STABILIZATION OF GREENHOUSE GAS CONCENTRATIONS

T.M.L. Wigley

Introduction

Article 2 of the United Nations Framework Convention on Climate Change (the Framework Convention) agreed to at the Earth Summit meeting in Rio de Janeiro in 1992 states that the ultimate objective of the Convention is "to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Such stabilization should be achieved, to paraphrase Article 2, in ways that would not disrupt the global economy. The goal of this paper is to provide an overview of a range of stabilization issues including: the construction of stabilization pathways for different targets; the emissions requirements to achieve stabilization; and the climate consequences of following a stabilization pathway as opposed to a no-climate-policy pathway. Article 2 embraces all greenhouse gases (GHGs). However, in terms of its influence on future climate, CO_2 is by far the most important GHG. The present paper therefore concentrates on CO_2, but also considers the role of non-CO_2 greenhouse gases and sulfate aerosols.

There are strong theoretical reasons, supported by observational evidence, for supposing that human influences have already altered the global climate and will

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continue to do so in the future. The central estimate of future global-mean warming over the next 100 years (in the absence of climate policies) is 3°C,approximately five times the warming that has occurred over the past 100 years. The 90% probability interval for 1990-2100 warming is 1.7-4.9°C. Since GHG changes are responsible for this warming, reducing its magnitude requires reducing the buildup of GHG concentrations in the atmosphere. Stabilization of these concentrations will eventually stabilize the climate system within the limits of natural variability.

The word 'eventually' is important here because, due to the ocean's strong thermal inertia, the climate system only responds slowly to changes in atmospheric composition. The climate system will take decades to centuries to stabilize after atmospheric composition is stabilized; and sea level will continue to rise for centuries to millennia.

In the following, Section II provides background information about changes in CO_2 and equivalent CO_2 levels that might occur in the absence of climate mitigation policies,based on the recent IPCC Third Assessment Report (TAR) and the Special Report on Emissions Scenarios (SRES). Section III considers emissions and concentration changes that are expected to occur if no policies are introduced to reduce future climate change (the SRES 'no-climate-policy'scenarios). Section IV gives a set of policy scenarios corresponding to different CO_2 concentration stabilization pathways (or 'profiles') with stabilization targets from 350 to 750 ppm,and derives the emissions required to follow these profiles. Section V considers the emissions and climate consequences of these different pathways for the specific case of stabilization at 550 ppm. Since future climate change is determined not by CO_2 alone, but by all greenhouse gases, Section VI will consider how CO_2 and equivalent CO_2 stabilization are related. Finally, Section VII shows how changes in SO_2 emissions (which will occur as a byproduct of policy-driven changes in CO_2 emissions) affect the climate consequences of CO_2 stabilization.

Equivalent CO_2 Concentrations

The Framework Convention does not give any specific stabilization target(s) for GHGs. Instead, it states that avoiding dangerous interference to the climate system should be a factor (along with mitigation costs) in defining target(s). In other words, to define a set of targets for concentration stabilization of the various GHGs, we need first determine what level of future climate change will likely lead to dangerous interference. Working Group 2 of the TAR has tried to address this problem, and come up with a threshold for global-mean warming of 2-3°C above which dangerous interference becomes more likely. How, then, can we keep future global warming below this threshold? To answer this, it is necessary to introduce some simple concepts from climate science.

When we change the composition of the atmosphere, we change the balance between incoming (short-wave) radiation from the Sun and the outgoing (long-wave) radiation from the Earth's surface and atmosphere. The imbalance is called radiative forcing. For positive radiative forcing (i.e., an excess of incoming over outgoing radiation) the climate system acts to restore the balance by increasing the amount of outgoing radiation, which it does by warming the surface and atmosphere. For a given change in atmospheric composition the amount of warming is determined by two factors, the amount of radiative forcing, and how sensitive the system is to a change in forcing (the latter is called the 'climate sensitivity'). It is common practice to use the forcing for a doubling of CO_2 as a baseline and define the climate sensitivity as the equilibrium warming for a CO_2 doubling.

Another useful concept is that of 'equivalent CO_2 concentration'. In climate science, radiative forcing is a primary unifying variable, since all perturbations to the climate system can be expressed in terms of radiative forcing, and because the forcings from different sources can be combined additively. Thus,if we change the concentrations of a number of different gases,their effect on the climate (at least at the global-mean level) is determined by the sum of their individual forcings. For any given total forcing there will be a corresponding change in CO_2 concentration that gives the same forcing. This is called the 'equivalent CO_2 concentration'.

Stabilization of the climate system means stabilization of the equivalent CO_2 level. This can only be achieved practically if we stabilize the concentrations of all anthropogenic GHGs. If all gases bar CO_2 could be stabilized at their present concentration levels,then CO_2 would be our only concern and the equivalent CO_2 stabilization level (or 'target') would be precisely the same as the stabilization target for CO_2 alone. If,however, non-CO_2 GHGs were stabilized at levels above present, then the target for CO_2 would have to be lower to compensate for the additional radiative forcing arising from these gases.

No-Climate-Policy Background

To provide a context for stabilization requirements, this Section gives future projections of CO_2 emissions and concentrations, and equivalent CO_2 concentrations, under a no-climate-policy assumption (often erroneously referred to as "business as usual", since many technological and other changes are already assumed). This information is based on the SRES scenarios and uses appropriate formulae and atmospheric composition changes from the TAR.

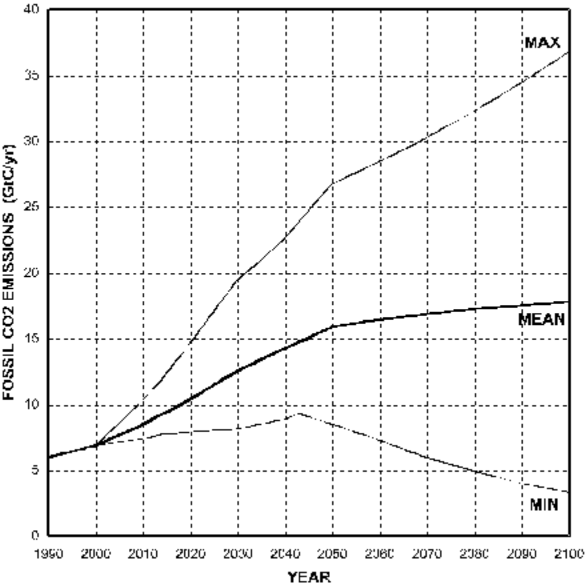
The SRES emissions scenarios are based on four different narrative "storylines" (labeled A1,A2, B1 and B2) that determine the driving forces for emissions (population growth and demographic change, socioeconomic development, technological advances, etc.) Briefly, the A/B distinction corresponds to an emphasis on: (A) market forces; or (B) sustainable development. The 1/2 distinction corresponds to: (1) higher rates of economic growth, and economic and technological convergence between developing and more developed nations; versus (2) lower economic growth rates and a much more heterogeneous world.

The SRES data comprise a set of 35 complete emissions scenarios for GHGs, for "reactive gases" that influence or control the build up of GHGs (CO, NO_x and VOCs), and for SO_2. SO_2 is important because it produces sulfate aerosols,small particles that have an important cooling effect on the climate. Perhaps the most important thing to note about SO_2 emissions in the SRES scenarios is that they incorporate the effects of emissions controls directed towards reducing pollution from acidic precipitation and improving urban air quality. As a consequence, SO_2 emissions in the SRES scenarios generally decline over the 21st century, and are much lower than in earlier scenarios (which did not account for these factors). Further information about the role of SO_2 emissions is given in Section VII below.

Figures 1 and 2 give the range and mean (across scenarios) of fossil CO_2 emissions and CO_2 emissions from land-use changes (primarily deforestation). The additional deforestation curve shown in Figure 2, essentially a smoothed and simplified version of the mean, is a standard projection that is used in all the stabilization calculations described below.

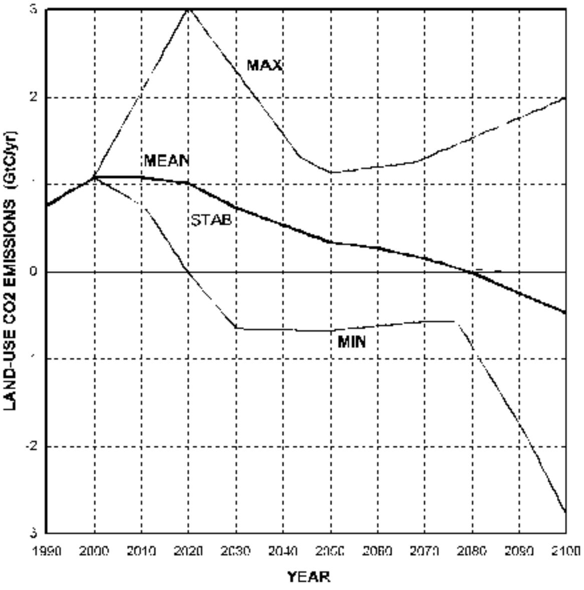
Figure 3 shows the corresponding range and mean for future CO_2 concentration changes, both with and without the inclusion of climate feedbacks on the car-

Figure 1:SRES Range of Fossil CO_2 Emissions



Range and mean of fossil CO_2 emissions (fossil fuel combustion plus cement production) for the IPCC SRES emissions scenarios.

Figure 2:SRES Net Deforestation Emissions



Range and mean of net land-use change CO_2 emissions for the IPCC SRES emissions scenarios (primarily deforestation). The thin curve (STAB) is a simplified version of the mean used in inverse stabilization calculations.

bon cycle. It shows that, for many of the SRES emissions scenarios, CO_2 concentrations are still increasing rapidly at the end of this century. At the low end,however, a number of scenarios show CO_2 concentrations stabilizing or nearly stabilizing by the end of the century even in the absence of specific climate policies (viz., seven of the eight scenarios in the B1 group, and one from the A1 group). This is a result of the socioeconomic assumptions made for these scenarios: the B1 group assumes a strong emphasis on sustainability in the future together with strong economic growth (allowing resources to be directed towards environmental issues) and rapid technological development (including non-fossil energy technologies) and their wide dissemination.

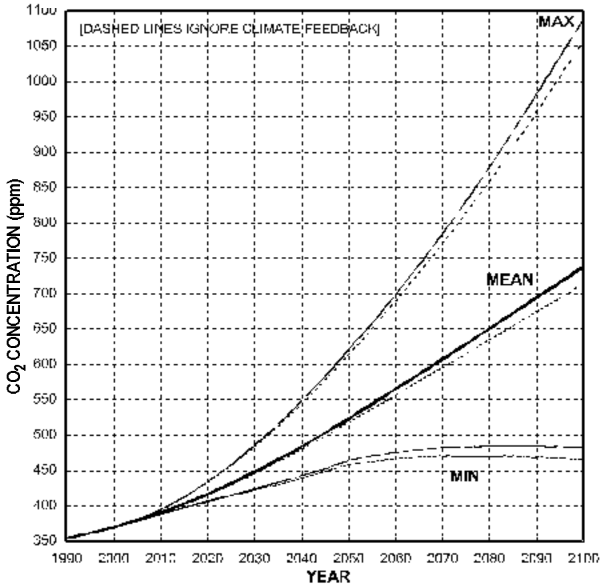
Figure 4 shows the full SRES radiative forcing projections expressed in equivalent CO_2 terms. Because of the influences of non-CO_2 GHGs and the general decline in SO_2 emissions (which leads to positive aerosol radiative forcing), equivalent CO_2 concentrations are much higher than those for CO_2 alone. At the low end,however, stabilization is still achieved in the absence of climate policies.

Emissions Requirements for CO_2 Stabilization

We now consider what emissions are required to achieve stabilization of CO_2 concentration at a range of different 'target' levels. There are two methods that may be used to determine these emissions. In the first, the 'forward method', an energy-economic Integrated Assessment (IA) model is used. The starting point is a specified concentration stabilization target and a no-climate-policy 'baseline' emissions scenario (e.g., one of the SRES scenarios). Geographically- and sector-specific policies to reduce CO_2 emissions (or enhance sinks) are then progressively introduced into the baseline scenario until, by trial and error, the original no-policy concentration projection is transformed to one in which CO_2 concentration stabilizes at the specified target. An example using this method will be given in Section VII.

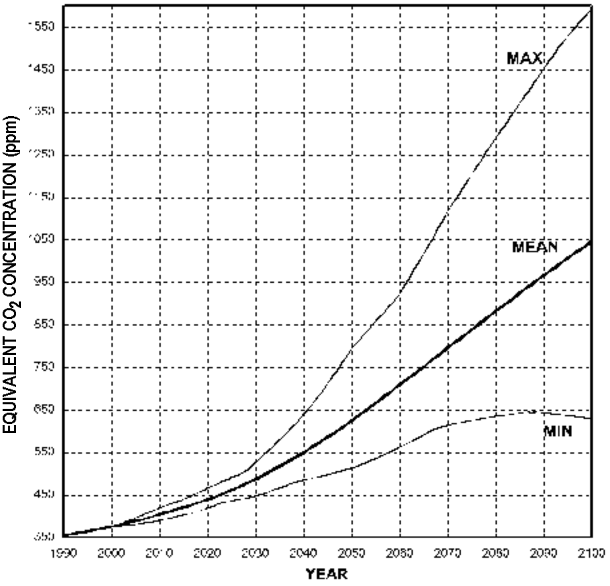
The second method,illustrated in Section IV, is the 'inverse method'. Here,the starting point is also a specified concentration stabilization target, but the pathway by which it is reached is also specified. The emissions are then determined directly by running a carbon cycle model in inverse mode (i.e., using the concentrations as input and obtaining the emissions as output, in contrast to the forward mode where emissions are the input and concentrations are the output). The inverse method requires specification of the full concentration pathway to stabilization,

Figure 3:IPCC SRES CO_2 Concentrations



Range and mean of projected CO_2 concentrations for the IPCC SRES emissions scenarios. The dashed lines ignore climate feedbacks on the carbon cycle.

Figure 4:IPCC SRES Equivalent CO_2 Concentrations



Range and mean of SRES radiative forcing expressed as equivalent CO_2 concentration (i.e., as the concentration for CO_2 alone that would give the same radiative forcing from 1990 as the total for all gases in the emissions scenario).

which, in turn, requires specification of a no-policy baseline scenario, a date at which emissions begin to depart significantly from the baseline, a target concentration level and achievement date, and an 'anchor point' between the departure and stabilization dates that fixes the overall concentration pathway or profile. For any given target, there are a number of different pathways that concentration changes may follow in order to reach the target, as will be shown below.

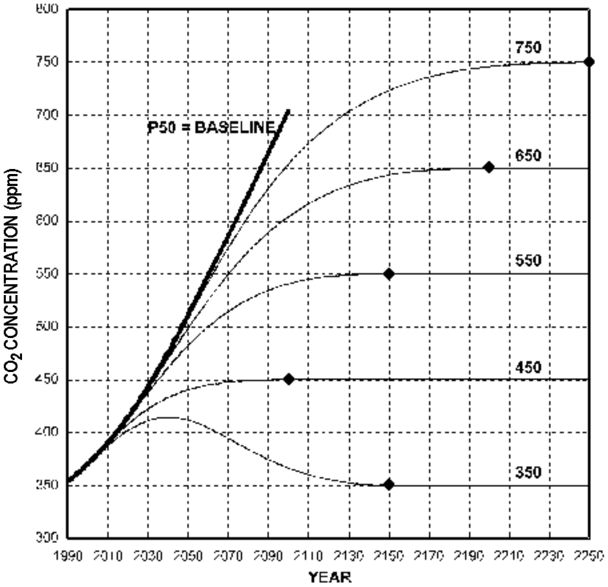
The primary example of such concentration-stabilization profiles is the set of WRE profiles (T.M.L. Wigley, R. Richels, J.A.Edmonds, *Nature 379*, 240-243,1996). An updated set of WRE profiles is shown in Figure 5, using the median of the SRES fossil emissions scenarios (denoted the 'P50' scenario) as the no-climate-policy baseline. Figure 6, which shows the implied total anthropogenic CO_2 emissions, demonstrates that while emissions can increase in the immediate future and still allow eventual concentration stabilization, in the longer term emissions must decrease to levels substantially below those prevailing today. Emissions must continue to decrease with time for centuries because, as the ocean and terrestrial carbon pools accumulate carbon, so the magnitudes of the fluxes into these pools decreases. This continuing decrease in the magnitude of the total sink for atmospheric CO_2 requires a compensating decrease in the source (anthropogenic emissions) to maintain a stable level in the atmosphere.

Sensitivity to Stabilization Pathway

The emissions results in Figure 6 are specific to the chosen concentration pathway from the present to the stabilization point and are quite sensitive to the details of the pathway. In the present analysis, this sensitivity is explored in two ways, by changing the assumed baseline scenario, and by changing the departure date. These will be illustrated here by using the 550 ppm stabilization case.

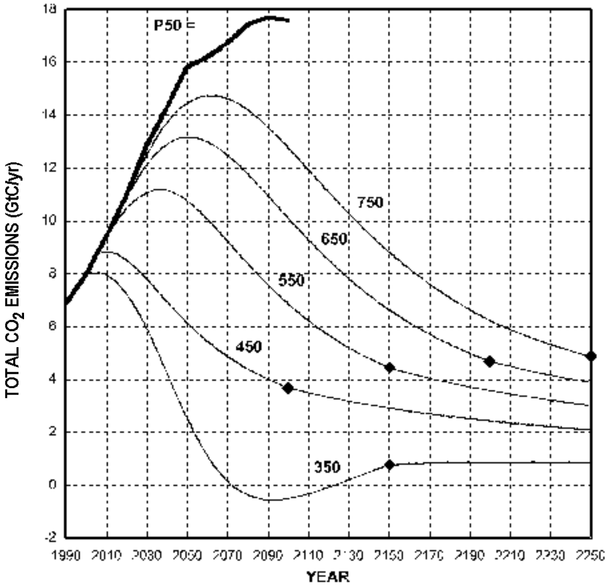
First, I consider baseline emissions projections that are significantly below or above the SRES median (P50) case. At the low end, I assume that the baseline is a perturbation of the P50 case in which policies are introduced to meet the original emissions targets of the Kyoto Protocol through fossil CO_2 reductions alone. At the high end, I use the upper bound of the SRES set (Figure 1). Second, to explore the effect of a later departure from the P50 baseline, I use 2020 (instead of 2010) as the departure date. These modifications lead to four different concentration pathways, all achieving stabilization at 550 ppm in 2150, shown in Figure 7. In mid-century

FIGURE 5: REVISED WRE STABILIZATION PROFILES



Updated WRE concentration stabilization profiles. Concentrations follow the P50 baseline scenario until 2000,2005,2010, 2015 or 2020 for stabilization levels of 350,450,550, 650 or 750 ppm respectively. The diamonds indicate the date at which stabilization is achieved.

FIGURE 6: EMISSIONS FOR REVISED WRE STABILIZATION PROFILES



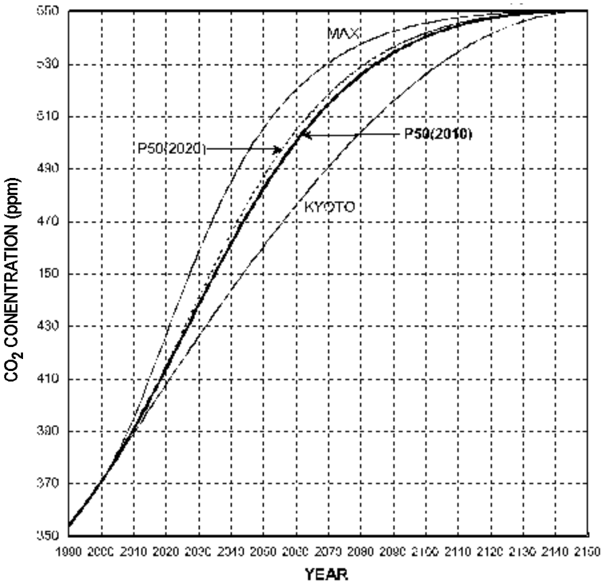
Total CO$_2$ emissions (fossil plus net land-use) required to follow the updated WRE concentration stabilization profiles shown in Figure 5. The diamonds indicate the date at which stabilization is achieved.

(2050) they span a relatively wide range (approximately 45 ppm) of concentration possibilities.

Figure 8 shows the implied total anthropogenic emissions compared with the P50 scenario. Depending on the concentration pathway, there is a wide range of emissions trajectories, with peak emissions varying by more than 40 percent (from 9.3GtC/yr in 2045 to 13.2GtC/yr in 2026 – GtC means gigatonnes of carbon equivalent, with 'giga' meaning 10^9 and tonnes meaning metric tons, 10% larger than U.S. tons). Although I have not attempted to assess these differences in terms of mitigation costs (which must be baseline dependent), it is likely that the lower emissions trajectories will entail higher costs initially, then lower costs around the maximum emissions points (because of the less rapid transition from rising to falling emissions), and similar costs beyond this (because the rates of emissions decline are similar). Of course, the relative costs will also depend on how the future is discounted, and on the technologies available to achieve a reduction in emissions. The technology issue is complex:although the high emissions case presents a bigger and more immediate technological challenge, the lower initial mitigation costs may allow greater investment in fossil-free technologies in order to meet this challenge. Conversely, the more aggressive emissions targets in the lower emissions trajectory cases might spur investment and research into technologies that will make later reductions easier.

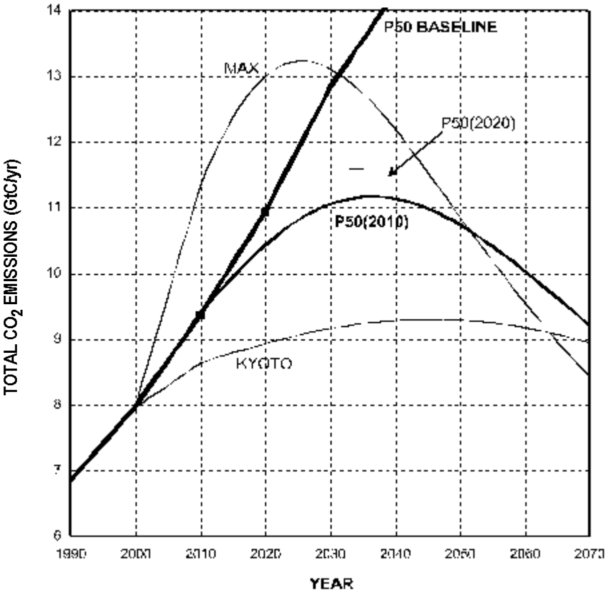
A less controversial point is the difference between the two central (P50 baseline) cases. While these have very similar emissions trajectories, it is almost certain that the 2020 departure case would entail lower mitigation costs than the 2010 departure. Whether or not this is preferred depends on the differences in averted climate change damages. To assess these (in a rather ad hoc way), Figure 9 shows the global-mean temperature projections for the four different concentration profiles using the same climate model as employed in the IPCC TAR. The temperature differences between the two P50 baseline cases are entirely negligible (and far beyond detection given the magnitude of natural climatic variability). Thus, on the benefits side, it is unlikely that these two cases can be distinguished; while there are almost certainly clear differences in terms of mitigation costs. This would argue in favor of following the 2020 departure profile. Whether or not this contention is valid depends, of course, on a more detailed economic assessment, and on whether an appropriate additional investment is made in technology in order to more cost-effectively meet the challenge of the (very slightly) more rapid mid-21st century emissions reductions that are a consequence of the later departure date.

FIGURE 7: DIFFERENT PATHWAYS TO STABILIZATION AT 550 PPM



Alternative concentration pathways achieving stabilization at 550 ppm in 2150. The bold curve (P50(2010)) is as in Figure 5, following P50 until 2010. P50(2020) is similar, but follows P50 until 2020. MAX follows the SRES scenario that has the highest concentrations to 2010. KYOTO follows a scenario where all countries meet their emissions goals under the original Kyoto Protocol, which leads to CO_2 concentrations slightly lower than P50.

FIGURE 8: TOTAL CO_2 EMISSIONS: DIFF. PATHWAYS TO 550 PPM



Total CO_2 emissions (fossil plus net land-use) required to follow the 550 ppm stabilization profiles shown in Figure 7.

Another result that obtains from Figure 9 is the slow rate at which temperatures in the P50 stabilization cases fall below those in the no-policy case, a consequence of the massive thermal inertia of the oceans. Even in 2050, three or four decades after the date in which CO_2 levels in the stabilization case begin to diverge from the no-policy baseline, the signal of the response to the mitigation policy is still less than $0.2^{\circ}C$, a difference that would not be detectable above the 'noise' of natural climatic variability. By this time, in order to follow the stabilization pathway, very large investments would have to have been made – and yet the 'return' on these investments would not be visible. Continued investment is going to require more faith in climate science than currently appears to be the case.

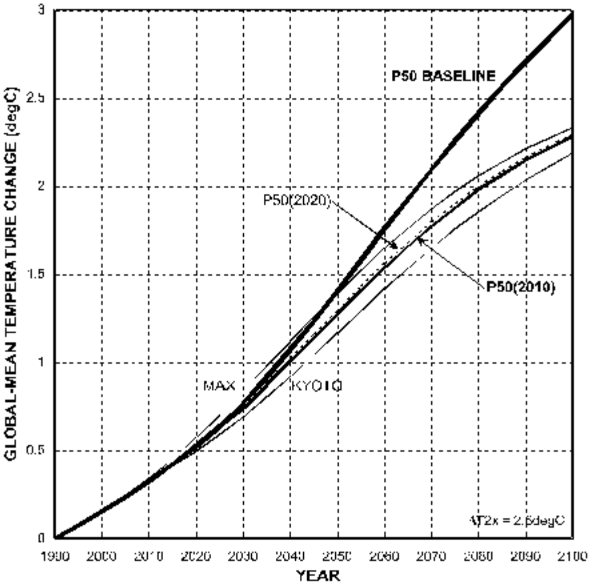
Equivalent CO_2 Stabilization

The above examples consider only stabilization of CO_2. In order to stabilize the climate, we require stabilization of equivalent CO_2 concentrations. The difference between these two is determined by the radiative forcing effects of non-CO_2 gases and aerosols, and by how much we can achieve in terms of stabilizing this forcing.

Figure 10 shows the range of non-CO_2 forcings in the SRES scenarios. Out to 2070 there are some scenarios in which this contribution to total forcing is negligible. In these cases, total forcing is effectively the same as CO_2 forcing, so, if this trend were maintained, stabilization of CO_2 would also lead to equivalent-CO_2 (and climate) stabilization. On the other hand, there are scenarios in which there is a large absolute component of forcing arising from non-CO_2 sources. In these cases, CO_2 stabilization will still leave us with increasing forcing and the climate system will not be stabilized.

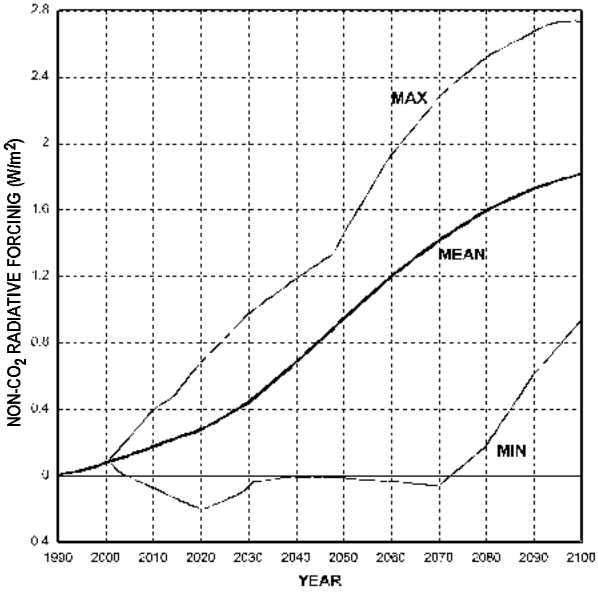
Clearly, the role of forcing from non-CO_2 sources depends on the particular scenario being considered. We can, however, obtain a general picture of its importance by considering its average value (middle curve in Figure 10). To quantify the role of non-CO_2 gases and their influence on the choice of CO_2 stabilization target, let us suppose that the CO_2 stabilization profiles in Figure 6 represent profiles for equivalent-CO_2 stabilization. Let us further suppose that the target for equivalent-CO_2 stabilization is specified. What, then, is the likely target for just CO_2 alone, assuming we do nothing to reduce future non-CO_2 forcing?

FIGURE 9: TEMPERATURE FOR DIFFERENT PATHWAYS TO 550 PPM



Global-mean temperature changes for the 550 ppm stabilization profiles shown in Figure 7, using best-estimate climate model parameters (including a climate sensitivity of 2.6°C).

FIGURE 10: NON-CO_2 FORCINGFOR SRES SCENARIOS



Range and mean of anthropogenic forcing from all sources except CO_2 for the IPCC SRES emissions scenarios.

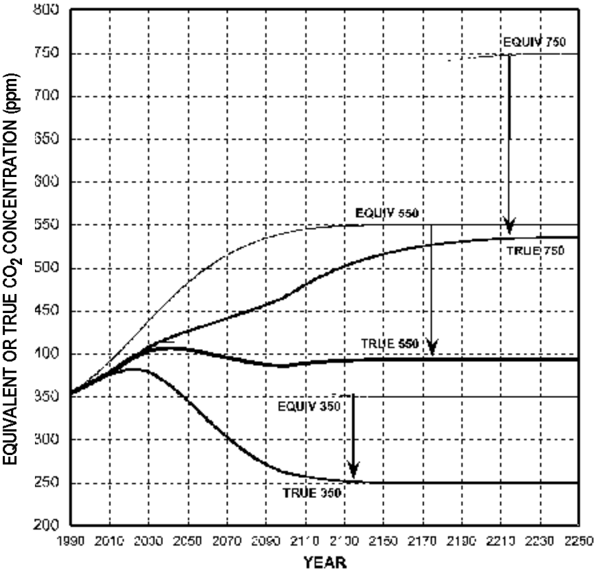
What this CO_2 target might be, using the average value for non-CO_2 forcing, is shown in Figure 11 for equivalent-CO_2 stabilization targets of 350, 550 and 750 ppm. The effect of non-CO_2 forcing leads to CO_2 targets that are far below the original equivalent-CO_2 targets: the 750 ppm equivalent-CO_2 target translates to a target of around 540 ppm for CO_2 alone, 550 ppm translates to around 400 ppm, and 350 ppm translates to around 250 ppm. Achieving any of these targets, especially the latter two, is a daunting task. The only possible solution is to reduce the magnitude of future non-CO_2 forcing.

The logical next question,then, is 'what is the potential for reducing non-CO_2 forcing?' Part of this forcing is due to sulfate aerosols. To reduce sulfate aerosol forcing, however, would require increasing SO_2 emissions levels, which would exacerbate other environmental problems. There is some potential for reducing the forcing due to those halocarbons that are not controlled under the Montreal Protocol (these gases, the HFCs, PFCs and SF_6, are included in the Kyoto Protocol), but the scope here is relatively small since these gases contribute only a small amount to future radiative forcing. Nitrous oxide (N_2O) is also covered by the Kyoto Protocol, but the long atmospheric lifetime of this gas (which means that the response to any reduction in emissions will be slow) and uncertainties in the scope for reducing N_2O emissions mean that it is not a strong candidate. This leaves methane (CH_4), the reactive gases (which control the build up of tropospheric ozone, a powerful greenhouse gas), and absorbing (carbonaceous) aerosols as potential contributors to reducing future radiative forcing increases.

The scope for reduced forcing via reductions in emissions of carbonaceous aerosols is highly uncertain. At present, the IPCC TAR estimates that this is a very small contributor to forcing, so even eliminating these aerosols would have only a minor effect. (Some scientists, however, believe the current carbonaceous aerosol forcing is substantially higher than the TAR estimate; e.g., J.E. Hansen, M. Sato, *Proc. Nat. Acad. Sci. 98*, 14778-14783,2001)

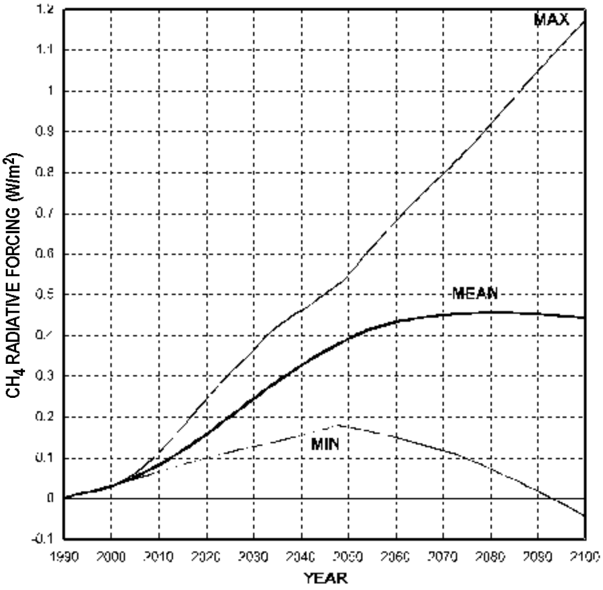
Methane forcing under the SRES scenarios is shown in Figure 12, while forcing due to the effects of reactive gases is shown in Figure 13. For most of the SRES emissions scenarios, these Figures show that projected changes in methane and reactive gas emissions will cause warming, although their combined influence on future climate is quite small (around 10%) relative to that of CO_2. However, they do account for a significant fraction of total non-CO_2 forcing — on average about 50%. Thus,

FIGURE 11: EQUIVALENT VS TRUE CO_2 STABALIZATION PROFILES



Required CO_2 concentration pathways for equivalent CO_2 stabilization at 350, 550 and 750 ppm,assuming non-CO_2 forcing follows the mean SRES result shown in Figure 10.

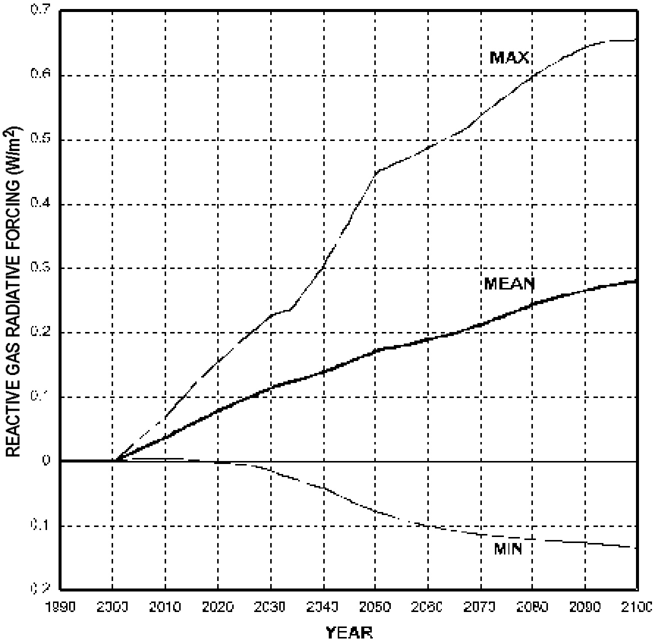
FIGURE 12: CH_4 FORCING FOR SRES SCENARIOS



Range and mean of methane radiative forcing for the IPCC SRES emissions scenarios. The forcing values here ignore the effects of reactive gas emissions changes on methane concentration, which are included in Figure 13.

together, they could be used to halve the gap between the CO_2 and equivalent-CO_2 curves in Figure 11. This result, of course, is meant to give only a general idea of the potential for reductions in non-CO_2 gases to contribute to climate stabilization. The actual potential is highly dependent on the assumed no-policy baseline scenario, and better quantification requires a scenario-by-scenario analysis.

FIGURE 13: REACTIVE GAS FORCING FOR SRES SCENARIOS



Range and mean of radiative forcing arising indirectly from emissions of the reactive gases (CO, NOx and VOCs) for the IPCC SRES emissions scenarios. This is the sum of reactive-gas effects on tropospheric ozone forcing and the lifetime of methane and (a very small effect) hydrogen-containing halocarbons.

The Effect of CO_2-SO_2 Coupling

If, as a result of climate mitigation policies, CO_2 emissions were to be reduced through reduced combustion of fossil fuels,SO_2 emissions would also be reduced, since most such fuels contain sulfur. The consequent reduction in sulfate aerosol forcing would lead to a warming effect that would, at least partly, offset the effect of reduced CO_2.

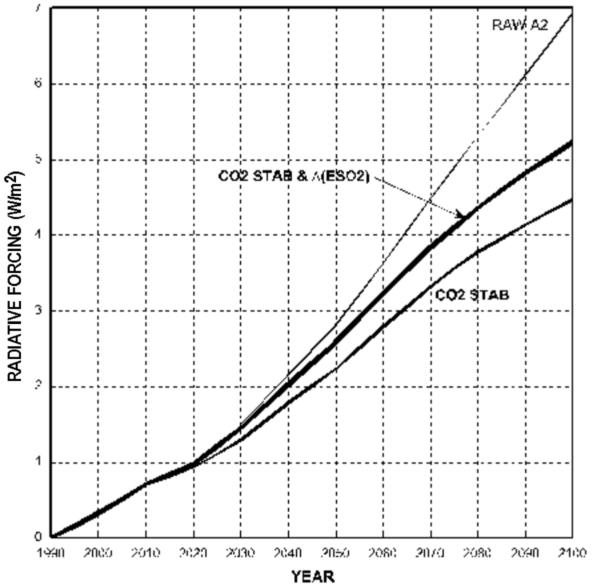
The extent of this offsetting effect is illustrated in Figures 14 and 15. It is likely to be strongest in scenarios that have the highest SO_2 emissions; specifically, those in the A2 scenario group. I quantify it here only for one scenario from that group (the A2 'marker' scenario used in the IPCC TAR), which is probably an extreme case (at least in absolute terms). To do so, I compare radiative forcing and temperature changes for the original A2 scenario with those for a modification of this scenario in which CO_2 emissions have been reduced to follow the 550 ppm CO_2 concentration-stabilization profile. By using the forward method to determine these emissions, described earlier, one also obtains the attendant changes in SO_2 emissions. Both the CO_2 and SO_2 changes are then used to calculate the effects of stabilization at 550 ppm on future forcing (Figure 14) and warming (Figure 15). These results can then be compared with those for the case in which only CO_2 changes are considered to quantify the SO_2 influence.

For the first three decades (CO_2 reductions below the baseline case begin in 2010), the negative influence (i.e., warming) of the reduction in SO_2 emissions is comparable to (and offsets) the positive effect (cooling) of reduced CO_2 levels. Subsequently, the SO_2 effect continues to produce a significant offset compared to the case where SO_2 emissions are assumed not to change. By 2100, the decrease in SO_2 emissions associated with a carbon reduction policy offsets about half of the effect of reduced CO_2 concentrations.

While this result is only for one, arguably extreme scenario, the qualitative results derived for it will apply in general: the SO_2 emissions reductions that necessarily accompany policy-driven reductions in CO_2 emissions have the potential to appreciably mask the anticipated response to these reductions.

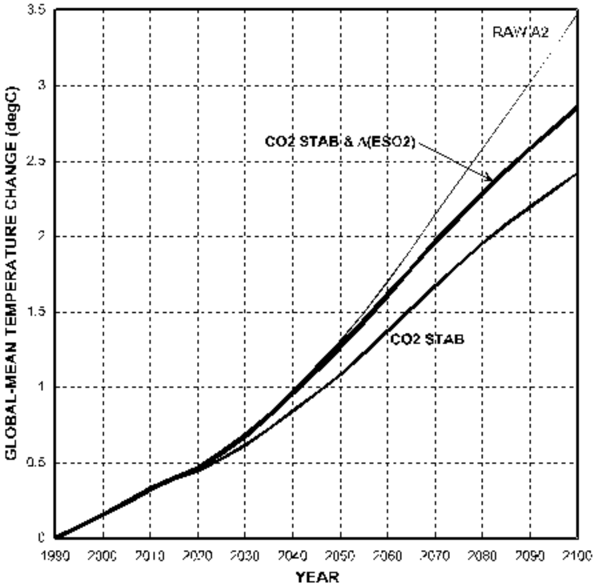
To further confuse the stabilization issue, it should be noted that the offsetting influence of stabilization-related SO_2 emissions changes may make it even harder to detect the climate effects of a CO_2 emissions-reduction policy. For CO_2 reductions alone, the policy-response climate signal is relatively well defined. When SO_2 emissions changes are also involved, however, because of the much larger uncertainties surrounding the effects of sulfate aerosol forcing, the signal will be less well defined, which will hamper detection. (It will,however, have a more complex spatial character, which may aid detection.) In any event, both the CO_2 and SO_2 signals (i.e., the changes in climate arising specifically from the emissions reduction policies), and their sum, will be small for many decades and so almost certain to be

Figure 14: SRES A2: CO_2 To 550 ppm, With & Without △(ESO_2)



Effect on radiative forcing of changes in SO_2 emissions likely to follow from policy-driven reductions in CO_2 emissions because of their common sources (for the SRES A2 marker scenario). The upper curve is for the original (RAW) A2 scenario. The lower curve shows the forcing that would occur if CO_2 emissions were to follow the updated WRE550 stabilization pathway, but with no concomitant changes in SO_2 emissions. The middle curve shows the effect of the latter changes.

Figure 15:SRES A2: CO_2 To 550ppm, With & Without △ (ESO_2)



As for Figure 14, but for global-mean temperature changes using best-estimate climate model parameters (including a climate sensitivity of 2.6°C).

obscured by the background noise of natural climatic variability. As noted above, even after a considerable effort to reduce CO_2 emissions, the consequences of this effort will not be immediately apparent.

Conclusions

Stabilization of atmospheric CO_2 concentrations will eventually require reductions in CO_2 emissions to far below present levels. Although reductions do not have to begin immediately, given the magnitude of the reductions eventually required it would be prudent to begin work now on developing mechanisms and technologies that can move us away from our current heavy dependence on fossil fuels. The technological challenge of meeting future energy demands largely through fossil-free sources is a formidable one.

In terms of the timing of a significant departure from a baseline, no-climate-policy emissions scenario, the effects of a 'delay'from 2010 to 2020 are negligible in terms of the reduction in future climate change, but possibly significant for mitigation (emissions reduction) costs. A later departure from the baseline would therefore appear to have some advantages, provided the time is used effectively to develop the required fossil-free technologies.

The concentration stabilization profiles outlined here have been for CO_2 alone. However, because the ultimate goal is climate stabilization, these should be considered as equivalent CO_2 stabilization profiles. Since future increases in forcing from non-CO_2 sources appear inevitable, the corresponding CO_2 stabilization levels may be substantially below the equivalent CO_2 levels: for example, an equivalent CO_2 target of 550 ppm translates to a CO_2 stabilization target of around 400 ppm if forcing from non-CO_2 sources is assumed to follow an average trajectory. Reductions in methane and reactive gas emissions appear to offer the best potential for reducing the pressure on CO_2 reductions. It should be noted,however, that pollution concerns regarding tropospheric ozone (which were not expressly considered in the development of the SRES scenarios) will likely lead to reductions in reactive gas emissions independent of any climate policies.

As a final point, it was shown that the expected cooling response to CO_2 emissions reductions could, for 3 or 4 decades, be completely masked by the effect of concomitant reductions in SO_2 emissions. This masking, together with the slow response of the climate system to any emissions changes, will make it difficult to detect the effects of such changes, probably for many decades. Demonstrating the efficacy of mitigation policies will therefore present a considerable challenge for scientists in order to convince policy makers and the public that the predictions of their climate models are reliable.