The Kyoto Protocol: CO₂, CH₄ and climate implications

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Abstract. Kyoto Protocol implications for CO₂, temperature and sea level are examined. Three scenarios for post-Kyoto emissions reductions are considered. In all cases, the long-term consequences are small. The limitations specified under the Protocol are interpreted in terms of both CO₂ and CH₄ emissions reductions and a new emissions comparison index, the Forcing Equivalence Index (FEI), is introduced. The use of GWPs to assess CO₂-equivalence is assessed.

Introduction

The U.N. Framework Convention on Climate Change seeks to stabilize greenhouse gas concentrations in the atmosphere. As a first step towards this, a "Protocol" was agreed at the Third Conference of Parties in Kyoto, Japan, aimed at reducing emissions of greenhouse gases in developed countries (as listed in Annex B of the Protocol). In global terms (i.e., summed over Annex B countries) the emissions target is 5.2% below the 1990 level, to be achieved over 2008-2012. Article 3, para. 1 of the Protocol states that the overall reduction should be "at least 5 per cent". For the calculations here I assume a 5% reduction by 2010 as the target.

The Protocol involves a “basket” of greenhouse gases: CO₂, CH₄, N₂O, SF₆ and a number of halocarbons. Any country may therefore reach its target by combining emissions reductions for a range of gases in some CO₂-equivalent sense. The term “CO₂-equivalence”, while used specifically in the Protocol, is not rigorously defined, other than by saying that some form of Global Warming Potential (GWP) should be used in its determination (Article 5, para. 3).

Here I consider first the Protocol’s implications for CO₂ assuming that CO₂ alone is used to achieve the target. The Protocol involves commitments only to 2010. Since its long-term effects depend on reductions achieved after 2010, I consider a range of post-2010 cases (Table 1). Next, I determine by an inverse calculation the exact equivalent emissions reductions for CH₄ required if CH₄ alone were used to reach the target. Finally, I determine the Protocol’s implications for global-mean temperature and sea level.

CO₂ Concentrations

Determining CO₂ concentrations under the Protocol requires defining a “no Protocol” baseline against which to measure the Protocol effects. To do this, I use the central IPCC “existing policies” emissions scenario, IS92a (Leggett et al., 1992), modified slightly to match observed data over 1990-96 (Wigley, 1997). To fully define the Protocol cases, I assume that the “no Protocol” case is followed to 2000, and that Annex B emissions decline linearly after this to reach 95% of their 1990 level in 2010. To show the sensitivity of results to post-2010 assumptions, I then use three scenarios for emissions over 2010-2100: no further emissions reductions after 2010 (NOMORE; i.e., all countries follow the baseline changes after 2010); constant Annex-B emissions after 2010 (this requires small additional emissions reductions); larger Annex B reductions chosen to achieve a decline of 1% per year, compounded, over 2010-2100 (B = -1%). Global emissions for these three cases are shown in Fig. 1.

To obtain CO₂ concentrations, these emissions plus IS92a land-use-change emissions are used to drive the carbon cycle model of Wigley (1993), initialized as described in Enting et al. (1994) with 1980s-mean carbon budget data from Schimel et al. (1996). Although the absolute projected concentrations are subject to appreciable uncertainties (Schimel et al., 1996), the concentration changes effected by the emissions reductions are less sensitive to these uncertainties (Wigley et al., 1997). Concentration reductions range from 20 ppmv to 80 ppmv by the year 2100 (Fig. 1). Large additional emissions reductions would therefore be required in the future if concentration stabilization is to be achieved.

Initially, however, the concentrations shown here lie below the stabilization profiles defined by Wigley et al. (1996). This is because the Protocol-based emissions used here initially lie below those assumed in constructing these stabilization profiles. This does not mean that the actions implied by the Protocol are unnecessary. The determination of the optimum magnitude and timing of emissions reduction steps is a complex economic problem that has yet to be solved.

Equivalent CH₄ Emissions Reductions

Part of the emissions reductions required under the Protocol (and subsequently) will likely come from reductions in the emissions of non-CO₂ gases. To determine the relative effectiveness of different gases in this regard, one must convert non-CO₂ emissions to equivalent-CO₂ emissions. The only method currently proposed to do this is to use GWPs (Albritton et al., 1996). It is possible, however, to determine CO₂-equivalent emissions more directly; see below.

GWPs are used to convert an emissions change in gas X (ΔEx) to equivalent-CO₂ emissions, (ΔEₓ) using

\[(ΔE_{CO₂}) = (ΔE_x)(GWP_x)\]  

(1)

Applying equ. (1) is not straightforward, however, because GWPs are not uniquely defined; they vary considerably with time horizon (Albritton et al., 1996). Furthermore, there is reason to believe that conventional GWPs produce serious errors when applied to realistic scenarios (Harvey, 1993). An alternative is to calculate the full time history of equivalent emissions directly. This can be done by calculating the radiative forcing changes for any given Protocol scenario assuming emissions changes in CO₂ alone, and then, via an inverse calculation, determining the year-by-year...
Table 1. Fossil CO2 emissions data (GtC/yr). "B" denotes Annex-B countries, while "RoW" (Rest of World) refers to non-Annex B countries. Bunker fuels used in international air and marine transport account for the GLOBE minus B + RoW difference. The remaining columns give the emissions reductions for the three scenarios considered.

<table>
<thead>
<tr>
<th>Yr.</th>
<th>MODIFIED IS92a REDUCTIONS</th>
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<td>NO MORE</td>
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<td>1991</td>
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Year emissions changes for gas X that lead to precisely the same radiative forcing changes. I will refer to the emissions ratio so derived as the Forcing Equivalence Index (FEI): i.e.,

$$\text{FEI}_X(t) = \frac{\Delta \text{CO2}(t)}{\Delta X(t)}$$  \hspace{1cm} \text{(2)}$$

Eqs (1) and (2) show that FEIs and GWPs perform the same function. The difference is that eq. (2) is an identity, while eq. (1) is a relationship that is only hypothesized as being correct. Comparing FEI and GWP values gives some insight into the validity of eq. (1) and the accuracy with which GWPs can determine CO2 equivalence (where equivalence is defined in terms of radiative forcing).

I illustrate this using methane. For CO2 forcing, I use Shine et al. (1990). This probably overestimates the forcing (Harvey et al., 1997), but it is the de facto standard for policy calculations. For CH4, I also use the standard IPCC forcing relationship. The gas cycle model I used is Osborn and Wigley (1994), with current IPCC best estimates for lifetime and adjustment time (Prather et al., 1996). The model accurately matches the IPCC concentration projections. For CH4 forcing, the effects of CH4-derived changes in tropospheric O3 and stratospheric H2O concentrations are included; these are the only indirect effects currently included in CH4 GWPs.

As a baseline for CH4 concentrations, I use results based on the IS92a emissions scenario, adjusted to give a balanced budget in 1990 (Prather et al., 1996, p. 96), and follow IPCC in keeping CO, NOx and VOC emissions at their current levels. Because the main results produced here are concentration differences, the assumption regarding CO, NOx and VOC emissions has only a small effect. More generally, results are insensitive to the background concentration scenario because of compensating nonlinearities in the AE-AC and AC-AQ relationships for CH4.

Figure 2 shows the three CO2 emissions reduction cases, the corresponding radiative forcing reductions, and the inverse-calculated reductions in CH4 emissions that lead to the same forcing changes. The forcing reductions of 0.2-0.5 W/m^2 by 2100 are small compared with the future forcing changes expected to occur in the absence of emissions limitation policies (e.g., some 6 W/m^2 for the IS92a scenario).

Fig. 2 (bottom) shows the CH4 emissions reductions required to produce the forcing reductions shown in the

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Figure 1. Upper panel: baseline (IS92a) global fossil CO2 emissions scenario, compared with emissions under the three extended Protocol scenarios. Lower panel: corresponding CO2 concentration projections.

![Figure 1](image1.png)

Figure 2. Top panel: global fossil CO2 emissions reductions for the three extended Protocol scenarios. Middle panel: radiative forcing reductions for the three scenarios compared with the reductions that would occur if CH4 emissions were held constant after 2000. Bottom panel: CH4 emissions reductions required to produce the above forcing reductions.

![Figure 2](image2.png)
middle panel. The similarity between the forcing reduction for constant CH₄ emissions and that for the B = -1% scenario (middle panel) indicates that an emissions reduction of order 400TgCH₄/yr by 2100 (which is the emissions change in IS92a) would be required to match B = -1%. This result is confirmed by the full inverse calculation.

The Protocol’s need to determine CO₂-equivalence is fulfilled by these calculations, but only for three specific cases. Is it possible to generalize these results by using a GWP-like scaling factor as in equ. (1)? If this were possible, then the ratio of CH₄ to CO₂ emissions reduction would have to be both time invariant and independent of the CO₂ emissions reduction scenario. Since GWPs vary strongly with time horizon, time invariance is unlikely. Scenario independence also fails, as can be shown by calculating the ratios between ΔE₃₄₄(t) (Fig. 2, bottom panel) and ΔE₃₄₄(t) (Fig. 2, top).

These ratios (FEI values) are shown in Fig. 3, compared with time-dependent conventional GWPs (the year 2000, the year when reductions begin, corresponds to zero time horizon). The GWPs here differ slightly from those given by IPCC (Albritton et al., 1996, Table 2.9). For consistency, to allow a true “like with like” comparison, CH₄ GWPs were recalculated using the same models, background concentrations and parameter values used in the full equivalence calculations.

Figure 3 shows that there is no single scaling factor that can convert between CO₂ and CH₄ emissions. The scaling is not only time-dependent (as suspected a priori), but also scenario dependent. For the cases considered here, conventional GWPs, if used to convert CH₄ emissions reductions to equivalent-CO₂ emissions reductions will underestimate the latter (i.e., underestimate the effectiveness of the CH₄ emissions reduction)—even if continuous GWPs are used. The underestimation ranges from 3% for a short (10 year) time horizon, up to 40% at a time horizon of 100 years. If discrete GWPs were used (which is all that is currently available in the IPCC literature) the errors would be even larger. For example, using the 100-year GWP to convert CH₄ emissions reductions in coming decades to equivalent-CO₂ reductions (as suggested in some pre-Kyoto proposals; see Wigley et al., 1997, Table A1) would underestimate the importance of the methane reductions by a factor of three. The 2010 CO₂ emissions reduction here is 0.73GtC/yr=2670TgCO₂/yr. Using the 100-year GWP gives an equivalent CH₄ emissions reduction of 126TgCH₄/yr. The correct inverse-calculated value is only 41TgCH₄/yr. Although this error is largely a result of an inappropriate choice of time horizon, a more equitable and accurate alternative to the conventional GWPs currently available would clearly be advantageous.

**Temperature and Sea Level Implications**

If CO₂-equivalence is based on radiative forcing, and calculated accurately for non-CO₂ gases, then the temperature and sea level implications of the Protocol may be calculated from the CO₂-alone case. I therefore interpret the CO₂ concentration reduction results (Fig. 1) as equivalent-CO₂ concentration reductions. To determine the corresponding climate changes, I use the models used by IPCC (Kattenberg et al., 1996: see also Raper et al., 1996; Harvey et al., 1997).

Figure 4 (top) shows temperature changes relative to 1990 for a climate sensitivity of 2.5°C equilibrium warming for 2xCO₂. Lower panel; reductions in global-mean warming due to the central Protocol scenario (B=CONST) for climate sensitivities of 1.5°C, 2.5°C (cf., top panel) and 4.5°C.

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![Figure 3](image-url)  
**Figure 3.** Forcing Equivalence Indices (FEI) and Global Warming Potentials (GWP). Upper three curves give the ratio of CO₂ emissions reduction (TgCO₂/yr) to CH₄ emissions reduction (TgCH₄/yr) using the data in Fig. 2. Lowest curve gives conventional GWPs (GWP(t)). IPCC GWP values are shown as open circles. FEIs behave erratically for very short time horizons because the inverse calculations are sensitive to small changes in forcing rates of change.
The Protocol, therefore, even when extended as here, can be considered as only a first and relatively small step towards stabilizing the climate. The influence of the Protocol would, furthermore, be undetectable for many decades.

Sea level rise reductions accrue even more slowly than warming reductions. The B=CONST reduction is 1.4–3.7 cm in 2100 (7–4%) depending on the climate sensitivity and ice-melt assumptions. For the NOMORE and B = -1% cases, the reduction by 2100 reaches 0.8–2.1 cm (4–2%) and 2.5–6.4 cm (13–7%) respectively. In percentage terms, the higher sea level values are reduced the least. As noted in Kattenberg et al. (1996) and Raper et al. (1996), the prospects for stabilizing sea level over coming centuries are remote, so it is not surprising that the Protocol has such minor effects.

Conclusions

Three Kyoto Protocol cases have been examined. These extend the Protocol beyond 2100 by assuming: no further reductions in Annex B emissions; constant Annex B emissions; or a decline in Annex B emissions at 1% compound per year. If equivalent-CO₂ emissions reductions are effected by reductions in CO₂ emissions alone, CO₂ concentration reductions are from 20 to 80 ppmv in 2100. For comparison, a 170 ppmv reduction is required if concentrations were to follow a pathway stabilizing at 550 ppmv. Large additional emissions reductions are required at some future date (certainly earlier than 2040) if concentration stabilization is to be achieved at 550 ppmv or lower.

The Protocol is also interpreted in terms of reductions in CH₄ emissions alone. By 2010, CH₄ emissions would have to drop by 41TgCH₄/yr to be exactly equivalent to the CO₂ emissions reduction (0.73GtC/yr) in radiative forcing terms. By 2100, the corresponding results are 230TgCH₄/yr and 2.16 GtC/yr for the B=CONST (i.e., constant equivalent-CO₂ emissions) extension of the Protocol. The practicality of meeting the Protocol target via methane emissions reductions depends, of course, on the magnitude of current anthropogenic emissions. Globally, these are around 400TgCH₄/yr, with large country-to-country variations. Roughly 40% of global emissions are in Annex B countries.

The ratio of CO₂ to equivalent-CH₄ emissions reductions provides a new index (the Forcing Equivalence Index) that relates the radiative forcing effects of the emissions reductions of the two gases exactly, rather than approximately, as is the case for conventional (IPCC) GWPs. FEIs realistically capture the sensitivity of equivalent emissions to the chosen emissions reduction path. Policies for implementing multi-gas aspects of the Protocol should consider this sensitivity.

Finally, reductions in temperature and sea level rise under the Protocol and the extensions considered here are relatively small, but nonetheless important as a first step towards stabilizing the climate system.

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References


