Reflections—Managing Uncertain Climates: Some Guidance for Policy Makers and Researchers

Frank J Convery* and Gernot Wagner†

Abstract

Climate change—and, by extension, climate policy—is beset with unknowns and unknowables. This "Reflections" presents an overview of approaches to managing climate uncertainties, in the hopes of providing guidance for current policy decisions as well as future research. We propose the following guidance for policy makers: Treat climate change as a risk management problem; recognize that benefit-cost analysis is only the first of many steps in deciding on optimal climate policy; in assessing abatement choices, use a discount rate that declines over time; recognize the importance of framing, evidence, and connecting the dots; reward modesty. We suggest the following questions for consideration by researchers: Can we improve forecasting? Can we improve the way we address non-linearities and possible irreversibilities? What other (sub-)disciplines merit a closer look? How can we create the right incentives for updating and expanding economic damage functions and climate-economy models? What alternative decision criteria merit further exploration? What does 'not knowing' tell us?

Keywords: climate change, global warming, climate sensitivity; risk, uncertainty, unknowns, fat tails.

JEL: Q54, D81

* Environmental Defense Fund and University College Dublin; e-mail: fconvery@edf.org
† Environmental Defense Fund, adjunct associate professor at Columbia University's School of International and Public Affairs, and research associate at Harvard Kennedy School; e-mail: gwagner@edf.org

We are grateful to Matt Kahn, Suzy Leonard, Bob Litterman, Thomas Sterner, Martin L. Weitzman, Matthew Zaragoza-Watkins, and participants in the "Beyond IPCC: Future paths for climate research" workshop at the University of Gothenburg for valuable discussions and comments, to Katherine Rittenhouse for excellent research assistance, and to Princeton University Press for permission to reprint Figures 1 and 2 from Wagner & Weitzman (2015).

Introduction

How should policy makers deal with the pervasive uncertainties inherent in every link of the climate chain—from emissions to concentrations to temperatures to impacts to society's reaction? This "Reflections" aims to provide some guidance to policy makers grappling with this issue and to help identify priorities for future research. In doing so, we hope to show how uncertainty—far from a topic to be avoided—ought to be embraced by policy makers (and indeed the public) in their deliberations about climate policy. The world knows enough to act decisively and soon on climate policy. We believe that what we don't know only hastens the case for action.

To grasp the importance—and difficulty—of dealing with uncertainty, readers need look no further than some past headlines in *The Economist*. In 1913, it titled an editorial "Neighbours and Friends," arguing how "slowly but surely…war between the civilized communities of the world" was becoming "an impossibility" (*Economist* 1913). One year later, World War I had begun. Four years after that, 16 million people were dead. The week of March 29, 1986, *The Economist* put "The Charm of Nuclear Power" on its cover (*Economist* 1986). Less than a month later, reactor four of the Chernobyl nuclear plant exploded, to this date the worst nuclear accident in history.

Trying to make predictions and decisions under uncertainty is no easy task, and errors can have major repercussions. Even when *The Economist* has gotten things right, it still highlights some important lessons. In 2005, the magazine declared "the worldwide rise in house prices" to be "the biggest bubble in history" and warned to "prepare for the economic pain when it pops" (*Economist* 2005). Although it was right about the bubble, timing matters. Calling a bubble too early may be costlier than losing money once it bursts.[1] Thus, managing uncertainty properly can result in riches, or at least the avoidance of excessive losses—something demonstrably more important (Kahneman 2012).

Uncertainty is particularly important for environmental economics and policy. In fact, Pindyck (2007) discussed the challenge of addressing uncertainty in the very first issue of this journal:

> "In a world of certainty, the design of environmental policy is relatively straightforward, and boils down to maximizing the present value of the flow of social benefits minus costs. But the real world is one of considerable uncertainty—over the physical and ecological impact of pollution, over the economic costs and benefits of reducing it, and over the discount rates that should be used to compute present values. […] Incorporating uncertainty correctly into policy design is therefore one of the more interesting and important research areas in environmental economics."

Dealing with uncertainty is hard under the best of circumstances, but the challenge is compounded when examining climate change, an issue that uniquely combines four characteristics—it is global, long-term, irreversible, *and* uncertain.

Here the uncertainties often even go beyond what economists typically mean when they use the term "uncertainty." Ever since Knight (1921), "uncertainty" has been used to describe situations in which we cannot assign probabilities to outcomes. Risk is like playing a game of cards. Uncertainty is more difficult because the probabilities are unknown—like playing cards without knowing how many cards of each type there are. Predicting stock market returns is more difficult than playing a game of cards because of the large and indefinite range of possible outcomes. In

[1] Indeed, truth prematurely uttered is scarcely of more value than error. In 2002, one of us foresaw the end of the Irish economic boom that began around 1992 (Clinch, Convery and Walsh, 2002). But house prices rose by 65% between 2002 and 2007, before crashing from 2008 onwards.

this case, as much as for climate change, we are in a situation of 'deep-seated uncertainty,' what Zeckhauser (2006) calls "ignorance." We wouldn't go quite that far, but 'deep-seated' is surely an apt qualifier.[2]

Many have pointed to the problem uncertainty poses. Pindyck (2013a), for example, offers a powerful critique of the use of integrated assessment models (IAMs) to assess climate policy, focusing in particular on their treatment of uncertainty: "IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading." Many others, including Stern (2013, 2015), largely agree. Weitzman (2009, 2011, 2012, 2014) and Wagner and Weitzman (2015) highlight the importance of tail risks and grapple with the implications. Heal and Millner (2014b) discuss the implications for decision theory, and Fisher and Le (2014) discuss the implications for policy more broadly. Yet there is thus far no clear consensus in the literature on how best to address uncertainty in climate change. The remainder of this article seeks to make sense of the persistent uncertainties inherent in climate science and, thus, climate policy—focusing first on persistent uncertainties in long-run climate predictions and then addressing implications for policy makers and researchers.

Uncertainty and Equilibrium Climate Sensitivity

One of the key climate parameters is equilibrium climate sensitivity—how temperatures eventually react as atmospheric CO_2 concentrations double. Despite significant advances in climate science, the 'likely' range for climate sensitivity has remained 1.5-4.5°C (2.7-8.1°F) for more than three decades (Wagner and Weitzman 2015). The confidence of estimates being within that range has increased, though the range itself has not changed. In 2007, the IPCC did narrow the likely range to 2-4.5°C (3.6-8.1°F), only to go back to its original range in 2013.

[2] Another term is 'deep uncertainty,' though we prefer 'deep-seated' or 'persistent' simply because 'deep uncertainty' is often used interchangeably with "ambiguity," which has its own specific definition (Millner, Dietz, and Heal 2013).

Meanwhile, the ‘most likely’ value for climate sensitivity has been around 2.5 or 3°C (4.5 or 5.4°F), until the IPCC stopped using any specific number altogether in 2013. Thus, there appears to be greater and more deep-seated uncertainty around this crucial climate parameter than was thought possible only five years earlier.

The IPCC’s removal of 3°C (5.4°F) as the ‘most likely’ value may well have been an effort to counter the natural tendency to focus on the average rather than the range. However, that step is still insufficient to capture the full range of uncertainty. As Weitzman (2009, 2011, 2012, 2014), Wagner and Weitzman (2015), and many others demonstrate, the relatively wide ‘likely’ range doesn’t tell all. It is the upper bound (or possible lack thereof) of climate sensitivity that ought to command particular attention because steeply increasing damage functions make even small chances of high temperature increases incredibly costly—‘catastrophic’ to use a more colloquial yet apt description. In the final analysis, climate change is a risk management problem on a planetary scale, with no chance of a do-over. That, in short, is the unprecedented nature of this problem.

Persistent uncertainty calls for stronger climate policy today

All too often, uncertainty has been seen as an excuse for inaction on climate policy. This is clearly the wrong response in the face of uncertainty (Risky Business Project 2014, Wagner and Weitzman 2015). There is a chance—a small chance, but a chance nonetheless—that consensus climate predictions will turn out to have been too pessimistic. The IPCC (2013), for example, puts the probability of eventual temperatures rising by less than 1°C (1.8°F) due to a doubling of CO_2 concentrations in the atmosphere at 0 to 5%, calling it “extremely unlikely.” Clearly, we cannot take comfort in this up-to-1-in-20 chance, for at least three reasons:

1. Climate sensitivity is but one uncertain step

First, the uncertainty about climate sensitivity is only one of many. Just the first step in projecting climatic outcomes—calculating future emissions trajectories—is already beset with enormous uncertainties: The famous 'IPAT' equation breaks down impact (here, carbon emissions) into three components: population, affluence, and technology.[3] Each of these components is difficult to predict individually. When combined they result in enormous uncertainty around future emissions pathways. Each other step in the climate chain—from emissions at one end to society's reaction to the final impacts at the other—comes with further compounding uncertainties. Pindyck (2013a, 2013b) emphasizes the critical importance of uncertainty in economic damage functions when trying to monetize the costs of impacts. Crost and Traeger (2014) similarly show how uncertainty around the speed with which damages rise with rising temperatures defines the final outcome.[4]

2. Atmospheric CO_2 concentrations expected to more than double

Second, the 'likely' climate sensitivity range of 1.5-4.5°C (2.7-8.1°F) describes only the long-term temperature increase for a doubling of CO_2 concentrations—and double they will, short of a dramatic course correction. In fact, in its "new policies scenario," the IEA (2013) predicts that CO_2 concentrations will rise to 700 parts per million (ppm) by 2100, two-and-a-half times the 280 ppm seen before the industrial revolution, and that scenario already assumes many steps in the right direction. At 700 ppm, the eventual range of temperature increases, based on the 'likely' climate sensitivity range, spans 2- 6°C (3.6- 10.8°F). Note that even the *lower* end of this range sees eventual temperatures rise by as much as the oft-banded—and itself highly uncertain—2°C (3.6°F) threshold that has formed the basis for a number of political commitments.

[3] See Ehrlich Holdren (1971) for the original "IPAT" formulation, and Chertow (2000) for a comprehensive discussion.
[4] In fact, Crost and Traeger (2014) show how it is precisely the speed with which damages rise—the exponent in the damage function—that has the largest effect, with uncertainty in the level of damages having little effect or even lowering the resulting mitigation.

3. Tail risks may yet dwarf all else

Third, the potentially long and 'fat' upper tail of the climate sensitivity distribution may yet wag us.[5] This is because although the lower end of the distribution is typically and sensibly cut off at 0°C, consensus science sees no such certain threshold on the upper end. In contrast to the IPCC's (2013) view that any climate sensitivity realization below 1°C (1.8°F) is "extremely unlikely"—a (perhaps overly precise) probability of 5% and below—it assigns the label "very unlikely"—10% and below—to anything above 6°C (10.8°F). This implies that the climate sensitivity distribution is skewed to the right, which means that higher temperature realizations are more likely than low ones (see Figure 1).

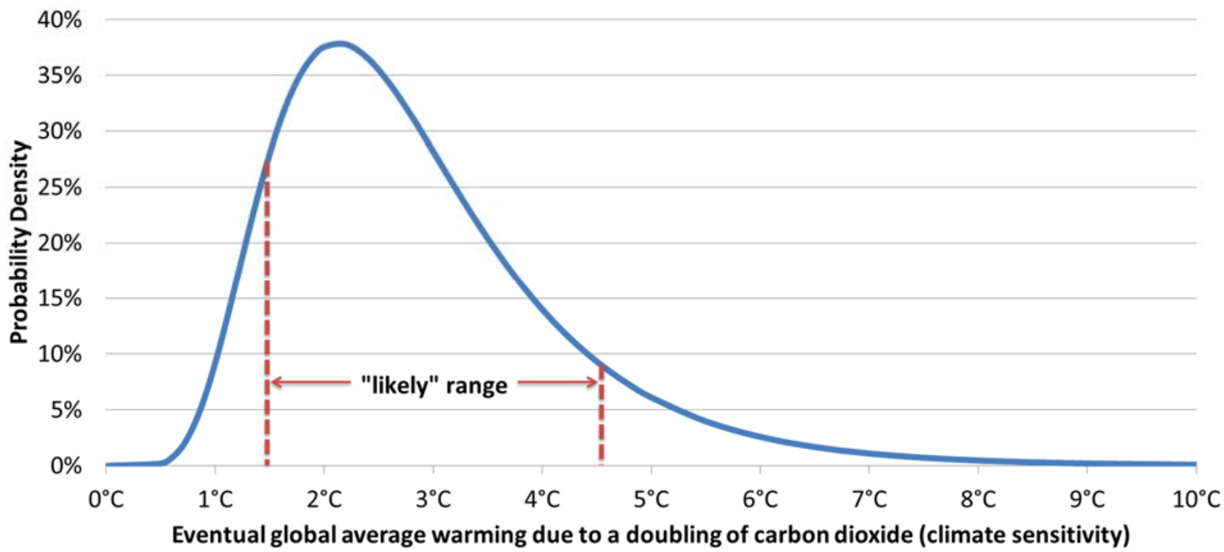

Figure 1—Climate sensitivity calibrated using a log-normal distribution

Notes: The figure fits a log-normal distribution around the IPCC's (2013) "likely" range for climate sensitivity.

[5] To illustrate, we follow Wagner and Weitzman (2015) in fitting a log-normal distribution around the IPCC's "likely" range for climate sensitivity (Figure 1), a distribution that technically isn't 'fat' but rather rests between what statisticians would declare 'thin' and 'fat'-tailed.

Source: Wagner & Weitzman (2015)

Whatever the final climate sensitivity realization, searching for the precise, single estimate is largely beside the point. The key is that we cannot *exclude* values that are even higher than the upper end of the "likely" range.

Guidance for Policy Makers

What guidance can we offer to policy makers as they grapple with the implications of deep-seated uncertainty when making climate policy? For one, it is clear that there is currently no simple off-the-shelf solution to help those in the policy process make sure that they understand and appropriately consider the uncertainty that surrounds climate change. However, there are some helpful ways of thinking about and framing the issue, and questions that can be raised, that will ensure that it is not ignored. With this in mind, we offer some guidance here. Although acting on these recommendations will not necessarily guarantee effective action on climate change, we believe that *not* acting on them will likely lead to failure.

1. **Treat climate change as a risk management problem**

Few scientists would dispute that global average temperature increases of 2, 3, or even 4°C (3.6, 5.4, or 7.2°F) would entail profound, Earth-as-we-know-it-altering changes. The last time global average temperatures were about 2 to 3.5°C (3.6 to 6.3°F) above preindustrial levels—roughly 1 to 2.5°C (1.8 to 4.5°F) above today's levels—sea levels were up to 20 meters (66 feet) higher than today, and today's subtropical fauna roamed the Arctic (IPCC, 2013).[6] Eventual global average warming of 5 or even 6°C (9 or 10.8°F) is beyond most scientists' data and most people's imagination. But when we combine our climate sensitivity calibration based on the

[6] That was a bit over 3 million years ago, when global CO_2 concentrations stood at 400 ppm—today's levels!

IPCC's (2013) consensus statements, conservatively interpreted in Figure 1, with the IEA (2013) 700 ppm scenario, that's where we end up -- a greater-than-10-percent chance of eventually *exceeding* average global warming of 6°C (10.8°F), as shown in Figure 2.

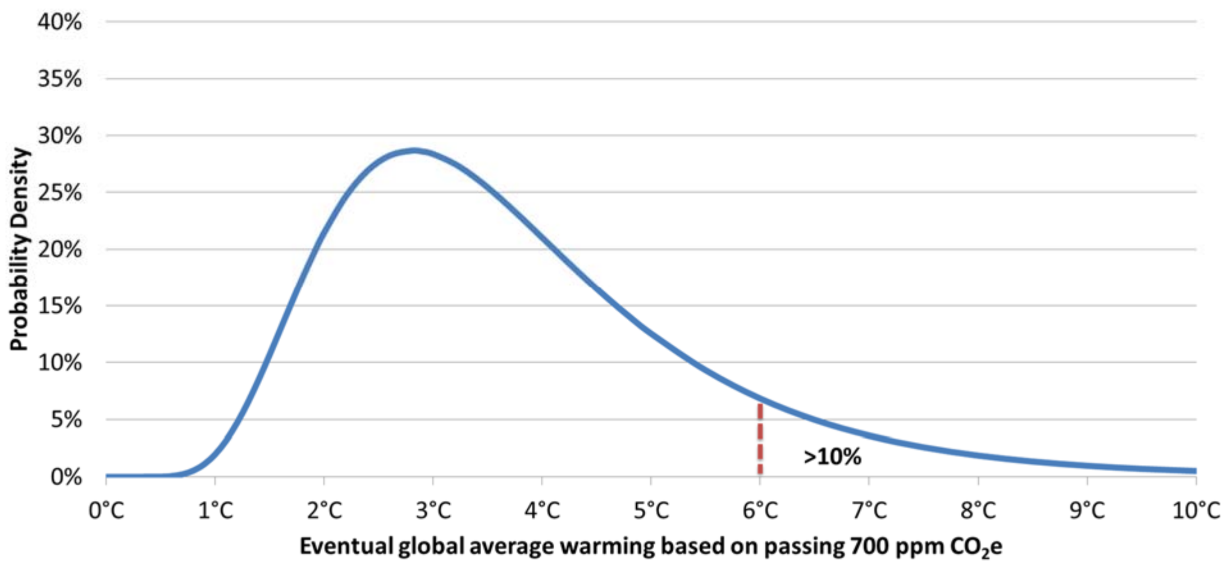

Figure 2—Equilibrium temperature calibrated using a log-normal distribution

Notes: The figure fits a log-normal distribution around the IPCC (2013) "likely" range for climate sensitivity, and assumes atmospheric concentrations of 700 ppm CO_2e.

Source: Wagner & Weitzman (2015)

What does zeroing in on the tail risks tell us? For one, it emphasizes the importance of seeing climate change as a risk management problem (Risky Business Project 2014, Wagner and Weitzman 2015). Average projections are bad enough, but it's the small-probability, high-impact events that ought to command particular attention. That possibility all but calls for a precautionary approach to climate policy.

2. Recognize that benefit-cost analysis is only one of many steps in deciding on optimal climate policy

Benefit-cost analysis is a good framework for thinking about policy evaluation, has been the basis for U.S. government policy since Ronald Reagan's presidency, and has been used the world over (Revesz and Livermore, 2008). It is clearly necessary. However, it is also far from sufficient for dealing with something as remote, uncertain, and seemingly unique—at least in human timescales—as climate change.

To be clear, benefit-cost analysis is an important first step, but it is only one such step in evaluating policies, particularly when it comes to determining the optimal global effort to address climate change. The problem is that, in practice, benefit-cost analysis of climate change policy does not (and perhaps cannot) capture the full range of uncertainties and deal with them satisfactorily. For example, the current practice of treating uncertainty by running and re-running standard climate-economy models in a Monte-Carlo-style analysis produces internally inconsistent results (Crost and Traeger, 2013).

Nordhaus (2013, 2014), Pindyck (2013a), Stern (2013, 2015), Sunstein (2007), and many others have tried to analyze climate change within the framework of benefit-cost analysis. Nordhaus (2013) provides perhaps the single best summary of conventional approaches.[7] Pindyck (2013a) answers the question of "what climate models tell us" with "very little." He concludes that this does not mean that stringent climate policy is unjustified and goes on to argue that climate policy cannot be made "based on 'consensus' probability distributions;" rather it should be "based on the possibility of a catastrophic outcome, something that is far outside the realm of these models and probability distributions." We agree. To bolster this argument, Pindyck (2014) focuses on the crucial trade-off between the mean predictions and variance of

[7] See Weitzman (2015) for a review of Nordhaus (2013).

eventual temperature outcomes (i.e., the difference in what we can expect will happen versus the variance in how certain we are about the particular prediction). Indeed, he argues that standard climate-economy models fall victim to two important fallacies in dealing with uncertainty: by necessity, they focus on what is known and can be quantified, thus leaving out what isn't known and can't be quantified, and they convey a false sense of precision. Weitzman (2009, 2011, 2012, 2014) makes perhaps the most persuasive case for going beyond standard benefit-cost analysis, arguing that climate change is among a small list of potentially catastrophic low-probability, high-impact events that deserve special attention far beyond what standard treatments can offer (Wagner and Weitzman, 2015).

Martin and Pindyck (2014) counter this argument by exploring what they call "the strange economics of Scylla and Charybdis" – the belief that the fact that many events have potential fat tail properties that warrant 'special treatment' (i.e., going beyond standard benefit-cost analysis) may result in none getting such treatment. Although that conclusion holds in Martin and Pindyck's (2014) analysis, it is unclear that reality conforms to their model. We would argue that existential risk on a planetary scale deserves quite different attention than, for example, "inspection and surveillance programs to avert nuclear terrorism" or "the construction of levees to avert major flooding," two of the examples discussed by Martin and Pindyck. One could add asteroids, genetically modified organisms, robots run amok, and many others to that list. It is clear that climate change is not the only potential catastrophe facing the planet. However, climate change may, in fact, be in the unique position of having the biggest gap between the types of investments (both public and private) that science tells us are necessary and current levels of spending on it (Wagner and Weitzman, 2015).

Thus, at the very least, persistent uncertainties imply that we need to move beyond benefit-cost analysis as the sole decision criterion. Heal and Millner (2013, 2014b) present a range of alternative decision criteria, with a version of a 'precautionary principle' being perhaps the most prominent. Viewing climate policy as a risk management problem all but prescribes this approach. None of this precludes looking to the social cost of carbon for guidance. But the estimate of $40 per ton of CO_2 emitted today (U.S. Government Interagency Working Group on Social Cost of Carbon 2013) would then need to be viewed as a lower bound for decision-making, not least because it is based on a constant rather than declining discount rate.[8]

3. In assessing abatement choices, use a discount rate that declines over time

One operative word throughout our discussion of climate policy has been ‘eventually’. Some climate impacts are felt today, but none of the most dramatic changes are expected now. In fact, the higher is climate sensitivity, the longer it will take to reach equilibrium temperature increases (Roe and Bauman, 2013). The precise timescale is, once again, highly uncertain, but ‘centuries’ seems like a fair assessment. Although damages may be beyond anyone’s imagination, as long as they are not truly infinite, standard economics tells us they should be discounted in today’s dollars.

If a society is to implement rational climate policy, one of the most important decisions it must make is how much value to place on future generations (Summers and Zeckhauser, 2008). This raises the crucial issue of which discount rate to use, with all its normative implications. In fact, given the long-term nature of global warming, discounting may trump all other issues, with the possible exception of tail risks.

Economists have had heated debates about the appropriate discount rate for evaluating climate change policies. Nordhaus (2013, 2014) uses a rate of slightly above 4 percent and argues for a relatively low price on carbon. Stern (2007) uses 1.4 percent and recommends a much higher

[8] The precise central estimate is $37 per ton of CO_2 emitted in 2015 in 2007 dollars, equal to about $40 in 2015 dollars. Nordhaus’s (2014) preferred estimate is closer to $20: in 2005 dollars, it is $18.6 for a ton emitted in 2015. The difference to the U.S. government’s central estimate can almost entirely be explained by the choice of discount rates: 4.2% for Nordhaus versus 3% for the U.S. government. Not also that Nordhaus’s (2014) estimate is significantly higher than his own estimate of $12 only four years earlier (Nordhaus, 2010). Both are lower than the “illustrative carbon prices needed for a 2½°C temperature limit” in Nordhaus (2013), Figure 33.

price sooner. Weitzman (2001) argues for a low and declining rate. Gollier and Weitzman (2010) also argue for a declining rate.[9] The U.S. Government Interagency Working Group on Social Cost of Carbon (2013) uses 3 percent as its central case.

In fact, although the *level* of the discount rate is debatable, there is much greater consensus about the declining nature of the long-term rate. Tellingly, it is largely the uncertainty surrounding the appropriate discount rate that leads to arguments for declining rates (Arrow *et al* 2013, 2014; Heal and Millner 2014a). The further out one goes into the future, the greater the uncertainty and, hence, the steeper the decline over time. The latest empirical research on this issue, which examines pricing in British and Singaporean housing markets for contracts extending 99 to 999 years versus those issued in perpetuity (Giglio, Maggiori, and Stroebel, 2014), arrives at a similar conclusion about declining rates.

Let's choose, solely for the sake of argument, a discount rate that ranges from 1 to 7 percent. The former is the lower bound of the real, risk-free rate. The latter is the upper bound of the U.S. Office of Management and Budget's recommended discount rate for regulatory analysis and government investments (OMB 1992).[10] We could then proceed in two different ways: either we discount first using two rates and then average the resulting discounted values, or we first take the average of the two discount rates and then discount using a single rate of 4 percent (the average of 1 and 7). If we average the discounted values, $1 billion in climate mitigation benefits 100 years from now translates into roughly $200 million today. However, if we use a 4 percent discount rate, the result is $20 million. The value derived by using the average of the two discounted values dwarfs (by a factor of ten) the value derived by using the average discount rate, and this difference only grows larger as we go further out into the future. Thus, the greater

---

[9] Gollier (2012) provides a good summary of the most pertinent issues. Traeger (2013) resolves the apparent puzzle presented by Gollier and Weitzman's work, culminating in Gollier and Weitzman (2010). Traeger shows how uncertainty can affect the value of a particular project via two channels—economic growth without the project, and the marginal productivity of the project in question.

[10] Seven percent is not the rate suggested for discounting long-term climate policy. The U.S. Government Interagency Working Group on Social Cost of Carbon (2013) uses 3 percent as its central value.

is the uncertainty in the discount rate, the greater are the expected costs of future damages. Or, conversely, an uncertain discount rate makes implementing climate policy today more attractive.

As long as there is any disagreement about the appropriate discount rate (something that will surely always be the case), the argument for using a low, declining discount rate stands, regardless of the source of the underlying uncertainty. This conclusion reflects the discounting practices in the UK, France, and elsewhere. However, it is not explicitly reflected in current calculations of the U.S. social cost of carbon (Cropper *et al.*, 2014).

4. Recognize the importance of framing and evidence, and connect the dots

Next we move from more concrete issues—fat tails, benefit-cost analysis, and discounting—toward the philosophical. Thus, the advice here is necessarily vague. Admonishing someone to apply one of Leonardo da Vinci's core principles of dealing with uncertainty—looking for links between different ideas (Gelb 2000)—may sound simple. But, as with so many things, it is easier said than done. Hindsight, after all, is twenty-twenty. Moreover, we can't point to a specific climate policy example to illustrate the importance of framing, evidence, and then connecting the dots, largely because the world is still at the very beginning stages of having a comprehensive global climate policy. Instead, we turn to the banking and economic crisis that began in 2008.

Appelbaum (2012) assesses the deliberations of the meetings of the U.S. Federal Reserve that occurred during 2006 and finds that none of the governors or presidents saw any link between the over-heating of the housing market and the viability of the banking system. They failed spectacularly to adopt da Vinci's principle – i.e., connect the dots. Symptomatic of this failure are the comments by Janet Yellen, then President of the Federal Reserve Bank of San Francisco, now chairman of the Federal Reserve ("Of course, housing is a relatively small sector of the economy, and its decline should be self-correcting"). Others, including Blinder

(2013), analyze the warning flags that were in plain sight, most of which were identified by outside observers well before the crash, but which were ignored.

In contrast, Alfred Marshall's approach, which led to his magnum opus, *Principles of Economics*, provides a refreshing positive example.[11] Marshall ventured into the field, believing in first-hand information. His intellectual background included metaphysics, evolutionary biology and psychology, his philosophical lodestone was Hegel—individuals should govern themselves according to their own conscience, not in blind obedience to authority—his passion was data: "I am greedy for facts," and his style was to defer publication until he was fully comfortable with the quality of his evidence, analysis and conclusions. For a contemporary example, Piketty's (2014) *Capital in the Twenty-first Century* is similarly the result of years of painstaking research.

Unfortunately, for most researchers and policy makers, the pressure and incentives to publish profusely on the one hand and to make quick policy decisions on the other, are intense. This may well mean that we miss the realities that do not appear among the 'known knowns' captured in our current models yet shape our future. All of this leads to our next and final recommendation:

5. Reward modesty

When dealing with uncertainty, the most important—and perhaps hardest—thing to say may be simply: 'I don't know'. Levitt and Dubner (2014) present these three words as the starting point for good analysis.

It is rare for experts to admit, or believe in, their own ignorance. Kahneman (2012, pp. 219) points to Tetlock (2005) as showing that those of modest mien often had better performance at

[11] For a recent reprint, see Marshall (2004). The information relating to Marshall is drawn from Nasar (2011), pp. 48-90.

making predictions, but were rarely asked for their opinion. The most famous were also the most assertive, but paradoxically had the worst performance:

> "'Experts in demand,' he writes, 'were more over confident than their colleagues who eked out existences far from the limelight.' Tetlock also found that experts resisted admitting that they had been wrong and when they were compelled to admit error, they had a large collection of excuses […] Experts are just human in the end. They are dazzled by their own brilliance and hate to be wrong."

Levitt and Dubner (2014) make the point that the incentives facing the analytical community are perverse. There is no feedback loop punishing poor prediction. And, in fact, it appears that in the media, arrogance and vigor of assertion will always trump performance. This reality is unlikely to change, but the import for those in the policy process is clear. Listen carefully to the quiet voice that says to you: "I don't know."

Opportunities for Researchers

Humility is a key tool for dealing with uncertainty. Some aspects of climate change are simply unknowable, at the very least in the timescales necessary to be able to act and influence long-term climate outcomes. Nassim Nicholas Taleb (2007) has his fun showing how most of us are ill-equipped to deal with (persistent) uncertainty. Human nature prompts us to conflate Knightian (1921) "risk"—known probabilities, known set of outcomes—with Knightian "uncertainty"—unknown probabilities. In other words, humans often think uncertainty plays out as it does in a casino, when in fact it does anything but that.

Researchers are not immune to this folly. The guidance we have laid out for policy makers—and especially the final one of simply saying "I don't know"—ought to be the starting point for researchers, too. But "I don't know" should also be a rallying cry for trying to know more. This section offers suggestions to encourage researchers to examine some of the fundamental questions that may ultimately help us deal with (climate-related) uncertainty.

1. Can we improve forecasting?

Climate policy relies heavily on predictions. Improving the underlying climate models is one thing, but what about the socio-economic components of models attempting to forecast human behavior? Harford (2014) describes the ongoing research led by Philip Tetlock and Barbara Mellors called the "Good Judgment Project." Based on 20,000 participants who assign probabilities to possible outcomes, the project is designed to move beyond "I don't know" by testing whether (and how) it is possible to improve forecasting, an area that is critical to the design and execution of climate policy. The project began in 2011 and is scheduled to run until 2016. Mid-way through, a preliminary conclusion is that better forecasting is indeed possible: some people are able to predict geopolitical events with an accuracy that far outstrips chance (Harford 2014).

A number of elements appear to improve forecasting performance. According to Harford (2014), these include:

> Training: "A 20 minute course about how to put a probability on a forecast, correcting for well-known biases, provides lasting improvements in performance."
>
> Teamwork: "When the project assembled the most successful forecasters into teams who were able to discuss and argue, they produced better predictions."
>
> Singular focus: "…The most basic explanation of their success is that they have a single uncompromised objective of seeing into the future—and this is rare."

> Feedback and keeping score: "They receive continual feedback about the success and failure of every forecast, and there were no points for radicalism, originality, boldness, conventional pieties, contrariness, or wit."

> Open mindedness: "The thinking style most associated with making better forecasts was something psychologists call 'actively open minded thinking'….The project found successful forecasters aren't afraid to change their minds, are happy to seek out conflicting views and are comfortable with the notion that fresh evidence might force them to abandon an old view of the world and embrace something new."

These findings are preliminary and will need validation and peer review. However, if valid and replicable, it would be very useful to test their relevance for climate economics, to see whether and how forecasts could be improved.

2. Can we improve the way we address non-linearities and possible irreversibilities?

The climate system is beset with tipping points. Witness the irreversible collapse of parts of the West Antarctic ice sheet (Joughin et al., 2014, and Rignot et al., 2014). The (theoretical) possibility and empirical implications of non-linearities and tipping points are beginning to find their way into climate-economy models (e.g., Ceronsky et al. 2011, Keller, Bolker, and Bradford, 2004, Lemoine and Traeger, 2014ab, Lontzek, Cai, and Judd, 2012, van der Ploeg and de Zeeuw, 2014). However, the work is far from done. Some tipping points interact with—and, thus, are as difficult as addressing—irreversibilities, which inevitably invoke the specter of 'infinity' with all the difficulties that involves. Other elements of non-linearities 'simply' point to the need to explore climate damage functions that don't follow neat quadratic, exponential, or other simple functional form patterns (e.g., Crost and Traeger 2014, Sterner and Persson 2008). Much empirical work remains to be done to draw definitive conclusions about the importance of different types of damage functions, although one conclusion has already clearly emerged:

virtually all non-linearities and possible tipping points point in one direction, that of more steeply rising climate damages. That once again implies a higher social cost of carbon.

At the very least, this conclusion should lead us to take a close look at what Fisher and Le (2014) frame as Type 1 vs Type 2 errors, something all-too familiar from other areas such as medical decisions and standard statistical applications: “We are confronted with the possibility of two types of errors: type 1, that a very modest policy will lead to disastrous climate consequences; and type 2, that a stringent policy will lead to unnecessarily high mitigation expenses.” Economics as a discipline has traditionally done a good job of incorporating the latter into benefit-cost calculations, via estimates of capital lock-in and their general equilibrium implications. We have been less successful at incorporating climate-related irreversibilities into our models.

Concerning their framing of the Type 1/Type 2 errors, Fisher and Le (2014) argue that: “While neither outcome is desirable, it seems more important to avoid the former because it can impose extraordinary costs for centuries, or possibly millennia, whereas the latter is reversible in a few years (or at most a few decades)—and at relatively low cost if done within the normal replacement cycle of capital.” Is this framing justified? Are there other options that would improve how we address irreversibility? These questions hit at the heart of climate as a risk management problem and are an important area for future research – i.e., to move beyond simple conjectures and instead point to where the errors will go.

We also need to recognize that there are powerful psychological barriers: committing a Type 1 error as defined here is akin to committing an error of omission, while Type 2 errors are akin to errors of commission. The former are typically evaluated much less harshly than the latter, leading us to do too little mitigation.[12] Thus, the design of policies that address these errors is also an important avenue for future research.

3. What other (sub-)disciplines merit a closer look?

As illustrated in our discussion of Marshall, reaching beyond one's own field can pay large dividends (Nasar, 2011). As a group, economists are generally quite comfortable with applying our tools to issues that are outside of our discipline, from public health to psychology to many other policy questions not immediately related to dollars and cents. We are arguably much less comfortable with using tools from other disciplines to help answer our own questions. And we don't have to look far to find a case in point, one that comes from within our own discipline: looking to financial economics to inform climate-economy models.

Financial economists have long known about the so-called 'equity premium puzzle', the fact that equities pay a large premium above risk-less bonds (Kreps and Porteus, 1978; Weil, 1989). Weitzman (2007) has taken this puzzle as a point of departure and attempted to solve it by introducing catastrophic risks in the form of fat tails within a framework of Bayesian statistics. He shows that taking extreme events (more) seriously reverses the equity premium puzzle (i.e., now the question may be not why the premium is so high, but why it is so low). This insight is itself an example of broadening one's lens as a researcher to include tools from other disciplines, in this case long-dormant Bayesian statistics. Moreover, this approach has provided the starting point for further work on fat tails in the context of climate change (Weitzman, 2009, 2011, 2012, 2014).

Weitzman (2007) resolves the equity premium puzzle without relying on preference specifications introduced by Epstein and Zin (1989, 1990, 1991). They showed that the equity premium puzzle can be reconciled—i.e., solved—by using a set of preferences that goes

[12] See Wagner and Weitzman (2015) for a summary in the context of geoengineering.

beyond the standard power-utility treatment. Ackerman, Stanton, and Bueno (2012), Crost and Traeger (2014), Daniel, Litterman, and Wagner (2015), Ha-Duong and Treich (2004), and Jensen and Traeger (2014) have been among those to examine Epstein-Zin utility functions in the context of standard climate-economy models. The initial verdict: calibrating climate-economy models to reflect risk aversion factors that come from financial economics increases the optimal carbon price significantly. Crost and Traeger (2014), for example, do so in DICE and find that the carbon price increases threefold under certain specifications. Daniel, Litterman, and Wagner (2015) do so in a Pindyck (2012) willingness-to-pay (WTP) framework: together with conservative assumptions around catastrophic events, WTP to avoid climate damages above a certain threshold increases more than tenfold. Neither analysis is anywhere close to the final word on how financial economics can and should inform climate-economy modeling. Rather, they identify directions for further research where joint work among financial and environmental economists could prove to be particularly fertile.[13]

This nexus between climate and financial economics itself is but one area for fruitful cross-fertilization among disciplines. Others are completely outside the realm of economics—from looking to insights from psychology and behavioral economics (e.g., Kahneman, 2012, the "Good Judgment Project" described earlier) to history to other (social) sciences.

4. How can we create the right incentives for updating and expanding economic damage functions and climate-economy models?

Climate-economy models, IAMs, play a crucial role in climate economics and policy. For example, the current U.S. social cost of carbon (around $40 per ton of CO_2 emitted in 2015 in current prices) is calculated using inputs from three models: DICE, FUND, and PAGE (U.S. Government Interagency Working Group on Social Cost of Carbon, 2013). All three models

[13] Another potential strand of research would be to identify the correct climate-*beta*, the link between climate damages and consumption.

share one important characteristic: they each are the brainchild of a single academic—William Nordhaus, Richard Tol, and Chris Hope, respectively. To date, a very small number of researchers maintain these models[14], even though they have enormous influence on policy making.

We believe that the operation of these models should be scaled up enormously—“IBM-ified” (Wagner and Weitzman, 2015). This requires creating incentives for graduate students and others to move beyond simply playing with the models on the margin to contributing to their core functionalities. As of now, IAMs lag years behind the latest science. For example, the 2013 update of the U.S. social cost of carbon reflected scientific understanding circa 2007, at the time of the Fourth Assessment Report of the IPCC (IPCC, 2007). The IPCC (2013) has since completed its Fifth Assessment Report and scientific progress is continuing.

Updating and expanding IAMs begins with improving damage functions that translate temperature increases into economic damage values. Doing that requires having an incentive structure that creates a working environment where economists and scientists collaborate much more than is currently the case. But we need to go beyond “IBM-ifying” current models to consider alternative frameworks. That begins with the inclusion of the latest insights from financial economics (discussed earlier). It also requires answering crucial questions such as whether economic damages have the greatest effect on levels of economic output or growth rates themselves. These issues ultimately go to the core of how IAMs function, how the social cost of carbon is calculated, and how the benefits and costs of mitigation policies are assessed.[15]

[14] This is true even for DICE, despite the fact that it has been open source since its creation in the early 1990s, now available at: http://www.econ.yale.edu/~nordhaus/homepage/. FUND, now jointly maintained by David Anthoff, is an open-source model, available at: http://www.fund-model.org/

[15] Pizer *et al*. (2014) provide a list of possible improvements. Fisher and Le (2014) further support and extend this discussion. Aldy (2015) discusses the importance of including adaptation and geoengineering in the portfolio of possible responses when estimating the optimal price of CO_2.

5. What alternative decision criteria merit further exploration?

It's one thing to get IAMs—and, thus, our ability to conduct standard benefit-cost analysis—right. Moving beyond this framework is quite another. Heal and Millner (2013, 2014b) are leading the way in this regard by identifying a taxonomy of alternative decision criteria. Traeger (2014) merges them with a concrete application to IAMs. None of these criteria suggests that benefit-cost analysis—i.e., the numbers coming from IAMs—should be scrapped. But they do point to potentially better ways to interpret those numbers. Much work remains to be done to arrive at a consensus among economists on a set of criteria that policy makers can confidently use in their decisions.

6. What does 'not knowing' tell us?

When it comes to climate policy, sometimes "I don't know" may indeed be the full answer. This is because some climate-related issues aren't just uncertain but simply unknowable on timescales relevant to making reasoned climate policy.

The correct draw of climate sensitivity appears to be one such issue. The scientific community will surely know the correct realization eventually, perhaps in hundreds of years. But by then it will be too late to act on it. What we are left with for now is a 'likely' range of 1.5 to 4.5°C (2.7 to 8.1°F) for climate sensitivity or—combined with the IEA (2013) 700 ppm scenario—a resulting, eventual temperature range of 2 to 6°C (3.6 to 10.8°F). Either end of that range points to the fact that we can expect climate change to be bad. The big question is how bad, and the even bigger question is how to protect ourselves from the greater-than-10% chance of going beyond the upper bound.

Given such inherent and persistent uncertainty, the question becomes: What can researchers contribute right now? When it comes to climate sensitivity, we will not know the precise draw in time to act on that knowledge, but we can point to the direction of what to expect. Thus, 'not knowing' is only a partial answer, as we do know the direction of the likely uncertainty. Or put in more concrete terms: What we know points to a social cost of $40 per ton of CO_2 (in current dollars); what we *don't* know points to a potentially much higher number.

Thus, the challenge for researchers is threefold: 1. to develop ever better estimates of the true cost of unmitigated global warming and hence the benefits of reasoned climate policy; 2. to describe what we don't (or can't) know as accurately as current research will allow; and 3. to help policy-makers to make appropriate decisions based on what we know as well as what we don't and can't know.

References

Ackerman, Frank, Elizabeth A. Stanton, and Ramón Bueno. 2012. "Epstein-Zin utility in DICE: Is risk aversion irrelevant to climate policy?" E3 working paper.

Aldy, Joseph E. 2015. "Pricing climate risk mitigation." *Nature Climate Change*, published online 6 April.

Arrow, K., M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, Robert S. Pindyck, William A. Pizer, Paul R. Portney, Thomas Sterner, Richard S. J. Tol, and Martin L. Weitzman, 2013."Determining Benefits and Costs for Future Generations." *Science* 341, no. 6144: 349-350.

Arrow, Kenneth J., Maureen L. Cropper, Christian Gollier, Ben Groom, Geoffrey M. Heal, Richard G. Newell, William D. Nordhaus, Robert S. Pindyck, William A. Pizer, Paul R. Portney, Thomas Sterner, Richard S. J. Tol, and Martin L. Weitzman. 2014. "Should Governments Use a Declining Discount Rate in Project Analysis?" *Rev Environ Econ Policy* 8: 145-163.

Appelbaum, Binyamin, 2012. "Inside the Fed in '06; Coming Crisis, and Banter", *New York Times* January 13, pp. A1, A3, http://www.nytimes.com/2012/01/13/business/transcripts-show-an-unfazed-fed-in-2006.html?pagewanted=all&_r=0

Blinder, Alan S., 2013. *After the Music Stopped—the financial crisis, the response and the week ahead*, Penguin Press, New York.

Ceronsky, Megan, David Anthoff, Cameron Hepburn, and Richard S. J. Tol. 2011. Checking the price tag on catastrophe: The social cost of carbon under non-linear climate response. ESRI Working Paper, No. 392. http://www.econstor.eu/handle/10419/50174

Chertow, Marian R. "The IPAT equation and its variants." *Journal of Industrial Ecology* 4, no. 4 (2000): 13-29.

Clinch, J Peter, Frank J Convery and Brendan M Walsh, 2002. *The End of the Celtic Tiger—challenges ahead*, O'Brien Press, Dublin.

Cropper, ML, MC Freeman, B Groom, WA Pizer, 2014, "Declining Discount Rates", *The American Economic Review* 104 (5), 538-543.

Crost, Benjamin, and Christian P. Traeger. 2013. "Optimal climate policy: uncertainty versus Monte Carlo." *Economics Letters* 120, no. 3: 552-558.

Crost, Benjamin and Christian P. Traeger. 2014. "Optimal CO_2 mitigation under damage risk valuation" *Nature Climate Change* **4**, 631–636.

Daniel, Kent D., Robert B. Litterman, and Gernot Wagner, 2015. "Applying Asset Pricing Theory to Calibrate the Price of Climate Risk: A Declining Optimal Price for Carbon Emissions," Columbia Graduate School of Business working paper.

The Economist, "Neighbours and Friends" (June 28, 1913): 1547.

The Economist, “The Charm of Nuclear Energy” (March 29, 1986): 1.

The Economist, “In come the waves” (June 18, 2005): 73.

Ehrlich, Paul R., and John P. Holdren. "Impact of population growth." *Science* 171, no. 3977 (1971): 1212-1217.

Epstein, Larry, and Stanley Zin. 1989. “Substitution, risk aversion, and the temporal behavior of consumption growth and asset returns I: A theoretical framework.” *Econometrica* 57, 937–969.

Epstein, Larry, and Stanley Zin. 1990. “‘First-order’ risk aversion and the equity premium puzzle.” *Journal of Monetary Economics* 26, 387–407.

Epstein, Larry, and Stanley Zin. 1991. “Substitution, risk aversion, and the temporal behavior of consumption growth and asset returns II: An empirical analysis.” *Journal of Political Economy* 99, 263–286.

Fisher, Anthony C. and Phu V. Le, 2014. Climate Policy: Science, Economics, and Extremes, *Review of Environmental Economics and Policy*, volume 8, issue 2, Summer 2014, pp. 307–327 doi:10.1093/reep/reu009

Gelb, Michael J., 2000. *How to Think Like Leonardo da Vinci*, New York: Random House

Giglio, Stefano, Matteo Maggiori, and Johannes Stroebel. 2014. “Very long-run discount rates,” NBER Working Paper No. 20133.

Gollier, Christian. 2012. *Pricing the Planet’s Future: The Economics of Discounting in an Uncertain World*. Princeton University Press.

Gollier, Christian, and Martin L. Weitzman. 2010. “How Should the Distant Future Be Discounted When Discount Rates Are Uncertain?” *Economics Letters* 107.3: 350–53.

Goulder, Lawrence H., and Andrew R. Schein. 2013. “Carbon Taxes vs. Cap and Trade: A Critical Review.” NBER Working Paper No. 19338.

Ha-Duong, Minh, and Nicholas Treich. 2004. “Risk Aversion, Intergenerational Equity and Climate Change”. *Environmental and Resource Economics* 28: 195-207.

Harford, Tim, 2014, “How to see into the future”, *Financial Times*, “Life and Arts” section, September 6-7: pp. 1-2.

Heal, Geoffrey M. and Antony Millner. 2013. “Uncertainty and Decision in Climate Change Economics.” NBER Working Paper No. 18929.

Heal, Geoffrey M. and Antony Millner. 2014a. “Agreeing to disagree on climate policy.” *PNAS* 2014 111 (10) 3695-3698.

Heal, Geoffrey M. and Antony Millner. 2014b. “Reflections: Uncertainty and Decision Making in Climate Change Economics.” *Review of Environmental Economics and Policy* (Winter) 8 (1): 120-137.

Intergovernmental Panel on Climate Change (IPCC). 2007. *IPCC Fourth Assessment Report: Climate Change 2007* (AR4) (2007).

Intergovernmental Panel on Climate Change (IPCC). 2013. IPCC Fifth Assessment Report: Climate Change 2013 (AR5) (2013-2014).

International Energy Agency (IEA), 2013. “World Energy Outlook 2013.” http://www.worldenergyoutlook.org/publications/weo-2013/.

Jensen, Svenn and Christian P. Traeger. 2014. “Optimal Climate Change Mitigation under Long-Term Growth Uncertainty: Stochastic Integrated Assessment and Analytic Findings.” *European Economic Review* 69(C): 104-125.

Joughin, Ian, Benjamin E. Smith, and Brooke Medley. 2014. “Marine Ice Sheet Collapse Potentially under Way for the Thwaites Glacier Basin, West Antarctica.” *Science* 344.6185: 735–38.

Kahneman**,** Daniel, 2012. *Thinking, Fast and Slow*, Farrar, Strauss & Giroux.

Keller, Klaus, Benjamin Bolker, and David F. Bradford. 2004. “Uncertain climate thresholds and optimal economic growth.” *Journal of Environmental Economics and Management* 48: 723–741.

Keohane, 2009. Nathaniel O. “Cap and Trade, Rehabilitated: Using Tradable Permits to Control U.S. Greenhouse Gases.” *Review of Environmental Economics and Policy* vol. 3, no. 1 42-62. http://reep.oxfordjournals.org/content/3/1/42.abstract.

Knight, Frank H, 1921. “*Risk, uncertainty, and profit.*” Hart, Schaffner & Marx

Kreps, David M., and Evan L. Porteus. 1978. “Temporal resolution of uncertainty and dynamic choice theory.” *Econometrica: journal of the Econometric Society* 46, 185-200.

Lemoine, Derek and Christian P. Traeger. 2014a. “Watch Your Step: Optimal Policy in a Tipping Climate.” *American Economic Journal: Economic Policy* 6(1): 1–31.

Lemoine, Derek and Christian P. Traeger. 2014b. “Playing the Climate Dominoes: Tipping Points and the Cost of Delaying Policy.” Working paper.

Levitt, Steven D. and Stephen J Dubner, 2014. *Think Like a Freak,* New York, HarperCollins.

Lontzek, Thomas S., and Yongyang Cai, and Kenneth L. Judd. 2012. “Tipping Points in a Dynamic Stochastic IAM.” Working Paper.

Marshall, Alfred. *Principles of economics*. Digireads.com Publishing, 2004.

Martin, Ian W.R., and Robert S. Pindyck. 2014. “Averting catastrophes: the strange economics of Scylla and Charybdis.” National Bureau of Economic Research working paper No. w20215.

Metcalf, Gilbert E., 2009. “Designing a carbon tax to reduce U.S. greenhouse gas emissions,” *Review of Environmental Economics and Policy* vol. 3, no. 1 63-83. http://reep.oxfordjournals.org/content/3/1/63.abstract.

Millner, Antony, Dietz, Simon, & Heal, Geoffrey. 2013. Scientific ambiguity and climate policy.*Environmental and Resource Economics*, *55*(1), 21-46.

Nasar, Sylvia, 2011. *Grand Pursuit—the story of economic genius*, Fourth Estate, London.

Nordhaus, William D. 2010. “Economic Aspects of Global Warming in a Post-Copenhagen Environment.” *Proceedings of the National Academy of Sciences* 107.26: 11721–26.

Nordhaus, William D. 2013. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*, Yale University Press.

Nordhaus, William. 2014. "Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches." *Journal of the Association of Environmental and Resource Economists* 1, no. 1.

Office of Management and Budget (OMB). 1992. “Circular No. A-94 Revised,” October 29.

Piketty, Thomas. *Capital in the Twenty-first Century*. Harvard University Press, 2014.

Pindyck, Robert S, 2007. "Uncertainty in environmental economics." *Review of environmental economics and policy* 1, no. 1: 45-65.

Pindyck, Robert S. 2012. “Uncertain outcomes and climate change policy.” *Journal of Environmental Economics and Management* .

Pindyck, Robert S., 2013a. “Climate Change Policy: What do the models tell us?“ *Journal of Economic Literature* vol.51, no. 3.

Pindyck, Robert S., 2013b. “The Climate Policy Dilemma” *Rev Environ Econ* Policy, Summer 7 (2): 219-237.

Pindyck, Robert S. 2014. “Risk and return in the design of environmental policy.” Forthcoming in: *Journal of the Association of Environmental and Resource Economists*.

Pizer, William, Matthew Adler, Joseph Aldy, David Anthoff, Maureen Cropper, Kenneth Gillingham, Michael Greenstone et al. 2014. "Using and improving the social cost of carbon." *Science* 346, no. 6214: 1189-1190.

Revesz, Richard, and Michael Livermore, 2008. *Retaking rationality: How cost-benefit analysis can better protect the environment and our health.* Oxford University Press.

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl. 2014. “Widespread, Rapid Grounding Line Retreat of Pine Island, Thwaites, Smith and Kohler Glaciers, West Antarctica from 1992 to 2011.” *Geophysical Research Letters* 41.10: 3502–9.

Risky Business Project. *Risky Business: The Economic Risks of Climate Change in the United States*. 2014. http://riskybusiness.org.

Roe, Gerard H., and Yoram Bauman, 2013. “Climate sensitivity: should the climate tail wag the policy dog?” *Climatic change* 117, no. 4: 647-662.

Stern, Nicholas. 2007. *Stern Review Report on the Economics of Climate Change*. Cambridge and New York: Cambridge University Press.

Stern, Nicholas. 2013. "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models." *Journal of Economic Literature*, 51(3): 838-59.

Stern, Nicholas. 2015. *Why are we waiting? The logic, urgency, and promise of tackling climate change*. MIT Press.

Sterner, Thomas, and U. Martin Persson, 2008. "An Even Sterner Review: Introducing Relative Prices into the Discounting Debate." *Review of Environmental Economics and Policy* 2.1: 61–76.

Summers, L., and Zeckhauser, R. 2008. Policymaking for posterity. *Journal of Risk and Uncertainty*, *37*(2-3), 115-140.

Sunstein, Cass R. *Worst-Case Scenarios*, Harvard University Press, 2007.

Taleb, Nassim Nicholas, 2007. *The Black Swan*, Random House.

Tetlock, Philip E. 2005. *Expert Political Judgment: How Good is It? How Can We Know?,* Princeton: Princeton University Press. P. 233.

Traeger, Christian P. 2013. "Discounting under uncertainty: Disentangling the Weitzman and the Gollier effect." *Journal of Environmental Economics and Management* 66, no. 3: 573-582.

Traeger, C.P. 2014, "Why Uncertainty Matters - Discounting under Intertemporal Risk Aversion and Ambiguity," *Economic Theory 56(3): 627-664*.

U.S. Government Interagency Working Group on Social Cost of Carbon. 2013. "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866." http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf.

van der Ploeg, Frederick, and Aart de Zeeuw. 2014. "Climate Tipping and Economic Growth: Precautionary Capital and the Price of Carbon." OxCarre Research Paper 118.

Wagner, Gernot and Martin L. Weitzman, 2015. *Climate Shock: the Economics Consequences of a Hotter Planet*, Princeton University Press.

Weil, Philippe. 1989. "The equity premium puzzle and the risk-free rate puzzle." *Journal of Monetary Economics* 24, 401–421.

Weitzman, Martin L. 2001. "Gamma discounting." *American Economic Review*: 260-271.

Weitzman Martin L. 2007. "Subjective Expectations and Asset-Return Puzzles." *American Economic Review* 2007;97(4): 1102-30.

Weitzman, Martin L. 2009. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." *Review of Economics and Statistics*;91(1):1-19.

Weitzman, Martin L. 2011. "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change." *Review of Environmental Economics and Policy* 5 (2): 275-292.

Weitzman, Martin L. 2012. "GHG Targets as Insurance Against Catastrophic Climate Damages." *Journal of Public Economic Theory*;14(2): 221-244.

Weitzman, Martin L. 2014. "Fat tails and the social cost of carbon." *American Economic Review: Papers & Proceedings*, 104(5): 544-6.

Weitzman, Martin L. 2015. "Review of *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World,"* forthcoming in *Review of Environmental Economics and Policy*.

Zeckhauser, Richard J. 2006. "Investing in the Unknown and Unknowable." *Capitalism and Society* 1(2).