Stabilizing Long-Term Temperature: The Issues of Uncertainty, Timing, Costs and Technology

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Abstract

The UN Framework Convention on Climate Change shifted the attention of the policy community from stabilizing greenhouse gas emissions to stabilizing atmospheric greenhouse gas concentrations. While this represented a step forward, it did not go far enough. Concentrations are not the end of the line, but only one more link in the causal chain between human activities and impacts. In this paper, we move further along the causal chain and focus on global-mean temperature change. Although closely related to concentrations, we believe that temperature incorporates several additional factors crucial for policy-making.

The paper examines the potential value of technology in reducing the costs of stabilizing long-term temperature. We compare the costs of staying beneath a particular temperature ceiling in a technology-rich and a technology-poor world. We find that the difference can easily be of the order of trillions of dollars worldwide. We also examine how expectations about the long-term cost of greenhouse gas abatement affects both the near-term rate of emission reductions and the price of abatement. The analysis suggests that, whereas expectations about future costs have little effect on the near-term rate of departure from the emissions baseline, these expectations have a substantial effect on the near-term price of abatement.

1. Introduction

Virtually all aspects of the climate debate have been controversial: the rate and magnitude of potential change, the ensuing impacts, and the efficacy and costs of various countermeasures. Yet, there is one area where nearly all agree. Reducing greenhouse gas emissions will require fundamental changes in the way in which we produce, transform, and use energy.[1-3] How we go about making these changes will, in large part, determine the price tag for dealing with the threat of climate change. We can make the necessary investments today to ensure ample supplies of low-cost alternatives in the future. Or we can continue the current decline in energy research, development, and demonstration (RD&D) and make do with high-cost substitutes that are already on the shelf. The present analysis examines the implications of choosing one path over another. We find that the difference can easily be of the order of trillions of dollars worldwide over the 21st century.

The initial focus of climate policy was exclusively on emissions abatement. Those who suggested that resources be devoted to other alternatives such as technology development, adaptation, or even reducing scientific uncertainty were often accused of trying to avoid real action. Only recently has there been widespread acceptance that climate policy must embrace a portfolio of actions.[4] Policy makers have come to the realization that the choice is not selecting one action over another, but deciding what combination of actions makes sense – recognizing that the emphasis is apt to change across countries and over time.

As with most portfolios, investments tend to be interrelated. Here, we focus on two types of investment: those to reduce carbon dioxide (CO2) emissions, both in the near and longer term; and those to develop economically and environmentally attractive substitutes for high carbon-venting technologies. In particular, we compare the costs of meeting alternative climate goals in a technology-rich and a technology-poor world. We also explore the implications for the timing of emission reductions.

Our focus is on the energy sector and the potential role of new energy technologies in addressing the climate challenge. As a result, the analysis deals primarily with CO2. Although it is the most important man-made greenhouse gas, CO2 is not the only radiatively active gas. We consider the other trace gases identified in the Kyoto Protocol when exploring cost-effective strategies for meeting our climate objectives.[5]

Calculating the benefits from climate-friendly technologies[*] is no mean task. How large is the natural resource base and what are the physical and political constraints on the rates of extraction? How will the ways we produce, transform, and use energy change? What will be the costs, timing, and availability of the alternatives? And what will be the accompanying environmental obstacles? The above list is not meant to be exhaustive, but only to be indicative of the types of challenges facing those trying to quantify the benefits of energy RD&D.

[*] Henceforth, the term technologies will be used to refer to energy-sector supply and demand technologies.

The payoff will also depend on whether society places a price on CO2 and other greenhouse gases and on how these prices may change over time. In the present analysis, we place a constraint on global–mean temperature change and calculate the implicit price associated with the cap. Clearly, one can pick a variety of endpoints for conducting such an analysis. The UN Framework Convention on Climate Change focuses on the atmospheric concentration of greenhouse gases.[6] However, we believe that temperature is a better measure. Although closely linked to concentrations, temperature is a more meaningful metric incorporating several additional factors relevant for policymaking. There are also technical problems associated with using concentrations in a multi-gas analysis. These do not arise when the focus is on temperature.[7-8]

For some time, climate analysts have tried to include uncertainty explicitly in their studies.[9-17] As noted by Moss and Schneider, providing a range of possible outcomes with no indication of their likelihood can be misleading.[18] Yet, the causal chain that links human activities to future temperature is fraught with uncertainty. The "curse of dimensionality" makes it extremely difficult for any one analysis to provide a formal treatment of all relevant uncertainties. At the very least, analysts can attempt to deal with those uncertainties that are most critical to the issue at hand. Here we attach *subjective* probabilities to: (a) income growth, (b) climate sensitivity, and (c) the rate of heat uptake by the deep ocean. We also deal with the uncertainty surrounding a temperature cap, but only through sensitivity analysis.

Three major caveats are in order. First, an absolute limit on any particular end point, whether it be concentrations or temperature, implies that damages are infinite beyond a ceiling. It would be preferable to balance the costs of climate policy with what such a policy buys in terms of reduced damages.[19] Unfortunately, our understanding of the nature of future damages and how to value them is so rudimentary that a formal cost-benefit analysis is questionable. For the time being, we use temperature as a surrogate, assuming that a particular ceiling reflects a political decision as to what constitutes an "ample margin of safety."

Second, we assume complete "where" and "when" flexibility.[*] That is, through trade in emission rights, reductions will be made wherever it is cheapest to do so, regardless of the geographical location. Similarly, there is banking and borrowing over time so that reductions will take place whenever it is cheapest to do so. This approach does not imply that reductions can be delayed indefinitely. Eventually, any temperature ceiling will become a binding constraint. To the extent that these two tenets of economic efficiency (where and when flexibility) are violated, the costs of a particular ceiling will be higher.[20]

Third, we need to recognize the "act then learn, then act again" nature of the decision problem. A key issue is to specify the rate and magnitude of greenhouse gas reductions. This is not a once-and-for-all decision, but one that will be revisited over time. There will be ample opportunity for learning and mid-course corrections. The challenge is to identify a sensible set of near-term decisions in the face of the many long-term uncertainties. This paper provides useful information for the decision-making process,

[*] With complete where and when flexibility, we can separate the issue of efficiency from that of equity.

but stops short of analyzing the question of what to do now. For an example of how such information can be used to determine a rational hedging strategy, see ref. 13. We believe that this is a crucial area for future research.

2. The model

The analysis is based on MERGE (a **m**odel for **e**valuating the **r**egional and **g**lobal **e**ffects of greenhouse gas reduction policies). This section provides a brief overview of MERGE. For details on the model's structure, data, and key information sources, the reader is encouraged to visit our website:

www.stanford.edu/group/MERGE

MERGE is an intertemporal general equilibrium model. There is international trade in oil, gas, and energy-intensive goods. Each of the model's nine regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region's wealth includes capital, labor, and exhaustible resources.

Like its predecessors, the current version (MERGE 5.0) is designed to be sufficiently transparent so that one can explore the implications of alternative viewpoints in the greenhouse debate. The model integrates sub-modules that provide reduced-form descriptions of the energy sector, the economy, emissions, concentrations, temperature change, and damage assessment.

MERGE combines a bottom-up representation of the energy supply sector together with a top-down perspective on the remainder of the economy. For a particular scenario, a choice is made among specific activities for the generation of electricity and for the production of non-electric energy. Oil, gas, and coal are viewed as exhaustible resources. There are introduction constraints on new technologies and decline constraints on existing technologies.

Outside the energy sector, the economy is modeled through nested constant elasticity production functions. The production functions determine how aggregate economic output depends upon the inputs of capital, labor, electric and non-electric energy. In this way, the model allows for both price-induced and autonomous (non-price) energy conservation and for interfuel substitution. It also allows for macroeconomic feedbacks. Higher energy and/or environmental costs will lead to fewer resources available for current consumption and for investment in the accumulation of capital stocks. Economic values are reported in U.S. dollars of constant 1998 purchasing power.

A number of gases have been identified as having a positive effect on radiative forcing.[21] In addition to CO2, methane (CH4), and nitrous oxide (N2O), MERGE 5.0 has been extended to incorporate the so-called "second basket" of greenhouse gases included in the Kyoto Protocol. These are the hydrofluorocarbons (HFCs), the perfluorocarbons (PFCs), and sulphur hexafluoride (SF6).

For CO2, we relate emissions to concentrations using a convolution ocean carbon cycle model and assuming a neutral biosphere. The other gases are modeled with one-box models with constant lifetimes. In spite of these simple representations, projected gas concentrations agree well with those given in the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report (TAR)[22] for the SRES illustrative scenarios.[23]

We also consider the cooling effect of sulphate aerosols assuming that SO2 emissions follow the SRES B2 scenario (ref. 23) in all cases (i.e., we assume that there is no "feedback" effect of greenhouse gas mitigation policies on the emissions of SO2).

For radiative forcing we use relationships consistent with the TAR for greenhouse gases, and the median aerosol forcing from Wigley and Raper (ref. 14). As shown in the latter, temperature projections are relatively insensitive to aerosol forcing uncertainties.

Projections for the non-CO2 greenhouse gases are based largely on the guidelines provided by *EMF 21: Multi-Gas Mitigation and Climate Change*.[24] Reductions from the reference path are determined by a set of time-dependent marginal abatement cost curves. For details, the reader is directed to the MERGE website.

When dealing with multiple gases, we need some way to establish equivalence among gases. The problem arises because the gases are not comparable. Each gas has its own lifetime and specific radiative forcing. The IPCC has suggested the use of global warming potentials (GWPs) to represent the relative contribution of different greenhouse gases to the radiative forcing of the atmosphere (ref. 4). However, a number of studies have pointed out the limitations of this approach (e.g., ref. 7). In MERGE 5.0, we adopt an alternative approach. We make an endogenous calculation of the incremental value of emission rights for the non-CO2 greenhouse gases relative to CO2 in each time period. The marginal abatement costs then provide the necessary basis for the tradeoffs among gases (ref. 8).

The Kyoto Protocol states that Annex B commitments can be met by "the net changes in greenhouse gas emissions from sources and removal by sinks resulting from direct human-induced land use change and forestry activities limited to aforestation, reforestation, and deforestation since 1990, measured as verifiable changes in stocks in each commitment period" (ref. 5). MERGE incorporates this option for offsets. We suppose that marginal sink enhancement costs rise with the quantity of enhancement. We assume that the potential for sink enhancement increases over time, but is eventually limited by the cumulative capacity for carbon absorption in forests.

3. Treatment of technologies

According to the International Energy Agency, investment in energy RD&D has declined by approximately 50% worldwide between 1980 and 1999.[25] This calls into question technological baselines constructed over the past decade. See, for example, the IPCC central case IS92a scenario that has served as the basis for many past analyses (ref. 21). For the present analysis, we construct two illustrative technology scenarios. In the pessimistic ("business as usual") case, we assume that the current downward spiral in energy RD&D continues unabated, and that the transition to a less greenhouse gas intensive economy is achieved with technologies that are currently on the shelf or in the marketplace. In the optimistic scenario, we are much more sanguine. A reversal of current investment trends in energy RD&D leads to a much brighter technological future.

Clearly, technology investment will be influenced by the price that society places on greenhouse gases. If a high price is deemed warranted, the current downward trend in energy RD&D is more likely to be reversed. Although there are differences in RD&D costs between the two scenarios, we ignore these differences and quantify only the differences in payoffs. This is justifiable because, in general, we find that RD&D costs are measured in billions of dollars, but that the payoffs could run into the trillions. The payoff is determined by the costs of meeting a particular climate goal with and without the advanced supply and demand-side technologies described below.

The detail in which technology is described in a particular analysis depends upon the focus. For the present analysis, we attempt to examine the differences between being in a technology-rich and technology-poor world. We are particularly interested in the impacts of such differences on the timing and costs of emission reductions. The level of detail for such an analysis requires assumptions about the availability, costs, performance characteristics, and greenhouse gas emissions from various categories of technologies and how these parameters change across space and time. The level of specificity would be much greater if we were to model the competition between different approaches within a particular category of technology. Whereas such detail is necessary to address certain questions, it is not called for here.

In MERGE, a distinction is made between electric and non-electric energy. Table 1 identifies the alternative sources of electricity supply. The first five technologies represent sources serving electricity demand in the base year (2000). The second group of technologies includes candidates for serving electricity needs in 2010 and beyond. The composition of the latter group differs in our two scenarios.

In the pessimistic scenario, we assume that future electricity demand will be met primarily with new, state-of-the-art gas and coal plants. In addition, there is a technology to which we refer to as ADV-HC (**adv**anced **h**igh-**c**ost carbon-free electricity generation). Its distinguishing characteristic is that, once introduced, it is available at a high but constant marginal cost. Any of a number of technologies could be included in this category: solar (in several forms), advanced nuclear, biomass, and others. For a discussion of possible candidates, see ref. 3. Given the enormous disagreement as to which of these technologies or combination of technologies will eventually win out, in terms of economic attractiveness and public acceptability, we refer to them generically rather than attempt to identify one or two winners.

Because knowledge is not fully appropriable, private markets are likely to underinvest in RD&D.[26] For our optimistic scenario, we assume that this market imperfection is overcome through a sustained commitment on the part of the public sector to direct investment, the subsidy of private sector RD&D, or both. As a result, fuel cells, and integrated gasification combined cycle with carbon capture and sequestration are added to our list of technologies. We also add a category similar to ADV-HC, but whose

Table 1. Electricity Generation Technologies Available to U.S.[a]
(shaded rows represent technologies available only in the optimistic scenario)

Technology name	Identification/ Examples	Earliest possible introduction date	Costs in 2000[b] (Mills/kWh)	Potential cost reduction due to learning-by-doing (LBD) (Mills/kWh)	Carbon emission coefficients (Billion tons per TWH)
HYDRO	Hydroelectric, geothermal and other renewables	Existing in base year	40.0		0.0000
NUC	Remaining initial nuclear	Existing in base year	50.0		0.0000
GAS-R	Remaining initial gas fired	Existing in base year	35.7		0.1443
OIL-R	Remaining initial oil fired	Existing in base year	37.8		0.2094
COAL-R	Remaining initial coal fired	Existing in base year	20.3		0.2533
GAS-N	Advanced combined cycle	2010	30.3		0.0935
GAS-A	Fuel cells with capture and sequestration	2030	47.7		0.0000
COAL-N	Pulverized coal without CO2 recovery	2010	45.0		0.1955
COAL-A	Fuel cells with capture and sequestration	2040	55.9		0.0068
IGCC	Integrated gasification and combined cycle with capture and sequestration	2020[c]	52.0		0.0240
ADV-HC	Carbon-free technologies; costs do not decline with LBD	2010	100.0		0.0000
LBDE[d]	Carbon-free technologies; costs decline with LBD	2010	100.0	70.0	0.0000

[a] Introduction dates and costs may vary by region.

[b] Except for oil and gas costs and the learning-by-doing component, we assume that the cost of all technologies decline at a rate of 0.5% per year beginning in 2000. Note that this column is used to calculate the autonomous learning component. The earliest possible introduction date is specified in the previous column.

[c] IGCC is currently available: however, without capture and sequestration.

[d] For the LBDE technologies, it is necessary to specify an initial quantity. We assume that the cumulative experience prior to 2000 is only 0.2 TkWh global.

learning costs decline by 20% for every doubling of capacity. This is called LBDE (learning-by-doing, electric). LBDE provides a learning component to those technologies grouped under ADV-HC.*

Table 2 identifies alternative sources of nonelectric energy within the model. Notice that oil and gas supplies for each region are divided into 10 cost categories. The higher cost categories reflect the potential use of non-conventional sources. With regard to carbon-free alternatives, the choices have been grouped into two broad categories: RNEW (low-cost renewables such as ethanol from biomass) and NE-BAK (high cost backstops such as hydrogen produced through photovoltaics and electrolysis). The key distinction is that RNEW is in limited supply, but NE-BAK is available in unlimited quantities at a constant but considerably higher marginal cost. As in the case of electric energy, we have added a new category of technologies for our optimistic scenario. This is called LBDN (learning-by-doing, non-electric). As with its counterpart in the electric sector, costs are a declining function of cumulative experience.

Table 2. Nonelectric Energy Supplies Available to U.S.[a]
(shaded row represents technology only available in an optimistic scenario)

Technology name	Description	Cost in 2000 ($/Gj)[b]	Potential cost reduction due to learning-by-doing ($/Gj)	Carbon emission coefficients (tons of carbon per GJ)
CLDU	Coal-direct uses	2.50		0.0241
OIL-1-10	Oil	3.00-5.25		0.0199
GAS-1-10	Gas	2.00-4.25		0.0137
SYNF	Coal-based synthetic fuels	8.33		0.0400
RNEW	Renewables	6.00		0.0000
NEB-HC	Nonelectric backstop	14.00		0.0000
LBDN[c]	Carbon-free technologies; costs decline with learning-by-doing	14.00	6.00	0.0000

[a] Costs may vary by region.
[b] Except for the learning-by-doing component, we assume that the costs of all technologies decline at a rate of 0.5% per year beginning in 2000.
[c] We assume that cumulative experience prior to 2000 is only one GJ.

* For a discussion of learning-by-doing, see ref. 27.

Except for the learning-by-doing component, we assume that the costs of all technologies decline at a rate of 0.5% per year beginning in 2000. This is the case for both the pessimistic and optimistic scenarios.

The energy-producing capital stock is typically long-lived. In MERGE, introduction and decline constraints are placed on all technologies. For new technologies, we assume that production in each region is constrained to 1% of total production in the year in which it is initially introduced and can increase by a factor of three for each decade thereafter. As for the decline rate, we limit it to 2% per year. The decline rate, however, does not apply to existing technologies. This is to allow for the possibility that some climate constraints may be sufficiently tight to force premature retirement of existing capital stock.

Turning to the demand-side, to allow for greater progress at the point of end-use, we assume that the long-run price elasticities are 25% higher in the optimistic technology scenario. Here we assume that we succeed in removing the barriers to increased efficiency and that the costs of doing so do not outweigh the benefits.

4. Treatment of uncertainty

In this paper, we attempt to compare the costs of stabilizing global-mean temperature in a technology-rich and a technology-poor world. Mitigation costs will depend not only on the characteristics of the energy system, but also on a number of socioeconomic and scientific considerations each of which is highly uncertain. These include factors influencing future greenhouse gas emissions, the carbon cycle, radiative forcing, climate sensitivity, and the efficiency with which heat is transferred from the surface into the deeper ocean. It would be virtually impossible to include all of these factors in a rigorous probabilistic analysis. Rather, we have chosen to focus on three areas of uncertainty that we feel are particularly relevant to the present analysis. The dominant importance of future emissions and climate sensitivity to global-mean temperature is well documented.[14, 28] In addition, because of the importance of the lag between potential and realized temperature change to the present analysis, we add response time to our list of critical uncertainties.[*]

Future greenhouse gas emissions are particularly difficult to project. In a previous study (ref. 11) we examined the sensitivity of the emissions of carbon dioxide to five factors: potential economic growth; the elasticity of price-induced substitution between energy, capital, and labor; the rate of non-price induced energy efficiency improvements; the availability of economically competitive carbon-free alternatives to coal-fired electricity; and the costs of the nonelectric backstop alternative to liquid fuels. The analysis showed that economic growth was by far the most important determinant of future emissions. Figure 1 shows five projections of growth over the 21st century and the authors' subjective probability for each.[†]

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[*] The response time is defined as the time it takes for the temperature to reach (1 – 1/e) of the equilibrium response – see Appendix.

[†] These projections coincide remarkably well with the full range of SRES (ref. 23) scenarios for the year 2100.

Figure 1. Potential Gross World Product

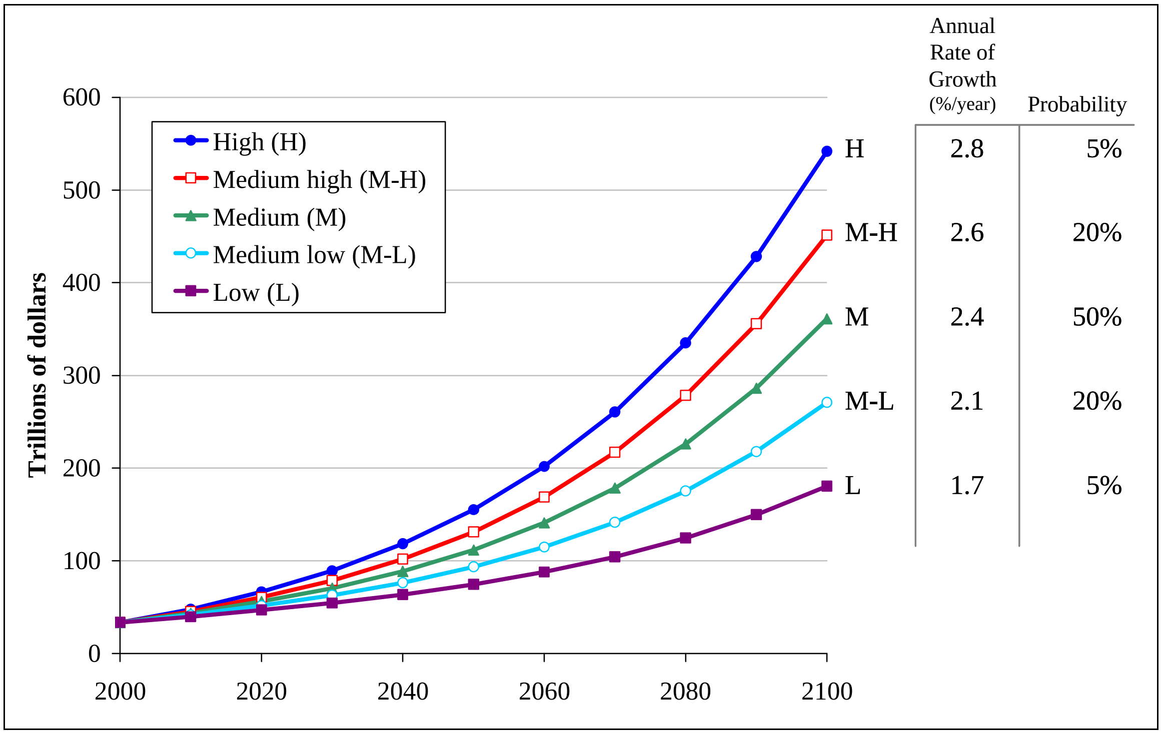
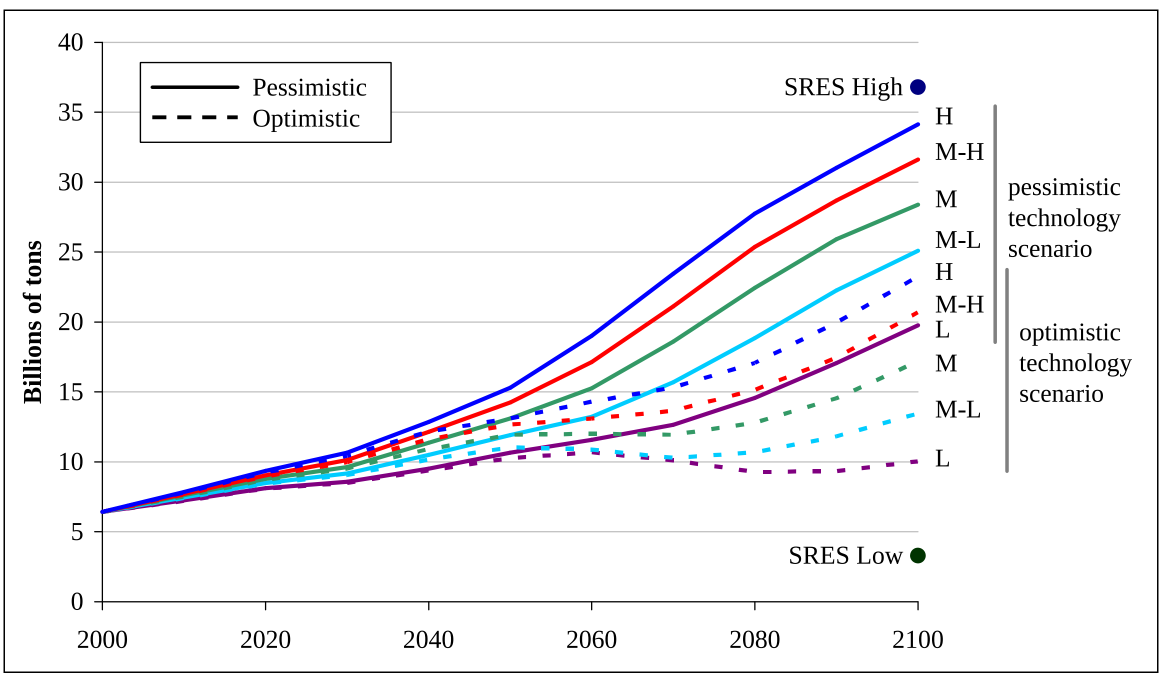


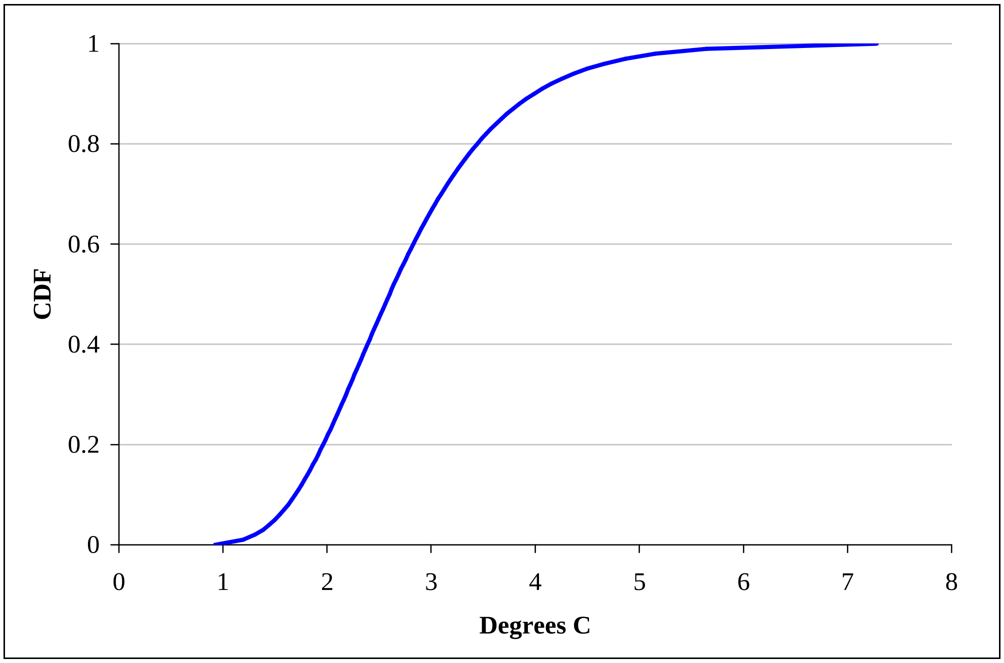
Figure 2 shows the resulting projections of future carbon emissions. The solid lines and the dashed lines correspond to the pessimistic and optimistic technology scenarios, respectively.

Figure 2. Carbon Emissions Baselines



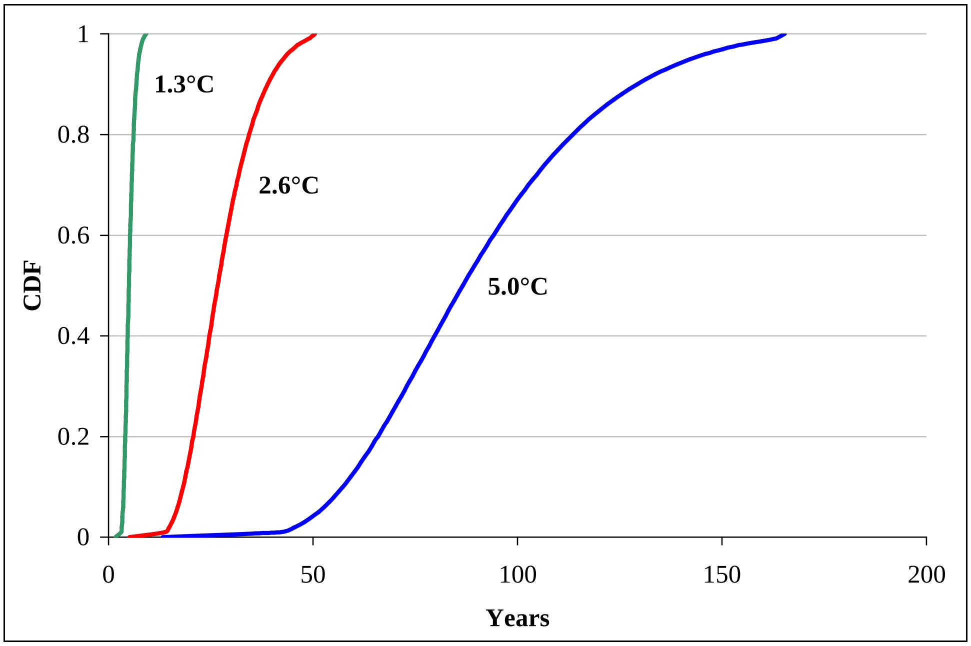
Climate sensitivity is defined as the equilibrium global-mean surface temperature change in response to a doubling of CO2 concentrations. The cumulative distribution function (CDF) in Figure 3 corresponds to the log-normal probability distribution adopted by Wigley and Raper (ref. 14). For purposes of the present analysis, we focus on the tails of the distribution. This yields discrete probabilities of 5%, 90%, and 5% for climate sensitivities of 1.3°, 2.6°, and 5.0°C, respectively.

Figure 3. Climate Sensitivity



As noted in refs. 14 and 16, the two properties that control the climate system's decadal to century response to radiative forcing are the climate sensitivity and the rate of heat uptake by the ocean. The rate at which heat is transferred from the surface into the deeper ocean is determined by the climate sensitivity, the ocean's effective vertical diffusivity, and changes in the ocean's thermohaline circulation. In the MERGE climate model, the rate of ocean heat uptake is characterized by a single (response time) parameter. The values used for this time scale are based on a calibration of the model against the upwelling-diffusion, energy-balance model (MAGICC) used in the IPCC TAR and in ref. 14 (see Appendix). Figure 4 shows the response time for alternative climate sensitivities, accounting for thermohaline circulation changes and uncertainties in vertical diffusivity.

Figure 4. Response Time for Alternative Climate Sensitivities



For purposes of the analysis that follows, we calculate discrete conditional probabilities based on each of the 3 CDFs in Figure 4, again focusing on the tails of the distribution. See Table 3.

Table 3. Response Times (years)

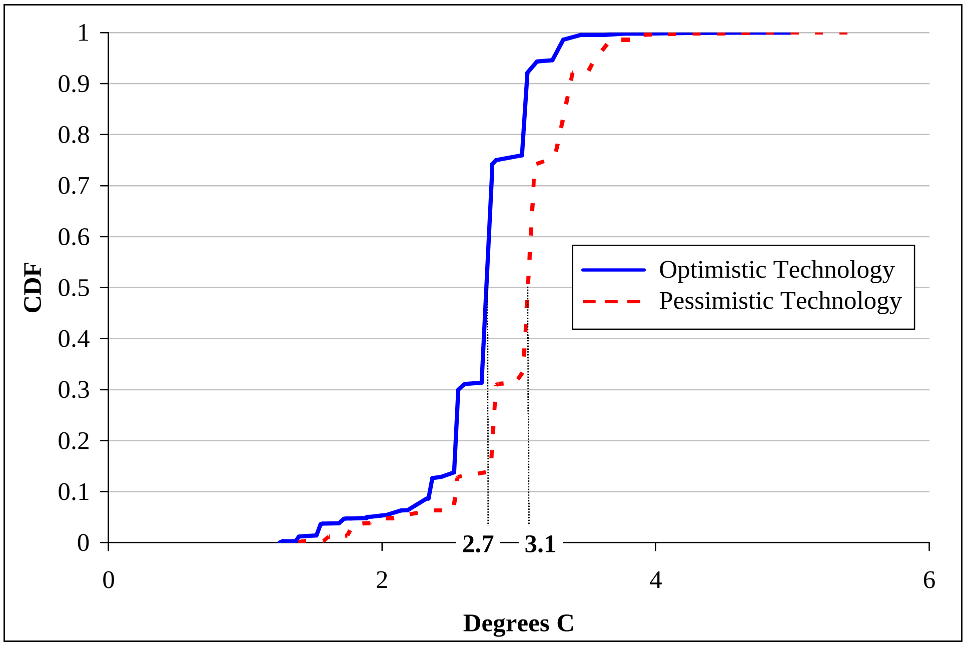
Discrete Conditional Probability	Climate Sensitivity		
	1.3°C	2.6°C	5.0°C
5%	4	15	57
90%	5	25	96
5%	8	39	158

5. Temperature change in the absence of climate policy

Having discussed the numerical inputs, we now turn to the results. Using MERGE, we begin by estimating cumulative distribution functions (CDFs) for our two technology scenarios. In this section, we assume the absence of policy to mitigate climate change. From Figure 5, we see that the range is remarkably similar to the recent IPCC projections (see ref. 23). Whereas the IPCC presents a range of 1.4° to 5.8°C between 1990 and 2100, we project a range of 1.2° to 5.5°C between 2000 and 2100.* Allowing for the warming from 1990 to 2000, these two sets of projections are virtually identical.

* Note that all estimates of warming in this paper are measured from the year 2000.

Figure 5. Temperature Increase During 21st Century in the Absence of Mitigation Policy (50th percentile values highlighted)



However, unlike the IPCC, we assign probabilities to various outcomes. The analysis suggests that the extreme ends of the range are highly unlikely. Table 4 shows the 5th, 50th, and 95th percentiles for each of the two technology scenarios. For the pessimistic scenario, there is only one chance in 20 that the temperature increase will be less than 2.1°C or more than 3.6°C.

Table 4. Likelihood of Temperature Change Over the 21st Century in the Absence of Climate Policy

	5th percentile	50th percentile	95th percentile
Pessimistic technology scenario	2.1°C	3.1°C	3.6°C
Optimistic technology scenario	1.9°C	2.7°C	3.3°C

Notice that shifting from the pessimistic to the optimistic scenario results in only a modest shift in the CDF. The explanation is straightforward. Suppose that all parameters were to take on their median values. The difference in emissions between the two technology scenarios can be attributed to two factors: 1) learning-by-doing which drives down the price of the electric backstop technologies to the point where they are economically competitive with conventional gas and coal, and 2) the long-run price elasticities. However, from Figure 2, note that the emission baselines representing the median values do not diverge substantially until the second-half of the century. With a climate sensitivity of 2.6°C, the response time is of the order of 25 years. Hence, we should not be surprised to see so little difference in the median values for temperature change in 2100. With the higher climate sensitivity, the response time is such that there is insufficient time for substantial divergence in temperature by 2100. With the lower climate sensitivity, the rate of temperature change is so small that the faster response times have little influence.

Because we have focused on the tails of the distributions for climate sensitivity and response time, the distributions tend to rise sharply for the middle fractiles. We would see a less rapid rise in the CDFs if we were to use more points in characterizing the individual distributions, but there would be little change in the tails of the distributions and in their median values.

6. A ceiling on temperature increase

We next turn to the issue of temperature ceilings. We begin with a 2°C cap on temperature increase from 2000. This may seem ambitious given that approximately 95% of the outcomes in Figure 5 exceed this level by 2100. One measure of the difficulty of meeting a temperature ceiling is how fast we must depart from the emissions baseline. Although we are focusing on temperature rather than atmospheric concentrations, for CO2 the issue remains one of cumulative emissions. For any given climate sensitivity, a global-warming ceiling defines a carbon budget. The challenge is to determine how the budget should be allocated over time to meet the climate goal at minimum cost.

Figure 6 shows the cost-effective rate of departure for the pessimistic and optimistic scenarios. Notice that the rate of departure begins slowly and increases over time. This is consistent with "when" flexibility.[29] A gradual rate of departure reduces the pressure to prematurely retire existing long-lived capital stock (e.g., power plants, buildings, and transport) and provides more time to develop and introduce new, economically competitive carbon-free technologies into the energy system.

Interestingly, the rate of the departure from the baseline through 2030 is virtually insensitive to the technology scenario. The explanation has to do with the timing and costs of the new technologies and the size of the carbon budget. The near-term options for reducing CO2 emissions are limited to fuel switching from coal and oil to natural gas, and to price-induced conservation. This is because the payoff from technology investment is "back loaded." The development and deployment of new technologies does not happen overnight. The payoff is initially modest, but increases over time. Fortunately, with a 2°C cap there is still some leeway to emit CO2. It makes sense to use what remains of the carbon budget in the early years when the alternatives are expensive and to transition gradually to a less carbon-intensive economy.

Even if we are pessimistic about the technological future, using the remainder of the carbon budget early-on reduces the need for a precipitous reduction in the existing carbon-producing and carbon-using capital stock. Hence, regardless of one's views on technology, this makes little difference in the initial rate of departure from the baseline. This is the case whether we are focusing on the median or the tails of the CDFs. See Table 5.

Figure 6. Reductions in Carbon Emissions from the Baseline with 2°C Temperature Cap During 21st Century (50th percentile values highlighted)

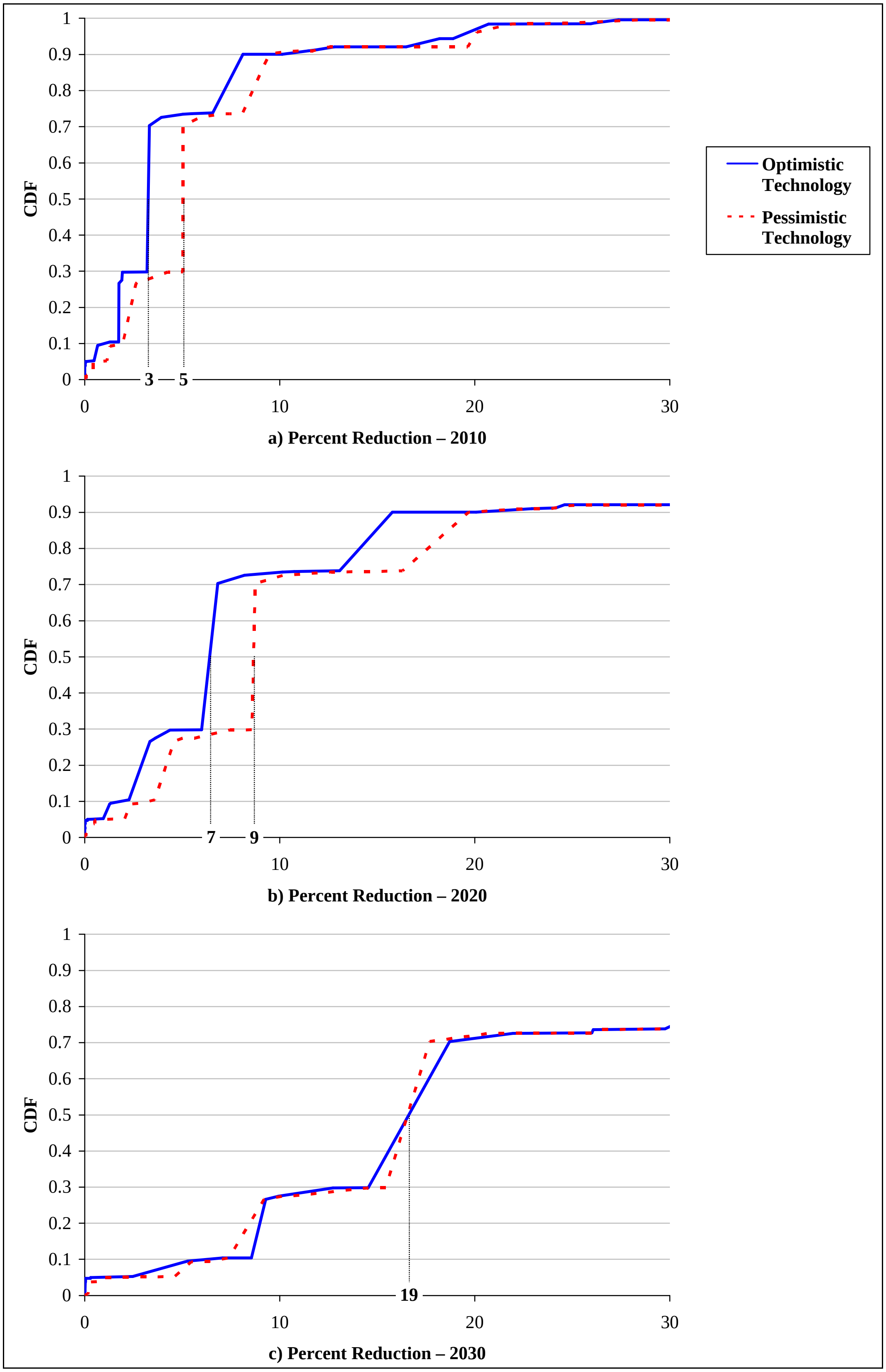


Table 5. Percentage Reduction from the Baseline (percent)
for a 2°C Cap on Temperature

	Pessimistic Technology Scenario			Optimistic Technology Scenario		
	5th percentile	50th percentile	95th percentile	5th percentile	50th percentile	95th percentile
2010	0	5	20	0	3	19
2020	1	9	37	0	7	40
2030	1	19	53	0	19	60

A second measure of the difficulty of meeting a constraint is the implicit price that would have to be placed on carbon to meet the particular goal. That is, how high would we have to raise the price of carbon-intensive technologies to make them less desirable than the noncarbon-venting alternatives?

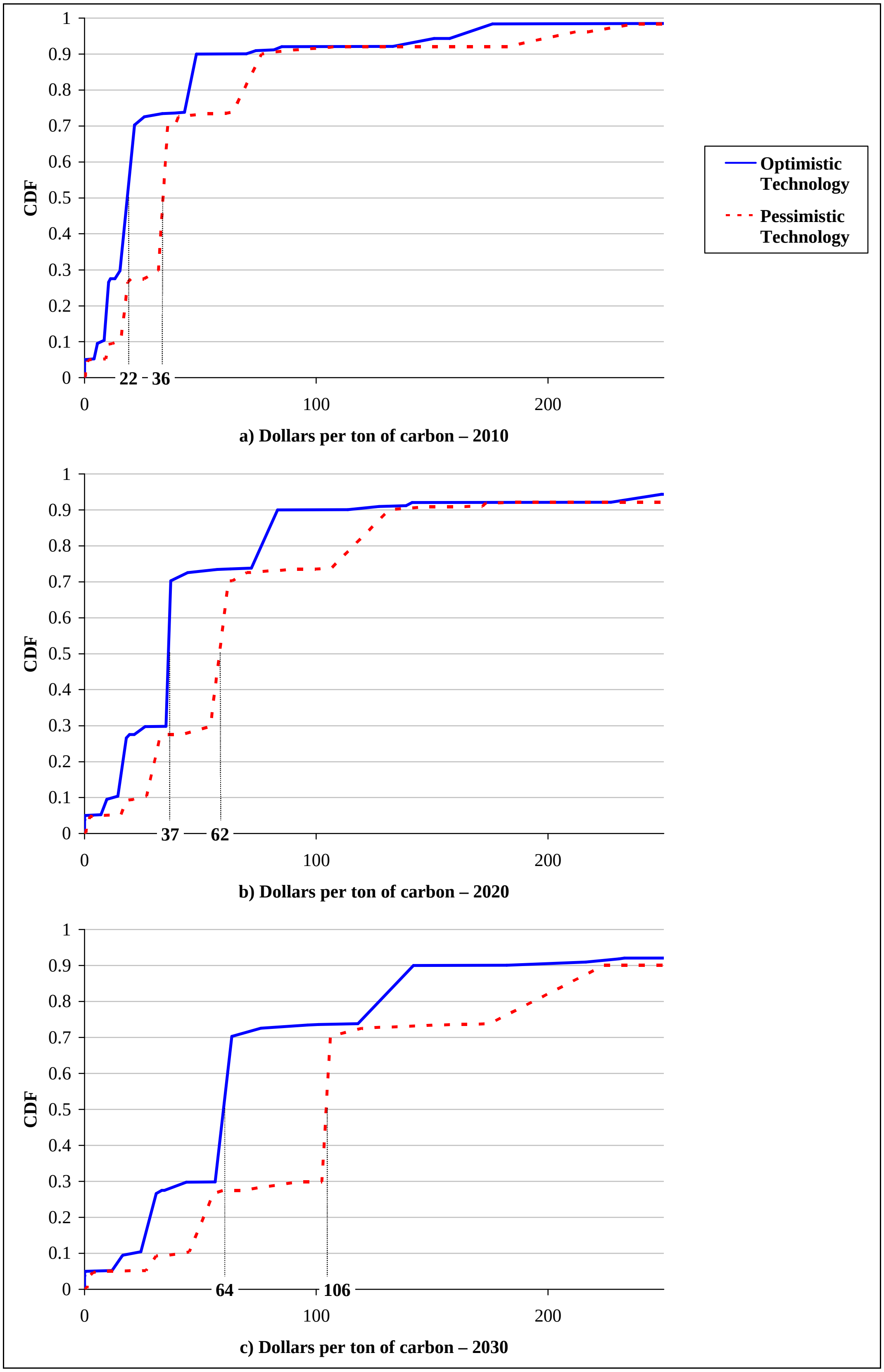
Figure 7 indicates the magnitude of the carbon tax that would be required to limit the temperature increase to 2°C. The tax is computed for 2010, 2020, and 2030 for each of the technology scenarios. Note that the results appear sensitive to our technological perspective. That is, the less sanguine we are about the prospects for low-cost alternatives, the higher the carbon tax in the early years. This is because, when accounting for future developments, the economically efficient tax will rise at a rate approximating the return on capital. The long-term price of energy will govern the initial level of the tax. The more pessimistic we are about the long term, the higher the tax in the near term.

From Table 6, we see that the distributions are skewed to the right. This reflects the difficulty of maintaining a temperature cap of 2°C when climate sensitivity is high and/or we have a rapid response time.

Table 6. Price of Carbon ($/ton) with a 2°C Cap on
Temperature Increase from 2000

	Pessimistic Technology Scenario			Optimistic Technology Scenario		
	5th percentile	50th percentile	95th percentile	5th percentile	50th percentile	95th percentile
2010	2	36	212	0	22	176
2020	4	62	355	0	37	255
2030	6	106	637	0	64	409

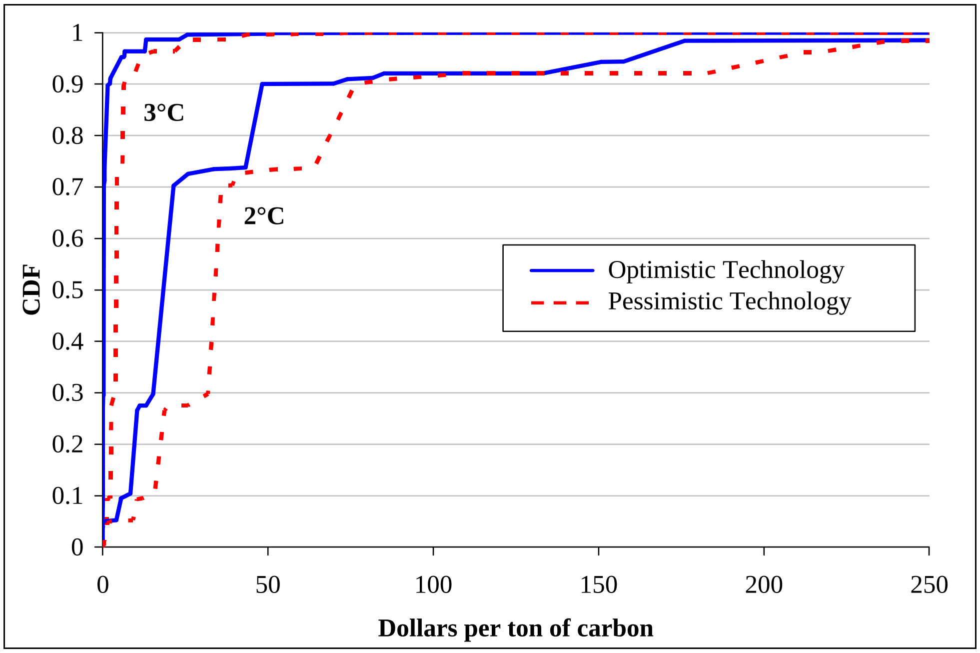
Figure 7. Carbon Prices with 2°C Temperature Cap (50th percentile values highlighted)



But what if we were to have a higher cap, say 3°C? From Figure 5, note that approximately 95% of the outcomes exceed 2°C. Two-thirds of the outcomes exceed 3°C for the pessimistic technology scenario and only one-quarter of the outcomes exceed 3°C for the optimistic technology scenario. Also, from Figure 5, note that for the majority of the outcomes that exceed 3°C, the amount by which this threshold is exceeded tends to be minor.

Figure 8 compares the carbon taxes in 2010 required to maintain 2° and 3°C caps. In each case, the tax is computed for the pessimistic and optimistic technology scenarios. As we would expect, the difficulty of maintaining a 3°C cap is considerably less than that for a 2°C cap. With a 3°C ceiling, we would also expect a lower carbon tax trajectory and a slower rate at which emissions depart from the baseline.

Figure 8. Carbon Prices in 2010 with 2° and 3°C Temperature Caps



7. The role of technology in containing the costs of climate policy

There has been a 50% decline in energy RD&D worldwide since 1980. For purposes of the present analysis, we suppose that the continuation of this trend will result in the pessimistic technology scenario. Conversely, the optimistic scenario is designed to reflect a reversal of current trends. In this section, we explore the benefits from an RD&D effort sufficient to bring about the more optimistic of our two technological futures.

Care must be taken to define what is meant by benefits. Losses are incurred when the imposition of a temperature constraint leads to a reallocation of resources from the patterns that would be preferred in the absence of the constraint. A temperature constraint will lead to fuel switching and to more expensive price-induced conservation activities. There are also changes in domestic and international prices. In most cases, these forced adjustments result in a reduction in economic performance. Low cost, carbon-free substitutes can reduce this loss in economic performance. It is this reduction in losses that is referred to as the benefits of RD&D.

In calculating benefits, we do not subtract the costs of the additional RD&D. That is, we deal with *gross*, not *net*, benefits. Nor do we account for the reduced environmental damages resulting from the temperature constraint. In the case of the latter, we assume that climate goals will be met with whatever technologies are available. Hence, environmental benefits will be the same in both the pessimistic and optimistic scenarios.

We begin with a 2°C temperature cap. Figure 9 compares discounted consumption losses for each of the two technology scenarios. Over the period of a century the losses can be of the order of trillions of dollars. However, the Figure suggests that the losses can be reduced substantially if we are successful in achieving the more ambitious technology objectives.

Figure 9. Present Value of Consumption Losses Over 21st Century with 2°C Constraint on Temperature Increase (50th percentile values highlighted)

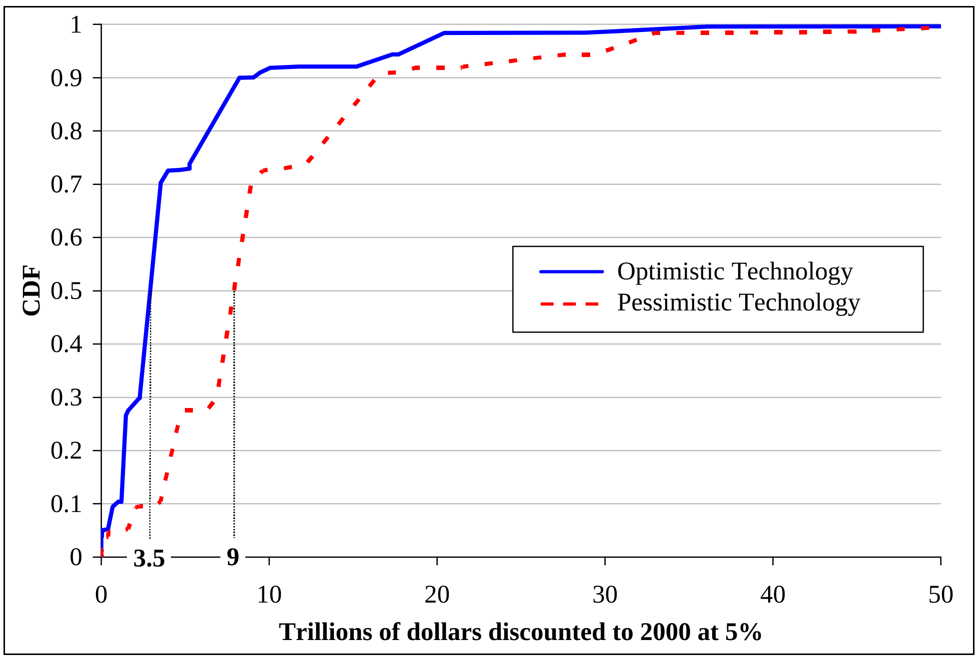


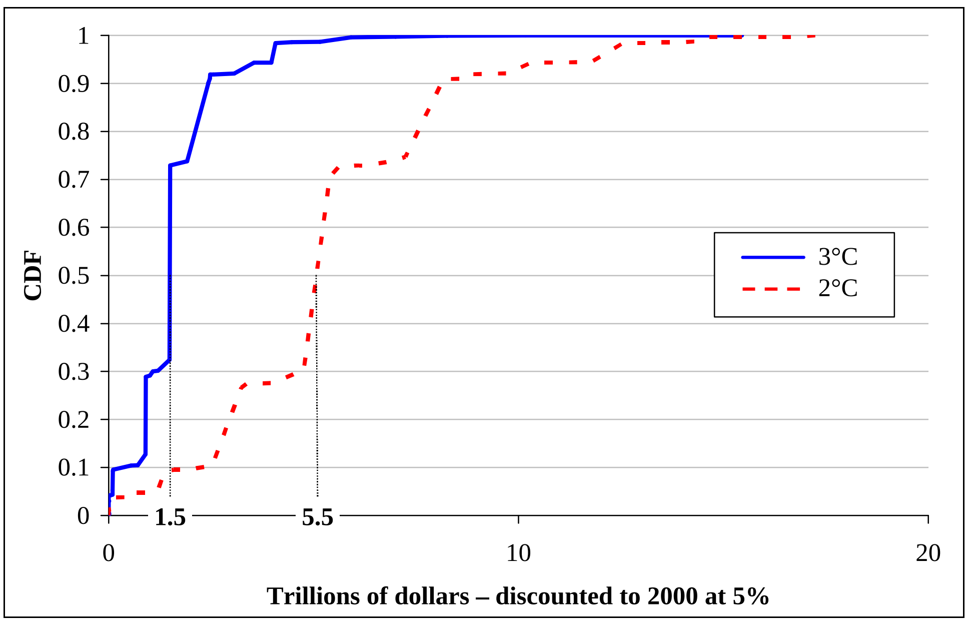
Table 7 shows the discounted present value of consumption losses under the two technology scenarios for the 5th, 50th, and 95th percentiles. The Table also shows the differences in consumption losses between the two scenarios. That is, these are the benefits from moving from the pessimistic to the optimistic technology scenario.

Table 7. Difference in Consumption Losses for Two Technology Scenarios Under a 2°C Temperature Cap – discounted to 2000 at 5% in trillions of dollars

	5th percentile	50th percentile	95th percentile
Consumption losses under pessimistic scenario	1.0	9.0	30.0
Consumption losses under optimistic scenario	0.0	3.5	17.7
Benefits of optimistic scenario	1.0	5.5	12.3

Figure 10 compares the benefits for the 2° and 3°C temperature caps. As we would expect, the payoff declines as the stringency of the constraint is weakened. Nevertheless, the payoff is still likely to be substantial even with the higher temperature cap.

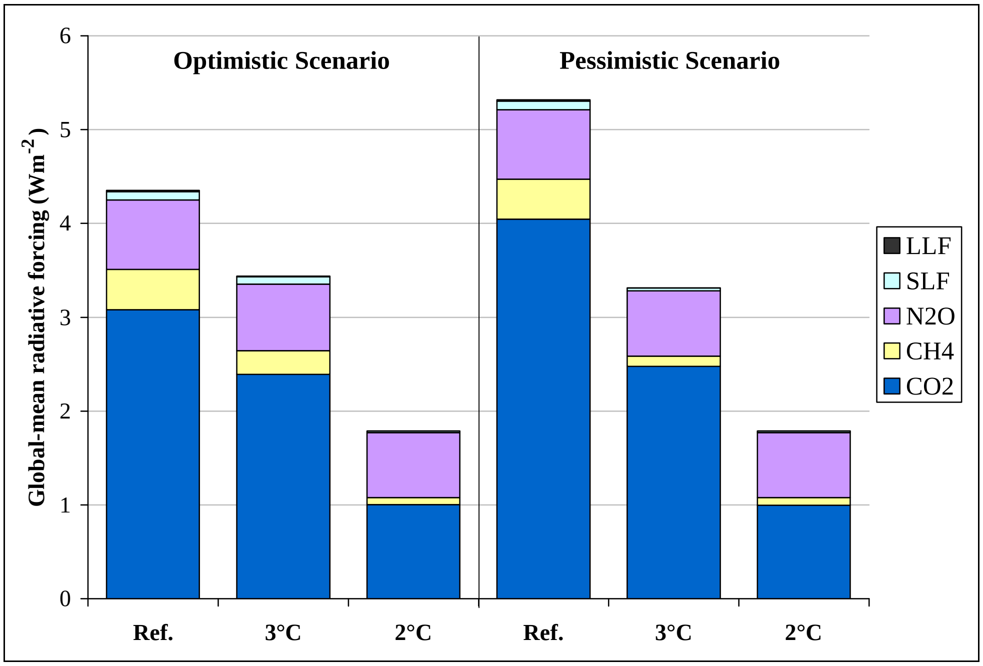
Figure 10. Gross Benefits from R&D Program Under Alternative Temperature Constraints (50th percentile values highlighted)



8. The relative contribution of the various greenhouse gases to radiative forcing

As noted earlier, the analysis encompasses the six categories of greenhouse gases identified in the Kyoto Protocol. With our focus on the energy sector and the costs of meeting a particular temperature ceiling in a technology-rich and technology-poor world, our attention has been on CO2. It is interesting, however, to note the contribution of the other gases in meeting the temperature constraints. Figure 11 shows our projections for the globally and annually averaged anthropogenic radiative forcing due to changes in the concentrations of greenhouse gases over the 21st century.* Here the second basket of gases (the HFCs, PFCs, and SF6) are combined under just two categories: short-lived fluorinated gases (SLF) and long-lived fluorinated gases (LLF).†

Figure 11. Contributions to Radiative Forcing, 2000-2100



Among the non-CO2 greenhouse gases, CH4 with its relatively short lifetime (12 years) makes the greatest contribution to meeting the temperature ceilings. The impact of the relative cost of abatement can be seen when comparing the 3°C cases. Under the optimistic technology scenario, less pressure is placed on reducing CH4. This is because CO2 abatement is relatively inexpensive when compared with the pessimistic scenario. The short-lived fluorinated gases also play a role, but there are insufficient quantities to offset the need for large CO2 reductions.

* The temperature cap is imposed in all periods. Because MERGE is an intertemporal optimization model, there may be some minor differences between scenarios with regard to the year that the cap becomes binding. For this particular example, we adopt the median values for income growth, climate sensitivity and response time.

† There are a large number of second basket gases, which are modeled in MERGE using a representative short-lived fluorinated gas (HCF134a) and a representative long-lived fluorinated gas (SF6). An equivalent concentration of HCF134a is used to represent all gases with short lifetimes (less than 65 years), while an equivalent concentration of SF6 is used to represent all gases with longer lifetimes. Total radiative forcing changes for all second basket gases can be modeled quite accurately by this simple representation.

9. Why is temperature a more meaningful metric than atmospheric concentrations?

The UN Framework Convention on Climate Change shifted the attention of the policy community from stabilizing greenhouse gas emissions to stabilizing atmospheric greenhouse gas concentrations. While this represented a step forward, it did not go far enough. Concentrations are not the end of the line, but only one more link in the causal chain between human activities and impacts. In the present analysis, we go beyond atmospheric concentrations and include radiative forcing, climate sensitivity, and response times. Not only does the focus on temperature avoid the problems associated with the use of GWPs, but it also provides a more meaningful metric for policy-making purposes.

Focusing on concentrations ignores several factors that are critical to the determination of impacts. From Table 8, note that for a particular temperature cap, the associated CO2 concentrations can vary widely. This is because temperature change is sensitive to climate sensitivity and the time it takes for the temperature system to adapt to a change in radiative forcing. For example, if climate sensitivity is low, atmospheric CO2 concentrations will have a smaller impact on temperature than if it is high. Hence, given the current uncertainties in our understanding of the temperature system, it is impossible to project with any degree of confidence the effect of a given concentration ceiling on temperature.

Table 8. Peak Atmospheric CO2 Concentrations (PPMV)
Under Alternative Temperature Caps[a]

		5th percentile	50th percentile	95th percentile
2°C	Pessimistic	417	472	743
	Optimistic	414	445	503
3°C	Pessimistic	535	574	669
	Optimistic	523	580	592

[a] For the 5th and 50th percentiles, concentrations decline after they reach their maximum values during the 21st century. In the case of the 95th percentile, concentrations continue to rise beyond 2100 for all but the lowest scenario.

10. Some concluding remarks

The analysis has yielded some policy-relevant results. For the "no policy" case, the analysis produces a temperature range for 2100 that is remarkably similar to that of the IPCC. However, unlike the IPCC, we attempt to determine the likelihood of various temperature outcomes. This is done by assigning probabilities to three critical areas of uncertainty: those relating to future economic activity, climate sensitivity, and how quickly the temperature system responds to changes in radiative forcing. The results suggest that the temperature projections at the tails of the range are far less likely than those in the middle.

Focusing on the energy sector and CO2, the analysis confirms previous findings suggesting that, for a given constraint, a gradual departure from the emissions baseline is preferable to a more rapid departure. This result appears to be insensitive to one's expectations about the long-term cost of greenhouse gas abatement. However, expectations about future costs have a substantial effect on the near-term price of abatement. Specifically, the more optimistic one's views about the future availability of low-cost carbon-free substitutes, the lower the near-term carbon tax.

The analysis also suggests that investment in energy RD&D is no "magic bullet," but it can substantially reduce the economic losses arising from mitigation associated with a temperature constraint. Stabilizing temperature is likely to require a fundamental restructuring of the global energy system. It is hard to imagine that the costs will not be substantial. But investments in the broad portfolio of energy technologies required to meet the emerging needs of both developed and developing countries can dramatically reduce the size of the price tag.

Finally, we find that, given the uncertainty in the climate system, focusing on atmospheric concentrations is likely to convey a false sense of precision. The causal chain between human activity and impacts is fraught with uncertainty. From a benefit-cost perspective, it would be desirable to minimize the sum of mitigation costs and damages. Unfortunately, our ability to quantify and value impacts is limited. For the time being, we must rely on a surrogate. Focusing on temperature rather than on concentrations provides much more information on what constitutes an ample margin of safety. Concentrations mask too many uncertainties that are crucial for policy making.

Appendix

Climate Model

The climate model in MERGE is a simple one-box model where the box represents the ocean and its size defines the thermal inertia of the climate system. This in turn determines the lag between externally-imposed forcing and global-mean temperature response. While this is clearly an oversimplification of the climate system, such a model can still be used to characterize the response to external forcing in a quantitatively realistic way by calibrating the model against more realistic models.

In a one-box model, the response is determined by two parameters: a climate sensitivity that defines the equilibrium response and a time scale or "response time" (equivalent to the box size) that defines how rapidly the system approaches equilibrium. Defining a suitable single time scale for global-mean temperature response is difficult because the ocean, a primary determinant of the response time, operates on multiple time scales. There is, therefore, no unique way to define a response time – and different ways to define a response time will lead to different values. The way the response time is defined here is to consider the response to a step forcing change of 5 W/m^2, and define the response time as if the response were exponential. The response time (τ) is then how long it takes for the temperature to reach (1 – 1/e) of the equilibrium response.

Note that, if the response were exponential, and characterized by a single time scale, then one would reach ($1 - 1/e^2$) of the equilibrium response after a time equal to 2τ. In fact, it takes much longer than this to reach this point – a consequence of the fact that, as time goes by, the influence of deeper layers in the ocean becomes increasingly more important. This effectively causes the thermal inertia of the system to increase with time, so the system's characteristic response time scale also increases with time. Equally, the initial response is much more rapid than the exponential decay model would lead one to expect – representing the response of the oceanic mixed layer with its relatively small thermal inertia. In spite of these deficiencies, a one-box model still captures the essential features of the system's response, provided an appropriate response time is used. Here we choose appropriate response times using the upwelling-diffusion, energy-balance climate model MAGICC,[30-31] the same model that was used for global-mean temperature projections in the IPCC TAR. MAGICC, in turn, has been calibrated against a number of state-of-the-art coupled atmosphere/ocean GCMs.

The main determinants of the response time, τ, are the climate sensitivity (ΔT_{2x}; °C), and the effective vertical diffusivity of the ocean (K_z; cm^2/sec). Table A gives τ results (in years) from MAGICC, using TAR best-estimate results for all other parameters. In parentheses are approximate results obtained using the following best-fit formula:

$$\tau = [a + b(\Delta T_{2x})]^2$$

$$a = 0.04233(K_z)^2 - 0.4261(K_z) + 0.466$$

$$b = -0.06071(K_z)^2 + 0.7277(K_z) + 0.668$$

Note that the dependence of τ on ΔT_{2x} is crucial.

Table A. τ Results (in years) from MAGICC

	ΔT_{2x} = **1.0°C**	ΔT_{2x} = **2.0°C**	ΔT_{2x} = **3.0°C**	ΔT_{2x} = **4.0°C**	ΔT_{2x} = **5.0°C**
K_z = **1.0** cm^2/s	2.1 (2.0)	7.6 (7.5)	16.6 (16.7)	29.4 (29.4)	46.3 (45.7)
K_z = **2.0** cm^2/s	3.3 (2.8)	12.6 (12.6)	29.0 (29.4)	53.4 (53.4)	86.0 (84.4)
K_z = **3.0** cm^2/s	4.3 (3.5)	17.5 (17.5)	41.5 (42.0)	77.3 (77.2)	125.1 (123.0)

As a test, the best-estimate (median) values for ΔT_{2x} and K_z are 2.6°C and 2.3 cm^2/sec (see ref. 14). The MAGICC value for τ is 24.3 years. The above formula gives a value of 24.6 years. Extrapolation outside the above parameter ranges will lead to errors, but the probability of being outside the above ranges is small.

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