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

Steven Rose, Delavane Diaz, Geoffrey Blanford
Energy & Environmental Analysis Research Group

Webcast
July 25, 2017

New Journal Article

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

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

Be sure to download current version. Publisher formatting problem corrected.

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.

ELECTRIC POWER RESEARCH INSTITUTE

Motivation

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

ton of CO_2

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

What does $42 mean?

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

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

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)

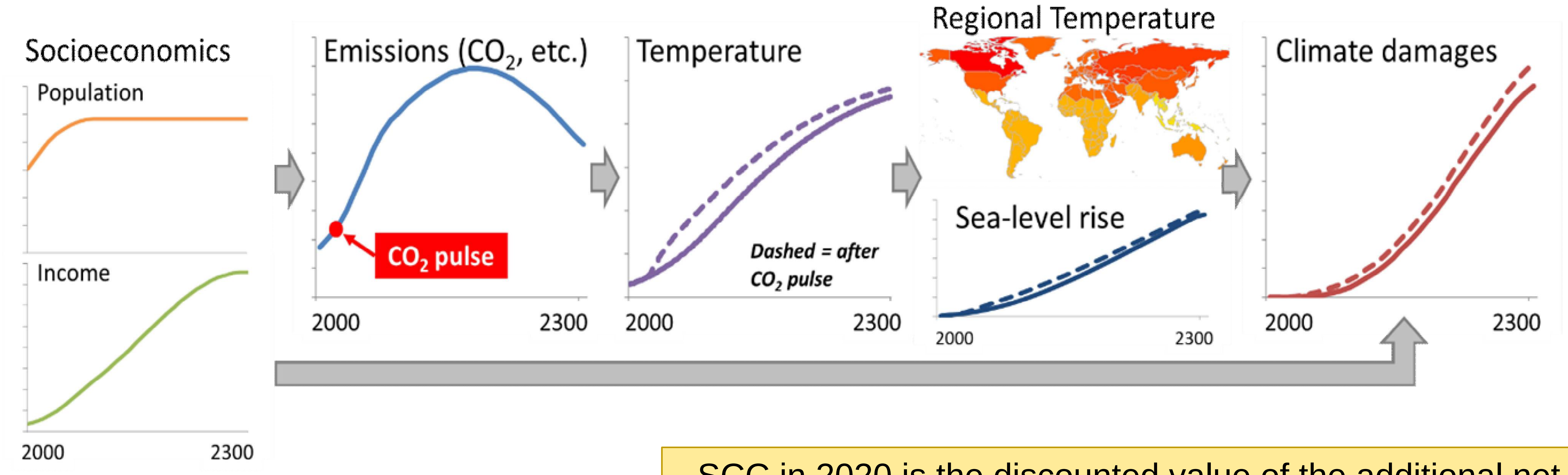
ELECTRIC POWER RESEARCH INSTITUTE

This Study

- **First direct comparison of SCC modeling and detailed assessment of the inner-workings**
  - Information essential to understanding, evaluating, improving the state-of-the-art and estimates
  - Information essential to potential SCC users
  - A requisite first step before other issues can be broached (e.g., omitted impact categories and biases, equity weighting, intergenerational discounting)
- **Is designed to establish a new common analytical ground for moving forward**
  - Improving understanding, informing use, informing estimation, and identifying research priorities
  - Providing the community of policy-makers, stakeholders, and scientists greater technical clarity on SCC modeling and global climate damage estimation
- **While we analyze particular versions of SCC models (USG), our perspectives and insights apply to other modeling, other applications (e.g., SC-CH_4), and aggregate climate risks and goals**
  - The go to models and values – the starting point and raw material for current and future valuation of greenhouse gases
- **This study represents an enhancement and refinement of the earlier EPRI report that was a key input to the recent National Academy of Sciences SCC study on updating estimation**

Social Cost of Carbon Modeling Mechanics

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

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

EPRI ELECTRIC POWER RESEARCH INSTITUTE

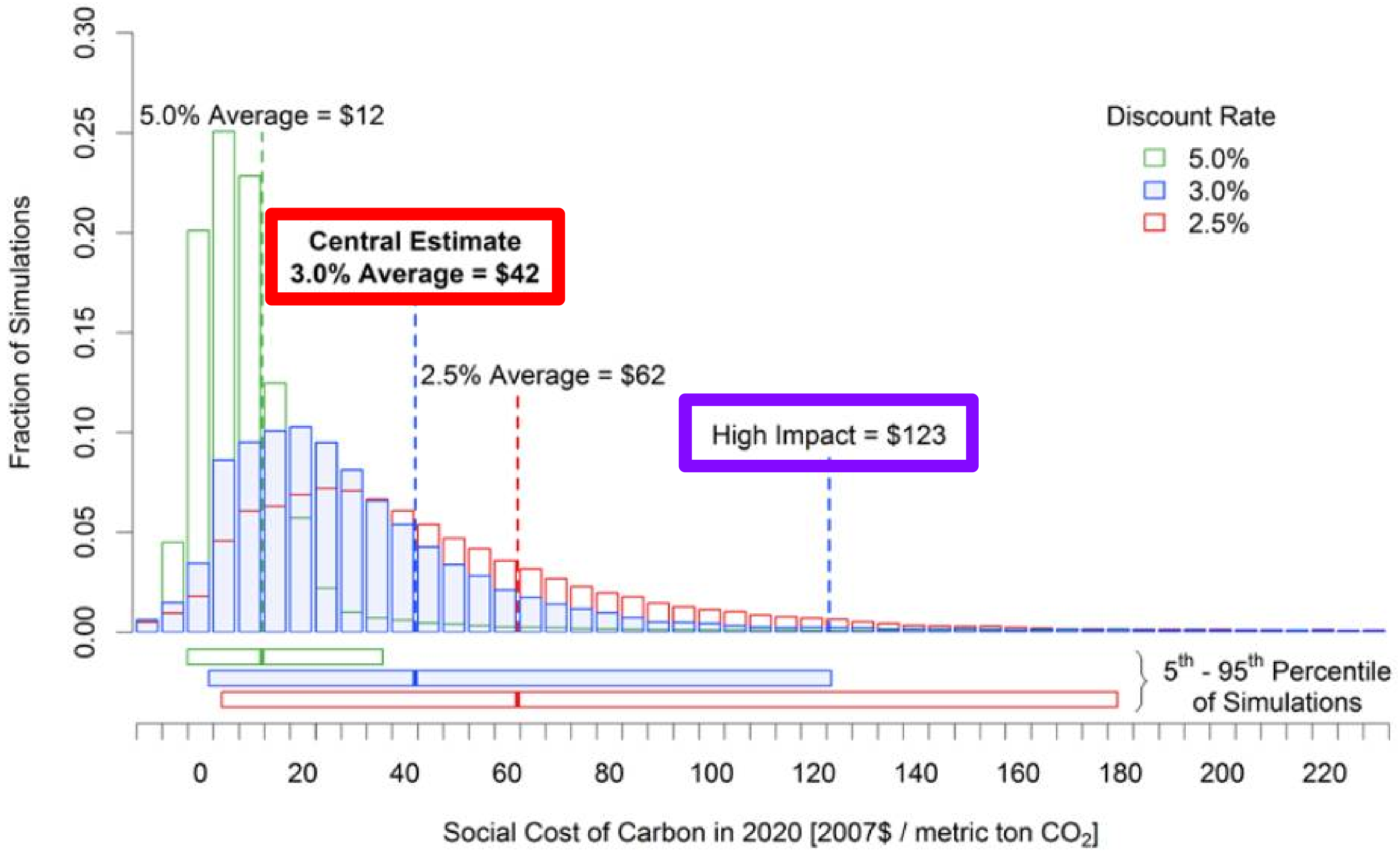
USG SCC Values

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)

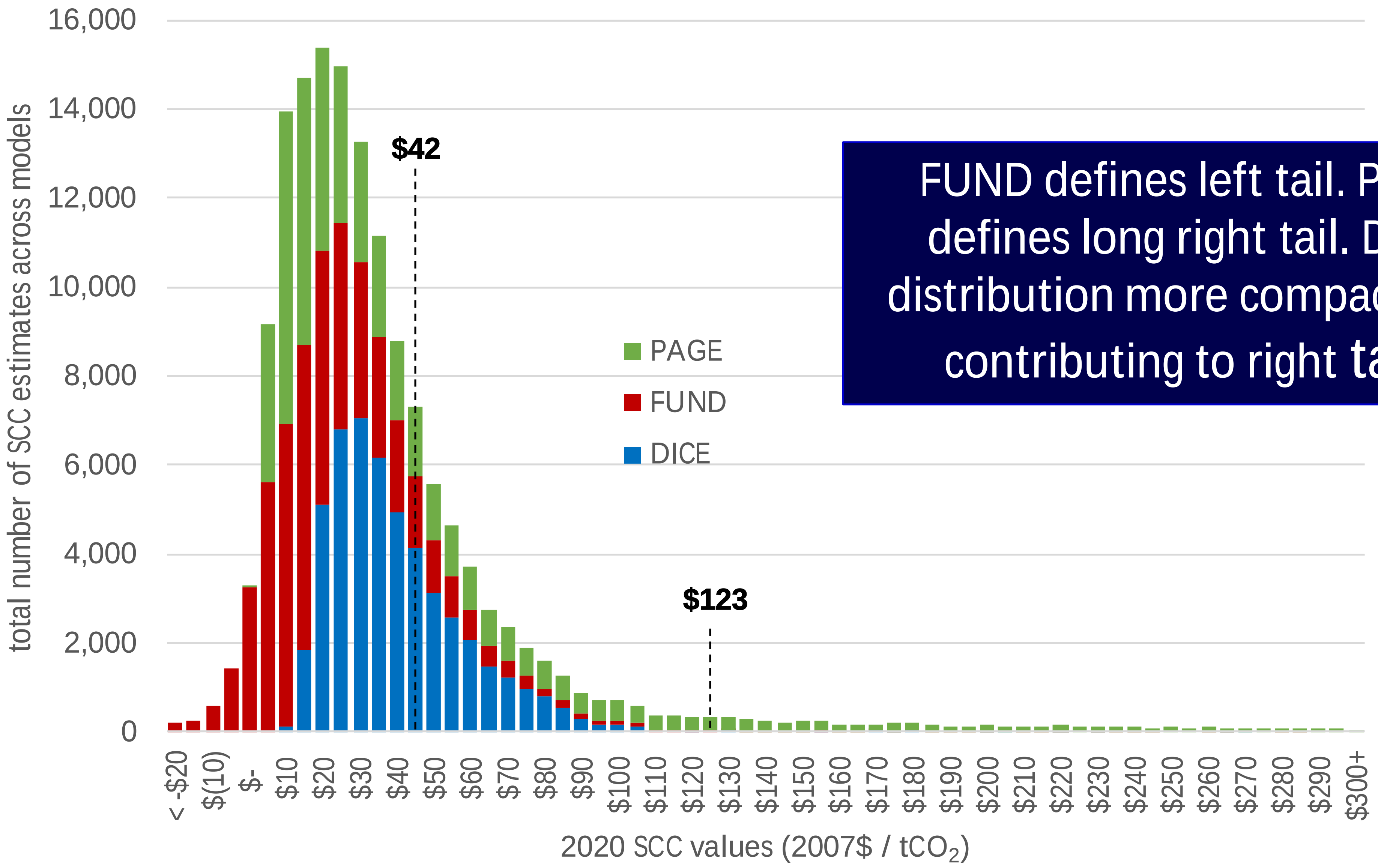
Figure ES-1: Frequency Distribution of SC-CO_2 Estimates for 2020[3]



USG (2016)

The Role of Individual Models in USG SCC Estimates

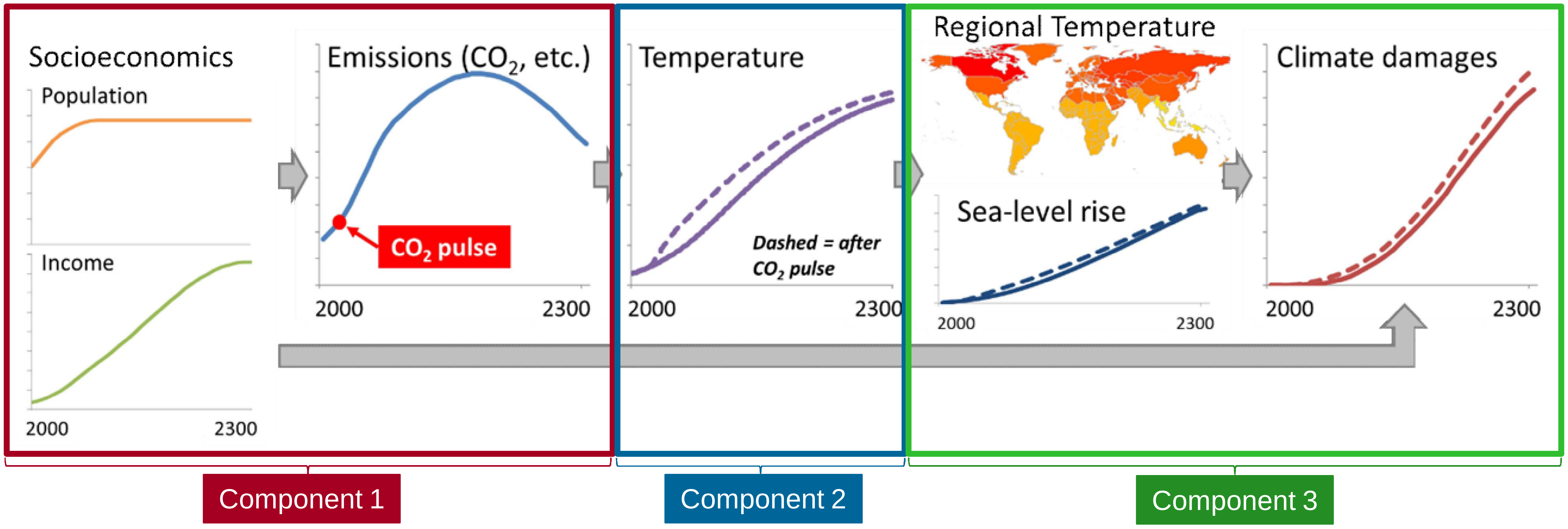
Histogram of the 150,000 SCC estimates behind the USG SCCs for 2020 with a 3% discount rate



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.

Assessment SCC Modeling Component-by-Component & Overall



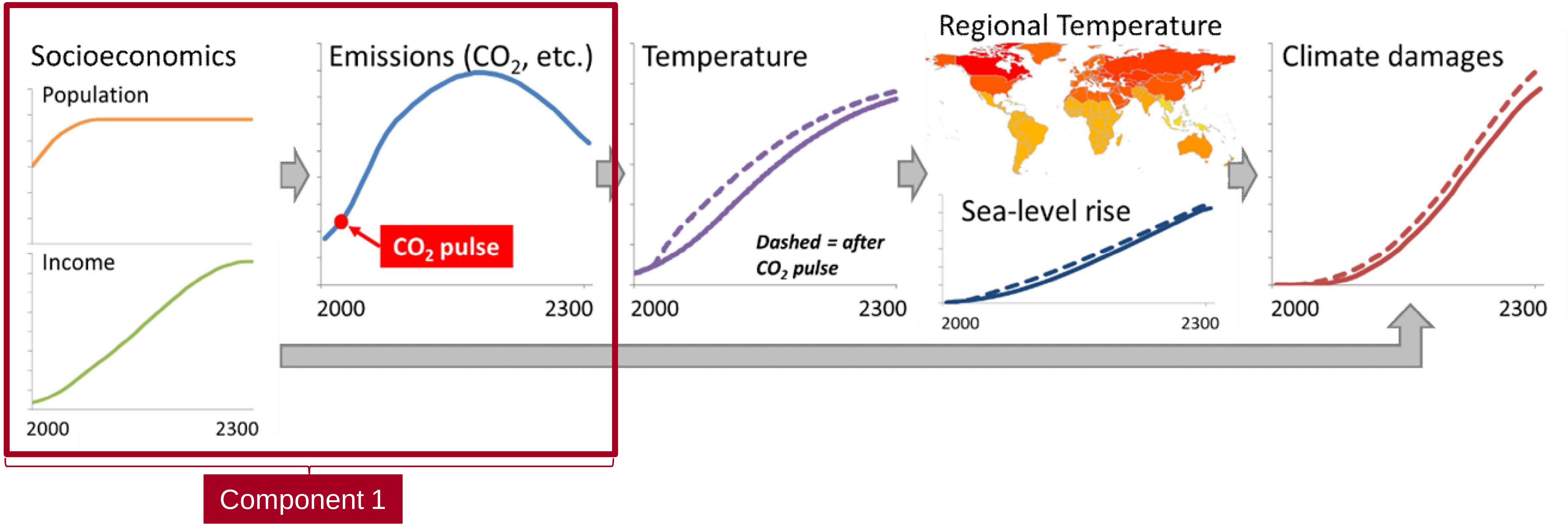
Reviewing modeling & code, programming components, running diagnostic scenarios, comparing, exploring multiple perspectives

- 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

Sample of Component Assessment Results and Insights…

Informing interpretation & assessment by elucidating model behavior, differences, causes

Socioeconomics & Emissions Component Assessment



Socioeconomics & Emissions Component Assessment

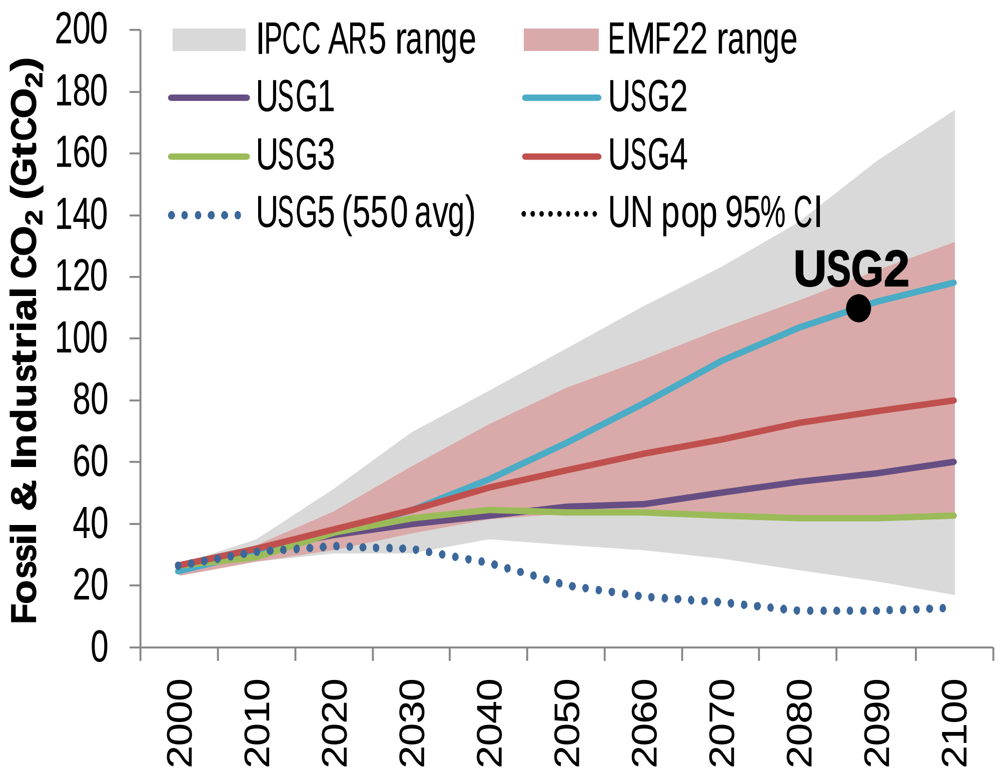
- Explore the following questions:
  - What sort of socioeconomic and emissions **uncertainty** is currently represented in the USG exercise?
  - Is there **additional uncertainty** to consider?
  - Are results **sensitive** to alternative assumptions?
- Evaluate inputs and model structure, and other component analyses informs last question

Socioeconomic & Emissions Inputs
Income (Gross Domestic Product)
Population
Fossil and industrial CO_2 emissions
Land CO_2 emissions
Kyoto non-CO_2 emissions or forcing
Other non-CO_2 emissions or forcing

Global CO_2, Income, and Population Uncertainty

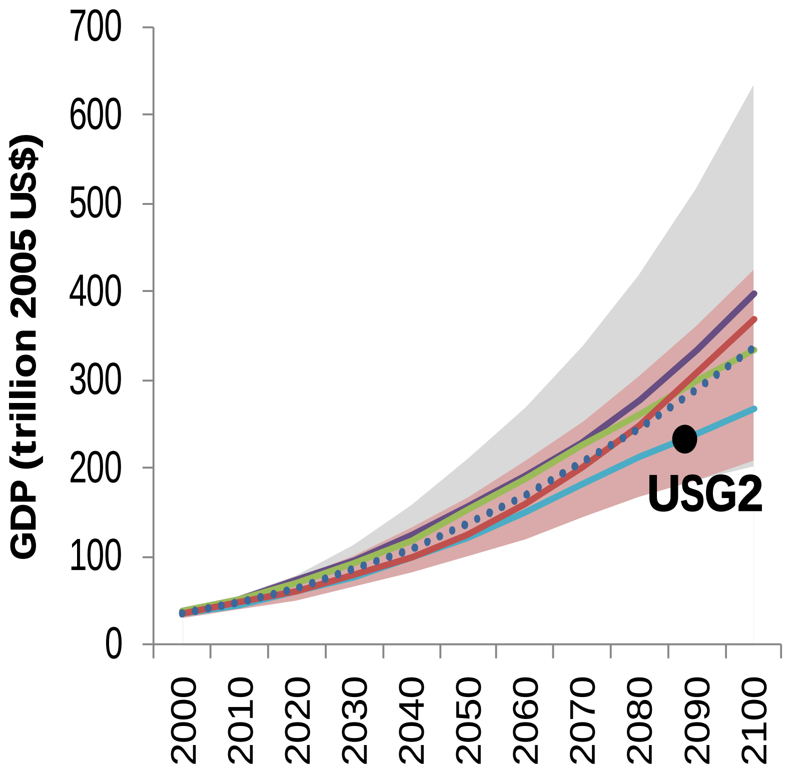
Projections for USG SCC futures and literature ranges

Global fossil & industrial CO_2

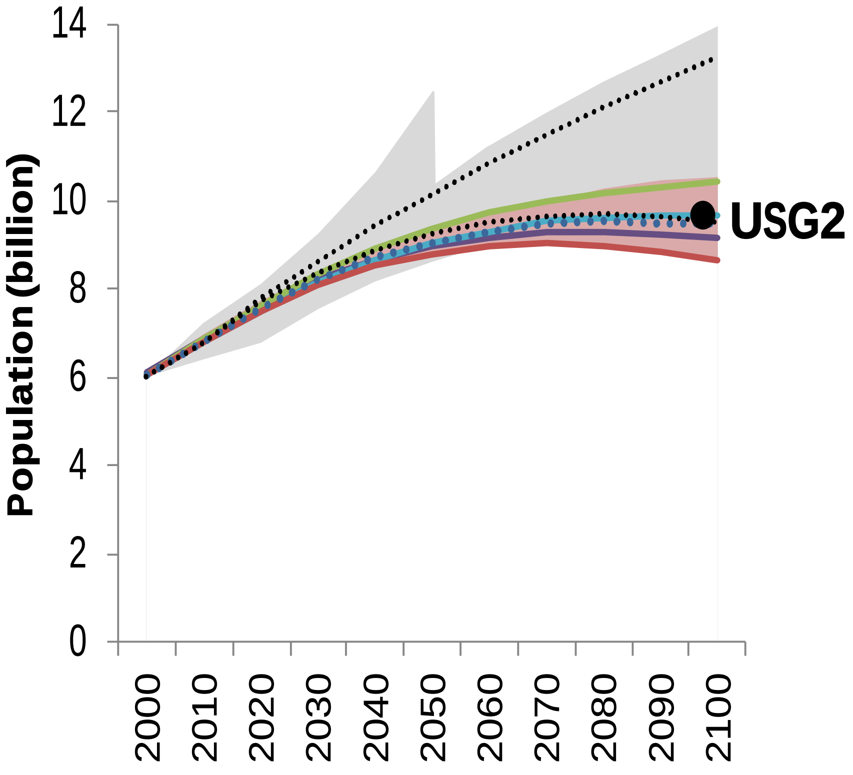


Note – some scenarios only to 2050.

Global income



Global population



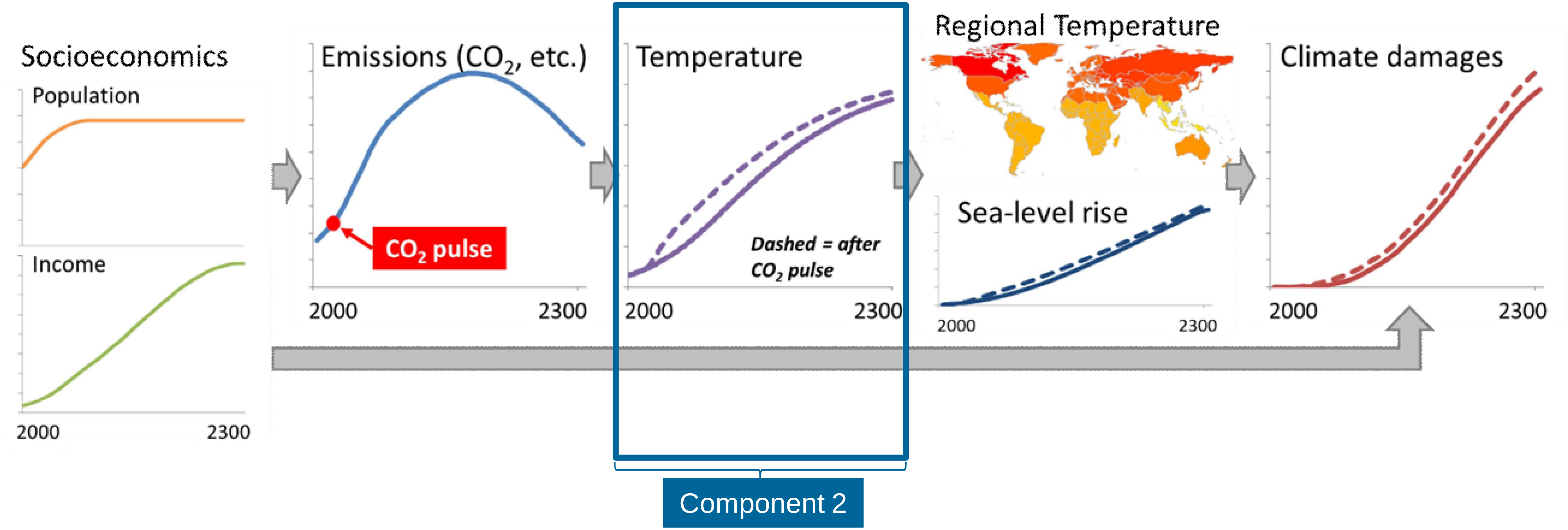
Broader and additional uncertainty to consider beyond that in the USG exercise (variables modeled & relationships). And, need method for assigning probabilities.

Socioeconomics & Emissions Input Implementation

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

Differences in climate forcing agents modeled, and how inputs enter models. Artificial differences.

Climate Modeling Component Assessment



Climate Modeling Component Assessment

- Explore the following questions:
  - How do the **climate models** underlying SCC calculations behave, and are they similar?
  - What do the **incremental climate responses** look like from each model, and are they similar?
  - How do the USG SCC model responses **compare** to more detailed climate models?
- Evaluate model structure, code each model's component, and run diagnostics with standardized emissions & radiative forcing inputs

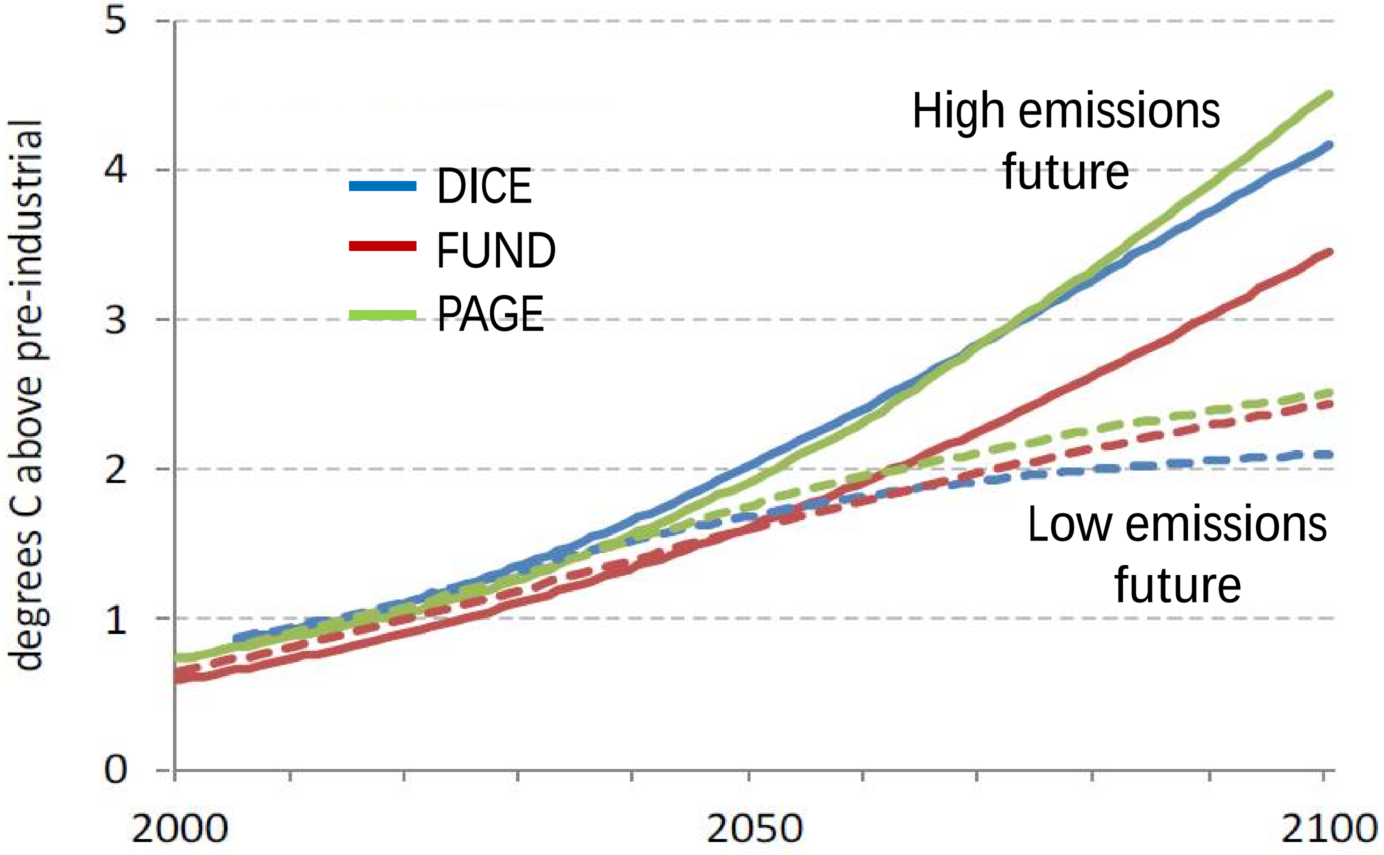
Modeling Structural Characteristics	
Atmospheric concentrations	
	CO_2
	Non-CO_2 Kyoto
	Non-CO_2 non-Kyoto
Radiative forcing	
	CO_2
	Non-CO_2 Kyoto
	Non-CO_2 non-Kyoto
Global mean temperature	
Ocean temperatures	
Climate feedback	
Implementation of CO_2 pulse	
Parametric uncertainty	
Time steps	

Structural differences across DICE, FUND, & PAGE in all characteristics

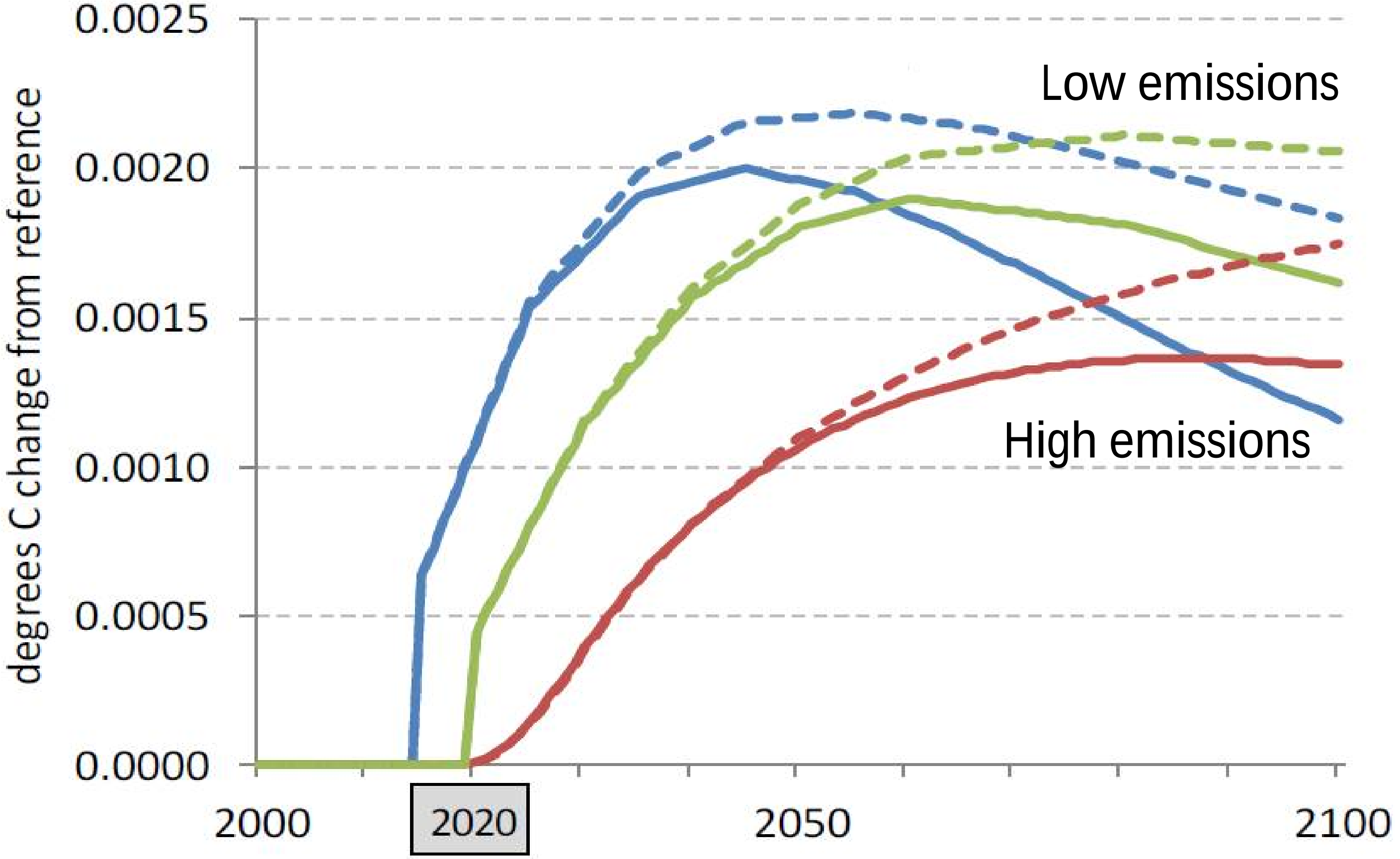
Global Temperature Responses to 2100

(with equilibrium climate sensitivity 3˚C)

Global mean temperature change

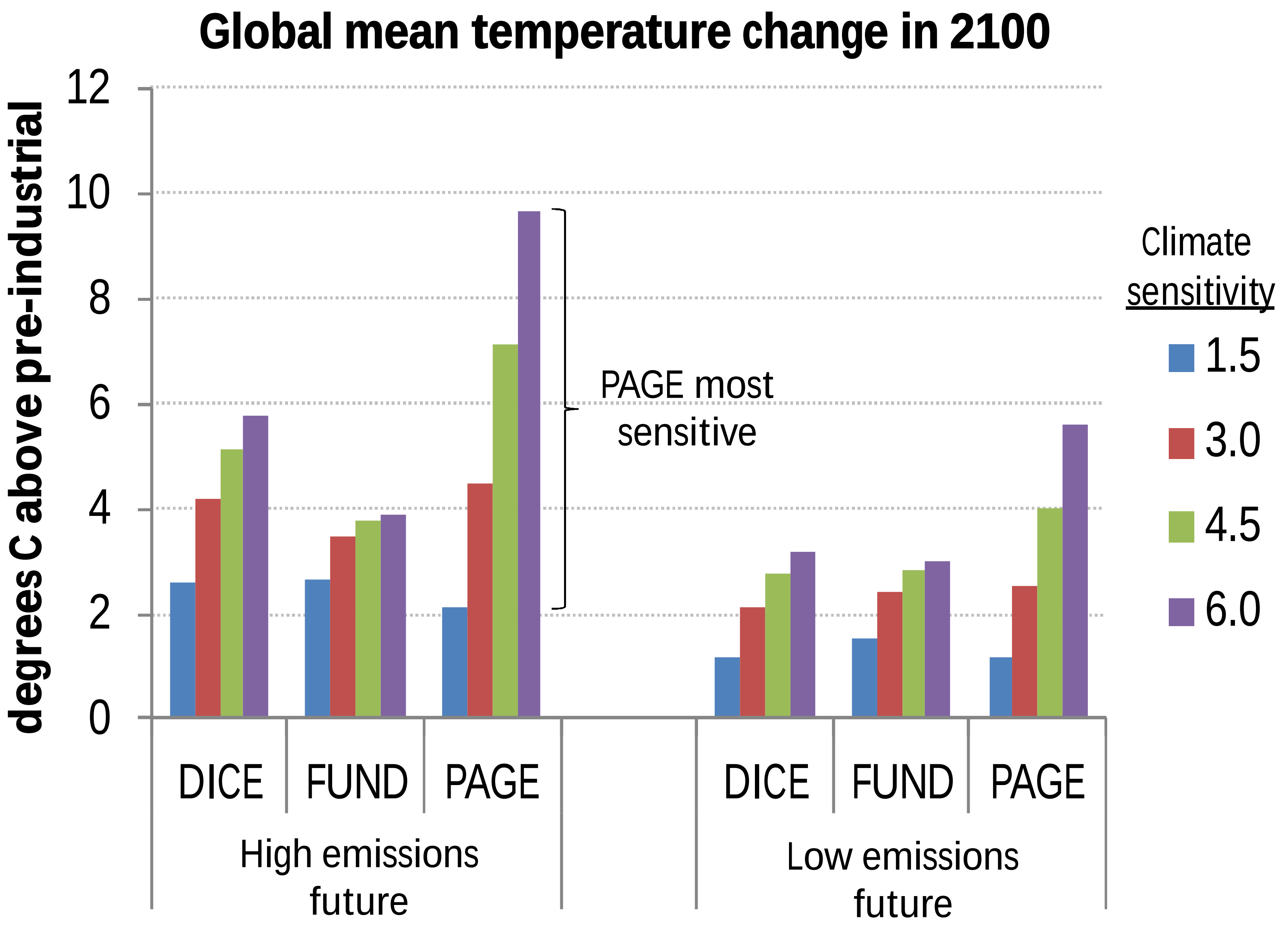


Incremental global temperature change (from 2020 1 billion tC pulse)



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

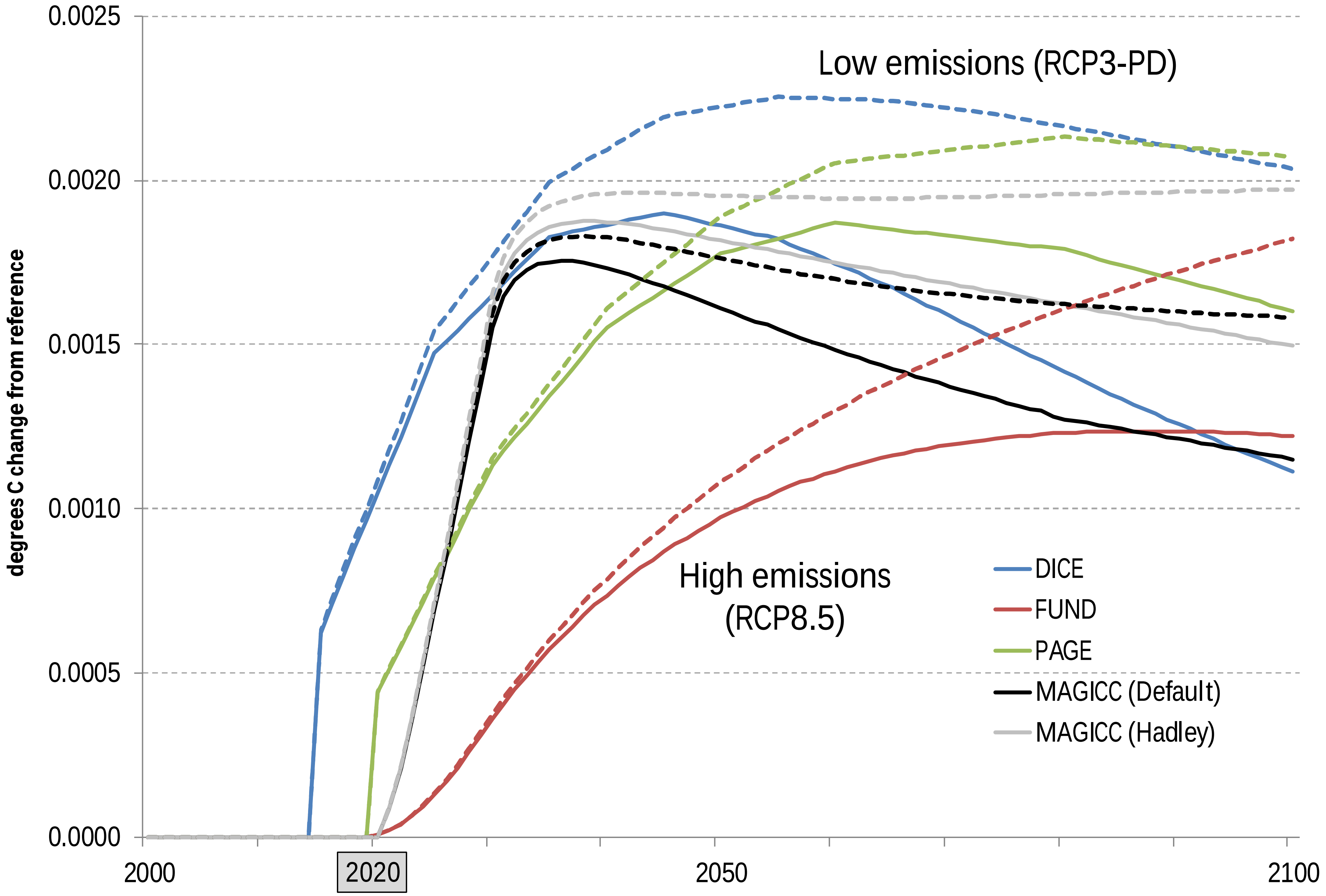


PAGE most sensitive, FUND least sensitive.

PAGE not adjusting rate of temperature response.

Comparing Incremental Temperature Responses to Literature

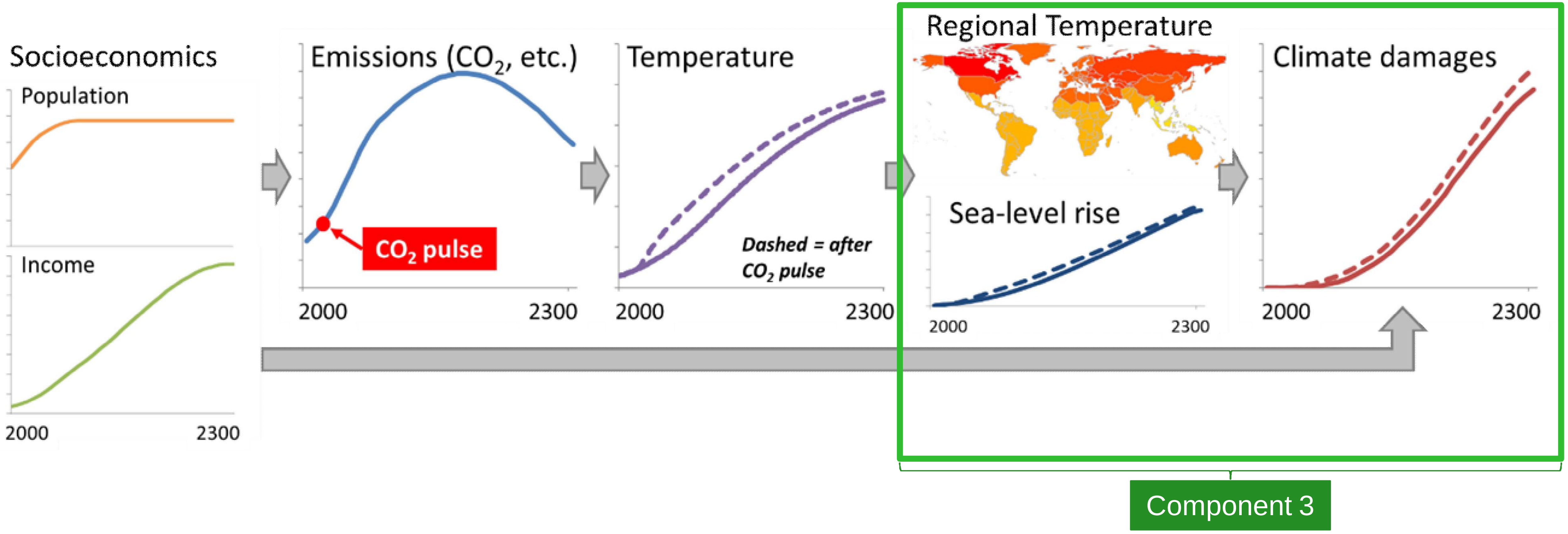
(USG models vs. MAGICC with RCP emissions inputs and equilibrium climate sensitivity 3˚C)



A more complex model (MAGICC) suggests a different climate response

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Climate Damages Modeling Component Assessment



Climate Damages Modeling Component Assessment

- Explore the following questions:
  - What are the **detailed constituents of damages** underlying SCC calculations?
  - How **sensitive** are the damage estimates to alternative assumptions and formulations?
  - How do damage estimates **respond incrementally** to a marginal change in emissions?
- Evaluate model structure, code each model's component, and run diagnostics with standardized climate & socioeconomic inputs

Modeling Structural Characteristics
Global mean sea-level rise
Regional temperatures
Regions
Damage categories
Damage drivers
Damage specifications
Adaptation
Climate benefits
Catastrophe
Parametric uncertainty
Other features

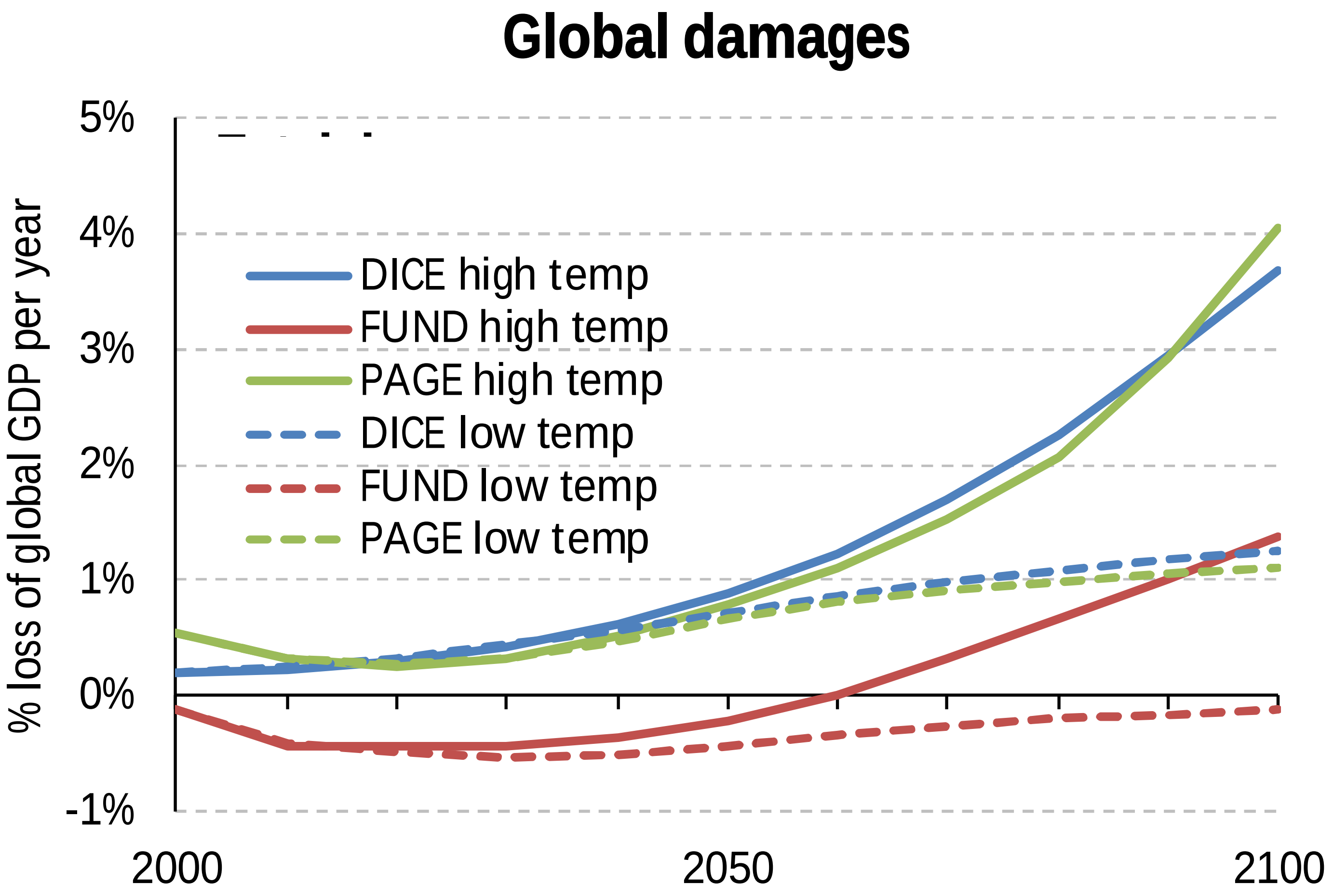
Structural differences across DICE, FUND, & PAGE in all characteristics

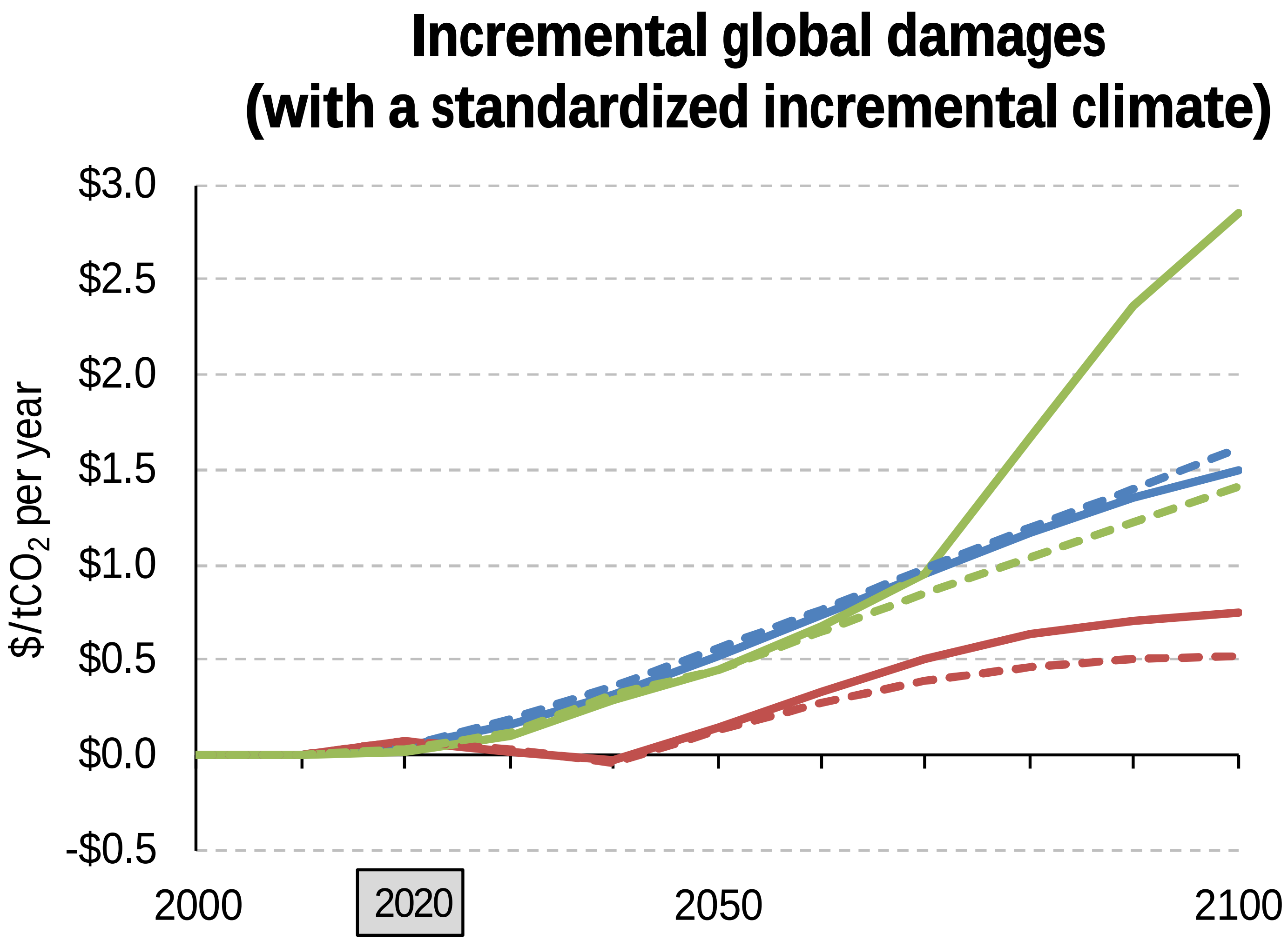
Damage Specifications Literature Basis

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	

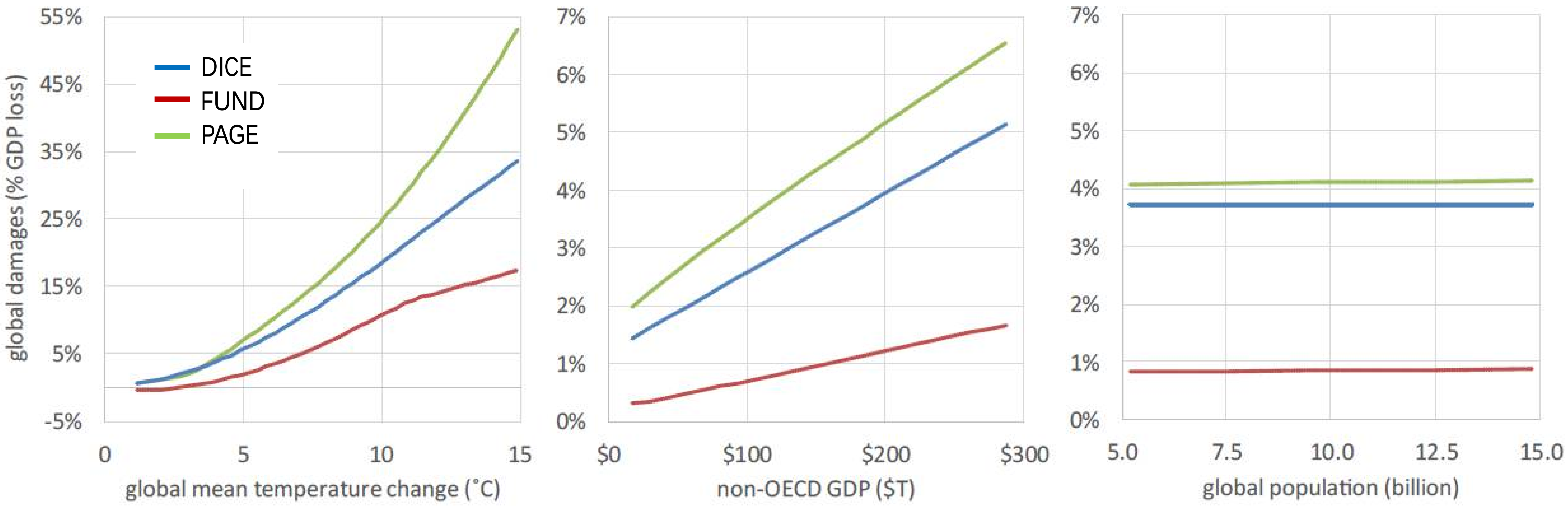
Global Damage Responses to 2100





Significant differences in damage outcomes and sensitivity for the same society & global climate. Trace to modeling features (e.g., sea-level rise, regional temperatures, functional forms and drivers, specific categories, adaptation).

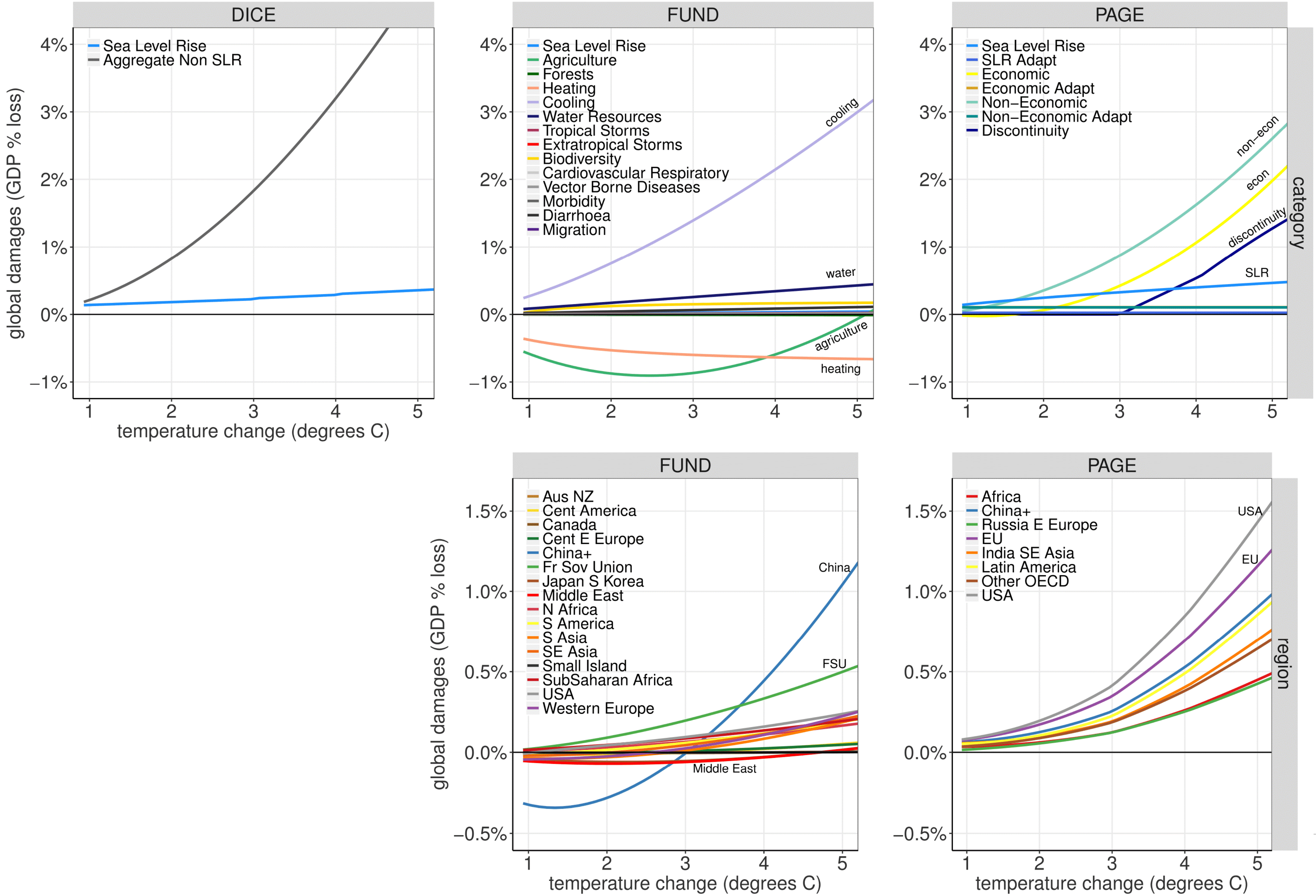
Implied Damage-Driver Relationships from Sensitivity Analyses



PAGE damages systematically more sensitive to key drivers.
FUND systematically less sensitive.

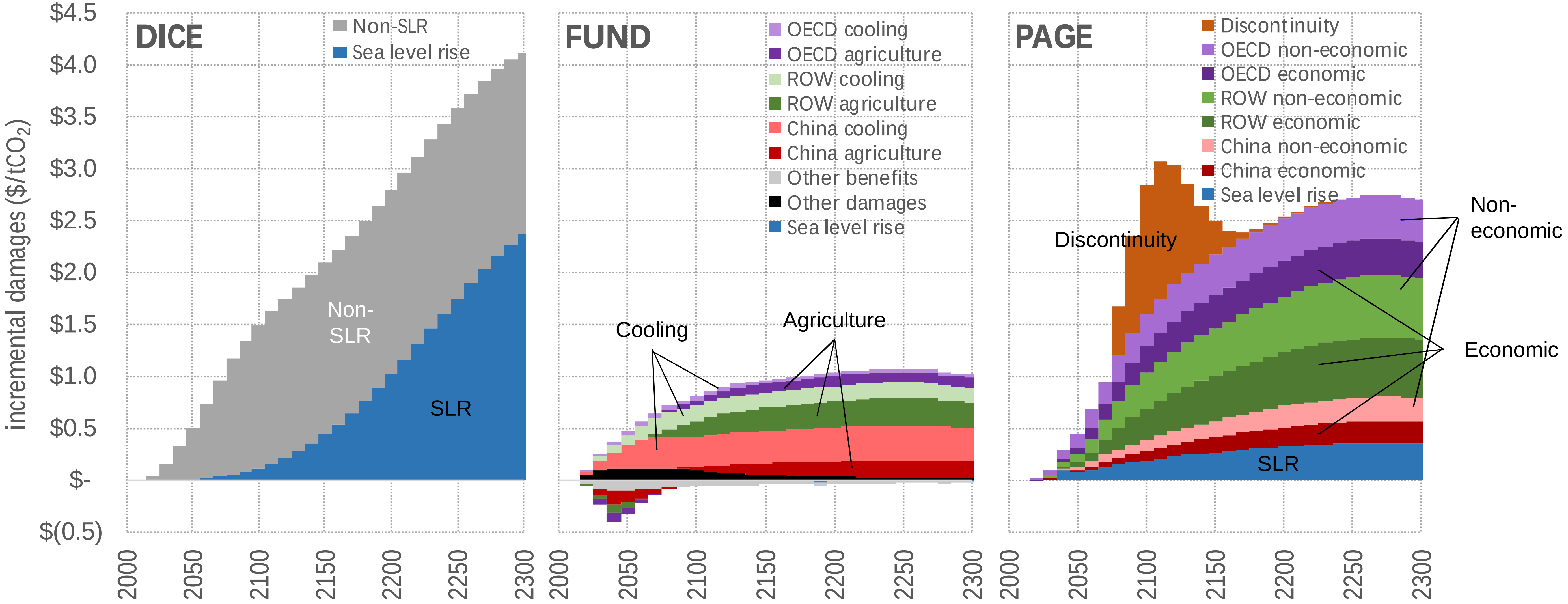
ELECTRIC POWER RESEARCH INSTITUTE

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)

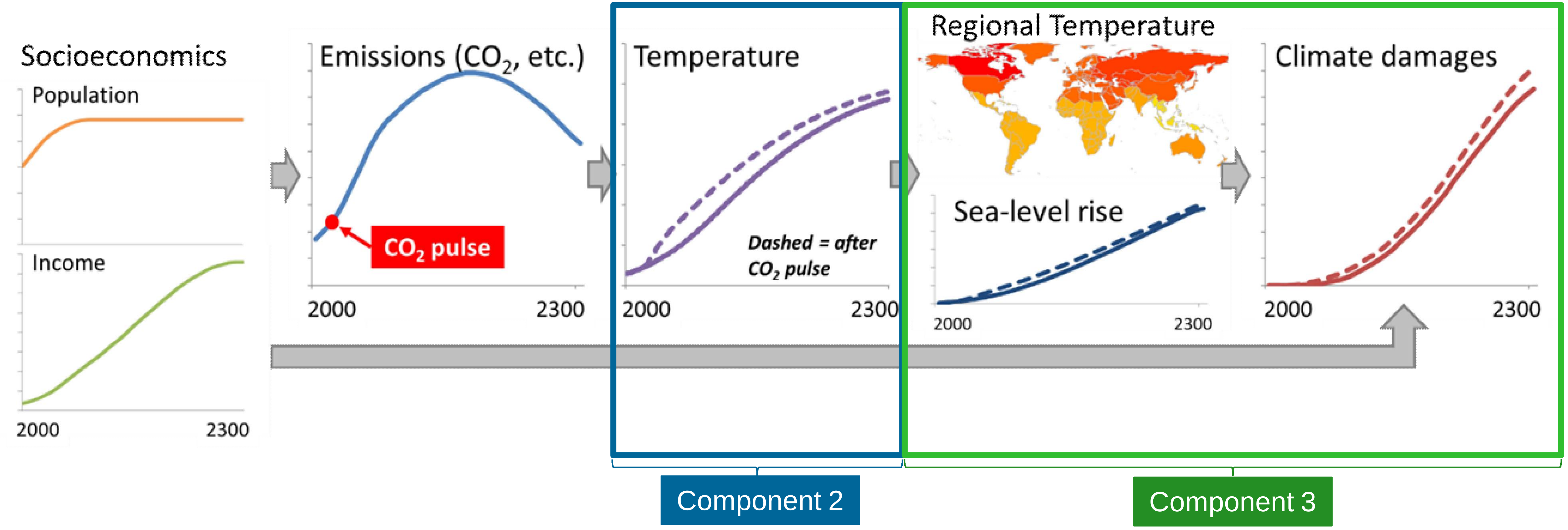
Key Factors of Annual Incremental Damages to 2300



Model specific features dominate incremental damages

ELECTRIC POWER RESEARCH INSTITUTE

Model-Specific Uncertainty in Climate and Damages



ELECTRIC POWER RESEARCH INSTITUTE

Model-Specific Uncertainty in Climate and Damages

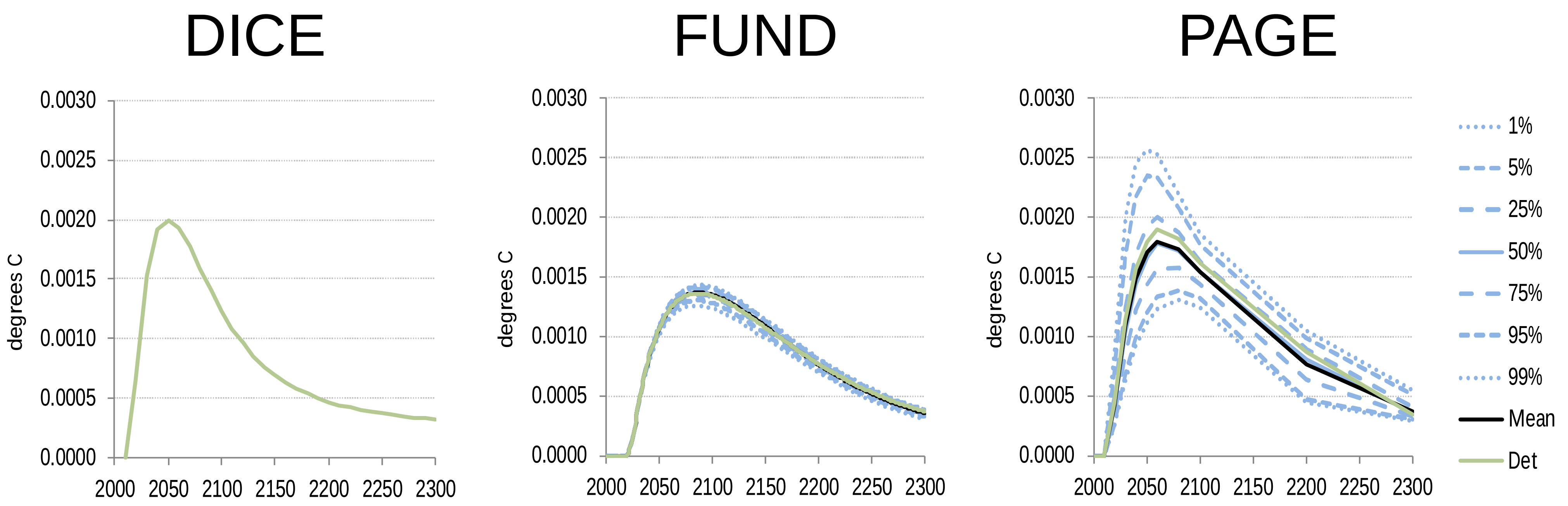
- We also assess climate and damage component probabilistic specifications and behavior
- We code probabilistic versions of both components, and independently run each with standardized inputs and random draws over model-specific component parameters
  - 2500 draws, parameters independently drawn, Latin Hypercube sampling
- Also run MAGICC probabilistically for comparison
  - With model-specific and ECS uncertainties

Model	Uncertain climate parameters	Uncertain damage parameters	Distribution specifications
DICE	0	0	N/A
FUND	11	442 (384 region specific)	Normal, truncated normal, triangular, gamma
PAGE	10	35	Triangular

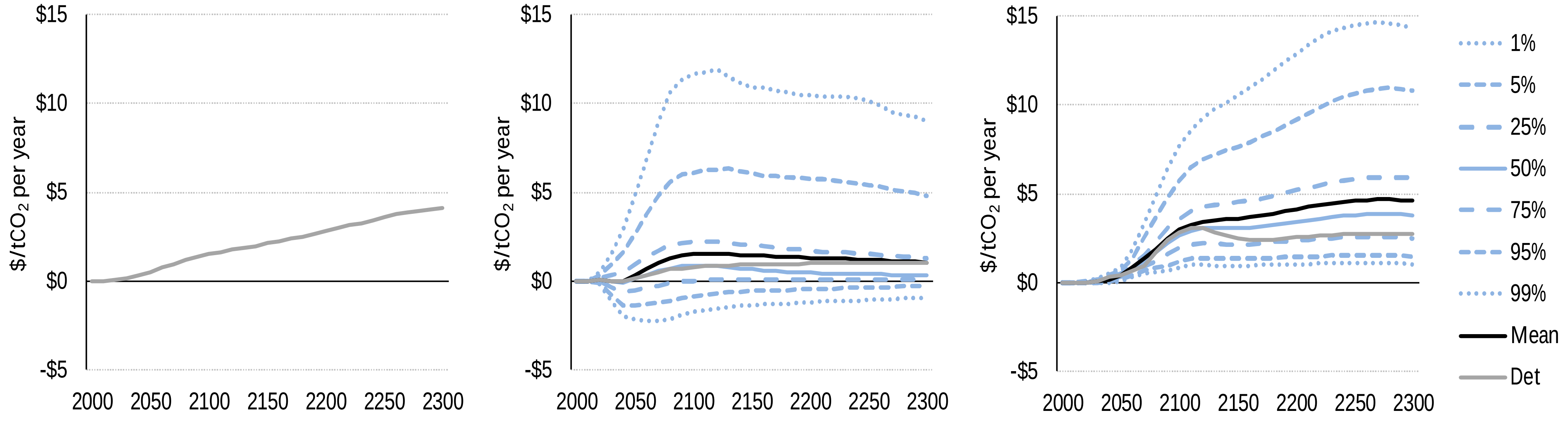
Probabilistic Incremental Climate and Damage Responses

Different uncertainty considered across models contributing to SCC distribution outcomes

Incremental temperatures to 2300*



Incremental damages to 2300#



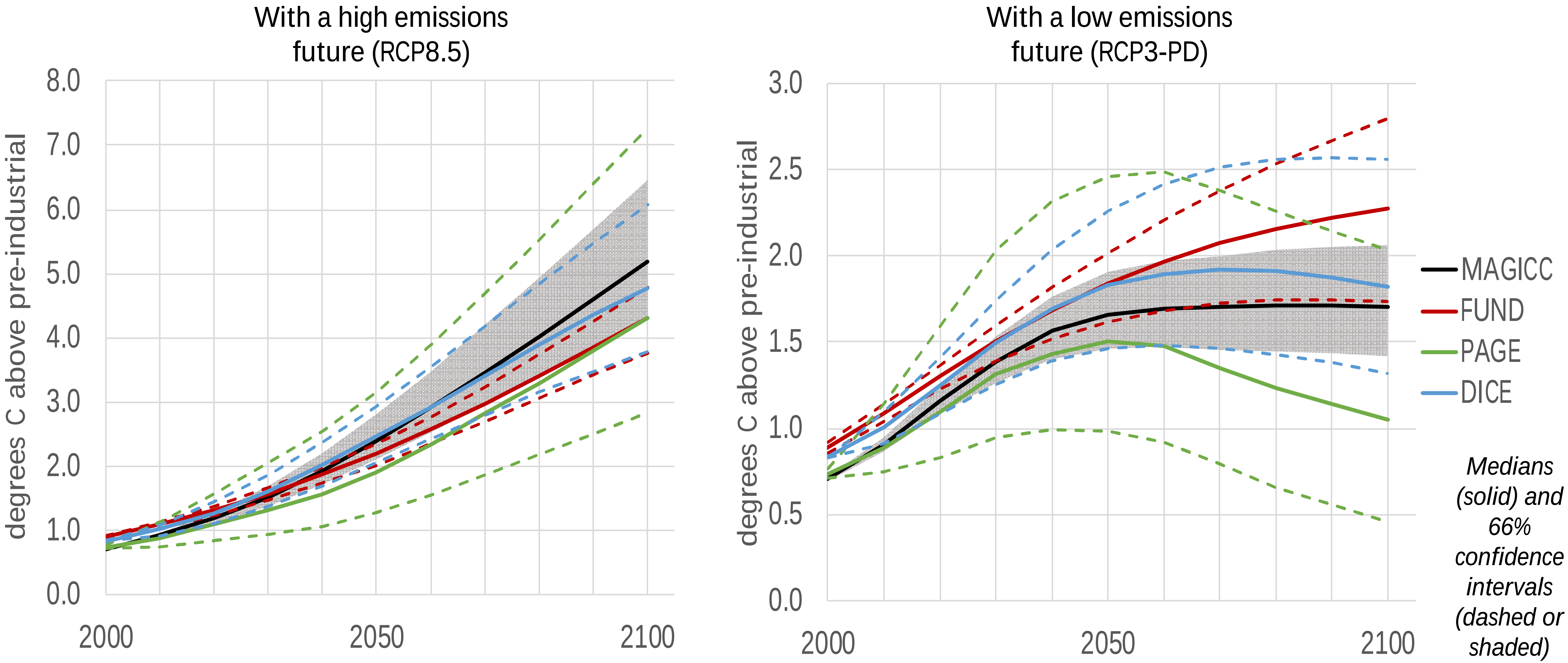
* With high emissions reference, climate sensitivity 3˚C

With high temperature reference, USG2 socioeconomics

ELECTRIC POWER RESEARCH INSTITUTE

Comparing Probabilistic Temperature Responses to Literature

(model-specific and ECS uncertainties modeled)



Medians (solid) and 66% confidence intervals (dashed or shaded) shown

A more complex model (MAGICC) suggests very different climate uncertainty

Summary of Component Assessment SCC Insights

- **Independent component assessments isolate and elucidate differences in model structure, intermediate behavior, and tendencies that help interpret SCC results**
- **FUND produces more compact SCC distributions & lowest averages**
  - Lowest incremental temperature and damage responses
  - More muted sensitivity to uncertainties (emissions, ECS, temp, income)
- **DICE produces larger right tails & higher average SCCs**
  - Higher and earlier incremental temperature and damage responses
  - Most sensitivity to emissions, more sensitive than FUND to other uncertainties
  - Lack of parametric uncertainty contributes to more compact distributions
- **PAGE produces longest right tails & highest average SCCs**
  - Higher and earlier incremental responses, incremental damages highest over long run
  - Most sensitive to many uncertainties (ECS, temp, income)
  - Parametric uncertainty specification further contributing to higher values
- **We also identify model-specific elements that underlie differences. Some differences artificial. All differences need justification.**

Evaluation of USG Experimental Design

- Our component assessments…
  - Accommodate evaluation of individual model SCCs in terms of concrete underlying elements
  - And, provide intimate understanding and comparable model details that allow us to reflect on the overall experimental design and identify opportunities for improvement

- The USG experimental design is defined by a set of methodological choices

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)

- The USG experimental design is novel
  - Nothing like it in the literature
- There are alternatives and the choices affect results
- Clear communication and justification important for peer and public evaluation

Summary of Experimental Design Assessment

- Conceptual motivation behind many choices pragmatic (e.g., incorporating uncertainty, discounting projections)

- Clear issues & opportunities for improvement to provide greater confidence in estimates
  - **Transparency and justification** for individual models, differences, experimental design
  - **Structural uncertainty** representation – some differences artifical and not scientific uncertainty
  - **Input and parametric uncertainty** representation – alternative representations, additional uncertainties, and constraints on what is reasonable
  - **Comparability and independence** of results – in question, but needed for pooling results
  - **Robustness** of results (insensitivity to alternative assumptions) – not likely currently. Could be more so.
  - **Multi-model approach** – reconsideration would be practical. Creates challenges (transparency, justification, comparability, and independence).
    - One idea: develop a model component-by-component – full experimental control, statistically comparable results, greater transparency regarding modeling and uncertainty, utilization of expertise

Illustration of Experiment Design Alternatives and Implications

e.g., Alternative model and scenario weighting

SCCs based only 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

Concluding Remarks

- **Our study objective is to improve understanding of SCC estimation**
  - To facilitate informed dialogue, assessment, decision making, and scientific advances
- **Essential to understand and assess the state-of-the-art**
  - Anyone wanting/needing to value greenhouse gas emissions
- **This 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
- **We observe fundamental scientific issues with current modeling (components to multi-model approach), and opportunities for immediate and longer-term improvement, including peer review**
- **Clear immediate (< 1 year) opportunities to revise for greater confidence in results**
  - e.g., prioritizing models and scenarios, revising inputs, and/or adjusting modeling

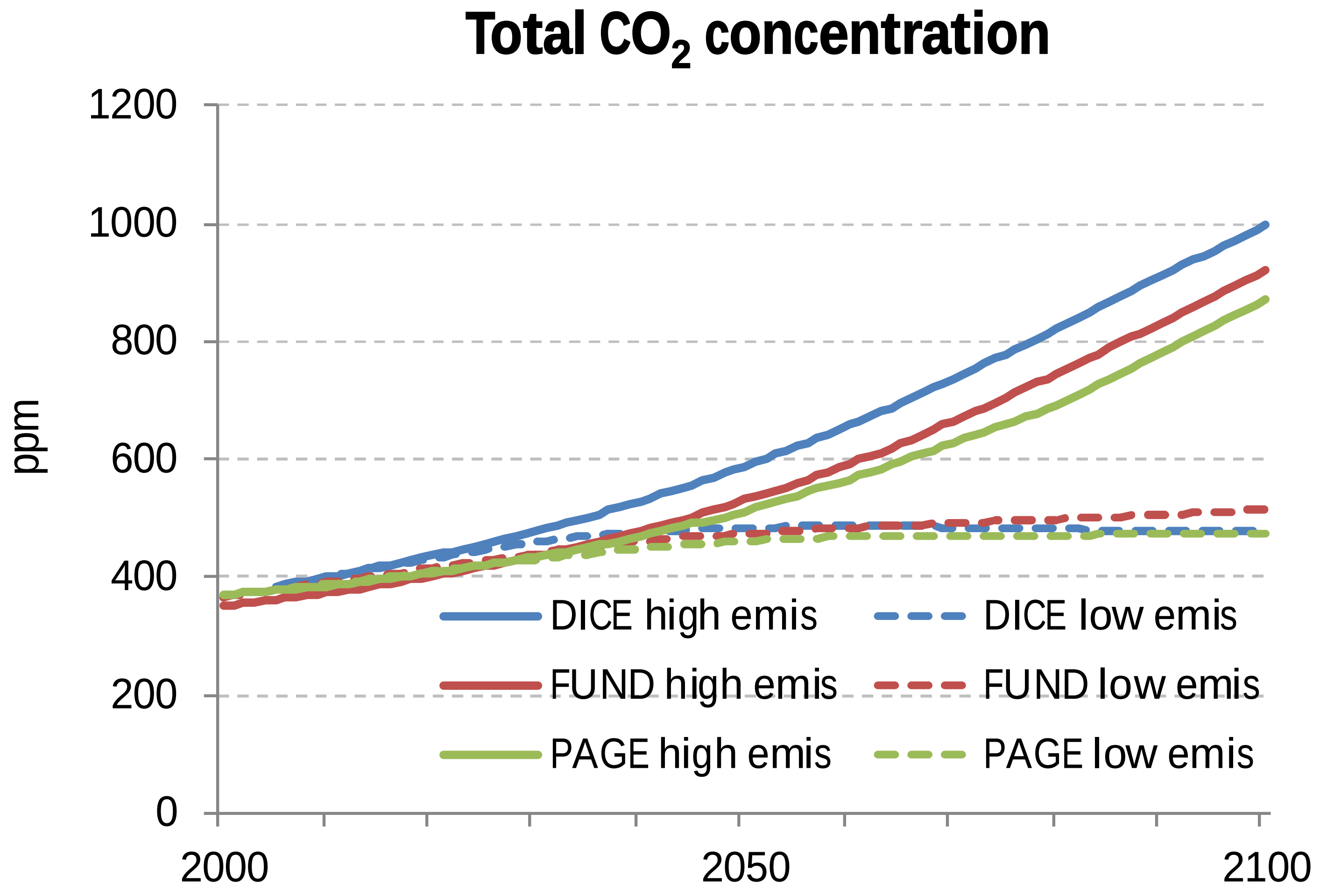
Thank you for joining us today!

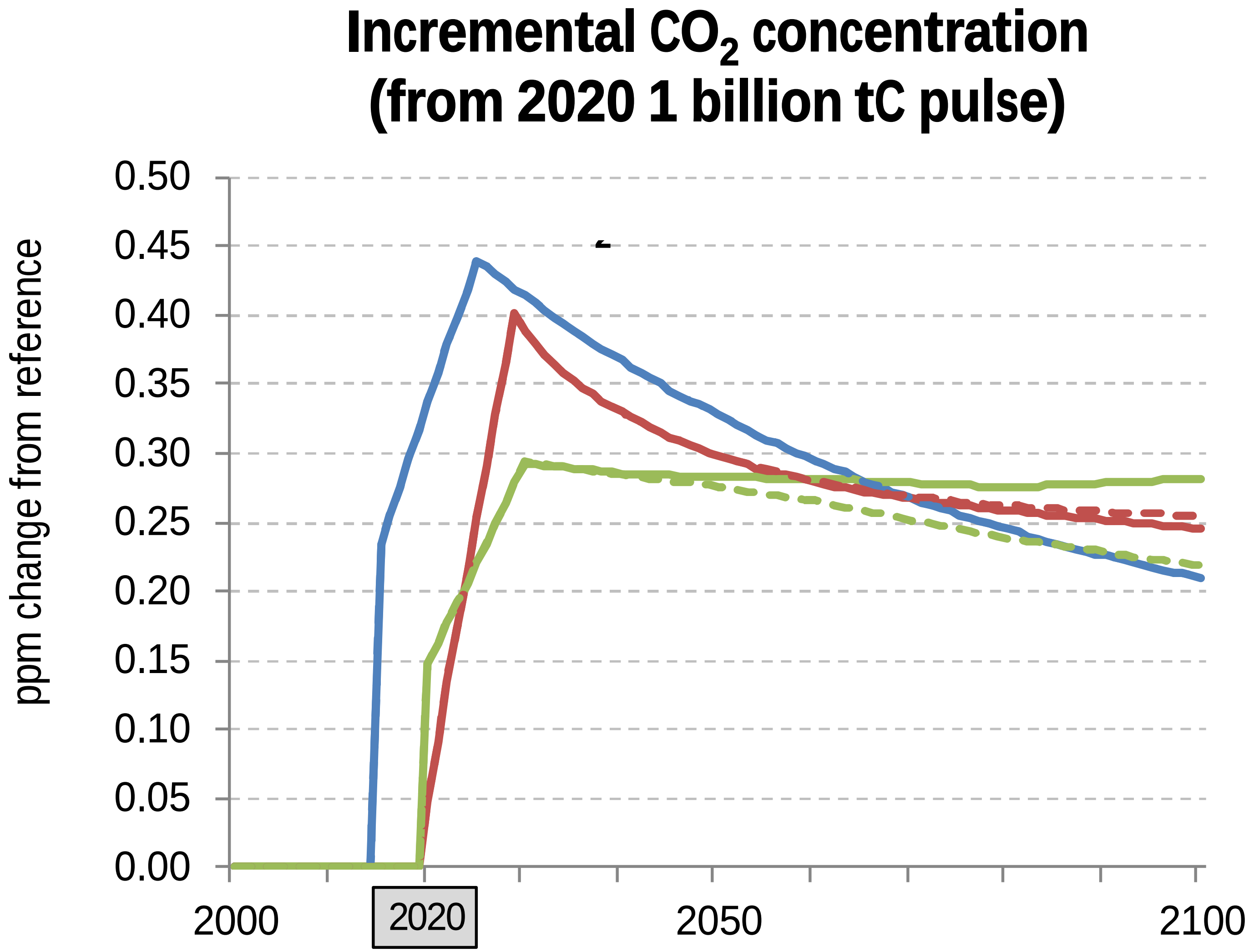
Upcoming EPRI SCC Webcasts

- August 16, 2-3 pm EDT
  - *Social Cost of Carbon Pricing of Power Sector CO_2 Emissions: Accounting for Emissions Leakage and Other Social Implications from Subnational Policies*
- TBD
  - *Applying the Social Cost of Carbon: Technical Considerations*

For further information: srose@epri.com

CO_2 Concentration Responses





Meaningful differences in outcomes and sensitivity for the same inputs. Trace to modeling & implementation features (e.g., carbon accumulation, feedback).