MULTI-GAS EMISSIONS PATHWAYS TO MEET CLIMATE TARGETS

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Abstract. So far, climate change mitigation pathways focus mostly on CO_2 and a limited number of climate targets. Comprehensive studies of emission implications have been hindered by the absence of a flexible method to generate multi-gas emissions pathways, user-definable in shape and the climate target. The presented method 'Equal Quantile Walk' (EQW) is intended to fill this gap, building upon and complementing existing multi-gas emission scenarios. The EQW method generates new mitigation pathways by 'walking along equal quantile paths' of the emission distributions derived from existing multi-gas IPCC baseline and stabilization scenarios. Considered emissions include those of CO_2 and all other major radiative forcing agents (greenhouse gases, ozone precursors and sulphur aerosols). Sample EQW pathways are derived for stabilization at 350 ppm to 750 ppm CO_2 concentrations and compared to WRE profiles. Furthermore, the ability of the method to analyze emission implications in a probabilistic multi-gas framework is demonstrated. The risk of overshooting a 2 °C climate target is derived by using different sets of EQW radiative forcing peaking pathways. If the risk shall not be increased above 30%, it seems necessary to peak CO_2 equivalence concentrations around 475 ppm and return to lower levels after peaking (below 400 ppm). EQW emissions pathways can be applied in studies relating to Article 2 of the UNFCCC, for the analysis of climate impacts, adaptation and emission control implications associated with certain climate targets.

1. Introduction

Ten years after its entry into force, the United Nations Framework Convention on Climate Change (UNFCCC) has been ratified by 188 countries.[1] It calls for the prevention of 'dangerous anthropogenic interference with the climate system' (Article 2). In order to study the transient climate impacts of human-induced greenhouse gas (GHG) emissions and its implications for emission control policies, multi-gas emissions pathways that capture a wide range of intervention and non-intervention emission futures are required.

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The aim of this study is to present a method that can simultaneously meet three goals relevant to studies relating to Article 2.

- The first goal is to generate multi-gas emissions pathways consistent with the range of climate policy target indicators under discussion. The *target parameter* and its *level* can be freely selected. Examples of target parameters include CO_2 concentrations, radiative forcing, global mean temperatures or sea level rise.
- The second goal is that the multi-gas pathways generated should have a treatment of non-CO_2 gases and radiative forcing agents that is consistent with the range of multi-gas scenarios in the literature. The inclusion of a non-CO_2 component in the newly created emissions pathways might significantly improve on mitigation pathways generated in the past but without the necessity of a comprehensive analysis of mitigation options across energy, agriculture, and other sectors. Several studies have shown that it is important to take into account the full range of greenhouse gases including, but not limited to, the six greenhouse gases and gas groups controlled by the Kyoto Protocol both for economic cost-effectiveness and climatic reasons (Reilly et al., 1999; Hansen et al., 2000; Manne and Richels, 2001; Sygna et al., 2002; Eickhout et al., 2003; van Vuuren et al., 2003). However, until recently, most studies have focused on CO_2 only.
- The third goal is to create a *method* to generate multi-gas pathways for user-specified climate targets. Developing a flexible method, rather than only a limited number of mitigation pathways, has significant advantages. For example, it can facilitate a comprehensive exploration of the emission implications of certain climate targets, given our scientific uncertainties in the main climate systems components, such as climate sensitivity and ocean diffusivity.

There are two broad classifications of emissions pathways: a non-interventionist (baseline) path or one with some level of normative intervention (mitigation). Furthermore, a distinction is drawn here between *scenarios* and *emissions pathways*. Whereas the latter focus solely on emissions, a *scenario* represents a more complete description of possible future states of the world, including their socio-economic characteristics and energy and transport infrastructures. Under this definition, many of the existing '*scenarios'* are in fact *pathways*, including the ones derived in this study. Following the distinction between 'emission *scenarios'* and 'concentration *profiles'* introduced by Enting et al. (1994), the term '*profiles'* is here used for time trajectories of concentrations.

Existing mitigation pathways or scenarios differ in many respects, for example in regard to the type and level of their envisaged climate targets (see overview in Table I).

One of the major challenges for the design of global mitigation pathways is the balanced treatment of CO_2 and non-CO_2 emissions over a range of climate targets with varying levels of stringency. Another major challenge is highlighted by the

TABLE I
Overview of intervention pathways and scenarios

Name	Climate Target	Characteristic/comment	Reference
'S' profiles	CO_2 concentration stabilization at 350, 450, 550, 650 and 750 ppm	CO_2 profiles developed as part of a carbon-cycle inter-comparison exercise (Enting et al., 1994). CO_2 emissions departed from 'business-as-usual' in 1990. CO_2 emissions varied only.	(Enting et al., 1994; Houghton et al., 1994)[15]
'WRE' profiles	CO_2 concentration stabilization at 350, 450, 550, 650, 750 and 1000 ppm	Variant of 'S' profiles with a later departure from 'business-as-usual' emissions depending on the target concentration level. CO_2 emissions varied only.	(Wigley et al., 1996)
Post-SRES (IPCC stabilization scenarios)	CO_2 concentration stabilization at levels between 440 and 750 ppm	Emission scenarios developed during and subsequent to the work for the Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000). Model dependent coverage and variation of major greenhouse gases and other radiative forcing agents.	Different modeling groups, namely AIM, ASF, IMAGE, LDNE, MARIA, MESSAGE, MiniCAM, PETRO, WorldScan (see e.g. Morita et al., 2000; and figure 2-1d in Nakicenovic and Swart, 2000)[16]
TGCIA450	CO_2 concentration stabilization at 450 ppm	Single pathway with coverage of all major greenhouse gases and radiative forcing agents to complement the non-intervention SRES illustrative scenarios for AOGCM based climate impact studies.	(Swart et al., 2002)
IMAGE Se	CO_2 equivalent concentration stabilization (based on radiative forcing of all GHGs included in Kyoto Protocol) at 550, 650 and 750 ppm	Following the concept of stabilizing CO_2 equivalent concentrations (Schimel et al., 1997), the IMAGE team designed CO_2-equivalent emissions pathways (based on 100-year GWP) with both (a) non-CO_2 GHG emissions leading to 100 ppm CO_2 equivalent concentrations and (b) non-CO_2 emissions according to cost-optimal mixes.	(Eickhout et al., 2003) (van Vuuren et al., 2003)

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TABLE I
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Name	Climate target	Characteristic/comment	Reference
MESSAGE-WBGU '03	CO_2 concentration stabilization at 400 and 450 ppm	Three intervention scenarios generated with MESSAGE for energy-related CO_2 and non-CO_2 emissions based on different SRES baselines (A1-450; B1-400; B2-400). Non-energy related emissions based on AIM model. Commissioned by WBGU (2003).	(Nakicenovic and Riahi, 2003)
EMF-21	Radiative forcing stabilization at 4.5 W/m^2	Baseline and model-dependent, cost-optimized scenarios for all major greenhouse gases and other radiative forcing agents. To be published.	Various modeling groups; (de la Chesnaye, 2003)
EQW	Freely selectablev[17]	Emissions pathways with all major radiative forcing agents 'consistently' varying with the stringency of climate target. Freely selectable departure year from 'business-as-usual'.	This study

debate on '*early action'* versus '*delayed response*' (see e.g. Ha-Duong et al., 1997; see e.g. Azar, 1998). Both issues arise from the fact that a long-term concentration, temperature or sea-level target can be achieved through more than one emissions pathway. Emissions in one gas (e.g. CO_2) can be balanced against reductions in another gas (e.g. N_2O), which leads to a 'multi-gas indeterminacy'. This is somewhat parallel to the debate on the 'timing of emission reductions', since emissions in the near-term may be balanced against reductions in the long-term. Obviously, there is a clear difference too: The 'timing' of emission reductions touches intergenerational equity questions much more directly than trade-offs between gases. Only indirectly, trade-offs between gases might have some implications for intergenerational issues, e.g. if states operate under a 'Global Warming Potential' (GWP) based commitment period regime for gases of different lifetimes (Smith and Wigley, 2000b; Sygna et al., 2002). This paper proposes a method, which is characterized by its unique way of handling the 'multi-gas indeterminacy'.

In the next section we review previous approaches to handling non-CO_2 gases in intervention pathways and in climate impact studies (Section 2). The 'Equal Quantile Walk' (EQW) method is presented subsequently (Section 3). EQW generated multi-gas pathways are presented and compared with existing mitigation pathways (Section 4). Limitations of the EQW method are discussed subsequently

(Section 5). Finally, we conclude and suggest future work that can build on the presented method (Section 6).

2. Previous Approaches to Handling Non-CO_2 Gases in Mitigation Pathways and Climate Impact Studies

To date, four different approaches have been used to handle the treatment of non-CO_2 emissions in mitigation pathways. The simplest and most widely applied approach we term here the '*one size fits all*' approach, which means that different CO_2 pathways are complemented by a single set of non-CO_2 emissions. For example, the IPCC Second Assessment Report (SAR) focused only on CO_2 when assessing stabilization scenarios (see IPCC, 1996, section 6.3). The temperature implications of the S profiles (see Table I) were thus derived in the SAR by assuming constant emissions for SO_2 and constant concentrations for non-CO_2 greenhouse gases at their 1990 levels. Subsequently, Schimel et al. (1997) presented estimates of how non-CO_2 emissions might change in the future for the S profiles. Azar and Rhode (1997) presented temperature implications of the S profiles by assuming a 1W/m^2 contribution by other greenhouse gases and aerosols. However, the non-CO_2 emissions or radiative forcing contributions were still assumed to be independent of the CO_2 stabilization levels. The Third Assessment Report (IPCC TAR) presented the temperature effects of S and WRE profiles by assuming a common non-intervention scenario (SRES A1B) for non-CO_2 emissions (see figure 9.16 in Cubasch et al., 2001).

Clearly, it is inconsistent to assume 'non-intervention' scenarios for non-CO_2 gases in a general 'climate-policy' intervention scenario. An overestimation of the associated effect on global mean temperatures for a certain CO_2 concentration is likely to be the result. There are a number of ways in which non-CO_2 gases might be accounted for more realistically, including the approach presented in this paper. Mitigation scenarios might want to assume a consistent mix of climate and air pollution related policy measures to lower CO_2 emissions as well as to make use of the extensive non-CO_2 mitigation potentials (see e.g. de Jager et al., 2001). Furthermore, constraints on carbon emissions are likely to be automatically correlated with lower non-CO_2 emissions from common sources (e.g. limiting the burning of fossil fuels generally results in both, lower CO_2 and lower aerosol emissions). Indeed, the approaches described below take account of such correlations between CO_2 and non-CO_2 gases in various ways.

The second approach that has been used may be referred to as '*scaling'* and was first employed by Wigley (1991). Non-CO_2 emissions, concentrations or radiative forcing are proportionally scaled with CO_2. Some studies analysed the S profiles and accounted for non-CO_2 gases, including sulphate aerosols, by scaling the radiative forcing of CO_2. For example, the combined cooling effect of SO_2 aerosol and warming effect of non-CO_2 greenhouse gases has been assumed to add 23%

to the CO_2 related radiative forcing in Wigley (1995) and Raper et al. (1996); 23% is the 2100 average for the 1992 IPCC emission scenarios (Leggett et al., 1992) according to Wigley and Raper (1992). Later, aerosols and greenhouse gases have been treated separately. For both the S and WRE-profiles, SO_2 emissions were either held constant at their 1990 levels or the negative forcing due to sulphate aerosols ('S(x)') was directly scaled with changes in CO_2 emissions since 1990 ('F(x)/F(1990)'), according to $S(x) = [S(1990)/F(1990)] * F(x)$. The scaling procedure for sulphate emissions was a significant improvement to explicitly capture the correlated nature of SO_2 and fossil CO_2 emissions. The positive forcing of non-CO_2 greenhouse gases has then been assumed to be 33% of the CO_2 related radiative forcing (Wigley et al., 1996).

A third approach is to take source-specific reduction potentials for all gases into account. Thus, rather than assuming that proportional reductions are possible across all gases, emission scenarios are developed by making explicit assumptions about reductions of the different gases. Realized reductions vary with the stringency of the climate target. In case of most of the Post-SRES scenarios, reductions in non-CO_2 emissions result from systemic changes in the energy system as a result of policies that aim to reduce CO_2 emissions. This in particular involves CH_4 from energy production and transport (see e.g. Post-SRES scenarios as presented in Morita et al. (2000), and Swart et al. (2002)). This method does not directly take into account the relative costs of reductions for different gases.

A fourth, more sophisticated, approach is to find cost-optimizing mixes of gas-to-gas reductions with the help of more or less elaborated energy and land-use models. In its simplest form, a set of (time-dependent) Marginal Abatement Cost curves (MAC) for different gases are used, thus enabling the determination of an optimal set of reductions across all gases (see e.g. den Elzen and Lucas, accepted). Some studies mix both model-inherent cost estimates and exogenous MACs (see e.g. van Vuuren et al., 2003; den Elzen et al., 2005). Ideally, dynamically coupled (macro-)economic-energy-landuse models could aim to find cost-effective reduction strategies that take into account model-specific assumptions about endogenous technological development, institutional and regulatory barriers as well as other driving forces for CO_2 and non-CO_2 emissions. Some of the more sophisticated models within the Energy Modelling Forum (EMF) 21 model-inter-comparison study aim to do so (de la Chesnaye, 2003).

One important distinction among scenarios of this fourth 'cost-optimizing' approach can be drawn in regard to what exactly the modeling groups optimize. Some optimizing methods handle the 'multi-gas indeterminacy' by finding a cost-optimizing solution for matching a prescribed aggregated emission path (see e.g. den Elzen and Meinshausen, 2005). In this way the substitution between gases is done using GWPs, which closely reflects current political (emission trading) frameworks. A different method is to determine gas-to-gas ratios by finding a cost-efficient emission path over time to match a long-term climate target. In this latter approach, GWPs are not used to determine the substitution between gases but an intertemporal optimization is performed to find cost-efficient emission paths towards a certain climate target. In general, the outcomes of these two optimization methods can be rather different, with the GWP-based approaches suggesting earlier and deeper cuts of short-lived greenhouse gases. The latter intertemporal optimization approaches rather advise to solve the 'multi-gas indeterminacy' in favor of reductions of long-lived gases from the beginning with reductions of short-lived gases, such as CH_4, only becoming important closer to times, when the climate target might be overshoot.

Whilst the '*one size fits all*' and the '*scaling*' approaches have the virtue of computational simplicity, they have the clear disadvantage that the emission levels from the non-CO_2 gases and forcing agents may be economically or technologically 'unrealistic'. In other words, the assumed contribution of non-CO_2 gases and forcing agents is unlikely to be consistent with the underlying literature on multi-gas greenhouse mitigation scenarios based, for example, on methods three and four. The much more sophisticated third and fourth methods described here have the compelling advantage of generating multi-gas pathways consistent with a process based understanding of emission sources and control options and their relationship to other economic factors, as well as dynamic interactions amongst sectors–as in the case of the more sophisticated studies within method four. These methods are usually based on integrated assessment models (e.g. MESSAGE, IMAGE, AIM etc). So far, the volume of output and the complexity of input assumptions and related databases has militated against their use for generating large numbers of scenarios for arbitrary climate targets and different time paths of emissions. However, a solid exploration of emission implications of climate targets would require sensitivity studies with (large ensembles) of multi-gas mitigation pathways.

Thus, the EQW method offers a computationally flexible approach to derive multi-gas emissions pathways for a wide range of climate targets and scientific parameters, by extending and building upon scenarios under approaches three and four above. Obviously, EQW pathways are an amendment to, but not a replacement of the mitigation scenarios of approaches three and four. The generation of EQW pathways vitally depends on such mitigation scenarios, which capture the current knowledge on mitigation potentials. There are numerous questions that are best answered by specific scenarios under approaches three and four, e.g. in regard to implications for energy infrastructure and economic costs, which cannot be answered by EQW emissions pathways alone. However, EQW pathways are a vital extension, when it comes to explore the (multi-gas) emission implications under various kinds of climate targets, possibly in a probabilistic framework (see e.g. Section 4.2). Whether certain emission reductions are considered feasible is outside the scope of this study and is a judgment that is likely to change over time as new insights into technological, institutional, management and behavioral options are gained. Furthermore, the EQW pathways might be used to append CO_2-only scenarios with a corresponding set of non-CO_2 emissions pathways.

Many climate impact studies that explore climate change mitigation futures reflect the scarcity of fully developed multi-gas mitigation pathways to date. For example, Arnell et al. (2002) and Mitchell et al. (2000) made assumptions similar to those used in the IPCC SAR (IPCC, 1996, Section 6.3). Their implementation of the S750 and S550-profiles assumes constant concentrations of non-CO_2 gases at 1990 levels, but did not consider forcing due to sulphate aerosols. Some studies bound CO_2 concentrations at a certain level, e.g. 2× or 3× pre-industrials levels, after having followed a 'no climate policy' reference scenario, e.g. IS92a (see e.g. Cai et al., 2003). Other studies assume 'no climate policy' trajectories for non-CO_2 gases, thereby focusing solely on the effect of CO_2 stabilization (Dai et al., 2001a,b) – although it should be noted that theses studies made a deliberate choice to consider the effects of CO_2 reductions alone in order to explore sensitivities in a controlled way.

3. The 'Equal Quantile Walk' Method

We will refer to the presented method as the 'Equal Quantile Walk' (EQW) approach for reasons explained below. A concise overview on the consecutive steps of the EQW method is provided in Figure 1. The approach aims to distil a '*distribution of possible emission levels*' for each gas, each region and each year out of a compilation of existing non-intervention and intervention scenarios in the literature that use methods three and four above (see Figure 1 and Section 2). Once this distribution is derived, which is notably not a probability distribution (cf. Section 5.1.2), emissions pathways can be found, that are 'comparably low' or 'comparably high' for each gas. In this way the EQW method builds on the sophistication and detailed approaches that are inherent in existing intervention and non-intervention scenarios without making its own specific assumptions on different gases' reduction potentials.

Here, the term '*comparably low*' is defined as a set of emissions that are on the same 'quantile' of their respective gas and region specific distributions. Hence, the approach is called 'Equal Quantile Walk' (cf. Figure 3 and Section 3.3). For example, the *quantile path* can, over time, be derived by prescribing one specific gas's emissions path in a particular region, such as fossil fuel CO_2 for the OECD region (Section 3.2). The corresponding *quantile path* is then applied to all remaining gases and regions and a global emissions pathway is obtained by aggregating over the world regions (Section 3.3). Consequently, EQW pathway emissions for one gas can go up over time, while emission of another gas go down, but an EQW pathway for a more ambitious climate target will be assumed to have lower emissions across all gases compared to an EQW pathway for a less ambitious climate target. Subsequently, a simple climate model is used to find the corresponding profiles of global mean temperatures, sea levels and other climate indicators. Here we use the simple climate model MAGICC 4.1 (Wigley and Raper, 2001, 2002; Wigley, 2003a). This

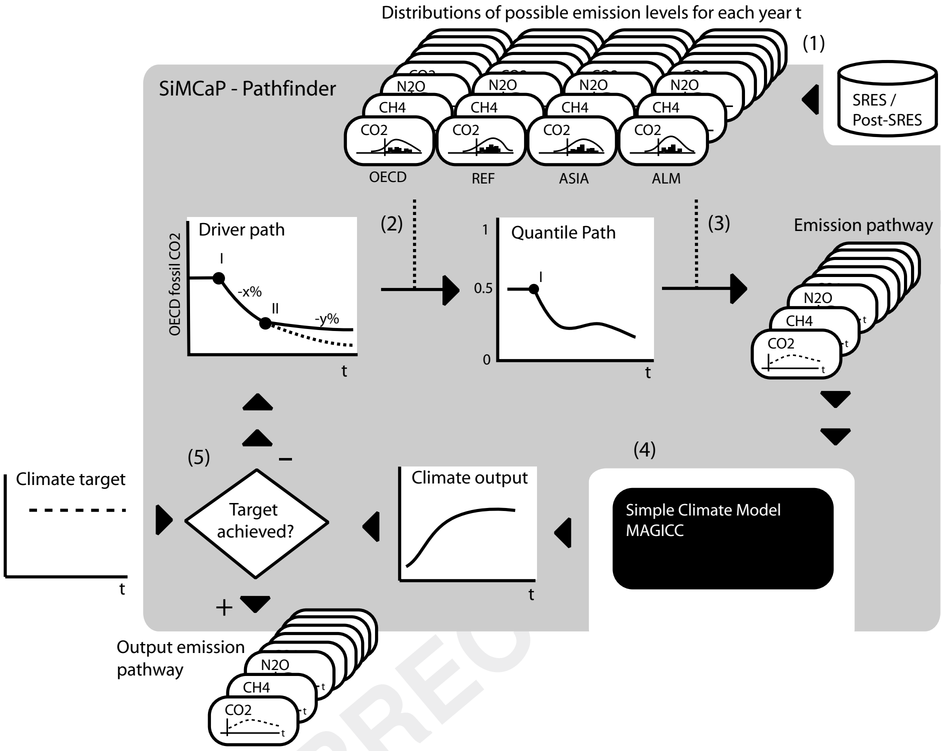

Figure 1. The EQW method as implemented in SiMCaP's 'pathfinder' module. (1) The 'distributions of possible emission levels' are distilled from a pool of existing scenarios for the 4 SRES world regions OECD, REF, ASIA and ALM.[13] (2) The common quantile path of the new emissions pathway is derived by using a driver emission path, such as the one for fossil CO2 emissions in OECD countries. The driver path is here defined by sections of constant emission reductions ('$-x/y\%$') and years at which the reduction rates change ('I' and 'II'). (3) A global emissions pathway is obtained by assuming that – in the default case-the quantile path that corresponds to the driver path applies to all gases and regions. (4) Using the simple climate model MAGICC, the climate implications of the emissions pathway are computed. (5) Within SiMCaP's iterative optimisation procedure, the quantile paths are optimised until the climate outputs and the prescribed climate target match sufficiently well.

is the model that was used for global-mean temperature and sea level projections in the IPCC TAR (see Cubasch et al., 2001 and Section 3.4 and Appendix A).

An iterative procedure is used to find emissions pathways that correspond to a predefined arbitrary climate target. This is implemented in the 'EQW pathfinder' module of the 'Simple Model for Climate Policy Assessment' (SiMCaP). More specifically, SiMCaP's iterative procedure begins with a single 'driver' emission path (such as fossil CO_2 in the OECD region) and then uses the 'equal quantile' assumption to define emissions for all other gases and regions. The driver path is then varied until the specified climate target is sufficiently well approximated using a least-squares goodness of fit indicator (see Figure 1). SiMCaP's model components and a set of derived EQW emissions pathways are available from the authors or at http://www.simcap.org.

3.1. DISTILLING A DISTRIBUTION OF POSSIBLE EMISSION LEVELS

In order to determine a possible range of different gases' emission levels a set of scenarios is needed. Here, the 40 non-intervention IPCC emission scenarios from the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000)[2] are used in combination with 14 Post-SRES stabilization scenarios from the same six modeling groups,[3] as presented by Swart et al. (2002). This combined set of 54 scenarios is used in this study to derive the distributions of possible emission levels. The Post-SRES intervention scenarios are scenarios that stabilize atmospheric CO_2 concentrations at levels between 450 ppm to 750 ppm. Most of the Post-SRES scenarios only target fossil CO_2 explicitly, although lower non-CO_2 emissions are often implied due to induced changes on all energy-related emissions. For halocarbons (CFCs, HCFCs and HFCs) and other halogenated compounds (PFCs, SF_6), the post-SRES scenarios, however, provide no additional information. Therefore, the A1, A2, B1 and B2 non-intervention IPCC SRES scenarios were supplemented with one intervention pathway in order to derive the distribution of possible emission levels. Since most of the halocarbons and halogenated compounds can be reduced at comparatively low costs compared to other gases (cf. USEPA, 2003; Ottinger-Schaefer et al., submitted), the added intervention pathway assumes a smooth phase-out by 2075. Clearly, future applications of the EQW method can be based on an extended set of underlying multi-gas scenarios (such as EMF-21), thereby capturing the best available knowledge on multi-gas mitigation potentials.

The combined density distribution for the emission levels of the different gases has been derived by assuming a Gaussian smoothing window (kernel) around each of the 54 scenarios. The resulting non-parametric density distribution for a given year and gas can be viewed as a smoothed histogram of the data (see Figure 2). A narrow kernel would reveal higher details of the underlying data until every single scenario is portrayed as a spike–as in a high-resolution histogram. Wider kernels can also be used to some degree to interpolate and extrapolate information of the limited set of reduction scenarios into underrepresented areas within and outside the range of the scenarios. Thus, the chosen kernel width has to strike a balance between-on the one hand-allowing a smooth continuum of emission levels and the design of slightly lower emissions pathways and-on the other hand-appropriately reflecting the lower bound as well as the possibly asymmetric nature of the underlying data.

In this study, a medium width of the kernel is chosen-close to the optimum for estimating normal distributions (Bowman and Azzalini, 1997). For a limited number of cases a narrower kernel width was chosen, namely for the N_2O related

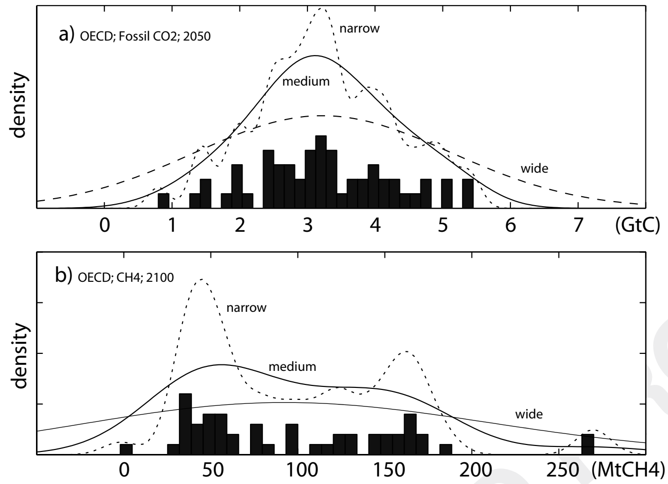

Figure 2. Derived non-parametric density distribution by applying smoothing kernels with default kernel width for this study (solid line 'medium'), a wide kernel width (dashed line 'wide') and a narrow kernel width (dotted line 'narrow'). See text for discussion.

distributions in order to better reflect the lower bound of the distribution. A narrower kernel for N_2O guarantees a more appropriate reflection of the sharp lower bound of the distribution of N_2O emission levels, which is suggested by the pool of existing SRES & post-SRES scenarios (see Figure 9c). The application of a wider kernel would have resulted in an extensive lapping of the derived non-parametric distribution into low emission levels that are not represented within the set of existing scenarios. The inclusion of a wider set of currently developed multi-gas scenarios might actually soften this seemingly hard lower bound for N_2O emissions in the future.[4] Furthermore, the distribution of possible emission levels might extend into negative areas, which is, for most emissions, an implausible or impossible characteristic. Thus, derived distributions have been truncated at zero with the exception of land-use related net CO_2 emissions.

Land use CO_2 emissions, or rather CO_2 removal, have been bound at the lower end according to the SRES scenario database literature range as presented in figure SPM-2 of the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000). Specifically, the applied lower bound ranges between −1.1 and −0.6 GtC/yr between 2020 and 2100. The maximum total uptake of carbon in the terrestrial biosphere from policies in this area over the coming centuries is assumed to approximately restore the total amount of carbon lost from the terrestrial biosphere. Specifically, it was assumed that from 2100 to 2200, the lower bound for the land-use related CO_2 emission distribution smoothly returns to zero so that the accumulated sequestration since 1990 does not exceed the deforestation related emissions between 1850 and 1989, estimated to be 132 GtC[5] (Houghton, 1999; Houghton and Hackler, 2002).

3.2. DERIVING THE QUANTILE PATH

For an EQW pathway, emissions of each gas in a given year and for a given region are assumed to correspond to the same quantile of the respective (gas-, year- and region-specific) *distribution of possible emission levels*. Depending on the climate target and the timing of emission reductions, the annual quantiles might of course change over time (cf. inset (2) in Figure 1). It is possible to prescribe the *quantile path* directly. For example, aggregating emissions that correspond to the time-constant 50% quantile path would result in the median pathway over the whole scenario data pool. In general, however, what we do is prescribe one of the gases' emissions as '*driver path*', for example the one for fossil CO_2 emissions in OECD countries. The corresponding *quantile path* can then be applied to all other gases in that region. If desired, the same quantile path may be applied to all regions. For a discussion on the validity of such an assumption of 'equal quantiles' the reader is referred to Section 5.1.1 with alternatives being briefly discussed in Section 5.1.7. Theoretically, one could for example also prescribe aggregate emissions as they are controlled under the Kyoto Protocol (Kyoto gases) and any consecutive treaties using 100-yr GWPs.[14] Specifically, one could derive the corresponding *quantile path* by projecting the prescribed aggregate emissions onto the distribution of possible aggregate emission levels implied by the underlying scenarios. Such quantile paths, possibly regionally differentiated due to different commitments, could then be applied to all gases individually in the respective regions, provided a pool of standardized scenarios for the same regional disaggregation existed.

In this study, we have adopted a fairly conventional set of climate policy assumptions to derive the emissions pathways. One of the key agreed principles in the almost universally ratified United Nations Framework Convention on Climate Change (UNFCCC, Article 3.1) is that of "common but differentiated responsibilities and respective capabilities" which requires that "developed country Parties should take the lead in combating climate change".[1] As a consequence, it is appropriate to allow the emission reductions in non-Annex I regions[6] to lag behind the driver. Furthermore, a constant reduction rate (exponential decline) of absolute OECD fossil CO_2 emissions has been assumed for 'peaking' scenarios after a predefined 'departure year' from the baseline emission scenario (here assumed to be the median over all 54 IPCC scenarios). For 'stabilization' scenarios, the annual rate of reduction was allowed to change once in the future in order to lead to the desired stabilization level (see inset 2 within Figure 1). A constant annual emission reduction rate has been chosen for two reasons: (a) simplicity, and (b) because of the fact that such a path is among those that minimize the maximum of annual reductions rates needed to reach a certain climate target.

Up to the predefined *departure year*, e.g. 2010, emissions follow the median scenario (quantile 0.5; cf. Figure 3). The departure year can differ from region to region and indeed, as noted above, this is required by the UNFCCC and codified further in the principles, structure and specific obligations in the Kyoto Protocol.

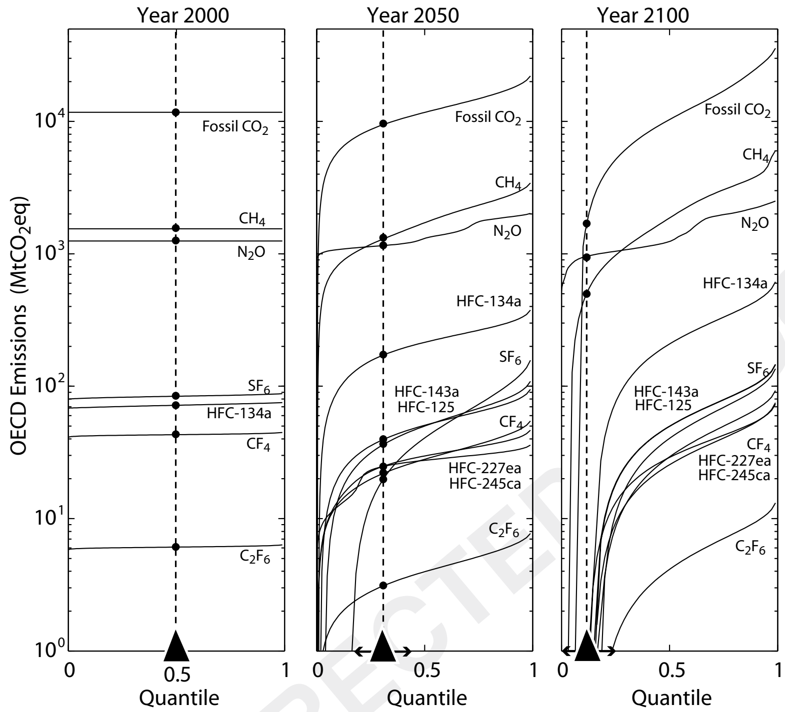

Figure 3. The derived distributions of possible emission levels displayed as (inverse) cumulative distribution functions for OECD countries in the years 2000 (right), 2050 (middle) and 2100 (left). The nearly horizontal lines for the year 2000 (left panel) illustrate that all 54 underlying scenarios share approximately the same emission level assumptions for the year 2000 (basically because these scenarios are standardized). In later years, here shown for 2050 and 2100, the scenarios' projected emissions diverge, so that the lower percentile (left side of each panel) corresponds to lower emissions compared to the upper percentile (right side of each panel) of the emission distributions. Thus, the slope of cumulative emission distribution curves goes from lower-left to upper-right. New mitigation pathways are now constructed by assuming a set of emissions for each year that corresponds to the same quantile (black triangles) in a respective year. These quantiles can for example be chosen so that a prescribed emission path for fossil CO_2 is matched. The non-fossil CO_2 emissions are then chosen according to the same quantile (see dots on dashed vertical lines). The same procedure is applied to other non-OECD world regions by using either the same or different quantile path (see text). For this illustrative figure (but not for any of the underlying calculations within the EQW method), all emissions have been converted to Mt CO_2-equivalent using 100-yr GWPs.[14] Note the logarithmic vertical scale, which causes zero and negative emissions not being displayed.

Here non-Annex I countries are assumed to diverge from the baseline scenario a bit later (2015) than Annex-I countries (2010) and follow a *quantile path* that corresponds to a hypothetically delayed departure of fossil fuel CO_2 emissions in OECD countries.

Generally, it should be noted that there could be a difference between actual emissions and the assumed emission limitations in each region to the extent that emissions are traded between developed and developing countries.

3.3. FINDING EMISSIONS PATHWAYS

Once the non-parametric *distributions of possible emission levels* (Section 3.1) are defined and the *quantile paths* (3.2) prescribed, multi-gas emissions pathways for any possible climate target can be derived. For any specific year, the emission levels of each greenhouse gas and aerosol for different regions are selected according to a specific single quantile for the particular year and region. This will result in a set of emissions that is 'comparably low' or 'high' in relation to the underlying pool of existing emission scenarios (see Figure 3). As a final step a smoothing spline algorithm has been applied to the individual gases pathways other than the driver path, restricted to the years after the regions' departure year from the baseline scenario.

3.4. THE CLIMATE MODEL

All major greenhouse gases and aerosols are inputs into the climate model, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), the two most relevant perfluorocarbons (CF_4, C_2F_6), and five most relevant hydrofluorocarbons (HFC-125, HFC-134a, HFC-143a, HFC-227ea, HFC-245ca), sulphur hexafluoride (SF_6), sulphate aerosols (SO_2), nitrogen oxides (NO_x), non-methane volatile organic compounds (VOC), and carbon monoxide (CO). Emissions of these gases are calculated for the different climate targets using the EQW method. Thus, these emissions were varied according to the stringency of the climate target. For the limited number of remaining human-induced forcing agents, the assumed emissions follow either a '*one size fits all*' or '*scaling*' approach, due to the lack of data within the pool of SRES and Post-SRES scenarios. Specifically, the forcing due to substances controlled by the Montreal Protocol is assumed to be the same for all emissions pathways. Similarly, emissions of other halocarbons and halogenated compounds aside from those eight explicitly modeled are assumed to return linearly to zero over 2100 to 2200 ('*one size fits all*'). The combined forcing due to fossil organic carbon and black organic carbon was scaled with SO_2 emissions after 1990 ('*scaling*'), as in the IPCC TAR global-mean temperature calculations.

A brief description of the default assumptions made in regard to the employed simple climate model MAGICC and natural forcings are given in the Appendix.

4. 'Equal Quantile Walk' Emissions Pathways

The following section presents some results in order to highlight some of the key characteristics of the EQW method. First, we compare the results of the EQW method with previous CO_2 concentration stabilization pathways. It is shown that there can be a considerable difference in terms of non-CO_2 forcing for the same CO_2

stabilization level, which is the result of EQW pathways taking into account the non-CO_2 mitigation potentials to the extent that they are included in the underlying multi-gas scenarios. Second, we examine two sets of peaking pathways, where the global mean radiative forcing peaks and hence where concentrations do not necessarily stabilize (not as soon as under CO_2 stabilization profiles at least). In principle, these may be useful in examining emissions pathways corresponding to climate policy targets that recognize that it may be necessary to lower peak temperatures in the long term in order to take account of–for example–concerns over ice sheet stability (Oppenheimer, 1998; Hansen, 2003; Oppenheimer and Alley, 2004). Provided one makes specific assumptions on the most important climate parameters, such as climate sensitivity, one could also derive temperature (rate) limited pathways (not shown in this study).

4.1. COMPARISON WITH PREVIOUS PATHWAYS

This section compares EQW multi-gas emissions pathways with emissions of the S and WRE CO_2 stabilization profiles. In order to allow a comparison between these emissions pathways, sample ‘EQW’ emissions pathways were designed to reach CO_2 stabilization at 350 to 750 ppm. After the default departure years (2010 for Annex I regions and 2015 for non-Annex I), the quantile path corresponds to a rate of reduction of OECD fossil CO_2 emissions between −5.2% and −0.5% annually depending on the stabilization level. These annual emission reductions are adjusted at a point in the future (derived in the optimization procedure) in order to allow CO_2 concentrations to stay at the prescribed stabilization levels (see Table II).

While fossil CO_2 emissions between WRE and these sample EQW pathways converge in the long-term, the near and medium-term fossil CO_2 emissions differ (see Figure 4). For the lower stabilization levels, the assumptions chosen here for the EQW pathways lead to slightly higher fossil CO_2 emissions than the WRE pathways, which is mainly due to the fact that the land-use related CO_2 emissions are substantially lower under the EQW than under WRE. For the same reason, cumulative fossil CO_2 emissions are slightly higher for the EQW pathways than for the corresponding WRE pathways (not shown in figures). For the less stringent profiles, namely stabilization levels between 550 and 750 ppm, the EQW assumptions lead to fossil CO_2 emissions that are lower in the near term, but decline more slowly and are higher in the 22nd century and beyond. The main reason for this difference might be of a methodological nature rather than founded on differing explicit assumptions on ‘early action’ vs. ‘delayed response’. As for the original S profiles and many recent stabilization profiles (Eickhout et al., 2003), the WRE profiles were defined as smoothly varying CO_2 concentration curves using Padé approximants (cf. Enting et al., 1994) and emissions were determined by inverse calculations. In contrast to this ‘top-down’ approach, the EQW method can be categorized as a ‘bottom-up’ approach in the transient period up to CO_2 stabilization,

TABLE II

Reduction rates for OECD fossil CO_2 (*driver paths*), World fossil CO_2 and World aggregated Kyoto gases (6-GHGs) with and without 'Other CO_2' that are compatible with reaching CO_2 stabilisation levels from 350 to 750 ppm according to the EQW method. After the departure years (2010/2015 for Annex-I/ non-Annex I), OECD fossil CO_2 emissions are assumed to decrease at a constant rate ('Reduction rate I'). From the '*adjustment year*' onwards, the annual emission reduction rate is reduced in order to stabilize CO_2 concentrations ('Reduction rate II'). The three presented parameter values, reduction rate I and II and the adjustment year, are optimal in the sense, that the resulting CO_2 concentration profiles best match the prescribed stabilization levels under a least-squares goodness-of-fit indicator. Other sources' and gases' emissions follow the same *quantile path* (see Section 3.3) resulting in variable worldwide reduction rates for fossil CO_2 and aggregated emissions (using 100-yr GWPs) over time

	OECD Fossil CO_2			World Fossil CO_2	World 6-GHGs excl. 'Other CO_2'	World 6-GHGs incl. 'Other CO_2'
CO_2 stabilization level (ppm)	Reduction rate I (%/year)	Adjustment year	Reduction rate II (%/year)	Range reduction rates 2020–2100 (%/year)	Range reduction rates 2020–2100 (%/year)	Range reduction rates 2020–2100 (%/year)
350	−5.17	2120	0.00	−1.05 to −4.64	−0.61 to −3.24	−0.28 to −5.19
450	−2.18	2070	−0.74	−0.62 to −1.31	−0.65 to −0.93	−0.71 to −1.57
550	−0.93	2211	−0.38	+0.62 to −1.01	+0.40 to −0.82	+0.03 to −1.12
650	−0.63	2327	−0.01	+0.86 to −0.67	+0.66 to −0.59	+0.40 to −0.77
750	−0.46	2379	0.00	+0.98 to −0.48	+0.80 to −0.44	+0.59 to −0.55

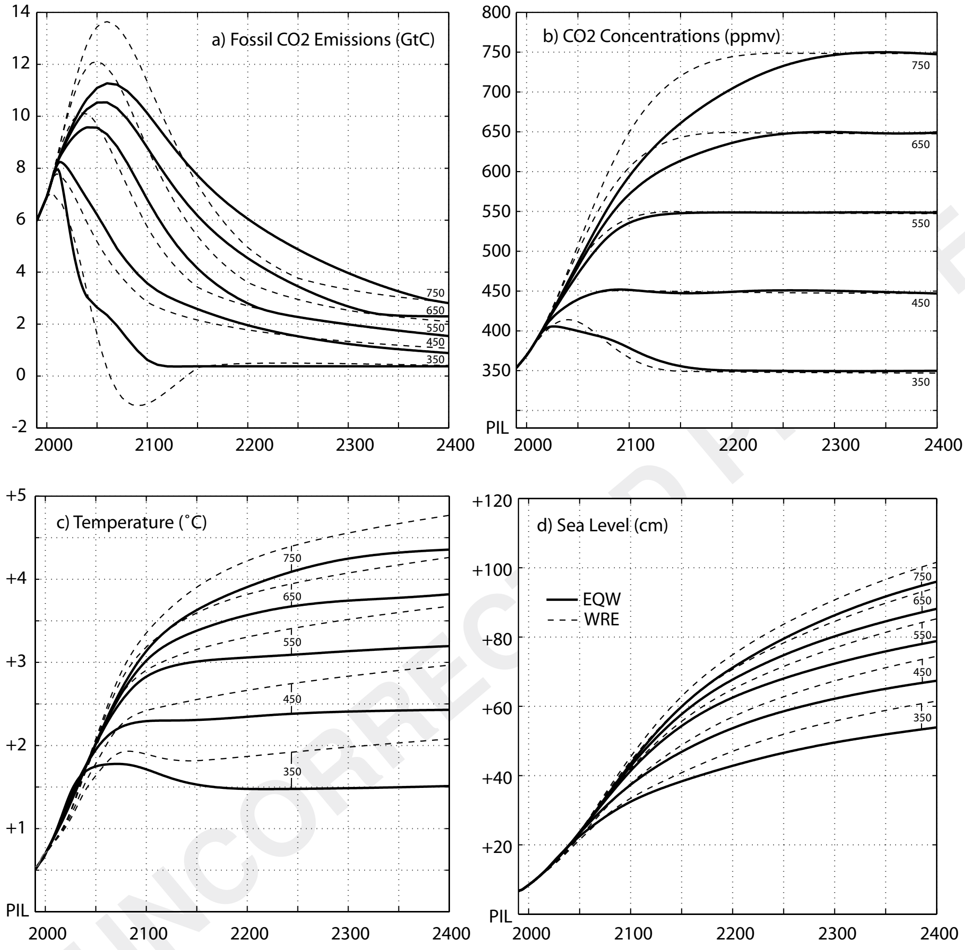

Figure 4. Comparison of WRE profiles (dashed) with EQW profiles (solid). (a) Fossil CO_2 pathways differ (see text) for the (b) prescribed CO_2 stabilization levels at 350, 450, 550, 650 and 750 ppm. (c) Global mean surface temperature increases above pre-industrial levels ('PIL') are lower for the EQW profiles for any CO_2 stabilization (c) due to lower non-CO_2 emissions. Correspondingly, sea level increases are lower for EQW profiles (d). As in the IPCC TAR (cf. figure 9.16 in Cubasch et al., 2001), the WRE CO_2 emissions pathways are here combined with non-CO_2 emissions according to the IPCC SRES A1B-AIM scenario (dashed lines).

since the profile towards CO_2 stabilization is prescribed by multiple constraints on the fossil CO_2 emissions rather than on CO_2 concentrations themselves.

Under the most stringent of the analyzed CO_2 concentration targets, stabilization at 350 ppm, near term fossil CO_2 emissions depart, slightly delayed, from the baseline scenario in comparison to the WRE350 pathway, which assumes a global departure in 2000 (cf. Figure 4). Compared to the S-profiles, this difference (for all stabilization levels) is even larger as the S profiles assume an early start of emission reductions in the 1990s and a smoother path thereafter, which already seems unachievable today, due to recent emissions increases.

A comparison including non-CO_2 gases can be done using the WRE profiles as they are presented in the IPCC TAR (see figure 9.16 in Cubasch et al., 2001). There, the effects for the WRE CO_2 stabilization profiles are computed by assuming non-CO_2 gas emissions according to the A1B-AIM scenario (see Figure 4 and Figure 5. For the comparison, it is thus important to keep in mind that the EQW pathways are not compared to the WRE CO_2 profiles *per se*, but to the WRE pathways in combination with this specific assumption for non-CO_2 emissions.

The EQW method chooses non-CO_2 emissions on the basis of the CO_2 quantile, which for all analyzed CO_2 stabilization profiles implies that it chooses emissions significantly below the A1B-AIM levels–as also the fossil CO_2 emissions are below those of the A1B-AIM scenario. Mainly due to these lower non-CO_2 emissions, the radiative forcing implications related to EQW pathways are significantly reduced for the same CO_2 stabilization level when compared to WRE pathways, i.e. for stabilization at 450 ppm (see Figure 5). Partially offsetting this ‘cooling’ effect is the reduced negative forcing due to decreased aerosol emissions. The negative forcing from aerosols can be significant (cf. dark area below zero in Figure 5) and can mask some positive forcing due to CO_2 and other greenhouse gases. In the year 2000, this masking is likely to be about equivalent to the forcing due to CO_2 alone (the upper boundary of the “CO_2” area is near the zero line in Figure 5). However, note that large uncertainties persist in regard to the direct and indirect radiative forcing of aerosols (see e.g. Anderson et al., 2003).[7] The total radiative forcing for the WRE450 scenario in 2400 is ca. 3.9 W/m^2 and around 3 W/m^2 for the EQW-S450C.

Owing to the effect on radiative forcing, the lowered non-CO_2 emissions that result from the EQW method lead to less pronounced global mean temperature increases in comparison to the WRE CO_2 stabilization profiles in combination with the A1B-AIM non-CO_2 emissions. For the same CO_2 stabilisation levels, the corresponding temperatures are about 0.5 °C cooler by the year 2400 (assuming a climate sensitivity of approximately 2.8 °C by computing the ensemble mean over 7 AOGCMs-see Appendix A). Consequently, the sea level rise is also slightly reduced when assuming the EQW pathways (cf. Figure 4).

4.2. RADIATIVE FORCING (CO_2 EQUIVALENT) PEAKING PROFILES

A variety of climate targets can be chosen to derive emissions pathways with the EQW method. In this section, two sets of multi-gas emissions pathways are chosen so that the corresponding radiative forcing peaks between approximately 2.6 and 4.5 W/m^2 with respect to pre-industrial levels. The CO_2 equivalent peaking concentrations are 475 to 650 ppm (see Figure 6). No time-constraint is placed on the attainment of the peak forcing.

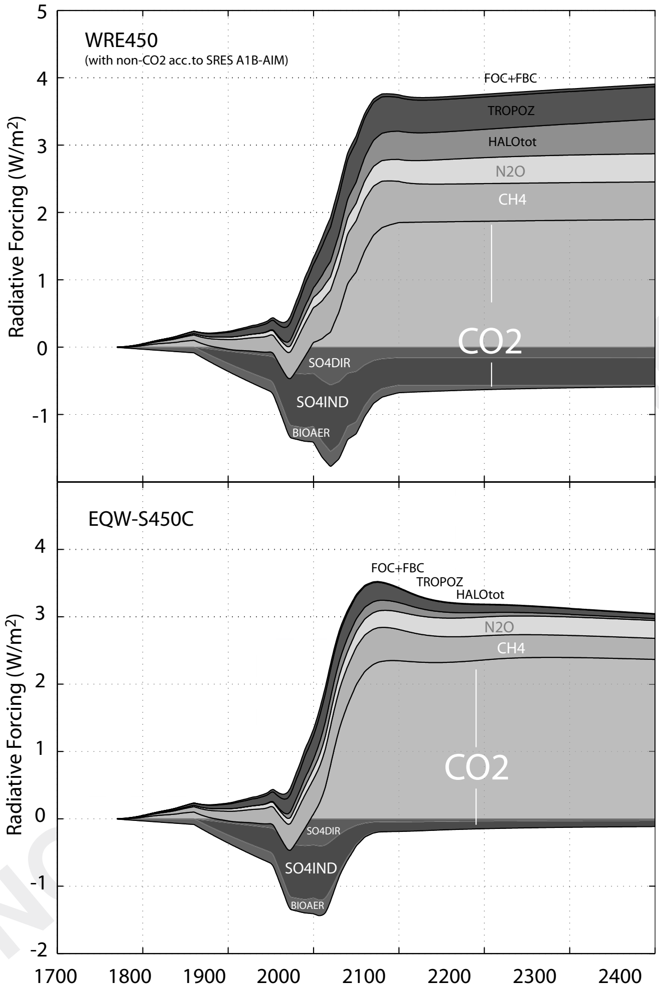

Figure 5. Aggregated radiative forcing as a result of the WRE emissions pathway (upper graph) and the EQW pathway (lower graph) for stabilization of CO_2 concentrations at 450 ppm. Since the 'EQW' multi-gas pathways take into account reductions of non-CO_2 gases, the positive radiative forcing due to CH_4, N_2O, tropospheric ozone ('TROPOZ'), halocarbons and other halogenated compounds minus the cooling effect due to stratospheric ozone depletion ('HALOtot') as well as the negative radiative forcing due to sulphate aerosols (indirect 'SO4IND' and direct 'SO4DIR') and biomass burning related aerosols ('BIOAER') is substantially reduced. The combined warming and cooling due to fossil fuel related organic & black carbon emissions ('FOC+FBC') is scaled towards SO_2 emissions (see text).

The first set 'A' of derived EQW peaking pathways assumes a fixed departure year, but variable rates of emission reductions thereafter. The second set 'B' holds the reduction rates of the driver emission path constant, but assumes varying departure years. Specifically, the peaking pathways 'A' assume a departure from the median emission scenario in 2010 for Annex I countries (IPCC SRES regions

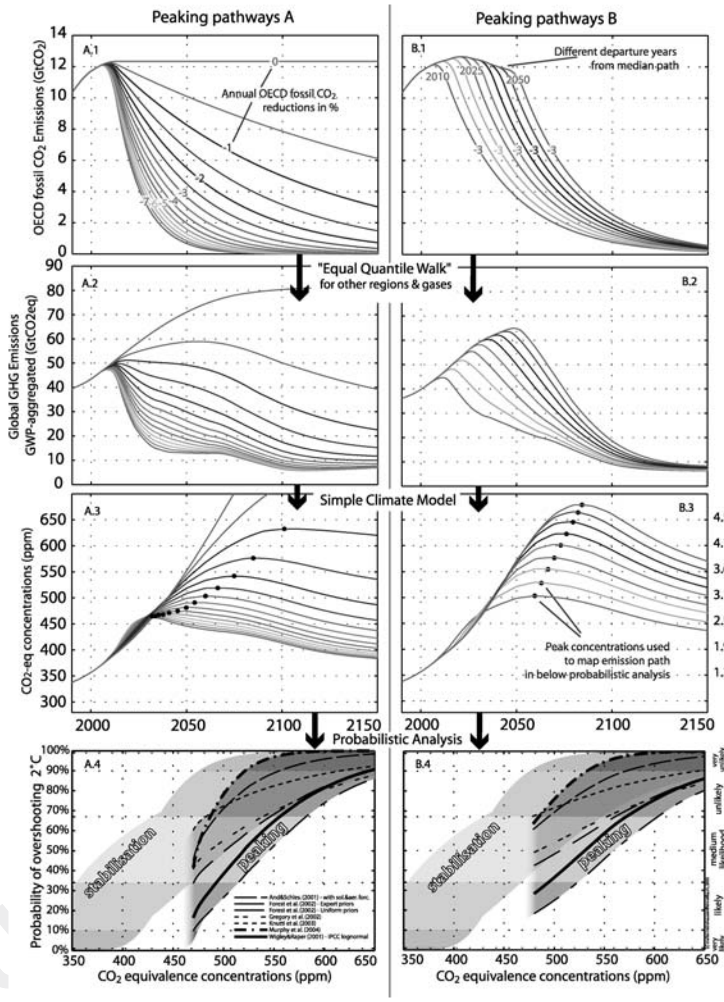

Figure 6. Two sets of multi-gas pathways derived with the EQW method. The two sets are distinct in so far as set A assumes a fixed departure year from the median emission path (2010) and a different reduction rate thereafter (−7% to 0%) (A.1). The pathways of set B assume a fixed reduction rate for OECD fossil CO2 emissions (−3%/yr), but variable departure years. Emissions of other gases and in other regions follow the corresponding quantile paths (see text). For illustrative purposes, the GWP-weighted sum of greenhouse gas emission is shown in panels A.2 and B.2. Using a simple climate model, the radiative forcing implications of the multi-gas emissions pathways can be computed, here shown as CO_2 equivalent concentrations with black dots indicating the peak values (A.3 and B.3). The temperature implications are computed probabilistically for each peaking pathway using a range of different climate sensitivity pdfs (see text). In this way, one can illustrate the probability of overshooting a certain temperature threshold (here 2°C above pre-industrial) under such peaking pathways given different climate sensitivity probability distributions (dashed lines in darker shaded area of A.4 and B.4). Lighter shaded areas depict the probability of overshooting 2°C in equilibrium in case that concentrations were stabilized and not decreased after the peak. The full set of emission data is available at http://www.simcap.org.

OECD[13] and a departure in 2015 for non-Annex I countries (ASIA & ALM). OECD fossil CO_2 emissions, the driver emission path, are assumed to decline at a constant rate, which differs between the individual pathways ‘A’, after the fixed departure year. The second set ‘B’ of peaking pathways assumes a departure year from the median emission scenario between 2010 and 2050 for Annex I countries (5 years later for non-Annex I countries), and a 3% decline of OECD fossil CO_2 driver path emissions. As highlighted in the method section, emissions in non-OECD regions and from non-fossil CO_2 sources are assumed to follow the *quantile path* corresponding to the preset driver path (see Figure 6, Section 3.2 and 3.3).

For the derived emissions pathways that peak between 470 and 555 ppm CO2eq, global fossil CO_2 emissions are between 46% to 113 % of 1990 emission levels in 2050 (see Table III) and 11% to 33% in 2100, depending on the peaking target.

In parallel to the greenhouse gas emissions, the EQW method derives aerosol and ozone precursor emissions that are ‘*comparably low*’ in regard to the underlying set of SRES/Post-SRES scenarios. Thus, despite the fact that sulphate aerosol precursor emissions (SO_x) have a cooling effect, SO_x emissions are assumed to decline sharply for the more stringent climate targets (see Table III). The linkage between SO_x and CO_2 emissions is also seen in mitigation scenarios from coupled socio-economic, technological model studies and is partially due to the fact that both stem from a common source, namely fossil fuel combustion (see as well Section 5.1.1). Another reason is that mitigation scenarios represent future worlds which inherently include environmental policies in both developed and developing countries-where the abatement of acid deposition and local air pollution has usually even higher priority than greenhouse gas abatement.

Depending on the shape of the emissions pathways (e.g. set A or B), and depending on the peak level between 470 and 650 ppm CO_2eq, radiative forcing peaks between 2025 and 2100. After peaking, radiative forcing (CO_2 equivalence concentrations) stays significantly above pre-industrial levels for several centuries. This is mainly due to the slow redistribution process(es)? for CO_2 between the atmospheric, oceanic and abyssal sediment carbon pools.

The temperature response of the climate system is largely dependent upon its climate sensitivity, which is rather uncertain. A range of recent studies have attempted to quantify this uncertainty in terms of probability density functions (PDFs) (see e.g. Andronova and Schlesinger, 2001; Forest et al., 2002; Gregory et al., 2002; Knutti et al., 2003; Murphy et al., 2004). These studies are used here to compute each emissions pathway’s probabilistic climate implications by running the simple climate model with an array of climate sensitivities, weighted by their respective probabilities according to particular climate sensitivity PDFs. The probabilistic temperature implications of the radiative forcing peaking pathway sets can then be shown in terms of their probability of overshooting a certain temperature threshold, here chosen as 2 °C above pre-industrial levels (see it Figure 6). The faster the radiative forcing drops to lower levels after the peak, the less time there is for the climate system to reach equilibrium warming. Thus, for peak levels of 550 ppm

TABLE III

Specifications (I), emission implications (II) and risks of overshooting 2°C (III) for three radiative forcing peaking pathways (cf. Figure 6). Departure years and annual OECD fossil CO_2 emission reductions (‘driver path’) were prescribed. For illustrative purposes only, greenhouse gas emissions (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) were aggregated using 100-year GWPs[14] including and excluding landuse related CO_2 emissions (‘other CO_2’). The maximum CO_2 equivalence concentration (radiative forcing) is shown and its associated risk of overshooting 2°C global mean temperature rise above pre-industrial for a range of different climate sensitivity probability density function estimates (see text). The risk of overshooting is clearly lower for the peaking pathways, where concentrations drop after reaching the peak level, in comparison to hypothetical stabilization pathways, where concentrations are stabilized at the peak

	Peaking pathway 1	Peaking pathway 2	Peaking pathway 3
I. Specifications			
Set of pathway	A	A/B	B
Departure years (Annex I/Non-Annex I)	2010/15	2010/15	2020/25
Driver path OECD fossil CO_2 reduction	−5%/yr	−3%/yr	−3%/yr
II. Emission implications			
Emissions (1990 level)	2050 Emissions relative to 1990		
Fossil CO_2 (5.98 GtC)	46%	80%	113%
CH_4 (309 Mt)	77%	94%	112%
N_2O (6.67 TgN)	68%	76%	81%
GHG excl. other CO_2 (8.72 GtCeq)	55%	82%	110%
GHG incl. other CO_2 (9.82 GtCeq)	41%	65%	90%
SO_x (70.88 TgS)	4%	13%	26%
III. Peak concentration and risk of overshooting			
Peak concentration CO_2eq ppm (radiative forcing W/m^2)[18]	470 (2.80)	503 (3.17)	555 (3.70)
Risk >2 °C (peaking)	5–60%	25–77%	48–96%
Risk >2 °C (stabilisation)	35–88%	49–96%	69–100%

CO_2eq and above, the peaking pathways B involve slightly lower risks of overshooting a 2 °C temperature thresholds, as their concentrations decrease slightly faster than for the higher peaking pathways of set A. The risk of overshooting 2 °C would obviously be higher for both sets, if radiative forcing were not decreasing after peaking, but stabilized at its peak value, as depicted by the lighter shaded areas in Figure 6 A.4&B.4 (Azar and Rodhe, 1997; Hare and Meinshausen, 2004; Meinshausen, 2005).

In summary, it has been shown that the EQW method can provide a useful tool to obtain a large numbers of multi-gas pathways to analyze research questions in a probabilistic setting. Furthermore, the results suggest that if radiative forcing is not peaked at or below 475 ppm CO_2eq (~2.8 W/m^2) with declining concentrations thereafter, it seems that an overshooting of 2 °C can not be excluded with reasonable confidence levels (see Figure 6).

5. Discussion and Limitations

The following section discusses some of the potential limitations, namely those related to the EQW method itself (Section 5.1), and those related to the underlying pool of scenarios (Section 5.2). In addition, the use of a simple climate model implies some limitations briefly mentioned in Appendix A.

5.1. DISCUSSION OF AND POSSIBLE LIMITATIONS ARISING FROM THE METHOD ITSELF

The following section briefly discusses several issues that are directly related to the proposed EQW method: namely the assumption of unity rank correlations (5.1.1); the question, whether the individual underlying scenarios are assumed to have a certain probability (5.1.2); regional emission outcomes (5.1.4); the baseline (in-)dependency (5.1.5); land-use change related emissions and their possible political interpretations (5.1.5); alternative gas-to-gas and timing strategies (5.1.7); and the probabilistic framework (5.1.8).

5.1.1. *Unity Rank Correlation*

New emissions pathways produced with the EQW method will rank equally across all gases in a specific region for a specific year. In other words, an emissions pathway for a less stringent climate target (e.g. peaking at 550 ppm CO_2eq) has higher emissions for all gases and all regions compared to an emissions pathway for a less stringent climate target (e.g. 475 ppm CO_2eq).

Note that this inbuilt unity rank correlation assumption of the EQW method does not necessarily lead to positive absolute correlations between different gases' or regions' emissions. In other words, for a particular EQW mitigation pathway, emissions of one gas, e.g. CO_2 in Asia, might still be increasing in a particular year, while emissions of another gas, e.g. methane in OECD, are already decreasing depending on the emission distributions in the underlying pool of emission scenarios.

The unity rank correlation could be an advantage of the EQW approach. However, it could also be a limitation in the presence of negative rank correlations for emissions: for example, if fossil fuel emissions were largely reduced due to a replacement with biomass, a negative correlation might arise between fossil fuel CO_2 and biomass-burning related aerosol emissions, such as SO_x, NO_x etc. Thus, if fossil fuel CO_2 emissions decrease, some aerosol emissions might increase. NO_x

and N_2O emission changes may be negatively correlated up to a certain degree as well. Coupled socio-economic, technological, and land use models, such as those used for creating the SRES and Post-SRES scenarios, are generally able to account for these underlying anti-correlation effects. Thus, the following analysis assumes that an analysis of the SRES and Post-SRES scenarios can provide insights about real world dynamics in regard to whether inherent process based anti-correlations of emissions are so dominant, that the unity rank correlation assumption at given aggregation levels would be invalidated.

The question is, therefore, whether any negative rank correlations are apparent at the aggregation level considered here, namely the 4 SRES world regions. For the pool of existing SRES and Post-SRES scenarios that are used, no negative rank correlations between fossil fuel CO_2 and any other gases' emissions are apparent at this stage of aggregation by sources and regions (see Figure 7 and Appendix B). The rank correlation between fossil fuel CO_2 and 'Other CO_2' or 'N_2O total' is basically zero or rather small, while rank correlations with other gases are positive, especially for the ASIA and ALM region.

Between fossil fuel CO_2 and the land-use and agriculture dominated 'Other CO_2' and 'N_2O' emissions, there is little or no rank correlation. In other words, in

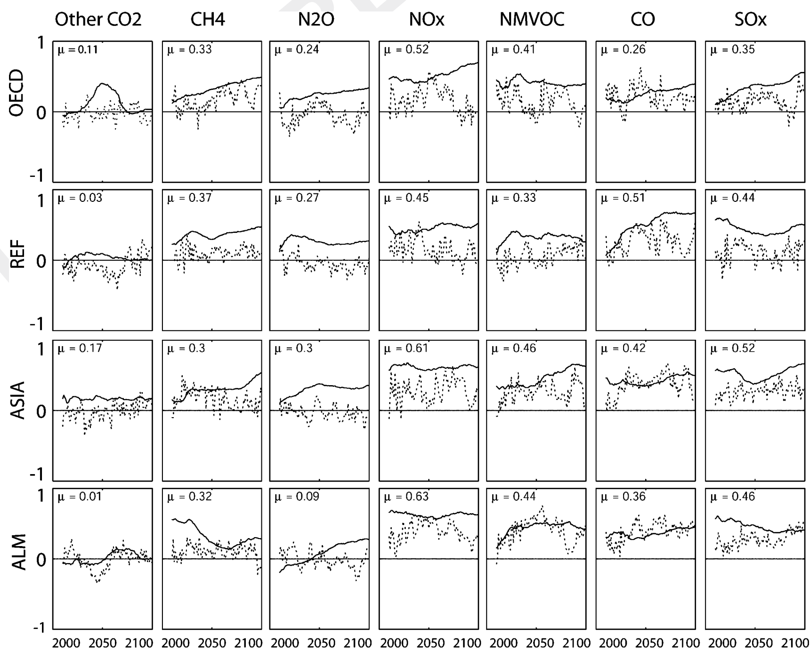

Figure 7. Rank correlations within the pool of existing SRES/Post-SRES scenarios between fossil fuel CO_2 emissions and other greenhouse gas emissions and aerosols (columns) for the 4 SRES World regions (rows). The Kendall rank correlation (solid line), its mean from 2010 to 2100 (μ) and the Spearman rank correlation (dotted lines) are given (see Appendix B).

the underlying SRES and post SRES data set, the sources of these emissions are largely unrelated. The primary reason for this is that 'Other CO_2' sources are at present dominated by tropical deforestation (Fearnside, 2000). Another reason why existing scenarios with low fossil fuel CO_2 emissions do not necessarily correspond to large reductions in deforestation emissions or large net sequestration appears to be that some modeling groups assume different policy mixes or different root causes of deforestation–potentially out of reach for climate policies.

In summary, the validity of the EQW approach is not limited as long as it is only applied at aggregation levels, where negative rank correlations are generally not evident, as is the case in this study. The fact that there are inherent, process based anti-correlations of certain emissions at local or more subsource-specific level(s), does not invalidate this unity rank correlation assumption, as long as these underlying anti-correlations are not dominant.

The differing population assumptions of the underlying scenarios might appear to be, at first sight, a reason for the positively rank correlated emissions across different gases. A scenario that assumes high population growth is likely to predict high human-induced emissions across all gases. However, a closer look at per-capita (instead of absolute) emissions shows that differing population assumptions are not the reason for the positively rank correlated emission levels nor the large variation of absolute emissions. Rank correlations across the different gases on a per-capita basis (a) are generally non-negative and (b) are not uniformly lower or higher across all regions and gases than do rank correlations that are based on absolute emissions. On average, these per capita rank correlations are only marginally lower than rank correlations based on absolute emissions. Specifically, the change of the mean Kendall rank correlation index over 2010 to 2100 is insignificantly different from zero (-0.008) when averaged over all gases. Maximal changes are $+0.07$ and -0.11 for some gases (standard deviation of 0.043), if per-capita emissions are analyzed instead of absolute emissions (cf. Figure 7).

Given the absence of negatively rank correlated emissions, the seeming disadvantage of the EQW approach, namely that it assumes unity rank correlation between fossil CO_2 emissions and those of other gases, might actually be an advantage. Since the EQW approach is primarily designed to create new families of *intervention* pathways, correlating reduction efforts between otherwise uncorrelated greenhouse gas sources might be a sensible characteristic. In other words, for those sources that are not correlated with fossil fuel CO_2 emissions, namely land-use dominated and agricultural emissions, the EQW approach suggests that a climate-policy-mix might tackle these sources in parallel to tackling fossil fuel emissions. Given that some policy options are available to reduce emissions in the land-use sector (see e.g. Pretty et al., 2002; see e.g. Carvalho et al., 2004)[8] it would seem very likely that the more a reduction effort is put into reducing fossil fuel related emissions, the more a parallel reduction effort will be put into reducing land-use related emissions as well.

5.1.2. *Assuming a Certain Probability of Underlying Scenarios?*

The application of some statistical tools within the EQW method assumes equal validity of each of the 54 scenarios within the underlying pool. This assumption, however, does not affect the outcome. As the following results show, the EQW method is rather robust to the relative 'probability' (weighting) within the scenario pool. Thus, the EQW method is largely independent of the assumed likelihood of single scenarios.

The sensitivity of the EQW method to different weightings of the underlying scenarios has been analyzed as follows. Four sensitivity runs have been performed. In each of them, members of one of the four IPCC scenarios families A1, A2, B1 and B2 have been multiplied three times. In effect, the original 54 plus the multiplied scenarios were then analyzed to derive the '*distributions of possible emission levels*', as outlined above (3.1). Keeping other parts of the EQW method the same, intervention pathways were derived for global-mean temperature peaking at 2 °C above the pre-industrial level. The results show that the pathways' sensitivities to the weighting are rather small. Obviously, if a scenario's frequency or weight-factor is changed, slightly different emissions pathways will result, since basically all scenarios differ with respect to relative gas and regional shares (see Table IV).

Obviously, assuming a different set of scenarios altogether in order to derive the *distribution of possible emission levels* might change the outcome considerably.

It should be kept in mind that the EQW method is not designed to determine how likely it might be that future emissions will be below a certain level. Similar to the medians calculated by Nakicenovic et al. (1998) for the IPCC database, the derived '*distributions of possible emission levels*' are by no means probability estimations (cf. e.g. Grubler and Nakicenovic, 2001). If, however, one would have a set of scenarios with a well defined likelihood for each of them, then more far reaching conclusions could be drawn instead of designing normative scenarios, as is done here.

5.1.3. *Sensitivity to Lower Range Scenarios*

If the EQW method produces a new emissions pathway near to or slightly outside the range of existing scenarios, there is a high sensitivity to scenarios in the underlying data base that are at the edge of the existing distribution. Certain measures can and are applied to limit this sensitivity, and its undesired effects, by (a) using an appropriate kernel-width to derive the 'distribution of possible emission levels' (see Section 3.1), (b) enlarging the pool of underlying scenarios by explicit intervention scenarios at the lower edge of the distribution, namely by the inclusion of Post-SRES stabilization scenarios, while at the same time (c) restricting the pool to scenarios of widely accepted modeling groups with integrated and detailed models.

Clearly, entering 'unexplored' terrain with this approach is only a second best option in the absence of fully developed scenarios for the more stringent climate targets. Ideally, the EQW method would be applied on a large pool of scenarios including those with the most stringent climate targets. Such fully developed mit-

TABLE IV

Sensitivity analysis with respect to the underlying SRES scenario family frequencies. The common climate target 'peaking below 2°C' is prescribed for and met by all 5 pathways assuming a climate sensitivity of 2.8°C (7 AOGCM ensemble mean). Whereas the first pathway (EQW-P2T) was derived by using the underlying data pool of 54 unique scenarios, the four sensitivity pathways were derived by multiplying the frequency of A1, A2, B1 or B2 scenario family members three times (3 × A1 to 3 × B2). Shown are the emission levels in 2050 compared to 1990 levels for different gases (a) and regions (b) and the annual reduction rate for OECD fossil CO2 emissions (c)

	EQW-P2T (%)	3 × A1 (%)	3 × A2 (%)	3 × B1 (%)	3 × B2 (%)
(a) Gas-by-gas results for region "World"					
(Emission levels in 2050 compared to 1990)					
Fossil CO_2	73	68	71	78	82
CH_4	91	93	87	96	82
N_2O	74	78	75	73	74
F-gases	67	64	58	71	64
6-gas	76	74	75	80	80
6-gas (incl. 'Other CO_2')	61	60	60	65	65
(b) Regional results for "6-gas" (incl. 'Other CO_2')					
(Emission levels in 2050 compared to 1990)					
OECD	37	34	35	41	43
REF	11	13	8	18	5
ASIA	110	110	112	109	118
ALM	85	78	80	90	85
World	61	60	60	65	65
(c) Driver path					
(Annual reduction rate)					
OECD fossil CO_2	−3.3	−3.6	−3.6	−2.9	−2.6

igation scenarios might be increasingly available in the future. For example, new MESSAGE and IMAGE model runs (Nakicenovic and Riahi, 2003; van Vuuren et al., 2003) and forthcoming multi-gas scenarios developed within the Energy Modeling Forum EMF-21 (see e.g. de la Chesnaye, 2003) could build the basis of updated EQW pathways.

5.1.4. *Regional Emissions & Future Commitment Allocations*

Geo-political realities, the historic responsibility of different regions, their ability to pay, capability to reduce emissions, vulnerability to impacts as well as other fairness and equity criteria will inform the global framework for the future differentiation of reduction commitments. Thus, splitting up a global emissions pathway and choosing a commitment differentiation is not solely a scientific or economic issue, but rather a (sensitive) political one.

Regionally different emission paths result from the application of the EQW method to the 4 SRES regions. This is a direct consequence of the regional emission shares within the pool of underlying SRES / Post-SRES scenarios as well as possibly regionally differentiated *departure years* from the median (see Section 3.2). Thus, the EQW method is not, in itself, an emission allocation approach based on explicit differentiation criteria. The method captures the spectrum of allocations in the pool of underlying existing scenarios and allows for some flexibility by setting regionally differentiated departure years for example.

Under default assumptions, the derived emissions pathways entail an increasing share of non-Annex I emissions independent of the climate target (Figure 8). This is in accordance with many of the approaches for the differentiation of future commitments (den Elzen, 2002; Höhne et al., 2003). Nevertheless, a sensitivity analysis with different climate parameters, departure years and possibly different quantile paths for different regions allows making important contributions in the discussion on future commitments. In addition, EQW pathways can be used as input for detailed emission allocation analysis tools, such as FAIR (den Elzen and

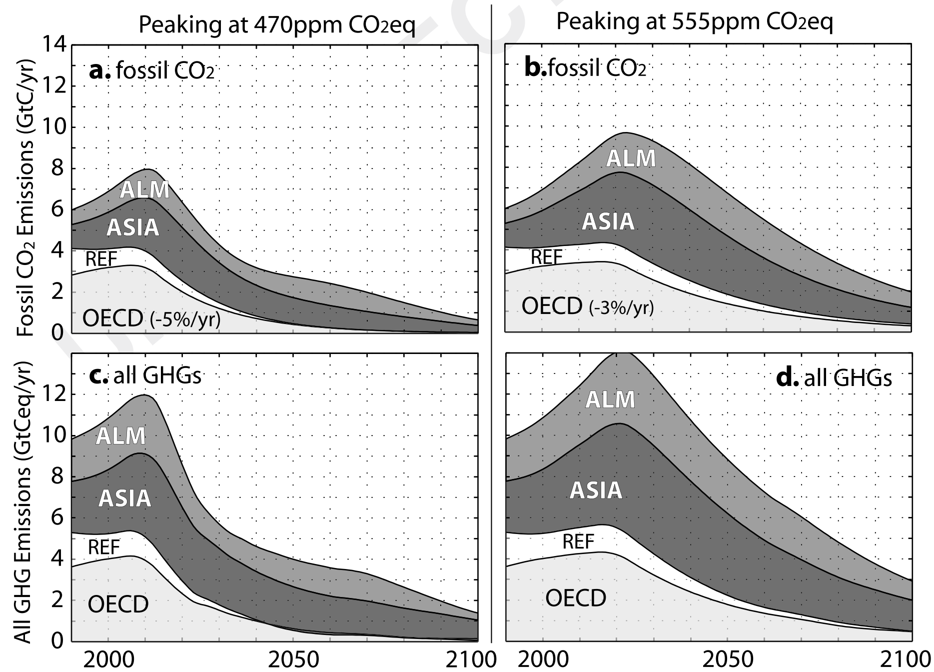

Figure 8. The regional implications of EQW emissions pathways for a peaking at 470 ppm CO_2eq (a, c) and 555 ppm CO_2eq (b, d). Whereas Annex I countries (bright slices OECD and REF) caused the lion's share of emissions in the past, the more populated non-Annex I regions (darker slices ALM and ASIA) are projected to cause higher emissions in the future under the derived intervention pathways. This characteristic holds for fossil CO_2 emissions (top row) and the aggregated set of greenhouse gas emissions including land-use related CO_2 emissions (lower row).

Lucas, accepted), in order to obtain assessments of future climate regime proposals that are consistent with certain climate targets.

5.1.5. *Baseline Independency & Absence of Socio-Economic Paths*

In line with the most popular previous mitigation pathways, the derived pathways do not attempt to reflect a certain socio-economic development pathway. The socio-economic characteristics of a future world can hardly be derived by walking along certain quantiles of the distributions of GDP development, productivity, fertility, etc. As pointed out by Grubler and Nakicenovic (2001): "Socioeconomic variables and their alternative future development paths cannot be combined at will and are not freely interchangeable because of their interdependencies. One should not, for example, create a scenario combining low fertility with high infant mortality, or zero economic growth with rapid technological change and productivity growth – since these do not tend to go together in real life any more than they do in demographic or economic theory."

The lack of a socio-economic description of the future world is a disadvantage of the EQW method in comparison to intervention scenarios derived according to fully developed scenario approaches with or without cost-optimization (see methods three and four as described in Section 1). However, the baseline independency and more general nature of the presented EQW pathways allows for a more ubiquitous application and for further comparative analyses in regard to the emission implications of certain climate targets. Alternatively, a restriction of the underlying pool of scenarios to one specific scenario family would allow the derivation of baseline-dependent intervention pathways.

5.1.6. *Land-Use-Change Related Emissions – A Word of Caution*

The following paragraph is a general word of caution on the interpretation of land-use related sinks and emissions within the EQW pathways. There are several distinctive characteristics of land-use versus energy related emission reductions that complicate their appropriate reflection and interpretation in intervention scenarios. Firstly, in regard to land-use related CO_2 net removals (cf. Figure 6, left column, graph b): sequestration might not bind the carbon for a very long time. Today's biospheric sinks might turn into tomorrow's sources. Therefore, enhancement of (temporary) biospheric CO_2 sequestration is not equivalent to restricting fossil fuel related emissions under a long-term perspective (Lashof and Hare, 1999; Kirschbaum, 2003; Harvey, 2004). Secondly, the root causes of land-use related emissions are even more complex for land-use emissions than for energy related emissions (Carvalho et al., 2004). Thus, without a carefully balanced policy mix, negative side effects for biodiversity, watershed management, and local communities might offset carbon uptake related benefits under a broader sustainability agenda. Thirdly, land-use related emission allowances under the current rules of the Kyoto Protocol are largely windfall credits that do not reflect additional sequestration or real emission reductions. Fourthly, 'natural' variability of the biospheric carbon stock poses risks for the regime stability of an emission control architecture. Given these issues, the presented results should be regarded with care. In particular, they should not be misinterpreted as a call for the advancement of sink related emission allowances in the way followed so far under the international climate change regime.

5.1.7. *Studying Alternative Gas-to-Gas and Timing Strategies*

Some studies analyze the relative merits of focusing reduction efforts on some specific radiative forcing agents, such as methane and ozone precursors (see e.g. Hansen et al., 2000). Deriving alternative emissions pathways that reflect differing gas-to-gas mitigation strategies for the same climate target might thus be a desirable part of a broader sensitivity analysis. The method could be extended by applying different '*quantile paths'* to different gases, not only different regions. Such a 'Differentiated Quantile Walk' method could allow systematically analyzing different mitigation strategies. For example, methane and nitrous oxide emissions could be reduced according to a '*quantile path*' that is equivalent to a 3% annual reduction of fossil fuel CO_2 emissions, while in fact fossil CO_2 is reduced by only 2% annually (cf. Section 3.2).

The flexible nature of the EQW method allows deriving pathways with different timings for emission reductions. As already demonstrated by the presentation of stabilization and peaking profiles, emissions pathways for various *target paths* can be derived. Depending on the definition of the *index* or *quantile paths* (Sections 3.2 and 3.3), emissions pathways can be designed that result in a monotonic increase of temperature or CO_2 concentrations up to a final target level with stabilization thereafter or subsequent dropping (e.g. overshooting (see e.g. Wigley, 2003b) or peaking profiles). Furthermore, the possibility to freely define the departure year for various regions allows future studies to undertake sensitivity studies contributing to the debate on '*early action*' versus '*delayed response*' (cf. Section 1 and Meinshausen, 2005).

5.1.8. *Probabilistic Framework*

The EQW method can be used to systematically explore the effect of uncertainties in the climate system upon emission implications in a probabilistic framework (see Section 4.2). A probabilistic framework is important to allow for the definition of an optimal hedging strategy against dangerous climate change. Any 'best guess' parameter model runs might lead to a systematic underestimation of optimal reduction efforts. A 'best guess' answer in regard to the emission implications will only imply a 50% certainty to actually achieve the climate target. Under both a '*cost-benefit*' and a '*normative target*' policy framework, policymakers might want to design more ambitious reduction policies in order to hedge against the possibility of overshooting the target or against the possibility of costly mid-course adjustments. Specifically, fossil fuel related CO_2 emissions (allowances) in OECD countries would have to decrease by 3% annually after 2010, with emissions from other sources and regions corresponding to the same quantile path, in order to limit the risk of overshooting 2 °C to 25% to 77% (see Table III). 3% annual emission reductions may not be sufficient, if one wishes to ensure that the warming trajectory never exceeds the 2 °C target with a higher certainty.

5.2. DISCUSSION OF LIMITATIONS ARISING FROM THE UNDERLYING DATABASE

The derived emissions pathways will inevitably share some of the limitations of the underlying pool of existing scenarios. In the following, quantitative and qualitative limitations of the scenario database are briefly highlighted (Section 5.2.1). Subsequently, one of the qualitative limitations, namely the potentially inadequate reflection of land-use related non-CO_2 emissions, is discussed in more detail and a comparison to recently developed cost-optimized mitigation scenarios is drawn (Section 5.2.2).

5.2.1. *Quantitatively and Qualitatively Limited Pool of Scenarios*

The 54 SRES and Post-SRES scenarios used in this study provide a solid basis for the derived emissions pathways. However, as the number and quality of long-term emission scenarios will increase in the future, thanks to ongoing concerted research efforts, the quality of and level of detail in the derived EQW pathways should also be enhanced. Most importantly, the sensitivity to single scenarios would be lowered by basing the EQW method on more scenarios, provided that these scenarios are in turn based on sound and independently researched studies of mitigation potentials. Lowering this sensitivity to single scenarios seems especially warranted for the lower emissions pathways (cf. Section 5.1.3). Going beyond the mere number of scenarios, an extended time horizon, and higher detail in terms of (standardized) regional and source-specific information in the scenarios, would enhance the usefulness of derived EQW pathways.

Furthermore, some qualitative limitations within the set of used SRES and Post-SRES should be kept in mind when using the presented EQW pathways. For example, the SRES and Post-SRES scenarios were developed prior to the year 2000. Thus, the original scenarios and the derived intervention emissions pathways might not fully match actual emissions up to the present day, although differences seem to be limited (van Vuuren and O'Neill, submitted).

5.2.2. *A Comparison with Recently Derived Multi-Gas Scenarios*

The Post-SRES scenarios within the underlying pool might have one shortcoming in common: all those scenarios were primarily focused on energy related reduction potentials with little details on other sectors and sources, such as land-use related non-CO_2 emissions (see e.g. Jiang et al., 2000; Morita et al., 2000).

To explore this potential limitation, a comparison with some of the recent mitigation scenarios has been done, which have been developed in relation to a coordinated modeling effort in the context of the Energy Modeling Forum (de la

Chesnaye, 2003). These scenarios are designed to find cost-optimized multi-gas reduction paths with a more sophisticated representation of non-CO_2 greenhouse gases than captured by most previous scenarios. For that purpose, a standardized database of mitigation measures for the most important sources of CH_4, N_2O and halocarbons and halogenated compounds was developed. The various modeling groups used different approaches, ranging from macro-economic models to more technology-rich and integrated assessment ones. For the most important sources of CH_4 and N_2O, i.e., agricultural and land use-related sources, the measures captured in the range of 10–50% of total emissions at cost levels of 200 US$/tC. For energy and industrial sources, the potential reductions were higher-and ranged up to nearly 100%. After incorporating the non-CO_2 reduction options into the models, cost-optimal reduction scenarios for a radiative forcing stabilization at 4.5 W/m^2 were derived. Some modeling teams, such as the IMAGE group and the developers of MERGE, also developed scenarios for other climate targets involving in some cases the full range of land use and agriculture emissions (see e.g. Manne and Richels, 2001; van Vuuren et al., 2003).

In the following, EMF-21 multi-gas scenarios of the participating modeling groups[9] are compared to an EQW emissions pathway (see Figure 9). All pathways and scenarios are designed to achieve a moderately ambitious climate target, namely to lead to a maximal radiative forcing of 4.5W/m^2. In general, the EQW pathway falls well within the range spanned by the EMF-21 scenarios. For CO_2 and N_2O, the EQW result is in fact close to the EMF-21 median. For CH_4, the EMF-21 median seems to be lower than the EQW result indicating that specific attention to reduction possibilities of CH_4 can result in lower CH_4 emissions. Differences between emission trajectories of EMF-21 and the EQW pathway are even reduced, if the set of emission sources were standardized. In particular for N_2O and to some degree for CH_4, the EMF-21 results are rather scattered already in the historic year 2000 as some models have not included all emission sources. In addition, different definitions are used for land-use related N_2O emissions in terms of what constitutes the anthropogenic part.

The main conclusion is that the presented EQW pathways seem to be already similar to those found in more detailed modeling studies that account for specific mitigation options as suggested by EMF-21 work. At this rather moderate climate target of 4.5W/m^2, the different emissions pathways do not widely diverge. For all gases, emissions end up in 2100 slightly below current emission levels. This is both the case in the EQW and the EMF-21 results.

It would be an improvement, though, to extend the sample of scenarios that EQW draws from by including these EMF-21 scenarios and other elaborated multi-gas scenarios in the underlying scenario pool, as they become available for a standardized set of emission sources. Thereby the EQW method could capture a wider range of non-CO_2 mitigations options. The '*distribution of possible emission levels*' within EQW will become less dependent on differences in driving forces and models (that are currently likely to dominate the range) and more dependent on

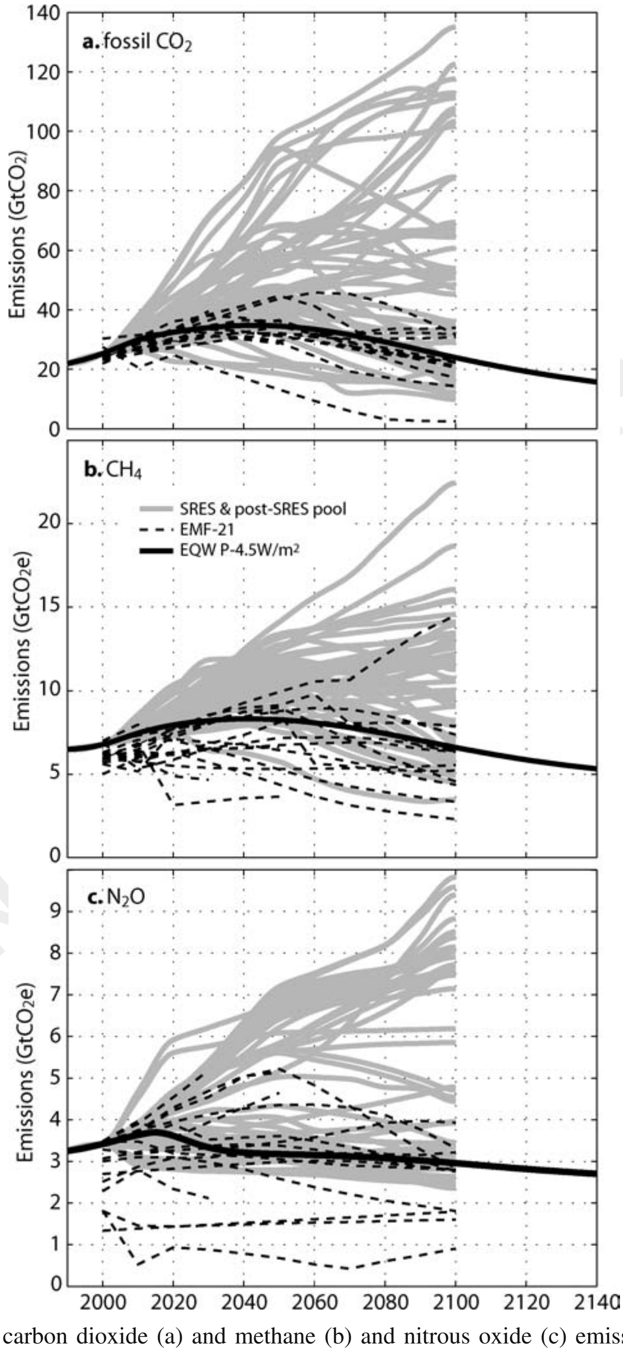

Figure 9. Fossil carbon dioxide (a) and methane (b) and nitrous oxide (c) emissions of an EQW pathway (solid black line), the IPCC SRES and Post-SRES scenarios used as underlying scenario pool in this study (solid grey lines) and recently developed multi-gas scenarios under the EMF-21 (dashed black lines). The EQW pathway and the EMF-21 scenarios are designed to lead to a maximal radiative forcing of 4.5 W/m^2. Discussion see text.

the potential for emission reductions among the different gases and their relative costs.

6. Conclusions and Further Work

This study proposes a method to derive emissions pathways with a consistent treatment of all major greenhouse gases and other radiative forcing agents. For example, multi-gas emissions pathways can be derived for various climate target indicators and levels, such as stabilization of CO_2 concentrations at 450 ppm or for peaking of radiative forcing at 2.6 W/m2 ($\approx$470 ppm CO_2 equivalence) above the pre-industrial level. The proposed EQW method has various advantages, such as being flexible and applicable to various research questions related to Article 2 of the UNFCCC. For example, derived EQW emissions pathways can be used to perform transient climate impact studies as well as to study emission control implications associated with certain climate targets. Of course, the EQW method can only fill a niche, and cannot replace other more mechanistic multi-gas approaches, e.g. cost optimization procedures. On the contrary, the EQW method is crucially dependent on and builds on a large pool of existing and fully developed scenarios. Thus, the derived region-specific and gas-specific emission paths respect the '*distributions of possible emission levels*' as they were outlined before by many different modelling groups. Another characteristic of the EQW pathways is that they are, to a large extent, baseline independent. Thus, the EQW pathways could be attractive for designing comparable climate impact and policy implication analyses.

Achieving climate targets that account for, say, the risk of disintegrating ice sheets (Oppenheimer, 1998; Hansen, 2003; Oppenheimer and Alley, 2004) or for large scale extinction risks (Thomas et al., 2004) almost certainly requires substantial and near term emission reductions. For example, to constrain global-mean temperatures to peaking at 2 °C above the pre-industrial level with reasonable certainty (say >75%) would require emission reductions of the order of 60% below 1990 levels by 2050 for the GWP-weighted sum of all greenhouse gases (cf. peaking pathway I in Table III). If the start of significant emission reductions were further delayed, the necessary rates of emissions reduction rates were even higher, if the risk of overshooting certain temperature levels shouldn't be increased (den Elzen and Meinshausen, 2005; Meinshausen, 2005). Thus, since more rapid reductions may require the premature retirement of existing capital stocks, the cost of any further delay would be increased, probably non-linearly. There are a number of other reasons, why one might want to avoid further delay. Firstly, future generations face more stringent emission reductions while already facing increased costs of climate impacts. Secondly, the potential benefits of 'learning by doing' (Arrow, 1962; Gritsevskyi and Nakicenovi, 2000; Grubb and Ulph, 2002) were limited due to the more sudden deployment of new technology and infrastructure. Thirdly, a further delay of mitigation efforts risks the potential foreclosure of reaching certain climate targets. Thus, a delay might be particularly costly if, for example, the climate sensitivity turns out to be towards the higher end of the currently assumed ranges (cf. Andronova and Schlesinger, 2001; Forest et al., 2002; Knutti et al., 2003).

So far, the development of optimal hedging strategies against dangerous climate change has been hampered by the absence of a method to generate flexible and consistent multi-gas emissions pathways. In this regard, the EQW method could be an important contributor towards the development of more elaborate and comprehensive climate impact and emission control studies and policies in a probabilistic framework.

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Appendix A

This Appendix A entails a description of (a) the employed simple MAGICC and (b) the assumptions made in regard to solar and volcanic forcings.

A.1. THE MODEL

(a) For the computation of global mean climate indicators, the simple climate model MAGICC 4.1 has been used.[10] MAGICC is the primary simple climate model that has been used by the IPCC to produce projections of future sea level rise and global-mean temperatures. The description in the following paragraph is largely based on Wigley (2003a). Information on earlier versions of MAGICC has been published in Wigley and Raper (1992) and Raper et al. (1996). The carbon cycle model is the model of Wigley (1993), with further details given in Wigley (2000) and Wigley and Raper (2001). Modifications to MAGICC made for its use in the IPCC TAR (IPCC, 2001) are described in Wigley and Raper (2001, 2002) and Wigley et al. (2002).

Additional details are given in the IPCC TAR climate projections chapter 9 (Cubasch et al., 2001). Sea level rise components other than thermal expansion are described in the IPCC TAR sea level chapter 11 (Church et al., 2001) with an exception in relation to the contribution of glaciers and small ice caps as described in Wigley (2003a). Gas cycle models other than the carbon cycle model are described in the IPCC TAR atmospheric chemistry chapter 4 (Ehhalt et al., 2001) and in Wigley et al. (2002). The representation of temperature related carbon cycle feedbacks has been slightly improved in comparison to the MAGICC version used in the IPCC TAR, so that the magnitude of MAGICC's climate feedbacks are comparable to the carbon cycle feedbacks of the Bern-CC and the ISAM model (see Box 3.7 in Prentice et al., 2001).[11]

A.2. PARAMETER CHOICES

Ensemble mean outputs of this simple climate model are the basis for all presented calculations in this study. An exception are the probabilistic results of Section 4.2, where MAGICC TAR default parameters were complemented by the probability density distributions of different authors' estimates of climate sensitivity, to obtain probabilistic forecasts (see e.g. Andronova and Schlesinger, 2001; Forest et al., 2002; Gregory et al., 2002; Knutti et al., 2003; Murphy et al., 2004). The ensemble outputs are computed as means of seven model runs. In each run, 13 model parameters of MAGICC are adjusted to optimal tuning values for seven atmospheric-ocean global circulation models (AOGCMs). This 'ensemble mean' procedure is widely used in the IPCC Third Assessment Report and described in Appendix 9.1 (see Table 9.A1 in Cubasch et al., 2001; Raper et al., 2001). By using this 'ensemble mean' procedure, the implicit assumptions in regard to climate sensitivity and ocean diffusivity are based on the seven AOGCMs. The mean climate sensitivity for those 7 AOGCMs models is 2.8 °C per doubled CO_2 concentration levels (median is 2.6 °C). Clearly, if emission scenarios are derived with single model tunings or different climate sensitivities then different emission paths will be found to correspond to any given climate target, reflecting the underlying uncertainty in the science. In general, the CO_2 concentration and radiative forcing scenarios are less model parameter dependent than the temperature focused scenarios.

A.3. CAVEATS

MAGICC is probably the most rigorously tested model among the simple climate models. Nevertheless, general caveats apply as well. There are still uncertainties in regard to many aspects of our understanding of the climate system, appropriate model representations and parameter choices, such as for gas cycles and their interactions, temperature feedbacks on the carbon cycle, ocean mixing, the climate's sensitivity etc. For example, large uncertainties persist in regard to the radiative forcing due to reactive gas emissions, such as NOx. In this case, MAGICC uses simple algorithms developed for the IPCC Third Assessment Report (see Wigley et al., 2002 for further information on this). However, in most cases, the effect of these uncertainties on long-term global-mean temperature projections is relatively small. The large uncertainties in regard to indirect aerosol forcing are another example. Obviously, a best estimate parameter as used in the IPCC Third Assessment Report calculations and in this study does not reflect these uncertainty ranges. However, at the global mean level the effect of aerosol forcing uncertainties is limited for long-term projections as aerosol precursor emissions are expected to decline over the 21st century, as discussed in (Wigley and Raper, 2002). The major source of uncertainty for long-term global-mean temperature projections, the climate sensitivity, has been explored in this study (see Section 4.2, and A.2). Future applications will benefit from a truly probabilistic framework (cf. Section 5.1.8).

A.4. NATURAL FORCINGS

Historic solar and volcanic forcings have been assumed, as presented in the IPCC TAR and according to Lean et al. j (1995) and Sato et al. (1993), respectively (see Figure 6–8 in Ramaswamy et al., 2001). Recent studies suggested that an up-scaling of solar forcing might lead to a better agreement of historic temperature records (e.g. Hill et al., 2001; North and Wu, 2001; Stott et al., 2003). In accordance with the best fit results by Stott et al. (2003, Table II), a solar forcing scaling factor of 2.64 has been assumed for this study. Accordingly, volcanic forcings from Sato et al. (1993) have been scaled down by a factor 0.39 (Stott et al., 2003, Table 2). However, there is considerable uncertainty in this regard and it should be noted that mechanisms for the amplification of solar forcing are not yet established (Ramaswamy et al., 2001, section 6.11.2; Stott et al., 2003). Future solar and volcanic forcings have been assumed in accordance with the mean forcings over the past 22 and 100 years respectively, i.e. $+0.16$ W/m^2 for solar and -0.35 W/m^2 for volcanic forcing and scaled as described above.[12]

Appendix B

Spearman rank correlations ‘SRCorr’ between fossil fuel CO_2 emissions and the emissions of gas g at time t are given as:

$$\text{SRCorr}_{g,t} = \frac{(R_{\text{fCO}_2,t} - \mu)(R_{g,t} - \mu)}{\sigma^2}$$

where $R_{g,t}$ is the vector of rank indexes for each scenario at time t for gas g, $R_{\text{fCO}_2,t}$ is the vector of rank indexes for each scenario at time t for fossil CO_2 emissions,

μ is the mean of all ranks (in this case half the number of scenarios +0.5) and σ is the standard deviation of the rank indexes. Another indicator is the Kendall rank correlation indicator given as:

$$\mathrm{KRCorr}_{g,t} = \frac{1}{n(n-1)} \sum_{i=1}^{n} \left(\sum_{s=1}^{n} \mathrm{sign}(e_{\mathrm{fCO_2},s} - e_{\mathrm{fCO_2},i}) \mathrm{sign}(e_{g,s} - e_{g,i}) \right) \quad \text{with } s \neq i$$

where n is the number of scenarios, $e_{g,s}$ the emission of gas g for scenario s and where the function 'sign(..)' returns −1 for negative and +1 for positive differences in emissions between two scenarios.

Notes

[1]The United Nations Framework Convention on Climate Change (UNFCCC) is available online at http://unfccc.int/resource/docs/convkp/conveng.pdf. Its status of ratification can be accessed at http://unfccc.int/resource/conv/ratlist.pdf.

[2]The 40 IPCC SRES scenarios were used as presented in the IPCC SRES database (version 1.1), available at http://sres.ciesin.org/final_data.html, accessed in March 2004.

[3]For details on the six modelling groups (AIM, ASF, IMAGE, MARIA, MESSAGE, MiniCAM) that quantified the 40 SRES and 14 Post-SRES scenarios used, see Box TS-2 and Appendix IV in Nakicenovic and Swart (2000), available online at http://www.grida.no/climate/ipcc/emission/, accessed in May 2004.

[4]However, even among the recently developed EMF-21 scenarios, only very few suggest that N2O emissions might fall much below current levels (cf. Figure 9) as most of the spread among EMF-21 scenarios seems to stem from different N_2O source inclusions and definitions, not from reduction potentials.

[5]This does not mean that overall terrestrial carbon stocks are restored to pre-industrial levels. Elevated CO_2 concentrations are thought to increase the total amount of terrestrial biotic carbon stocks. Thus, despite a partially counterbalancing effect due to climate change (Cramer et al., 2001), terrestrial carbon stocks are likely to increase above levels in 1850, if the directly human-induced carbon uptake due to future afforestation and reforestation programmes is equivalent to the directly human-induced deforestation related emissions since 1850.

[6]Annex I refers to the countries inscribed in Annex I of the United Nations Framework Convention on Climate Change and corresponds to the IPCC SRES regions OECD and REF. Consequently, non-Annex I corresponds to the IPCC SRES regions ASIA and ALM.

[7]In the future, the negative radiative forcing from sulphur aerosols is likely to become much less important according to the majority of SRES and post-SRES scenarios, which expect reduced sulphur emissions as a consequence of air pollution control policies.

[8]Given that fossil CO_2 emissions have been used as the '*driver path*', correlations have been analyzed between fossil CO_2 emissions and other radiative forcing agent emissions. However, correlations among different sets of gases can be more complex, particularly when analyzed on a less aggregated level. For example, Wassmann et al. (2004) showed that in the rice-wheat system in Asia there are clear antagonisms between measures that reduce methane and nitrous oxide: reducing one often leads to increases in the other.

[9]The participating modelling groups for EMF-21 are AIM, AMIGA, COMBAT, EDGE, EPPA, FUND, GEMINI-E3, GRAPE, GTEM, IMAGE, IPAC, MERGE, MESSAGE, MiniCAM, SGM,

WIAGEM. The work of these groups is gratefully acknowledged. Emission scenarios of these modelling groups are plotted in Figure 9.

[10]MAGICC 4.1 has been developed by T.G.L. Wigley, S. Raper and M. Hulme and is available at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html, accessed in May 2004.

[11]This improvement of MAGICC only affects the no-feedback results. When climate feedbacks on the carbon cycle are included, the differences from the IPCC TAR are negligible.

[12]The alternative, to leave natural forcings out in the future, is not really viable, since the model has been spun up with estimates of the historic solar and volcanic forcings. Assuming the solar forcing to be a non-stationary process with a cyclical component and assuming that the sum of volcanic forcing events can be represented as a Compound Poisson process, it seems more realistic to apply the recent and long-term means of solar and volcanic forcings, respectively, for the future.

[13]The four SRES World regions are: OECD – Members of the OECD in 1990; REF – Countries undergoing economic reform, namely Former Soviet Union and Eastern Europe; ASIA – Asia; ALM – Africa and Latin America. See Appendix III in Nakicenovic and Swart (2000) for a country-by-country definition of the groups.

[14]Since the introduction of the GWP concept (1990), it has been the subject of continuous scientific debate on the question of whether it provides an adequate measure for combining the different effects on the climate system of the different greenhouse gases (Smith and Wigley, 2000a; Smith and Wigley, 2000b; Manne and Richels, 2001; Fuglestvedt et al., 2003). The GWP concept is very sensitive to the time horizon selected, and can only partially take into account the impacts of the different lifetimes of the various gases. Economists currently criticise GWP for not taking economic efficiency into account. However, despite its limitations, the GWP concept is convenient and has been widely used in policy documents such as the Kyoto Protocol. To date, no alternative measure has attained a comparable status in policy documents.

[15]Data on the 'S' profiles is available at http://cdiac.ornl.gov/ftp/db1009/, accessed in March 2004.

[16]Note that the 14 Post-SRES scenarios used in this study have been selected from those modelling groups that provided the 40 SRES scenarios as well, namely AIM, MESSAGE, IMAGE, ASF, MiniCAM, and MARIA (see as well endnote iii).

[17]In this study CO_2 stabilization profiles are derived for 350 to 750 ppm, temperature peaking profiles between 1.7 °C and 4 °C above pre-industrial levels as well as radiative forcing peaking profiles at 3.5 to 5.5 W/m^2. As shown later, the EQW methodology allows one to easily deriving profiles for different target variables, such as CO_2 concentrations, global mean temperatures, radiative forcing or sea level, and for different profile shapes, such as stabilization, overshooting or peaking scenarios.

[18]The peak concentration is shown for the 7 AOGCM ensemble mean. Due to the temperature feedback on the carbon cycle, the actual peak concentration varies slightly depending on the assumed climate sensitivity.

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