Estimating Climate Damages: Where Do We Stand?

Michael Hanemann

Why does this matter?

- Estimating damages is a crucial component for
  - Setting a Pigouvian tax on CO_2
  - Conducting cost-benefit analysis of mitigation or adaptation
    - At a macro scale
      - What difference would it make if we overshot 2C warming?
    - At a micro scale
      - Evaluating energy efficiency regulations

What is the problem?

- A prolem of free-riding?
- A problem of procrastination?
  - St. Augustine: "O Lord, let me be virtuous, but not just yet."
- There is a tradeoff: current pain incurred, vs future pain (uncertaint) avoided.
- The reluctance to make this tradeoff reflects a widespread perception (in the US, at least) that the damages from future warming (to the US, at least) will be modest.
  - Based on findings from DICE model ove rpast 20 years

- The context is estimating damages as part of an Integrated Assessment Model (IAM).

- But, first, it is necessary to distinguish between two types of IAM.

Integrated Assessment Models

IAMs link:

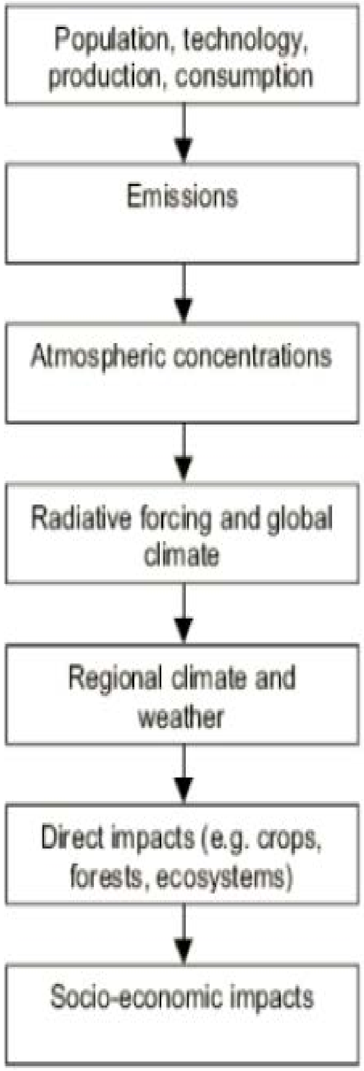
Economic output

The generation of GHG emissions

The change in global average annual temperature, ΔT (via a simplified representation of the carbon cycle)

Impacts on human well being

Changes in economic output



Two types of IAM

I. Many economy-wide models do *not* represent the damages of climate change. They trace the link from economic activity to the emission of GHGs, to changes in global climate, but not the link from that to damages.
   - Typically with a detailed representation of the energy sector.
   - Used to measure the cost of meeting a target warming.

II. There is only a handful of IAMs that include a representation of the economic impacts ("damage") of climate change.
   - It is these models that have been used to calculate estimates of the Social Cost of Carbon.

The main IAMs used to calculate the social cost of carbon

- Three IAMS have received most attention in this literature, all developed in the 1990s.
  - DICE, first version appears in 1991/1992.
    - Updates in 1999, 2007, 2010, 2013.
  - PAGE, first version appears 1991/1992.
    - Updates in 1995, 2002, 2009.
  - FUND, first version appears ~1994.
    - Multiple updates. Version 3.5 used in 2010; version 3.8 used in 2013.
  - The models have undergone various refinements and updates. While the details have changed, their general structure has stayed same.
    - Updating has focused more on the carbon cycle than on the damage function

Damage functions at a cross-roads

- The existing IAMs have been forcefully criticized by Pindyck
- The US Government's use of the models in 2010/2013 to estimate a Social Cost of Carbon (SCC) has drawn attention, criticism, and litigation.
- A growing conceptual literature challenges the way damages are formulated.
- A growing empirical literature estimates impacts of weather on GDP and finds starkly different results from what the IAMs predict.

Pindyck (2013)

- IAMs "so deeply flawed as to be close to useless as tools for policy analysis."
- The damage functions "are not based on any economic theory. They are just arbitrary, made up to describe how GDP goes down when temperature goes up."
- "We know almost nothing, so developers of IAMs can do little more than make up functional forms and corresponding parameter values."

How were the damage functions formulated?

Are those criticisms valid?

THE REPRESENTATION OF DAMAGES

- The monetized damages (the willingness to pay to avoid damages) are expressed as proportional (i.e., a *percentage*, D_t) to current GDP in t.
- They are a function of the current warming in period t.
  - No other climate variable (e.g., precipitation, humidity etc) is included.
  - Warming measured as change in global annual average temperature (ΔT).
- In DICE and PAGE, the damage functions are calibrated in a very simple manner.
- In FUND, the damage functions are more complex, but based on simple, cross-section regressions.

What is assumed in DICE formulation

- The DICE-style damage function represents the damages as a proportional reduction in annual production.
- This implies that damages are:
  - Reversible from period to period as output varies
  - Independent of past levels or rates of warming, or of the cumulative degree of warming in the past.
  - Devoid of lingering effects, including impacts on stocks of capital, whether physical, human or natural.

A two-parameter damage function (*a*, *b*)

- The mapping from ΔT_t to D_t is represented by a simple reduced-form equation, calibrated to damages estimated at some benchmark temperature change, ΔT^*.
- The percentage damage in year t is given by:

$$D_t = a[\Delta T_t/\Delta T^*]^b$$

- When $\Delta T = 0$, $D_t = 0$.
- When ΔT equals the benchmark ΔT^*, $D_t = a$.
  - The value of *a* was estimated from 1990s era studies of damages when a doubling of CO_2 concentration occurs (which determined the benchmark value ΔT^*, typically ~2.5C).
- The coefficient *b* determines damages when $\Delta T \neq 0$ and $\Delta T \neq \Delta T^*$.
- In DICE, b=2.
- In PAGE, b is a random variable taking values 1,2 or 3.
- FUND has a more complex structure, and b is set at more specific values.

Calibration of the damage function

- In DICE and PAGE, it was calibrated to an estimate of damages at the benchmark level of warming (~2.5C).
- That benchmark was constructed sector by sector, using various estimation techniques.
  - Process models
  - For DICE, based on US EPA's 1989 Impact Assessment
- These were all projections
  - Not based on actual data (current warming = 0.8C)
  - Not based on econometric analysis (except FUND, which largely used cross-section regressions)

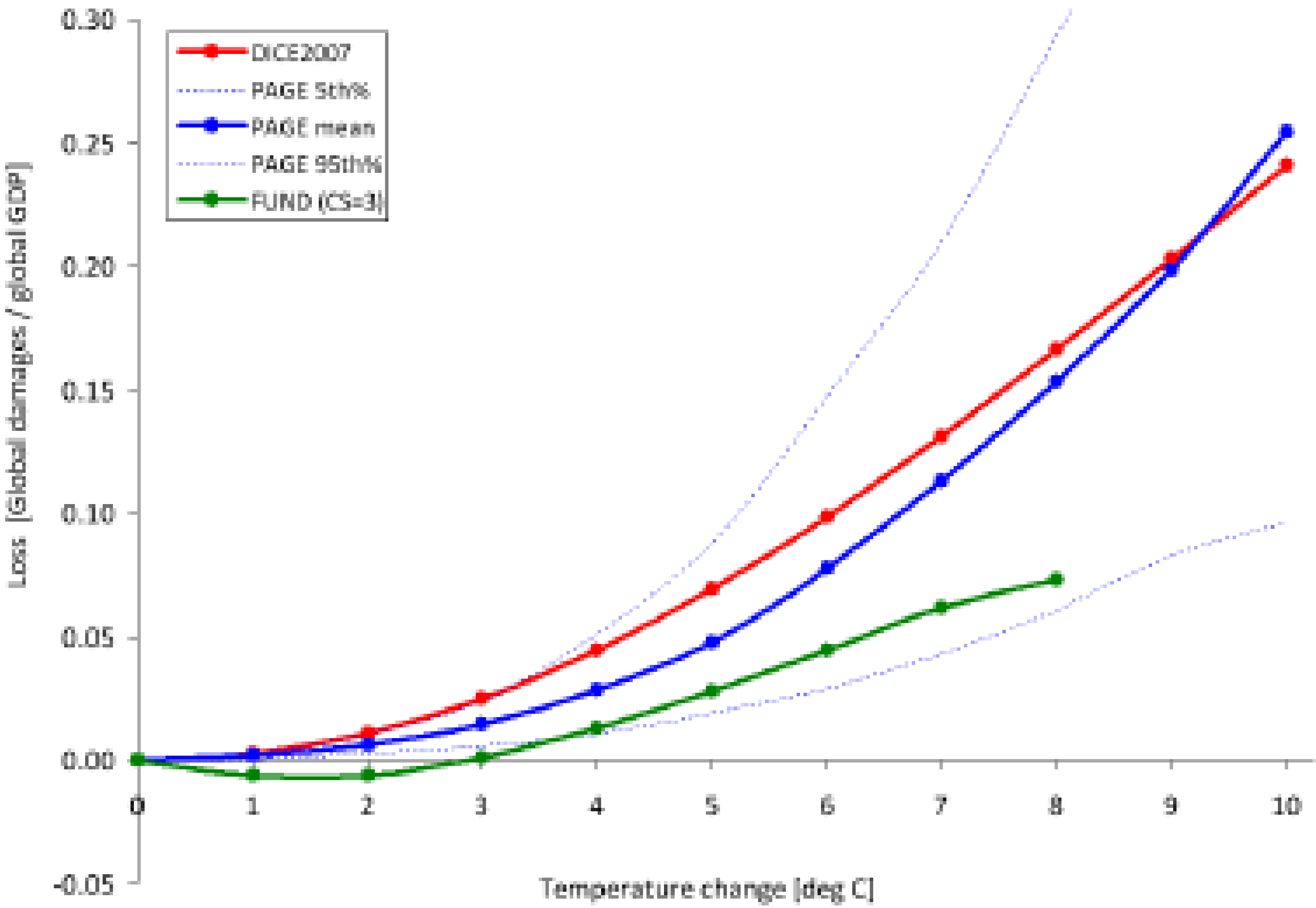
IAMs use an outdated literature

- In 1990s, when IAMs first developed, the damage functions were in line with the economic estimates of damages then available.
- But, the IAMs have not kept up with the literature appearing since 2001.
- DICE cites ~25 studies, almost all pre-2001
- FUND cites 32 studies, 28 before 2002
- PAGE cites 8 studies, 7 from 2006-9
- These IAMs cite ~50 studies in total, most dating from before ~2001.

Current extent of literature (Web of knowledge)

- "Climate change," "damages," "economic impacts"
  - 39 papers through 1999
  - 136 papers, 2000-2009
  - 209 papers, 2010-2013
- "Climate change, "cost"
  - 4822 papers
- "Climate change," "impacts"
  - ~75,000 papers
- Newer studies are spatially downscaled, temporally disaggregated, show higher damages.

The damage functions



How could one judge credibility?

- What do the damage functions say about the effects of the warming currently experienced?
  - So far, this question has not been posed.
  - It was not addressed in the recent US national assessment, since impacts were not monetized.
    - It was addressed in the recent Austrian assessment.
- What is the sectoral composition of damages? Is that credible?
  - The evidence there is troubling.

Sectoral decomposition of damages is highly idiosyncratic across IAMs

- Where sectoral disaggregations were given by the IAMs, they seem odd (e.g., DICE, FUND).
- The sectoral decomposition varies among IAMs in a highly idiosyncratic manner.

Divergent decompositions of global damage

- FUND:
  - Single largest component is damage to energy (2/3 total)
  - Second largest is water
  - Health impact is small component of “other”
  - The damages are offset by a large *gain* to agriculture, which reduces the total cost by half
- DICE:
  - no damage to water
  - almost zero damage to energy
  - a small loss to agriculture.
  - health and human life is small, amounting to half of agricultural impact

The Social Cost of Carbon in the US

- An Interagency Working Group (IWG) was formed to develop an estimate of the Social Cost of Carbon (SCC) -- the discounted present value of the increment in damages associated with the emission of an additional ton of CO_2 in a given year (e.g., 2015).
- This value was to be used by federal agencies when assessing costs and benefits of major federal regulations.
- Performed in 2010, repeated in 2013.

2013 SCC (corrected July 2015)

Revised Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
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

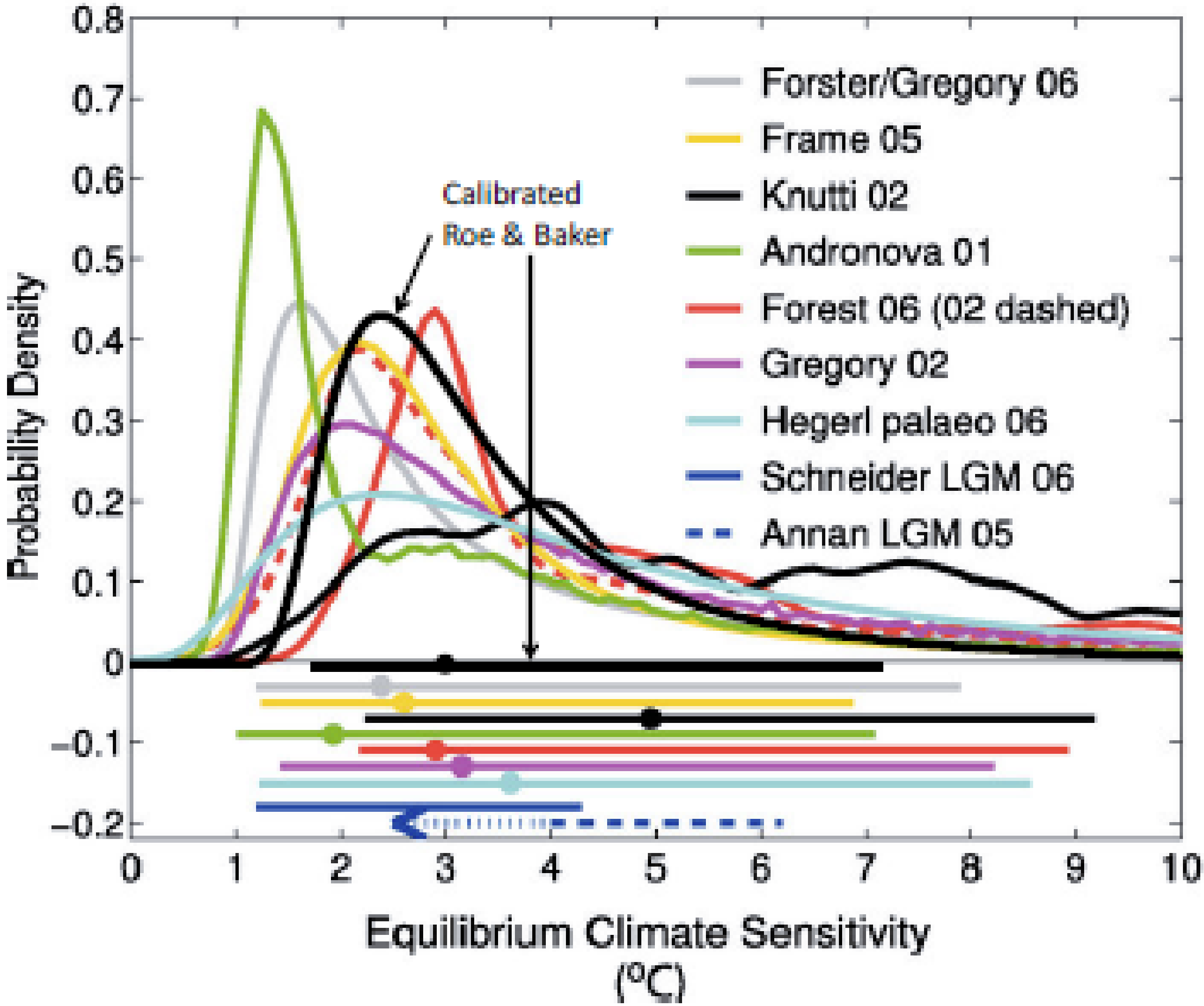
What the federal government did

- Used DICE, FUND, PAGE.
- Weighted results equally across IAMs.
- Standardized the emissions that drive the models.
  - Changed DICE from an optimization to a simulation mode.
  - Projected emissions through 2300
    - Used the best known four of the ten BAU emissions scenarios from the EMF-22 model inter-comparison in 2008.
    - Added a fifth emission scenario keyed to 550ppm in 2100.
    - Extended the five emissions projections from 2100 to 2300.
- Monte Carlo simulation of the value of the climate sensitivity; 10,000 draws from the Roe-Baker distribution.
- Three discount rates: 2.5%, 3% and 5%.
- 150,000 simulations for each of DICE, FUND, PAGE.
  - 5 emission scenarios; 3 discount rates; 10,000 draws.

How to generate the SCC value for 20xx

A. Run the model with the given emission trajectory and the given value of the climate sensitivity.
    a. The model starts in January 2010 and runs to December 2300.
B. For each time period, calculate the warming and the resultant damage in that period.
C. Introduce a one-time pulse of emissions in 20xx. In other periods, emissions are unchanged.
D. Re-run model.
E. For each period, calculate the warming and the resultant damage in that period.
F. Calculate discounted present value of the differences in damages, (E) - (B), from 20xx through 2300.

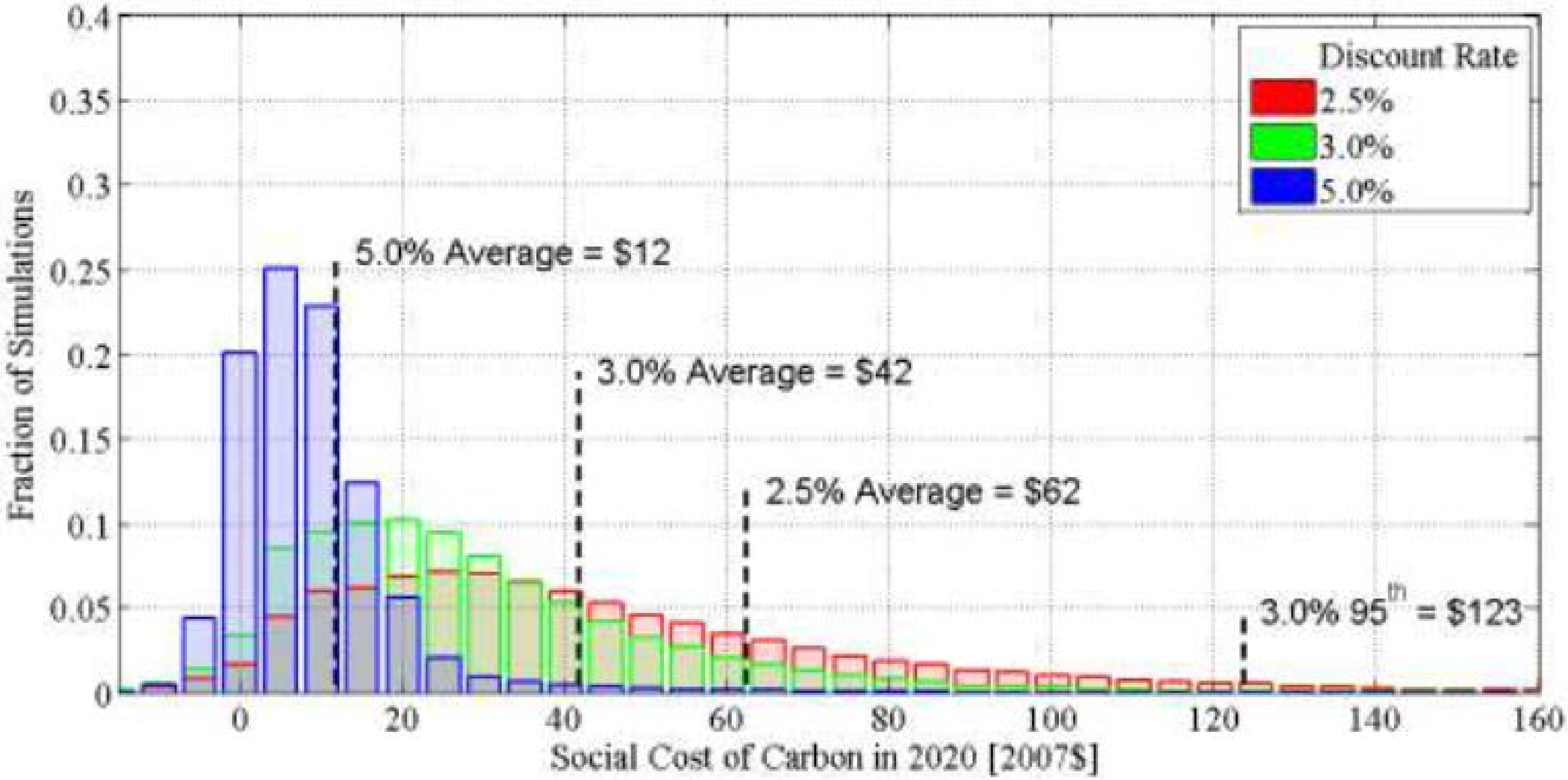
Figure 2: Estimates of the Probability Density Function for Equilibrium Climate Sensitivity (°C)



A distribution of SCC values

- For each of the three models, and each of the three discount rates, this generates an empirical pdf distribution of 50,000 values.
- The IWG presented the mean, and also the 95-percentile value, across the 150,000 values for each of the 3 models combined, using the given discount rate,

Distribution of SCC Estimates for 2020 (in 2007$ per metric ton CO_2)



The Minnesota proceeding

- The question of whether the 2013 IWG SCC estimate is reasonable, and is the best available estimate, is being addressed in a trial before two Administrative Law Judges.
- The parties include:
  - Minnesota Department of Commerce (retained me)
  - Clean Energy Organizations
  - Peabody Energy Corporation
  - Minnesota Power, Otter Tail Power, & Great River Energy
  - Minnesota Large Industrial Group (MLIG)
  - Xcel Energy

Issues raised

- Is it legitimate to weight the IAMs equally?
- Is it legitimate to "switch off" the optimal growth aspect of DICE, using external projections of future GDP and emissions?
- Is it appropriate to project emissions and impacts through 2300, or should one stop earlier (e.g., 2100 or 2140)?
- Was it appropriate to use the Roe & Baker distribution for the climate sensitivity? Should a single value have been used?
- What discount rate should be applied to future damages?
- Is it legitimate to use the mean of the distribution of SCC values?
- Are the damage functions reliable for the levels of warming that could arise?

Should the three IAMs be weighted equally?

- The Federal SCC exercise was the first time ever that three models have been compared in any systematic manner -- the first time they have been run side by side with similar inputs.
- No researcher previously had effective access to all three models.
- Such a model inter-comparison was long overdue.
  - It raises issues about the rationale for some of the differences
- In 2014, EPRI recoded all 3 models into a common coding language. This highlighted further differences and idiosyncrasies.
  - This also would permit mixing of model components.

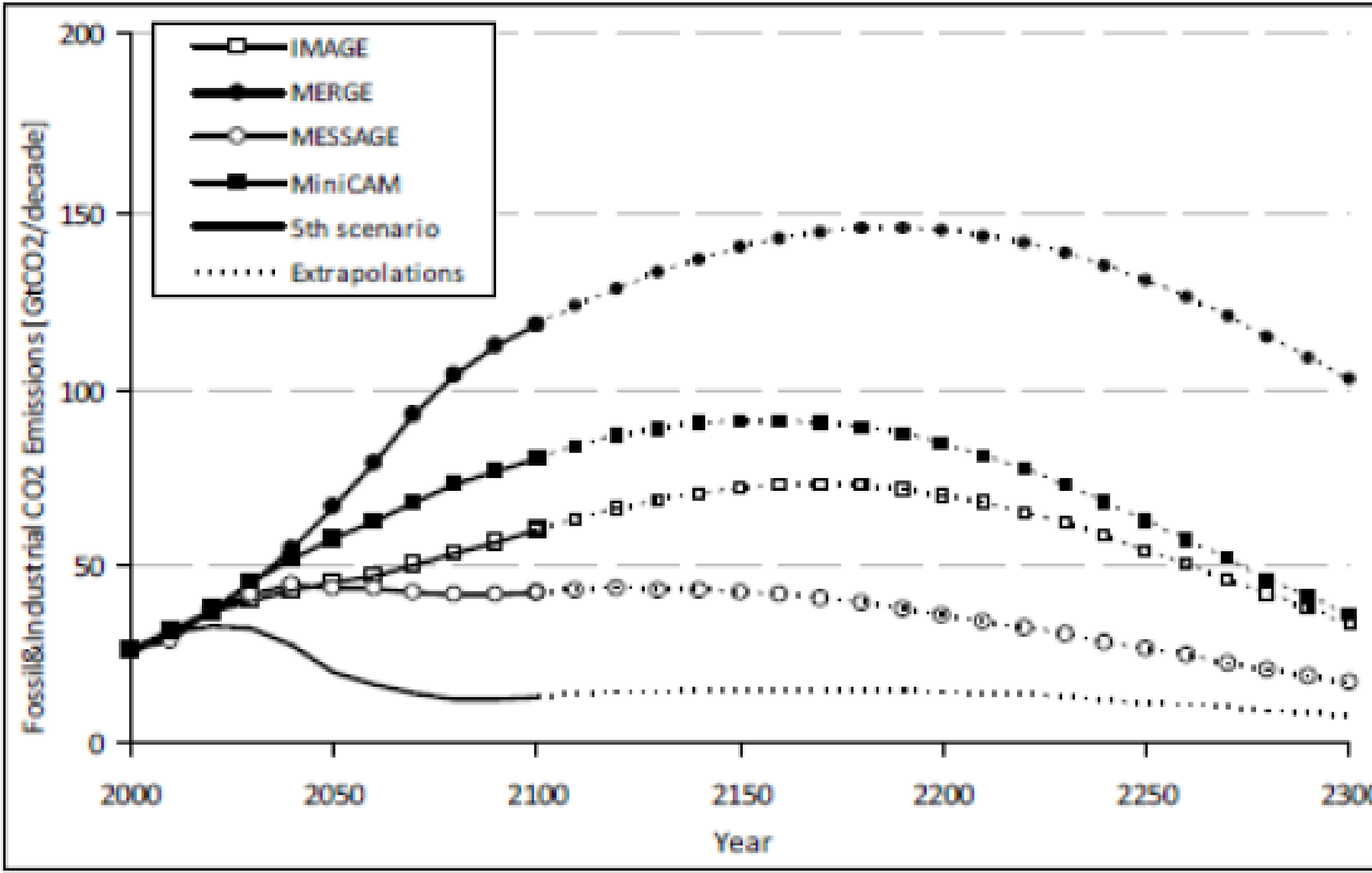
Is it legitimate to switch off the optimal growth component of DICE?

- How realistic is it to model the evolution of global investment, global GDP and global emissions as it determined by a unitary, infinitely long-lived decision maker?
- I suspect the optimal growth component of DICE may be an unnecessary -- an unrealistic --distraction.
- This relates, also, to the projection of future emissions.

The projection of future emissions

- The IWG chose to use 4 BAU projections, plus a fifth scenario with emissions that attain 2C in 2100 (like RCP 2.6).
- It weighted the 5 scenarios equally -- which was questioned.
- Projecting emissions from 2100 (as in the EMF exercise) to 2300 was questioned.
- It was asserted that mankind would realize the danger and greatly reduce emissions well before any large warming was experienced.

1B. PROJECTIONS THROUGH 2300 (IWG, 2010, Figure A4)



Optimization vs projection

DICE WITH ALTERNATIVE DAMAGE FUNCTIONS							
	Peak CO_2 (ppm)		Peak Warming (C)		Warming (C) in 2200	Warming (C) in 2300	Social Cost of Carbon 2015 ($)
DICE DAMAGE FUNCTION	Year Attained	Level	Year Attained	Level			
OPTIMIZATION							
Nordhaus	2100	602	2130	3.38	2.5	0.3	$18.60
BUSINESS AS USUAL							
Nordhaus	2225	1275	2290	6.85	6.44	6.85	$19.04

"Emissions will be reduced anyway"

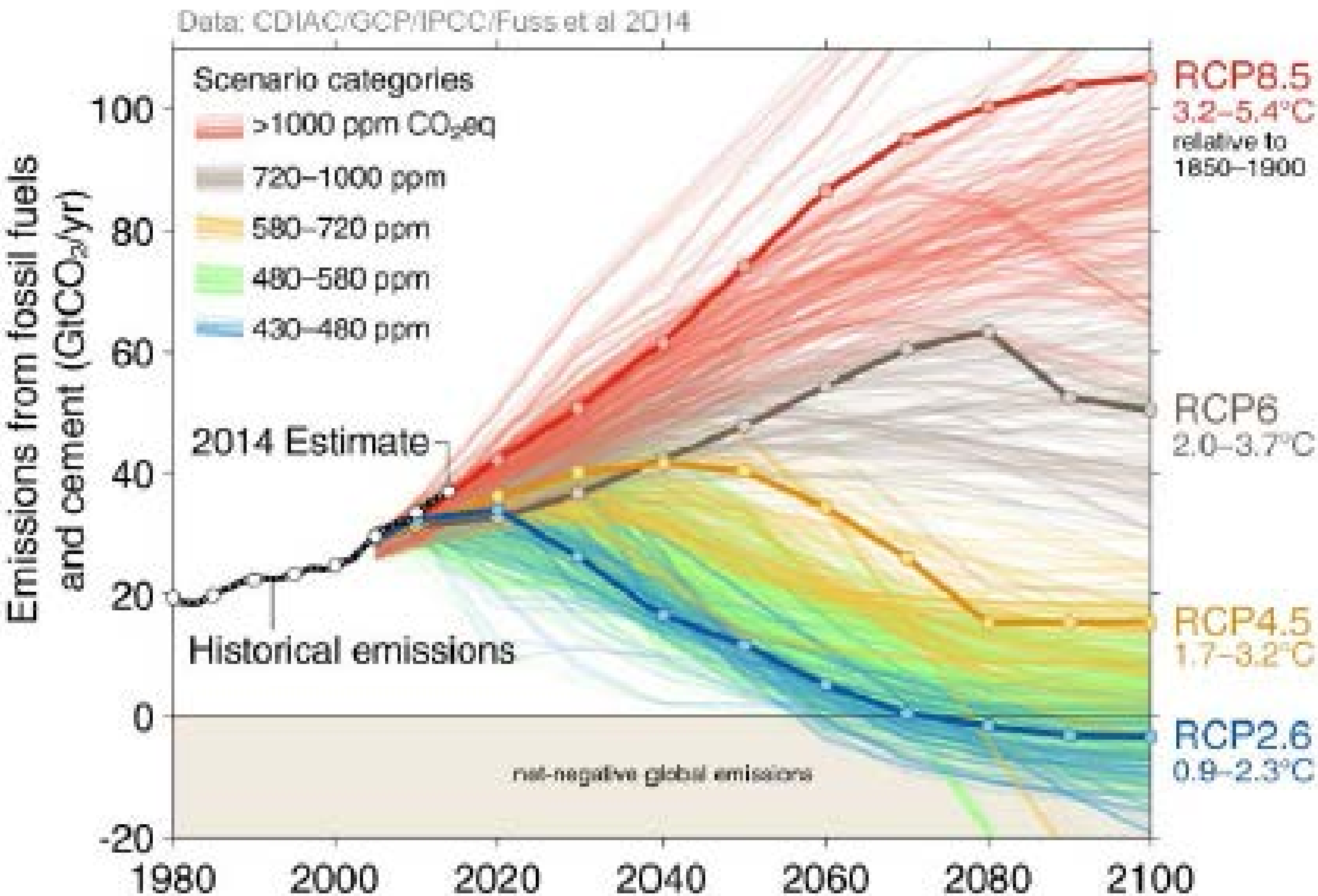


Figure 1- Observed Emissions and Emissions Scenarios

How much warming might we face?

- The following two slides depict projected warming, and illustrate:
  - The difference made by different assumptions regarding future emissions
  - The difference between looking out to 2300 versus 2100
  - The impact of different values of the climate sensitivity
    - 3.0 (the median)
    - 5.86 (the 90th percentile)

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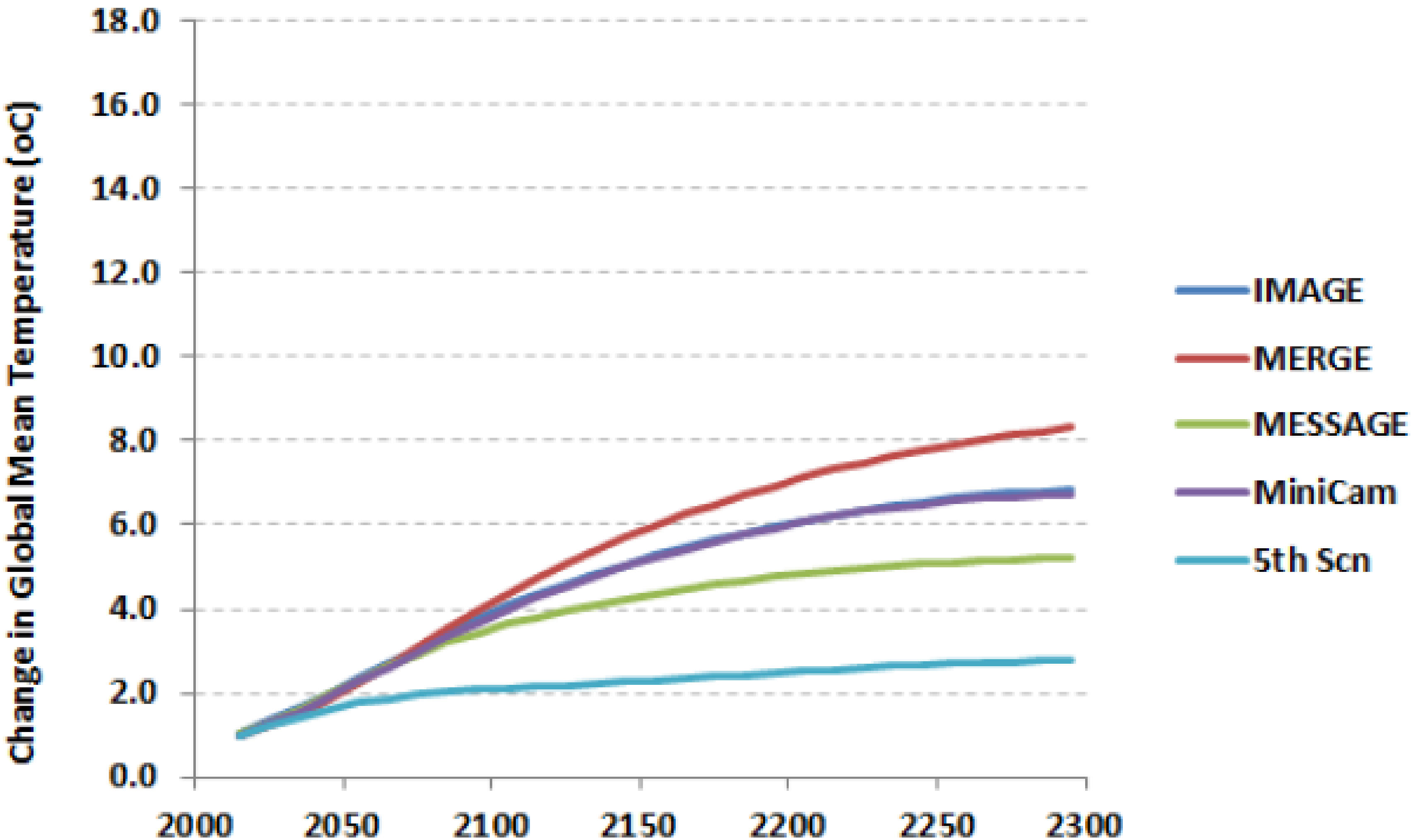
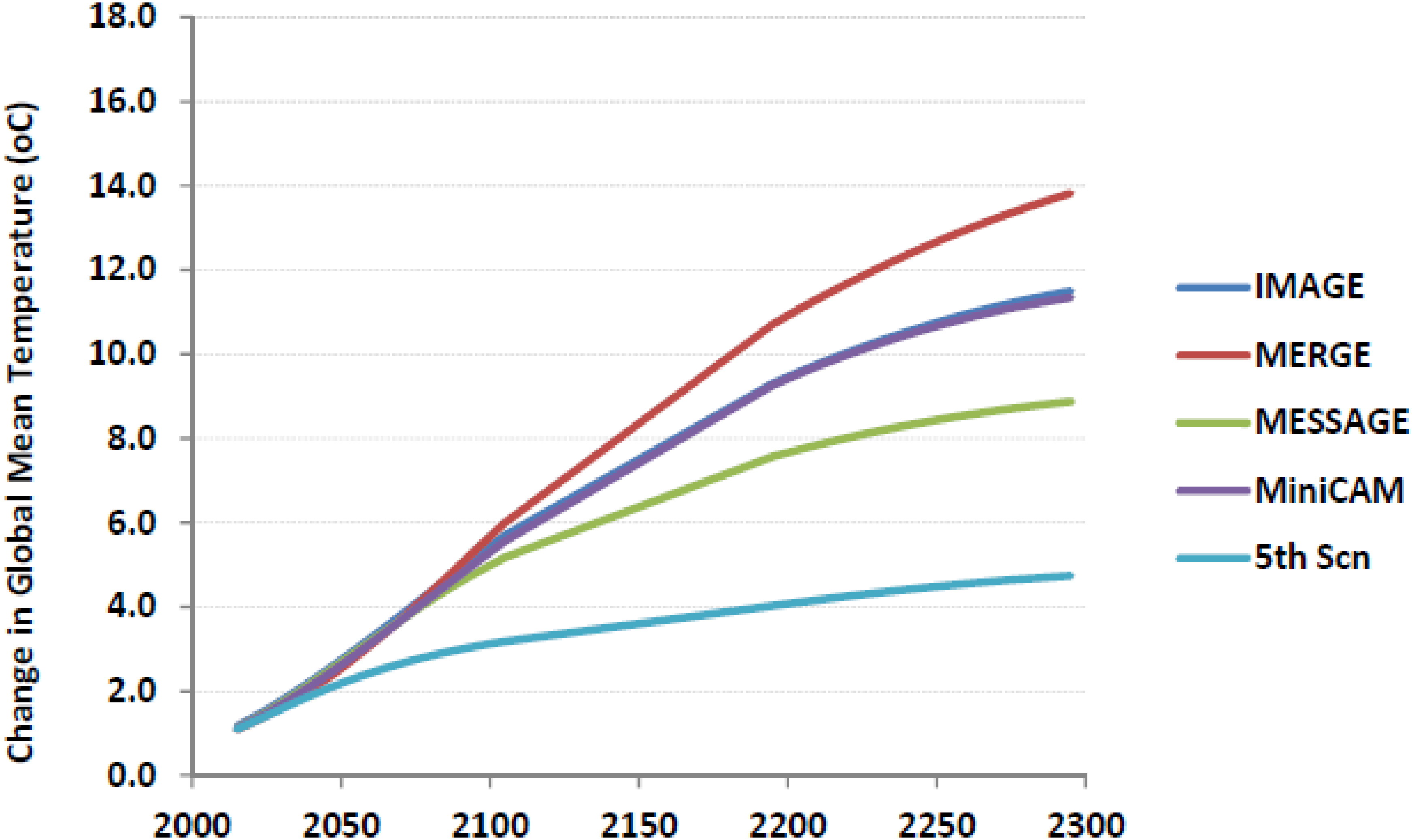
IWG projection of warming: DICE, Climate Sensitivity = 3



IWG projection of warming: DICE, Climate Sensitivity = 5.86



Results across the three IAMs

- About 50% of the IWG's runs of each IAM (which are averaged together to form the IWG's SCC estimates) have temperature increases greater than the following values:[104]
  - By 2100: between 3.5 °C and 4.5 °C,
  - By 2200: between 4.8 °C and 7.7 °C,
  - By 2300: between 5.2 °C and 9.0 °C.
- About 10% of the IWG's runs of each IAM (which are averaged together to form the IWG's SCC estimates) have temperature increases greater than the following values:[105]
  - By 2100: between 4.5 °C and 9.4 °C,
  - By 2200: between 7.7 °C and 15.2 °C,
  - By 2300: between 8.9 °C and 17.5 °C.

	DISCOUNTED PRESENT VALUE OF $100		
Discount rate	100 YEARS	200 YEARS	300 YEARS
5.5%	$0.409	$0.002	$0.000
5.0%	$0.674	$0.005	$0.000
3.0%	$4.979	$0.248	$0.012
2.5%	$8.208	$0.674	$0.055
2.0%	$13.534	$1.832	$0.248
1.50%	$28.650	$8.208	$2.352

Discounting the future

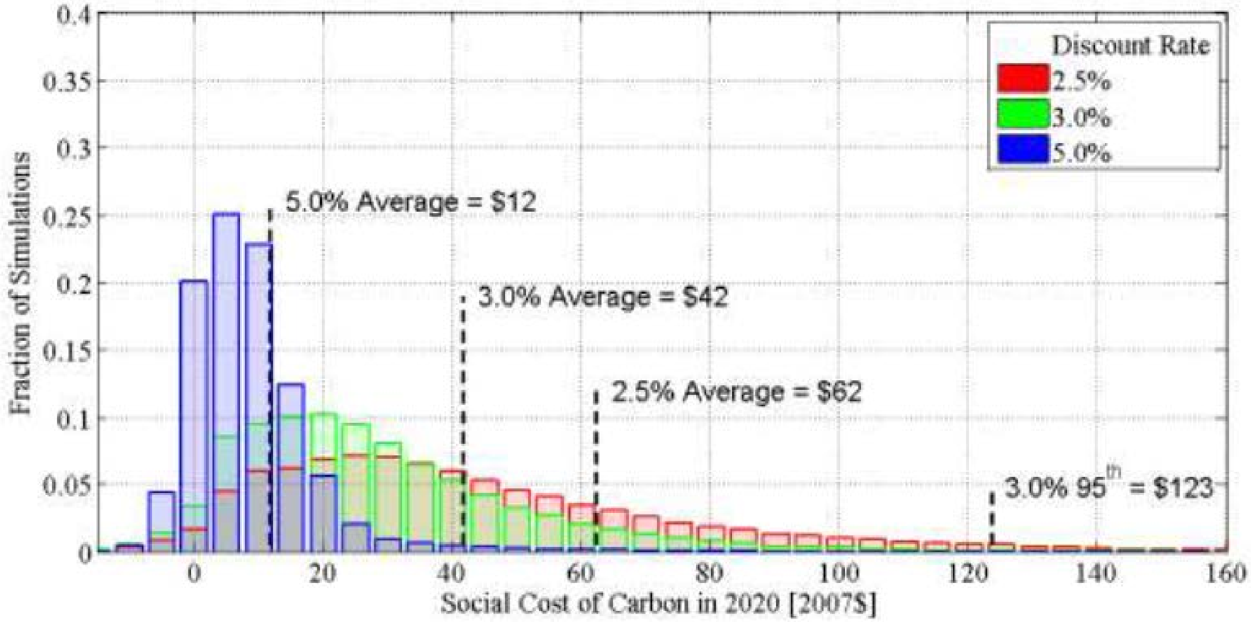
- It is not news that discounting plays a crucial role in determining an optimal mitigation policy.
- This is starkly illustrated in the IWG's SCC projections, through the interaction of:
  - Sensitivity analysis on the climate sensitivity value.
  - Explicitly tracking warming impacts through 2300.
  - Explicitly applying three alternative discount rates.
- It occurs to me that most impacts associated with tipping points are more likely to occur in the 2300 time frame than the 2100 frame.
  - Thus, they are massively sensitive to the choice of discount rate.

Rethinking the discount rate?

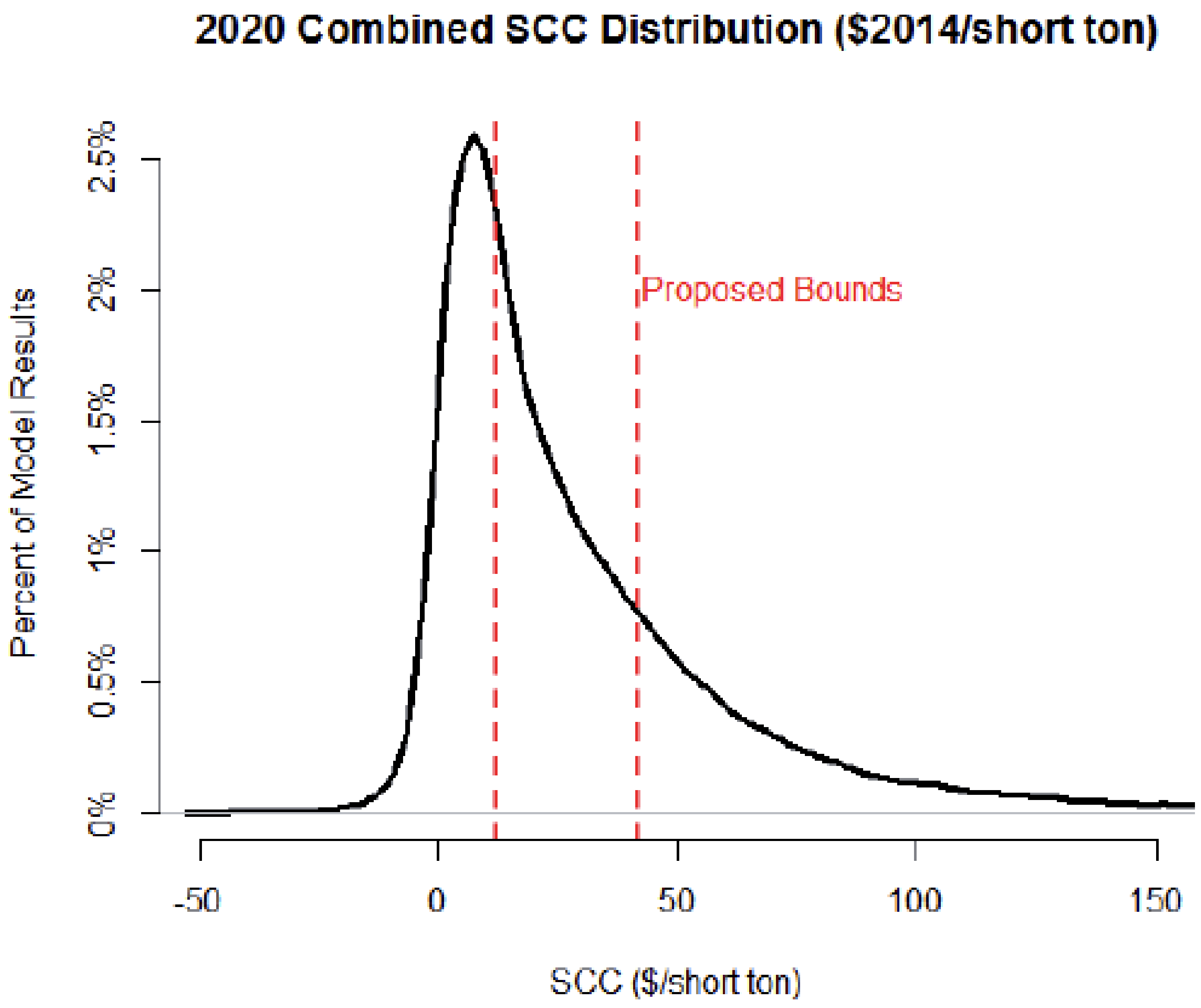
- Should it be endogenous?
- If so, is the infinitely-lived representative agent with constant preferences, unchanged over 300 years, a satisfactory model? Instead, why not:
  - Adopt the Ryder-Heal (1973) model where one expects more out of life as one grows richer, thus damping down the declining marginal utility factor in Ramsey.
  - Adopt the Sterner-Person formulation with imperfect substitution between consumption and climate damage?
  - Adopt an OLG model?
  - Adopt a model with consumption growth uncertainty?
- If we take tipping points seriously, maybe we should rethink the discount rate.

How to deal with the uncertainty

- The Federal IWG focused on the mean value of the SCC using a 3% discount rate
- It was criticized for not using the median or the inter-quartile range.

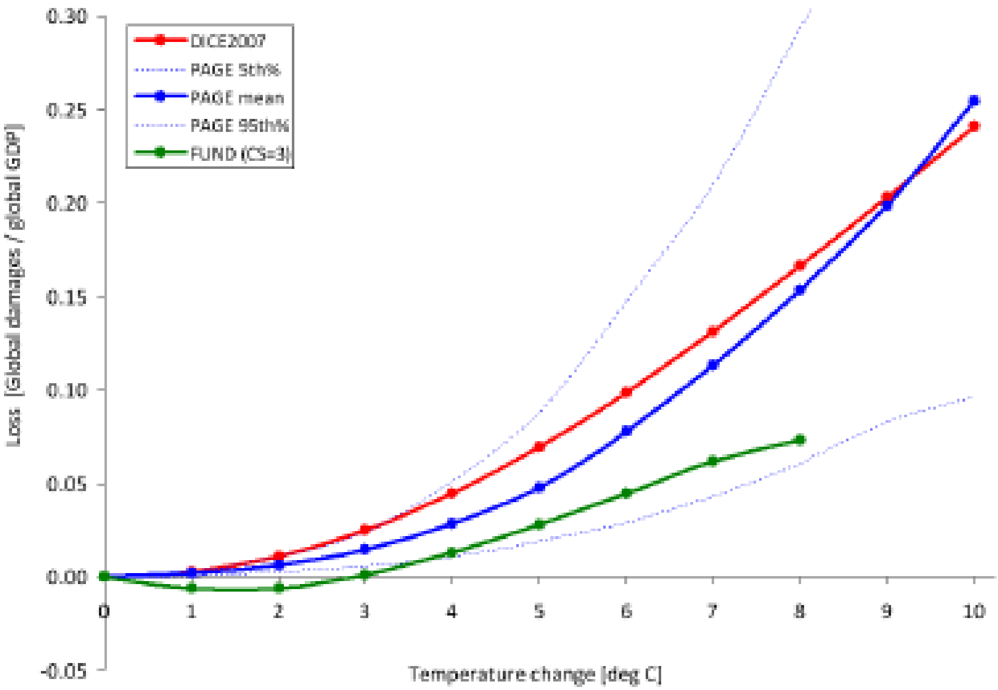


How Xcel proposed to truncate "outliers"



Can the damage function legitimately be extended to high degrees of warming?

- This question was first raised by Weitzman.
- It was suggested at the trial that, because the damage function was not calibrated to actual data (a la Dell et al), it was too high.



What would it mean to calibrate damages to actual data?

- One has to distinguish between weather and climate.
- One also has to distinguish between the global versus the local climate.
  - Mitigation policy focuses on global emissions and global climate.
  - Impacts and adaptation play out at local spatial scales.
  - An increase of 4.1C in *global* average *annual* temperature corresponds to
    - An increase of 5.8C in annual average *California* temperature
    - An increase of 8.3C in *summertime* average California temperature
    - An increase of 10C in summertime temperature in California's *major urban and agricultural areas*.

- One cannot calibrate damages to the actual experience with high global temperatures because such temperatures have never been experienced in human history.
  - The global temperature has been warmer than now several times during the interglacials.
  - It was last 2C warmer than now about 2.8 million years ago.
  - It was last 6C warmer than now about 40 million years ago
  - The existing IAM damage functions suggest that a 6C warming would reduce global GDP by 4 - 9%.

Some recent findings

- Some key findings in the recent literature cast doubt on the validity of the algebraic formulation and empirical calibration of the IAM damage functions.
  - Empirical panel-data analyses of the effects of weather shocks on GDP and other economic metrics.
  - Conceptual findings from simulations with alternative algebraic specifications of the damage function.

Empirical findings

- Starting with Dell, Jones & Olken (2009) and Hsiang (2010), evidence that short-term increases in temperature and cyclone events are associated with large reductions in economic output, not just in agriculture but also in industrial and other non-ag sectors.
- Pathways
  – Response of human labor to thermal stress, causing reduced productivity
  – Destruction of physical capital and infrastructure

Dell, Jones and Olken (2012)

- Higher temperatures substantially reduce rates of growth, not simply the level of output. But this effect occurs only in poor countries; in rich countries, no discernible effect.
- Higher temperature affects numerous dimensions of poor countries' economies, including reducing industrial output as well as agricultural output, and political stability.
- The effects persist. Using shifts from 1970 to 2000 suggests that adaptation may not undo them in the medium term.

Global non-linear effect of temperature on economic production

Marshall Burke[1,2]*, Solomon M. Hsiang[3,4]* & Edward Miguel[4,5]

- The new paper by Burke et al. in *Nature* extends the Dell et al data from 2003 through 2010.
- Burke et al allow for a nonlinear effect of temperature shocks, whereas Dell et al estimated a linear relationship.
- Dell et al. found strong negative effects of warmer temperatures on growth in poor countries but not in rich countries.
- Burke et al finds effects in both sets of countries.
  - There is a nonlinearity -- benefits at first then damage.
  - There is heterogeneity across countries.

Global non-linear effect of temperature on economic production

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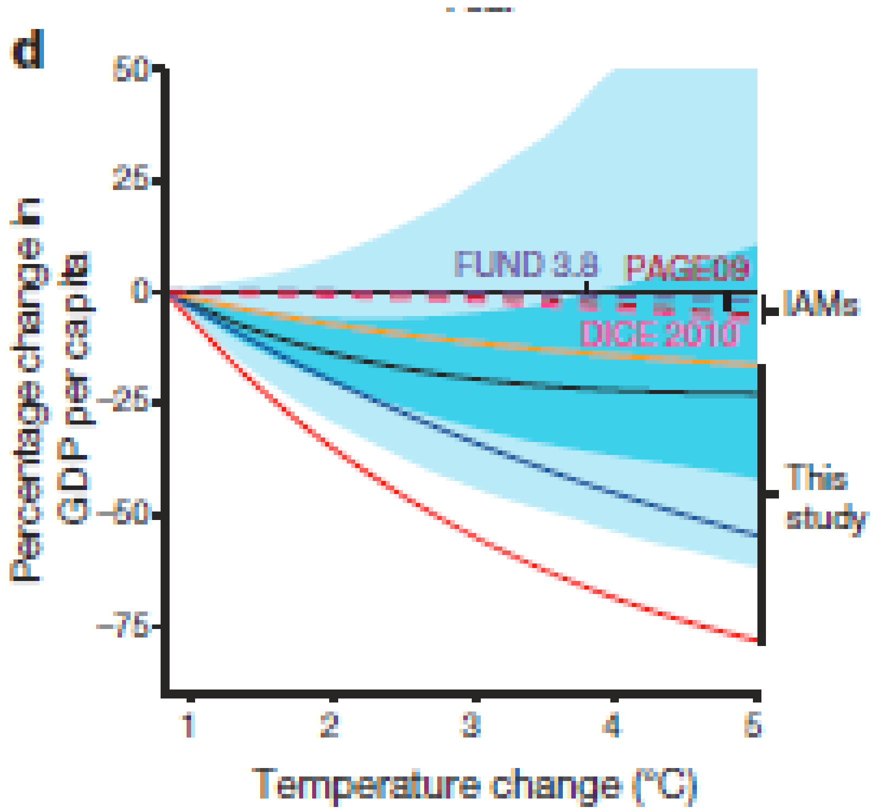


Limitations of the econometrics

- GDP itself is not a welfare metric. It does not reflect loss of well being, not non-market impacts.
- The effect of a weather shock is not the same as that of a change in climate.
  - Adaptation in the long-run could temper the impact.
  - But, some adaptations that are viable in the short-run (e.g., over drafting ground water) are not viable in the long run.
- Correlating national GDP with national annual temperature masks impacts occurring at smaller spatial and temporal scales (e.g., extreme weather events).
  - There is reason to believe these cause most of the damages.
  - They may not be adequately reflected.

The proportion of impacts due to extreme events

- Illustrated by results in Schlenker, Fisher & Hanemann REStat 2006
- Distinguishes the effects of
  - Temperature within the regular range (8-32^{0}C)
  - Extreme temperature (above 34^{0}C)
  - Precipitation
- The overwhelming majority of the impact is associated with changes in the occurrence of extreme temperature.
- This has implications for what we should be measuring, and in which locations
- Extreme events are not captured in existing IAM damage functions, which employ change in *annual average* (*global*) temperature.

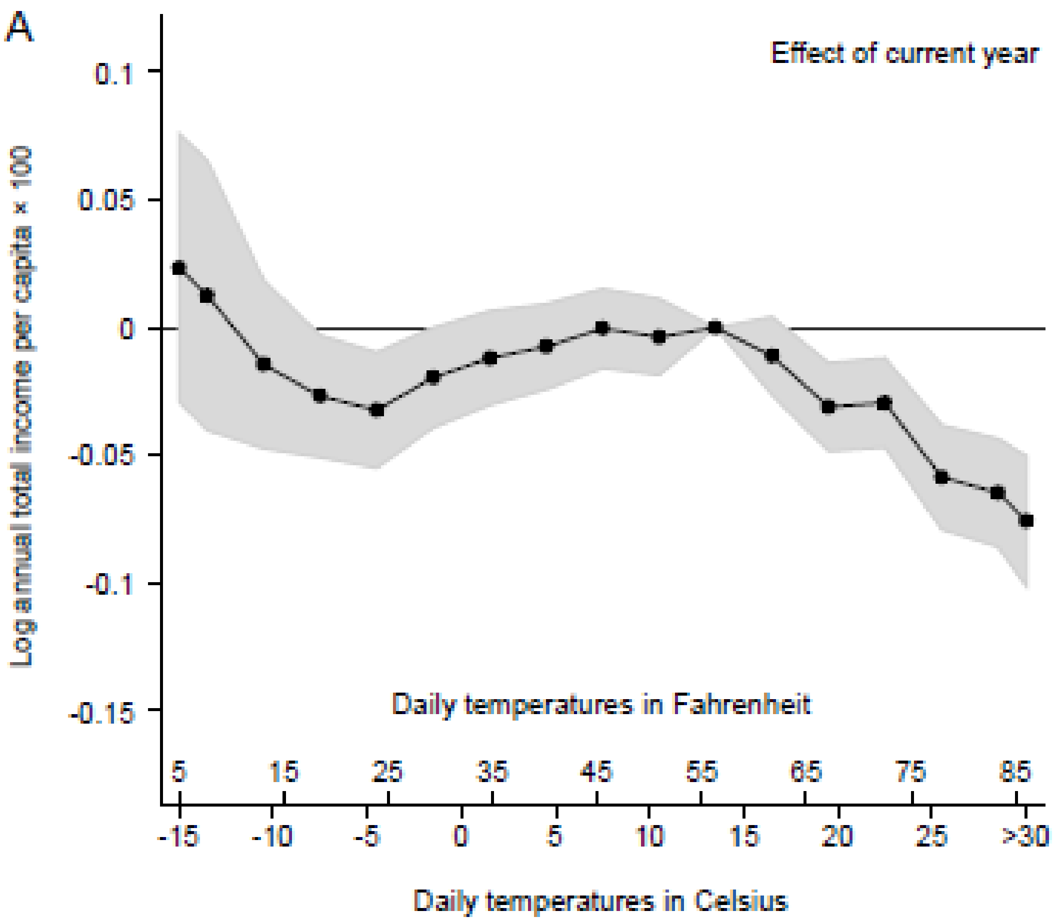
Importance of extreme temperature, especially near-term (Schlenker et al., 2006)

	Proportion of net economic loss to US agriculture due to change in:	
	Precipitation & degree days 8-32C	Degree days over 34C
2020-2049 both emission scenarios 2070-2099 B1 scenario	10-20%	80-90%
2070-2099 A1Fi scenario	40%	60%

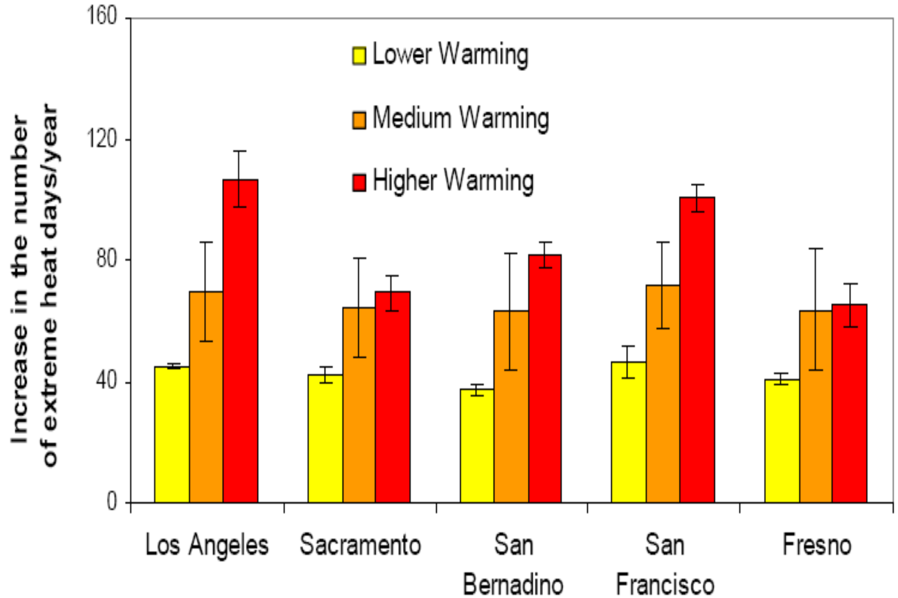
DOES THE ENVIRONMENT STILL MATTER? DAILY TEMPERATURE AND INCOME IN THE UNITED STATES

Tatyana Deryugina
Solomon M. Hsiang

Working Paper 20750
http://www.nber.org/papers/w20750



Heat waves



(Source: Drechsler et al. 2006)

Figure 11. Projected increase in the number of extreme heat days relative to 1961–1990. *Extreme heat* is defined as the average temperature that is exceeded less than 10% of the days during the historical period (1961–1990), or approximately 36 days a year.

In summary

- It seems likely that, for the next three or four decades at least, most of the economic effects of climate change will be associated with such local extreme events.
  - If they occur infrequently, the economic effects will be small.
  - If they occur frequently, those effects will be larger.
- To model the incidence of local extreme events, one needs a fine spatial scale – with spatial down scaling – and one needs a finer temporal scale than the GCM outputs that have typically been used so far.
  - Daily rather than monthly.
  - In some cases (e.g., floods, energy demand and supply) hourly.
- Extreme events are not captured in existing damage functions used in the IAMs, which are framed around the change in *annual average* (*global*) temperature, nor are they captured in the recent econometric analyses.

In addition there are conceptual issues about the damage function

- Mathematical form
  - Multiplicative versus additive (Weitzman)
  - GDP an imperfect substitute for damage (Sterner)
  - Impacts on capital stock separated out
- Stochastic optimization versus deterministic optimization with sensitivity analysis
  - Computation solved by Traeger et al, Cai & Judd et al.
  - Tipping points
- Epstein Zinn utility, separating risk aversion from consumption smoothing

- The evidence from simulations of these modifications to the formulation of the damage function in DICE is that they can significantly raise the SCC.

Conclusion

- The existing assessments of the damages from climate change are likely to significantly under-estimate them.
  - Adaptation is not well incorporated.
  - But we do not know how quick, cheap, or effective adaptation will turn out to be against unprecedented and large climate change.
- How we discount future impacts also needs to be reconsidered.
- The climate changes we face are unprecedented in human history. It is not clear that we are presently doing justice to that fact in our damage assessments.