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CO_2 and non-CO_2 radiative forcings in climate projections for 21st century mitigation scenarios

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Abstract Climate is simulated for reference and mitigation emissions scenarios from Integrated Assessment Models using the Bern2.5CC carbon cycle-climate model. Mitigation options encompass all major radiative forcing agents. Temperature change is attributed to forcings using an impulse-response substitute of Bern2.5CC. The contribution of CO_2 to global warming increases over the century in all scenarios. Non-CO_2 mitigation measures add to the abatement of global warming. The share of mitigation carried by CO_2, however, increases when radiative forcing targets are lowered, and increases after 2000 in all mitigation scenarios. Thus, non-CO_2 mitigation is limited and net CO_2 emissions must eventually subside. Mitigation rapidly reduces the sulfate aerosol loading and associated cooling, partly masking Greenhouse Gas mitigation over the coming decades. A profound effect of mitigation on CO_2 concentration, radiative forcing, temperatures and the rate of climate change emerges in the second half of the century.

1 Introduction

This study assesses the role of individual radiative forcing (RF) agents in climate change and mitigation of climate change in emission scenarios for the 21st century. Global mean surface temperature is a central proxy for many of the impacts of climate change. We analyse the contributions of individual RF agents to the magnitude and the rate of temperature change over time, as well as the mitigated temperature change. A particular emphasis is placed on the rate of change in global mean temperature, which codetermines the impact of climate change and the costs of adaptation. By focusing on temperature rather than RF we are able to capture time lags of the climate system response. We also consider mitigation in the context of sea level rise as an important impact on a longer timescale, and of risks associated with high levels of CO_2 through effects other than global warming.

We investigate a set of reference and mitigation scenarios for global emissions of the major anthropogenic greenhouse gases (CO_2, CH_4, N_2O, halocarbons, SF_6), aerosol and tropospheric ozone precursors (SO_2, CO, NO_x, VOCs) throughout this century. Most of the scenarios were generated as part of the Energy Modeling Forum project 21 (EMF-21) (Weyant et al. 2006), with several Integrated Assessment Models (IAM): AIM (Fujino et al. 2006), EPPA (Reilly et al. 2006), IMAGE (Van Vuuren et al. 2006), IPAC (Jiang et al. 2006), MESSAGE (Rao and Riahi 2006), MiniCAM (Smith and Wigley 2006). These IAMs are well known for providing comprehensive scenarios to climate modellers, inter alia the SRES illustrative scenarios used in the IPCC reports (Nakićenović and Swart 2000). Summary IAM model descriptions are given in Van Vuuren et al. (2008).

The EMF-21 project is a collaboration of modelling groups assessing the potential of multigas mitigation policies. Before EMF-21, most attention in climate policy modeling was paid to reducing CO_2 emissions from the energy sector. In EMF-21, special attention was given to non-CO_2 GHGs and CO_2 sinks such as managed forests or carbon capture and storage facilities (CCS). Some of the IAMs participating in EMF-21 (MiniCAM, EPPA/ISGM, MERGE) also provided the multigas scenarios described in detail in Clarke et al. (2008).

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The IAMs represented here feature representations of the energy system and other parts of economy, such as trade and agriculture, on varying levels of spatial and process detail. Scenarios are generated by minimizing the total systems costs under the constraints set by societal drivers (population, welfare, technological innovation). Most scenarios are related to SRES "storylines" (Nakićenović and Swart 2000) (Tab. 1). Adding a constraint on radiative forcing leads to scenarios with policies specifically aimed at mitigation (mitigation scenarios). Mitigation policies can be assessed by comparing these mitigation scenarios with corresponding scenarios that are not constrained to a forcing target (reference scenarios). The cost of climate change impacts is not explicitly considered in this scenario generation process.

The mitigation scenarios analysed here are constrained by stabilisation of total RF in the period 2100 to 2150 (RF target). All IAMs provided a multigas mitigation scenario with the common EMF-21 target of $4.5\,\mathrm{Wm}^{-2}$ with respect to the preindustrial state (taken as the year 1765 in the simulations). Additional scenarios are included with RF targets ranging from $2.6\,\mathrm{Wm}^{-2}$ to $5.3\,\mathrm{Wm}^{-2}$ (Tab. 1).

IAMs draw on a wide range of technological options representative of the current scientific debate to reduce GHG emissions in mitigation scenarios. Feasibility of these technologies is an implied assumption and is not addressed explicitly. This is true also for the reference scenarios, which feature important efficiency improvements unprompted by mitigation policies. It has been argued that baseline emissions could be much higher if technological development is less effective as assumed Pielke et al. (2008). The feasibility of additional improvements is presumably no less uncertain. Riahi et al. (2007) have addressed these issues by analyzing the contribution of selected technology clusters to mitigation with respect to several reference scenarios and at different levels of stringency. As already in Rao and Riahi (2006), they emphasize the diversity of the mitigation portfolio, but also demonstrate that carbon sink technologies are consistently part of solutions to stringent forcing constraints.

All IAMs represented here include options for non-CO_2 mitigation that are cheaper than CO_2 mitigation, and the multigas mitigation scenarios generally imply lower costs than corresponding CO_2-only scenarios (Fujino et al. 2006; Jiang et al. 2006; Rao and Riahi 2006; Reilly et al. 2006; Smith and Wigley 2006; Van Vuuren et al. 2006). On the other hand, non-CO_2 mitigation potentials are bounded by the total amount of non-CO_2 emissions in the reference scenarios, which remain inferior to the required CO_2 reduction over the century. Since models minimize mitigation costs, they produce mitigation scenarios that begin mostly with reductions of non-CO_2 gases and then follow with more expensive CO_2 mitigation. This is a well-known result that has been reported by several participant groups in EMF-21 (eg. Rao and Riahi 2006; Smith and Wigley 2006; Van Vuuren et al. 2006). Here we explore how this evolution of the mitigation portfolio affects global mean surface temperatures in mitigation scenarios.

Mitigation scenarios have been widely used to investigate options and measures to "achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system" (United Nations 1992). Comprehensive multigas mitigation scenarios as used in this paper, however, have only recently become available. Earlier mitigation scenarios are much less comprehensive in terms of relevant processes and forcing agents considered. They focus strongly on CO_2, and only a few consider non-CO_2 agents (Schimel et al. 1997; Metz et al. 2001).

The working group I parts of the IPCC Third and Fourth Assessment reports (TAR, AR4) discuss CO_2 concentration stabilisation profiles, which implicitly are mitigation scenarios (Enting et al. 1994; Wigley et al. 1996; Prentice et al. 2001; Cubasch et al. 2001; Meehl et al. 2007; Plattner et al. 2008). In contrast to the emission scenarios used here, in CO_2 stabilization profiles the CO_2 emissions are inferred in a top-down manner from predefined concentrations. The role of non-CO_2 GHGs in mitigation and stabilisation is not considered. Neither of the two IPCC working group I reports include climate projections based on bottom-up multigas mitigation scenarios, which infer emissions from general development trends through explicit and detailed modelling of technological processes. Some participant groups in EMF-21 have reported results from climate projections of their IAM in the EMF-21 special issue on multigas scenarios. A more detailed investigation of climate projections for multigas scenarios has been published recently for three IAMs (MiniCAM, EPPA/ISGM, MERGE) by Levy II et al. (2008).

We further analyse climate projections for a set of reference and mitigation scenarios from six different IAMs (Tab. 1). Included are scenarios earmarked for simulations with Earth System Models (ESM) and Earth System models of intermediate complexity (EMIC) for the next IPCC Assessment report (AR5), termed Representative Concentration Pathways (RCP, Tab. 1). By using one EMIC to simulate RF and temperature across emission scenarios from a group of different IAMs, it is possible to separate general robust trends from model-dependent features. The range of global temperature projections for these mitigation and reference scenarios is discussed in Van Vuuren et al. (2008). Here we show how the different forcings (GHG and aerosols) give rise to the projected temperature evolution over this century, and how each of them affects this path as a result of various degrees of mitigation efforts. Specifically, we analyse (i) the contribution of forcing agents to climate change in the past and up to 2100, (ii) the role of forcing agents for mitigation, (iii) the mitigation effect on the rate of global mean temper-

Table 1 Scenario overview. The SRES storyline is indicated where applicable; quantitative interpretations of storylines vary accross models. Radiative forcing targets corresponding to the year 2100 are indicated for mitigation scenarios. For each scenario, the values of key climate indicators in the year 2100 are listed as simulated with standard model settings. Rates of change are means over the last decade of the century. The calculation of CO_2 and RF in IAMs and Bern2.5CC differs, therefore forcing targets do not necessarily equal the RF simulated here.

			Climate indicators for 2100						
Target (Wm^{-2})	EMF[a]	RCP[b]	CO_2 ppm	CO_{2eq}[c] ppm	RF (Wm^{-2})	RF_{mix}[d] (Wm^{-2})	T (°C)	$\frac{dRF}{dt}$ $(\frac{Wm^{-2}}{10\,yr})$	$\frac{dT}{dt}$ $(\frac{°C}{10\,yr})$
AIM (B2)									
Ref		×	647	884	6.2	6.5	3.1	0.41	0.30
4.5	×		530	598	4.1	4.5	2.4	0.15	0.13
EPPA									
Ref			900	1507	9.0	9.0	4.5	0.82	0.54
4.5	×		589	720	5.1	5.1	2.8	0.13	0.12
IMAGE (B2)									
Ref			727	990	6.2	6.6	3.2	0.28	0.28
5.3			620	717	5.1	5.3	2.8	0.16	0.13
4.5	×		565	665	4.7	4.7	2.7	0.10	0.13
3.7			485	573	3.9	3.9	2.4	0.03	0.09
2.9		×	434	495	3.1	3.1	2.0	-0.10	0.01
2.6		×	400	457	2.7	2.6	1.8	-0.15	-0.02
IPAC (B2)									
Ref			711	1008	6.9	7.0	3.4	0.39	0.26
4.5	×		552	725	5.1	5.1	2.8	0.11	0.11
MESSAGE (A2)									
Ref		×	956	1773	9.9	9.9	4.9	0.89	0.50
4.5			510	694	4.9	4.9	2.8	-0.07	0.08
MESSAGE (B2)									
Ref			665	1025	7.0	6.9	3.5	0.40	0.26
4.6	×		523	706	5.0	4.9	2.8	-0.18	0.05
3.2			401	522	3.4	3.3	2.3	-0.40	-0.07
MiniCam (B2)									
Ref			759	956	6.6	6.6	3.3	0.49	0.39
4.5			561	642	4.5	4.5	2.7	0.08	0.12
4.5	×	×	586	670	4.7	4.7	2.8	0.08	0.13
4.0			516	585	4.0	4.0	2.4	0.02	0.09
3.5			478	537	3.5	3.6	2.2	-0.02	0.05

[a] Scenario for EMF-21 target of $4.5 Wm^{-2}$.

[b] Selected as Representative Concentration Pathway scenario for the next IPCC report with possible minor modifications. The choice between IMA2.6 and IMA2.9 is as yet undecided.

[c] CO_2 concentration equivalent for total RF.

[d] RF for well-mixed GHG, i.e. all forcings except aerosol and tropospheric O_3.

ature change and the contribution of individual RF agents to the overall warming rate.

2 Methods

2.1 Model

We use the Bern2.5CC EMIC to calculate RF and climate change from the emissions scenarios across the different IAMs, using the same model setup as in Van Vuuren et al. (2008). Most IAMs contain simple climate-carbon cycle model formulations, often based on MAGICC (Wigley and Raper 2001) or the Bern substitute model (Joos et al. 1996). By using one model for the carbon cycle-climate simulation we avoid differences that may arise from the somewhat different climate-carbon cycle representations within the IAMs.

Model components represent (i) the physical climate system, (ii) the cycling of carbon and related elements, and (iii), RF by atmospheric CO_2, non-CO_2 greenhouse gases (GHG) and aerosols (Plattner et al. 2001; Joos et al. 2001). The model setup used here includes only anthropogenic RF, solar variability and volcanism are not considered. Solar forcing over the 20th century has been much smaller than the anthropogenic GHG forcing and reliable prediction of 21st century solar and volcanic forcing is lacking.

Apart from surface temperature, steric sea level rise, mostly a result of thermal expansion, is also calculated in Bern2.5CC. The Bern2.5CC steric sea level rise tends to be high in comparison with, e.g., the CMIP (Meehl et al. 2005) group of Atmosphere-Ocean General Circulation models (AOGCMs; Plattner et al. 2008), particularly when the Atlantic meridional overturning circulation (AMOC), which is sensitive in the model, shuts down (Knutti and Stocker 2000). We note that contributions from changes in ice sheets, alpine glaciers, and other terrestrial water storage are not taken into account here.

CO_2 RF is parametrised according to Myhre et al. (1998), as described in Joos et al. (2001) and used in Forster et al. (2007). RF of non-CO_2 GHGs is calculated as the product of concentrations and radiative efficiencies as given in Forster et al. (2007). Non-CO_2 concentrations are modelled with first-order decay and atmospheric residence times partly depending on concentrations of other gases (Prather et al. 2001). The RF of aerosols, which have very short residence times, is modelled as proportional to aerosol precursor emissions. For sulfate aerosols, SO_2 emissions are used, for organic and black carbon (OC/BC) aerosols, CO emissions are used as a proxy of incomplete combustion. The best estimates of aerosol forcing efficiencies (Forster et al. 2007), used for the simulations shown here, imply an important role of aerosols in the anthropogenic influence on climate. Aerosol RF in the scenarios used in this study is mostly due to sulfate aerosol. The remainder is a positive RF from organic and black carbon, which accounts for just a few percents. The RF by individual aerosol types and processes is uncertain, but total aerosol RF is constrained by observations and climate model simulations (Forster et al. 2007). A detailed account of the non-CO_2 RF model is given in Joos et al. (2001). Radiative efficiencies and life times are updated according to Forster et al. (2007).

Feedbacks of atmospheric CO_2 and climate on carbon fluxes are captured by the explicit representation of the carbon cycle in the Bern2.5CC model. The atmospheric CO_2 concentration affects carbon uptake through CO_2 dissolution in the ocean and CO_2 fertilisation on land. The climate-carbon cycle feedback arises from the dependence of soil carbon decay on temperature, the response of the global vegetation distribution to climate change, the temperature-dependent solubility of CO_2 in the ocean and changes in surface-to-deep transport and in the marine biological cycle (Joos et al. 1999, 2001; Plattner et al. 2001), where the first of these factors is dominant in the model on a centennial timescale. Feedbacks for the non-CO_2 GHGs are not modeled. For example, methane is not represented in the carbon cycle model. A limited coverage of feedbacks is provided by the atmospheric chemistry parametrisations.

The model reference case is obtained with the standard setup of the carbon cycle model and an equilibrium climate sensitivity of 3.2 K for a nominal doubling of CO_2. Climate and carbon cycle uncertainty (vertical bars in Fig. 1) is bounded by “endmember” combinations of assumptions: The uncertainty in climate sensitivity is accounted for by additional simulations with sensitivities of 1.5 °C (low) and 4.5 °C (high). The low-CO_2 case is obtained by applying an efficiently mixing ocean and assuming heterotrophic respiration to be independent of global warming; the high-CO_2 case is obtained by applying an inefficiently mixing ocean and capping CO_2 fertilisation after the year 2000. A compound parameter uncertainty range was obtained by combining low-CO_2 with low climate sensitivity, and high-CO_2 with high climate sensitivity. The same approach was used in IPCC TAR and AR4 (Meehl et al. 2007; Joos et al. 2001; Prentice et al. 2001).

Simulations start from an equilibrated model state for the year 1765 with zero RF. Until 2000, CO_2, CH_4, and N_2O concentrations are prescribed according to ice core data and atmospheric observations as compiled by Joos and Spahni (2008); RF of the other non-CO_2 forcing agents in the past is calculated as described in Joos et al. (2001), except for updated parametrisations as mentioned above, and a newer estimate of SO_2 emissions (Stern 2005). From year 2000 onwards, simulations are driven by the emissions of CO_2 and non-CO_2 GHGs and aerosol precursors from the IAM scenarios. The scenarios were harmonized to a common emission level in the year 2000, as described in Van Vuuren et al. (2008).

2.2 Attribution method

The value of partitioning anthropogenic climate change by forcing agents lies in the separate consideration of gases or aerosols with differing dynamics and a different level of scientific understanding.

The need to deal with several components on an equal footing is commonly addressed by using the Global Warming Potential (GWP) measure. All scenario models featured here except AIM rely on GWPs to compare and substitute forcing agents (Weyant et al. 2006). GWPs, though of practical use, are a limited concept that afford comparability of different forcing agents only with respect to a given time horizon, here 100 years. GHG emissions equivalent in terms of GWPs cause similar heat input to the climate system over 100 years, but the temperature response at any given time may differ. An alternative measure proposed for comparison of unit emissions of different GHGs is the Global Temperature Potential (GTP Shine et al. 2005). GTPs take the climate response into account and are comparable in terms of temperature, but also strongly dependent on the time frame considered (unless sustained emissions are considered (Shine et al. 2005)).

Some forcing agents have a well-known radiative efficiency, and some agreements exists about their future emission trajectory. Such is the case for the gases listed under the Montreal Protocol (all scenarios assume a phase out as defined in the protocol). On the other extreme, aerosols are characterized by strongly scenario-dependent, i.e., uncertain emissions and a poorly constrained radiative efficiency. In the IPCC AR4, aerosol RF is still assigned the greatest uncertainty of all forcing components (Forster et al. 2007). By partitioning global temperature change into contributions from different forcings the varying uncertainties associated with each of them can be considered.

The attribution of global temperature change to RF agents requires that the individual effects are additive. Forster et al. (2007) suggest that this is a good assumption, as studies with several different GCMs "have found no evidence of any nonlinearity for changes in GHGs and sulphate aerosol". A linear approximation of the Bern2.5CC climate model is given by the impulse-response substitute formulation (Joos and Bruno 1996):

$$\delta T = \frac{1}{a_{oc}hc}\int_{t_0}^{t}\left[R(t') - \delta T(t')\frac{R_{2\times}}{\delta T_{2\times}}\right] r(t-t')\,\mathrm{d}t' \qquad (1)$$

where δT is the deviation of global mean surface air temperature from the preindustrial state, R is radiative forcing, $R_{2\times}$ is the RF for twice the preindustrial CO_2 concentration, $\delta T_{2\times}$ is the equilibrium temperature change corresponding to $R_{2\times}$, r is an impulse-response function, c is the heat capacity of water per unit volume, h is the depth of the mixed ocean surface layer, a_{oc} is the fraction of the earth surface covered by oceans, and t is time. The impulse-response function is given as

$$r(t) = a_{0j}\sum_{i=1}^{5} a_{ij}\, e^{-t/\tau_{ij}} \qquad j = \begin{cases} 1 & \text{if} \quad t < 4\,\mathrm{yr} \\ 2 & \text{if} \quad t \geq 4\,\mathrm{yr} \end{cases}, \qquad (2)$$

where a_{ij}, τ_{ij} are two sets of coefficients and time scales, respectively. They define two functions for the short and the long term response, which are matched around year 4.

The temperature response of the Bern2.5CC model is not strictly linear, as ocean circulation can change in response to climate change and lead to a feedback affecting ocean heat uptake. Thus the substitute model does not reproduce the temperature changes simulated with the original Bern2.5CC perfectly. However, in the range of conditions and timescales considered here, this nonlinearity is small (Plattner et al. 2001), with substitute model temperatures at 2100 within 0.2 K of the complete model, except in the sensitivity simulations with high climate sensitivity or low-CO_2 settings combined with high RF, where most substitute simulations are about 0.5 K too small, and the ones with the highest RF up to more than 1 K too small. This nonlinearity arises due to strong changes in the AMOC which occur under strong warming. However, for the scenarios considered here, the relative contributions of different forcings are less sensitive, because they are all similarly affected by the deviation between Bern2.5CC and its substitute. Thus the separation of the individual forcing contributions is reliable.

The global mean surface temperature change attributable to each GHG or aerosol, δT_i is obtained by solving equation (1) for the corresponding forcing R_i, with $\sum_i \delta T_i = \delta T$ for the sum over all forcings.

In the standard setup of Bern2.5CC with a climate sensitivity of $\delta T_{2\times} = 3.2\,°\mathrm{C}$, global temperature change affects ocean and land uptake of carbon, resulting in a positive climate-carbon cycle feedback. This leads to higher atmospheric CO_2. The temperature change due to CO_2 without the carbon cycle-climate feedback is obtained by inserting in equation (1) the RF corresponding to the atmospheric CO_2 from a Bern2.5CC simulation with climate sensitivity set to zero in Bern2.5CC. The temperature change in the standard simulation results from all anthropogenic forcing agents including CO_2, non-CO_2 GHGs, and aerosols.

The relationship between RF and climate change is affected by the uncertainty in climate sensitivity. However, this uncertainty affects all forcings in a similar way, except for CO_2, which is influenced by the climate-carbon cycle feedback. The climate-carbon cycle feedback plays a limited role in the results discussed here. The warmings due to this feedback are governed by the main temperature response of each scenario and vary accordingly. This variation among scenarios is small compared with the total warming and does not greatly affect the temperature differences between the scenarios in the standard model setup. The feedback generally amplifies the general warming trend and therefore does not introduce a qualitatively different behaviour (Fig. 2).

The carbon cycle uncertainty for the substitute simulations was estimated using the RF from the Bern2.5CC sensitivity simulations as described in section 2.1.

A similar decomposition of temperature change for different forcings has been done before, to allocate mitigation burdens according to historical responsibility for climate change (den Elzen et al. 2005; Den Elzen and Schaeffer 2002; Trudinger and Enting 2005). This necessitates an attribution of climate change to emissions, and, unlike the RF-temperature relationship, involves essential nonlinearities and a choice among several possible attribution formalisms.

3 Results

The reference scenarios (Tab. 1) provide a range of plausible future emissions in the absence of specific mitigation policies. These emissions lead to climate change characterised by global mean surface air temperature rise above preindustrial levels by the year 2100 of 3–3.5 °C for scenarios based on the B2 storyline and about 4.5–5 °C for others, not including the climate and carbon cycle model uncertainty (Fig. 1, Tab. 1). The corresponding range in RF is 6–7 $\mathrm{W m^{-2}}$ (B2), and 9-10 $\mathrm{W m^{-2}}$ (others), respectively; the range in CO_2 is 650–760 ppm (B2), and 900–960 ppm (others) respectively.

The mitigation scenarios demonstrate that the implementation of technological measures and political mechanisms for mitigation can have a profound impact on the climate change expected under the same scenario storylines. The set of mitigation scenarios considered here includes scenarios with radiative forcing targets from 2.6 to 5.3 Wm^{-2} in the year 2100 (Fig. 1). Global temperature deviations in 2100 range from 1.8 to 2.8 K above preindustrial levels at the standard climate sensitivity of 3.2 °C. Simulated RF and CO_2 are in the range of 2.7–5.1 Wm^{-2} and 400–619 ppm, respectively.

Trends in the year 2100 indicate that radiative forcing is stabilised by the end of this century in many mitigation scenarios (IMAGE 2.6–3.7 Wm^{-2}, IPAC-EMF, MESSAGE-EMF), or close to stabilisation (IMAGE 5.3 Wm^{-2}, EPPA-EMF, see Fig. 1). A number of mitigation scenarios show a negative forcing trend in 2100 (IMAGE 2.6–2.9, MESSAGE 3.2–4.6).

Temperatures respond to stabilising RF levels with some delay. While the temperatures for the more stringent mitigation scenarios seem stable in 2100 or even declining, the temperatures for the scenarios that comply with the 4.5Wm^{-2} target of the EMF are still rising in 2100. However, the rate of temperature increase and therefore of climate change is greatly reduced with respect to the reference scenarios.

Sea level responds to global warming by thermal expansion on centennial to millenial timescales. The contrast between the reference and mitigation scenarios appears later than with temperature and evolves more slowly, and accordingly, none of the mitigation scenarios show a stabilized sea level in 2100. However, the simulations still indicate a mitigation potential of 1-2 tenths of a meter until 2100. The reference scenarios span a range of 0.41–0.60 m above the preindustrial sea level, as opposed to 0.27–0.40 m for the mitigation scenarios. Further, steric sea level rise is markedly decelerating in all mitigation scenarios while in all the reference scenarios it is still accelerating in 2100.

Thus, the magnitude and the rate of climate change and steric sea level rise, as well as the trends at the turn of the 22nd century show a substantial abatement due to mitigation policies.

The uncertainty in carbon cycle and climate feedbacks as defined in section 2.1 strongly affects the effects and impacts of emissions (Fig. 1). For example, for the MESSAGE A2-based reference scenario, the climate sensitivity range of 1.5–4.5°C for a nominal doubling of CO_2 in 2100 translates to a range of 883-1015 ppm for atmospheric CO_2 and 2.9–6.4 °C for global mean surface temperature, respectively. The carbon cycle uncertainty corresponds to a range of 800–1213 ppm and 4.2–6.0°C, and the combined climate-carbon cycle uncertainty to a range of 789–1305 ppm, and 2.6–8.3°C, respectively. For comparison, the multimodel range of CO_2 SRES-A2 projections from the C4MIP project (Friedlingstein et al. 2006), is 730–1020 ppm in 2100. Non-CO_2 RF is not included in C4MIP, thus temperature projections are not comparable. The likely (in the IPCC sense) range given in the IPCC AR4 Summary for Policymakers for an A2 scenario is 2.7–6.1 °C above preindustrial for global mean surface air temperature in the last decade of this century, assuming a pre-2000 warming of 0.7 °C, which corresponds to the Bern2.5CC simulation with the standard setup and is compatible with observations (Alley et al. 2007). Though the feedback strength determining the absolute climate response remains fairly uncertain, the contrast from reference to mitigation scenarios is qualitatively similar in any setup.

The uncertainty range for steric sea level rise is related to that of surface temperature, with two exceptions: (i) for a time scale of one century it is more limited at the upper end (0.72 m in 2100 for MESSAGE A2 reference) because it takes more time to heat up the ocean, and (ii) the carbon cycle sensitivity settings have partly compensating effects: In the low-CO_2 case, for example, efficient ocean mixing means relatively stronger ocean heat uptake and thermal expansion, but at the same time, atmospheric CO_2 and surface temperatures driving sea level rise are lower, partly due to increased ocean uptake, but mostly due to increased land carbon storage. The converse applies to the high-CO_2 case.

3.1 The contribution of forcing agents to climate change in the past and in this century

In 2000, the most important GHG, CO_2, accounts for about the same global mean surface temperature change since preindustrial as do the other GHGs combined. The simulated cooling by aerosols in 2000 offsets about half of the warming by all GHGs (Fig. 2).

However, the share of warming caused by CO_2 increases after the year 2000 in all scenarios. By 2100, it accounts for twice the warming attributed to the non-CO_2 GHGs or more in many scenarios, particularly some mitigation scenarios (cf. section 3.2). Toward the end of the century, the share of GHG warming attributable to CO_2 decreases again slightly only for the scenarios MESSAGE 3.2 (after 1960) and MESSAGE 4.5 (after 1990). MESSAGE mitigation scenarios feature the steepest reduction of net CO_2 emissions in the set. The climate-carbon cycle feedback contributes to the growing influence of CO_2. It is comparable in magnitude to the individual non-CO_2 GHGs.

The partitioning of non-CO_2 GHG warming varies across models. In the reference scenarios, generally CH_4 ranks first, followed by tropospheric ozone, N_2O, HFCs/PFCs/SF6 and the Montreal gases and stratospheric ozone. This pattern is less clear in the mitigation scenarios, as different GHGs can be reduced at different rates. Nevertheless, in all cases CH_4 is still the most important non-CO_2 gas (cf. section 3.2). Model-specific differences are appar-

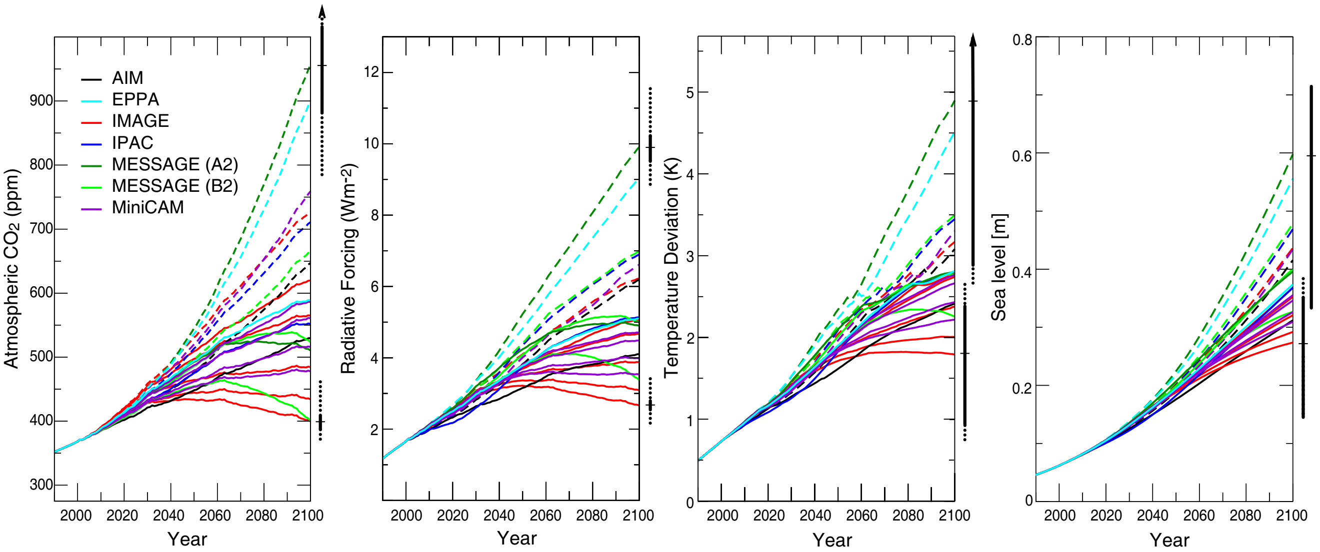

Fig. 1 Atmospheric CO_2, radiative forcing, global mean surface temperature, and steric sea level rise from Bern2.5CC simulations. Reference scenarios (dashed), and mitigation scenarios (solid) are shown for all emission models. Bars to the right of the graphs mark ranges in 2100 of uncertainty in climate sensitivity (solid), and carbon cycle and climate sensitivity combined (dotted) for the two bounding scenarios. The uncertainty bar of the high-end scenario (MESSAGE A2) extends beyond the plot range of CO_2 and temperature; climate sensitivity uncertainty is bounded at 1020 ppm and 6.4 K, total uncertainty at 1305 ppm and 8.3 K, respectively. Where the dotted uncertainty range for sea level is not visible, the carbon cycle settings are partly compensating the climate sensitivity settings (see main text).

ent, e.g., CH_4 contributes a particularly large fraction of non-CO_2 warming in all MESSAGE scenarios.

Aerosol cooling peaked in the seventies, offsetting 75% of GHG warming around 1970 (not shown). Since then, global SO_2 emissions have stagnated and eventually declined according to the estimate used here (Stern 2005). This decline is immediately expressed in aerosol RF, leading to stagnating aerosol cooling while GHG warming continued. The decline of SO_2 emissions is projected to continue into the future in reference and mitigation scenarios alike, while the OC/BC aerosol loading as estimated here does not show consistent decrease. However, the net positive forcing due to OC/BC aerosols never fully compensates the sulfate aerosol cooling as simulated for any of the scenarios.

3.2 The role of forcing agents in mitigation

The attribution to individual RF agents of the difference in warming between the mitigation and baseline cases (Fig. 3), reveals the shares of CO_2 and non-CO_2 GHGs in mitigation.

Total non-CO_2 emission abatement accounts for up to about 80% of the mitigated warming in the first decades of the century. However, CO_2 mitigation increases over time, and ends up as the clear leader in terms of avoided temperature change in all mitigation scenarios towards the end of the century. Scenarios with moderate mitigation targets (e.g. the EMF-21 scenarios with a 4.5 Wm^{-2} target) tend to rely proportionally more on the non-CO_2 GHGs for mitigation than those with more stringent targets. Non-CO_2 mitigation options tend to be relatively cheap compared to CO_2, but more limited in their potential to reduce RF. Accordingly, CO_2 mitigation comes in when the cheap non-CO_2 options are exhausted or a more stringent forcing target must be reached. Models which provided scenarios at several RF targets (IMAGE, MESSAGE, MiniCAM) show little flexibility of non-

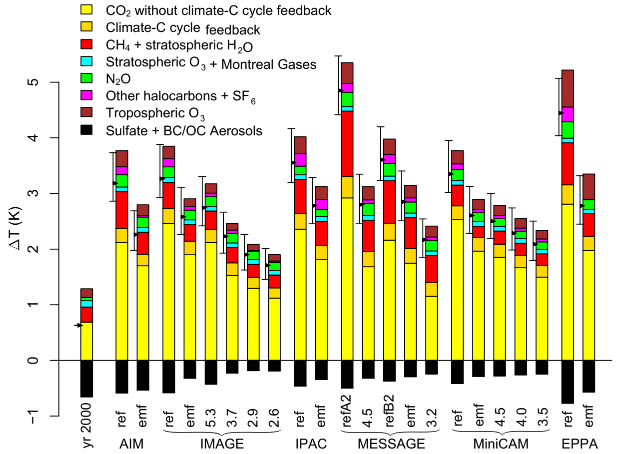

Fig. 2 Contribution of individual forcings to global mean surface temperature change since preindustrial time in 2000 (reconstructed) and in 2100 for the scenarios listed in Table 1. Attribution to individual forcings is done using the Bern2.5CC substitute model. The net temperature change (shown by black "ticks" next to the bars) corresponds to the total bar height minus the negative contributions from aerosols. Error bars indicate uncertainty related to the carbon cycle settings (cf. section 2.2). The pulse-response range given here differs slightly from the full model-range given in section 3.

CO_2 mitigation options to the level of stringency; almost all mitigation beyond the EMF-target of 4.5Wm^{-2} is achieved through CO_2 (cf. Van Vuuren et al. 2006).

Thus, the previously reported preference for non-CO_2 mitigation in an early phase, and conversely, the shift towards a greater role fort CO_2 mitigation at later times and more stringent targets (eg. Rao and Riahi 2006; Van Vuuren et al. 2006) is consistent accross the scenario set, and reflects clearly in the projected warming.

In the non-CO_2 mitigation portfolio, CH_4 ranks first in importance, followed by HFCs/PFCs/SF6 and tropospheric ozone, and finally N_2O, which often constitutes a minor category. The share of warming due to each GHG does not always correspond to its importance in the mitigation portfolio, as some emissions (e.g., N_2O) are harder to control than others. Due to its comparatively long lifetime of about 120 yr, the share of N_2O mitigation tends to increase over the long term. The amplification of the mitigation effect by the climate-CO_2 feedback is of similar importance as the minor non-CO_2 GHGs.

There is some variability between models and scenarios as to the non-CO_2 mitigation portfolio, which depends on the scenario assumptions and the variable implementation of mitigation options in the models. The comparison of the mitigation portfolios is complicated by the fact that different baseline scenarios are used. For example, MESSAGE 4.5 is based on an A2 scenario, while MESSAGE-EMF shares the same forcing target, but uses a B2 scenario as reference. The B2 storyline emphasises technological development, and consequentially many technologies with a mitigation potential are already implemented in the baseline and do not contribute to the mitigated warming shown in Fig. 3 (Riahi et al. 2007). Because different baseline scenarios are used, the most stringent mitigation targets do not always coincide with the strongest mitigation (MESSAGE 4.5, EPPA-EMF). In the case of MESSAGE, the 3.2 Wm^{-2} forcing target cannot be reached from the A2 baseline, but from the B2 baseline it can. The potential of the mitigation options considered is not sufficient to compensate for the difference in the socio-economical drivers assumed in the two scenarios. Thus the feasibility of a mitigation target is conditional on the storyline assumption (Riahi et al. 2007).

As SO_x emissions are related to the use of fossil fuels (especially coal), and fossil fuels get “cleaner” in baseline and mitigation scenarios alike, mitigation measures lead to a sizeable reduction of the aerosol load. This reduction is especially pronounced in the stringent scenarios that cut CO_2 emissions early on (Fig. 3). In the first decades of the 21st century, the warming due to SO_2 emission abatement rivals the cooling due to GHG mitigation in many scenarios, especially those with stringent targets. While aerosol abatement is a co-benefit for air pollution reduction, it potentially lessens the impact of mitigation measures in the early 21st century (eg. Smith and Wigley 2006; Van Vuuren et al. 2006). Furthermore, it increases the uncertainty of climate projections over this period. However, the warming due to aerosol abatement tends to quickly stabilise, while GHG abatement leads to increasing mitigation. This is due to the fact that in the mitigation scenarios, the bulk of aerosol precursor emission reductions occurs in the first half of the century and then reaches a minimum level, while the reference scenarios reduce less and later.

3.3 Warming rate and the role of forcing agents

The rate of change in temperature and other climatic variables is an issue of importance quite independent of that of the mitigation target and stabilisation level. Rates of change codetermine the impact of climate change and costs of adaptation (e.g., Adger et al. 2007).

Mitigation does not show strong effects on temperature evolution over several decades. Several factors explain this slow start. The first is inertia in the climate system and in the socio-technological system. The second is that the “deadline” of the RF target is still too far to induce substantial mitigation efforts in the scenarios with moderate targets. The third is sulfate aerosol abatement as discussed in section 3.2. Scenarios with stringent RF targets show particularly rapid and strong SO_2 emission abatement. Due to the very short atmospheric lifetime of aerosols, high aerosol warming rates can result (Fig. 3, bottom). Consequently, even in aggressive mitigation scenarios global temperature increases at rates not far below the baseline rates of change until the mid 21st century (Fig. 4). A similar result has been reported for the IMAGE (Van Vuuren et al. 2006) and for the MiniCAM scenarios (Smith and Wigley 2006) using the climate component of these IAMs (MAGICC).

The second half of the century only reveals the huge difference between baseline and mitigation scenarios. Some mitigation scenarios show a trend reversal in rates of temperature change for certain forcings (particularly, CH_4, tropospheric and stratospheric O_3 from IMAGE and MiniCAM). Rates of temperature change due to CO_2 are strongly decreased in the more ambitious mitigation scenarios, and negative rates (including the climate-carbon cycle feedback) are seen in the IMAGE 2.6 and the MESSAGE 3.2 scenarios. This is the delayed response to atmospheric CO_2 levels receding since the 2050ies in these scenarios as a result of major CO_2 emission reductions.

While warming decelerates in mitigation scenarios as stabilisation at the forcing target is approached (-0.01 to 0.18 °C/decade over the last 25 yrs), it further accelerates in the references (0.26 to 0.54 °C/decade). Thus the substantial difference in the temperature levels reached in 2100 builds up during quite a short period. Looking further ahead after

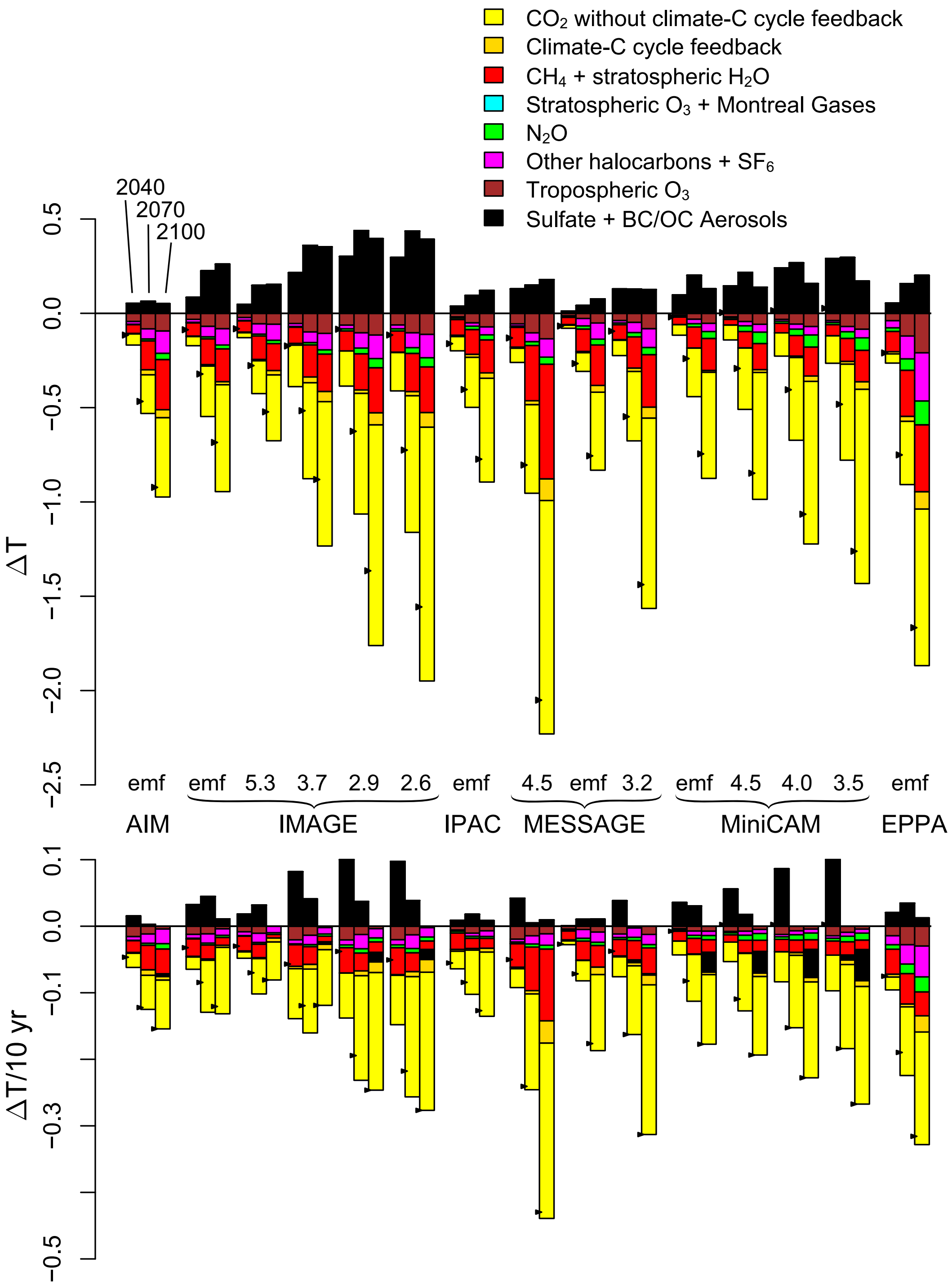

Fig. 3 Effect of mitigation on temperature change attributed to individual forcings using the Bern2.5CC substitute model. The difference ΔT in global mean surface temperature between each mitigation scenario and the corresponding reference scenario is shown in the top panel ($\Delta T = 0$ in the year 2000), and the difference in the mean rate of change in the bottom panel. Each three adjacent bars correspond to temperatures in 2040, 2070, and 2100, and to 25 yr-average rates from these dates backwards, respectively. The net temperature contrast due to mitigation is shown by black "ticks".

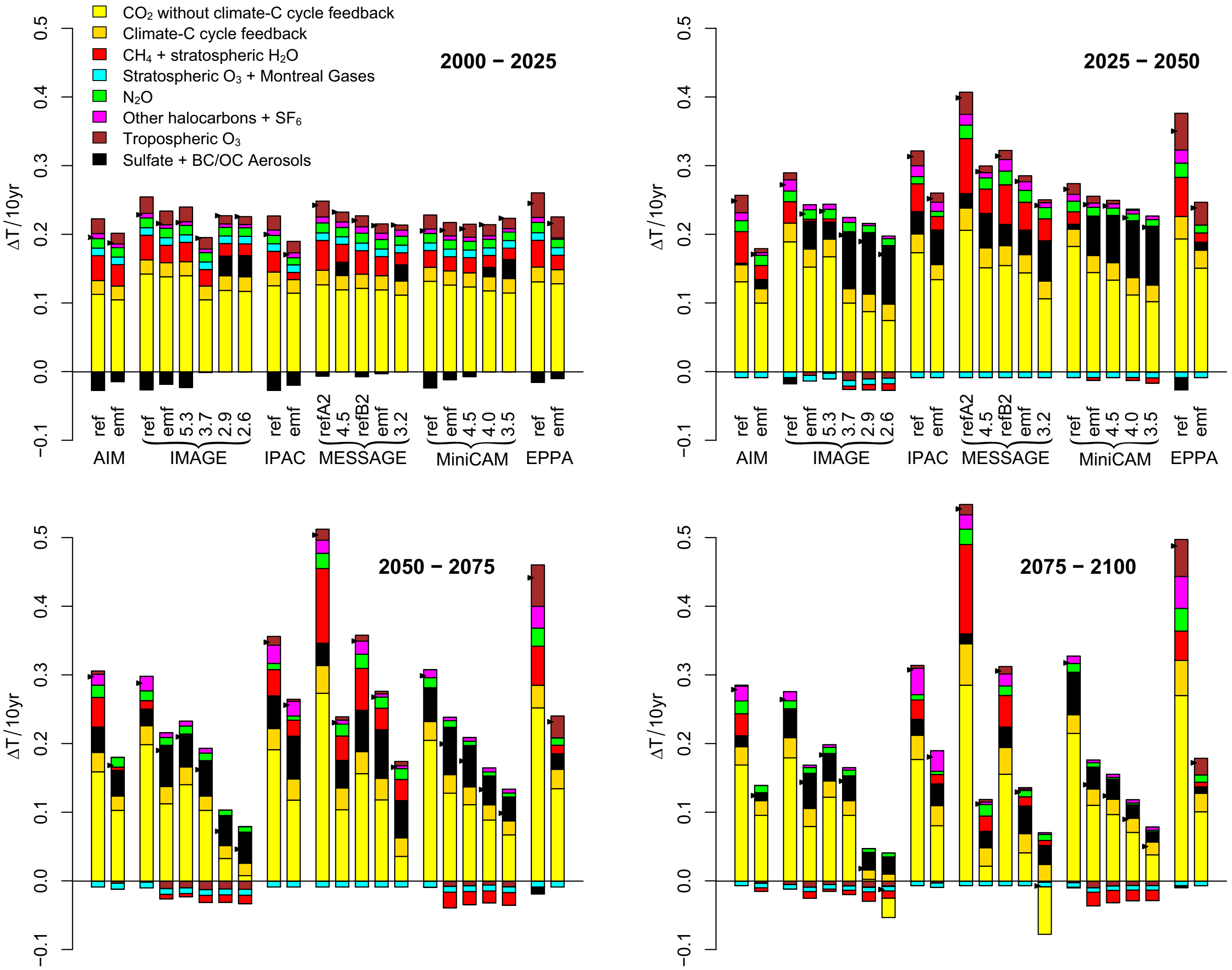

Fig. 4 Rate of global mean surface temperature change. Contributions of individual radiative forcing agents are attributed using the Bern2.5CC substitute model. Each panel shows the mean rate of change over a 25-yr period, as indicated in the panels. The net warming rate is shown by the black ticks at the side of each bar. For comparison, the average global warming rate from 1901 to 2005 is estimated to 0.06–0.07 °C per decade (Trenberth et al. 2007).

2100, it is clear that this gap must continue to widen drastically, as the emissions and warming trends of the reference scenarios continue unchecked through the year 2100.

4 Discussion and conclusions

Simulated CO_2 warming, non-CO_2 GHG warming, and net aerosol cooling are about equal in magnitude in the year 2000. Later in the century, the cooling influence of sulfate aerosols decreases while the temperature change due to GHGs continues to grow, led by the main GHG, CO_2. The relative contribution of CO_2 to the total warming increases in all scenarios with respect to the year 2000. Only in the scenarios with the strongest CO_2 drawdown (MESSAGE 4.5, 3.2) this share starts declining again towards the end of the century. There are several reasons behind this shift. First, activities that cause CO_2 emissions (mostly energy use) are projected to grow much faster than activities that cause emissions of the major non-CO_2 GHGs CH_4 and N_2O (mostly agriculture). Second, while oceans and the terrestrial biosphere absorb much of the emitted CO_2, a sizeable fraction accumulates in the atmosphere and remains airborne for hundreds and even thousands of years. In contrast, the major non-CO_2 GHGs (CH_4, tropospheric O_3, N_2O) are relatively short-lived. Third, the contribution from the carbon cycle-climate feedback is growing in the course of the century. Finally, the potential of non-CO_2 abatement to reduce RF is limited. To offset CO_2 warming over longer times, ever increasing emission cuts in non-CO_2 agents would be necessary, eventually exhausting the non-CO_2 mitigation potential. Thus the situation seen primarily in scenarios with moderate RF targets where non-CO_2 GHGs contribute an important share to mitigation, is transitory. Stabilisation of scenarios complying with the EMF-21 target at RF levels reached in 2100 implies an equilibrium global mean temperature change of about 4°C above preindustrial assuming standard model settings. Even such moderate mitigation would require that net CO_2 emissions be eventually reduced to very low levels compared to today, as demonstrated by the allowable emissions calculated for corresponding stabilisation pathways (e.g. Plattner et al. 2008).

The limited potential of non-CO_2 mitigation is already apparent before 2100, in that the share of mitigation due to CO_2 emission cuts increases with the stringency of the RF target (cf. Rao and Riahi 2006; Van Vuuren et al. 2006). Almost all mitigation beyond the EMF-target of $4.5\,\mathrm{Wm^{-2}}$ is achieved through CO_2 abatement. Sink technologies are instrumental to make these additional net CO_2 emissions reductions possible (Rao and Riahi 2006; Smith and Wigley 2006; Van Vuuren et al. 2006). The feasibility of sink options such as CCS and afforestation on an appropriate scale is, however, uncertain.

Mitigation of rising atmospheric CO_2 concentrations is important not only with respect to climate change, but also with respect to the impacts of elevated CO_2 on natural ecosystems, particularly ocean acidification. Steinacher et al. (2008) show that the Arctic surface ocean will become corrosive to the aragonite shells of marine organisms for CO_2 above about 460 ppm. In the most stringent scenarios, this concentration is not exceeded. The impact of elevated CO_2 concentrations on agriculture and possibly other ecosystem services may be favorable, but is also very uncertain (Fischlin et al. 2007). These are additional reasons why CO_2 mitigation is not substitutable and why focusing on non-CO_2 mitigation can only be a short-to-medium term strategy.

Although non-CO_2 mitigation does not rid us of the need to tackle CO_2 emissions, it does lend flexibility to the mitigation problem. Non-CO_2 mitigation is a significant item in the mitigation portfolio, accounting for the greater part of mitigated warming until mid-century in many scenarios. In the context of a given stabilisation target, the abatement of non-CO_2 RF increases the cumulative allowable CO_2 emissions. Consequently, the consideration of non-CO_2 options lead to significantly lower simulated costs of mitigation (Fujino et al. 2006; Jiang et al. 2006; Rao and Riahi 2006; Reilly et al. 2006; Smith and Wigley 2006; Van Vuuren et al. 2006).

While temperature increases above the preindustrial average projected for 2100 exceed present levels by several times, the speed at which we experience global change today is already very high in historical context. Joos and Spahni (2008) show that rates of change in RF from CO_2, CH_4, and N_2O in the 20th century are at least an order of magnitude higher than during the past 20000 yr. They find that the current rate of change in net anthropogenic RF exceeds decadal-scale rates of change in natural forcings of the last millenium.

The reference scenarios show how failure to address climate mitigation can lead to acceleration of RF change further beyond the natural range. Projected temperatures rise at multi-decadal rates unprecedented at global scale in the documented human experience (e.g., Esper et al. 2002; Mann and Jones 2003), reaching about 0.3 °C/decade (B2 storylines), and about 0.5 °C/decade (others), respectively. Considerably higher rates of climate change are possible if the assumptions on efficiency improvements and lowered carbon intensities in these reference scenarios prove too optimistic (Pielke et al. 2008).

IAMs tend to implement costly mitigation efforts as late as it is compatible with the forcing target. Additionally, the implementation of abatement policies is also impeded by socio-economic inertia. Nevertheless, substantial CO_2 emission abatement starts before about 2030 in all mitigation scenarios and earlier for the lowest targets, because the RF target is a strong constraint on the cumulative CO_2 emissions over the century. Non-CO_2 emission abatement starts even earlier than CO_2 abatement. This is related to the use of GWP as a constant exchange rate between the prices of emission reductions in different GHGs. Early abatement of short-lived GHGs such as methane is not cost-effective in the context of a RF target for the year 2100 (Manne and Richels 2001; van Vuuren et al. 2006), but can nonetheless be considered to be beneficial and reasonable (Van Vuuren et al. 2006), since the “deadline” at 2100 is arbitrary and as such no basis for delaying mitigation.

Despite early inception of mitigation efforts, warming progresses at similar rates in mitigation as in reference scenarios over the first half of the century. Climate inertia delays the response of global temperature to emission reductions, and adds commited warming carried over from 20th century emissions. A further delay can arise from aerosol abatement as a by-product of mitigation efforts. In the second half of the century, however, the impact of mitigation efforts unfolds, with drastically reduced rates of change in CO_2, RF, and temperature in the mitigation scenarios. In 2100, rates of temperature change are below simulated present levels in all mitigation scenarios, and even reach zero for the lowest RF targets of around $3\,\mathrm{Wm^{-2}}$. Timely and extensive mitigation efforts addressing emissions of all RF agents, in particular CO_2, are required to avoid a further acceleration of climate change.

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References

Adger W, Agrawala S, Mirza M, Conde C, O'Brien K, Pulhin J, Pulwarty R, Smit B, Takahashi K (2007) Assessment of adaptation practices, options, constraints and capacity. In: Parry M, Canziani O, Palutikof J, van der Linden P, Hanson C (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp 717–743

Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Friedlingstein P, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Manning M, Matsuno T, Molina M, Nicholls N, Overpeck J, Qin D, Raga G, Ramaswamy V, Ren J, Rusticucci M, Solomon S, Somerville R, Stocker TF, Stott PA, Stouffer RJ, Whetton P, Wood RA, Wratt D (2007) Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, United Kingdom and New York, NY, USA

Clarke LE, Edmonds JA, Jacoby HD, Pitcher HM, Reilly JM, Richels RG (2008) Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Synthesis and Assessment Product 2.1a. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., USA

Cubasch U, Meehl GA, Boer GJ, Stouffer RJ, Dix M, Noda A, Senior CA, Raper S, Yap KS (2001) Projections of future climate change. In: Houghton JT, Ding Y, Griggs D, Noguer M, van der Linden P, Dai X, Maskell K, Johnson CA (eds) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 525–582

Den Elzen M, Schaeffer M (2002) Responsibility for past and future global warming: Uncertainties in attributing anthropogenic climate change. Climatic Change 54:29–73

den Elzen M, Fuglestvedt J, Hohne N, Trudinger C, Lowe J, Matthews B, Romstad B, de Campos CP, Andronova N (2005) Analysing countries' contribution to climate change: scientific and policy-related choices. Environmental Science & Policy 8:614–636

Enting IG, Wigley TML, Heimann M (1994) Future emissions and concentrations of carbon dioxide: Key ocean/atmosphere/land analyses. Tech. Rep. 31, *CSIRO*, Div. of Atmos. Res., Melbourne, Victoria, Australia

Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295:2250–2253

Fischlin A, Midgley G, Price J, Leemans R, Gopal B, Turley C, Rounsevell M, Dube O, Tarazona J, Velichko A (2007) Ecosystems, their properties, goods, and services. In: Parry M, Canziani O, Palutikof J, van der Linden P, Hanson C (eds) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp 211–272

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts RA, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Dorland RV (2007) Chapter 2: Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, United Kingdom and New York, NY, USA

Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, Brovkin V, Doney S, Eby M, Fung I, Govindasamy B, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler KG, Schnur R, Strassmann K, Thompson S, JWeaver A, Yoshikawa C, Zeng N (2006) Climate-carbon cycle feedback analysis: results from the C^4MIP model intercomparison. J Climate 19:3337–3353

Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) Multi-gas mitigation analysis on stabilization scenarios using aim global model. Energy Journal 27:343–353

Jiang K, Hu X, Songli Z (2006) Multi-gas mitigation analysis by ipac. Energy Journal 27:425–440

Joos F, Bruno M (1996) Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric CO_2 and global warming. Phys Chem Earth 21:471–476

Joos F, Spahni R (2008) Rates of change in natural and anthropogenic radiative forcing over the past 20000 years. Proceedings of the National Academy of Sciences of the United States of America 105(5):1425–1430

Joos F, Bruno M, Fink R, Stocker TF, Siegenthaler U, Le Quéré C, Sarmiento JL (1996) An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus 48B:397–417

Joos F, Plattner GK, Stocker TF, Marchal O, Schmittner A (1999) Global warming and marine carbon cycle feedbacks on future atmospheric CO_2. Science 284:464–467

Joos F, Prentice IC, Sitch S, Meyer R, Hooss G, Plattner GK, Gerber S, Hasselmann K (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Global Biogeochem Cycles 15:891–907

Knutti R, Stocker TF (2000) Influence of the thermohaline circulation on projected sea level rise. J Climate 13:1997–2001

Levy II H, Shindell D, Gilliland A, Horowitz L, Schwarzkopf M (eds) (2008) Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., USA

Mann ME, Jones PD (2003) Global surface temperatures over the past two millennia. Geophysical Research Letters 30

Manne AS, Richels RG (2001) An alternative approach to establishing trade-offs among greenhouse gases. Nature 410:675–677

Meehl GA, Covey C, McAvaney B, Latif M, Stouffer RJ (2005) Overview of the coupled model intercomparison project. Bull Am Meteorol Soc 86:89–9

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SC, Watterson IG, Weaver AJ, Zhao ZC (2007) Chapter 10: Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, United Kingdom and New York, NY, USA

Metz B, Davidson O, Swart R, Pan J (eds) (2001) Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, UK

Myhre G, Highwood EJ, Shine KP, Stordal F (1998) New estimates of radiative forcing due to well mixed greenhouse gases. Geophysical Research Letters 25:2715–2718

Nakićenović N, Swart R (eds) (2000) Special Report on Emission Scenarios. Intergovernmental Panel on Climate Change, Cambridge

University Press, New York

Pielke R Jr, Wigley T, Green C (2008) Dangerous assumptions (commentary). Nature 452(3):531–532

Plattner GK, Joos F, Stocker TF, Marchal O (2001) Feedback mechanisms and sensitivities of ocean carbon uptake under global warming. Tellus 53B:564 592

Plattner GK, Knutti R, Joos F, Stocker TF, von Bloh W, Brovkin V, Cameron D, Driesschaert E, Dutkiewiz S, Eby M, Edwards NR, Fichefet T, Hargreaves JC, Jones CD, Loutre MF, Matthews HD, Mouchet A, Müller SA, Nawrath S, Price A, Sokolov A, Strassmann KM, Weaver AJ (2008) Long-term climate commitments projected with climate - carbon cycle models. Journal of Climate 21:2721–2751

Prather M, Ehhalt D, Dentener F, Derwent R, Dlugokencky E, Holland E, Isaksen I, Katima J, Kirchhoff V, Matson P, Midgley P, Wang M (2001) Atmospheric chemistry and greenhouse gases. In: Houghton JT, Ding Y, Griggs D, Noguer M, van der Linden P, Dai X, Maskell K, Johnson CA (eds) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 239–287

Prentice IC, Farquhar GD, Fasham MJ, Goulden MI, Heimann M, Jaramillo VJ, Kheshgi HS, LeQuéré C, Scholes RJ, Wallace DWR (2001) The carbon cycle and atmospheric CO_2. In: Houghton JT, Ding Y, Griggs D, Noguer M, van der Linden P, Dai X, Maskell K, Johnson CA (eds) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 183–237

Rao S, Riahi K (2006) The role of non-CO_2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. Energy Journal 27:177–200

Reilly J, Sarofim M, Paltsev S, Prinn R (2006) The role of non-CO_2 ghgs in climate policy: Analysis using the mit igsm. Energy Journal 27:503–520

Riahi K, Grübler A, Nakićenović N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Change 74:887–935, DOI 10.1016/j.techfore.2006.05.026

Schimel D, Grubb M, Joos F, Kaufmann RK, Moos R, Ogana W, Richels R, Wigley T (1997) IPCC Technical Paper III. Stabilisation of atmospheric greenhouse gases: physical, biological, and socio-economic implications. Intergovernmental Panel on Climate Change. Eds.: J. T. Houghton, L. G. Meira Filho, D. J. Griggs, and K. Maskell

Shine K, Fuglestvedt J, Hailemariam K, Stuber N (2005) Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Climatic Change 68(3):281–302

Smith SJ, Wigley TML (2006) Multi-gas forcing stabilization with minicam. Energy Journal 27:373–391

Steinacher M, Joos F, Frölicher TL, Plattner GK, Doney SC (2008) Imminent ocean acidification projected with the ncar global coupled carbon cycle-climate model. Biogeosciences Discussions 5(6):4353–4393

Stern DI (2005) Global sulfur emissions from 1850 to 2000. Chemosphere 58:163–175

Trenberth K, Jones P, Ambenje P, Bojariu R, Easterling D, Tank AK, Parker D, Rahimzadeh F, Renwick J, Rusticucci M, Soden B, Zhai P (2007) Chapter 3: Observations: Surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, United Kingdom and New York, NY, USA

Trudinger C, Enting I (2005) Comparison of formalisms for attributing responsibility for climate change: Non-linearities in the brazilian proposal approach. Climatic Change 68:67–99

United Nations (1992) United Nations Framework Convention on Climate Change. URL `http://unfccc.int`

Van Vuuren DP, Eickhout B, Lucas PL, Den Elzen MGJ (2006) Long-term multi-gas scenarios to stabilise radiative forcing – exploring costs and benefits within an integrated assessment framework. Energy Journal 27:201–233

Van Vuuren DP, Meinshausen M, Plattner GK, Joos F, Strassmann KM, Smith SJ, Wigley TML, Raper SCB, Riahi K, de la Chesnaye F, den Elzen MGJ, Fujino J, Jiang K, Nakicenovic N, Paltsev S, Reilly JM (2008) Temperature increase of 21st century mitigation scenarios. Proceedings of the National Academy of Sciences 105(40):15,258–15,262, DOI 10.1073/pnas.0711129105

van Vuuren DP, Weyant J, de la Chesnaye F (2006) Multi-gas scenarios to stabilize radiative forcing. Energy Economics 28:102–120

Weyant JR, de la Chesnaye FC, Blanford GJ (2006) Overview of emf-21: Multigas mitigation and climate policy. Energy Journal 27:1–32

Wigley TML, Raper SCB (2001) Interpretation of high projections for global-mean warming. Science 293:451–454

Wigley TML, Richels R, Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature 379:240–243