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Climate Policy: Science, Economics, and Extremes

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Reflections

Climate Policy: Science, Economics, and Extremes

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Introduction

It seems fair to say that climate scientists, and natural scientists more generally, believe that climate change is a major, perhaps the most important, environmental problem facing us this century (IPCC 5th Assessment Report [AR5] 2013a; Climate change: Evidence and causes [National Academy of Sciences/Royal Society] 2014; Melillo, Richmond, and Yohe 2014). Two very recent discoveries—that the formerly stable ice sheet in northeast Greenland is now melting rapidly (Khan et al. 2014) and that early-stage collapse of the West Antarctic ice sheet has begun and is irreversible (Joughin, Smith, and Medley 2014)—are particularly alarming because they make more certain and bring nearer in time a massive sea level rise and the resulting inundation of coastal and low-lying areas. The potential for sea level rise and other adverse impacts of climate change was noted in 2007 in the IPCC's 4th Assessment Report (AR4 2007a). However, concern has become more urgent since then because of the greater than expected increases in both melting and emissions of greenhouse gases (GHGs), as well as recent extreme weather events in the United States and elsewhere including heat waves, droughts, and intense storms that are all predicted consequences of global warming.

One could argue that the extreme events of the past few years simply represent fluctuations in a stable climate regime. However, even if this were true, these events are important indicators of expected conditions under further warming. This argument has become even more difficult to support in light of a recent study by research teams for the US National Oceanographic and Atmospheric Administration and the UK Met Office, which detected the "fingerprints" of climate change on about half of the twelve most extreme weather events of 2012 (Peterson et al. 2013).[1]

In contrast to the scientific literature, much of the economic literature gives the impression that global warming does not require aggressive action in the near term. In fact, there is a story

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[1]For example, climate change contributed to the rise in temperatures during the heat wave in the United States; drove the record loss of Arctic sea ice; and fueled the devastating storm surge of Superstorm Sandy.

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that when a prominent economist was asked what he thought ought to be done about the recently identified problem of climate change, he responded, "What's the problem? When I cross from Washington, DC, to Virginia and it's five degrees warmer, I take off my jacket." However, even many serious economic analyses suggest that only modest steps to control GHGs (relative to those recommended by climate scientists) are appropriate at this time, with a gradual increase in stringency toward the end of the century, which is the usual time horizon for simulations in integrated assessment models (IAMs) such as Dynamic Integrated Climate-Economy (DICE) (Nordhaus 1993, 2007a), Climate Framework for Uncertainty, Negotiation and Distribution (FUND) (Tol 1997), and Policy Analysis of the Greenhouse Effect (PAGE) (Hope 2006). These recommendations would also appear to be consistent with some empirical findings of minor potential impacts of global warming on US agriculture, considered the most vulnerable sector of the economy (Deschenes and Greenstone 2007; Mendelsohn, Nordhaus, and Shaw 1994).

To be fair, economists have not spoken with one voice. Other empirical studies of US agriculture suggest the potential for large and statistically significant negative impacts toward the end of the century (Fisher et al. 2012; Schlenker, Hanemann, and Fisher 2005, 2006). Although there are conflicting results for the United States, there does seem to be general consensus that the impacts on many developing countries will be substantially negative, perhaps catastrophic for those already facing food insecurity (Cline 2007; Mendelsohn, and Dinar 1999).

At the global level, the *Stern Review* (2007)[2], which argues that strong action should be taken in the near term to reduce emissions of GHGs, has received a great deal of attention both within and outside the economics community. However, economists have generally been critical, arguing that Stern's policy recommendations are unwarranted, stemming from some combination of an overestimate of potential damages, an unrealistically low discount rate, and perhaps also a low elasticity of the marginal utility of consumption assumed in his model simulations. Widely cited critical reviews include Nordhaus (2007b) and Weitzman (2007), although Weitzman suggests that Stern's policy recommendations may be right but for the wrong reasons, not the right one, namely the Weitzman hypothesis on the importance of potentially catastrophic outcomes in the "fat tails" of a distribution (Weitzman 2009). In addition, a symposium published in this journal ("The Economics of Climate Change: The *Stern Review* and its Critics") includes critical reviews by Mendelsohn (2008) and Weyant (2008), which are balanced, however, by an "even Sterner" view of the need for urgent action on climate change by Sterner and Persson (2008).

Our view is that much of the economic analysis to date has tended to understate the magnitude of the problem and (perhaps) overstate the costs of addressing it. This is reflected in a recent article in this journal by Pindyck (2013a), "The Climate Policy Dilemma," which argues against stringent controls. In this article, we offer some reflections on climate policy, stimulated in part by Pindyck (2013a), but also based on the scientific and economic literature more generally. Interestingly, in a more recent article, which came to our attention as we were finalizing ours, Pindyck (2013b) makes a case for what might be called an "active" control policy—that is, one that is not necessarily *immediately* stringent but is nonetheless based on some of the same considerations that we will argue form the basis for a relatively stringent policy.

[2]This study, which was commissioned by the British government, used the PAGE model.

Because, in a sense, the earlier paper by Pindyck (2013a) is the starting point for our discussion, we provide a brief summary of it here. Pindyck (2013a) examines the arguments for a policy of stringent controls on GHG emissions and concludes that such a policy can be justified—if at all—only on the basis of the possibility of a *catastrophic* climate outcome. He goes on to suggest that even here, the case is weak. Pindyck bases his argument in part on a critique of the Weitzman (2009) hypothesis, showing that fat tails on a distribution of climate outcomes need not imply a high willingness to pay (WTP) to avert a climate catastrophe. Finally, he raises the question of what to do about climate policy when the WTP to avert a catastrophe is indeed high, given an assumed high WTP to avert other potential catastrophes (nuclear, biological, and so on).

It seems to us that the main policy implication of Pindyck (2013a)—skepticism regarding stringent controls on GHG emissions—although appropriately hedged due to the massive uncertainty surrounding future climate and impact variables, does not necessarily follow. Thus we suggest instead that there are reasons to support a policy of relatively stringent controls. This difference in policy recommendations is due primarily to what we believe are questionable assumptions (both explicit and implicit) in Pindyck (2013a) and elsewhere in the economic literature concerning future climate change, its impacts, and the costs of averting climate and other potential catastrophes. These questionable assumptions result in part from the need to update some of the projections and findings based on recent research, and in part from what we regard as important omitted impacts. Our views are also influenced by our understanding of the roles of discounting and irreversibilities, both of which are key issues in the debate about how to address climate change.

In the next section, we review recent climate change projections, focusing on aspects that are often not included in the IAMs or other policy analyses. This is followed by an examination of potential impacts including those not addressed in the models because they are not included in conventional measures of economic output or income. We then offer some reflections on the controversial issue of discounting in climate policy. Next we discuss the issue of irreversibility in both climate and economic systems. The penultimate section considers catastrophic climate change in the context of other potential catastrophes. We conclude with a brief discussion of implications for climate policy.

Climate Change Projections

This section examines several recent climate change projections, starting with the most prominent, those by the Intergovernmental Panel on Climate Change (IPCC).

IPCC Projections

The most recent IPCC projection (AR5, 2013a) of global mean temperature (GMT)[3]—what we might call the "business as usual" case—is characterized by continued heavy fossil fuel use that is not significantly constrained by climate policy: an increase of 3.7°C (relative to 1986–2005

[3]This projection is based on the highest Representative Concentration Pathway (RCP) for GHGs in the atmosphere (RCP 8.5). RCP2.6, RCP4.5, RCP6, and RCP8.5 in AR5 are named after a range of radiative forcing values in the year 2100 relative to preindustrial values (2.6, 4.5, 6, and 8.5 watts per square meter, respectively) (Wikipedia).

levels) by the end of the century, with a 90 percent probability range of 2.6°C to 4.8°C. Since GMT has already increased by approximately 0.8°C relative to the preindustrial level, 3.7°C is actually 4.5°C relative to the preindustrial level.[4] Either way, this projected change in GMT is well above the 2°C increase that most climate scientists believe must not be exceeded if we are to avoid a broad range of disastrous consequences. There are at least two reasons that the IPCC estimate may in fact be too low.

Impact of Arctic permafrost releases

First, the IPCC projection omits the additional increase in GMT due to Arctic permafrost releases of carbon dioxide (CO_2) and methane.[5] Although this omission may be defensible on the grounds that the cumulative release is uncertain at this time, it is already occurring on a small scale (United National Environment Programme [UNEP] 2012). It may not be sufficient to affect GMT, but it is certain to greatly increase under the temperatures projected by the IPCC.[6] The concern is that this is a positive feedback loop: the higher the temperature, the greater the release of methane and CO_2; the greater the release, the greater the increase in temperature; and so on.

Moreover, such increases in releases from the Arctic permafrost are not merely hypothetical. A recent study of the East Siberian Arctic Shelf conservatively estimates that the current methane release from submarine permafrost is 19 million tons annually, twice the level previously estimated (Shakhova et al. 2013). The reason for concern is that the permafrost in shallow water has warmed closer to the thawing point than terrestrial permafrost, and increased storm activity may accelerate significant atmospheric emissions of methane pulses, adding to the positive feedback. The situation could worsen dramatically because there are much larger stores of methane (as much as 50 billion tons) in undersea structures (called methane clathrates) off the East Siberian Shelf, and, under the right circumstances, these could release much greater amounts of the gas, as much as 5 billion tons annually over a ten-year period in one scenario (Whiteman, Hope, and Wadhams 2013).

Conservative approach of the IPCC

A second reason that the IPCC projections may be too low is that the IPCC tends to be conservative: recall the underestimate of GHG emissions and Arctic ice melting in the IPCC's previous report (AR4) in 2007. One possible explanation for this conservatism is that the Summary for Policy Makers (SPM) must be approved by all member governments, some of which are large producers of fossil fuels, some of which are developing countries, some of which are rich countries, and so on.[7] This is not to suggest any attempt to misrepresent findings, but rather that it could help to explain the IPCC's tendency to be conservative in drawing conclusions.

[4]In the past, the projected increase in GMT has generally been presented relative to the preindustrial level.
[5]Methane has a much greater warming potential but a shorter atmospheric life than CO_2.
[6]Bear in mind that Arctic amplification will result in an increase of 2.2 to 2.4 times the increase in GMT (IPCC 2013a, AR5 WG1, p. 398), so that a 4°C increase in GMT implies an increase of at least 8°C in Arctic latitudes.
[7]For an illuminating discussion of the difficulties inherent in a process in which the reviewers of a scientific document are also interested parties in negotiations based on the document, see *The Economist,* "Inside the Sausage Factory," May 10–16, 2014.

MIT Projections

The MIT Integrated Global System Model (Sokolov et al. 2009) projects a somewhat less conservative median increase in GMT over this century of 5.2°C, with a range of 3.5°C to 7.4°C, a 14 percent probability of warming between 6°C and 7°C, and an alarming 11 percent probability of warming beyond 7°C.[8] We are perhaps not the best judges of the merits of alternative climate models. Nevertheless, given the MIT model's comprehensiveness and thorough testing and documentation, with no apparent potential for bias, it certainly seems worth considering alongside the IPCC projections. However, it appears that the MIT model projections also exclude the permafrost feedback.

The Appropriate Time Horizon

All projections face the issue of the appropriate time horizon (or end point). Early discussions of climate change focused on an end point of a doubling of the atmospheric concentration of CO_2 from the preindustrial level of 280 ppm to 560 ppm, rather than choosing a particular date. More recently, in the IPCC's AR4 and AR5 and elsewhere, the end point is the year 2100. Given current (Fall 2013) concentrations of 400 ppm for CO_2 alone and 470 to 480 for CO_2-equivalent (CO_2-eq),[9] and assuming that current rates of accumulation continue, a doubling will be reached well before the end of this century because the IPCC projects concentrations of just under 1,000 ppm of CO_2 and just over 1,300 ppm of CO_2eq by 2100 under RCP8.5 (IPCC AR5; SPM 2013b). Thus shifting the end point to the end of the century makes sense. However, even this end point is problematic because neither the doubling nor the end of the century represents an equilibrium (i.e., an end to the warming process).

In a comprehensive, rigorous, and remarkably foresighted analysis, Cline (1992) concludes that an appropriate end point would be approximately the end of the twenty-third century, for two reasons. First, fossil fuel (mainly coal) reserves would be either exhausted or choked off by a rising price due to scarcity. Second, in about two hundred years, a much greater reservoir of water will be exposed to the mixing of dissolved CO_2 in the upper ocean with the deep ocean, thus greatly increasing ocean absorption of CO_2. Cline (1992, 56–58) estimates an increase in GMT of approximately 10°C by 2300. Moreover, the increase will be even greater in the Arctic, which has implications for melting ice and methane and CO_2 release.

With the exception of Fisher and Hanemann (1993), there appears to be little if any discussion of the end-point issue in the subsequent economic literature. Perhaps this is due to the focus of the scientific literature, first on a doubling of atmospheric concentrations of GHGs and then on the end of the twenty-first century.

Long-Term Projections

Recently, however, some estimates of changes in GMT by the year 2300 have appeared that are consistent with the early calculations by Cline. In simulations conducted for AR5, the German

[8]Again, 0.8°C should be added to these figures to reflect the increase from the preindustrial level.
[9]This adds trace gases such as methane and nitrous oxide and converts to an amount of CO_2 required for an equivalent warming.

Climate Computing Center (DKRZ 2014) projects an increase of nearly 10°C from the 1986–2005 level to 2300.[10]

Other recent long-term projections, reported in the *New Scientist*, suggest that a "burn everything" scenario could lead to atmospheric concentrations of CO_2 as high as 2,000 ppm, leading to a global temperature rise of 10°C, with the danger of runaway processes leading to "hyperwarming" once temperatures reach this level (Marshall 2011). Finally, a study in PNAS (Sherwood and Huber 2010) projects a possible eventual warming of 12°C from fossil fuel burning.

It is important to note that this section has discussed "worst case" scenarios (i.e., those implied by unconstrained emissions of GHGs). We are not predicting that this will happen, for several reasons, including innovations in nonfossil energy technologies and in carbon capture and storage (CCS). Rather, we argue that unless economists and decision makers have a clear understanding of the potentially catastrophic impacts of unconstrained emissions, analyses and policies that would lead to a timely development of these alternatives seem unlikely. We turn next to estimates of the potential impacts of projected climate changes.

Potential Impacts and Estimation Problems

Economic models help illustrate the links between the climate and the economy, and they are an important component of the multidisciplinary analysis that is needed to address climate change. However, there are major problems with the estimates of potential damages in the IAMs. This has implications for both the optimal control trajectory for GHGs in the models and the estimates of the social cost of carbon (SCC), which is calculated from model outputs and is the basis for policy analyses and rulemaking by governmental agencies such as the US Office of Management and Budget and US Environmental Protection Agency. First, damage functions and estimates appear to have little connection to the empirical findings from econometric studies of sectoral impacts, particularly on agriculture, as we discuss later. More generally, economy-wide damage functions are simply not known, especially at the global level. Thus, as Pindyck (2013b) argues, there is little empirical, or for that matter theoretical, foundation for the specification of functional forms and parameters in the models. This suggests that their quantitative results and policy prescriptions are somewhat arbitrary.

We agree with Stern (2013) that there are gross underestimations of damages in economic impact models and IAMs, and we discuss some additional issues that are not adequately addressed in the models including the importance of nonlinearities, environmental impacts, extreme events, and capital losses.

The Importance of Nonlinearity in Modeling Climate Change Impacts

One type of nonlinearity that has generally not been captured in economic models is represented by the possibility of catastrophic events and tipping points in climate systems (i.e., the threshold beyond which climate change can no longer be accommodated). For example, under the Sherwood and Huber (2010) projection of a potential 12°C increase in GMT by the end of the twenty-third century, regions currently holding the majority of the human population

[10]This is an extension of the RCP8.5 scenario.

would become uninhabitable due to induced hyperthermia as dissipation of metabolic heat becomes impossible. This would begin to occur in some regions with an increase in GMT of 7°C, which, as noted earlier, has an 11 percent probability of occurring by the end of the twenty-first century in the MIT model (Sokolov et al. 2009). The point is that heat stress imposes a limit on human adaptation to climate change, which, to our knowledge, has not been considered in previous models or policy analyses.

Another tipping point could come from sea level rise. An increase in GMT of 4°C to 5°C by the end of the twenty-first century would lead to permanent abandonment of some islands and low-lying areas, including large portions of some countries, due to inundation from the resulting 1 meter rise in sea levels (World Bank 2012). If we add in the effect of a (complete) melting of the West Antarctic Ice Sheet, which is already in the early stages of an irreversible collapse and is a serious concern for the period beyond 2100 (Joughin et al. 2014), the projected rise in sea level would be much greater—about 8 meters (Poore, Williams, and Tracey 2011). The complete melting of the Greenland Ice Sheet, which is also already melting, would add about 6.5 meters. A reduction in both ice sheets, similar to past (presumably incomplete) reductions in the geologic record, would add at least 10 meters, resulting in flooding of about 25 percent of the US population, with the major impact on people and infrastructure along the East and Gulf Coast states (see Figure 1). As with potential methane releases, things could get much worse. During the early Pliocene era (2.4 to 5 million years ago), which was about 3°C warmer than today, sea levels were as much as 15 to 25 meters higher than today, suggesting that part of the much larger East Antarctic Ice Sheet, generally believed to be more stable, must have been vulnerable to melting (Hansen et al. 2013).

Nordhaus and Sztorc (2013) respond to criticism that damage functions that fail to capture nonlinearities caused by extreme events or abrupt changes understate potential damages by adding 25 percent to the damage function to account for all nonmonetized impacts. This approach seems arbitrary at best, and almost certainly still underestimates damages, especially as we look beyond the end of the century. For example, Ackerman, Stanton, and Bueno (2010) use the standard DICE model to show that temperature increases of up to 19°C can involve a loss in output of as little as 50 percent. However, given the globally catastrophic impact of even a 10°C increase, it seems unlikely that human civilization could survive a 19°C increase. Others have proposed a damage function of higher order polynomials to address the underestimates of damages at excessive levels of warming. But tinkering with the functional form also seems arbitrary, especially in light of the sensitivity of results to functional specifications. For example, raising the temperature exponent from 2 to 3 in a standard damage function causes damages to jump from 10.4 percent of output to 33.3 percent when the elasticity of marginal utility is 1, or from 3.3 percent to 29.1 percent when the elasticity is 2 (Stern 2008).

Some recent articles take a more promising approach to modifying the clearly unsatisfactory damage functions by explicitly introducing the possibility of tipping points and extreme or catastrophic events, along with modeling the associated uncertainty of these events. For example, Ceronsky et al. (2011) use the FUND model to estimate the SCC under what they characterize as low-probability, high-damage events, including large-scale release of oceanic methane hydrates and climate sensitivity[11] above "best guess" levels. They find a mean SCC that is as much as three times conventional estimates. These results suggest that the potential for

[11]This indicates the response of temperature to a given increase in atmospheric concentrations of GHGs.

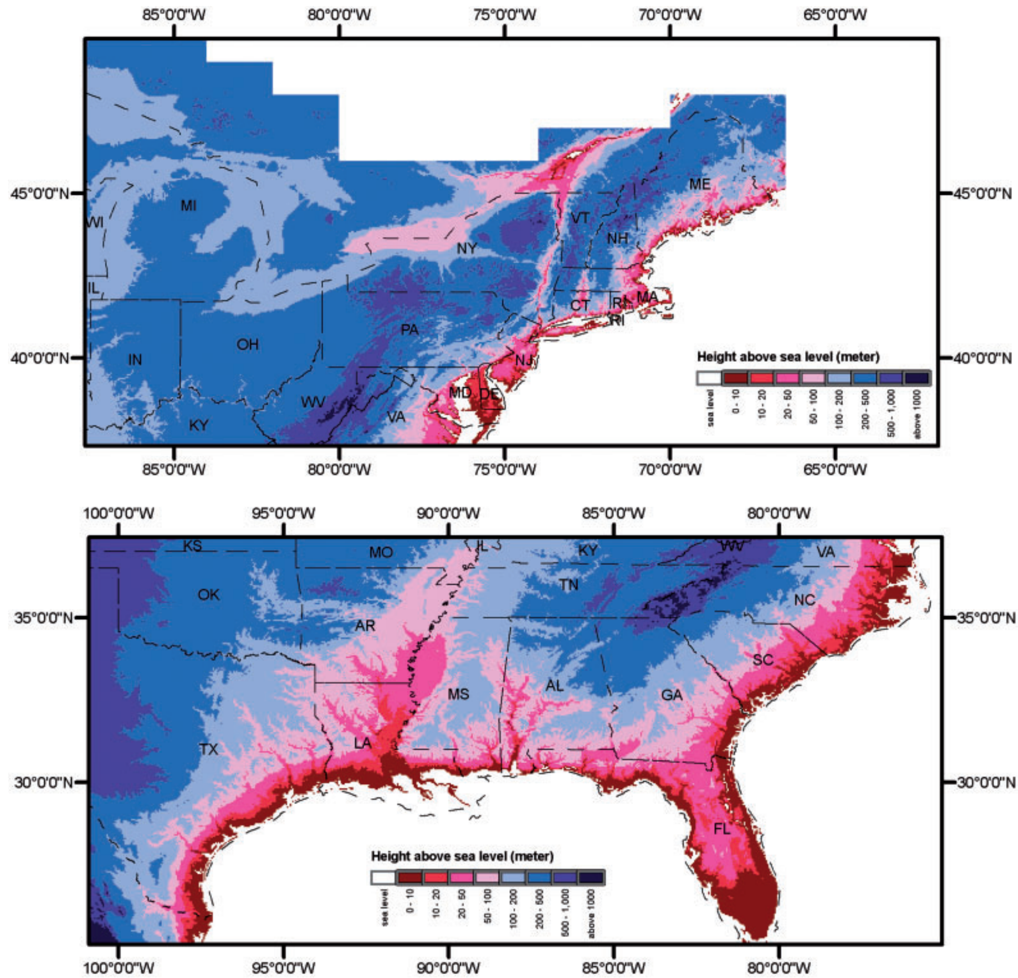

Figure 1 Risk of sea level rise (inundation; transient flooding already occurring), North East and South East/Gulf Coast of the United States

Notes: The maps show land elevation above sea level, based on a 2.5-arcminute Digital Elevation Model for the conterminous United States.

Source: The PRISM Climate Group at Oregon State University.

catastrophic outcomes can justify an aggressive policy of near-term mitigation. Using a modified DICE model, Lemoine and Traeger (2012) study the impact on the optimal carbon tax in of two kinds of tipping points, one involving climate sensitivity and the other a longer carbon cycle. They find that relative to a model that excludes possible tipping points, the optimal near-term carbon tax is increased by up to 45 percent, and peak warming is reduced by 0.5°C. These and other recent modeling efforts aimed at accounting for relevant nonlinearities are a step in the right direction for models to provide guidance to policy, although they necessarily remain only partial in their ability to capture potential impacts.

Kopp, Hsiang, and Oppenheimer (2013) suggest a very different approach: basing empirical damage functions on the observed response of human systems to climate variability. This approach is supported by work that has been done on potential damages in the most extensively studied sector of the US economy: agriculture. In a series of econometric studies, Schlenker

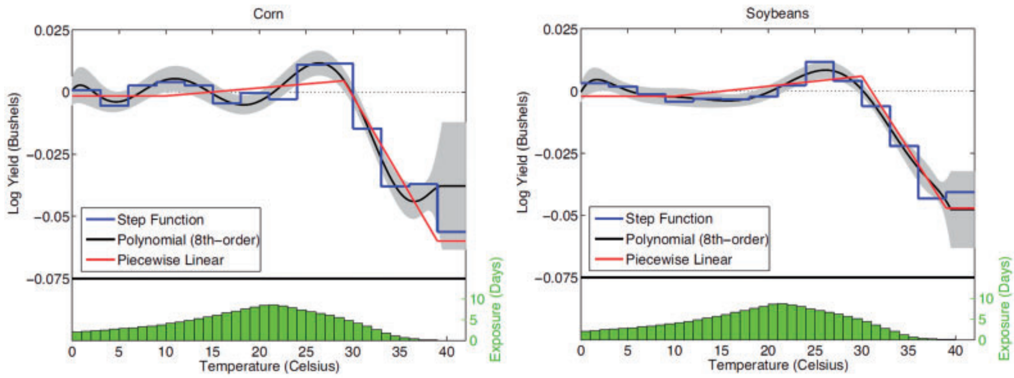

Figure 2 Nonlinear impact of temperature on US corn and soybean crop yields
Source: Schlenker and Roberts (2009; Figure 1, p. 15595).

et al. (2006) and Schlenker and Roberts (2009) have found a nonlinear impact that provides a better foundation for increased damages than an arbitrary add-on or change in exponents. The nonlinearity is exhibited in two ways. First, Schlenker et al. (2006) find that a dramatic increase in extreme heating days over the next several decades (measured by growing degree days that are at temperatures above 34°C) is responsible for nearly all of the potential negative impact of warming on US farmland value. Projected increases in *average* temperature are much less important. Second, Schlenker and Roberts (2009) find that crop yield functions exhibit sharply diminishing returns after an optimal temperature has been reached. More specifically, yields are stable or slowly increase with temperature up to 29°C for corn and 30°C for soybeans, but they then fall sharply with each additional degree (see Figure 2).

These results raise an interesting question: Might this sort of nonlinear relationship hold in other areas or activities affected by climate change including ecosystem functioning, and might it be appropriate to include when modeling damages in IAMs? It seems plausible, but more empirical research is needed.

Impacts on Environmental Goods and Services, Extreme Events, and Capital Losses

Much of the literature on damage estimates, including IAMs, effectively omits the direct impacts of climate change on environmental goods and services because these studies implicitly assume perfect substitutability between environmental and market goods. This means, as noted by Sterner and Persson (2008), that "a dollar's worth of climate damages, regardless of the kind, can be compensated by a dollar's worth of material consumption." They go on to argue that "if there are limits to substitutability . . . then our analysis of climate change needs to take into account the content of future growth." More specifically, because it is the environmental goods that can be expected to become relatively scarce, their shadow prices will be rising.[12] Using the DICE model, and making an assumption about the (limited) substitutability of market goods for environmental goods, Sterner and Persson (2008) show that the implied change in the

[12]For an early analysis along these lines, although not related to climate change, see Fisher and Krutilla (1975).

relative price between market and environmental goods has an effect on optimal abatement that is very similar to the effect produced by adopting the near-zero pure rate of time preference in the *Stern Review* (Stern 2007). Making both changes would require even more drastic reductions in GHG emissions over the next several decades.

As environmental impacts such as heat waves, wildfires, droughts, and intense storms become more frequent and more severe, they will undoubtedly affect the consumption that is included in the measured national income accounts. Hsiang and Jina (2013) examine the long-run impact of a major tropical storm on economic growth, and, based on an econometric analysis of several data sets, they find that national incomes decline relative to their predisaster trend and do not recover within twenty years. Moreover, they find that the cumulative effect of this persistently suppressed growth is both statistically significant and large: a 90th percentile event reduces per capita incomes by 7.4 percent two decades later.

One explanation for the findings of Hsiang and Jina (2013) may be that the event's immediate impact is to destroy infrastructure, which then affects productivity in subsequent periods. This raises a more general point—first noted by Fisher and Hanemann (1993) and discussed at some length in Stern (2013)—about estimates of losses associated with climate change, particularly in IAMs. That is, in their focus on income or output losses, IAMs do not capture capital losses, which in our judgment are likely to be more important in assessing extreme events such as the recent Superstorm Sandy and other major tropical storms, which cause extensive damage to coastal infrastructure and thus affect future productivity.

Two very recent studies also go beyond conventional damage estimates and suggest that the losses from climate change may be experienced more widely than previously believed. Using a variety of physiological and economic data sources, Heal and Park (2013) demonstrate a link between temperature and income. They identify the likely cause to be a link between temperature and labor productivity, with a broad measure of productivity falling when temperatures go beyond 22°C. Hsiang, Burke, and Miguel (2013) find a relationship (although not directly linked to gross domestic product [GDP] or productivity) between temperature and conflict, ranging from domestic violence to regional conflicts. These studies, as well as Hsiang and Jina (2013), suggest that the potential impacts of climate change over the next several decades are likely to be wide ranging, going well beyond those included in earlier sectoral studies or conventional damage estimates.

Discounting Issues

Any discussion of climate policy inevitably turns to the issue of how to discount the potential damages associated with climate change. This is because damages are expected to become increasingly severe over the next several decades and even centuries. This long time frame, along with the magnitude of the problem, makes the discounting decision more critical than for typical investment problems. Not surprisingly, optimal policy in the DICE model is more sensitive to changes in the discount rate (keeping within a plausible range) than to changes in other variables in alternative runs of the model (Nordhaus 1993, 2007a)—although as noted earlier, taking account of changing relative values of environmental and market goods over time, with limited substitutability of the latter for the former, can have a similarly dramatic effect.

Discussions of discounting in the context of climate change policy are often set in the framework of the Ramsey equation, which states that the consumption discount rate r is equal to the sum of two components: the pure rate of time preference ρ, and the product of the elasticity of the marginal utility of consumption θ and the rate of growth in per capita consumption g:

$$r = \rho + \theta * g$$

Controversy generally centers on the choice of ρ, and to a lesser extent on θ, although there can also be differences in expectations concerning g.

Pindyck (2013a) presents a hypothetical example involving two individuals, John and Jane, who are deciding how much of their respective (equal) incomes to spend and save. John saves 10 percent each year to help finance his grandchildren's college education; Jane saves nothing, instead spending on sports cars, boats, and expensive wines. Pindyck then poses the question of whether John's concern for his grandchildren makes him more *ethical* than Jane, and he answers it by saying that economists don't have much to say on this issue. We agree that as economists, we have little to say concerning John's and Jane's individual choices.

But does this example shed any light on the choice of the rate of time preference in the climate change problem? Many (we would guess most) people, even most economists, would argue that in the very different setting of a social choice—for example, how much (if anything) should the present generation do to ward off major and perhaps catastrophic impacts of climate change—some concern for the welfare of future generations, including Jane's grandchildren, is the ethical choice. In the context of the Ramsey equation, this means that ρ should be understood as the pure *social* rate of time preference, not the private rate implicit in Pindyck's example.

But how should this rate of time preference be specified? Although there is a vast literature on this issue, even in the context of climate policy, at the risk of oversimplifying, we distinguish between two approaches. The first approach, used throughout the *Stern Review* (Stern 2007), implicit in Pindyck (2013a), and advocated in a wide-ranging review of climate economics by Heal (2009), considers the choice of the rate of time preference to be an *ethical* decision, "a decision on the relative weights of different generations of human beings" (p. 9). Unlike the consumption growth rate, and to some extent the elasticity of marginal utility, the social rate of time preference is, in Heal's words, "exogenous to the economic problem." Once this is set, the discount rate (r in the Ramsey equation) can be determined by adding in the $\theta * g$ term. It is important to note that this generally implies a positive discount rate even if the pure rate of time preference is zero. That is, there is no preference for the present over future generations. This means, for example, that if the elasticity of the marginal utility of consumption $(\theta) = 1.5$ and the consumption growth rate $(g) = 2$ percent, then the discount rate $= 3$ percent.

Returning to the issue of the consumption growth rate, if we adjust it to reflect "consumption" of the nonmarket services of the natural environment that support the human economy (which are expected to be increasingly adversely affected by climate change), then the consumption growth rate, and hence the discount rate in the Ramsey equation, will be reduced. In fact, it could conceivably become negative at some point, especially if it is accompanied by a low or zero rate of time preference. Alternatively, following Heal (2009), we could distinguish between two separate discount rates, one for discounting ordinary consumption goods and the other for discounting nonmarket services of the environment, with the former clearly positive and the latter possibly negative. A negative discount rate would mean that from the perspective of the present, future losses resulting from the impact of climate change on nonmarket environmental services would look larger rather than smaller.

The second approach to specifying the pure rate of time preference, taken in the DICE model (Nordhaus 2007a), explicitly chooses the discount rate r so that it is consistent with observed rates of return on investment in private capital markets. This discount rate, together with $\theta * g$ in the Ramsey equation, means that there is an *implied* pure rate of time preference (positive). Thus this approach avoids any discussion of what constitutes an ethical choice by the current generation. We see two problems with this approach. First, it implicitly assumes that it is the *private*, rather than the social, rate of time preference that is relevant to a social choice concerning climate policy. Second, g is measured solely by the growth rate in per capita consumption of *conventional* market goods. In all fairness, most discussions of climate policy that take the alternative, ethical choice approach could also be criticized on the same grounds (i.e., that they implicitly neglect impacts on nonmarket goods).

These two approaches to specifying the pure rate of time preference for climate policy decisions are discussed at some length by Heal (2009, the ethical approach) and Nordhaus (2007a, the market approach), proving perhaps that this is a subject on which reasonable people (and economists) can differ. That said, our own view, which is similar to Heal's, is that there is no necessary connection between interest rates or rates of return in private capital markets and the pure rate of (social) time preference that is appropriate to climate policy decisions.

Irreversibilities

Pindyck (2013a) argues[13] that "the case for a stringent climate policy should be reasonably robust and not rely heavily on the value of a particular parameter" (in this case the rate of time preference). It seems to us, however, that one might argue equally well that it is the case for a mild (as opposed to stringent) climate policy, characterized by very modest controls in the near to medium term, that should be reasonably robust. 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. 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.[14]

This highlights one of the scientific community's main concerns about climate change: that in important respects it is irreversible. Once in the atmosphere, emissions persist for many decades or even centuries. Thus emissions are reversible only over a very long period that stretches well beyond the useful life of a piece of capital equipment or the time horizon in economic planning models; Furthermore, climate impacts such as the inundation of large areas and loss of species are essentially irreversible on human time scales.

[13]This is not strictly limited to discounting.

[14]The original analysis of the different degrees of reversibility (or irreversibility) in environmental policy, although not specifically related to climate change, is found in Krutilla (1967).

Somewhat surprisingly, a number of economic studies argue that the relevant dynamics actually suggest *less* rather than more control. These studies model the control decision as an investment (e.g., in a new energy system not based on fossil fuels) that is irreversible. Simulation modeling based on assumptions about climate and economic parameters from the DICE model suggests that the investment irreversibility dominates (i.e., has a bigger effect on the optimal control trajectory than the climate irreversibility). This means that some investment in alternative energy sources or other options for controlling emissions will be foregone or delayed. The control decision is further tilted toward delaying control of emissions because the models take into account uncertainty about the extent of climate change and its impacts. If learning is possible, we should refrain from some or all of the investment in reducing emissions today in order to make a better decision tomorrow when we will have better information about the potential benefits (see, e.g., Fisher and Narain 2003; Kolstad 1996; and Pindyck 2007).

One problem with these results is that they are based on climate change damage functions that we have argued grossly underestimate potential damages. An additional problem, specific to the treatment of irreversibilities, is that the models fail to capture a key feature of the climate policy decision problem*: the time scales for climate and investment irreversibilities are not the same;* in fact, they are likely to differ by orders of magnitude. This means that treating them symmetrically will produce a misleading result.

Another problematic feature of the models is that they treat the decision to invest in a new energy system as being a once-and-for-all, all-or-nothing decision. However, such decisions are not onetime, all or nothing. In fact, at any decision point (e.g., one of the ten-year time steps in the DICE model), there is an array of choices, and the option chosen will only tilt the mix of fossil fuel, renewable source, and energy-efficiency capital in one direction or another—until the next decision point. Moreover, once we disaggregate "investment" in this fashion, we can see there is a symmetry between alternative investments. That is, although investing in a fuel-efficient car, an array of solar collectors, or a facility to generate electricity from biofuels might be considered irreversible in the short to medium term, so is investing in another coal-burning power plant or another factory to produce SUVs that get only 11 miles to a gallon of gasoline.

Thus given the uniquely long time frame that is appropriate for considering climate policy options, the irreversibility (and therefore the option value) that matters is the one concerning climate change and its impacts, not investment in energy facilities.

Catastrophic Climate Change in Context

What would constitute catastrophic climate change? The scientific consensus in the IPCC reports and elsewhere appears to be that stabilization of atmospheric CO_2 concentrations at 450 ppm (or a CO_2 equivalent, or CO_2eq, level of approximately 530 to 550 ppm),[15] which is roughly consistent with a 2°C increase in GMT during this century (or about 2.8° C above the preindustrial level), is necessary to keep climate impacts from becoming likely to reach catastrophic levels. We note that some climate scientists and others now believe that even a target of 450 ppm is too high to forestall multiple major adverse impacts, and that a long-run level of

[15] This includes likely concentrations of other GHGs such as methane.

something like 350 ppm is required. Hansen et al. (2013) argue that the level of cumulative emissions associated with a 2°C warming would spur feedbacks leading to an eventual 3°C to 4°C warming.

The WTP Approach

Pindyck (2013a) frames the discussion of how to consider potential climate catastrophes in the context of other potential catastrophes in terms of WTP to avert or reduce the probability of occurrence of each type of catastrophe (e.g., climate, mega-virus, detonation of one or more nuclear weapons in a major city). He argues that although WTP to avert climate catastrophes may be as high as 10 percent of GDP, there may be a similar WTP for other catastrophes, which means we would need to spend something like 60 to 70 percent of GDP to avert all of the potential catastrophes. Thus Pindyck (2013a) draws the reasonable conclusion that this is an amount society would likely be unwilling to pay.

However, there are both conceptual and empirical difficulties with this approach to accounting for catastrophic climate change in the context of other catastrophes. We have argued that the benefits of controlling emissions (i.e., the averted damages) to reach a target atmospheric concentration of 450 ppm CO_2 are surely very great, although they are not capable of being fully monetized. It seems to us that the natural question, then, is what cost estimates should be used for weighing the costs against the benefits? A WTP of 10 percent of GDP is irrelevant if the costs are much lower, say just 1 to 2 percent of GDP.

We will return to the issue of costs, but we first need to point out another issue in using WTP in empirical studies of the benefits of environmental programs. We know from the literature on survey research (see Bjornstad and Kahn 1996) that WTP depends on the framing of the question. This is especially true when people are asked to value a good (or bad) with which they have little or no experience. This would be a serious concern in the context of climate change, where people are being asked about future consequences that are far beyond the realm of current or historical experience. A second concern is that the survey needs to include a credible payment mechanism. For example, the question might be "Would you be willing to pay an additional 10 percent in property taxes to finance a treatment plant that would reduce the concentrations of pollutant X in a nearby lake by 90 percent?" But what would the payment mechanism be in the context of climate change? Although many people have experienced natural disasters, the potential climate catastrophe is very different because it would mean an unending and increasing series of disasters that would occur much more frequently and over much wider areas.

Alternatives to WTP

We turn now to estimates of the costs of abatement (i.e., controlling emissions of CO_2 and perhaps other GHGs) and compare them to the benefits (i.e., the damages averted by holding further increases in GMT to less than 2°C). This approach has the clear advantage of being based on engineering/economic cost estimates, in which we can have more confidence than WTP. There is another important advantage of the cost-of-abatement approach: we can in principle rely on the market, or market-like incentives such as a carbon tax or a cap-and-trade mechanism, both to generate information about costs and, ideally, to minimize the costs of attaining the objective.

What can be said about the costs of meeting the scientific consensus target of stabilizing concentrations by the year 2100 at 450 ppm CO_2 or approximately 550 ppm CO_2eq? Projected costs of achieving these levels appear to be relatively modest (generally in the range of 1 to 2 percent of GDP), depending on the specific target and method of computation. Drawing on an extensive set of studies, Edenhofer et al. (2010) estimate that the cost of meeting the extremely low stabilization target of 400 ppm CO_2eq would be less than 2.5 percent of global GDP (measured as discounted cumulative losses to the year 2100), with costs of achieving the medium and higher stabilization levels of 450 ppm and 550 ppm being approximately 1.5 percent and 0.8 percent, respectively. A McKinsey study (McKinsey Global Institute 2008), which focuses on improvements in energy efficiency as well as alternative energy sources, puts the cost of keeping the CO_2eq level at 500 ppm at 0.6 to 1.4 percent of global GDP in 2030. In AR4 (IPCC 2007b), the IPCC estimates it would cost 0.6 percent of GDP in 2030 and 1.3 percent in 2050 to meet a target in the range of 535 to 590 ppm CO_2eq. AR5 (2014) estimates a cost of 0.6 percent of GDP in 2030 and 1.7 percent in 2050 to meet a slightly more ambitious target in the range of 530 to 580 ppm.[16]

Energy Alternatives

Behind these control or mitigation cost estimates are estimates and assumptions about the costs of alternatives to fossil fuels. Although we are not familiar with all of the assumptions and methods in these studies, there is encouraging evidence concerning past trends at least, in the costs of wind and solar, two of the main alternatives for electricity generation. Both wind and solar have seen dramatic reductions in installation costs over the past several decades, and they are close to being (and in some areas already are) competitive (IPCC 2011). The cost of solar (photovoltaic) power is estimated to have declined by an astonishing 99 percent over the past several decades, from more than \$76 per watt in 1977 to less than \$1 (\$0.74) per watt in 2013 (*The Economist* 2012). Moreover, according to "Swanson's law," which suggests a 20 percent drop in the price of solar photovoltaic modules for every doubling of cumulative shipped volume, the cost of installation is expected to decrease further as adoption increases (Swanson 2006). Wind power installation cost has also declined sharply, by more than 50 percent, from approximately \$4,300/kw to less than \$2,000/kw over the 1982–2008 period (Wiser and Bolinger 2009).

It is also important to examine the cost of coal-based electricity generation with CCS. Although not strictly an alternative to fossil fuel–based generation, CCS provides another option for mitigation, one that is potentially more important than renewables as it would enable continued production from a very abundant source, especially in the United States. For example, a recent study estimates that the increase in the cost of electricity for a new coal power plant in the US Midwest is reduced from approximately 35 percent to 13 percent if the captured CO_2 can be used for enhanced oil recovery (Fowler et al. 2012). The study also finds

[16]These estimates, along with others from AR4 and AR5, are shown in Table 1 of the online supplemental materials.

that further decreases are possible as a result of the optimization of plant design and the development of more robust CO_2 sales markets over time.

Finally, any comparison of alternative energy sources needs to consider the nonclimate change-related environmental and health impacts of conventional fossil fuel use. For example, a recent National Academy of Sciences (NAS) study finds that air pollution from the burning of coal and oil results in $120 billion in health costs just for the United States (NAS 2010). This does not account for other damages, such as water pollution from ongoing extraction and transport, and from occasional disastrous oil spills. These are real costs, although for the most part they are not reflected in the prices of oil and coal. These costs are, however, relevant to estimates of the net social cost of reducing GHG emissions through substituting a mix of energy conservation, increased use of renewables, continuing substitution of natural gas for coal, and perhaps construction of new nuclear plants. Alternatively, these costs can be considered as a benefit of low-carbon fuels, thereby reducing the net social cost of substitution. To illustrate, accounting for only part of the damage unrelated to climate change associated with coal-based electricity generation yields a damage estimate of 3.2 cents/kwh (NAS 2010, 6–7). Subtracting this from the cost of wind-based generation would make wind power cheaper than coal in some locations where it is currently marginally more expensive, with similar results for solar photovoltaic generation (IPCC 2011).

Certainty of Potential Catastrophes and the Role of Policy

There are differences between a climate-related catastrophe and other potential catastrophes that make a simple adding up of WTP, or even costs, across catastrophes not very relevant to the climate policy debate. One important difference concerns the issue of certainty. In the case of climate change, we can be fairly certain that unless effective policy instruments and technologies to reduce emissions of GHGs are implemented, the kinds of consequences discussed earlier will occur. By the same token, if abatement efforts are increased, we can be fairly certain that we can at least reduce the frequency or severity of the various natural disasters. This kind of near-certainty—of the occurrence or nonoccurrence associated with specific policy measures—does not apply to other catastrophes such as the outbreak of a mega virus or detonation of a nuclear device by a rogue state or terrorist organization.

Admittedly, we are not experts on the prospects for averting or reducing the probability of these nonclimate catastrophes. That said, it is also not clear how much more can usefully be done to avert these catastrophes, and at what cost. Perhaps efforts such as more widely deployed monitoring mechanisms for detection of outbreaks of contagious diseases and more rapid communication and treatment would help. However, given the resources already devoted to these activities, any additional effort would likely account for only a tiny fraction of GDP. Similarly, with respect to nuclear terrorism, the United States and other countries are already devoting substantial resources to prevention. No doubt more could be done, but the costs would likely account for only a small fraction of current defense and intelligence expenditures, including those already devoted to this problem—and an even smaller fraction of GDP. In any event, given the relatively modest levels of additional averting expenditures (relative to GDP), it does not appear that controlling emissions of GHGs to hold a further increase in GMT to less than 2°C by the end of the century would be precluded by some increase in efforts to avert other catastrophes.

Concluding Reflections: Implications for Climate Policy

What are the implications of these reflections for climate policy? Our recommendation is a policy that some economists might consider fairly stringent: target stabilization of the atmospheric concentration of CO_2 at 450 ppm, or CO_2eq at about 550 ppm, consistent with a further increase in GMT of 2°C. As noted earlier, the scientific consensus is that this will reduce the probability or frequency of occurrence of some of the most damaging impacts. Moreover, this target appears to be attainable at reasonable cost—on the order of 1 to 2 percent of world GDP. One way to view this cost is as an insurance premium against the worst outcomes.

An alternative approach is, of course, to use one of the established IAMs to compute an optimal trajectory of emissions reductions. We have argued that this is unsatisfactory, for several reasons. First, the most severe potential impacts (e.g., on sea level rise) will occur in a time frame that goes well beyond what is considered in the models, and they would in any event be rendered insignificant by discount rates based on rates of return in private capital markets. But perhaps even more importantly, the impacts that are likely to be the most damaging are not adequately captured by the implicit assumption of perfect substitutability of conventional market goods for services of the natural environment that are essential to the functioning of the human economy. What would compensate for the loss of vast areas of productive land to a sea level rise of 10 meters, or even of 1 to 2 meters, and the resulting mass migrations and conflicts? It seems to us that it would be preferable for us as a society to take prudent actions in the near to medium term so that humankind is less likely to face this and perhaps equally serious challenges in the more distant future.

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