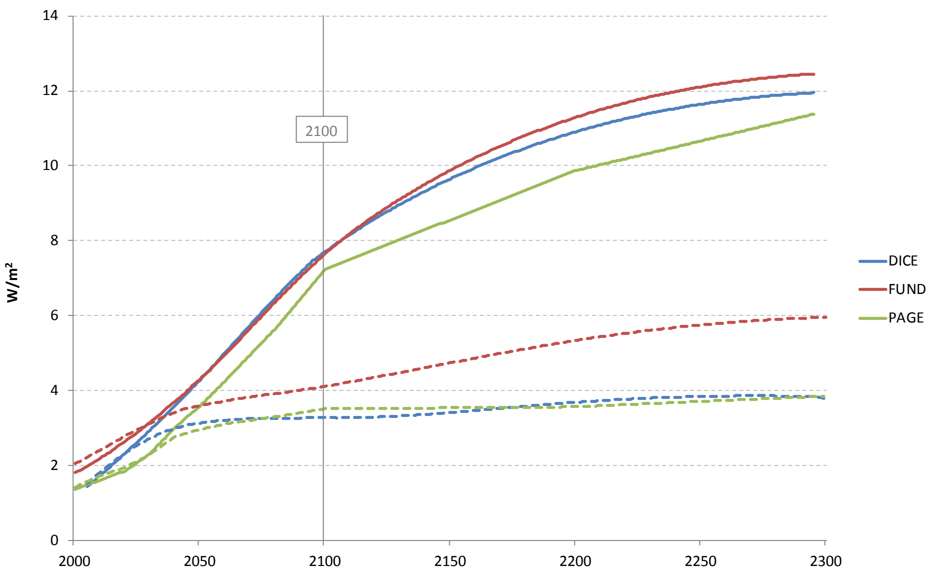


Figure S6(b). Total forcing to 2300 for USG2 (solid) and USG5 (dashed) scenarios.

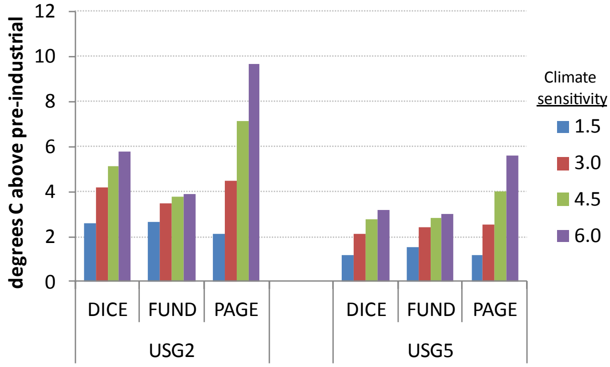
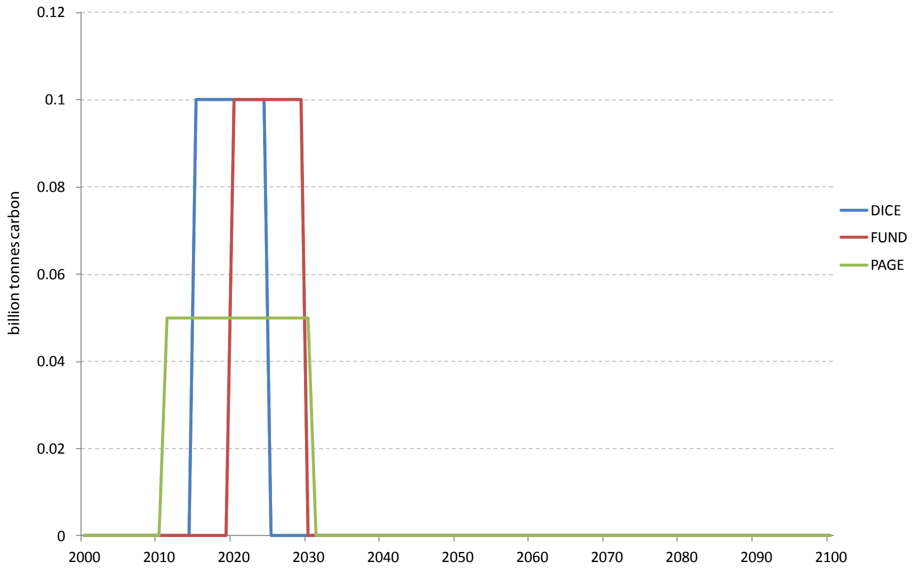


Figure S7. Sensitivity of 2100 temperature increase to climate sensitivity (ECS) for USG2 and USG5 scenarios.



Note: See Table S2 for details.

Figure S8. Emissions pulse implementation by model of a 1 GtC emissions pulse in 2020.

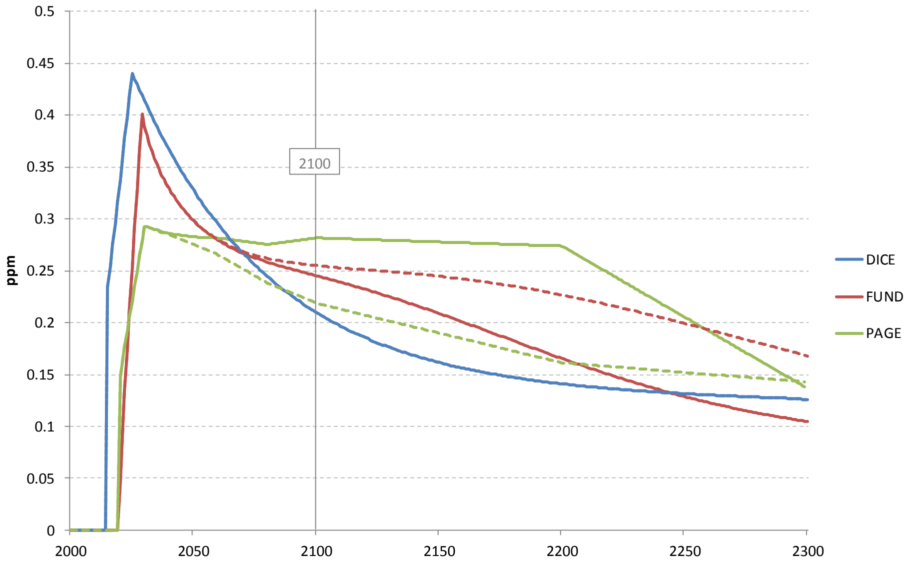


Figure S9. Incremental CO_2 concentration response to 2300 for USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020 (corresponds to Fig. 3(b)).

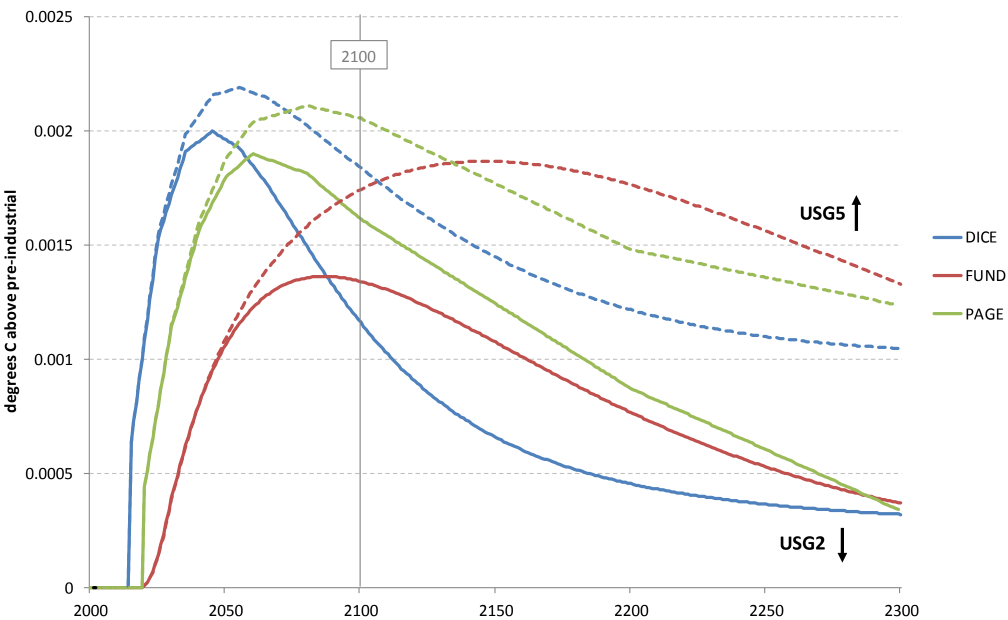


Figure S10. Incremental GMT response to 2300 for USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020 (corresponds to Fig. 3(d)).

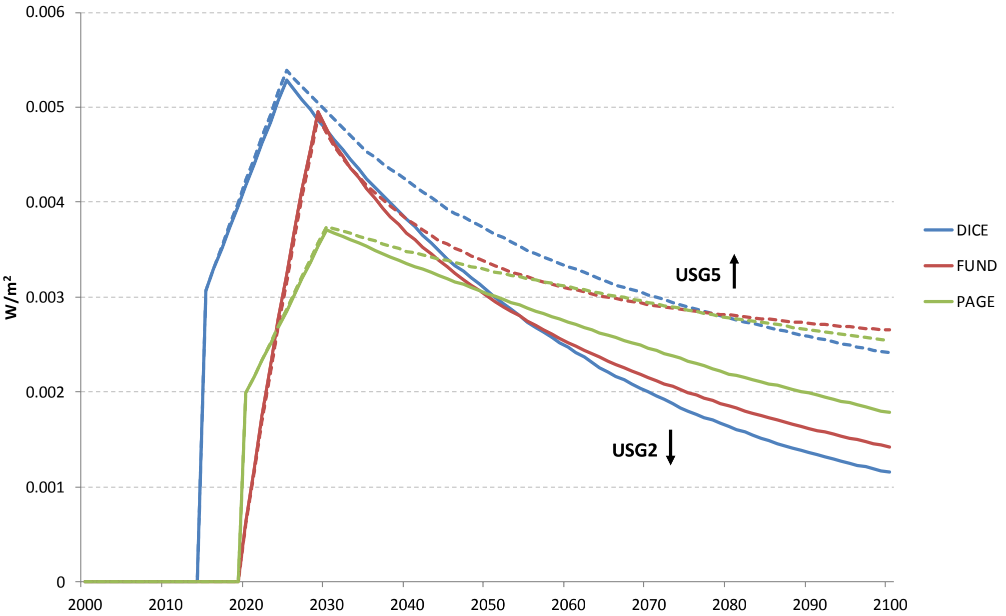


Figure S11(a). Incremental total forcing response to 2100 for USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020.

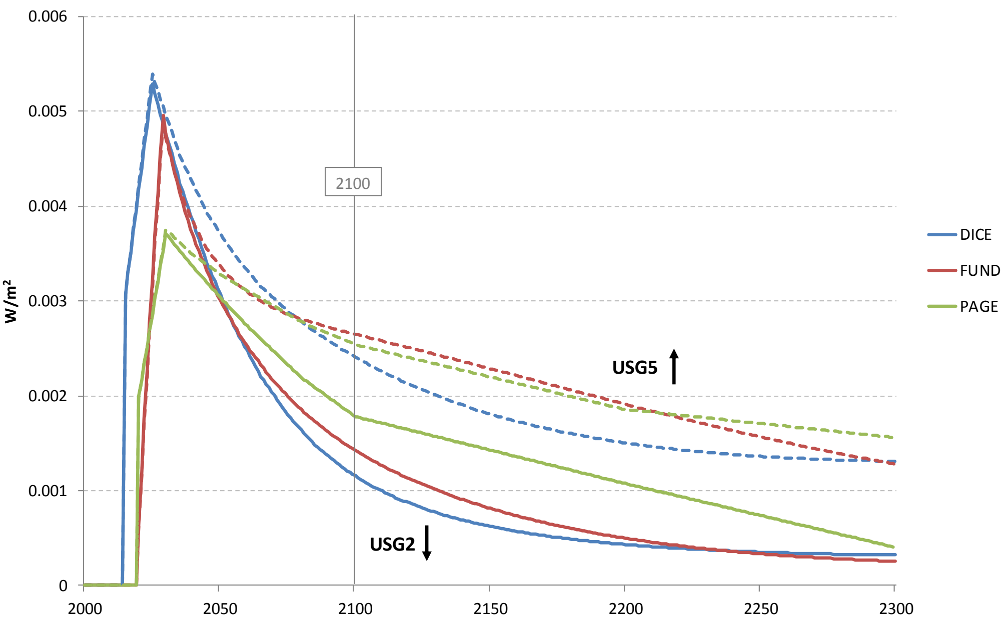


Figure S11(b). Incremental total forcing response to 2300 for USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020.

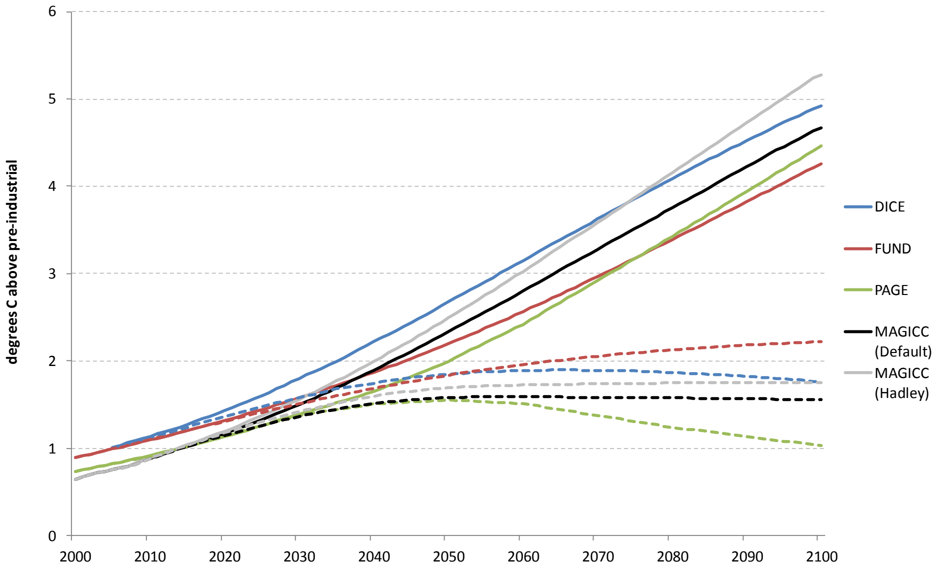


Figure S12. GMT increase in MAGICC versus the USG models for the RCP8.5 (solid) and RCP3-PD (dashed) standardized scenarios.

3. Climate Damages Modeling Component: Additional Information

Table S4. Literature sources for model damage specifications.

Model (version)	Damage category	Study	Basis	Links to SCC models
DICE (2010)[a]	Aggregate non-SLR	IPCC (2007), Tol (2009)[b]	Calibration	DICE, FUND, PAGE
	SLR coastal impacts	Undocumented		
FUND (v3.8)	Agriculture	Kane *et al.* (1992), Reilly *et al.* (1994), Morita *et al.* (1994), Fischer *et al.* (1996), Tsigas *et al.* (1996)	Calibration	
		Tol (2002b)	Income elasticity	
	Forestry	Perez-Garcia *et al.* (1995), Sohngen *et al.* (2001)	Calibration	
		Tol (2002b)	Income elasticity	
	Energy	Downing *et al.* (1995, 1996)	Calibration	
		Hodgson and Miller (1995)	Income elasticity	
	Water resources	Downing *et al.* (1995, 1996)	Calibration	
		Downing *et al.* (1995, 1996)	Income elasticity	
	Coastal impacts	Hoozemans *et al.* (1993), Bijlsma *et al.* (1995), Leatherman and Nicholls (1995), Nicholls and Leatherman (1995), Brander *et al.* (2006)	Calibration	
	Diarrhea	WHO Global Burden of Disease (2000)[c]	Calibration	
		WHO Global Burden of Disease (2000)	Income elasticity	
	Vector-borne diseases	Martin and Lefebvre (1995), Martens *et al.* (1995, 1997), Morita *et al.* (1994)	Calibration	
		Link and Tol (2004)	Income elasticity	
	Cardiovascular and respiratory mortality	Martens (1998)	Calibration	
	Storms	CRED EM-DAT database,[d] WMO (2006)	Calibration	
		Toya and Skidmore (2007)	Income elasticity	
	Ecosystems	Pearce and Moran, (1994), Tol (2002a)	Calibration	

Table S4. (*Continued*)

Model (version)	Damage category	Study	Basis	Links to SCC models
PAGE (2009)	SLR	Anthoff *et al.* (2006)[e]	Calibration and income elasticity	FUND
	Economic	Warren *et al.* (2006)[f]	Calibration	DICE, FUND, PAGE
	Noneconomic	Warren *et al.* (2006)	Calibration	DICE, FUND, PAGE
	Discontinuity	Lenton *et al.* (2008), Nichols *et al.* (2008), Anthoff *et al.* (2006), Nordhaus (1994)[g]	Calibration	DICE, FUND
	Adaptation costs	Parry *et al.* (2009)	Calibration	

Notes: [a]Specifics regarding the calibration of the DICE 2010 damage functions are not available. Based on National Academies of Sciences, Engineering, and Medicine (2017), Nordhaus (2010), and model files posted at http://www.econ.yale.edu/∼nordhaus/homepage/RICEmodels.htm, we conclude that DICE 2010 was calibrated at the global level to IPCC (2007) and Tol (2009) with the sector allocation of damages assumed unchanged and according to RICE 2000. RICE 2000 has regional damage calibrations for 12 global regions and includes the following damage categories: SLR, catastrophic, and aggregate other. RICE 2000 damage calibrations are described in Nordhaus and Boyer (2000) and based on literature dating back to the 1990s and early 2000s.

[b]Tol 2009 is a meta analysis of global damage studies some of which report impacts estimated by earlier versions of the SCC models, specifically DICE-94, RICE-96, RICE-99, DICE-99, PAGE95, PAGE2002, and FUND1.6.

[c]http://www.who.int/health_topics/global_burden_of_disease/en/.

[d]http://www.emdat.be/.

[e]Anthoff *et al.* (2006) is a study of coastal impacts that uses an earlier version of the FUND model (v2.8).

[f]Warren et al. (2006) is a review of damage modeling in earlier versions of four integrated assessment models: DICE/RICE-1999, MERGE 1995 and 2004, PAGE2002, and FUNDv2.9.

[g]Nordhaus (1994) is an expert elicitation on climate catastrophes, and is also used as the basis for catastrophic impacts in DICE prior to 2010.

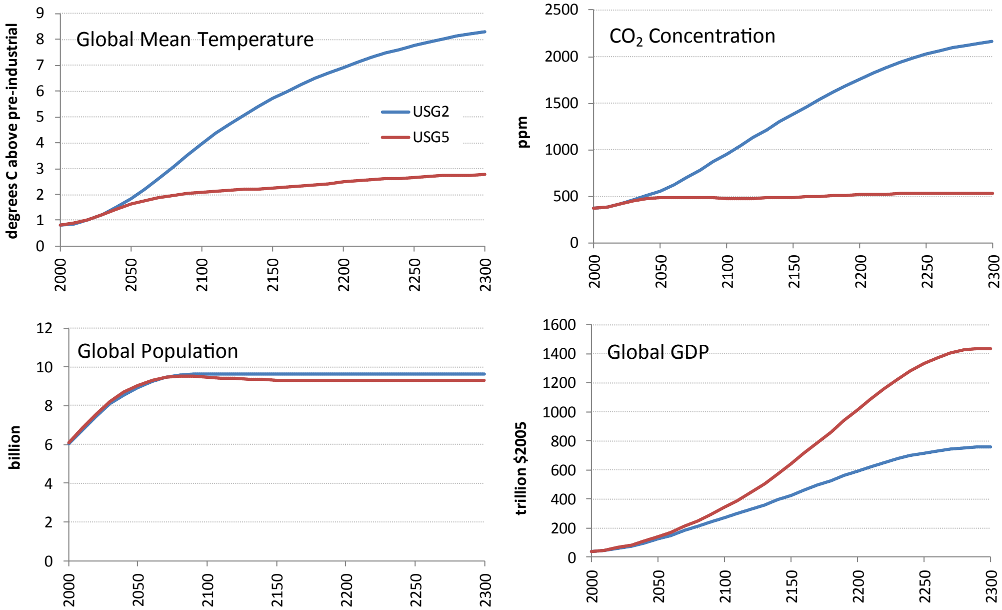


Figure S13. Standardized reference climate and socioeconomic inputs to 2300 for damage component diagnostics.

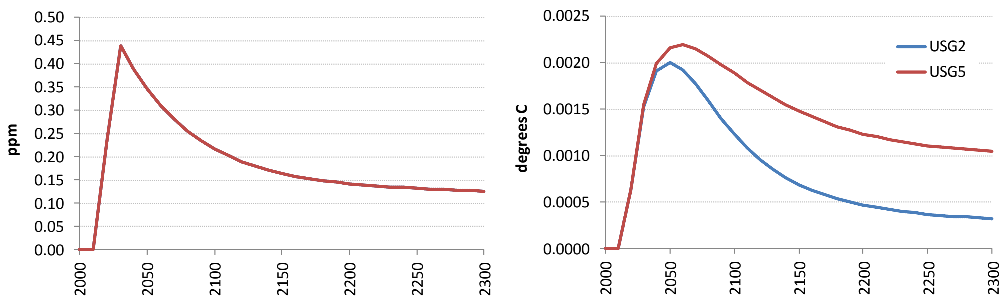


Figure S14. Standardized incremental CO_2 concentration (left) and GMT (right) inputs for damage component diagnostics.

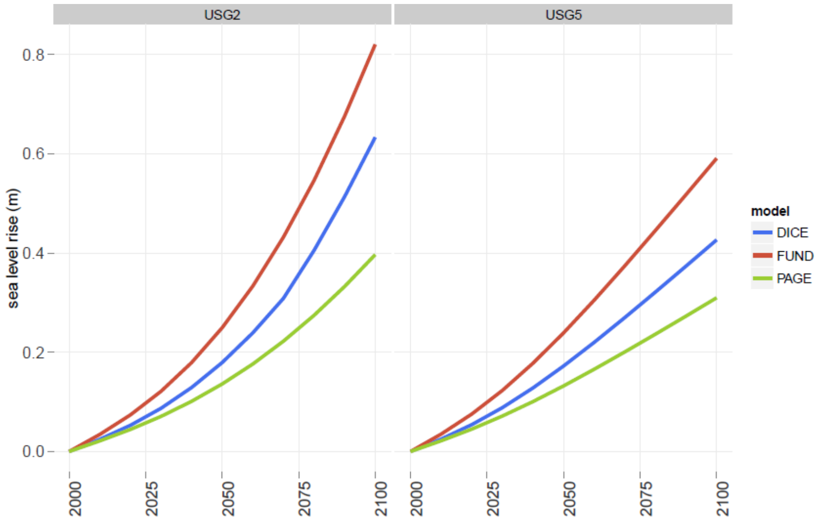


Figure S15. SLR from 2000 to 2100 with the standardized USG2 and USG5 climate.

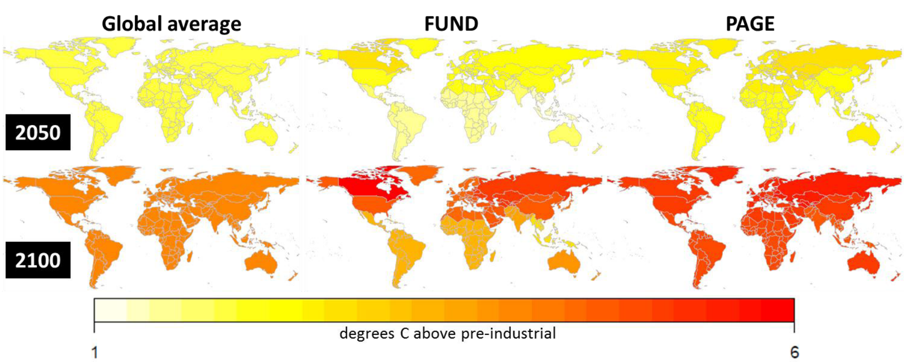


Figure S16(a). Regional average temperature change by 2050 and 2100 with the standardized USG2 climate.

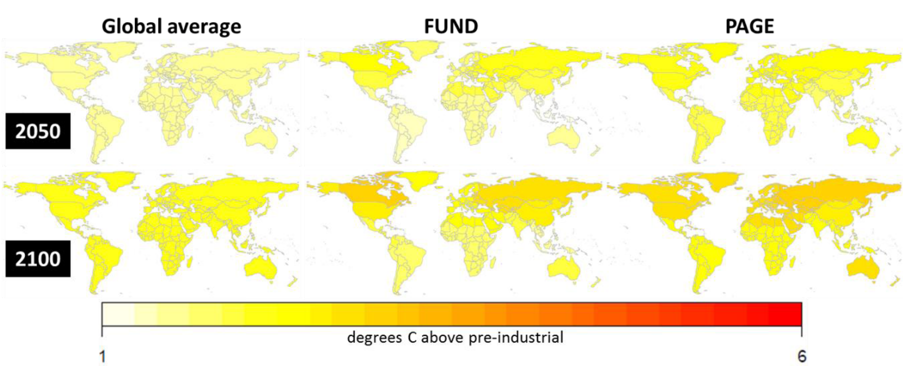


Figure S16(b). Regional average temperature change by 2050 and 2100 with the standardized USG5 climate.

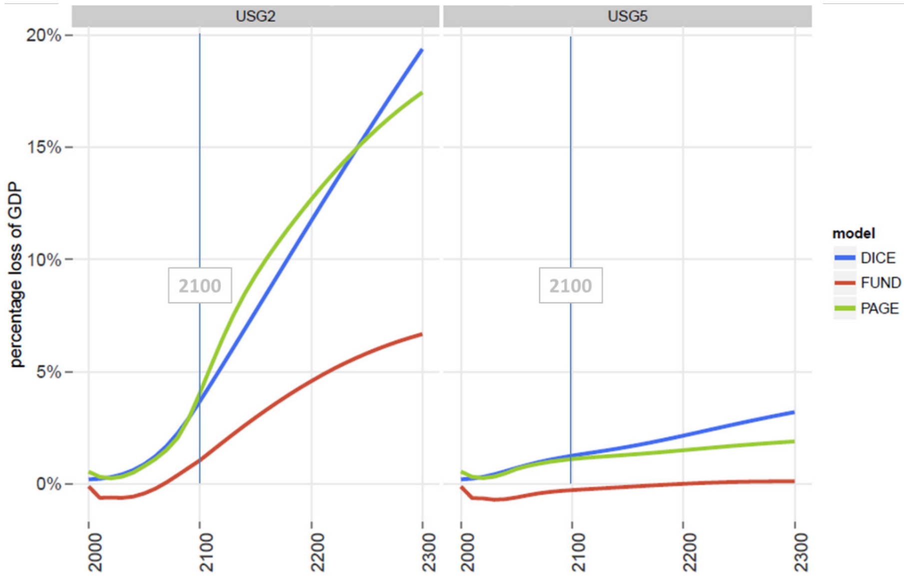
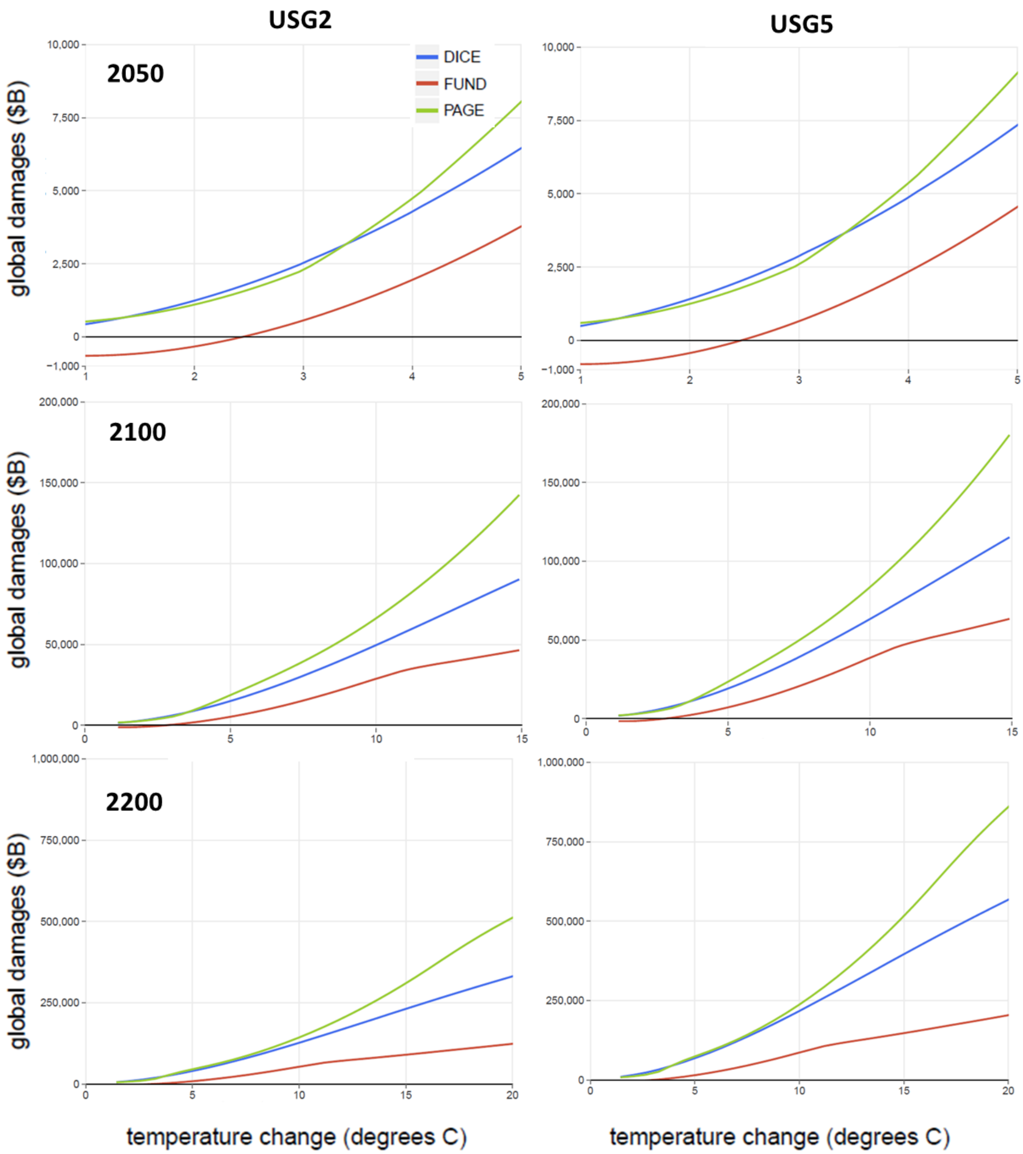


Figure S17. Total climate damages to 2300 as a fraction of GDP with the standardized USG2 and USG5 climate and socioeconomics (corresponds to Fig. 3(e)).



Notes: Axis' scales vary. See Fig. S13 for global socioeconomic details in 2050, 2100, and 2200. For 2100 and 2200 damages by category and region as a function of temperature see Rose *et al.* (2014).

Figure S18. Total climate damages as a function of temperature for 2050, 2100, and 2200 with USG2 and USG5 socioeconomics.

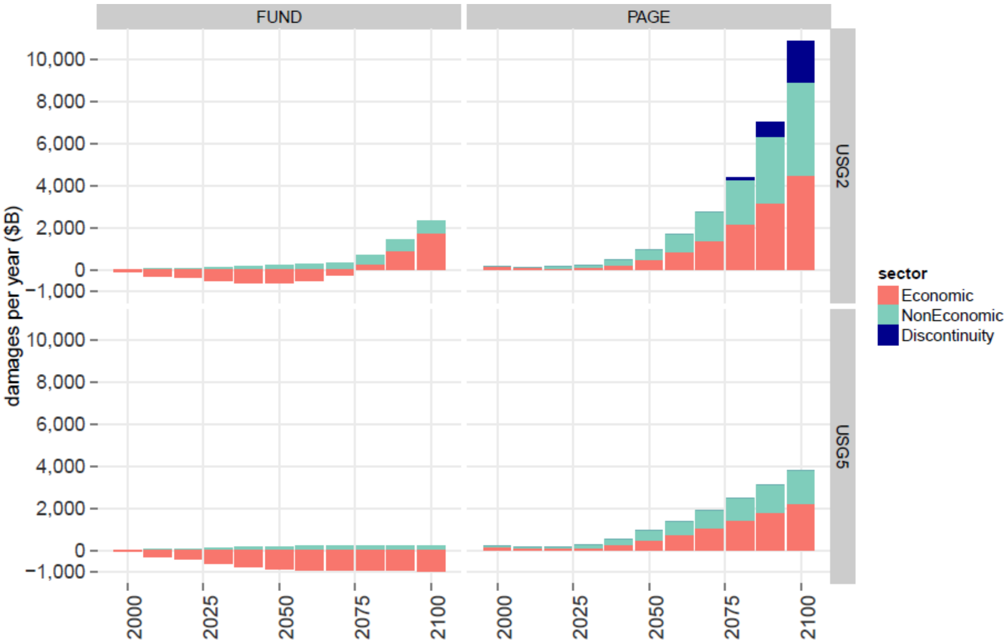


Figure S19. Total economic and noneconomic climate damages to 2100 (harmonized categories).[a]

[a]For FUND, "economic" damages include SLR, agriculture, forests, heating demand, cooling demand, water resources, and physical storm damage (tropical and extratropical). For PAGE, "economic" damages include SLR, and PAGE's economic damage category, as well as the corresponding adaptation costs. For FUND, "noneconomic" damages include storm deaths (tropical and extratropical), biodiversity, cardiovascular & respiratory health, vector-borne disease, morbidity, diarrhoea, and migration. For PAGE, "noneconomic" damages include PAGE's noneconomic damage category and corresponding adaptation costs. The description of PAGE's discontinuity is vague and we therefore are not able to clearly characterize the damages as "economic" or "noneconomic."

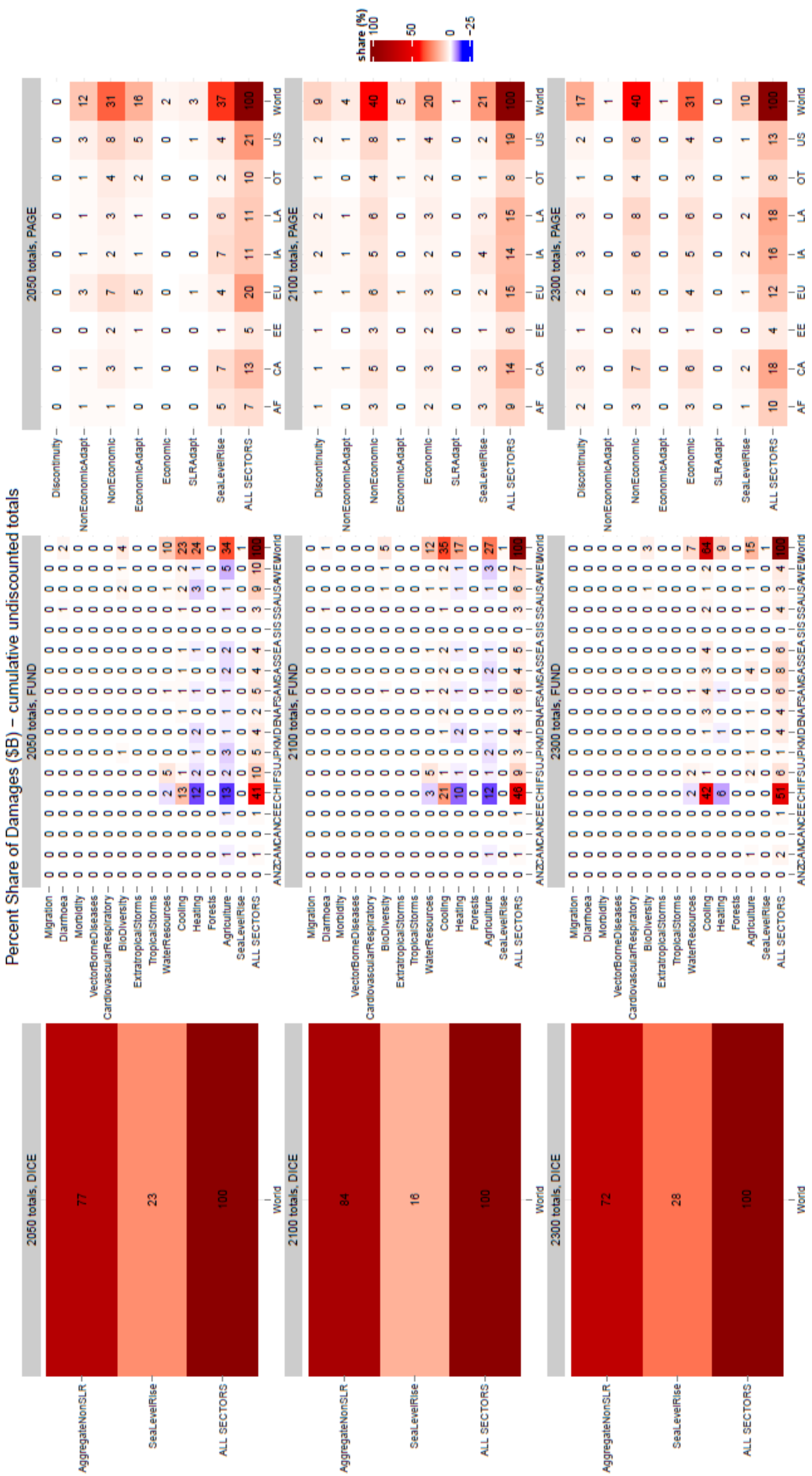


Figure S20(a). Total damages computed for USG2 decomposed by category (row) and region (column) for each model.

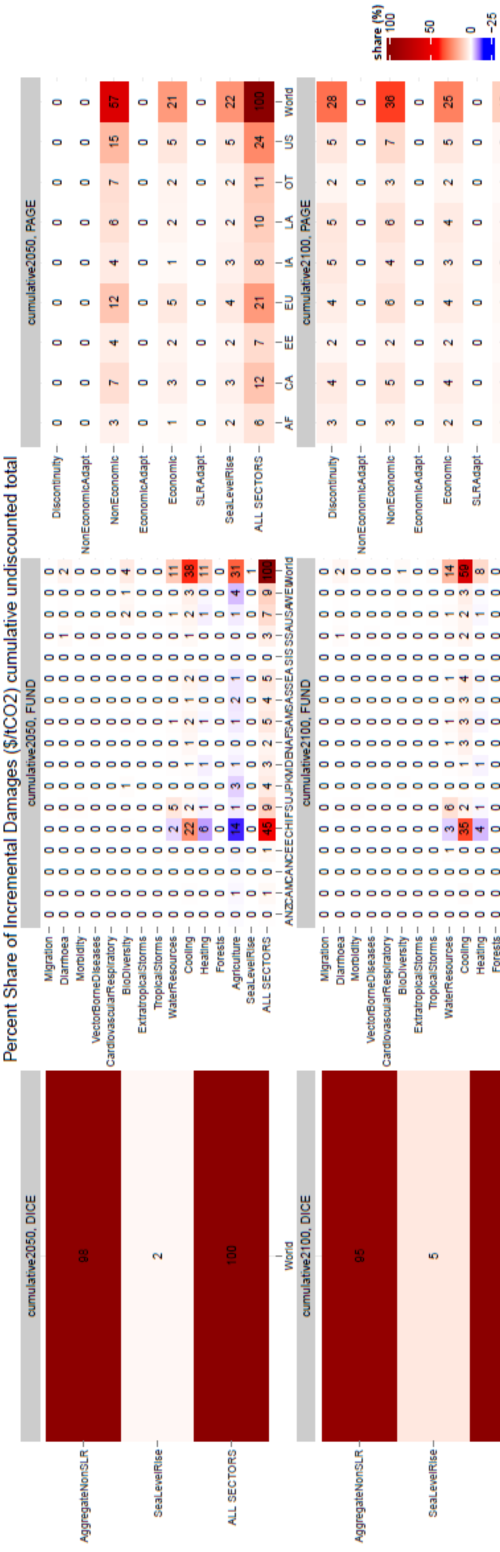
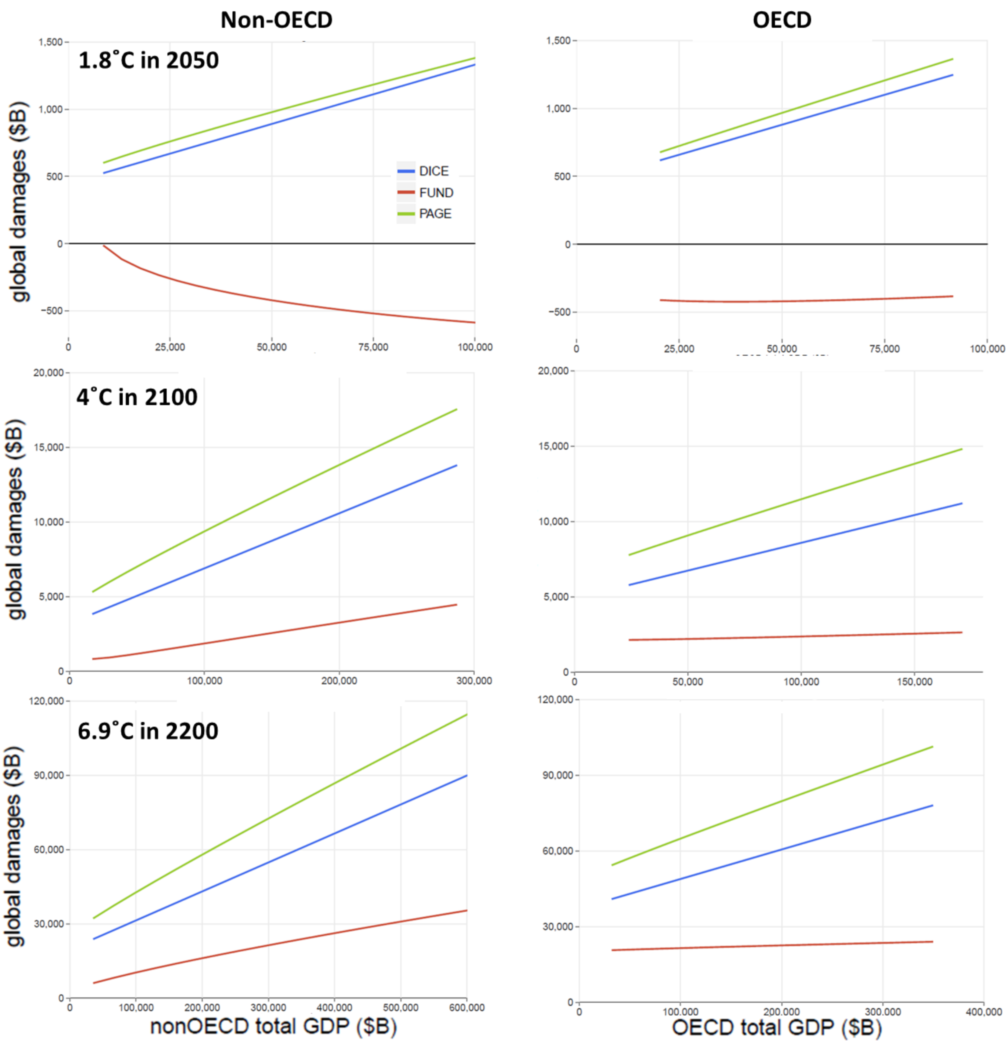
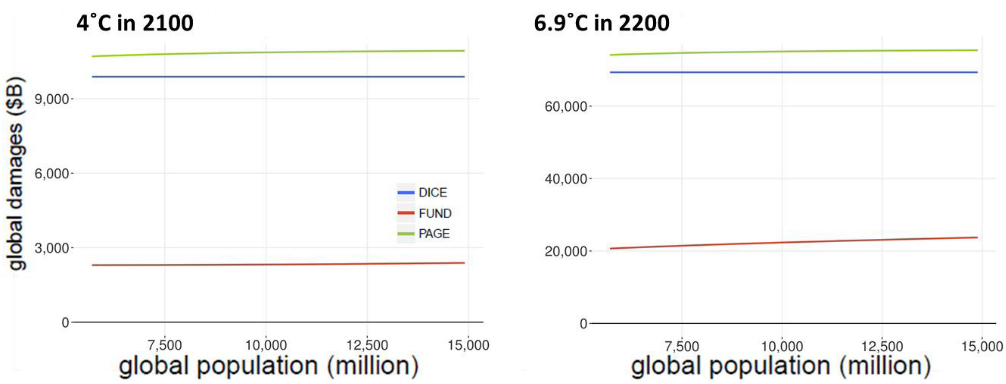


Figure S20(b). Incremental damages computed for USG2 scenario decomposed by category (row) and region (column) for each model.



Notes: Axis' scales vary. See Fig. S13 for corresponding population and GMT conditions.

Figure S21(a). Total climate damages as a function of non-OECD (left) and OECD (right) income for 2050, 2100, and 2200 with the standardized USG2 climate.



Notes: Axis' scales vary. See Fig. S13 for corresponding income and GMT conditions.

Figure S21(b). Total climate damages as a function of global population for 2100 and 2200 with the standardized USG2 climate.

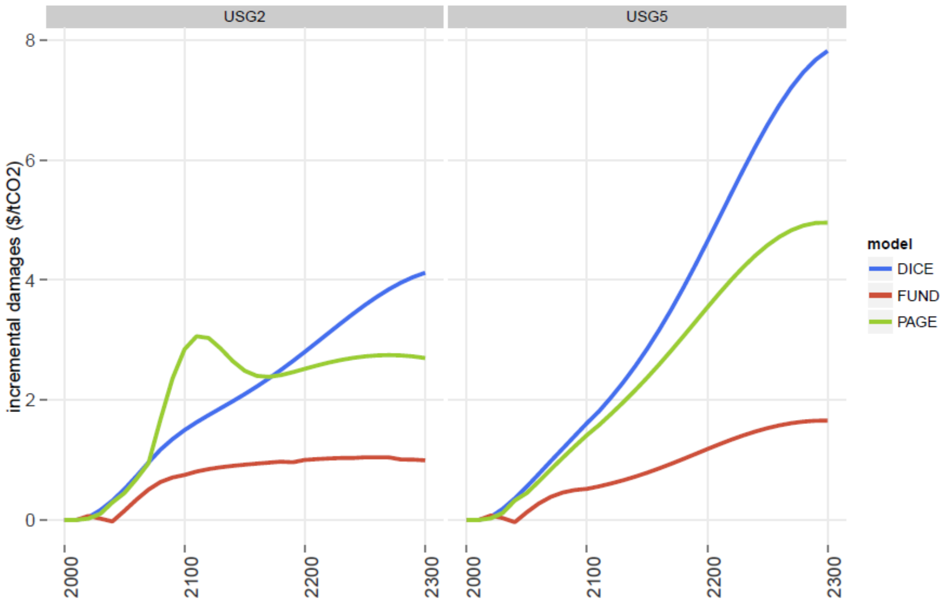


Figure S22. Incremental climate damages to 2300 with the standardized USG2 and USG5 climate and socioeconomics (corresponds to Fig. 3(f)).

References

Anthoff, D, RJ Nicholls, RSJ Tol and AT Vafeidis (2006). *Global and Regional Exposure to Large Rises in Sea-Level: A Sensitivity Analysis*. Working Paper 96, Tyndall Centre for Climate Change Research, Norwich, UK.

Bijlsma, L, CN Ehler, RJT Klein, SM Kulshrestha, RF McLean, N Mimura, RJ Nicholls, LA Nurse, H Perez Nieto, EZ Stakhiv, RK Turner and RA Warrick (1996). Coastal Zones and Small Islands. In *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses — Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, 1 edn, RT Watson, MC Zinyowera and RH Moss (eds.), Cambridge University Press, Cambridge, pp. 289–324.

Brander, LM, RJGM Florax and JE Vermaat (2006). The empirics of wetland valuation: A comprehensive summary and a meta-analysis of the literature. *Environmental & Resource Economics*, 33, 223–250. Doi:10.1007/s10640-005-3104-4.

Downing, TE, N Eyre, R Greener and D Blackwell (1996). *Full Fuel Cycle Study: Evaluation of the Global Warming Externality for Fossil Fuel Cycles with and without CO_2 Abatament and for Two Reference Scenarios*, Environmental Change Unit, University of Oxford, Oxford.

Downing, TE, RA Greener and N Eyre (1995). *The Economic Impacts of Climate Change: Assessment of Fossil Fuel Cycles for the ExternE Project*, Oxford and Lonsdale, Environmental Change Unit and Eyre Energy Environment.

Fischer, G, K Frohberg, ML Parry and C Rosenzweig (1996). Impacts of potential climate change on global and regional food production and vulnerability. In *Climate Change and World Food Security*, TE Downing (ed.), Springer-Verlag, Berlin, pp. 115–159.

Hodgson, D and K Miller (1995). Modelling UK Energy Demand. In T Barker, P Ekins and N Johnstone (eds.), *Global Warming and Energy Demand*, Routledge, London.

Hoozemans, FMJ, M Marchand and HA Pennekamp (1993). *A Global Vulnerability Analysis: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production and a Global Scale (Second, Revised Edition)*, Delft Hydraulics, Delft.

IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ML Parry, OF Canziani, JP Palutikof, PJ van der Linden and CE Hanson (eds.), Cambridge University Press, Cambridge, UK.

Kane, S, JM Reilly and J Tobey (1992). An empirical study of the economic effects of climate change on world agriculture. *Climatic Change*, 21, 17–35.

Leatherman, SP and RJ Nicholls (1995). Accelerated sea-level rise and developing countries: An overview. *Journal of Coastal Research*, 14, 1–14.

Lenton, TM, H Held, E Kriegler, JW Hall, W Lucht, S Rahmstorf and HJ Schellnhuber (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences USA*, 105(6), 1786–1793.

Link, PM and RSJ Tol (2004). Possible economic impacts of a shutdown of the thermohaline circulation: An application of FUND. *Portuguese Economic Journal*, 3, 99–114.

Martens, WJM (1998). Climate change, thermal stress and mortality changes. *Social Science and Medicine*, 46(3), 331–344.

Martens, WJM, TH Jetten, J Rotmans and LW Niessen (1995). Climate change and vector-borne diseases — A global modelling perspective. *Global Environmental Change*, 5(3), 195–209.

Martens, WJM, TH Jetten and DA Focks (1997). Sensitivity of malaria, schistosomiasis and dengue to global warming. *Climatic Change*, 35, 145–156.

Morita, T, M Kainuma, H Harasawa, K Kai, L Dong-Kun and Y Matsuoka (1994). *Asian-Pacific Integrated Model for Evaluating Policy Options to Reduce Greenhouse Gas Emissions and Global Warming Impacts*, National Institute for Environmental Studies, Tsukuba.

National Academies of Sciences, Engineering, and Medicine (2017). *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Committee on Assessing Approaches to Updating the Social Cost of Carbon, Board on Environmental Change and Society, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. doi: 10.17226/24651.

Nicholls, RJ and SP Leatherman (1995). The implications of accelerated sea-level rise for developing countries: A discussion. *Journal of Coastal Research*, 14, 303–323.

Nicholls, RJ, RSJ Tol and AT Vafeidis (2008). Global estimates of the impact of a collapse of the west antarctic ice sheet: An application of fund. *Climate Change*, 91(1–2), 171–191. doi: 10.1007/s10584-008-9424-y.

Nordhaus, WD (1994). Expert opinion on climatic change. *American Scientist*, 82, 45–51.

Nordhaus, W (2010). Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences*, 107(26), 11721–11726.

Nordhaus, WD and J Boyer (2000). *Warming the World: Economic Models of Global Warming*. The MIT Press, Cambridge, Massachusetts and London, England, pp. 245.

Parry, M *et al.* (2009). *Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates*. International Institute for Environment and Development and Grantham Institute for Climate Change, London.

Pearce, DW and D Moran (1994). *The Economic Value of Biodiversity*. EarthScan, London.

Perez-Garcia, J, LA Joyce, CS Binkley and AD McGuire (1995). *Economic Impacts of Climatic Change on the Global Forest Sector: An Integrated Ecological/Economic Assessment*. Bergendal.

Reilly, JM, N Hohmann and S Kane (1994). Climate change and agricultural trade: Who benefits, who loses? *Global Environmental Change*, 4(1), 24–36.

Rose, SK, D Turner, G Blanford, J Bistline, F de la Chesnaye and T Wilson (2014). *Understanding the Social Cost of Carbon: A Technical Assessment*. EPRI Report #3002004657 (Palo Alto, CA).

Sohngen, BL, RO Mendelsohn and RA Sedjo (2001). A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics*, 26(2), 326–343.

Tol, RSJ (2002a). Estimates of the damage costs of climate change — Part 1: Benchmark estimates. *Environmental and Resource Economics*, 21, 47–73.

Tol, RSJ (2002b). Estimates of the damage costs of climate change — Part II: Dynamic estimates. *Environmental and Resource Economics*, 21, 135–160.

Tol, R (2009). The economic effects of climate change. *J. Econ. Perspect.*, 23, 29–51.

Toya, H and M Skidmore (2007). Economic development and the impact of natural disasters. *Economics Letters*, 94, 20–25.

Tsigas, ME, GB Frisvold and B Kuhn (1996). Global climate change in agriculture. In *Global Trade Analysis: Modelling and Applications*, TW Hertel (ed.), Cambridge University Press, Cambridge.

Warren, R, C Hope, MD Mastrandrea, RSJ Tol, N Adger and I Lorenzoni (2006). Spotlighting impacts in integrated assessment. Research report prepared for the Stern Review on the Economics of Climate Change. Tyndall Working Paper 91. Available at: www.tyndall.ac.uk.

WMO (2006). Summary Statement on Tropical Cyclones and Climate Change, World Meteorological Organization. http://www.wmo.ch/pages/prog/arep/tmrp/documents/iwtc_summary.pdf.