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Authors
Fisher, A. C
Le, P. V

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Reflections on Climate Policy: Science, Economics, and Extremes

Anthony C. Fisher
and Phu V. Le

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Anthony C. Fisher and Phu V. Le

Department of Agricultural and Resource Economics
University of California at Berkeley

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Abstract

Climate scientists, and natural scientists generally, believe that climate change is a major problem, perhaps the most important one facing us this century, and increasingly linked to extreme weather events. On the contrary, the impression one gets from much of the economic literature, in particular simulations from the integrated assessment models (IAMs) used in policy analysis and at least in principle in the formulation of regulations by government agencies is that potential impacts are not large enough to warrant aggressive mitigation efforts in the near term. The models represent an important step in the needed interdisciplinary analysis of climate change, elucidating the links between climate and economy, but we argue that they grossly underestimate potential impacts and associated damages.

Events beyond the 21$^{\mathtt{st}}$ century are neglected, yet recent scientific findings suggest that, in the absence of significant controls on emissions of greenhouse gases (GHGs), global mean temperature (GMT) will rise by the end of the 23$^{\mathtt{rd}}$ century to as much as 10-12 degrees Celsius (10-12C) above the current level, and an increase of this magnitude would unleash catastrophic events on a global scale, such as a sea level rise of 10 meters or more. In fact, the emerging scientific consensus is that catastrophic impacts are likely even at much lower levels and that holding further increase in GMT to 2C will be necessary to avoid some of the most damaging events and impacts, yet the IAMs typically call for a level of mitigation that results in substantially higher temperatures toward the end of the century. There are several reasons for this. Even limiting the focus to the end of the century, the models neglect the possibility of extreme or catastrophic events, and nonlinearities more generally, such as possible tipping points that trigger irreversible changes in the climate system. Another difficulty is that damage functions are

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*Correspondence: `acfisher@berkeley.edu`

based on relatively modest projected changes in average temperatures when empirical analyses of the most vulnerable sector of the economy, agriculture, have shown that potential damages are associated with changes in extremes, such as more frequent and extended heat waves, not in averages. Further, damage functions are limited to potential losses in income or output, whereas evidence from extreme events such as intense tropical storms suggests that the major damage is losses in capital of various kinds, including coastal infrastructure, and subsequent losses in productivity, leading to reduced growth rates.

As the most severe impacts are expected to multiply in later years of this century and beyond, discounting is crucial. Two considerations suggest the appropriateness of a very low discount rate. First, we argue that the choice of a pure rate of (social) time preference is an ethical choice, and can be much lower than the rate of time preference implicit in observed rates of return in private capital markets. Second, the growth rate in per capita consumption, another component of the discount rate in the Ramsey equation, is appropriately reduced when non-market services of the natural environment that support the human economy are taken into account, as these are increasingly adversely affected by climate change.

The analysis of the role of irreversibilities in decisions on climate policy has emphasized the importance of an economic irreversibility, the decision to invest in a new non-fossil energy system, along with the physical irreversibility, the long residence time of greenhouse gases in the atmosphere and the resulting impacts on the natural environment and the economy. We observe that these irreversibilities are not symmetric, that the time scale of the investment irreversibility is measured in years or decades, while the climate irreversibility is measured in centuries or millennia. In the uniquely long period relevant to the discussion of climate policy, the irreversibility – and therefore the option value – that matters is with respect to climate change and its impacts.

In an encouraging development in the economic literature on climate change, a number of recent studies have modified IAMs to take into account relevant nonlinearities such as the possibility of tipping points, and extreme or catastrophic events. With these changes, the models generally call for more aggressive mitigation in the near to medium term, with a corresponding reduction in the temperature trajectory. Policy prescriptions based on these studies would be a great improvement over those based on the standard models. But deficiencies, including massive uncertainties and omission of impacts that cannot be monetized, remain, and we argue that the appropriate objective for policy is simply to limit emissions to achieve the scientific consensus, long run stabilization of the atmospheric concentration of carbon dioxide (CO_2) at 450 ppm, which would in turn limit further increase in GMT to 2C. Studies show that this can be achieved at a cost of 1-2% of world GDP, which can be regarded as a premium for insurance against the most devastating outcomes.

JEL Code: Q540
Keywords: Climate change, nonlinearities, catastrophic events

1 Introduction

It seems fair to say that climate scientists, and natural scientists generally, believe that climate change is a major problem, perhaps the most important environmental problem facing us this century, already having at least local impacts and sure to have more over the coming decades, possibly catastrophic, as for example the unexpectedly rapid melting of Arctic ice, somewhat surprisingly including the Greenland ice sheet, leading toward the end of the century to a dramatic rise in sea level. The most recent discovery, that the formerly stable ice sheet in northeast Greenland is now melting rapidly, is particularly alarming (Shfaqat et al., 2014), bringing nearer in time inundation of coastal areas and ocean acidification with devastating impacts on marine life and potential disruption of thermohaline circulation (IPCC 5th Annual Report-AR5, 2013). These and other disturbing outcomes were noted already in 2007 in AR4 and have emerged with greater urgency since then as a result of greater than expected increases in both melting and emissions of greenhouse gases (GHGs) - and perhaps also the run of extreme weather events including heat waves, droughts and intense storms in the U.S. and elsewhere, all predicted consequences of global warming.

One could argue that the extreme events of the past few years represent simply fluctuations in a stable climate regime, but even if this were true, they are important as indicators of expected conditions under further warming. And this argument has become more difficult to make, as a result of a recent study by research teams for NOAA and the UK Met Office which detected the fingerprints of climate change on about half of the 12 most extreme weather events of 2012 (Peterson et al., 2013). For example, climate change helped raise the temperatures during the run of 100F days in the American heat wave; drove the record loss of Arctic sea ice; and fueled the devastating storm surge of Superstorm Sandy - an interesting case, less obvious than heat waves and melting ice, but linked to climate change by the rise in sea level of nearly a foot at New York and along the New Jersey coast. Again, it's important to recognize that this storm is not just a one-time event, but an example of what by midcentury will be, according to a prominent geologist, "the new norm on the Eastern seaboard" (Wikipedia entry on Hurricane Sandy, 2014).

On the contrary, the impression one gets from much of the economic literature is that global warming is not an issue that requires dramatic action in the near term. The story goes that a prominent economist who, on being asked what he thought ought to be done about the recently identified problem of climate change, responded, "What's the problem? When I cross from Washington, DC to Virginia and it's five degrees warmer, I take off my jacket." But even serious analyses suggest that only modest steps (relative to those recommended by climate scientists) to control GHGs are appropriate at this time, with a gradual increase in stringency toward the end of the century, the usual time horizon for simulations in integrated assessment models (IAMs) such as DICE (Nordhaus, 1993, 2007a), FUND (Tol, 1997), and PAGE (Hope, 2006). This is consistent with the apparent empirical findings of minor potential impacts of warming on U.S. agriculture, considered the most vulnerable sector of the economy (Mendelsohn et al., 1994; Deschenes and Greenstone, 2007).

To be fair, economists have not spoken with one voice. With respect to agriculture, other empirical studies suggest a rather different outcome: substantial and significant negative impacts toward the end of the century (Schlenker et al., 2005, 2006; Fisher et al., 2012). Though there are conflicting results for the U.S., there seems to be general agreement on very substantial negative impacts on many developing countries, perhaps catastrophic for those already facing food insecurity (Mendelsohn and Dinar, 1999; Cline, 2007).

And of course on a macro level the *Stern Review* (2007), using the PAGE model, gives serious attention to potential damages from unchecked warming, and argues that strong action should be taken in the near term to reduce emissions of GHGs. The *Review*, commissioned by the British government, has received a great deal of attention both within the economics community and beyond. The reception by economists has however generally not been favorable. Reviews tend to be critical, arguing that Stern's policy recommendations are unwarranted, stemming from some combination of an over-estimate of potential damages, and an unrealistically low discount rate and/or elasticity of the marginal utility of consumption assumed in the model simulations. Widely cited critical reviews include those by Nordhaus (2007b) and Weitzman (2007) in the *Journal of Economic Literature*, although Weitzman suggests that Stern may in fact be right in his recommendations but for the wrong reasons, not the right one, the Weitzman hypothesis on the importance of potentially catastrophic outcomes in the "fat tails" of a distribution (Weitzman, 2009). A *Symposium on Climate Change* in this *Review* a year later includes critical reviews by Mendelsohn (2008) and Weyant (2008), along with one by Sterner and Persson (2008) that takes, as the paper's title suggests, an "even sterner" view of the need for urgent action.

So while the scientific community appears to take a near-unanimous view of the magnitude of the problem of climate change and the urgency of dealing with it, the impression one gets from the economic literature is, at best, mixed, with some of the more prominent empirical contributions suggesting that impacts will be modest (if not positive) in the most climate-sensitive sector of the U.S. economy, and IAM simulations that call for only modest steps to reduce emissions of GHGs in the near to medium term. Our view is that much of the analysis to date has a tendency to understate the magnitude of the problem and perhaps also to overstate the costs of dealing with it. This is evident in a recent statement of the case against stringent controls, "The Climate Policy Dilemma", in this *Review* by Pindyck (2013a). In what follows we offer some reflections on climate policy stimulated by the paper, broadening the focus as we go to the literature more generally, both scientific and economic. Interestingly, in another, still more recent paper which came to our attention as ours was in its final stages, Pindyck (2013b) makes a case for what we might call an active control policy, if not necessarily immediately stringent, based on some of the same considerations that we shall argue form the basis for a relatively stringent policy.

As the earlier paper by Pindyck in a sense sets the agenda for our discussion, we briefly summarize here. The paper 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. It goes on to suggest that even here, the case is weak, based in part on a critical analysis of the Weitzman 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, the paper poses the question of what to do about climate policy even in the event of a high WTP to avert a catastrophe, given the presence of other potential catastrophes (nuclear, biological, and so on), each with an assumed similarly high WTP to avert.

On reflection it seems to us that the main policy implication, skepticism regarding stringent controls on

GHG emissions, though appropriately hedged due to the massive uncertainty surrounding future climate and impact variables, does not necessarily follow. We suggest some reasons for supporting a policy of relatively stringent controls. The difference in policy recommendations is due primarily to what we regard as questionable assumptions, both explicit and implicit, here and elsewhere in the literature, about future climate change, impacts, and costs of averting climate and other potential catastrophes. In part this is just a matter of updating some of the projections and findings based on recent research. In part it has to do with what we regard as important omitted impacts. Our views on policy are also influenced by our understanding of the role of discounting and irreversibilities, key issues in the context of climate change.

The next section reviews recent climate change projections, with attention to aspects often not included, and therefore not reflected in the IAMs or other policy analyses. Section 3 looks at potential impacts, including those not immediately translated to conventional measures of economic output or income and so not taken into account in the models. Section 4 offers some remarks on the sensitive issue of discounting in climate policy. Section 5 discusses relevant (and irrelevant) irreversibilities. Section 6 considers catastrophic climate change in the context of other potential catastrophes, and Section 7 concludes with a discussion of implications for climate policy.

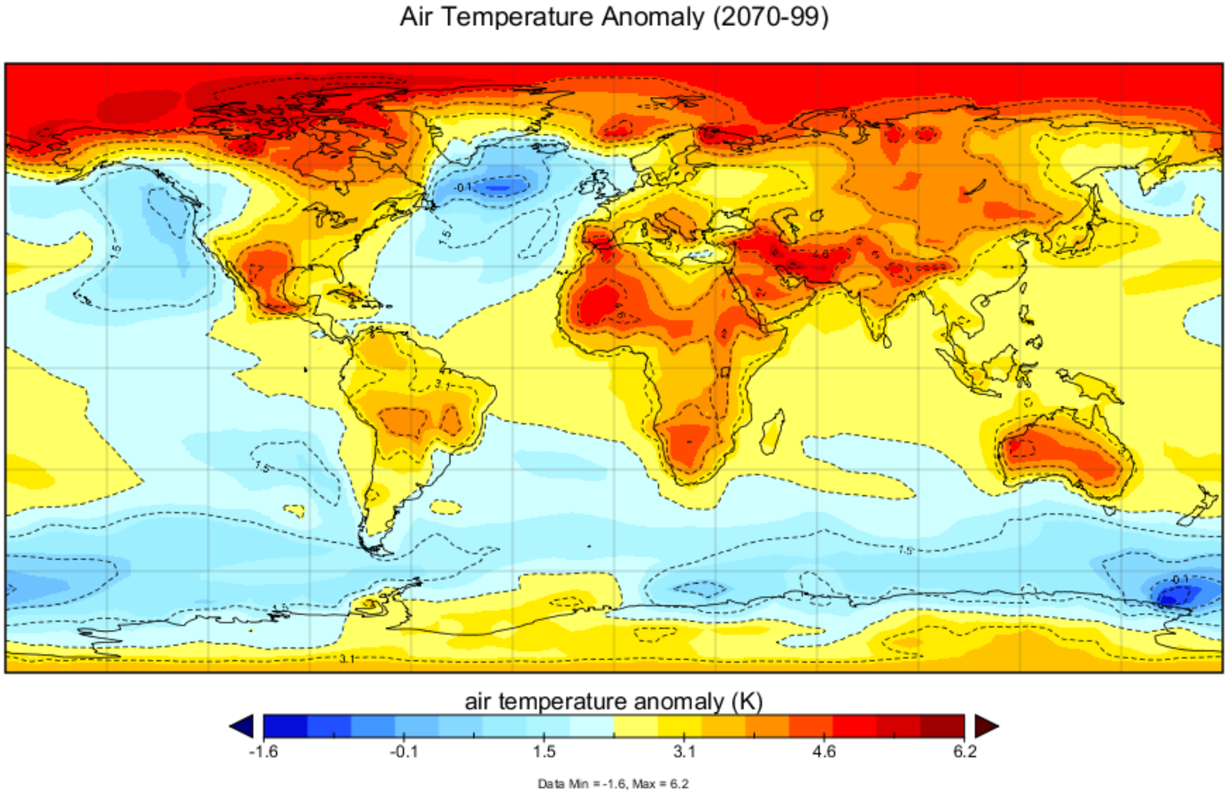
2 Climate Change Projections

We begin with the most recent IPCC projection (AR5, 2013) of global mean temperature (GMT) in the highest concentration pathway (RCP8.5) for GHGs in the atmosphere, what we might call the "business as usual" case, characterized by continued heavy fossil fuel use not significantly constrained by climate policy: an increase of 3.7C, with a 90% probability range of 2.6-4.8C relative to 1986-2005 by the end of the century. Since GMT has already increased by approximately 0.8C relative to the pre-industrial level, the 3.7C would look like 4.5C relative to the pre-industrial level, which is how the projected increase has typically been presented in the past. Either way, as we shall indicate, this falls well above the increase of 2C climate scientists believe must not be exceeded if we are to avoid a broad range of disastrous consequences.

There are reasons for believing that the IPCC estimate is in fact too low. First, it does not include the additional increase due to release from Arctic permafrost of CO_2 and methane, a gas with a much greater warming potential, though shorter atmospheric residence time. This may be defensible on the grounds that the cumulative release is uncertain at this time. However, it's already happening on a small scale, not sufficient to affect GMT, but certain to greatly increase under the temperatures projected by the IPCC, bearing in mind that temperatures at Arctic latitudes are increasing at 2.2-2.4 times the rate of temperatures at lower latitudes, with a projected increase of approximately 8C or more by the end of the century. A sense of the regional variation in projected temperature increases is given in Figure 1, based on an earlier IPCC report. 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.

This is not merely hypothetical. In a recent study of the East Siberian Arctic Shelf current methane release from submarine permafrost is conservatively estimated at 19 million tons annually, twice the level

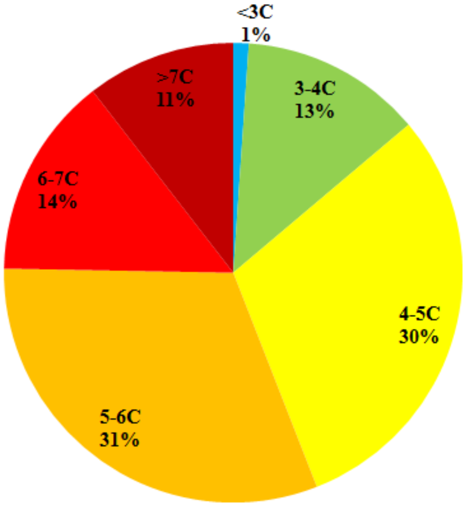
Figure 1: Projected temperature increases by the end of the 21st century under the SRES A2 emissions scenario (relatively high emissions, though not the highest). The temperature anomaly is averaged over the 2070-2099 period. The baseline is 1961-1990. Source: IPCC AR4-2007.



previously believed (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. Increasing storm activity may accelerate significant atmospheric emissions of methane pulses, adding to the positive feedback. It could get a lot worse. Much larger stores of methane, as much as 50 Gt, exist in undersea structures off the East Siberian Shelf, methane clathrates which, under the right circumstances, could release much greater amounts of the gas (Whiteman et al., 2013). Supposing this is released over a 10-year period, as in the Whiteman et al scenario, if we further assume a time pattern of 5 Gt released annually, this clearly dwarfs the current release of 19 million tons, with a correspondingly greater impact on temperatures.

A second reason for thinking the IPCC projections may be on the low side is that the IPCC tends to be conservative - recall the underestimate of GHG emissions and Arctic ice melting in the previous report, AR4, in 2007. A possible explanation is that the report, in particular the *Summary for Policy Makers*, must be approved by all member governments, including those of large producers of fossil fuels, and in particular those whose export earnings and a substantial fraction of GDP derive from this source. This is not to suggest any attempt to misrepresent findings by the IPCC, but could in part explain the tendency to be

Figure 2: Probabilistic prediction of global average surface temperature under no policy by 2100 relative to 1990. The median value is 5.2C. Source: Sokolov et al. (2009).



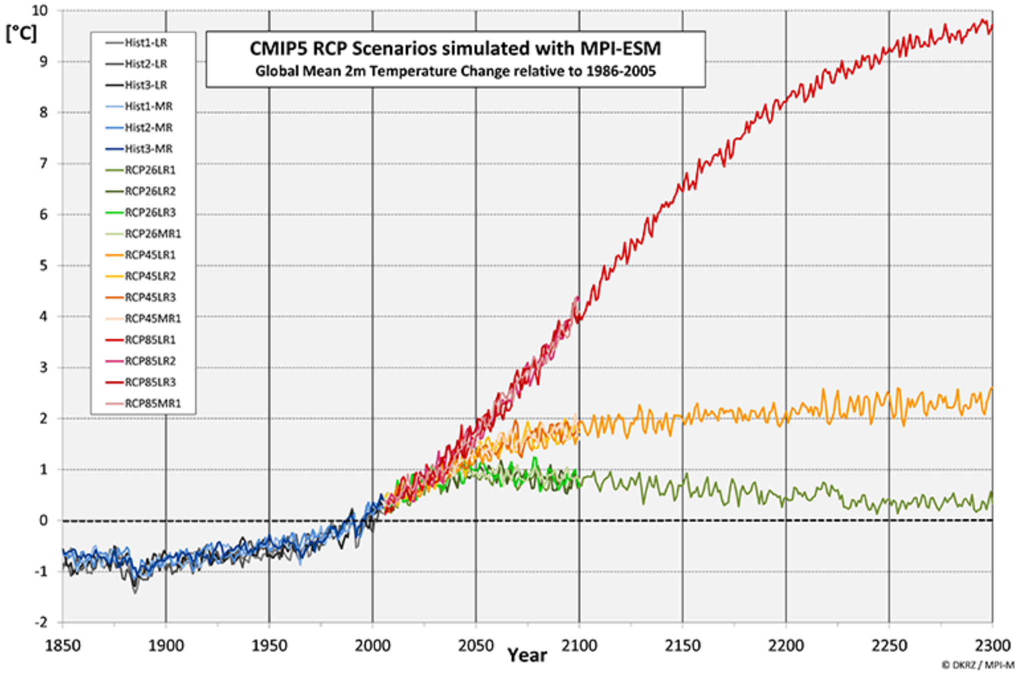
conservative in drawing conclusions.

An alternative set of projections, from the MIT Integrated Global System Model (Sokolov et al., 2009) shows a median increase in GMT of 5.2C (again, + 0.8C for the increase from the pre-industrial level), with a range of 3.5-7.4C (+ 0.8C). Moreover, as Figure 2 indicates, the distribution is not symmetric. The probability of warming more than 5C is 57%, less than 5C 43%. We are perhaps not the best judges of the merits of alternative climate models, but the MIT model, in its comprehensiveness and thorough testing and documentation, with no apparent potential for bias, is certainly worth looking at alongside the IPCC projections. It appears that the MIT model projections, like those of the IPCC, do not include the permafrost feedback, so they would also need to be augmented.

Finally, there is the issue of the appropriate time horizon for projections and planning. Early discussions of climate change focused on the end-point of a doubling of the atmospheric concentration of CO_2 from the pre-industrial level of 280 ppm, rather than a particular date. More recently, in the IPCC reports AR4 and AR5, and in the models and related policy analyses, the end-point is the year 2100. Given current (Fall, 2013) concentrations of 400 ppm for CO_2 alone and 470-480 for CO_2-equivalent (adding in trace gases such as methane and nitrous oxide and converting to an amount of CO_2 required for equivalent warming), and assuming a continuation of current rates of accumulation, the doubling will be reached well before the middle of this century. Since climate change is clearly a long-run problem, the shift in focus to the end of the century makes sense - as far as it goes.

The difficulty is that neither the doubling nor the end of the century represents an equilibrium, an end to the warming process. In a comprehensive, rigorous and remarkably foresighted analysis, Cline (1992 ch.2) calculates that an appropriate end-point in this sense would be approximately the end of the 23^{rd} century, or the year 2300, for two reasons. First, fossil fuel (mainly coal) reserves would be either exhausted or

Figure 3: Projected GMT by 2300. Source: DKRZ (2014).



choked off by a rising price due to scarcity. Second, mixing of dissolved CO_2 in the upper ocean with the deep ocean becomes important in about 200 years, exposing a much greater reservoir of water to mixing and thus greatly increasing ocean absorption. A conservative estimate of the increase in GMT by this date is approximately 10C, with a plausible range including substantially greater increases (Cline, 1992, pp.56-58) and of course greater still in the Arctic, with all that implies for melting ice and methane and CO_2 release.

Apart from another early discussion of the end-point issue, in Fisher and Hanemann (1993), there seems to be little if anything in the subsequent economic literature, perhaps due to the focus, first on a doubling of atmospheric concentrations of GHGs and then on the end of the 21st century in the scientific literature. Recently however some estimates of what might be expected by the year 2300 have appeared, consistent with the early calculations by Cline. The German Climate Computing Center (DKRZ, 2014), in simulations conducted for AR5, projects an increase of nearly 10C from the 1986-2005 level in an extension of the RCP8.5 scenario to 2300, as shown in Figure 3.

Other recent long-term projections reported in the *New Scientist* similarly suggest that a "burn everything" scenario could lead to atmospheric concentrations of CO_2 as high as 2000 ppm, in turn leading to a global temperature rise of 10C (Marshall, 2011). The report includes still more alarming speculations about the danger of runaway processes, once temperatures reach this level. And finally, a study in PNAS projects possible eventual warming of 12C from fossil fuel burning. The main point of the study is however the novel and sobering one that at these temperatures regions currently holding the majority of the human population would become uninhabitable due to induced hyperthermia as dissipation of metabolic heat becomes impossible (Sherwood and Huber, 2010). This takes us to potential impacts of projected climate changes, the subject of the next section.

We should make clear that we have been discussing in this section "worst case" scenarios, those implied by unconstrained emissions of GHGs, to the year 2100 and then beyond, to the year 2300. We are not predicting that this will happen, for several reasons including innovations in non-fossil energy technologies and in carbon capture and storage (CCS) that may make possible the continued burning of the very large reserves of coal (though with other health and environmental costs, as noted later on). The point is rather that, without a clear understanding on the part of economists and decision-makers of the potentially catastrophic impacts of unconstrained emissions, it becomes difficult to see how the analyses and policies that would lead to a timely development of these alternatives will occur.

3 Potential Impacts and Problems of Estimation

Considering first the impacts that go into the economic models used in policy analyses, we note that there are major difficulties with the estimates of potential damages in the IAMs, and therefore the optimal control trajectory for GHGs in the models, and also the social cost of carbon (SCC), calculated from model outputs and the basis for policy analyses and rulemaking by governmental agencies such as OMB and EPA. The models represent an important step in the multidisciplinary analysis needed to address climate change, and illustrate the links between climate and economy, given assumptions about a variety of functional forms and parameters. The difficulty comes in the use made of the results to make inferences about policy.

One problem is that damage functions and estimates appear to have little relation to empirical findings based on econometric studies of sectoral impacts. And more general, economy-wide damage functions are simply not known, especially on a global level. There is thus little empirical, or for that matter theoretical, foundation for the specification in the models of functional forms and parameters, as Pindyck (2013b) argues. This leads to a certain arbitrary character of the results and policy prescriptions.

Beyond the arbitrariness and the obvious uncertainty, there are several reasons for believing that there is very substantial bias, in the direction of underestimating damages. Stern (2013) provides a detailed and comprehensive discussion of what he characterizes as the gross underestimations in economic impact models and IAMs. We are generally in agreement, and raise some additional issues.

The Importance of Non-linearity in Modeling Climate Change Impacts

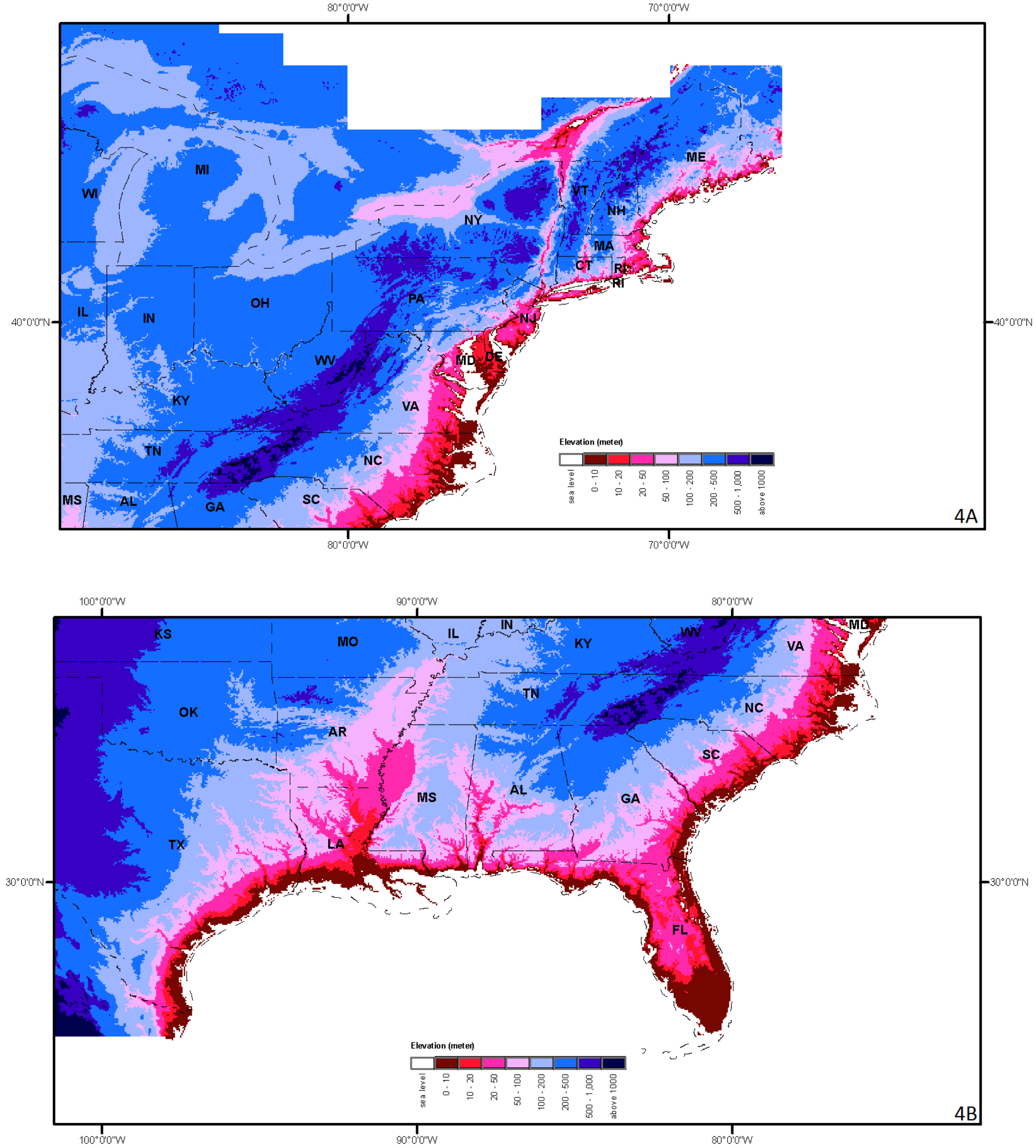
One type of nonlinearity, generally not captured in the models, is represented by catastrophic events and the possibility of tipping points in climate systems - the threshold beyond which climate change can no longer be accommodated. One example of this is, as noted in the last section, under a 12C increase in GMT, projected for the end of the 23rd century with no constraints on emissions of GHGs, regions currently holding the majority of the human population would become uninhabitable due to induced hyperthermia as dissipation of metabolic heat becomes impossible (Sherwood and Huber, 2010).

Another tipping point can come from sea level rise. The increase of 4-5C in GMT projected for the end of the 21st century would lead to permanent abandonment of living spaces such as islands and low-lying areas, including large portions of some countries, inundated by the resulting one meter rise in sea levels (World Bank Report, 2012). Adding in the effect of (complete) melting of the West Antarctic Ice Sheet, a serious concern for the period beyond 2100, the projected rise in sea level would be very much greater: about 8 meters (Poore et al., 2011). The Greenland Ice sheet, already melting, would ultimately add about 6.5 meters. Reduction of both similar to past reductions in the geologic record, presumably not complete, would add at least 10 meters, resulting in flooding of about 25% of the U.S. population, with the major impact on people and infrastructure along the East and Gulf Coast states. As with potential methane releases, it could get a lot worse. During the early Pliocene, which was about 3C warmer than today, sea levels were as much as 15-25 meters higher, suggesting that part of the much larger East Antarctic Ice Sheet, generally believed to be more stable, must have been eventually vulnerable to melting (Hansen et al., 2013). Potential impacts from extreme heat and sea level rise are displayed in Table 1 and Figures 4A and 4B.

Table 1: Examples of potentially catastrophic impacts.

1. Increase of 4-5C in GMT projected for the end of the 21st century would lead to permanent abandonment of living spaces such as islands and low-lying areas, including large portions of some countries, inundated by the resulting one meter rise in sea levels (World Bank Report, 2012).	2. Melting of the West Antarctic Ice Sheet, a serious concern for the period beyond 2100: the projected rise in sea level would be very much greater: about 8 meters (Poore et al., 2011).
3. The Greenland Ice sheet, already melting, would ultimately add about 6.5 meters.	4. Reduction of both similar to past reductions in the geologic record (presumably not complete) would add at least 10 meters, resulting in flooding of about 25% of the U.S. population, with the major impact on people and infrastructure along the East and Gulf Coast states.
5. During the Pliocene Epoch, 2.5-5 million years ago, which was about 3C warmer than today, sea levels were as much as 15-25 meters higher, suggesting that part of the much larger East Antarctic Ice Sheet, generally believed to be more stable, must have been eventually vulnerable to melting (Hansen et al., 2013).	6. An increase of 12C in GMT, projected for the end of the 23rd century with no constraints on emissions of GHGs: regions currently holding the majority of the human population would become uninhabitable due to induced hyperthermia as dissipation of metabolic heat becomes impossible (Sherwood and Huber, 2010).

Figures 4A and 4B. Risk of sea level rise (inundation; transient flooding already occurring), North East and South East/Gulf Coast states. Source: USGS 2.5-arcmin Digital Elevation Model.



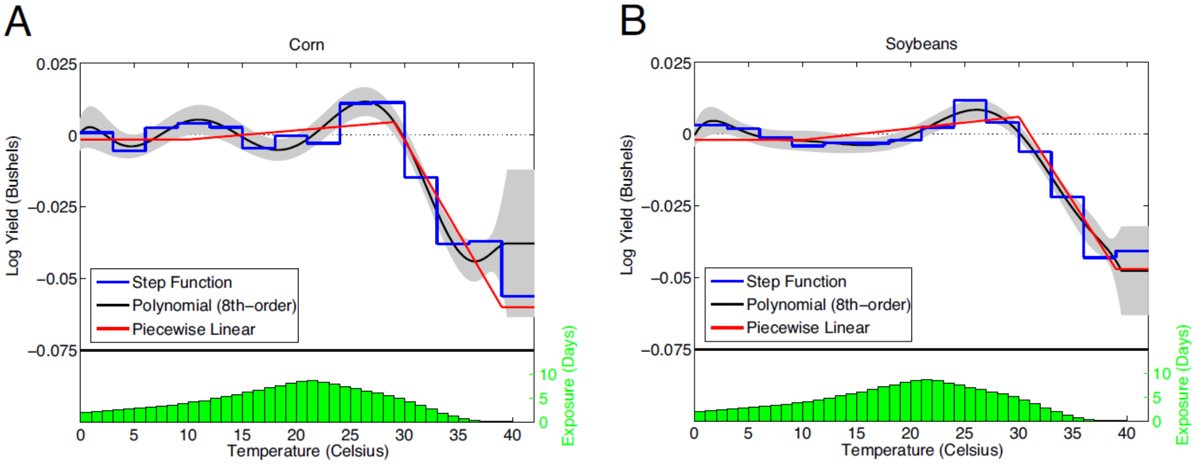
In response to criticism that damage functions that fail to capture nonlinearities caused by extreme events or abrupt changes understate potential damages, Nordhaus and Sztorc (2013) add 25% to the damage function to account for all non-monetized impacts. This seems arbitrary at best, and almost certainly still an underestimate, especially as we look beyond the end of the century. Others have proposed a damage function of higher order polynomials to address the issue of unrealistically low damages at excessive levels of warming. For example, Ackerman et al. (2010) show, using the standard DICE model, that temperature increases of up to 19C can involve a loss in output of as little as 50 percent. In light of the globally catastrophic impact of a 10C increase, it seems doubtful that human civilization could survive such an increase. But tinkering with the functional form to avoid this sort of unrealistic outcome also seems arbitrary, a serious concern in light of the sensitivity of results to functional specifications. Raising the temperature exponent from 2 to 3 in a standard damage function causes damages to jump from 10.4% of output to 33.3% when the elasticity of marginal utility is 1, or from 3.3% to 29.1% when the elasticity is 2 (Stern, 2008).

A more promising approach to modifying clearly unsatisfactory damage functions is taken in recent papers that introduce explicitly the possibility of tipping points and extreme or catastrophic events, along with modeling of the associated uncertainty. 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 (response of temperature to a given increase in atmospheric concentrations of GHGs) above "best guess" levels. The mean SCC in probabilistic simulations is well above conventional estimates, as much as two orders of magnitude in the case of the most extreme climate scenarios and a zero pure rate of time preference. The conclusion is that the potential for catastrophic outcomes of the sort modeled here can justify aggressive near-term mitigation, in contrast to the very modest steps called for when this is neglected. Lemoine and Traeger (2012) study the impact on the optimal carbon tax in a modified DICE model of two kinds of tipping points, one involving climate sensitivity and the other a longer carbon cycle. The optimal near-term carbon tax is increased by up to 45%, and peak warming reduced by 0.5C compared to a model without possible tipping points.

An approach along very different lines: empirical damage functions based on the observed response of human systems to climate variability, is suggested by Kopp et al. (2013). This is supported by our work on potential damages in the most extensively studied sector of the economy: agriculture. In a series of econometric studies we 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, a dramatic increase over the next several decades in extreme heating days, measured by growing degree days at temperatures above 34C, is responsible for nearly all of the potential negative impact of warming on farmland value in the U.S. estimated in Schlenker et al. (2006). Projected increases in a measure of average temperature increase are much less important. Second, crop yield functions exhibit sharply diminishing returns after an optimal temperature has been reached (Schlenker and Roberts, 2009). Yields are stable or slowly increase with temperature up to 29C for corn and 30C for soybeans, and then fall sharply with each additional degree, as shown in Figure 5.

An interesting question is, to what extent might this sort of relationship hold in other areas or activities affected by climate change, including ecosystem functioning, and might it be appropriate for modeling damages in IAMs? It seems plausible, but more empirical research will be needed to confirm this.

Figure 5. Nonlinear impact of temperature on crop yields. Source: Schlenker and Roberts (2009).



Impacts on the Environment, Extreme Events, and Capital Losses

Direct impacts of climate change on environmental goods and services are in effect omitted in much of the literature on damage estimates, including those in the IAMs, due to the implicit assumption of 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." In particular, it is the environmental goods that can be expected to become relatively scarce, so that their shadow prices will be rising (for an early analysis along these lines, though not in relation to climate change, see Fisher and Krutilla (1975)). As they illustrate using the DICE model, making some plausible (though admittedly speculative) assumptions about the value of nonmarket environmental goods and their (limited) substitutability by market goods, the implied change in relative price has an effect on optimal abatement very similar to that produced by adopting the near-zero pure rate of time preference in the *Stern Review*, while still keeping the higher rate used in DICE and preferred by some of the critics. Making both changes would call for still more dramatic 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 consumption included in the measured national income accounts, especially where they result in destruction of coastal infrastructure – which as we note below is not picked up in IAM damage functions – and especially in developing countries. A relevant and somewhat surprising finding here is reported in the recent paper by Hsiang and Jina (2013) on the long-run impact on economic growth of a major tropical storm. They find on the basis of exhaustive econometric analysis of several datasets that national incomes decline relative to their pre-disaster trend and do not recover within 20 years, and that the cumulative effect of this persistently suppressed growth is both significant and large: a 90th percentile event reduces per capita incomes by 7.4% two decades later.

One explanation may be that the immediate impact of the event is to destroy infrastructure, which in turn impacts 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, in particular in the IAMs. In their focus on losses in income or output, these models don't 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, with their extensive damage to coastal infrastructure and subsequent impact on productivity.

We note briefly a couple of very recent studies that similarly expand our focus beyond conventional damage estimates and suggest that losses may be more widely experienced than previously believed. Heal and Park (2013), drawing on a variety of data sources, both physiological and economic, demonstrate a link between temperature and income, identifying a link between temperature and labor productivity as a likely cause, with a broad measure of productivity falling beyond temperatures in the range of 18-22C. And although not directly linked to GDP or productivity, a relationship between temperature and conflict, ranging from domestic violence to regional conflicts has been found by Hsiang et al. (2013). The message from these studies, including Hsiang and Jina, is that 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.

4 Discounting

Any discussion of climate policy inevitably turns to the question of how to discount the potential damages associated with climate change, since damages are expected to become increasingly severe over the next several decades and even centuries. This time frame, along with the magnitude of the problem, makes the discounting decision more critical than in the typical investment problem. 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 over time of environmental and market goods, with limited substitutability of the latter for the former, can have a similarly dramatic effect.

Since the discussion on discounting in the climate problem is often set in the framework of the Ramsey equation, we write it below.

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

In words, 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. Controversy centers on the choice of ρ, and to a lesser extent on θ. Of course there can also be differing expectations concerning g – a point we'll come back to, as in our judgment it becomes important in thinking about climate policy.

Pindyck (2013a) presents a hypothetical example involving two individuals, John and Jane, deciding how much to spend and how much to save of their respective (equal) incomes, with John saving 10% each year to help finance the college education of his perhaps yet unborn grandchildren and Jane saving nothing, rather spending on sports cars, boats and expensive wines. He then poses the question of whether John's concern for his grandchildren makes him more ethical than Jane, and answers it by saying that economists don't have much to say about the question. We suspect the average person, confronted with these choices, might not hesitate to label John's choice the more ethical one. Or maybe not. In any event we agree that, as economists, we have little to say concerning John's or Jane's individual choice.

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

This leads to the question of how the rate of time preference should be specified. Although there is a vast literature on the question, even in the context of climate policy, at the risk of oversimplifying we can distinguish two approaches. One, implicit in Pindyck's example, used throughout the *Stern Review*, and advocated in a wide-ranging review of climate economics in this *Review* by Heal (2009), considers that the choice is an ethical one, "a decision on the relative weights of different generations of human beings." 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's important to note that this will ordinarily imply 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. If, for example, the elasticity $\theta = 1.5$ and the consumption growth rate $g = 2\%$, the discount rate $r = 3\%$.

Returning to the question of the consumption growth rate, we note that adjusting this to reflect "consumption" of the non-market services of the natural environment that support the human economy, and that are expected to be increasingly adversely affected by climate change, this rate, and therefore the discount rate in the Ramsey equation, will be reduced, and could conceivably become negative at some point, especially if accompanied by a low or zero rate of time preference. Alternatively, following Heal, we can distinguish two separate discount rates, one corresponding to ordinary consumption goods and the other to nonmarket services of the environment, with the former clearly positive and the latter possibly negative. Negative discounting, where appropriate, would of course mean that future losses look larger, not smaller, from the perspective of the present.

The other approach to the specification of the pure rate of time preference is exemplified in the DICE model (see Nordhaus (2007a)), where the left-hand side, the discount rate r, is explicitly chosen to be consistent with observed rates of return on investment in private capital markets. From this, along with the second term on the right-hand side, $\theta * g$, there is an implied pure rate of time preference (positive), thus bypassing any discussion of what constitutes an ethical choice by the current generation. There are two difficulties, in our judgment, with this approach. First, it implicitly assumes that the private rate of time preference, not the social rate, is relevant to a social choice on climate policy. And second, it measures g solely by the growth rate in per capita consumption of conventional market goods. In fairness, the same criticism (neglect of impacts on nonmarket goods) could be made of most discussions of climate policy that take the alternative, ethical choice approach.

The two approaches are discussed at some length with special reference to the climate problem by Heal (ethical) and Nordhaus (market), proving perhaps that this is a subject on which reasonable economists can differ. That said, our view, 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 appropriate to climate policy decisions.

5 Irreversibilities

Pindyck (2013a) raises an interesting point in the context of the discussion on discounting, though not strictly limited to discounting. He argues 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)." But it seems to us that one might equally well argue that the case for a mild (as opposed to stringent) climate policy, characterized by very modest controls in the near to medium term, should instead 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 large mitigation expenses. While neither outcome is desirable, the former strikes us as more important to avoid in that it can impose extraordinary costs for centuries, or millennia, depending on the nature of the impacts, whereas the latter is reversible in a few years or at most a few decades – and at relatively little cost if done within the normal replacement cycle of capital.

In this connection we note that one of the main sources of concern about climate change in the scientific community is precisely that in important respects it is irreversible. 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; once in the atmosphere they persist for many decades or even centuries. Further, impacts such as the inundation of large areas and loss of species, among many others, are essentially irreversible on human time scales.

Paradoxically, in a number of studies economists have argued that the relevant dynamics in fact suggest less control, not more. The control decision is modeled as an investment, for example in a new, non-fossil-fuel-based energy system, and the investment is also seen as irreversible. Simulation modeling based on what look like plausible assumptions from the DICE model about climate and economic parameters suggests that the investment irreversibility dominates. The decision is further tilted toward holding off on control of emissions taking into account uncertainty about the degree of climate change and the impacts. If learning is possible, the implication is to refrain from some or all of the investment in reducing emissions today in order to make a better decision tomorrow on the basis of better information about the potential benefits (see for example Kolstad (1996); Fisher and Narain (2003); Pindyck (2007)). The difficulty here is that the models fail to capture a key feature of the decision problem: *the time scales for climate and investment irreversibilities are not the same – in fact are likely to differ by orders of magnitude. Treating them symmetrically will produce a misleading result.*

Another problematic feature of the models is the treatment of the decision to invest in a new energy system as once-and-for-all, all-or-nothing. But the decision, or in practice the decisions, are not one-time, all-or-nothing. At any decision point, say one of the 10-year time steps in a model such as DICE, in reality an array of choices presents itself, and the outcome will tilt the mix of fossil fuel, renewable source, and energy-efficiency, capital in one direction or another – until the next decision point. Further, once we disaggregate "investment" in this fashion, a relevant symmetry becomes apparent. Investment in, say, a fuel-efficient car, or an array of solar collectors, or a facility to generate electricity from biofuels, might be considered irreversible in the short to medium term. But so is investment in another coal-burning plant to generate electricity, or another SUV getting 11 miles to a gallon of gasoline.

The conclusion we draw from this discussion is that *over the uniquely long period relevant to discussion of climate policy, the irreversibility – and therefore the option value – that matters is with respect to climate change and its impacts, and not investment in one or another energy facility.*

6 Catastrophic Climate Change in Context

Before considering climate change in the context of a world in which other potential catastrophes loom, we should indicate what might constitute catastrophic climate change. The scientific consensus is that stabilization of atmospheric CO_2 concentrations at 450 ppm (which implies a CO_2 equivalent, CO_2eq, level of about 550 ppm adding in likely concentrations of other GHGs such as methane), in turn roughly consistent with an increase in GMT of 2C toward the end of the century relative to the end of the last century, or about 2.8C above the pre-industrial level, will be necessary to keep climate impacts from becoming likely or very likely to reach what most, and certainly most scientists, would regard as catastrophic levels in terms of their impact on the natural systems that support human economic activity and even on the economy directly.

Pindyck (2013a) frames the discussion of how potential climate catastrophes are to be taken into account in climate policy, in view of the potential for catastrophes in other areas, in terms of WTP to avert or reduce the probability of occurrence of each type of catastrophe (climate, mega-virus, detonation of one or more nuclear weapons in a major city, and so on), taken alone. Although WTP to avert climate catastrophes may be as high as 10% of GDP (Pindyck's illustration), once we recognize that there may be a similar WTP for the others as well, we are confronted with something like 60-70% of GDP to avert all of the potential catastrophes, which he reasonably concludes society would probably be unwilling to pay.

There are a couple of difficulties with this approach, one conceptual and one empirical. On the one hand we have estimates, however uncertain, of the benefits of controlling emissions to reach a target of, let's say, an atmospheric concentration of CO_2 of 450 ppm, where the benefits are just the averted damages. The natural question is then, what are the costs, to be compared to the benefits? It may be that WTP is 10% of GDP, but this is irrelevant if the costs are much lower, say 1-2% of GDP. We'll return to the question of costs, but first note another difficulty with using WTP in this context, in the event one were to seriously contemplate an empirical study.

We know from the literature on survey research that WTP is dependent on the framing of the question, and that this is especially true when people are asked to value a good (or bad) with which they have little or no experience. This result would apply with special force to a question about future consequences so far beyond the realm of current or historical experience. A second concern is that, for a credible result, in addition to a well-defined good, within the realm of experience, a credible payment mechanism needs to be part of a survey. For example, the question might be: Would you be willing to pay an additional 10% in property taxes to finance a treatment plant that would reduce the concentrations of pollutant X in a nearby lake by 90%? It's hard to see what such a mechanism would be in the setting of climate change. We recognize that many people have experienced natural disasters. But the potential climate catastrophe is different in that it would mean an unending and increasing series of disasters, experienced much more closely together in time and over much wider areas.

If WTP is neither an appropriate nor a reliable measure in this case, what is? Again, we suggest simply looking at the costs of controlling emissions of CO_2 and perhaps other GHGs, and comparing these costs to the benefits, damages averted by holding further increases in GMT below 2C. There has of course been a great deal of research on this topic, which we only touch on briefly here, but the main point is that the method offers 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, to minimize the costs of attaining the objective. While academic or other publicly funded research on costs will no doubt be useful, firms will have an incentive to seek out this information and adapt it to their own circumstances. This is in clear contrast to the situation with respect to the non-climate catastrophes such as contagion or nuclear terrorism.

Now, what about the costs of meeting the scientific consensus target of stabilizing concentrations by the year 2100 at 450 ppm CO_2 or 550 ppm CO_2eq? Projected costs of achieving these levels appear to be relatively modest – generally in the range of 1-2% 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 very low stabilization target of 400 ppm CO_2eq would come to less than 2.5% of global GDP, measured as discounted cumulative losses to the year 2100, with medium and higher stabilization levels at 450 ppm and 550 ppm approximately 1.5% and 0.8% respectively. Focusing on improvements in energy efficiency in addition to alternative energy sources, a McKinsey study puts the cost at 0.6-1.4% of global GDP in 2030 to keep the CO_2eq level at 500 ppm (McKinsey Global Institute, 2008). The IPCC in AR4 (2007) estimates 0.6% of GDP in 2030 and 1.3% in 2050 to meet a target in the range 535-590 ppm CO_2eq, and in AR5 (2014) estimates 0.6% of GDP in 2030 and 1.7% in 2050 to meet a slightly more ambitious target in the range of 530-580 ppm (IPCC AR5-WG3 Summary for Policymakers, 2014). These and other estimates are displayed in Table 2.

Table 2: Survey of Costs (percent of global GDP) of Stabilization of CO_2eq, by Target Level.

Target (ppm-CO_2eq)	**Edenhofer et al. (2010)** [i]	**MGI** [ii] **[range]**	**IPCC AR4 WG3** [ii] **median [range]**	**IPCC AR5 WG3** [iii] **median [range]**
400	2.5	–	–	–
430-480	–	–	–	1.7 [1.0 - 3.7] in 2030
	–	–	–	3.4 [2.1 - 6.2] in 2050
	–	–	–	4.8 [2.9 - 11.4] in 2100
445-535	–	–	less than 3 in 2030	–
	–	–	less than 5.5 in 2050	–
450	less than 1.5	–	–	–
480-530	–	–	–	1.7 [0.6 - 2.1] in 2030
	–	–	–	2.7 [1.5 - 4.2] in 2050
	–	–	–	4.7 [2.4 - 10.6] in 2100
500	–	[0.6 to 1.4] in 2030	–	–
530-580	–	–	–	0.6 [0.2 - 1.3] in 2030
	–	–	–	1.7 [1.2 - 3.3] in 2050
	–	–	–	3.8 [1.2 - 7.3] in 2100
535-590	–	–	0.6 [0.2 - 2.5] in 2030	–
	–	–	1.3 [slightly negative - 4] in 2050	–
550	slightly more than 0.5	–	–	–
580-650	–	–	–	0.3 [0 - 0.9] in 2030
	–	–	–	1.3 [0.5 - 2.0] in 2050
	–	–	–	2.3 [1.2 - 4.4] in 2100
590-710	–	–	0.2 [-0.6 - 1.2] in 2030	–
	–	–	0.5 [-1 - 2] in 2050	–

Legend:

[i] Cost is percent loss in global GDP, cumulative to year 2100, discounted at 3%. The numbers are based on the MERGE model which predicts the highest mitigation cost.

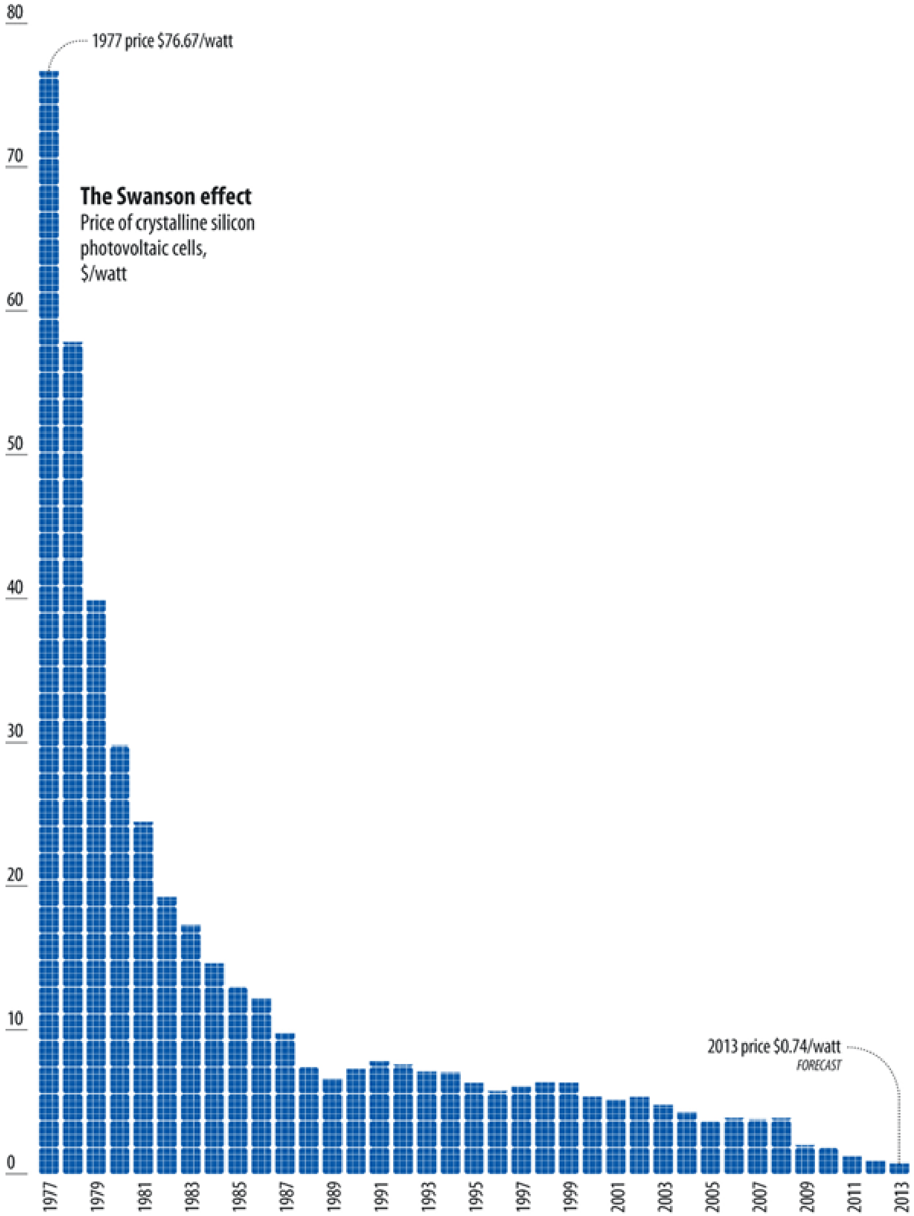
[ii] Cost is percent loss in global GDP in 2030 or 2050.

[iii] Cost is percent loss in global GDP in 2030, 2050, or 2100.

Some renewable energy sources for electricity generation have seen dramatic installation cost reductions over the past several decades, and many are close to being competitive (IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (2011)-Figure SPM.6a; The Economist (2012)). Moreover, the cost of installation is expected to decrease further as adoption increases, according to Swanson's law, which suggests a 20 percent drop in the price of solar photovoltaic (PV) modules for every doubling of cumulative shipped volume. Wind power installation cost has also sharply declined, by more than half, from approximately $4300/kw to less than $2000/kw over the 1982-2008 period (Wiser and Bolinger (2009)-Figure 21). Trends in costs of solar PV and wind power are displayed in Figures 6A and 6B below.

The recent uptick in the cost of wind power generation is explained in part by temporary market conditions including increases in demand leading to shortages in turbine components and increased materials and energy input prices, and also by up-scaling of turbine size and improved sophistication of turbine design

Figure 6A. Trends in installation costs of solar PV power, adapted from The Economist (2012).

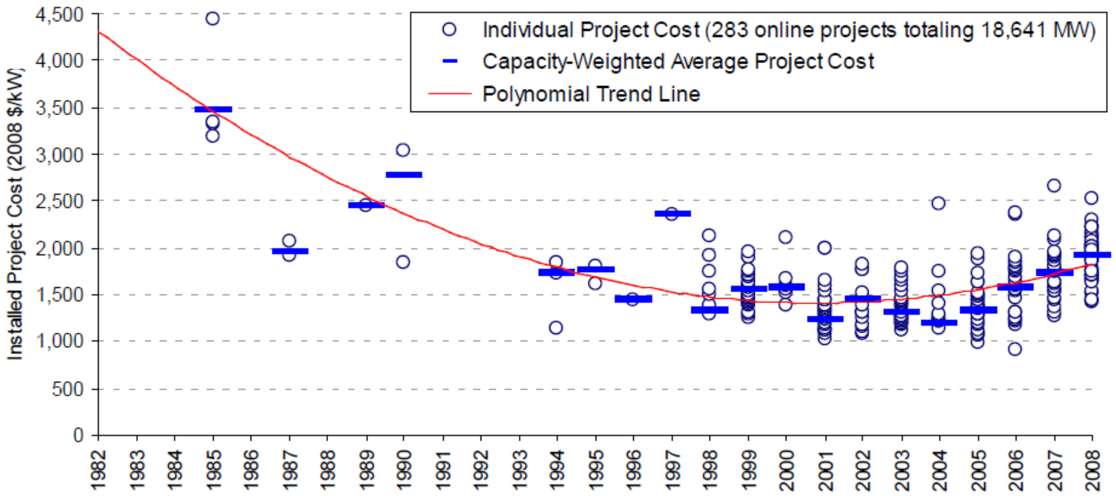


Source: Bloomberg, New Energy Finance

(improved grid interactions).

Finally, in connection with any assessment of energy alternatives, we need to take into account the non-climate change-related environmental and health impacts of conventional fossil fuel use. For example, a recent study finds that air pollution from the burning of coal and oil results in $120 billion in health costs just for the U.S. (NAS, 2010). This does not account for other damages, for example water pollution from ongoing extraction and transport, and from occasional disastrous oil spills. These are real costs, though they are for the most part not reflected in the prices of oil and coal. They are however relevant in considering

Figure 6B. Trends in installation costs of wind power (Wiser and Bolinger, 2009).



Source: Berkeley Lab database (some data points suppressed to protect confidentiality)

the net social cost of reducing GHG emissions by 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, they can be considered as a benefit of low-carbon fuels, thereby reducing the net social cost of substitution. For illustrative purposes, accounting for only part of the non-climate change-related damage associated with coal-based electricity generation yields an estimate of 3.2 cents/kwh, a weighted average, where the weights are the electricity generated by each plant (NAS, 2010, pp 6-7). Subtracting this from the cost of wind-based generation would make it cheaper than coal in some places, and subtracting it from the cost of solar PV would make that source competitive in some.

There are additional differences between the other potential catastrophes and a climate-related catastrophe that make a simple adding-up of WTP, or even costs, across catastrophes not very relevant to the climate policy debate. An important one is that we can be fairly certain that, without implementing well-understood policy instruments and technologies to reduce emissions of GHGs, the kinds of consequences discussed earlier will occur. By the same token, with additional efforts at abatement, we can be fairly certain that we can at least reduce the frequency or severity of the various natural disasters. The same kind of near-certainty – of occurrence or non-occurrence related to specific policy measures – cannot be invoked with respect to the other catastrophes such as outbreak of a mega-virus or detonation of a nuclear device by a rogue state or terrorist organization.

We admittedly don't know much about the prospects for averting or reducing the probability of these catastrophes; that would be a subject for a separate research project. That said, it's not clear how much more, at what cost, can usefully be done, or that there is a connection to climate policy. Perhaps more widely deployed monitoring mechanisms for detection of outbreaks of contagious diseases, more rapid communication and treatment, and so on, would help, but given the resources already devoted to these activities any additional effort would likely involve only a tiny fraction of national budgets, much less GDP. Similarly with respect to nuclear terrorism, the U.S. and other countries are already devoting substantial resources to prevention. No doubt more could be done, but the costs would come to only a small fraction of current defense and intelligence expenditures, including those already devoted to this problem – and again, an even smaller fraction of GDP. In any event, given the relatively modest levels of additional averting expenditures (relative to GDP), controlling emissions of GHGs to hold a further increase in GMT to less than 2C by the end of the century is not plausibly precluded by some increase in efforts to avert other catastrophes.

7 Implications for Climate Policy

What are the implications for climate policy? Based on the discussion to this point, our view is that policy should be what 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. The scientific consensus is that this will reduce the probability or frequency of occurrence of some of the most damaging impacts. Moreover, it should be attainable at reasonable cost, on the order of 1-2% of world GDP. We note that some climate scientists and others now believe that even a target of 450 ppm is too high to forestall multiplying major adverse impacts, and that a long run level of something like 350 ppm is required. Hansen et al. (2013) argue that the level of cumulative emissions associated with a 2C warming would spur feedbacks leading to an eventual 3-4C warming.

An alternative approach is of course to use one or several of the established integrated assessment models (IAMs) to compute an optimal trajectory of emissions reductions, typically to the year 2100. As we noted earlier, regulations by government agencies such as EPA and OMB are at least in principle based on the social cost of carbon (SCC), in turn derived from the standard models. In addition to elucidating a link between the workings of the economy and the climate system, the models have the virtue of providing very precise solutions to the problem of how much to cut emissions and when. Another advantage is that they generate a set of shadow prices readily adapted as carbon taxes, the policy instrument favored by most economists.

The difficulty, as we also noted earlier, is that the numerical results are not reliable as a guide to policy. Before reviewing some of the reasons for this judgment we should acknowledge that, if the results were to be accepted and implemented by policymakers this would be a step in the right direction. That said, there are deficiencies that result in what Stern (2013) has characterized as gross underestimation of potential damages from climate change, especially in the long run, and in turn to less than ideal mitigation.

What are the deficiencies, and why are they significant? Functional forms and parameters of damage functions, though consistent with economic theory in a general way, are somewhat arbitrary, not grounded in empirical research even about potential impacts on the most relevant commercial sector, agriculture. Nonlinearities here and elsewhere involving extreme conditions, and irreversible, extreme and catastrophic events, are not captured. The quantitative results that form the basis for policy prescriptions are extremely sensitive to assumptions, in particular about the discount rate. Almost anything occurring in 200-300 years, no matter how catastrophic, can be rendered insignificant by a discount rate based on current rates in private capital markets. This matters because the most severe potential impacts, for example on sea level rise, will occur in that time frame and as we have argued, the appropriate discount rate in thinking about climate policy is well below market rates. Perhaps most importantly, what are likely to be the most damaging impacts are not adequately captured by the implicit assumption of perfect substitutability of conventional market goods for services of the 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 1-2 meters, and the resulting mass migrations and conflicts?

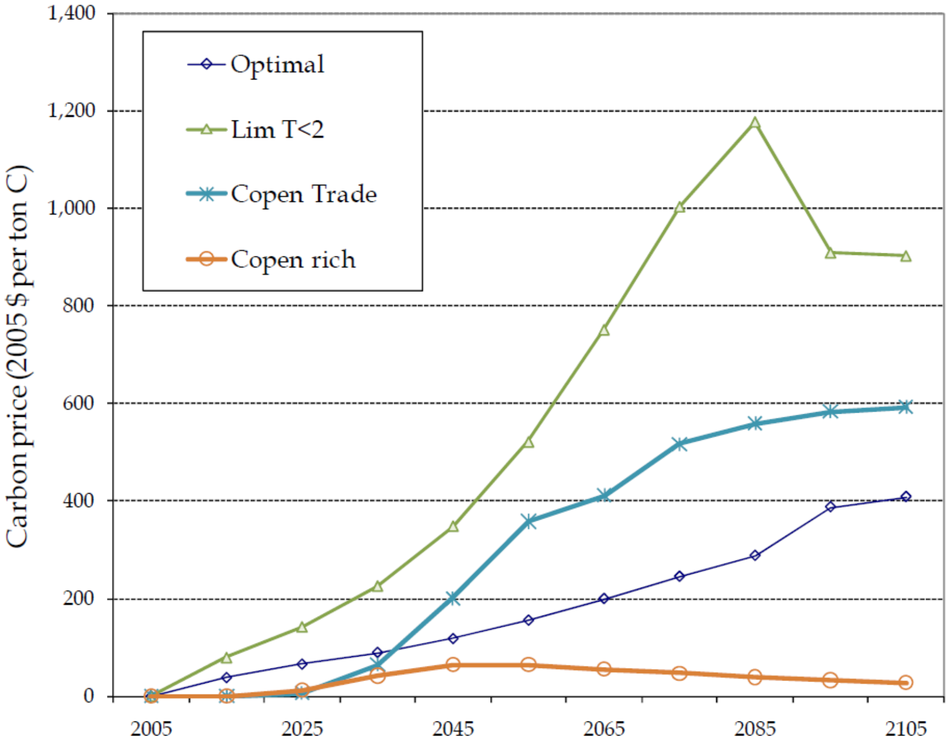
An intermediate approach, taken in a number of recent studies, is to amend or augment an IAM, for example to take into account relevant nonlinearities such as extreme conditions, irreversibilities and catastrophic events. These are useful contributions, and represent a further step in the right direction, the direction the models will have to go in to provide guidance to policy. But they are clearly unable to address all of the concerns about the models. The problems, and the unknowns, are too intractable, at least at this point. It seems doubtful for example that some of the most important potential impacts, such as massive sea level rise, with all of its consequences, or major loss of ecosystem support services, can be fully delineated, much less monetized. Depending on modeling choices, an optimal increase in GMT of 2C, or for that matter a still lower level, may be indicated, and this would certainly form the basis for a policy more consistent with the scientific consensus. But it seems to us preferable to simply adopt the consensus of 2C or less as the objective of mitigation policy, on the grounds that the benefits (damages averted) will be very great, certainly much greater than the costs of achieving them, even though they cannot be fully known or monetized. Another way to think about this is, as some have suggested, to consider the costs a premium for insurance against the worst outcomes.

Policy Instruments

Finally, we need to consider – very briefly – how any objective can be achieved in practice. In principle, two types of instruments may be needed: a tax (or subsidy) to internalize the externality, and public investment to address the public good aspects of the problem. On the tax side, a carbon tax would clearly be the best choice, as it would give all producers and consumers an incentive to economize on fossil fuels, switch from more carbon-intensive (coal) to less (natural gas), or to alternatives (renewables). But a potential problem is that the tax would have to be very high, even to achieve, for example, the optimal trajectory in the IAMs, much less to limit further increases in GMT to 2C. This is illustrated in Figure 7, showing carbon prices under different scenarios of the RICE model, a regionalized version of DICE (Nordhaus, 2010).

What leaps out is how much higher the prices are than any taxes we are likely to see, especially going forward, for reasons that are well understood. The price per ton of carbon is $38 in 2015, rising steadily to over $400 by the end of the century (2005 prices) in the optimal run. To limit the temperature change to 2C, comparable prices are $79 and $904 respectively, with a spike at about $1,200 in 2085. A carbon tax can and should play a role in mitigation, but realistically will be much lower even than the level needed to achieve the RICE optimum, much less the 2C solution. To achieve either of these objectives, the tax will

Figure 7. Carbon tax under different scenarios. Source: Nordhaus (2010).



need to be supplemented.

In the absence of a tax, or to supplement one, a negative tax on low carbon energy sources, or in other words, a subsidy, in the form of tax credits to conservation and renewables, seems appropriate. But subsidies are also problematic, potentially distortionary, since they are likely to affect some activities some energy sources, and some technologies, and not others. Ideally, a subsidy should be as broad-based as possible. A good example is in fact in place in the form of the federal tax credit for residential renewable energy, which applies to solar-electric systems, solar water heating systems, fuel cells, small wind-energy systems, and geothermal heat pumps.

In addition to a tax/subsidy, another instrument that will likely be needed is public investment in fundamental, basic research in potential low-carbon energy sources. A good example is provided by a new institute at UC Berkeley, which will explore the basic science of how to capture and channel energy on the molecular or nanoscale.

These are some examples, no doubt capable of expansion or improvement, of the kind of tax/subsidy/investment policies that in our judgment will be needed to achieve the desired reduction in emissions of GHGs, whether to follow the optimal trajectories in DICE and other IAMs, or to hold further increase in GMT to 2C or less.

References

Ackerman, Frank, Elizabeth A. Stanton, and Ramón Bueno, 2010. Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE. *Ecological Economics*, Vol. 69(8), pp. 1657-65.

Bender, Morris A., Thomas R. Knutson, Robert E. Tuleya, Joseph J. Sirutis, Gabriel A. Vecchi, Stephen T. Garner, and Isaac M. Held, 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science*, Vol. 327(5964), pp. 454-58, doi:10.1126/science.1180568.

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.

Cline, William R., 1992. The economics of global warming. Institute for International Economics.

Cline, William R., 2007. Global warming and agriculture: impact estimates by country. Washington: Center for Global Development and Peterson Institute for International Economics.

Committee on Health, Environmental, and other External Costs and Benefits of Energy Production and Consumption, National Research Council of the National Academies, 2010. Hidden costs of energy: Unpriced consequences of energy production and use. ISBN: 0-309-14641-0.

Deschenes, Olivier, and Michael Greenstone, 2007. The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *American Economic Review*, Vol. 97(1), pp. 354-85.

Edenhofer, Ottmar, Brigitte Knopf, Terry Barker, Lavinia Baumstark, Elie Bellevrat, Bertrand Chateau, Patrick Criqui, Morna Isaac, Alban Kitous, Socrates Kypreos, Marian Leimbach, Kai Lessmann, Bertrand Magné, Serban Scrieciu, Hal Turton, and Detlef P. van Vuuren, 2010. The economics of low stabilization: Model comparison of mitigation strategies and costs. *The Energy Journal*, Vol. 31 (Special Issue 1), pp. 11-48.

Elsner, James B., James P. Kossin, and Thomas H. Jagger, 2008. The increasing intensity of the strongest tropical cyclones. *Nature*, Vol. 455, pp. 92-95, doi:10.1038/nature07234.

Fisher, Anthony C., and John V. Krutilla, 1975. Resource conservation, environmental preservation and the rate of discount. *Quarterly Journal of Economics*, Vol. LXXXIX(3), pp. 358-70.

Fisher, Anthony C., and Michael W. Hanemann, 1993. Assessing climate change risks: valuation of effects. In Assessing Surprises and Nonlinearities in Greenhouse Warming, edited by J. Darmstadter and M. Toman. Washington, D.C.: Resources for the Future.

Fisher, Anthony C., and Urvashi Narain, 2003. Global warming, endogenous risk, and irreversibility. *Environmental and Resource Economics*, Vol. 25(4), pp. 395-416.

Fisher, Anthony C., Michael W. Hanemann, Michael J. Roberts, and Wolfram Schlenker, 2012. The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather: comment. *American Economic Review*, Vol. 102(7): 3749-60.

German Climate Computing Center (DKRZ) - Laboratory for Climate Researchers, http://www.dkrz.de/Klimaforschung-en/konsortial-en/ipcc-ar5/ergebnisse/Mitteltemperatur-en, accessed on January 4, 2014.

Hansen J., Kharecha P., Sato M., Masson-Delmotte V., and Ackerman F., et al., 2013. Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLoS ONE*, Vol. 8(12): e81648. doi:10.1371/journal.pone.0081648.

Heal, Geoffrey, 2009. Climate economics: A meta-review and some suggestions for future research. *Review of Environmental Economics and Policy*, Vol. 3(1), pp. 4-21, doi:10.1093/reep/ren014.

Heal, Geoffrey, and Jisung Park, 2013. Feeling the heat: Temperature, physiology & the wealth of nations. NBER Working Paper No. 19725, http://www.nber.org/papers/w19725.

Hope, Chris, 2006. The marginal impact of CO_2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated Assessment Journal*, Vol. 6(1), pp. 19-56.

Hsiang, Solomon, and Amir Jina, 2013. Development after disaster: the multidecadal impact of tropical cyclones on long-run economic growth. Unpublished working paper.

Hsiang, Solomon, Marshall Burke, and Edward Miguel, 2013. Quantifying the influence of climate on human conflict. *Science*, Vol. 341, 1235367 (2013), doi:10.1126/science.1235367.

IPCC, 2007: Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007: Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2011: Summary for policymakers. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2013: 5th Annual Report, Summary for policymakers. In Climate change 2013: the physical science basis, Working Group I Contribution to the IPCC Fifth Assessment Report.

IPCC, 2014: Summary for policymakers. Working Group III Contribution to the IPCC Fifth Assessment Report.

Knutson, Thomas R., John L. McBride, Johnny Chan, Kerry Emanuel, Greg Holland, Chris Landsea, Isaac Held, James P. Kossin, A. K. Srivastava, and Masato Sugi, 2010. Tropical cyclones and climate change. *Nature Geoscience*, Vol. 3, pp. 157-63, doi:10.1038/ngeo779.

Kolstad, Charles D., 1996. Learning and stock effects in environmental regulation: the case of greenhouse gas emissions. *Journal of Environmental Economics and Management*, Vol. 31(1), pp. 1-18.

Kopp, Robert E., Solomon M. Hsiang, and Michael Oppenheimer, 2013. Empirically calibrating damage functions and considering stochasticity when integrated assessment models are used as decision tools. Impacts World 2013, International Conference on Climate Change Effects, Potsdam, May 27-30. http://www.climate-impacts-2013.org/files/ial_kopp.pdf.

Lemoine, Derek M., and Christian P. Traeger, 2012. Tipping points and ambiguity in the economics of climate change. NBER Working Paper 18230, http://www.nber.org/papers/w18230.

Marshall, Michael, 2011. Hyperwarming climate could turn Earth's poles green. New Scientist, http://www.newscientist.com/article/mg21228392.300-hyperwarming-climate-could-turn-earths-poles-green.html, accessed on January 4, 2014.

McKinsey Global Institute, 2008. The carbon productivity challenge: curbing climate change and sustaining economic growth. McKinsey Climate Change Special Initiative, 2008.

Mendelsohn, Robert, William D. Nordhaus, and Daigee Shaw, 1994. The impact of global warming on agriculture: a Ricardian analysis. *American Economic Review*, Vol. 84(4), pp. 753-71.

Mendelsohn, Robert, and Ariel Dinar, 1999. Climate change, agriculture, and developing countries: Does adaptation matter? *The World Bank Research Observer*, Vol. 14(2), pp. 277-93.

Mendelsohn, Robert, 2008. Is The Stern Review an economic analysis? in Symposium: the economics of climate change: The Stern Review and its critics, *Review of Environmental Economics and Policy*, Vol. 2(1), pp. 45-60.

Nordhaus, William D., 1993. Optimal greenhouse-gas reductions and tax policy in the "DICE" model. *American Economic Review*, Vol. 83(2), pp. 313-17.

Nordhaus, William D., 2007a. The challenge of global warming: economic models and environmental policy. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.128.808&rep=rep1&type=pdf.

Nordhaus, William D., 2007b. A review of the Stern Review on the economics of global warming. *Journal of Economic Literature*, Vol. XLV (September 2007), pp. 686-702.

Nordhaus, William D., 2010. Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences (US)*, doi: 10.1073/pnas.1005985107.

Nordhaus, William D., and Paul Sztorc, 2013. DICE-2013R: introduction and user's manual. Website: dicemodel.net.

Peterson, Thomas C., Martin P. Hoerling, Peter A. Stott, and Stephanie C. Herring, 2013. Explaining extreme events of 2012 from a climate perspective. *Special Supplement to the Bulletin of the American Meteorological Society*, Vol. 94(9).

Pindyck, Robert S., 2007. Uncertainty in Environmental Economics. *Review of Environmental Economics and Policy*, Vol. 1(1), pp. 45-65.

Pindyck, Robert S., 2013a. The climate policy dilemma. *Review of Environmental Economics and Policy*, Vol. 7(2), pp. 219-37.

Pindyck, Robert S., 2013b. Climate change policy: What do the models tell us? *Journal of Economic Literature*, Vol. 51(3), pp. 860-72.

Poore, Richard Z., Richard S. Williams, Jr., and Christopher Tracey, 2011. Sea level and climate, USGS Fact Sheet 002-00, September, 2011.

Schlenker, Wolfram, Michael W. Hanemann, and Anthony C. Fisher, 2005. Will U.S. agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. *American Economic Review*, Vol. 95(1), pp. 395-406.

Schlenker, Wolfram, Michael W. Hanemann, and Anthony C. Fisher, 2006. The impact of global warming on U.S. agriculture: An econometric analysis of optimal growing conditions. *The Review of Economics and Statistics*, Vol. 88(1): pp. 113-25.

Schlenker, Wolfram, and Michael Roberts, 2009. Nonlinear impact effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of Sciences*, Vol. 106(37), pp. 15594-98, doi:10.1073/pnas.0906865106.

Shakhova, Natalia, Igor Semiletov, Ira Leifer, Valentin Sergienko, Anatoly Salyuk, Denis Kosmach, Denis Chernykh, Chris Stubbs, Dmitry Nicolsky, Vladimir Tumskoy, and Örjan Gustafsson, 2013. Ebullition and storm-induced methane release from the East Siberian Arctic Shelf. *Nature Geoscience*, doi:10.1038/NGEO2007.

Sherwood, Steven C., and Matthew Huber, 2010. An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences*, Vol. 107(21), 9552-9555, doi:10.1073/pnas.0913352107.

Shfaqat A. Khan, Kurt H. Kjær, Michael Bevis, Jonathan L. Bamber, John Wahr, Kristian K. Kjeldsen, Anders A. Bjørk, Niels J. Korsgaard, Leigh A. Stearns, Michiel R. van den Broeke, Lin Liu, Nicolaj K. Larsen, and Ioana S. Muresan, 2014. Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change*, doi:10.1038/nclimate2161.

Sokolov, A.P., P.H. Stone, C.E. Forest, R. Prinn, M.C. Sarofim, M. Webster, S. Paltsev, C.A. Schlosser 2013, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B. Felzer, J.M. Melillo, and H.D. Jacoby, 2009. Probabilistic forecast for twenty-first-century climate based on uncertainties in emissions (without policy) and climate parameters. *Journal of Climate*, Vol. 22(19), pp. 5175-5204.

Stern, Nicholas, 2007. The economics of climate change: The Stern Review. Cambridge and New York: Cambridge University Press.

Stern, Nicholas, 2008. Richard T. Elly lecture: the economics of climate change. *American Economic Review: Papers and Proceedings*, Vol. 98(2), pp. 1-37, doi:10.1257/aer.98.2.1

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*, Vol. 51(3), pp. 838-59.

Sterner, Thomas, and Martin U. Persson, 2008. An even sterner review: Introducing relative prices into the discounting debate. In Symposium: the economics of climate change: The Stern Review and its critics, *Review of Environmental Economics and Policy*, Vol. 2(1), pp. 61-76.

The Economist, 2012. Sunny uplands: alternative energy will no longer be alternative. http://www.economist.com/news/21566414-alternative-energy-will-no-longer-be-alternative-sunny-uplands, accessed on Jan 13, 2014.

Tol, Richard S.J., 1997. On the optimal control of carbon dioxide emissions: An application of FUND. *Environmental Modelling and Assessment*, Vol. 2(1997), pp. 151-63.

Weitzman, Martin L., 2007. A Review of The Stern Review on the economics of climate change. *Journal of Economic Literature*, Vol. XLV (September 2007), pp. 703-24.

Weitzman, Martin L., 2009. On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics*, Vol. 91(1), pp. 1-19.

Weyant, John P., 2008. A critique of the Stern Review's mitigation cost analyses and integrated assessment. In Symposium: the economics of climate change: The Stern Review and its critics, *Review of Environmental Economics and Policy*, Vol. 2(1), pp. 77-93.

Whiteman, Gail, Chris Hope, and Peter Wadhams, 2013. Climate science: vast costs of arctic change. *Nature*, Vol. 499, pp. 401-3, doi:10.1038/499401a.

Wikipedia's Hurricane Sandy Entry, http://en.wikipedia.org/wiki/Hurricane_Sandy, accessed on Jan 10, 2014.

Wiser, Ryan, and Mark Bolinger, 2009. 2008 wind technologies market report. U.S. Department of Energy.

World Bank, 2012. Turn down the heat: why a 4C warmer world must be avoided. A report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics.