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BEFORE THE
U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON NAURAL RESOURCES

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I am Patrick J. Michaels, Director of the Center for the Study of Science at the Cato Institute, a nonprofit, non-partisan public policy research institute located here in Washington DC, and Cato is my sole source of employment income. Before I begin my testimony, I would like to make clear that my comments are solely my own and do not represent any official position of the Cato Institute.

My testimony concerns the selective science that underlies the Obama Administration's determination of the Social Cost of Carbon and how a more inclusive and considered process would have resulted in a lower value for the social cost of carbon.

Earlier this month, the Administration's Interagency Working Group on the Social Cost of Carbon (IWG) released a report that was a response to public comments of the IWG determination of the social cost of carbon that were solicited by the Office of Management and Budget in November 2013. Of the 140 unique set of comments received (including a set of my own from which this testimony in drawn), the IWG adopted none.

Here, I address why this decision was based on a set of flimsy, internally inconsistent excuses and amounts to a continuation of the IWG's exclusion of the most relevant science—an exclusion which assures that low, or even negative values of the social cost of carbon (which would imply a net benefit of increased atmospheric carbon dioxide levels), do not find their way into cost/benefit analyses of proposed federal actions. If, in fact, the social cost of carbon were near zero, it would eliminate the justification for any federal action (greenhouse gas emissions regulations, ethanol mandates, miles per gallon standards, solar/wind subsidies, DoE efficiency regulations, etc.) geared towards reducing carbon dioxide emissions.

Equilibrium Climate Sensitivity

In May 2013, the Interagency Working Group produced an updated SCC value by incorporating revisions to the underlying three Integrated Assessment Models (IAMs) used by the IWG in its initial 2010 SCC determination. But, at that time, the IWG did *not* update the equilibrium climate sensitivity (ECS) employed in the IAMs. This was not done, despite there having been, since January 1, 2011, at least 14 new studies and 20 experiments (involving more than 45 researchers) examining the ECS, each lowering the best estimate and tightening the error distribution about that estimate. Instead, the IWG wrote in its 2013 report: "It does not revisit other interagency modeling decisions (e.g., with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity)."

This decision was reaffirmed by the IWG in July 2015. But, through its reaffirmation, the IWG has again refused to give credence to and recognize the importance of what is now becoming mainstream science—that the most likely value of the equilibrium climate sensitivity is lower than that used by the IWG and that the estimate is much better constrained. This situation has profound implications for the determination of the SCC and yet continues to be summarily dismissed by the IWG.

The earth's equilibrium climate sensitivity is defined by the IWG in its 2010 report (hereafter, IWG2010) as "the long-term increase in the annual global-average surface temperature from a doubling of atmospheric CO2 concentration relative to pre-industrial levels (or stabilization at a concentration of approximately 550 parts per million (ppm))" and is recognized as "a key input parameter" for the integrated assessment models used to determine the social cost of carbon.

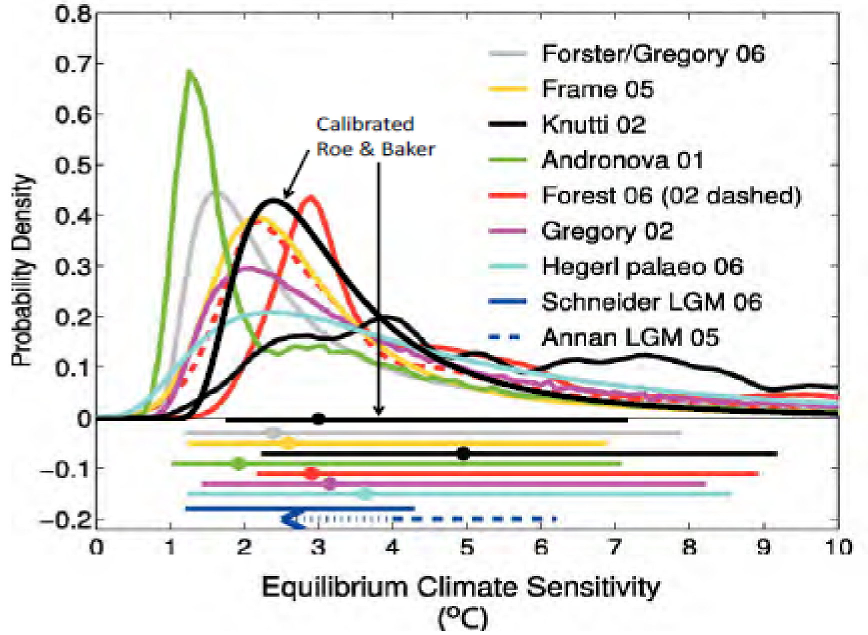
The IWG2010 report has an entire section (Section III.D) dedicated to describing how an estimate of the equilibrium climate sensitivity and the scientific uncertainties surrounding its actual value are developed and incorporated in the IWG's analysis. The IWG2010, in fact, developed its own probability density function (pdf) for the ECS and used it in each of the three IAMs, superseding the ECS pdfs used by the original IAMs developers. The IWG's intent was to develop an ECS pdf which most closely matched the description of the ECS as given in the *Fourth Assessment Report* of the United Nation's Intergovernmental panel on Climate Change which was published in 2007.

The functional form adopted by the IWG2010 was a calibrated version of Roe and Baker (2007) distribution. It was described in the IWG2010 report in the following Table and Figure (from the IWG2010 report):

Table 1: Summary Statistics for Four Calibrated Climate Sensitivity Distributions

	Roe & Baker	Log-normal	Gamma	Weibull
Pr(ECS < 1.5°C)	0.013	0.050	0.070	0.102
Pr(2°C < ECS < 4.5°C)	0.667	0.667	0.667	0.667
5th percentile	1.72	1.49	1.37	1.13
10th percentile	1.91	1.74	1.65	1.48
Mode	2.34	2.52	2.65	2.90
Median (50th percentile)	3.00	3.00	3.00	3.00
Mean	3.50	3.28	3.19	3.07
90th percentile	5.86	5.14	4.93	4.69
95th percentile	7.14	5.97	5.59	5.17

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

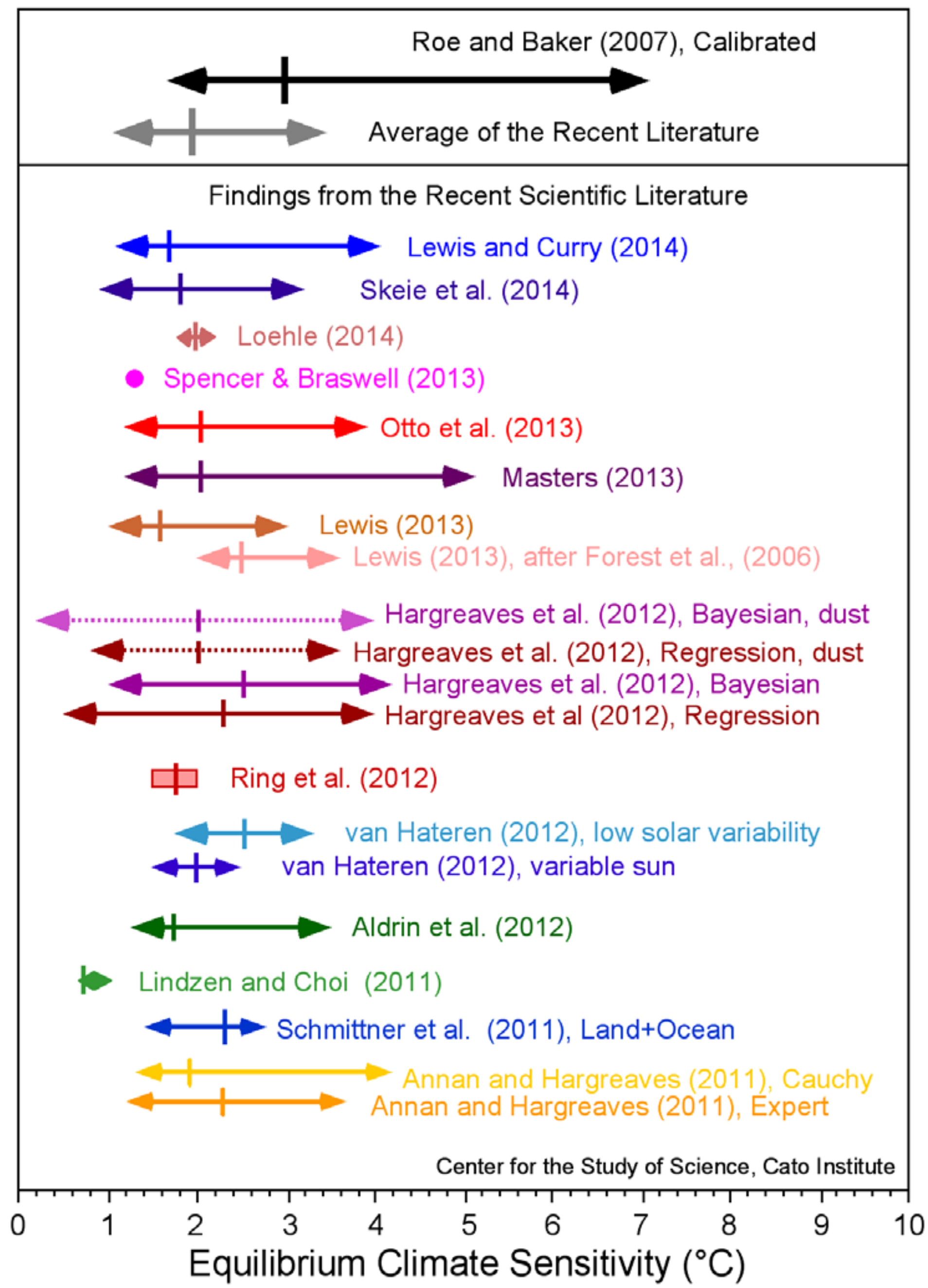


The calibrated Roe and Baker functional form used by the IWG2010 is *no longer scientifically defensible;* nor was it at the time of the publication of the IWG 2013 SCC update, nor at the time of the July 2015 update.

The figure below vividly illustrates this fact, as it compares the best estimate and 90% confidence range of the earth's ECS as used by the IWG (calibrated Roe and Baker) against findings in the scientific literature published since January 1, 2011.

Whereas the IWG ECS distribution has a median value of 3.0°C and 5th and 95th percentile values of 1.72°C and 7.14°C, respectively, the corresponding values averaged from the recent scientific literature are 2.0°C (median), 1.1°C (5th percentile), and 3.5°C (95th percentile).

These differences will have large and significant impacts on the SCC determination.



CAPTION: The median (indicated by the small vertical line) and 90% confidence range (indicated by the horizontal line with arrowheads) of the climate sensitivity estimate used by the Interagency Working Group on the Social Cost of Carbon Climate (Roe and Baker, 2007) is indicated by the top black arrowed line. The average of the similar values from 20 different determinations reported in the recent scientific literature is given by the grey arrowed line (second line from the top). The sensitivity estimates from the 20 individual determinations of the ECS as reported in new research published after January 1, 2011 are indicated by the colored arrowed lines. The arrows indicate the 5 to 95% confidence bounds for each estimate along with the best estimate (median of each probability density function; or the mean of multiple estimates; colored vertical line). Ring et al. (2012) present four estimates of the climate sensitivity and the red box encompasses those estimates. Spencer and Braswell (2013) produce a single ECS value best-matched to ocean heat content observations and internal radiative forcing.

The IWG2010 report noted that, concerning the low end of the ECS distribution, its determination reflected a greater degree of certainty that a low ECS value could be excluded than did the IPCC. From the IWG2010 (p. 14):

> "Finally, we note the IPCC judgment that the equilibrium climate sensitivity "is very likely larger than 1.5°C." Although the calibrated Roe & Baker distribution, for which the probability of equilibrium climate sensitivity being greater than 1.5°C is almost 99 percent, is not inconsistent with the IPCC definition of "very likely" as "greater than 90 percent probability," it reflects a greater degree of certainty about very low values of ECS than was expressed by the IPCC."

In other words, the IWG used its judgment that the lower bound of the ECS distribution was higher than the IPCC 2007 assessment indicated. However, the collection of the recent literature on the ECS shows the IWG's judgment to be in error. As can be seen in the chart above, the large majority of the findings on ECS in the recent literature indicate that the lower bound (i.e., 5th percentile) of the ECS distribution is lower than the IPCC 2007 assessment. And, the average value of the 5th percentile in the recent literature (1.1°C) is 0.62°C less than that used by the IWG—a sizeable and important difference which will influence the SCC determination.

In fact, the abundance of literature supporting a lower climate sensitivity was at least partially reflected in the new IPCC assessment report issued in 2013. In that report, the IPCC reported:

> Equilibrium climate sensitivity is *likely* in the range 1.5°C to 4.5°C (*high confidence*), *extremely unlikely* less than 1°C (*high confidence*), and *very unlikely* greater than 6°C (*medium confidence*). The lower temperature limit of the assessed *likely* range is thus less than the 2°C in the AR4…

Clearly, the IWG's assessment of the low end of the probability density function that best describes the current level of scientific understanding of the climate sensitivity is incorrect and indefensible.

But even more influential in the SCC determination is the upper bound (i.e., 95th percentile) of the ECS probability distribution.

The IWG2010 notes (p.14) that the calibrated Roe and Baker distribution better reflects the IPCC judgment that "values substantially higher than 4.5°C still cannot be excluded." The IWG2010 further notes that

> "Although the IPCC made no quantitative judgment, the 95th percentile of the calibrated Roe & Baker distribution (7.1 °C) is much closer to the mean and the median (7.2 °C) of the 95th percentiles of 21 previous studies summarized by Newbold and Daigneault (2009). It is also closer to the mean (7.5 °C) and median (7.9 °C) of the nine truncated distributions examined by the IPCC (Hegerl, et al., 2006) than are the 95th percentiles of the three other calibrated distributions (5.2-6.0 °C)."

In other words, the IWG2010 turned towards surveys of the scientific literature to determine its assessment of an appropriate value for the 95th percentile of the ECS distribution. Now, more than five years hence, the scientific literature tells a completely different story.

Instead of a 95th percentile value of 7.14°C, as used by the IWG2010, a survey of the recent scientific literature suggests a value of 3.5°C—more than 50% lower.

And this is very significant and important difference because the high end of the ECS distribution has a large impact on the SCC determination—a fact frequently commented on by the IWG2010.

For example, from IWG2010 (p.26):

> "As previously discussed, low probability, high impact events are incorporated into the SCC values through explicit consideration of their effects in two of the three models as well as the use of a probability density function for equilibrium climate sensitivity. Treating climate sensitivity probabilistically results in more high temperature outcomes, which in turn lead to higher projections of damages. Although FUND does not include catastrophic damages (in contrast to the other two models), its probabilistic treatment of the equilibrium climate sensitivity parameter will directly affect the non-catastrophic damages that are a function of the rate of temperature change."

And further (p.30):

> *Uncertainty in extrapolation of damages to high temperatures*: The damage functions in these IAMs are typically calibrated by estimating damages at moderate temperature increases (e.g., DICE was calibrated at 2.5 °C) and extrapolated to far higher temperatures by assuming that damages increase as some power of the temperature change. Hence, estimated damages are far more uncertain under more extreme climate change scenarios.

And the entirety of Section V [sic] "A Further Discussion of Catastrophic Impacts and Damage Functions" of the IWG 2010 report describes "tipping points" and "damage functions" that are probabilities assigned to different values of global temperature change. Table 6 from the IWG2010 indicated the probabilities of various tipping points.

Table 6: Probabilities of Various Tipping Points from Expert Elicitation -

Possible Tipping Points	Duration before effect is fully realized (in years)	Additional Warming by 2100		
		0.5-1.5 C	1.5-3.0 C	3-5 C
Reorganization of Atlantic Meridional Overturning Circulation	about 100	0-18%	6-39%	18-67%
Greenland Ice Sheet collapse	at least 300	8-39%	33-73%	67-96%
West Antarctic Ice Sheet collapse	at least 300	5-41%	10-63%	33-88%
Dieback of Amazon rainforest	about 50	2-46%	14-84%	41-94%
Strengthening of El Niño-Southern Oscillation	about 100	1-13%	6-32%	19-49%
Dieback of boreal forests	about 50	13-43%	20-81%	34-91%
Shift in Indian Summer Monsoon	about 1	Not formally assessed		
Release of methane from melting permafrost	Less than 100	Not formally assessed.		

The likelihood of occurrence of these low probability, high impact, events ("tipping points") is *greatly* diminished under the new ECS findings. The average 95th percentile value of the new literature survey is only 3.5°C indicating a very low probability of a warming reaching 3-5°C by 2100 as indicated in the 3rd column of the above Table and thus a significantly lower probability that such tipping points will be reached. This new information will have a large impact on the final SCC determination using the IWG's methodology.

The size of this impact has been directly investigated.

In their *Comment on the Landmark Legal Foundation Petition for Reconsideration of Final Rule Standards for Standby Mode and Off Mode Microwave Ovens*, Dayaratna and Kreutzer (2013) ran the DICE model using the distribution of the ECS as described by Otto et al. (2013)—a paper published in the recent scientific literature which includes 17 authors, 15 of which were lead authors of chapters in the recent Intergovernmental Panel on Climate Change's *Fifth Assessment Report*. The most likely value of the ECS reported by Otto et al. (2013) was described as "2.0°C, with a 5–95% confidence interval of 1.2–3.9°C." Using the Otto et al. (2013) ECS distribution in lieu of the distribution employed by the IWG (2013), dropped the SCC by 42 percent, 41 percent, and 35 percent (for the 2.5%, 3.0%, 5.0% discount rates, accordingly). This is a significant decline.

In subsequent research, Dayaratna and Kreutzer (2014) examined the performance of the FUND model, and found that it too, produced a greatly diminished value for the SCC when run with the Otto et al. distribution of the equilibrium climate sensitivity. Using the Otto et al. (2013) ECS distribution in lieu of the distribution employed by the IWG (2013), dropped the SCC produced by the FUND model to $11, $6, $0 compared with the original $30, $17, $2 (for the 2.5%, 3.0%, 5.0% discount rates, accordingly). Again, this is a significant decline.

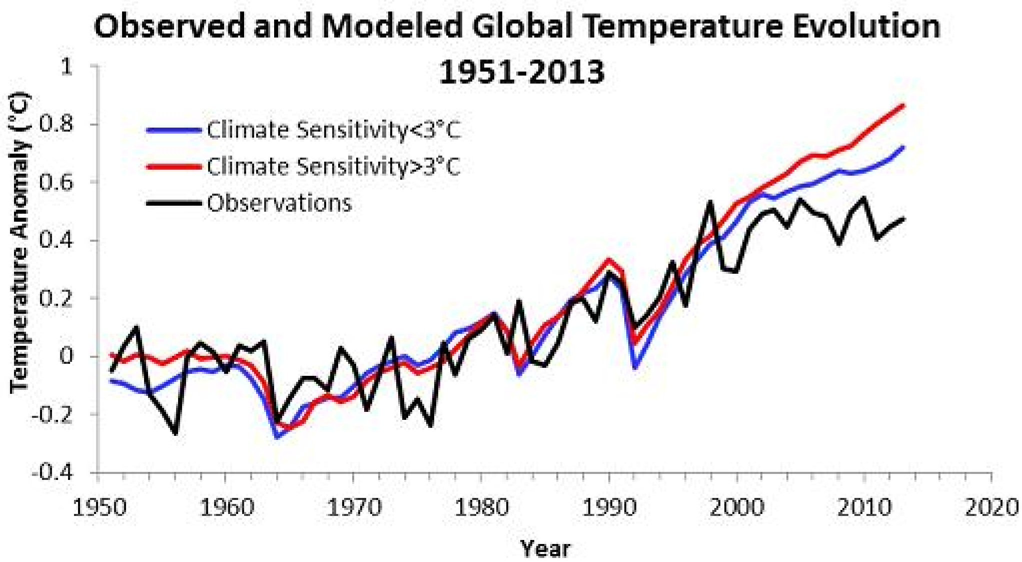
The Dayaratna and Kreutzer (2014) results using FUND were in line with alternative estimates of the impact of a lower climate sensitivity on the FUND model SCC determination.

Waldhoff et al. (2011) investigated the sensitivity of the FUND model to changes in the ECS. Waldhoff et al. (2011) found that changing the ECS distribution such that the mean of the distribution was lowered from 3.0°C to 2.0°C had the effect of lowering the SCC by 60 percent (from a 2010 SCC estimate of $8/ton of CO2 to $3/ton in $1995). While Waldhoff et al. (2011) examined FUNDv3.5, the response of the current version (v3.8) of the FUND model should be similar.

Additionally, the developer of the PAGE (Policy Analysis of Greenhouse Effect) model affirmed that the SCC from the PAGE model, too drops by 35% when the Otto et al. (2013) climate sensitivity distribution is employed (Hope, 2013).

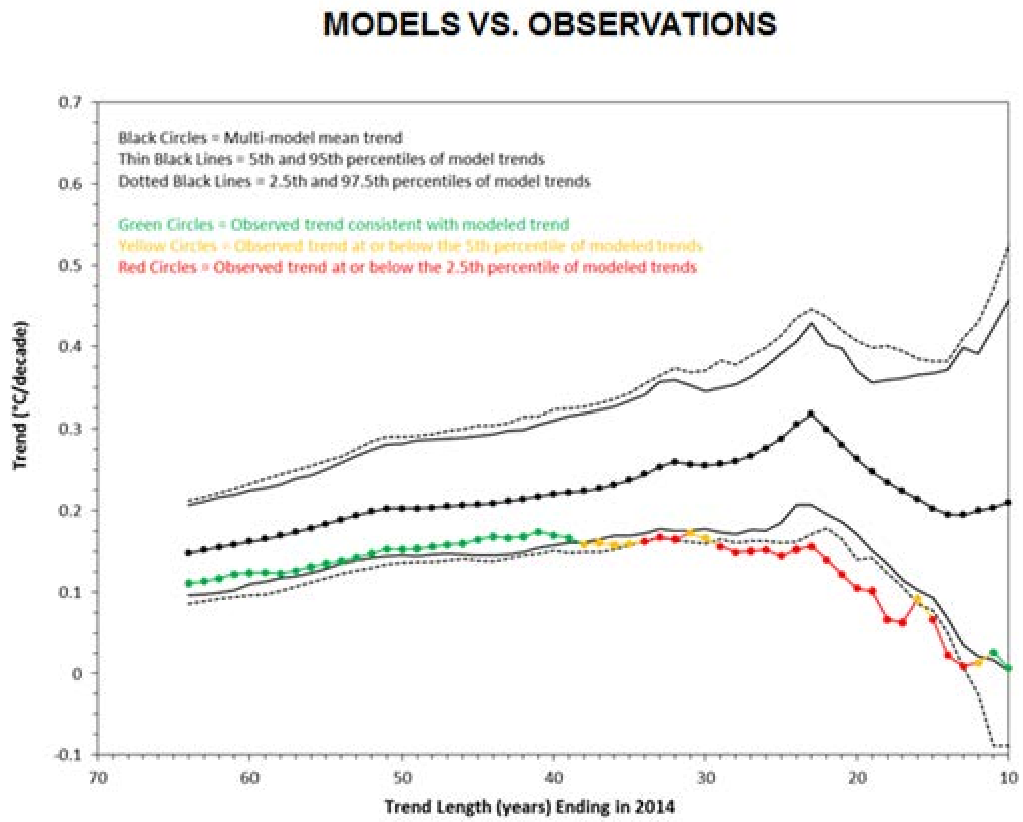
These studies make clear that the strong dependence of the social cost of carbon on the distribution of the estimates of the equilibrium climate sensitivity (including the median, and the upper and lower certainty bounds) requires that the periodic updates to the IWG SCC determination must include a critical examination of the scientific literature on the topic of the equilibrium climate sensitivity, not merely kowtowing to the IPCC assessment. There is no indication that the IWG undertook such an independent examination. But what is clear, is that the IWG did *not* alter its probability distribution of the ECS between its 2010, 2013, and 2015 SCC determination, despite a large and growing body of scientific literature that substantially alters and better defines the scientific understanding of the earth's ECS. It is unacceptable that a supposed "updated" social cost of carbon does not include updates to the science underlying a critical and key aspect of the SCC.

We note that there has been one prominent scientific study in the recent literature which has argued, on the basis of recent observations of lower tropospheric mixing in the tropics, for a rather high climate sensitivity (Sherwood et al., 2014). This research, however, suffers from too narrow a focus. While noting that climate models which best match the apparent observed behavior of the vertical mixing characteristics of the tropical troposphere tend to be the models with high climate sensitivity estimates, the authors fail to make note that these same models are the ones whose projections make the *worst* match to observations of the evolution of global temperature during the past several decades. The figure below shows the observed global surface temperature history from 1951-2013 compared with the temperature evolution projected by the collection of models used in the new IPCC 2013 report. We broke the climate models down into two groups—those which have a climate sensitivity greater than 3.0°C (as suggested by Sherwood et al., 2014) and those with a climate sensitivity less than 3.0°C. The Figure shows that while neither model subset does a very good job is capturing evolution of global temperature during the past 15-20 years (the period with the highest human carbon dioxide emissions), the high sensitivity models do substantially worse than the lower sensitivity models.



CAPTION: Observed global average temperature evolution, 1951-2013, as compiled by the U.K's Hadley Center (black line), and the average temperature change projected by a collection of climate models used in the IPCC Fifth Assessment Report which have a climate sensitivity greater than 3.0°C (red line) and a collection of models with climate sensitivities less than 3.0°C (blue line).

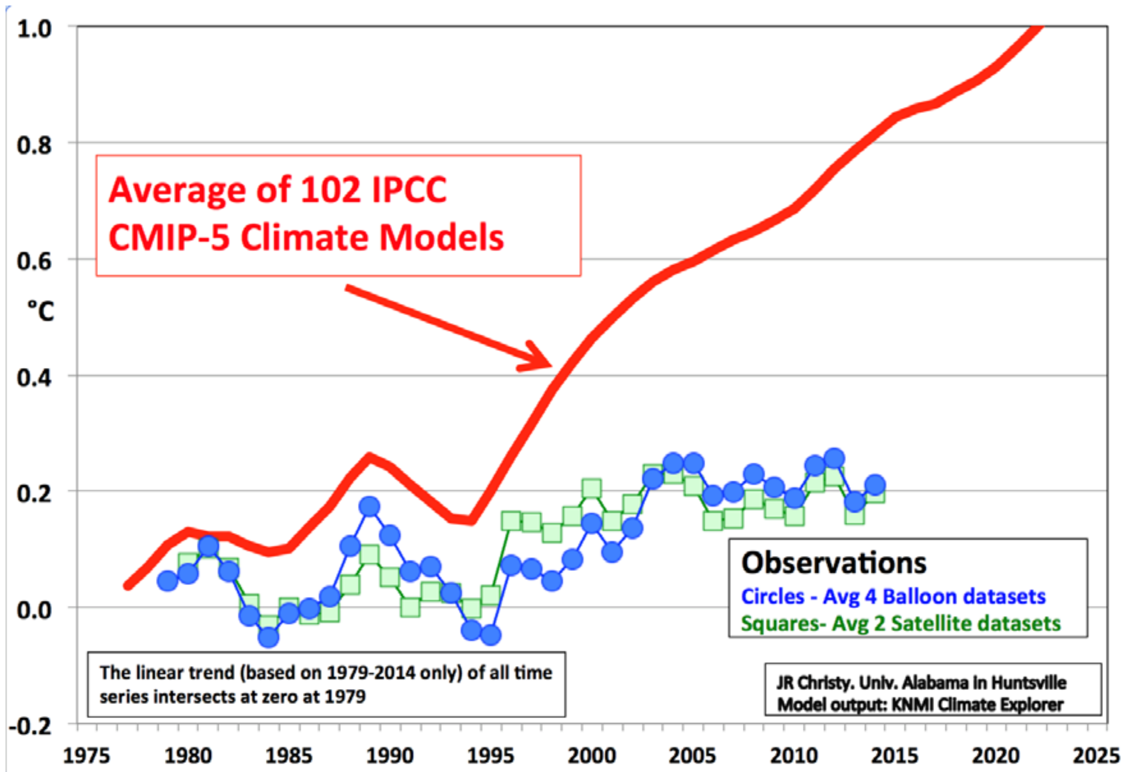
While Sherwood et al. (2014) prefer models that better match their observations in one variable, the same models actually do *worse* in the big picture than do models which lack the apparent accuracy in the processes that Sherwood et al. (2014) describe. The result can only mean that there must still be even bigger problems with *other* model processes which must more than counteract the effects of the processes described by Sherwood et al. After all, the overall model collective is still warming the world much faster than it actually is (see Figures below). In fact, for the observed global average surface temperature evolution for the past 30 years largely lies below the range which encompasses 95% of all climate model runs—an indication that the observed trend is statistically different from the trend simulated by climate models. And for periods approaching 40 years in length, the observed surface trend lies outside of (below) the range that includes 90% of all climate model simulations—and indication that the observed surface trend is marginally inconsistent with climate model simulations.



CAPTION: The annual average global surface temperature from 108 individual CMIP5 climate model runs forced with historical (+ RCP45 since 2006) forcings were obtained from the Climate Explorer website. Linear trends were computed through the global temperatures from each run, ending in 2014 and beginning each year from 1951 through 2005. The trends for each period (ranging in length from 10 to 64years) were averaged across all model runs (black dots). The range containing 90 percent (grey lines), and 95 percent (dotted black lines) of trends from the 108 model runs is also indicated. The observed linear trends for the same periods were calculated from the annual average global surface temperature record compiled by the U.K. Hadley Center (HadCRUT4) (colored dots). Observed trend values which were less than the 2.5th percentile of the model trend distribution were colored red, observed trend values which were between the 2.5th and the 5th percentile of the model trend distribution were colored yellow, and observed trend values greater than the 5th percentile of the model trend distribution were colored green. (Source: Michaels and Knappenberger, 2014)

We note that our statistics are based upon both the warm and the cold departures from predicted trends. In reality, the cold departure is what is of most interest from a policy perspective—for if warming is being demonstrably overpredicted, then policies based upon models that are in error are a substantial regulatory overreach. Our probability estimates are conservative as values at the .05 level are actually at the 2.5th percentile for warmth from the model ensemble.

The divergence between observations and climate model projections is even worse in the earth's low-to-mid atmosphere (Figure below). As shown by Christy (2015), there is a gross departure of "reality" from model predictions. Christy (2015) noted that "On average the models warm the global atmosphere at a rate three times that of the real world."



CAPTION: Five-year running mean temperatures predicted by the UN's climate models, and observed lower atmospheric temperatures from weather balloons and satellites.

These results argue strongly against the reliability of the Sherwood et al. (2014) conclusion and instead provide robust observational evidence that the climate sensitivity has been overestimated by both climate models, and the IWG alike.

Agricultural Impacts of Carbon Fertilization

Carbon dioxide is known to have a positive impact on vegetation, with literally thousands of studies in the scientific literature demonstrating that plants (including crops) grow stronger, healthier, and more productive under conditions of increased carbon dioxide concentration. A recent study (Idso, 2013) reviewed a large collection of such literature as it applies to the world's 45 most important food crops (making up 95% of the world's annual agricultural production).
Idso (2013) summarized his findings on the increase in biomass of each crop that results from a 300ppm increase in the concentration of carbon dioxide under which the plants were grown. This table is reproduced below, and shows that the typical growth increase exceeds 30% in most crops, including 8 of the world's top 10 food crops (the increase was 24% and 14% in the other two).

Idso (2013) found that the increase in the atmospheric concentration of carbon dioxide that took place during the period 1961-2011 was responsible for increasing global agricultural output by

3.2 trillion dollars (in 2004-2006 constant dollars). Projecting the increases forward based on projections of the increase in atmospheric carbon dioxide concentration, Idso (2013) expects carbon dioxide fertilization to increase the value of agricultural output by 9.8 trillion dollars (in 2004-2006 constant dollars) during the 2012-2050 period.

Average percentage increase in biomass of each of the world's 45 most important food crops under an increase of 300ppm of carbon dioxide.

Crop	% Biomass Change	Crop	% Biomass Change
Sugar cane	34.0%	Rye	38.0%
Wheat	34.9%	Plantains	44.8%
Maize	24.1%	Yams	47.0%
Rice, paddy	36.1%	Groundnuts, with shell	47.0%
Potatoes	31.3%	Rapeseed	46.9%
Sugar beet	65.7%	Cucumbers and gherkins	44.8%
Cassava	13.8%	Mangoes, mangosteens, guavas	36.0%
Barley	35.4%	Sunflower seed	36.5%
Vegetables fresh nes	41.1%	Eggplants (aubergines)	41.0%
Sweet potatoes	33.7%	Beans, dry	61.7%
Soybeans	45.5%	Fruit Fresh Nes	72.3%
Tomatoes	35.9%	Carrots and turnips	77.8%
Grapes	68.2%	Other melons (inc.cantaloupes)	4.7%
Sorghum	19.9%	Chillies and peppers, green	41.1%
Bananas	44.8%	Tangerines, mandarins, clem.	29.5%
Watermelons	41.5%	Lettuce and chicory	18.5%
Oranges	54.9%	Pumpkins, squash and gourds	41.5%
Cabbages and other brassicas	39.3%	Pears	44.8%
Apples	44.8%	Olives	35.2%
Coconuts	44.8%	Pineapples	5.0%
Oats	34.8%	Fruit, tropical fresh nes	72.3%
Onions, dry	20.0%	Peas, dry	29.2%
Millet	44.3%		

This is a large positive externality, and one that is insufficiently modeled in the IAMs relied upon by the IWG in determining the SCC.

In fact, only one of the three IAMs used by the IWG has any substantial impact from carbon dioxide fertilization, and the one that does, underestimates the effect by approximately 2-3 times.

The FUND model has a component which calculates the impact on agricultural as a result of carbon dioxide emissions, which includes not only the impact on temperature and other climate changes, but also the direct impact of carbon dioxide fertilization. The other two IAMs, DICE and PAGE by and large do not (or only do so extremely minimally; DICE includes the effect to a larger degree than PAGE). Consequently, lacking this large and positive externality, the SCC calculated by the DICE and PAGE models is significantly larger than the SCC determined by the FUND model (for example, see Table A5, in the IWG 2013 report).

But even the positive externality that results from carbon dioxide fertilization as included in the FUND model is too small when compared with the Idso (2013) estimates. FUND (v3.7) uses the following formula to determine the degree of crop production increase resulting from atmospheric carbon dioxide increases (taken from Anthoff and Tol, 2013a):

CO_2 fertilisation has a positive, but saturating effect on agriculture, specified by

(A.4) $$A^f_{t,r} = \gamma_r \ln \frac{CO2_t}{275}$$

where

- A^f denotes damage in agricultural production as a fraction due to the CO2 fertilisation by time and region;
- t denotes time;
- r denotes region;
- $CO2$ denotes the atmospheric concentration of carbon dioxide (in parts per million by volume);
- 275 ppm is the pre-industrial concentration;
- γ is a parameter (see Table A, column 8-9).

Column 8 in the table below shows the CO_2 fertilization parameter (γ_r) used in FUND for various regions of the world (Anthoff and Tol, 2013b). The average CO_2 fertilization effect across the 16 regions of the world is 11.2%. While this number is neither areally weighted, nor weighted by the specific crops grown, it is clear that 11.2% is much lower than the average fertilization effect compiled by Idso (2013) for the world's top 10 food crops (35%). Further, Idso's fertilization impact is in response to a 300ppm CO2 increase, while the fertilization parameter in the FUND model is multiplied by $\ln(CO2_t/275)$ which works out to 0.74 for a 300ppm CO_2 increase. This multiplier further reduces the 16 region average to 8.4% for the CO_2 fertilization effect—some 4 times smaller than the magnitude of the fertilization impact identified by Idso (2013).

Although approximately four times too small, the impact of the fertilization effect on the SCC calculation in the FUND model is large.

According to Waldhoff et al. (2011), if the CO_2 fertilization effect is turned off in the FUND model (v3.5) the SCC increases by 75% from \$8/tonCO_2 to \$14/tonCO_2 (in 1995 dollars). In another study, Ackerman and Munitz (2012) find the effective increase in the FUND model to be even larger, with CO_2 fertilization producing a positive externality of nearly \$15/tonCO_2 (in 2007 dollars).

Impact of climate change on agriculture in FUND model.

	Rate of change (% Ag. Prod/ 0.04°C)		δ_r^l		δ_r^q		CO_2 fertilisation (% Ag. Prod)	
USA	-0.021	(0.176)	0.026	(0.021)	-0.012	(0.018)	8.90	(14.84)
CAN	-0.029	(0.073)	0.092	(0.080)	-0.016	(0.009)	4.02	(6.50)
WEU	-0.039	(0.138)	0.022	(0.002)	-0.014	(0.013)	15.41	(11.83)
JPK	-0.033	(0.432)	0.046	(0.022)	-0.024	(0.030)	23.19	(36.60)
ANZ	-0.015	(0.142)	0.040	(0.071)	-0.016	(0.037)	10.48	(8.50)
EEU	-0.027	(0.062)	0.048	(0.097)	-0.018	(0.048)	9.52	(5.14)
FSU	-0.018	(0.066)	0.042	(0.075)	-0.016	(0.039)	6.71	(5.48)
MDE	-0.022	(0.032)	0.042	(0.071)	-0.017	(0.037)	9.43	(2.66)
CAM	-0.034	(0.061)	0.064	(0.043)	-0.030	(0.043)	16.41	(5.38)
SAM	-0.009	(0.060)	0.003	(0.005)	-0.004	(0.003)	5.96	(5.04)
SAS	-0.014	(0.021)	0.025	(0.024)	-0.011	(0.018)	5.80	(1.64)
SEA	-0.009	(0.482)	0.014	(0.004)	-0.010	(0.008)	8.45	(41.81)
CHI	-0.013	(0.075)	0.043	(0.076)	-0.017	(0.040)	19.21	(6.13)
NAF	-0.016	(0.023)	0.033	(0.043)	-0.014	(0.027)	7.27	(1.90)
SSA	-0.011	(0.026)	0.024	(0.034)	-0.010	(0.020)	5.05	(2.20)
SIS	-0.050	(0.103)	0.043	(0.077)	-0.017	(0.040)	23.77	(8.64)

Standard deviations are given in brackets.

Clearly, had the Idso (2013) estimate of the CO_2 fertilization impact been used instead of the one used in FUND the resulting positive externality would have been much larger, and the resulting net SCC been much lower.

This is just for one of the three IAMs used by the IWG. Had the more comprehensive CO_2 fertilization impacts identified by Idso (2013) been incorporated in all the IAMs, the three-model average SCC used by the IWG would be been greatly lowered, and likely even become negative in some IAM/discount rate combinations.

In its 2015 *Response to Comments Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*, the IWG admits to the disparate ways that CO_2 fertilization is included in the three IAMs. Nevertheless, the IWG quickly dismisses this as a problem in that they claim the IAMs were selected "to reflect a reasonable range of modeling choices and approaches that collectively reflect the current literature on the estimation of damages from CO2 emissions."

This logic is blatantly flawed. Two of the IAMs do not reflect the "current literature" on a key aspect relating to the direct impact of CO2 emissions on agricultural output, and the third only partially so.

CO_2 fertilization is a known physical effect from increased carbon dioxide concentrations. By including the results of IAMs that do not include known processes that have a significant impact on the end product must disqualify them from contributing to the final result. The inclusion of results that are known *a priori* to be wrong can only contribute to producing a less accurate

answer. Results should only be included when they attempt to represent known processes, not when they leave those processes out entirely.

The justification from the IWG (2015) that "[h]owever, with high confidence the IPCC (2013) stated in its Fifth Assessment Report (AR5) thaṭ '[b]ased on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive ones'" is completely irrelevant as CO_2 fertilization is an impact that is apart from "climate change." And further, the IAMs do (explicitly in the case of FUND and DICE or implicitly in the case of PAGE) include damage functions related to the climate change impacts on agriculture. So not only is the IWG justification irrelevant, it is inaccurate as well. The impact of CO_2 fertilization on agricultural output and its impact on lowering the SCC *must* be considered.

The Misleading Disconnect Between Climate Change and the Social Cost of Carbon in the Integrated Assessment Models

It is generally acknowledged, the results from IAMs are highly sensitive not only to the model input parameters but also to how the models have been developed and what processes they try to include. One prominent economist, Robert Pindyck of M.I.T. recently wrote (Pindyck, 2013) that the sensitivity of the IAMs to these factors renders them useless in a policymaking environment:

> Given all of the effort that has gone into developing and using IAMs, have they helped us resolve the wide disagreement over the size of the SCC? Is the U.S. government estimate of $21 per ton (or the updated estimate of $33 per ton) a reliable or otherwise useful number? What have these IAMs (and related models) told us? I will argue that the answer is very little. As I discuss below, the models are so deeply flawed as to be close to useless as tools for policy analysis. Worse yet, precision that is simply illusory, and can be highly misleading.
>
> …[A]n IAM-based analysis suggests a level of knowledge and precision that is nonexistent, and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily.

Nevertheless, federal agencies, such as the EPA and DoE incorporate the IWG determinations of the SCC into their cost/benefit analyses of proposed regulations—ill-advisedly so in my opinion.

Consider the following: the social cost of carbon should reflect the relative impact on future society that human-induced climate change from greenhouse gas emissions would impose. In this way, we can decide how much (if at all) we are willing to pay currently to reduce the costs to future society. It would seem logical that we would probably be more willing to sacrifice more now if we knew that future society would be impoverished and suffer from extreme climate change than we would be willing to sacrifice if we knew that future society would be very well off and be subject to more moderate climate change. We would expect that the value of the social cost of carbon would reflect the difference between these two hypothetical future worlds—the

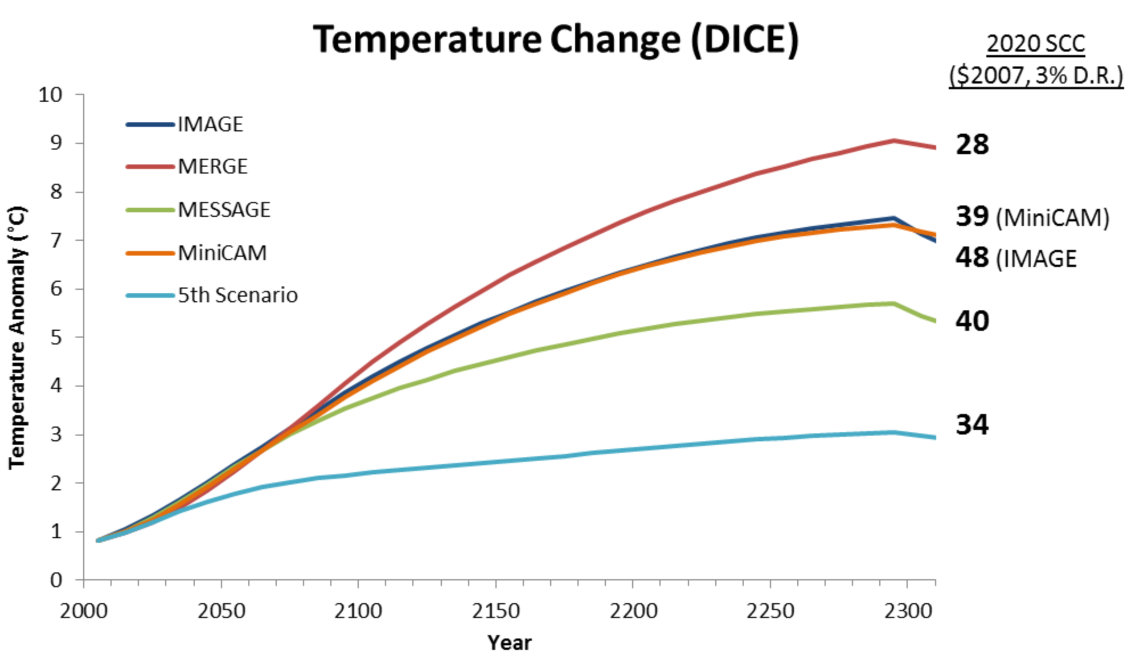
SCC should be far greater in an impoverished future facing a high degree of climate change than an affluent future with less climate change.

But if you thought this, you would be wrong.

Instead, the IAMs as run by the IWG2013 (and reflected in the July 2015 update) produce nearly the opposite result—the SCC is far *lower* in the less affluent/high climate change future than it is in the more affluent/low climate change future. Such a result is not only counterintuitive but misleading.

I illustrate this illogical and impractical result using the DICE 2010 model (hereafter just DICE) used by the IWG (although the PAGE and the FUND models generally show the same behavior). The DICE model was installed and run at the Heritage Foundation by Kevin Dayaratna and David Kreutzer using the same model set up and emissions scenarios as prescribed by the IWG. The projections of future temperature change (and sea level rise, used later in the Comment) were graciously provided to us by the Heritage Foundation.

The figure below shows the projections of the future change in the earth's average surface temperature for the years 2000-2300 produced by DICE from the five emissions scenarios employed by the IWG. The numerical values on the right-hand side of the illustration are the values for the social cost of carbon associated with the temperature change resulting from each emissions scenario (the SCC is reported for the year 2020 using constant $2007 and assuming a 3% discount rate—numbers taken directly from Table A3 of the IWG2013 report). The temperature change can be considered a good proxy for the magnitude of the overall climate change impacts.



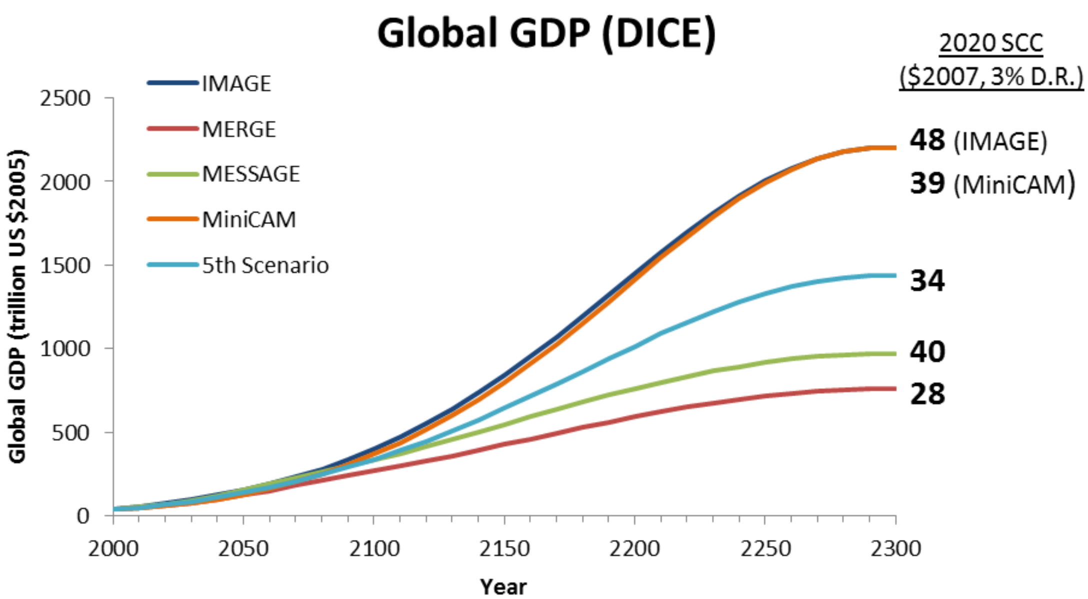
CAPTION: Future temperature changes, for the years 2000-2300, projected by the DICE model for each of the five emissions scenarios used by the IWG2013. The temperature changes are the arithmetic average of the 10,000 Monte Carlo runs from each scenario. The 2020 value of the SCC (in $2007) produced by the DICE model (assuming a 3%

discount rate) is included on the right-hand side of the figure. (DICE data provided by Kevin Dayaratna and David Kreutzer of the Heritage Foundation).

Notice in the figure above that the value for the SCC shows little (if any) correspondence to the magnitude of climate change. The MERGE scenario produces the greatest climate change and yet has the smallest SCC associated with it. The "5th Scenario" is a scenario that attempts to keep the effective concentration of atmospheric carbon dioxide at 550 ppm (far lower than the other scenarios) has a SCC that is more than 20% *greater* than the MERGE scenario. The global temperature change by the year 2300 in the MERGE scenario is 9°C while in the "5th Scenario" it is only 3°C. The highest SCC is from the IMAGE scenario—a scenario with a mid-range climate change. All of this makes absolutely no logical sense—and confuses the user.

If the SCC bears little correspondence to the magnitude of future human-caused climate change, than what does it represent?

The figure below provides some insight.



CAPTION: Future global gross domestic product, for the years 2000-2300 for each of the five emissions scenarios used by the IWG2013. The 2020 value of the SCC (in $2007) produced by the DICE model (assuming a 3% discount rate) is included on the right-hand side of the figure.

When comparing the future GDP to the SCC, we see, generally, that the scenarios with the higher future GDP (most affluent future society) have the higher SCC values, while the futures with lower GDP (less affluent society) have, generally, lower SCC values.

Combining the results from the two figures above thus illustrates the absurdities in the IWG's use of the DICE model. The scenario with the richest future society and a modest amount of climate change (IMAGE) has the highest value of the SCC associated with it, while the scenario with the poorest future society and the greatest degree of climate change (MERGE) has the lowest value of the SCC. A logical, thinking person would assume the opposite.

While we only directly analyzed output data from the DICE model, by comparing Tables 2 and Tables 3 from the IWG2010 report, it can be ascertained that the FUND and the PAGE models behave in a similar fashion.

This counterintuitive result occurs because the damage functions in the IAMs produce output in terms of a percentage decline in the GDP—which is then translated into a dollar amount (which is divided by the total carbon emissions) to produce the SCC. Thus, even a small climate change-induced percentage decline in a high GDP future yields greater dollar damages (i.e., higher SCC) than a much greater climate change-induced GDP percentage decline in a low GDP future.

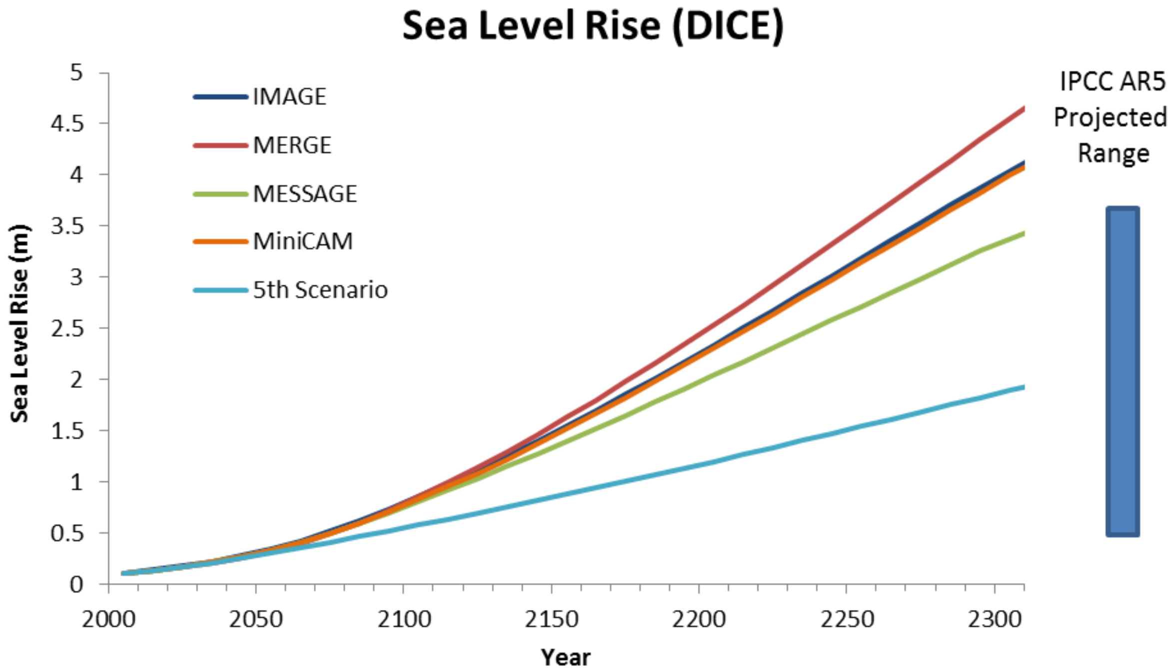
Who in their right mind would want to spend (sacrifice) more today to help our rich decedents deal with a lesser degree of climate change than would want to spend (sacrifice) today to help our relatively less-well-off decedents deal with a greater degree of climate change? No one. Yet that is what the SCC would lead you to believe and that is what the SCC implies when it is incorporated into federal cost/benefit analyses.

In principle, the way to handle this situation is by allowing the discount rate to change over time. In other words, the richer we think people will be in the future (say the year 2100), the higher the discount rate we should apply to damages (measured in 2100 dollars) they suffer from climate change, in order to decide how much we should be prepared to sacrifice today on their behalf.

Until (if ever) the current situation is properly rectified, the IWG's determination of the SCC is not fit for use in the federal regulatory process as it is deceitful and misleading.

Sea Level Rise

The sea level rise module in the DICE model used by the IWG2013/2015 produces future sea level rise values that far exceed mainstream projections and are unsupported by the best available science. The sea level rise projections from more than half of the scenarios (IMAGE, MERGE, MiniCAM) exceed even the highest end of the projected sea level rise by the year 2300 as reported in the *Fifth Assessment Report* (AR5) of the Intergovernmental Panel on Climate Change (see figure).



CAPTION: Projections of sea level rise from the DICE model (the arithmetic average of the 10,000 Monte Carlo runs from each scenario) for the five scenarios examined by the IWG2013 compared with the range of sea level rise projections for the year 2300 given in the IPCC AR5 (see AR5 Table 13.8). (DICE data provided by Kevin Dayaratna and David Kreutzer of the Heritage Foundation).

How the sea level rise module in DICE was constructed is inaccurately characterized by the IWG2013 (and misleads the reader). The IWG2013 report describes the development of the DICE sea level rise scenario as:

> "The parameters of the four components of the SLR module are calibrated to match consensus results from the IPCC's Fourth Assessment Report (AR4).[6]"

However, in IWG2013 footnote "6" the methodology is described this way (Nordhaus, 2010):

> "The methodology of the modeling is to use the estimates in the IPCC Fourth Assessment Report (AR4)."

"Using estimates" and "calibrating" are two completely different things. Calibration implies that the sea level rise estimates produced by the DICE sea level module behave similarly to the IPCC sea level rise projections and instills a sense of confidence in the casual reader that the DICE projections are in accordance with IPCC projections. However this is not the case. Consequently, the reader is misled.

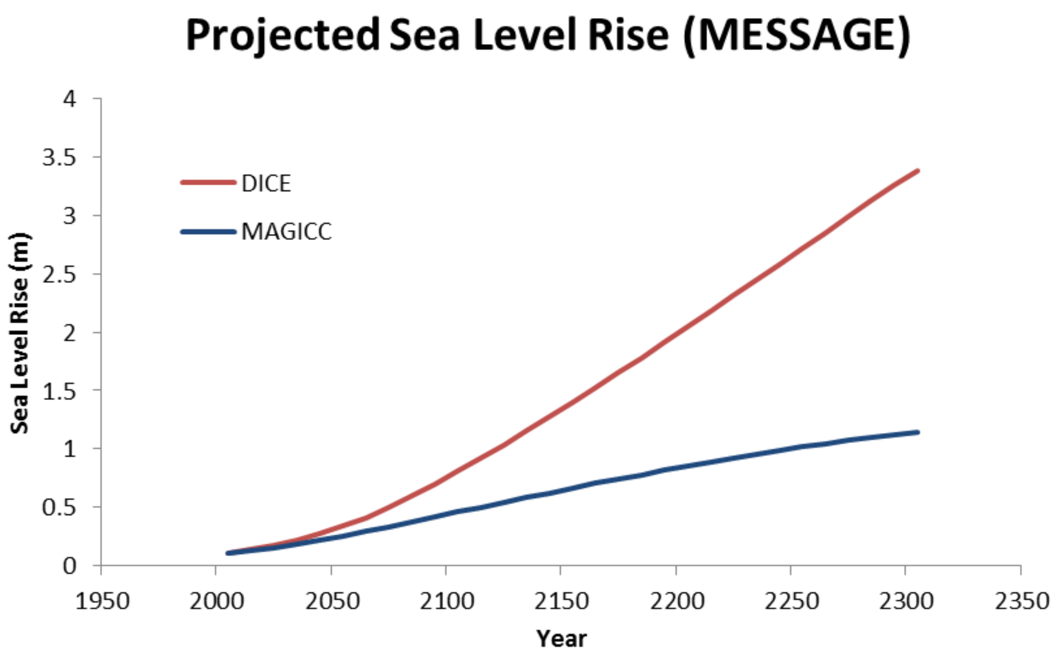
In fact, the DICE estimates are much higher than the IPCC estimates. This is even recognized by the DICE developers. From the same reference as above:

> "The RICE [DICE] model projection is in the middle of the pack of alternative specifications of the different Rahmstorf specifications. Table 1 shows the RICE,

base Rahmstorf, and average Rahmstorf. *Note that in all cases, these are significantly above the IPCC projections in AR4.*" [emphasis added]

That the DICE sea level rise projections are far above the mainstream estimated can be further evidenced by comparing them with the results produced by the IWG-accepted MAGICC modelling tool (in part developed by the EPA and available from http://www.cgd.ucar.edu/cas/wigley/magicc/).

Using the MESSAGE scenario as an example, the sea level rise estimate produced by MAGICC for the year 2300 is 1.28 meters—a value that is less than 40% of the average value of 3.32 meters produced by the DICE model when running the same scenario (see figure below).



CAPTION: Projected sea level rise resulting from the MESSAGE scenario produced by DICE (red) and MAGICC (blue).

The justification given for the high sea level rise projections in the DICE model (Nordhaus, 2010) is that they well-match the results of a "semi-empirical" methodology employed by Rahmstorf (2007) and Vermeer and Rahmstorf (2009).

However, subsequent science has proven the "semi-empirical" approach to projecting future sea level rise unreliable. For example, Gregory et al. (2012) examined the assumption used in the "semi-empirical" methods and found them to be unsubstantiated. Gregory et al (2012) specifically refer to the results of Rahmstorf (2007) and Vermeer and Rahmstorf (2009):

> The implication of our closure of the [global mean sea level rise, GMSLR] budget is that a relationship between global climate change and the rate of GMSLR is weak or absent in the past. The lack of a strong relationship is consistent with the evidence from the tide-gauge datasets, whose authors find acceleration of

> GMSLR during the 20th century to be either insignificant or small. It also calls into question the basis of the semi-empirical methods for projecting GMSLR, which depend on calibrating a relationship between global climate change or radiative forcing and the rate of GMSLR from observational data (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010).

In light of these findings, the justification for the very high sea level rise projections (generally exceeding those of the IPCC AR5 and far greater than the IWG-accepted MAGICC results) produced by the DICE model is called into question and can no longer be substantiated.

Given the strong relationship between sea level rise and future damage built into the DICE model, there can be no doubt that the SCC estimates from the DICE model are higher than the best science would allow and consequently, should not be accepted by the IWG as a reliable estimate of the social cost of carbon.

And here again, the IWG (2015) admits that these sea level rise estimates are an outlier on the high end, yet retains them in their analysis by claiming than they were interested in representing a "range" of possible outcomes. But, even the IWG (2015) admits that the IPCC AR5 assigned "a low confidence in projections based on such [semi-empirical] methods." It is internally inconsistent to claim the IPCC as an authority for limiting the range of possibilities explored by the IAMs (which it did in the case of equilibrium climate sensitivity) and then go outside the IPCC to justify including a wildly high estimate of sea level rise. Such inconsistencies characterize the IWG response to comments and weaken confidence in them.

I did not investigate the sea level rise projections from the FUND or the PAGE model, but suggest that such an analysis must be carried out prior to extending any confidence in the values of the SCC resulting from those models—confidence that we demonstrate cannot be assigned to the DICE SCC determinations.

High Social Cost of Carbon Estimates

A few papers have appeared in the recent scientific literature that have argued that the SCC should be considerably higher than that determined by the IWG. However, these papers suffer from serious flaws.

For example, Van den Bergh and Botzen (2014) purport to make a "conservative" estimate of the SCC that is nearly four times larger than the central estimate made by the IWG. This estimate suffers from the many of the issues described previously—a low discount rate, high climate sensitivity, and little to no positive benefits from agriculture. By including all sorts of imagined bad climate outcomes—with high monetary damages—and being largely dismissive of positive impacts, high SCC values are readily created by the authors.

Another recent analysis which arrived at an estimate of the social cost of carbon that was considerably higher than those made by the IWG was conducted by Moore and Diaz (2015). However, a careful examination shows that the assumptions made and methodologies employed therein produce a non-robust and ultimately unreliable result (McKitrick, 2015). Applying a better and more thorough methodology leads to results which are virtually opposite to those initially reported by Moore and Diaz (2015)—one in which the social cost of carbon is quite low and perhaps even positive.

According to McKitrick (2015), the major underlying flaw in the Moore and Diaz paper is the reliance on the results of Dell et al. (2012) in which a warming climate was linked to economic declines in both rich and poor countries. Using a more up-to-date dataset, McKitrick shows that the negative economic linkage to a warming climate is statistically insignificant and "not a robust basis for a policy assertion."

Furthermore, McKitrick (2015) shows that if a the more standard methodology is applied, where the temperature changes are areally-weighted rather than weighted by country-level population, the relationship between economic growth and temperature change reverses for rich countries and becomes statistically significant. According to McKitrick (2015), "each degree of warming significantly *increases* the annual income growth rate in rich countries by over 2 percentage points," while in poor countries, the relationship "is statistically insignificant."
In conclusion, McKitrick (2015) finds:

> The fact that the relevant poor-country coefficients are statistically insignificant implies they should not have been relied upon in Moore and Diaz (2015). And since the rich country coefficient corresponding to the [integrated assessment model] IAM structure is positive and significant, Moore and Diaz (2015) should actually have reported an acceleration of economic growth in rich countries associated with rising temperatures and a correspondingly reduced SCC. Also, since the rich countries begin with a larger GDP it is also likely that the overall global effect of warming on income growth would be positive, even applying the poor country coefficient. In any case the computations in Moore and Diaz (2015) are uninformative since they used coefficients from DJO based on an incomplete sample and a definition of temperature incompatible with their IAM.

Bottom line is that the Moore and Diaz (2015) high SCC estimates as well as the Dell et al. (2012) results upon which they were based, do not stand up under careful re-analysis. In fact, when assessed properly, they produce a low SCC estimate, in support of our overall analysis.

Overall, these new papers provide additional evidence as to the non-robust nature of current SCC determinations.

Conclusion

The social cost of carbon as determined by the Interagency Working Group in their May 2013 Technical Support Document (updated in November 2013 and July 2015) is unsupported by the robust scientific literature, fraught with uncertainty, illogical, and thus completely unsuitable and inappropriate for federal rulemaking. Had the IWG included a better-reasoned and more inclusive review of the current scientific literature, the social cost of carbon estimates would have been considerably reduced with a value likely approaching zero. Such a low social cost of carbon would obviate the arguments behind the push for federal greenhouse gas regulations.

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