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Linking Mid-century Concentration Targets to Long-Term Climate Change Outcomes

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Abstract

We present a framework that could inform the choice of an interim (mid-21st century) target in the making of climate mitigation policy. The idea of interim targets for greenhouse gas concentration has been proposed previously as a way to bridge short- and long-term climate targets, address concerns about the rate of temperature change, and provide guidance in planning for energy infrastructure while scientific understanding improves and long-term climate goals are negotiated. Our analysis relates a wide range of mid-century equivalent CO_2 (eCO_2) concentrations to rates of temperature increase as well as total long-term temperature increases, accounts for uncertainties in the carbon cycle and the climate response (including climate sensitivity, ocean diffusivity, and aerosol forcing), and provides a rough measure of the economic feasibility of different emissions pathways. Our results show, for example, that for a roughly 50% likelihood of limiting long-term warming to 2°C above the pre-industrial level, and with the constraint that global emissions should not have to be reduced by more than 2.5%/year, the mid-century concentration needs to remain below about 470 ppm eCO_2 (including only the Kyoto gases and defined relative to a year 2000 baseline). For a roughly 83% likelihood of achieving the same temperature goal, the mid-century target needs to be about 440 ppm. These targets require that emissions between 2010 and 2050 average to approximately the current level and the 1990 level, respectively. Our framework illustrates how delay in emissions reductions in the near term forecloses options in the long term. Finally, we demonstrate how near-term reductions of CO_2 from a particular source, deforestation, can significantly facilitate the achievement of long-term temperature goals.

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Introduction

One of the primary objectives in climate policy, as stated in the U.N. Framework Convention on Climate Change (UNFCCC, 1992), is to "prevent dangerous anthropogenic interference with the climate system." A body of scientific literature has accumulated recently identifying impacts of climate change that could be considered dangerous and estimating the amount of warming beyond which the risks of triggering such impacts rises considerably. Table 1 lists some of the main impacts that have been discussed, along with the associated temperature thresholds. Some impacts that could be considered dangerous have been estimated to begin occurring above ~1°C warming relative to the beginning of the industrial era or with a rate of warming exceeding 0.05°C/decade, and additional impacts that could be considered dangerous have been estimated to occur with ~2°C warming or with a rate of warming exceeding 0.3°C/decade.

Meeting the objective of the Framework Convention will be difficult for two reasons. First, widespread agreement on a long-term level or rate of warming that constitutes dangerous interference will be difficult to achieve given the varying perspectives on what impacts would constitute dangerous interference, uncertainty in the level or rate of warming that would lead to such impacts, and uncertainty in the emissions and atmospheric concentrations that would produce a given warming. For example, while the European Union and some other governments have adopted 2°C above pre-industrial as a limit on an acceptable amount of warming, it is by no means universally accepted.

Second, the dynamics of the climate system introduce an important time dimension to the problem. Because many climate-warming greenhouse gases have a long atmospheric lifetime (on the order of centuries), emissions must be reduced quickly and persistently in order to prevent substantial accumulations of the gases in the atmosphere. At the same time, economic realities require that mitigation plans account for the costs and technical feasibility of proposed reductions in global warming emissions, as is also recognized in the UNFCCC: the "stabilization of greenhouse gas concentrations" should proceed "within a time-frame sufficient to…enable economic development to proceed in a sustainable manner." As a result, the world runs the risk of committing itself to a dangerous level or rate of warming or to a need for sharp and economically disruptive cuts in emissions if too little is done in the near-term due to lack of political agreement on what should be done in the long-term.

O'Neill et al. (2005) proposed that one way of addressing this problem would be through the adoption of interim atmospheric concentration targets for climate change policy. Interim (mid-century) targets bridge short- (Kyoto Protocol-like) and long-term (century or longer) targets: they can guide short-term policy and economic decisions and limit the rate of warming over the next several decades, while keeping open a range of longer-term climate options as learning occurs and postponing a decision on a specific long-term goal. Interim targets have the benefit of better informing expectations of future carbon prices that are crucial to multi-decade investment decisions.

Other studies have examined the usefulness of multi-decade targets for global emissions (Corfee-Morlot and Höhne, 2003; Pacala and Socolow, 2004), development of emissions-free technologies (Hoffert et al., 2002), and radiative forcing (Hansen and Sato, 2004). Keppo et al. (2006) have explicitly examined the relationship between mid-century targets for atmospheric and energy system characteristics and longer-term climate change outcomes. Interim targets have also been receiving increasing attention in the policy arena and have already been incorporated in a number of recent proposals at the international, national, and state levels. For example, the World Business Council for Sustainable Development proposed in 2006 a policy framework that would establish a quantifiable, 50-year goal for the management of global greenhouse gas emissions (WBCSD, 2006), and the Global Roundtable on Climate Change, a group of prominent academics, business and NGO representatives, and policymakers convened by the Earth Institute at Columbia University, recommended that next steps in international climate change policy include the setting of an "ambitious but achievable" mid-century concentration target (GROCC, 2007). The U.K. has proposed a legally binding emissions target for itself of 60% below 1990 levels by 2050 (DEFRA, 2007), California has set a target of 80% below 1990 levels by 2050 (Office of the Governor, 2007), and the U.S. Climate Action Partnership (USCAP), a coalition of major corporations and NGOs, has advocated a domestic reduction of 60-80% below the current level by 2050 (USCAP, 2007).

In the present analysis, we present a framework that could inform the choice of an interim target, expanding upon the ideas in O'Neill et al. (2005). As in the previous study, we choose the year 2050 for the targets. In general, factors that should be considered in choosing an interim target include 1) temperature constraints (i.e., rates of climate change that should be avoided, and dangerous levels of long-term warming that should remain avoidable by mid-century), 2) economic and technological constraints (i.e., estimates of the emissions reduction pathways that would be too costly to achieve or technologically infeasible), and 3) uncertainties in the climate and economic systems (which are required to derive the constraints in 1) and 2)).

In this work, we focus on atmospheric pathways and the climate system and do not explicitly consider the economic and technological aspects of the problem. However, we implicitly consider economic costs and feasibility by framing the analysis in terms of the rate of emissions reduction associated with different pathways, which we consider a rough proxy for the cost and speed of developing and deploying new technologies and capital. For simplicity, we focus on global emissions rather than providing a detailed analysis of options for allocating emissions allowances among different regions or countries, although such an analysis could be incorporated into the framework.

Our framework includes the following set of features: it considers the rate of temperature increase as well as the total increase, it accounts for uncertainties in the carbon cycle (C cycle) and climate response, it considers a wide range of interim concentrations, post-2050 pathways, and long-term temperature outcomes rather than discrete sets of options, and the pathways are not restricted to stabilization at a particular higher-than-pre-industrial concentration. In the rest of this paper, we present results that relate a range of mid-century concentration targets to rates of temperature change that would be experienced over the next several decades, accounting for uncertainties in the climate system. We also relate a range of interim targets to the long-term temperature outcomes they would make feasible, contingent on reducing global emissions at particular rates after 2050. Finally, we illustrate the potential impact of a particular strategy for mitigating climate change, reducing emissions from tropical deforestation, on the range of achievable long-term climate outcomes.

Methods

Emissions Pathways

We constructed a wide range of emissions pathways in order to be able to assess the implications of a range of interim concentration levels for rates of temperature increase over the first half of the century and long-term levels of warming. Figure 1 shows a few sample pathways, including the ones with the lowest and highest cumulative emissions. Since our main goal is to illustrate basic relationships between interim targets and short- and long-term climate changes, in our main analysis we used a standardized shape for the pathways that is roughly consistent with the shape found in mitigation analyses (in which the deepest reductions are made farther into the future), but also present results illustrating the sensitivity to the assumed shape of the emissions path over the period 2000-2050. In the standardized pathway, we start with global anthropogenic emissions from 1990 to 2000 corresponding to the values assumed in the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). (Emissions for the historical period 1765-1990 are specified by the climate model we used, which is described in the next section.) We then assume a range of linear increases in emissions of the Kyoto gases (CO_2, including net emissions from land-use change, which is dominated by net deforestation, CH_4, N_2O, PFCs, HFCs, and SF_6) between the years 2000 and 2020. The increases range from 0% to 4% of 2000 levels per year, with all the Kyoto gases varying at the same rate in a particular pathway. From 2020 to 2030, emissions are held constant, from 2030 to 2050 they decrease linearly (at either 1% or 3% of 2000 levels per year), and from 2050 onward they decrease exponentially at a rate ranging from 0% to 4% per year (not relative to fixed 2000 levels). Various combinations of these increase/decrease rates were used in different model runs, and results were interpolated to display a continuum of climate outcomes. Note that we do not limit the scope of our analysis to stabilization pathways, in which concentrations stabilize at a particular elevated level indefinitely into the future; we allow for the possibility of concentrations and temperatures first peaking and then declining towards pre-industrial levels (Frame et al., 2006).

For simplicity, we specified the other forcings, including NO_x, VOCs, CO, and SO_2, as following the mean of the IPCC SRES scenarios through 2100, and then remaining steady at 2100 levels afterwards. Our primary motivation was the desire to characterize the interim target in terms of Kyoto gases only, since the radiative effects of these gases are global and the gases can therefore be meaningfully aggregated into a single, equivalent CO_2 concentration (i.e., the concentration of CO_2 that would produce the same forcing as the combination of all the Kyoto gases). However, our approach of using the mean of the SRES scenarios for the non-Kyoto gases neglects the fact that emissions of these pollutants are likely to be correlated to some extent with emissions of the Kyoto gases, and thus their radiative forcing could be overestimated or underestimated in our scenarios. We plan to include a more variable and precise treatment of non-

Kyoto gases in future work. For organic and carbonaceous aerosols generated from biomass burning and fossil fuel combustion, the MAGICC model (described below) sets them proportional to land-use change emissions and SO_2 emissions, respectively.

Model and Model Parameters

We used the MAGICC model of greenhouse gas cycles and climate to calculate the concentrations and global mean temperatures resulting from the emissions pathways (Wigley and Raper, 2002; Wigley et al., 2002; Wigley, 1993). MAGICC is an upwelling-diffusion energy-balance model coupled to a box model of the C cycle and simple mass balance models or parameterizations for the concentrations of other radiative forcing agents, with various adjustable parameters. We used version 4.1 of MAGICC, which was used in the IPCC Third Assessment except for a few recent minor updates. The model is described in detail in the aforementioned references as well as in the documentation accompanying the publicly available software (http://www.cgd.ucar.edu/cas/wigley/magicc/, viewed 2007). In our study, we used default parameter values in the MAGICC model except as noted in the following and summarized in Table 2. In all model runs, we adjusted the radiative forcing due to biomass burning aerosols in 1990 from -0.2 W m^{-2} to +0.06 W m^{-2} to reflect findings published since the IPCC Third Assessment Report (Forster et al., 2007 and references therein).

We considered uncertainties in the C cycle and in the climate response to forcings in our analysis. The C cycle uncertainty included the strength of the temperature feedback on the C cycle. The climate uncertainties included 1) climate sensitivity, 2) ocean diffusivity, and 3) sulfate aerosol forcing.

The temperature feedback on the C cycle acts as a positive feedback. To account for the uncertainty in this feedback, we simply turn it either on or off, using the default feedback strength in MAGICC for the “on” case. Although the present-day strength of terrestrial C uptake (and the related CO_2 fertilization effect) is also an important source of uncertainty in MAGICC’s treatment of the C cycle (Wigley, 2000), the model does not currently allow the user to freely specify the strength of its CO_2 fertilization effect. Thus, we neglected this uncertainty, using the default strength for the CO_2 fertilization effect in all model runs. Our results therefore understate the range of possible outcomes for CO_2 concentration and temperature.

Regarding the climate response parameters, it is well known that uncertainties in the climate sensitivity, rate of ocean heat uptake, and sulfate aerosol forcing are not independent (e.g. Meinshausen, 2006). To account for the correlations among them, we chose to focus on an uncertainty range for the climate sensitivity from the literature and adjust the other two parameters to be consistent with assumed climate sensitivity values based on an optimal fit to the observational record carried out by Meinshausen (2006). For climate sensitivity, we considered the “likely” range of values, 2.0-4.5°C, with a “most likely value” of about 3.0°C, reported in the IPCC Fourth Assessment Report (IPCC, 2007). Although the IPCC defines the “most likely value” as the mode of the distribution, we assume for the purposes of our analysis that it is equivalent to the median (50th percentile), which is a reasonable approximation for distributions that are not highly skewed (see for example Box 10.2, Figure 1 in IPCC, 2007). Based on the IPCC uncertainty guidance (IPCC, 2007), a probability of at least 66% can be assigned to the true climate sensitivity’s falling within the likely range; i.e. the values 2.0°C and 4.5°C correspond approximately to the 17^{th} and 83^{rd} percentiles, respectively. Other studies have given considerably different probability distribution functions (pdfs) for climate sensitivity, some of which have long tails extending into much higher values for climate sensitivity, but the IPCC estimate is a widely cited one and is based on consideration of a range of estimates. Note that our uncertainty analysis therefore can be considered conservative as it does not emphasize more extreme values for the climate sensitivity that are still plausible. However, our framework could easily be applied to an alternative climate sensitivity pdf. For specific values of ocean diffusivity and 1990 sulfate aerosol forcing, we used the "maximum likelihood estimates" from Meinshausen (2006) corresponding to different values of climate sensitivity, based on his "method B" that utilizes constraints from observations of both global mean surface temperature and ocean heat content.

We subtracted a small offset from the temperatures from each model run so that the temperature in year 2000 always matched the observed increase of ~0.7°C since the pre-industrial era; this was necessary as we express temperature results in degrees above pre-industrial. The offset ranged between 0.1 and 0.2°C, depending on the values used for the climate parameters.

Results

Rate of Temperature Change

We present the relationship between the equivalent CO_2 concentration (eCO_2) in 2050 and the interim rate of temperature increase in Figure 2. We define the eCO_2 concentration as the concentration of CO_2 that would produce a radiative forcing (relative to the 2000 level) equivalent to that produced by all the Kyoto gases. In the literature, the concentration of eCO_2 has also been defined relative to pre-industrial times; for comparison, a base year of 1750 results in a value for eCO_2 of ~420 ppm in 2000 instead of 369 ppm, considering only the Kyoto gases. We indicate in the plot the average annual global emissions between 2010 and 2050 corresponding to different interim concentrations as a guideline only, with the caveat that there is in reality not a one-to-one correspondence between the two quantities, due to uncertainties in the C cycle (and in natural emissions of other gases); we show the effects of C cycle uncertainties in the next figure. Figure 2 implies that higher interim targets would result in higher interim rates of temperature increase, as expected. The curves flatten slightly at higher concentrations, due to saturation of the radiative absorption by greenhouse gases as concentrations increase. Figure 2 is similar to results presented by O'Neill et al. (2005), except that in addition to considering a range of climate sensitivities, we also account for uncertainty in ocean diffusivity and sulfate aerosol forcing as described in section 2.2. Note that uncertainty in the C cycle parameters does not affect the relationship between eCO_2 concentration and temperature; it only affects the eCO_2 concentration that results from a given emissions path.

The results in Figure 2 indicate that it will be extremely difficult to limit the rate of warming in the near-term to 0.05-0.10°C/decade, a rate that would allow natural adaptation and thus avoid degradation of many ecosystems (see Table 1). Global average temperature has already been increasing by 0.10-0.16°C/decade over the past 50 years (IPCC, 2007), and to bring that rate below 0.1^{o}C/decade would require an interim eCO_2 target of ~430 ppm for the low climate sensitivity case, and an even lower target in the other cases. The current eCO_2 concentration (year 2006) is ~383 ppm and increasing by 2-3 ppm/y (http://www.esrl.noaa.gov/gmd/aggi/, accessed June 2007) so meeting that target would require huge reductions in emissions relative to business as usual (BAU). To meet the 430 ppm target, global emissions between 2010 and 2050 would need to average about 5% below the 1990 level, or ~20% below the current level, and almost 80% below the median of the IPCC SRES scenarios, the set of which represent possible pathways in the absence of mitigation policies.

On the other hand, the threshold of 0.3°C/decade sustained over many decades associated with collapse of the thermohaline circulation (see Table 1) provides a relatively weak constraint. Even for the high climate sensitivity case, our results indicate that an interim target of ~490 ppm, or an average emission rate about 30% above the 1990 level (~15% above the current level) and ~25% below the SRES median, would be sufficient. A goal between the two, of 0.2°C/decade, implies that the mid-century concentration would likely need to be between 430 and 510 ppm eCO_2.

Figure 3 shows the effect of uncertainties in the C cycle and climate sensitivity on the relationship between emissions and concentration. The plot indicates that uncertainties in the model parameters considered here have only a minor impact on the interim targets. For example, an interim concentration of 450 ppm eCO_2 corresponds to average emissions between 2010 and 2050 of 5-8% above the 1990 level. However, as noted in the section "Model and Model Parameters," we neglected uncertainty in the CO_2 fertilization effect and therefore understate the range of concentration outcomes. The reason for the asymmetry in the lower and upper uncertainty bounds is that we simply turned off the temperature-C cycle feedback for the low estimate while turning it on for both the median and high estimates, resulting in a greater contrast between the low and median estimates. A difference in only the climate sensitivity between the median and high cases on the other hand produces a smaller difference in concentrations.

Although the uncertainties in the C cycle and climate sensitivity considered here have a minor influence on interim concentrations, they (especially climate sensitivity) have a critical influence on the rate of temperature increase and the total long-term temperature increase, as was seen above and will be seen in the next section.

Interim Targets and Long-Term Options

The next two figures show long-term global average temperature increases as a function of both the interim concentration achieved and the rate of emissions reduction after 2050. In Figure 4, we show results using the best-guess parameter values, while in Figure 5 we include the effects of uncertainties in the climate and C cycle parameters. We express long-term temperature change in terms of the maximum 50-year average temperature during the period 2050-2300, since dangerous, irreversible impacts of climate change, such as those listed in Table 1, are more likely to be triggered by a sustained warming than by a brief exceedance of a threshold. Results are not very sensitive to the averaging period, as was demonstrated in tests using 10-year and 100-year averaging periods (not shown here).

As an example of how the information in Figure 4 can be interpreted, suppose that we wanted to avoid having to reduce global emissions by more than 2.5%/y after 2050, based on a judgment that such a rate would be economically infeasible (Den Elzen and Meinshausen, 2006). Then in order to keep open the option of meeting a long-term temperature goal of 2°C above pre-industrial, the plot shows that an interim target of at most 470 ppm would have to be met. If the concentration target were higher, it would require steeper, and possibly infeasible, emissions reductions after 2050 in order to meet the long-term goal. The interim target of 470 ppm would require that annual global emissions of Kyoto gases between 2010 and 2050 average to around 15% above the 1990 level, or roughly the present level, a challenging but feasible endeavor (e.g. Pacala and Socolow, 2004; see the "Conclusions" section of the current paper). Note that if, after meeting the 470 ppm interim target, it were decided that a higher long-term goal for warming of 3°C was sufficiently safe, emissions reductions after 2050 would only have to proceed at a rate of about half a percent per year.

Of course, one could begin with the higher long-term goal of 3°C and, assuming the constraint on emissions reductions is again 2.5%/y, the figure in this case indicates that an interim target of 590 ppm would be sufficient. This would allow emissions to essentially follow the SRES median trajectory (or even exceed it) until mid-century. However, if by mid-century it became apparent that a lower long-term goal of 2°C was required to avoid dangerous impacts, the option of reaching that goal would already be foreclosed.

This comparison illustrates the problem with focusing on only a single long-term goal in setting medium-term reduction targets, rather than considering the range of goals that might turn out to be desirable as we learn more about the climate and economic systems over time. It illustrates more generally that delaying emissions reductions in the short-term can foreclose options for the long term. This is also reflected in the increasing steepness of the contour lines in Figure 4 as the interim concentration increases. The cause of the increasing steepness is the fact that the higher the interim concentration, the greater the warming prior to 2050 and the greater the committed warming for beyond 2050. As a result, high rates of emissions reductions become necessary after 2050 to avert an increasingly imminent temperature threshold. When the interim concentration becomes sufficiently high, the emissions up until 2050 already commit the world to a prolonged exceedance of the warming threshold; in other words, even an emissions reduction of 100% in a year would not be sufficient to avert the exceedance, since the long atmospheric lifetimes of greenhouse gases limit the rate at which concentrations, and consequently temperature, can be decreased. An analogy is that one approaches a "cliff" as the interim concentration increases--at a certain concentration, one cannot move any further to the right along the x-axis if one wants to have a possibility of achieving a particular long-term temperature goal.

Figure 5 shows the additional challenges posed by uncertainties in the climate response (carbon cycle uncertainty plays a minor role in our particular results). For example, as discussed above, assuming a best estimate of climate sensitivity and a post-2050 emissions reduction constraint of 2.5%/y, keeping open the option of limiting warming to 2°C implies an interim target of 470 ppm eCO_2. However, when we consider uncertainty in the climate system, then the likely range for the interim target to achieve the same goal is between 440 and 540 ppm. In other words, a target of 440 ppm implies a greater than 83% chance of avoiding 2°C of warming, whereas a target of 540 ppm implies only a 17% likelihood. Thus, if one wants to minimize the risk of exceeding a particular temperature threshold, one must accept more drastic cuts in emissions.

Sensitivity to Shape of Emissions Pathway

We tested an alternative shape for the pre-2050 emissions pathways, shown in Figure 1. Instead of peaking in 2020 and declining after 2030, the alternative pathways increase linearly through 2050 (or for the lowest emissions pathway, decreases linearly through 2050). The long-term temperatures resulting from these pathways are shown in Figure 6 overlaid on those for the standard pathways. The results are similar to those for the standard pathways, except that the contour lines are shifted slightly towards the top of the graph (i.e. towards higher post-2050 emissions reduction rates for the same interim concentrations). The reason for this difference is that for a particular interim concentration and average emissions pre-2050, the emissions are higher in 2050 for the pathways that peak in 2050 than for the ones that peak in 2020. Thus, a higher rate of emissions reductions is needed after 2050 for the alternative pathways to achieve the same long-term temperature increase. Overall, the results for the standard pathways are useful for illustrating the level of emissions limitations that are needed to achieve different temperature goals, but in a precise policy application, the effect of the shape of the pathway should be considered.

Effect of Reducing Emissions from Deforestation

As an example of how long-term options can be affected by alternative scenarios for particular forcing agents, we present a comparison of two different scenarios for CO_2 emissions from deforestation. Deforestation, which currently occurs predominantly in the tropics, is a major source of CO_2, contributing about 10-25% of global greenhouse gas emissions (Santilli et al., 2005). Providing incentives to reduce deforestation could thus serve as a short-term approach to slowing the growth of global emissions and act as a bridge to a long-term regime in which all gases are reduced in all countries (Santilli et al., 2005; Silva-Chávez and Petsonk, 2005). The following analysis demonstrates the potential that reducing deforestation has for slowing the growth of global emissions and contributing towards the achievement of long-term goals.

In the following illustrative scenarios, we assume baseline deforestation emissions of 3 gigatonnes (Gt) C/y, at the upper end of estimates in the literature for current emissions rates (0.6-3.0 Gt C/y) (Santilli et al., 2005 and references therein; Lewis et al., 2006). This level of emissions is higher than the present-day level assumed in the other analyses in this work, 1.1 Gt C/y in year 2000, which is based on the value from the SRES scenarios. We choose a high estimate in order to accentuate the difference between the two deforestation scenarios. In the baseline scenario, emissions from deforestation are held constant at 3 Gt C/y through 2050. In the reduced deforestation scenario, emissions from deforestation start at the baseline level and are then reduced aggressively by 20%/decade relative to the initial level between 2010 and 2050. Note that the potential impact of policy on rates of deforestation is probably smaller than implied by the difference between these two scenarios, since various projections suggest that rates of deforestation may decline prior to 2050 even in the absence of policy (e.g. Nakicenovic and Swart, 2000; Houghton, 2005). The other gases are specified as described in the Methods section.

Figure 7 shows the long-term outcomes available for the two deforestation scenarios for a range of interim emissions of gases other than CO_2 from deforestation and for a range of emissions reduction rates post-2050 of all gases, including CO_2 from deforestation. We do not display interim concentrations along the x-axis, since, in essence, reducing deforestation emissions prior to 2050 reduces the total eCO_2 concentration in 2050 but does not alter the relationship among eCO_2 concentration in 2050, post-2050 emissions reductions, and long-term temperature. In other words, the two deforestation cases would look identical if they were plotted on an interim concentration scale. We confirmed that the relationship is indeed little changed (in a test not shown here); a slight difference in the relationship for the two deforestation scenarios results from the differing shapes of the pathways for total CO_2e emissions prior to 2050. We show only the best-guess results in Figure 7. Notice the significant difference in long-term options for the two deforestation cases. By reducing mid-century concentrations, pre-2050 reductions in deforestation ease the required emissions reductions post-2050 for a given temperature goal. The effect is especially pronounced for the 2°C goal, by up to ~2%/y, because the amount of eCO_2 already in the atmosphere in 2050 is so close to tipping the temperature over that threshold (this is related to the "cliff" effect discussed above).

Alternatively, for a particular rate of emissions reduction post-2050 and temperature goal, the allowable non-deforestation emissions budget between 2010 and 2050 is larger, especially for the higher temperature goals, by up to ~25% of 1990 emissions each year (~9 Gt CO_2e each year), if emissions from deforestation are reduced aggressively relative to the baseline case. This latter possibility might be particularly attractive to some countries, since fossil fuel-related emissions might not need to be decreased as rapidly in the near-term on a global basis if deforestation could be reduced significantly. However, delaying reductions in fossil fuel emissions could pose an economic challenge, since fossil-intensive technology may get locked in and be very expensive to eliminate in the long run. We do not analyze this economic issue further in this paper.

Conclusions

We have presented a framework that can be used by policymakers in choosing a climate target. Our framework focuses on the interim period, and presents decision makers with the ranges of mid-term and long-term climate outcomes available for different interim targets along with a rough measure of the difficulty of achieving particular outcomes. The particular analyses we presented in this paper could be modified in specific applications, e.g. with different pathway shapes before 2050, different mixes of Kyoto gases for achieving a given eCO_2 concentration target, different assumptions for emissions of non-Kyoto gases, different C cycle and climate parameter values, etc.

Our results indicate, for example, that a target of 2°C maximum long-term warming would be rather challenging to achieve. Assuming a maximum feasible emissions reduction of 2.5%/y, the concentration of eCO_2 in 2050 would have to be about 470 ppm or lower, for the best-guess C cycle and climate parameter values. This corresponds to global emissions between 2010 and 2050 that average around 15% above the 1990 level or roughly the current level. However, if climate sensitivity turns out to be high, a goal of 2° would require that the mid-century concentration be 440 ppm or lower and that emissions average to approximately the 1990 level over the next 40 years. Although it may seem an unachievable goal to hold emissions at the 1990 level on average in that time frame, an analysis by Pacala and Socolow (2004) suggests that existing technologies and approaches are more than sufficient to hold emissions flat over the next 50 years. They identify 15 possible options that could each provide at least one reduction "wedge," or an emissions reduction of 1 Gt C/y below BAU by 2054, and suggest that the world would need to implement around 7 wedges to stabilize CO_2 emissions at the current level. Since Pacala and Socolow use 2004 as their base year, holding emissions at the lower 1990 level would require a couple additional wedges, a requirement that is still achievable.

Our results also illustrate how delay in emissions reductions in the near term forecloses options in the long term—at a certain interim concentration, a "cliff" approaches, beyond which no amount of emissions reduction can avert a particular temperature threshold.

Further work could elaborate on the economic and technological implications of different interim targets and could address the issue of trade-offs among gases, as was explored by Keppo et al. (2006). Also, since we consider a global picture in this paper, actual policy making would require additional analysis on apportionment of emissions allowances among countries, as has been done by den Elzen and Meinshausen (2006) and Meng et al. (2007).

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Table 1. Estimated temperature thresholds for a selection of dangerous impacts of climate change (synthesis of published sources).

Threshold	Impact
°C above pre-industrial	
≥ 1	Regional declines in food production.[1]
1 - 2	Severe damage to Arctic, alpine, and other vulnerable ecosystems.[2] Widespread death of coral reefs.[3]
1.5 – 3.5	Up to 30% of species at increasing risk of extinction.[4]
1.7 – 2.7	Irreversible disintegration of the Greenland ice sheet, leading to sea level rise of up to 7 m (23 feet) and submergence of heavily populated coastal areas.5
2 – 3.5	Collapse of thermohaline circulation ("the ocean conveyor belt").[6]
2.5	Complete disappearance of Arctic summer sea ice;[7] collapse of traditional hunting societies, possible extinction of polar bears and other ice-dependent species.
2.7 – 3.7	Irreversible disintegration of the West Antarctic ice sheet;[8] additional sea level rise of 4-6 m (13-20 feet).
°C/decade	
0.05-0.1	Degradation of and loss of biodiversity in many ecosystems due to inability to adapt.[9]
0.3	Collapse of thermohaline circulation, if temperature increase sustained.[10]
0.4	All ecosystems rapidly deteriorate, aggressive opportunistic species dominate globe.[11]

[1] Heij, 2005
[2] Heij, 2005; ACIA, 2004
[3] O'Neill and Oppenheimer, 2002
[4] IPCC, 2007 (Working Group II)
[5] Gregory et al., 2004; Heij, 2005
[6] O'Neill and Oppenheimer, 2002 and references therein
[7] ACIA, 2004; Johannessen et al., 2004; Lindsay and Zhang, 2005
[8] Oppenheimer, 1998
[9] Warren, 2006 and refs. therein
[10] Stocker and Schmittner, 1997
[11] Warren, 2006 and refs. therein

Table 2. Model Parameter Values Used.

Parameter	**Lower Bound Climate Outcome**	**Best Guess**	**Upper Bound**	**Comments/References**
Temperature-C cycle feedback	Off	On	On	Using default feedback strength in MAGICC (IPCC, 2001).
Climate sensitivity	2.0°C	3.0°C	4.5°C	Values correspond roughly to the 17th, 50th, and 83rd percentiles in the climate sensitivity pdf, respectively (IPCC, 2007).
Ocean vertical diffusivity	0.5 $cm^2 s^{-1}$	0.8 $cm^2 s^{-1}$	1.4 $cm^2 s^{-1}$	Based on “maximum likelihood estimate” for a given value of climate sensitivity, from Meinshausen (2006), method B.
Indirect sulfate aerosol forcing in year 1990	-0.51 W m^{-2}	-0.77 W m^{-2}	-0.92 W m^{-2}	Based on “maximum likelihood estimate” for a given value of climate sensitivity, from Meinshausen (2006), method B.
Biomass burning aerosol forcing in year 1990	+0.06 W m^{-2}	+0.06 W m^{-2}	+0.06 W m^{-2}	Updated from value of -0.2 W m^{-2} from IPCC TAR (Forster et al., 2007 and references therein).

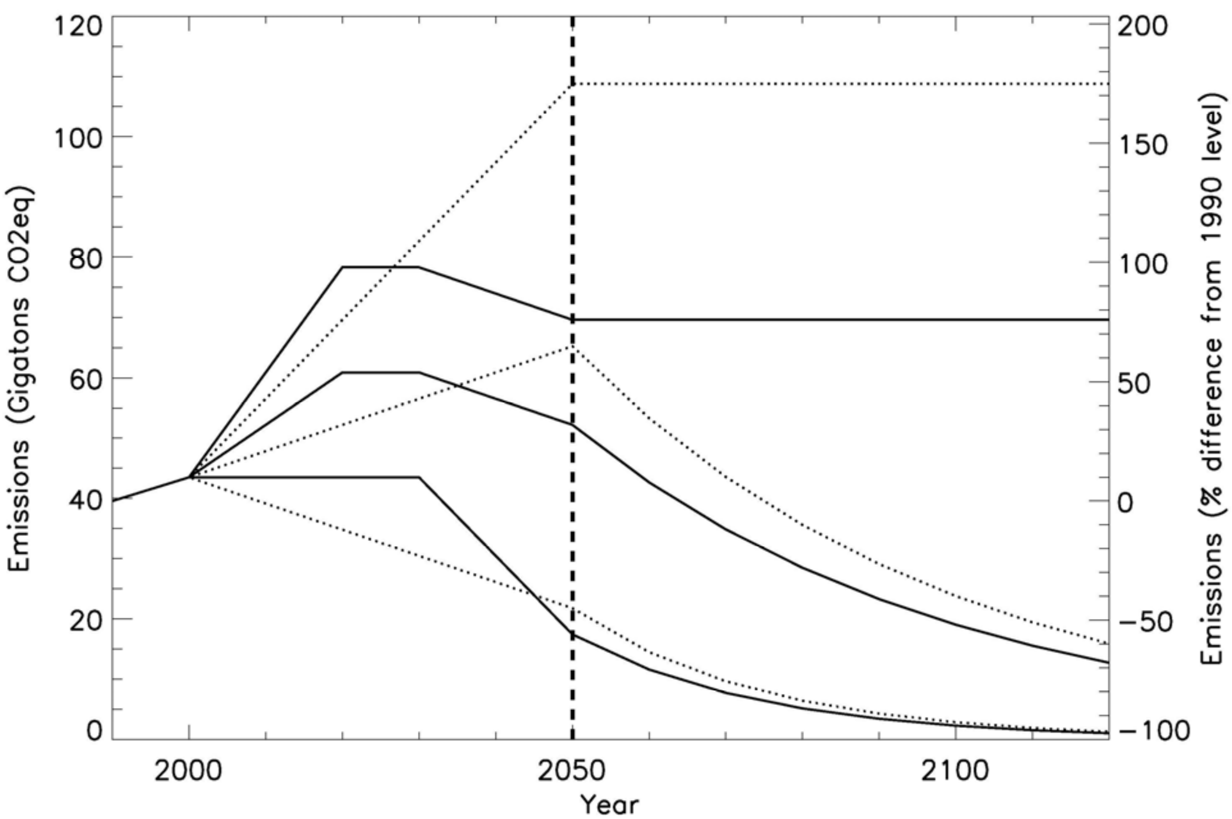

Figure 1. Illustrative global emissions pathways used in the standard analysis (solid curves) and sensitivity analysis (dotted curves). Note that we weight the gases by their global warming potentials (GWPs), with values taken from the IPCC Third Assessment Report (IPCC, 2001), only for the purpose of plotting aggregate emissions in terms of CO_2 equivalents (CO_2eq); the radiative effect of the gases is calculated explicitly in our climate model and independently of the GWP values. The pathways depicted here bracket the lowest and highest cumulative emissions. Specifically, the three standard curves (from lowest to highest) vary in the following manner: between 2000 and 2020, they increase linearly by 0%, 2%, and 4% of the 2000 level per year; from 2020 to 2030, they are constant; from 2030 to 2050 they decrease linearly by 3%, 1%, and 1% of the 2000 level per year; and after 2050, they decrease exponentially by 4%, 2%, and 0% per year. The three sensitivity curves change linearly by -1%, 1%, and 3% of the 2000 level per year from 2000 to 2050, and then decrease exponentially by 4%, 2%, and 0% per year after 2050.

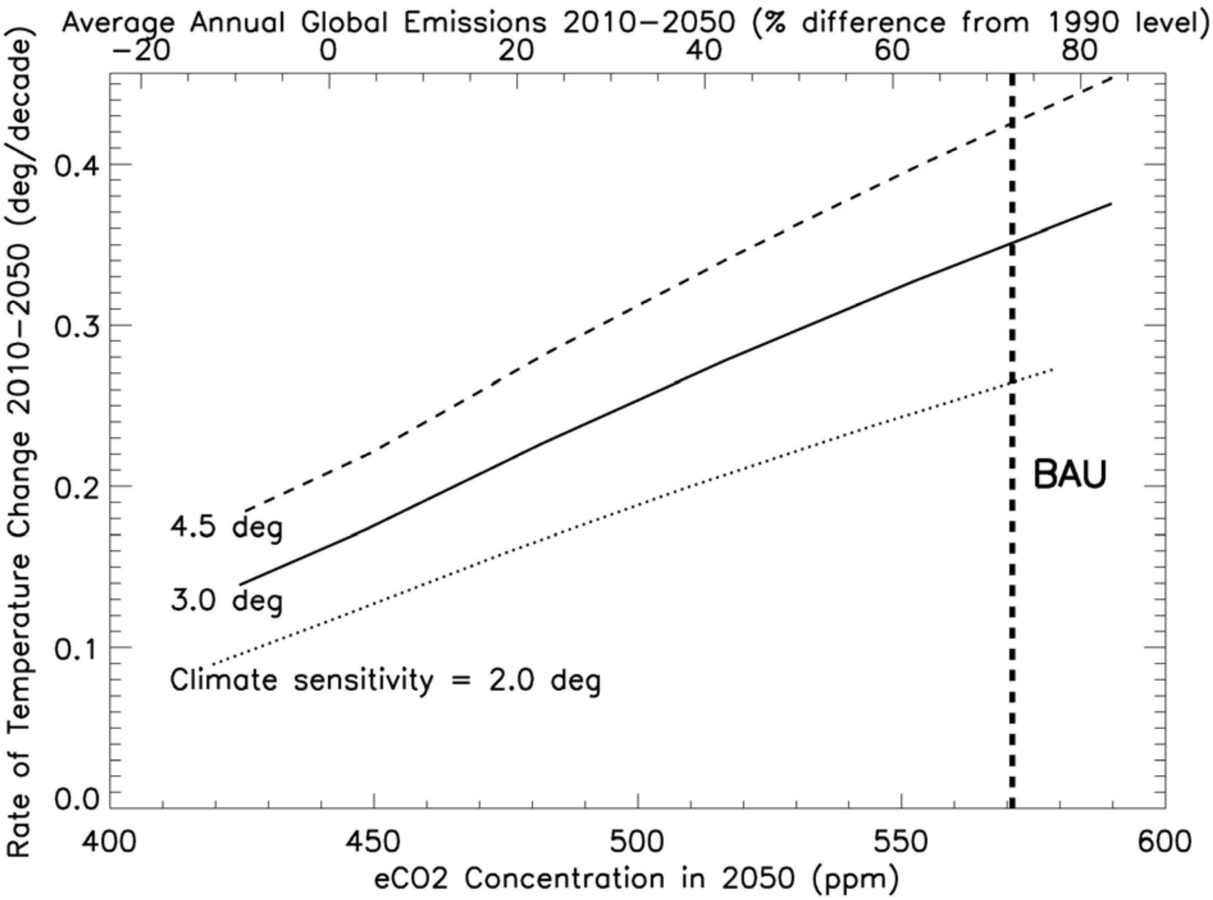

Figure 2. Interim rates of global average temperature change corresponding to a range of interim targets. Approximate emissions amounts corresponding to the interim concentrations are provided for guidance. The dashed line labeled 'BAU' represents the interim concentration/average emissions that would result from the median of the SRES scenarios, the set of which represent possible business-as-usual pathways. We do not extend the curves below 410 ppm because that mid-century concentration results from the lowest emissions pathway we considered (described in Figure 1), which is already implausibly low. The current (year 2006) concentration of eCO_2 is ~383 ppm, and current global emissions are roughly 15% above 1990 levels (Nakicenovic and Swart, 2000).

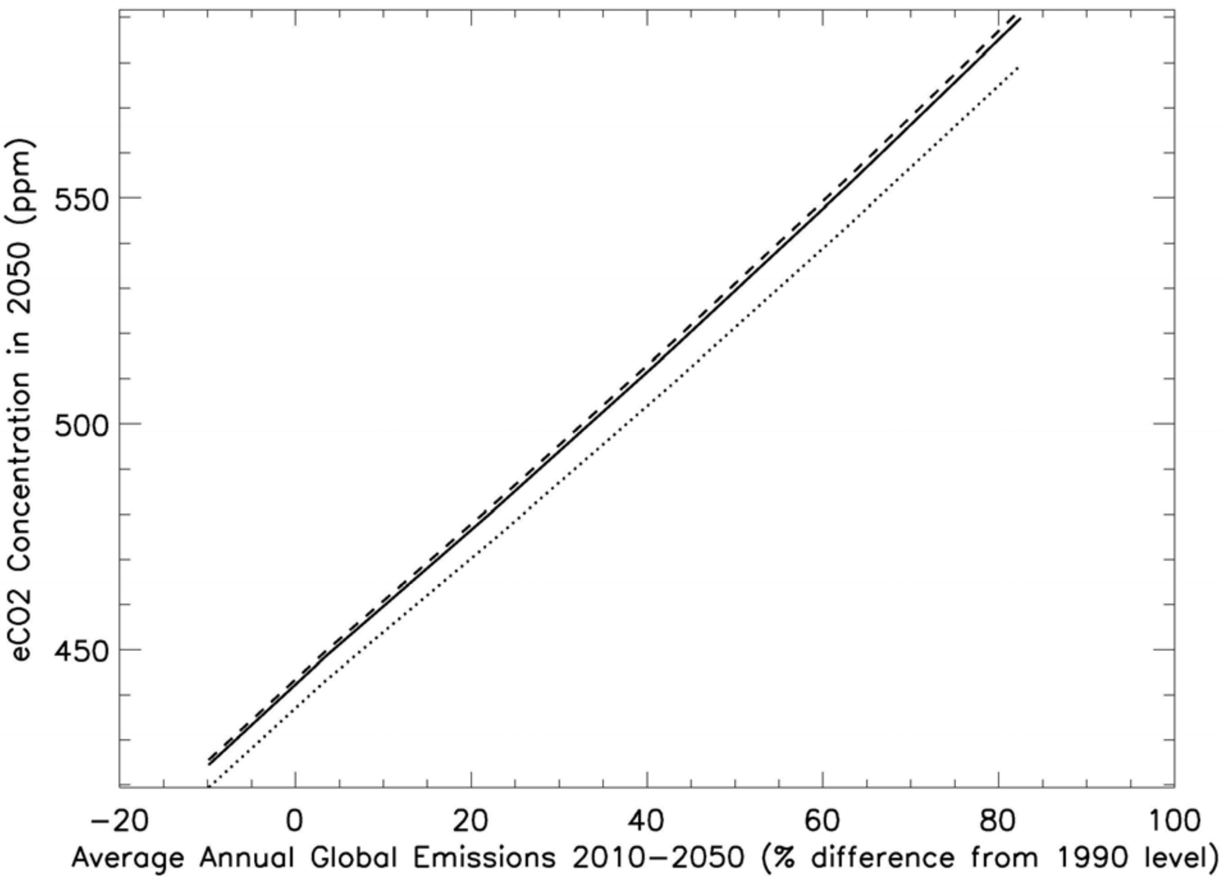

Figure 3. Uncertainty in the relationship between emissions and interim concentration. The solid curve corresponds to the best-guess C cycle and climate parameters, the dotted curve corresponds to the lower bound, and the dashed curve corresponds to the upper bound.

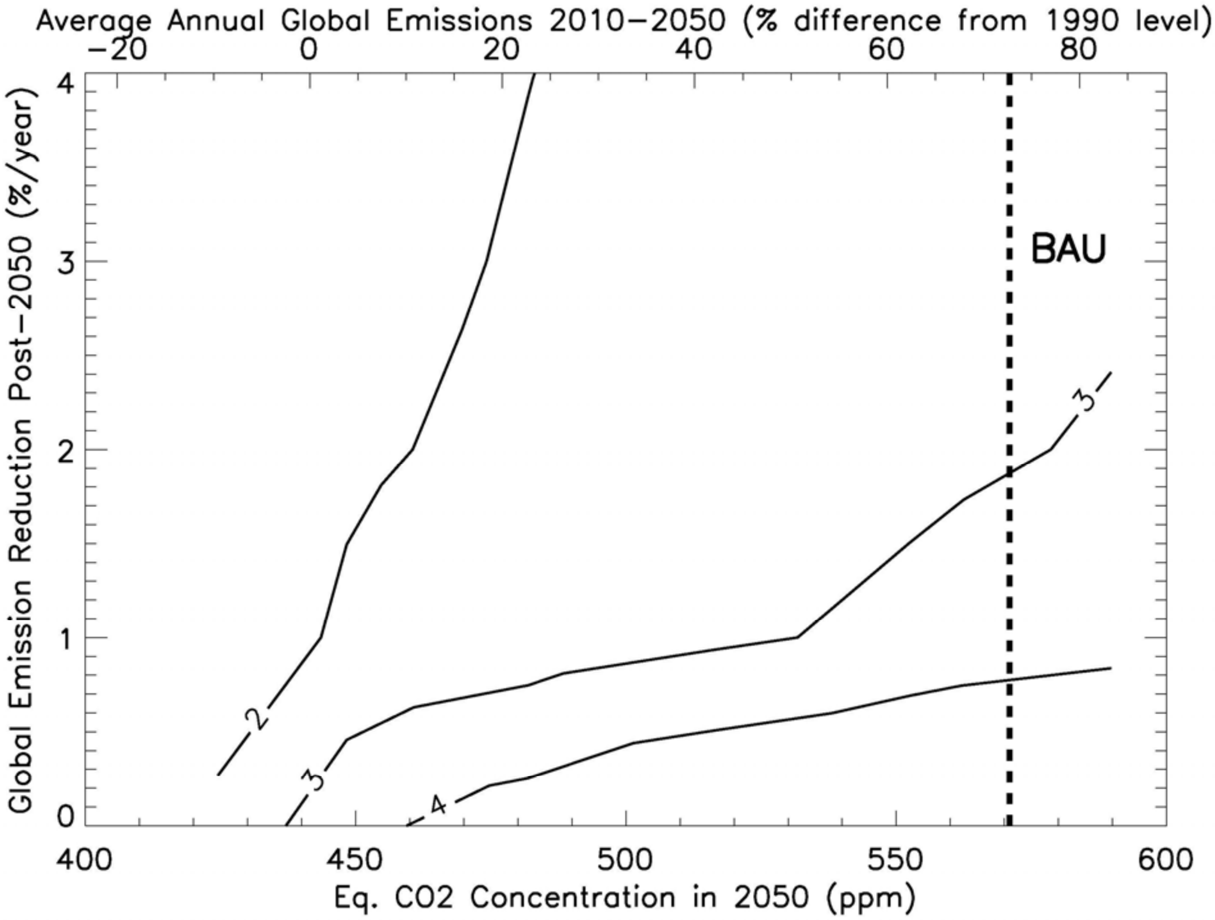

Figure 4. Interim targets and long-term options. Contours refer to maximum 50-year average temperatures during 2050-2300, in degrees C above pre-industrial, corresponding to different combinations of interim targets and rates of emissions reduction post-2050. Results here are based on the best-guess values for the C cycle and climate parameters. Approximate emissions amounts corresponding to the interim concentrations are provided for guidance. The dashed line labeled 'BAU' represents the interim concentration/average emissions that would result from the median of the SRES scenarios, the set of which represent possible business-as-usual pathways. The current (year 2006) concentration of eCO_2 is ~383 ppm, and current global emissions are roughly 15% above 1990 levels (Nakicenovic and Swart, 2000). Note that the slight jaggedness of the contour lines has no significance, being an artifact of interpolation performed on a limited number of data points.

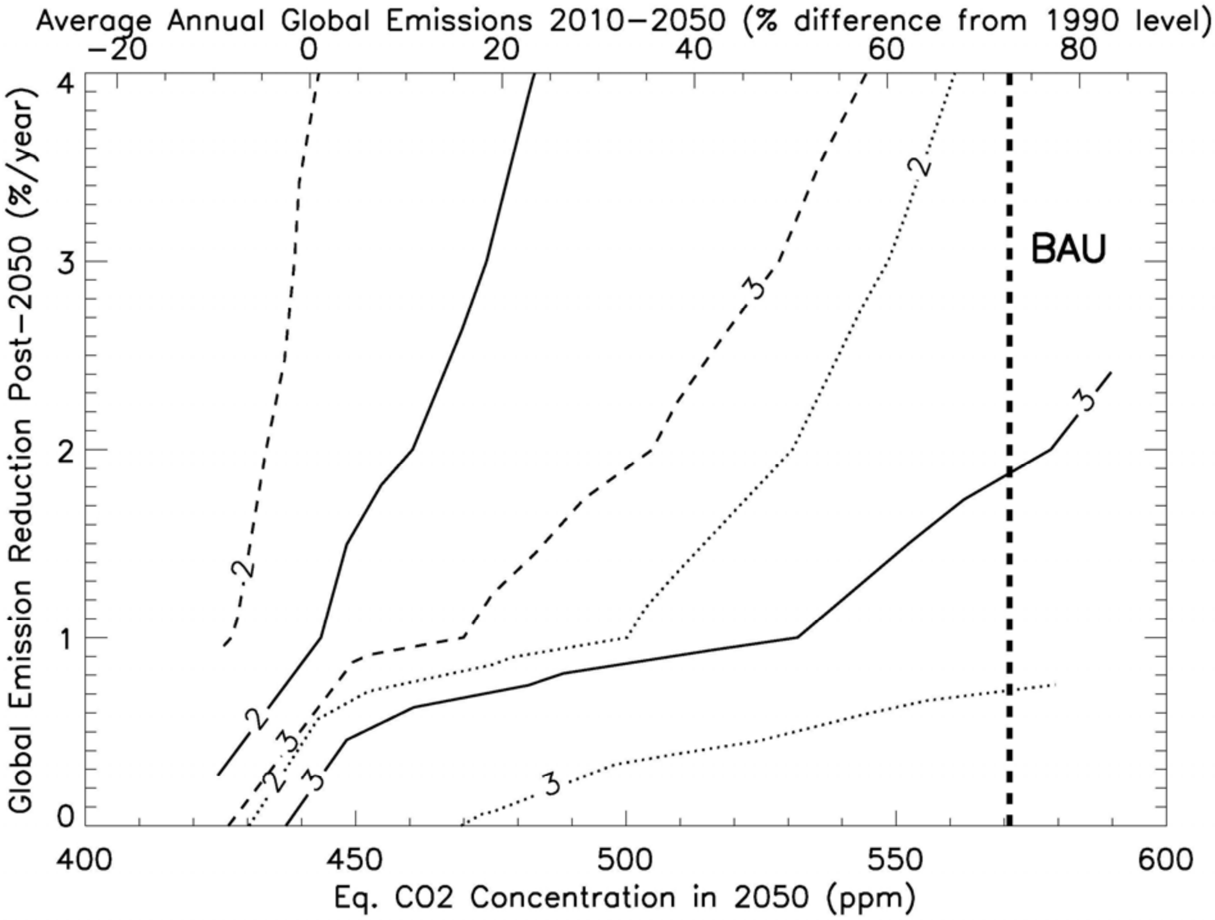

Figure 5. Same as Figure 4, except that effects of uncertainty in C cycle and climate parameters are included. Solid contour lines correspond to the best-guess parameters, dotted lines correspond to the lower bound, and dashed lines correspond to the upper bound.

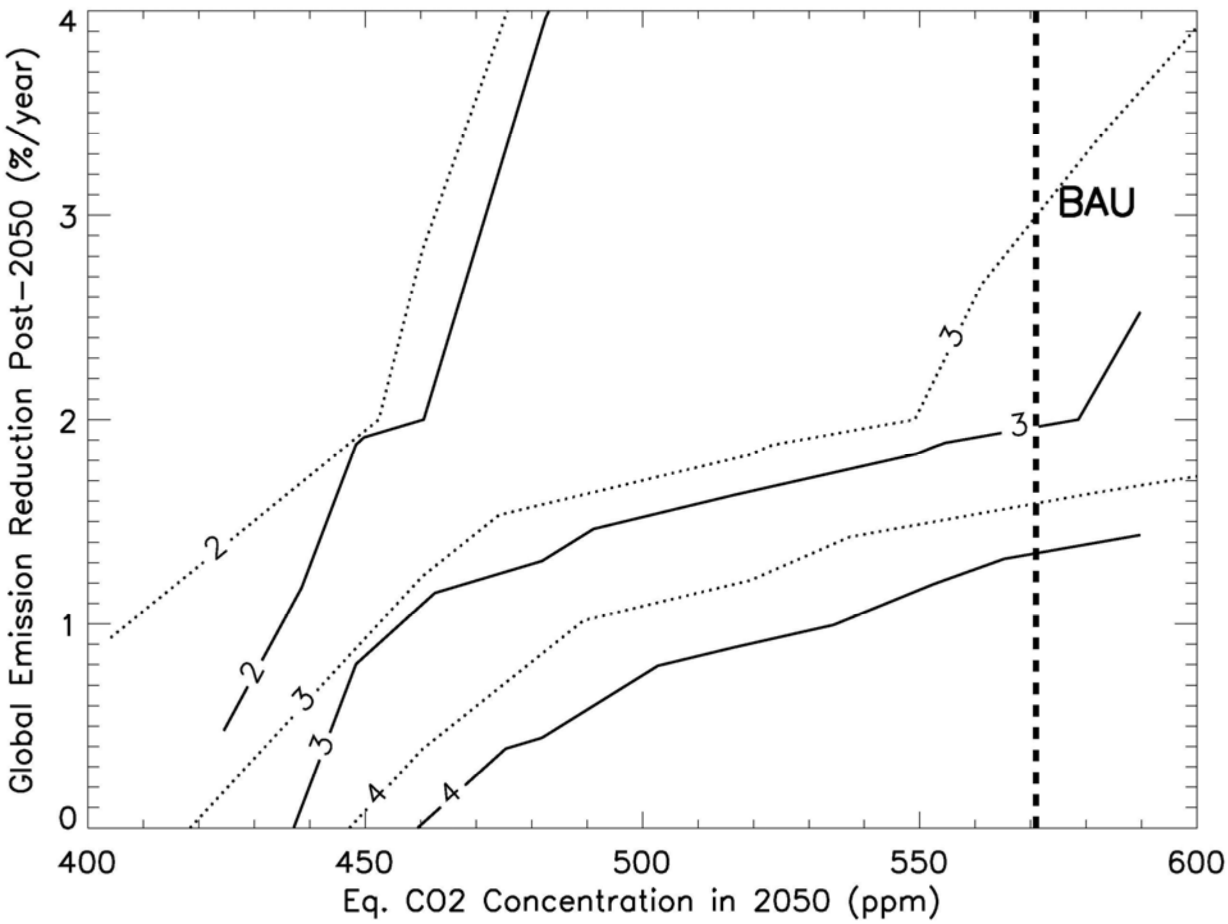

Figure 6. Similar to Figure 4, except that results for the alternative emissions pathways that peak in 2050 instead of 2020 are also included. Solid contours: standard pathways; dotted contours: alternative pathways. Average emissions are not shown along the top axis here since the relationship between pre-2050 emissions and 2050 concentration is slightly different for the two kinds of pathways; the difference arises from the fact that the timing of emissions before 2050 can affect the concentration in 2050, especially for short-lived gases.

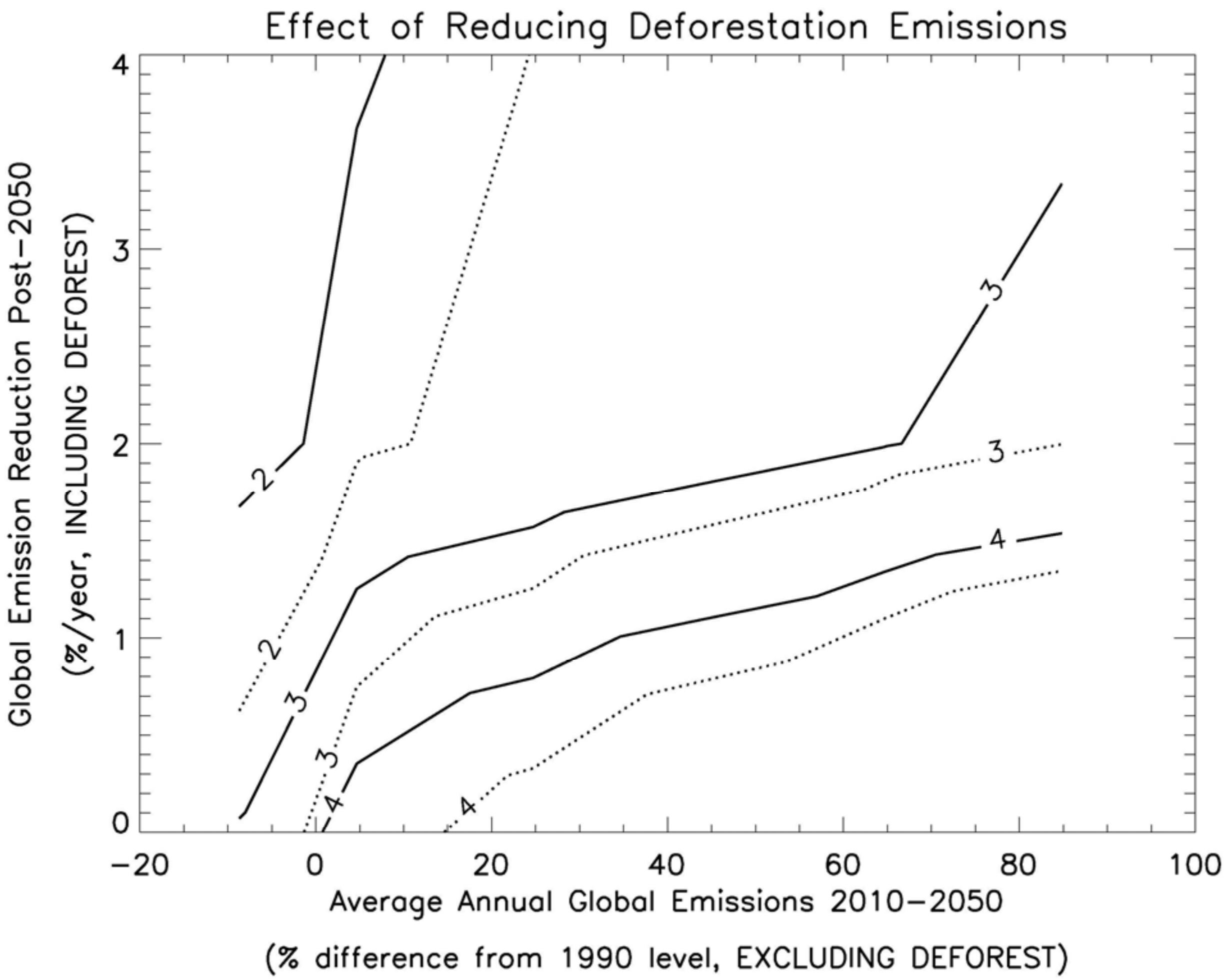

Figure 7. Long-term options for two different near-term scenarios for deforestation. Solid contours indicate long-term maximum temperature increases for the baseline deforestation case, and dotted contours indicate results for the reduced deforestation case.