Expecting a Black Swan and Getting a Dragon: Confronting Deep Uncertainty in Climate Change

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Comments Welcome

Abstract

Climate change is beset with deep uncertainties. That is particularly true for estimates of one of the key parameters: equilibrium climate sensitivity—how eventual temperatures react as atmospheric carbon dioxide concentrations double. We introduce peakedness of the climate sensitivity distribution as a way to interpret the IPCC's latest move to remove 3°C (5.4°F) as the "most likely" value for the climate sensitivity parameter.

Increased uncertainty as represented by decreased peakedness around an average climate sensitivity value increases willingness to pay to avoid climate change, entirely without relying on 'fat tails' or extreme values.

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JEL codes: Q54, D81.

What if a study utilizing a new insight on equilibrium climate sensitivity—how temperatures react over time as carbon dioxide concentrations double—produced results significantly below what most climate models and scientists now assume? The natural response would be to celebrate and to ease the push for stringent climate policy.

That celebration would be premature. It would primarily show that current climate science did not understand one of the most fundamental climate uncertainties nearly as well as had been thought. If there is one certainty, it is that the new data will not reveal

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all. Thus, the substantial change in estimates would point to even more and deeper uncertainties than previously thought.

To put the same matter in statistical terms, our mean estimate on climate sensitivity might have shifted down, but our estimate of its variance would have increased. Deeper uncertainty should magnify concerns, since marginal damages from rising temperatures increase rapidly.[2] Quite possibly, those magnified concerns would outweigh any reassurance from a lowered estimate on the mean.

A second statistical inference, and one we will focus on here, is that our estimate of the 'peakedness' of the underlying probability distribution would have gone down markedly. The chance of hitting close to the mean has decreased, while the 'likely' range around that mean would have increased. The result: under a set of reasonable assumptions, the willingness to pay to avoid damages from global warming increases with the addition of newer, lower climate sensitivity estimates: apparent good news turns into more bad news.

We focus on this second interpretation around 'peakedness,' or a lack thereof, in our subsequent analysis, beginning with section 2. Section 3 discusses some broader implications of deep climate uncertainties. Section 4 concludes.

1.

Double carbon dioxide concentrations and, consensus climate science has told us for over three decades, expect long-run temperatures to rise by around 3°C (5.4°F). That number has stood ever since Jule Charney chaired a National Academy of Sciences Ad Hoc Study Group on Carbon Dioxide and Climate in the late 1970s.[3] His range around this average was plus-minus 1.5°C (2.7°F).

That doubling of carbon dioxide concentrations is not a hypothetical. Concentrations are already up over 40 percent from preindustrial levels of around 280 parts per million (ppm) to around 400 ppm. At the rate we are going on emissions, pre-industrial levels will double well before the end of the century, *unless we significantly change course.*

The initial question is not hypothetical either. While carbon dioxide emissions have picked up this past decade, leading to the relentless upward trend in resulting carbon dioxide concentrations in the atmosphere, global average surface warming has fallen short of projections.[4] Perhaps an even more fundamental reconsideration is the newly discovered importance of black carbon.[5]

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[2] See Pindyck (2013), Weitzman (2009), Wagner and Weitzman (forthcoming), among others to discuss this mean-variance tradeoff.
[3] Charney *et al.* (1979).
[4] *Economist* (2013). See Nuccitelli & Mann (2013) for a factual rejoinder. Cowtan and Way (2013) show how global average surface warming since 1997 might have been underestimated by half.
[5] IPCC (2013).

Global warming turning out to be less severe than previously thought, were that the sole development, would merit celebration. But what it tells us about the current capabilities of climate science—notably the current understanding of how temperatures react as carbon dioxide emissions double—is that the uncertainties are greater than we thought. And this surprise is even more disturbing, since the relationship between carbon dioxide emissions and global temperatures is perhaps the most studied relationship in the climate debate. Some uncertainties elsewhere are surely greater.

While our understanding of Earth's climate is continuously advancing, deep uncertainties beset our understanding of climate change. A full accounting from industrial activity to eventual effects of climate change goes via greenhouse gas emissions to atmospheric concentrations—from concentrations to global average temperatures (the climate sensitivity parameter)—from temperatures to physical climate damages—from damages to their monetary consequences—and, at least as important, how society will respond to it all. Each of these steps comes with its own set of complications. For instance, enormous regional variations render already uncertain mean temperature increases even more so. Similarly, likely physical effects of climate change such as increased extreme weather events, increased ocean acidification, disturbances to the global water cycle, or profound effects on biodiversity all have important localized manifestations that may well dwarf global trends.

Not all of these uncertainties are 'deep,' though the one around climate sensitivity surely is. It is unlike risk, where we know the odds we face and don't know the precise draw. It also goes beyond traditional uncertainty, where we know the possible outcomes but don't know the risks attached to each.[6] A situation where even the future states of the world cannot be defined is one of ignorance, what we call "deep uncertainty."[7] That is where we are with climate sensitivity and, hence, long-run climate change projections in general.

Average projections are already sufficiently severe to warrant action now. Consensus projections put global average sea levels between 0.3 and 1 meters (1 and 3 feet) higher by 2100 than they are today.[8] But it is the extreme ends that should prompt us to even further action now. High estimates for sea-level rise go to 1.5 meters (5 feet) and 2 meters (6.6 feet), depending on whether one looks to the U.S. Army Corps of Engineers or the National Oceanic and Atmospheric Administration (NOAA) for guidance on estimates for 2100. And that's just for sea-level rise, a relatively well-studied, albeit deeply uncertain quantity. Other major consequences we haven't envisioned thrust us into the realm of deep uncertainties, a dark region where surprises lurk that could easily overthrow well-established beliefs.

Let us make three points clear. First, we recognize that a lesser temperature rise will give more credence to those who have criticized climate "alarmists" as having

[6] Knight (1921).
[7] Zeckhauser (2006).
[8] IPCC (2013).

significantly exaggerated matters. (However conscientious scientists are, their median estimates of consequences will be too high half the time, and never right on target.)

Second, we would be happy to accept good news. Thirty years hence, we may find, indeed it is 10% likely, that we will discover that climate change was less serious than our current 10th percentile estimate (assuming no bias in our estimation process). That would be fantastic news. By then, we may well know enough from improved science and physical observation to be pretty confident that the good outcome is real. However, when it comes to equilibrium climate sensitivity—perhaps the key summary parameter to capture the overall effects of carbon dioxide on average global warming—we are not hopeful that we will indeed know much more in thirty years or even beyond.

Third, we recognize that significant catastrophes can happen in what is merely a world of uncertainty. If we look at the 2007-8 financial meltdown, the primary terrible outcome was that a broad array of financial assets tumbled like dominoes. This was not an outcome that could not be imagined. In June 2005, *The Economist* declared "the worldwide rise in house prices" to be "the biggest bubble in history" and exhorted us to "prepare for the economic pain when it pops."[9] But quite apart from such a warning, this was merely a low probability event, perhaps a very low probability event, of the type we have seen before. Think of the Asian financial crisis a decade before, triggered by the collapsed of the Thai baht. The Dow Jones may plummet to 10,000 or zip up to 20,000, but it will not turn purple. If there were a chance that financial assets turned into colors, a chance that we could not possibly imagine, then we would be in the world of deep uncertainty.

Shift back to climate change. The fact that immediate temperature increases have fallen below consensus model projections by itself could be helpful. Indeed, it would prove to be unalloyed good news. But the surprising decrease has accompanying implications that cause concern. It might mean that temperatures were suppressed by a transitory phenomenon such as volcanic activity and will soon increase even faster to keep pace with the underlying trend. It surely tells us that the trend itself is more uncertain and our scientific understanding less secure than previously thought. Perhaps an entirely new process could be at work that the scientific literature had not yet considered.

Some of the possible effects of climate change are developments that scientists still have not fathomed. Look at recent history. As recently as 2007, consensus science predicted an Arctic free of summer sea-ice by the latter half of the century. By now, we are on track to have this occur in closer to ten than fifty years.

Three years ago, the U.S government, deploying the latest models, calculated a social cost of carbon dioxide at $25 per ton to date.[10] Re-running the same models today, the number is around $40, 60 percent higher.[11] The main reason for the shift was that

[9] *Economist* (2005).
[10] The $21 comes from Appendix 15A, Table 1, assuming a 3% discount rate.
[11] The 'central' estimate presented in Table 1 of the "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866" for a ton of carbon dioxide emitted in 2015.

economic models now include sea level estimates circa 2007, at the time when the fourth IPCC report was published, not even the latest, 2013, report. (Unlike our opening hypothetical, for these both mean and variance have moved unfavorably.)

2.

Estimates of climate sensitivity have not narrowed from 1.5 to 4.5°C (2.7 to 8.1°F)—the same as it has been when Jule Charney took a simple average from two prominent values at the time and added 0.5°C on either end. If anything, we have just taken a step back by removing the "most likely" label from what's long been considered the best guess: 3°C (5.4°F).

In 1990, the Intergovernmental Panel on Climate Change (IPCC) picked up Charney's range and enshrined it as its "likely" range for equilibrium climate sensitivity of 1.5 to 4.5°C (2.7 to 8.1°F).[12] The same held true until 2007, when the IPCC decided to narrow the range to 2 to 4.5°C (3.6 to 8.1°F). Apparent bad news: the lowest estimates for climate sensitivity seemed to be ever more out of reach. Though what has stayed constant between 1979 and 2007 was the "most likely" value of 3°C (5.4°F).

No longer. In its 2013 report, the IPCC decided to take two steps: widen the range again to include 1.5°C (2.7°F) as the lower bound of its "likely" range, and abandon a statement around the "most likely" value.[13] The combination of the two leads us to interpret the resulting change as one that seems to be best captured by a look at the distribution's decreased peakedness. The implications are profound. They point to deep-seeded, unresolved and perhaps largely unresolvable uncertainties around the all-important climate sensitivity parameter.

The peakedness of a distribution is a technical way of looking at how certain we are that the "most likely" single value is indeed just that. The technical term is "kurtosis," measured by the parameter θ.[14] The higher is θ, the lower is its peakedness. A standard normal distribution has $\theta = 2$. We fit this distribution around the IPCC's "likely" range of climate sensitivity between 1.5 and 4.5°C (2.7 and 8.1°F):

[12] Wagner and Weitzman (forthcoming).
[13] IPCC (2013), and Wagner and Weitzman (forthcoming). There is a mention of a "mean" climate sensitivity parameter of 3.2°C in Chapter 12 of the full IPCC report. However, the Summary for Policy Makers, the carefully negotiated summary document, no longer includes a statement of the "most likely" estimate (IPCC 2013).
[14] Based on equations (1a)-(1c) from Zeckhauser and Thompson (1970):

$$f(z;\mu,\sigma,\theta) = [2\sigma\Gamma(1+1/\theta)]^{-1} exp\left\{-\left|\frac{z-\mu}{\sigma}\right|^{\theta}\right\}$$

with $\sigma > 0$ and $\theta > 0$.

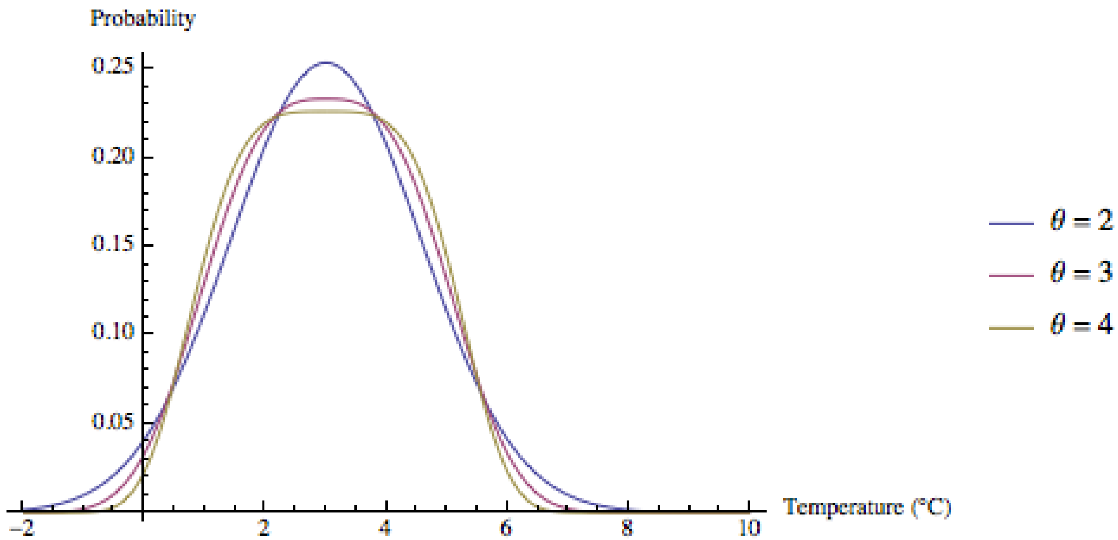

Figure 1—Climate sensitivity distribution, calibrating a standard normal distribution to the IPCC's 66% "likely" range of 1.5 to 4.5°C.

The assumed distribution is symmetric, and is not cut off at zero. These properties make it far from perfect to describe climate sensitivity. In fact, they bias our results toward being overly conservative—"conservative" in the sense that we are likely underestimating the true uncertainties involved, largely because we are not including "skewness" in our distribution. That omission becomes particularly evident toward the higher end of the temperature distribution, the potential all-important fat tails of extreme upper temperatures.[15]

Typically, climate sensitivity calibrations assume a heavily skewed distribution toward the right tail, and for good reason. No one seriously believes that doubling CO_2 would lead to *lower* temperatures, making it appropriate to cut the distribution off at zero. The IPCC itself declares a climate sensitivity of below 1°C (1.8°F) as "extremely unlikely," giving it a chance of under 5%. Our calibration, by contrast, gives values of below 1°C (1.8°F) a chance of around 10%. Conversely, the IPCC calls values above 6°C (10.8°F) "very unlikely," defined as probabilities between 0 and 10%.[16] Our calibration has values of 6°C (10.8°F) occurring with a chance of closer to 5%. While removing skewness from the equation does not allow us to explore the true distribution of climate sensitivity, it allows a more direct look at the implications of peakedness.

The most direct—if still imperfect—way of looking at the implications is to zero in on willingness-to-pay to avoid climate damages.[17] It is direct because it captures the economic essence of the problem: the worse the (economic) consequences of climate

[15] Pindyck (2012, 2013), Weitzman (2009), Wagner and Weitzman (forthcoming).
[16] A more appropriate interpretation of the probability of values above 6°C (10.8°F) may be 5 to 10%, as the IPCC had the choice of calling it "extremely unlikely," which would have captured probabilities below 5% (Wagner and Weitzman, forthcoming).
[17] Pindyck (2012, 2013).

change, the higher one's willingness-to-pay. It is imperfect because it ignores human nature. Psychologists tells us why one's willingness-to-pay often bears no relation to the magnitude of the problem.[18] Framing, for example, often trumps all: give people a choice between paying $1, 2, or 3 for a particular widget, and responses might tend toward $2. Sell the same widget giving people a choice of paying $2, 4, or 6, and their response may well be twice as high.

Willingness-to-pay here goes much beyond asking people their preferred number. It is the direct result of an intertemporal optimization problem looking at climate damages over time. Specifically, we follow Pindyck (2012, 2013) and ask how much society would be willing to pay to avoid global average temperatures exceeding 3°C (5.4°F) by 2100.

Note the important difference between these 3°C (5.4°F) of average warming by 2100 and the 3°C (5.4°F) from the climate sensitivity calibration. The latter estimates what happens to equilibrium temperatures—centuries hence—from a doubling of atmospheric carbon dioxide emissions. The former looks to actual temperatures in 2100. This estimation of warming by 2100 includes several other important uncertainties, further compounding the deep uncertainties inherent in the climate sensitivity parameter. Global atmospheric carbon dioxide concentrations are expected to pass 560 ppm, double their pre-industrial levels of 280 ppm, well before the end of the century. That does not necessarily mean that average temperatures will already exceed 3°C (5.4°F) by 2100. In fact, projected global average temperature increases by 2100, based on four wildly different IPCC scenarios, range from a low of 1°C (1.8°F) to a high of 5.5°C (9.9°F) above pre-industrial levels.[19] However, taking a rough average of the outer bounds of this range yields an average of slightly above 3°C (5.4°F) of average warming by 2100.

The relatively close match of IPCC's latest estimates for 2100 and the 3°C (5.4°F) central estimate from the 1.5 to 4.5°C (2.7 to 8.1°F) climate sensitivity match leads us to follow Pindyck (2012, 2013) and conflate the two distributions of climate sensitivity and temperatures by 2100.[20] This step decreases our absolute willingness-to-pay.[21] It does

[18] Wagner and Zeckhauser (2011).
[19] IPCC (2013).
[20] Specifically, we follow Pindyck (2012, 2013) in feeding the distribution plotted in Figure 1 into the equations Pindyck uses for temperature rises in 2100. To do so, we replace the temperature probability distributions plotted in Figure 1 of Pindyck (2013) with our distribution from footnote 14. The rest of the calibration follows the exact same steps taken in Pindyck (2012), leading up to his equation 17, the maximum fraction of consumption that society would forego in order to ensure temperature stays below a set level, at a set time in the future. Pindyck's (2012) and our values are 3°C (5.4°F) and 2100, respectively. The only minor departure from Pindyck (2012) is due to a small typographical error in Pindyck's (2012) equations 13 and 14: we switch the order of the differentials dT and $d\gamma$ to correspond to their respective integrals, such that the outer integral is integrated over T, and the inner is integrated over γ. Additionally, although equations 15 and 16 integrate time t to a limit of infinity, we followed Pindyck (2012)'s example of integrating time only to an upper limit of 500.
[21] That downward bias is compounded by the fact of our use of a standard normal temperature distribution, rather than the much more appropriate log-normal formulation, which excludes values below zero and emphasizes the importance of fat tails on the upper end. See Weitzman (2009), and Wagner and Weitzman (forthcoming).

not detract from our focus on the effects of decreased peakedness, increasing θ from the starting value $\theta = 2$.[22]

The main conclusion is clear: decreased peakedness leads directly to increased willingness-to-pay to avoid climate damages, based on rational calculations as opposed to behavioral responses, say, due to framing. The less certain we are about where the true value of climate sensitivity lies, the higher tends to be our willingness-to-pay to avoid damages from climate change:

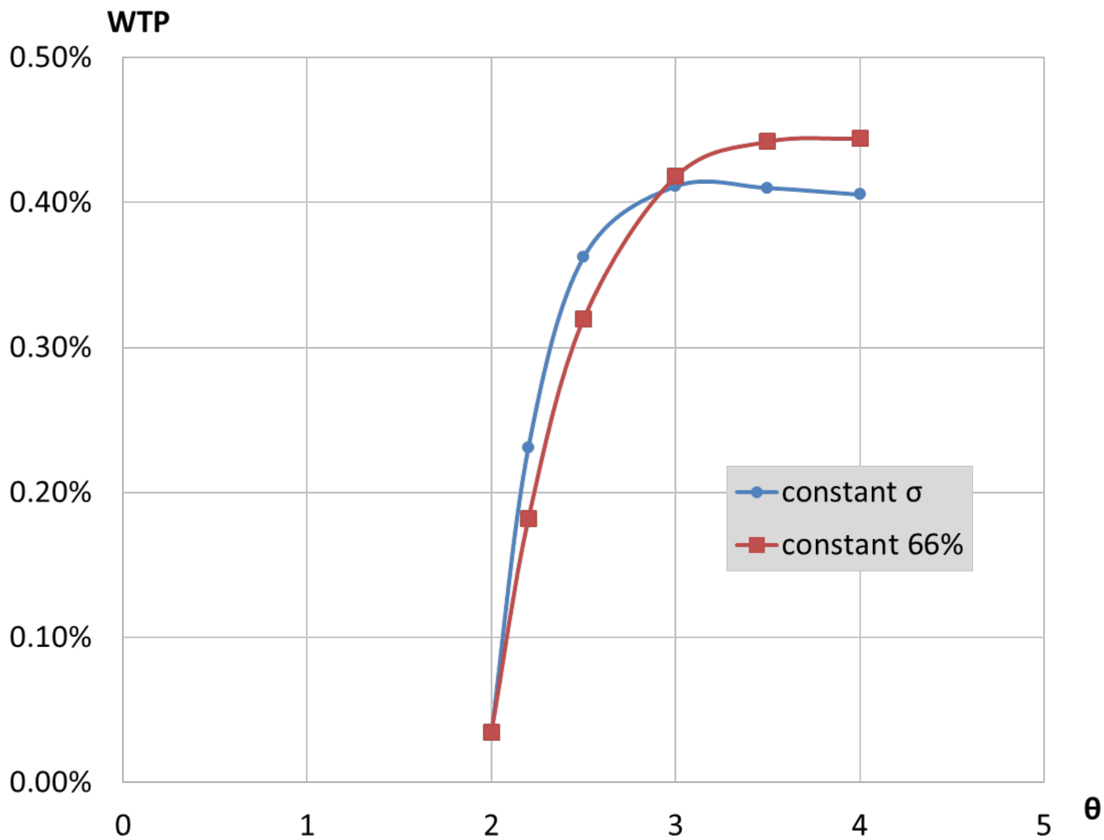

Figure 2—Willingness-to-pay (WTP) to avoid climate damages at various levels of peakedness (inversely related to θ).[23]

Importantly, this result holds true despite the clear limitations of our analysis. To repeat our earlier warning: Figure 2 highlights the importance of relative differences across willingness-to-pay levels with different levels of peakedness; the absolute willingness-to-pay levels are largely irrelevant, as deep uncertainty of climate sensitivity here does not

[22] Importantly, Zeckhauser and Thompson (1970)'s θ is not equal to kurtosis. It is rather a parameter that directly—and solely—affects kurtosis (what we call peakedness throughout the text), even though it operates in the opposite direction. For a normal distribution, $\theta = 2$, while kurtosis = 3. θ *increases* with a decrease in peakedness. The kurtosis of a uniform distribution = 1.8, while $\theta = \infty$ for the same uniform distribution.

[23] See footnotes 20–22 for technical details.

play out in the all-important (fat) upper tail of the distribution. Instead, it operates solely within the 1.5 and 4.5°C (2.7 and 8.1°F) IPCC "likely" range.

"Constant σ" in Figure 2 shows the results of varying θ, while keeping everything else constant. That shows the cleanest possible trade-off of various levels of peakedness. However, it also changes the probabilities of climate sensitivity between 1.5 and 4.5°C (2.7 and 8.1°F). In particular, increasing θ without other adjustments increases the likelihood of being between 1.5 and 4.5°C (2.7 and 8.1°F), cutting off tails (on both ends) even further.

By adjusting variance, σ, in addition to θ, we keep the IPCC's "likely" probability of 66% constant. The difference is small but important in itself. Constant 66% guarantees that willingness-to-pay is a strictly increasing function with θ. Any amount of increased uncertainty *within* the 66% likely range—a decrease in peakedness—leads to an increased willingness-to-pay to avoid climate damages.

3.

Uncertainty around the seemingly all-important climate sensitivity is not all. We haven't yet even considered the human and policy dimensions, which are themselves beset with major uncertainties. Deep uncertainty is a constant companion of policymaking for posterity.[24]

If a society is to make policy in this arena, how much value will it place on future generations? Is that different from how much it should spend to avoid imposing severe costs on future generations? This raises the crucial factor of discounting with all its normative implications. Given the long-term nature of global warming, discounting may trump almost all. A billion dollars' worth of benefits a hundred years from now translates into less than $20 million today at a 4 percent discount rate. Expensive actions to mitigate may not be worthwhile. However, if we "value" future generations more like our own and use, say, a 1 percent discount rate, that billion will correspond to over $350 million today. Suddenly a whole host of policies that benefit future generations begin to pass benefit-cost tests.

Epic battles have ensued over the normative question of what discount rate is appropriate. The lower the discount rate, the more restrictive will be the optimal climate policy. Nordhaus (2010) prefers 4 percent and argues for a relatively low price on carbon. Stern (2007) uses 1.4 percent and recommends a much higher price sooner.

Uncertainty around the true discount rate point to a declining rate over time. Pick, for instance, a range of 1 to 7 percent. The former is the lower bound of the real, risk-free rate. The latter is the upper bound of the Office of Management and Budget's

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[24] Summers & Zeckhauser, 2010.

recommended discount rate for regulatory analysis and government investments.[25] Now compare the range of discounted values to the discounted value of using the average rate of 4 percent. For $1 billion in climate mitigation benefits 100 years hence, the average of the discount values using rates of 1 and 7 percent is roughly $200 million. Compare that to the $20 million figure from using a 4 percent discount rate. The difference is a factor of ten, and it only grows the further out into the future we go. Recognizing uncertainty in the discount rate raises the expected cost of future damage.[26] Such uncertainty might be because society had not reached agreement, or because of uncertainty about future growth rates.

Climate policy also questions standard thinking around 'saving' for presumably wealthier future generations. The standard story goes something like this: Future generations will be much richer than we are, so why sacrifice portions of our measly incomes today when future generations are much more easily able to pay larger sums? Such thinking makes sense if mere wealth were involved, such as the question of how much we should invest to boost economic productivity, where most of the eventual productivity increases cannot be claimed by those who pay for them.

Thinking around climate policy is different in three important respects. The first is irreversibility. Since temperatures and sea levels will rise for centuries due to actions (not) taken today, it becomes almost irrelevant to argue that future generations would have an easier time decreasing their carbon emissions because they will be richer. Our choices—not their own—define their future.

Second, since future generations can indeed be expected to be richer, they would be willing to pay more for a stable climate. This is not merely a calculation of how much future generations would be willing to pay to avoid the worst. On a pure utilitarian basis, if climate and wealth are complements as we might expect, future generations will get more utility out of a superior climate.[27] This observation, combined with elements of irreversibility, implies the need for more climate action today for the benefit of future generations precisely because they will be richer.[28]

The third returns to the theme of deep uncertainty: We often just don't know. Thirty years of climate science have given us amazing advances in a host of areas. But climate science hasn't gotten us any further toward pinning down the range of equilibrium climate sensitivity of how much long-run temperatures react as atmospheric carbon dioxide concentrations double.

The implications of that third uncertainty may the most profound, especially because they are most easily quantified. The traditional focus has been on "fat tails" and extreme events, an undoubtedly important concept.[29] Introducing peakedness has similarly

[25] OMB (1992).
[26] Wagner and Weitzman (forthcoming).
[27] Summers and Zeckhauser (2010).
[28] Sterner and Persson (2008).
[29] Weitzman (2009), and Wagner and Weitzman (forthcoming).

profound implications and one clear conclusion: uncertainty increases the case for climate action.

4.

Climate uncertainty comes in three flavors: stochastic uncertainty, measurement uncertainty, and model uncertainty. The first is ever-present and hardly distinctive here. Measurement uncertainty is the simple fact that we don't know enough about fundamental parameters of phenomena we do understand. That type of uncertainty has indeed gone down over time. We know more now about many climatic phenomena than we did thirty years ago. Model uncertainty is the crux of the issue that concerns us. Three decades of amazing advances in climate science have gotten us no closer to pinning down the true value of climate sensitivity. If anything, the latest IPCC report may have taken a step back in that regard.

Extending the "likely" range of climate sensitivity to include lower values, 1.5°C (2.7°F) instead of 2°C (3.6°F), is presumably *good* news. There is the potential that climate change is not as bad as has been feared. Sadly, increasing the "likely" range and, in particular, removing the concept of "most likely" value of 3°C (5.4°F) entirely is *bad* news.

Despite important advances in other areas of climate science, we know even less now about equilibrium climate sensitivity than we did before the publication of the latest IPCC report. Given the increasing marginal costs of global warming, greater uncertainty, other factors equal, has an unambiguous implication for policy. Significant action to curb greenhouse emissions is more urgent.

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