Climatic Change
DOI 10.1007/s10584-011-0156-z

The RCP greenhouse gas concentrations and their extensions from 1765 to 2300

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Received: 17 September 2010 / Accepted: 21 June 2011

Abstract We present the greenhouse gas concentrations for the Representative Concentration Pathways (RCPs) and their extensions beyond 2100, the Extended Concentration Pathways (ECPs). These projections include all major anthropogenic greenhouse gases and are a result of a multi-year effort to produce new scenarios for climate change research. We combine a suite of atmospheric concentration observations and emissions estimates for greenhouse gases (GHGs) through the historical period (1750–2005) with harmonized emissions projected by four different Integrated Assessment Models for 2005–2100. As concentrations are somewhat dependent on the future climate itself (due to climate feedbacks in the carbon and other gas cycles), we emulate median response characteristics of models assessed in the IPCC Fourth Assessment Report using the reduced-complexity carbon cycle climate model MAGICC6. Projected 'best-estimate' global-mean surface temperature increases (using inter alia a climate sensitivity of 3°C) range from 1.5°C by 2100 for the lowest of the four RCPs, called both RCP3-PD and RCP2.6, to 4.5°C for the highest one, RCP8.5, relative to pre-industrial levels. Beyond 2100, we present the ECPs that are simple extensions of the RCPs, based on the assumption of either smoothly stabilizing concentrations or constant emissions: For example,

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the lower RCP2.6 pathway represents a strong mitigation scenario and is extended by assuming constant emissions after 2100 (including net negative CO_2 emissions), leading to CO_2 concentrations returning to 360 ppm by 2300. We also present the GHG concentrations for one supplementary extension, which illustrates the stringent emissions implications of attempting to go back to ECP4.5 concentration levels by 2250 after emissions during the 21st century followed the higher RCP6 scenario. Corresponding radiative forcing values are presented for the RCP and ECPs.

1 Introduction

A set of scenarios known as Representative Concentration Pathways (RCPs) has been adopted by climate researchers to provide a range of possible futures for the evolution of atmospheric composition (Moss et al. 2008; Moss et al. 2010). These RCPs complement and, for some purposes, are meant to replace earlier scenario-based projections of atmospheric composition, such as those from the Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart 2000). The RCPs are being used to drive climate model simulations planned as part of the World Climate Research Programme's Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2009) and other comparison exercises. The four RCPs are based on multi-gas emission scenarios which were selected from the published literature (Fujino et al. 2006; Smith and Wigley 2006; Clarke et al. 2007; Riahi et al. 2007; van Vuuren et al. 2007; Hijioka et al. 2008; Wise et al. 2009) and updated for release as RCPs (Masui et al. 2011; Riahi et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011b). Because they were produced by four different Integrated Assessment Models (IAMs), there are some inconsistencies in the relationships between emissions and concentrations that could complicate the interpretation of the climatic consequences of the four different scenarios. Furthermore, although *concentrations* drive traditional coupled atmosphere-ocean climate models, CMIP5 also includes simulations by Earth System Models (ESMs) with a full representation of the carbon cycle. These ESMs are optionally driven by prescribed *emissions* of carbon dioxide. The CMIP5 exercise, therefore, requires a set of historical and future pathways for both concentrations and emissions

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(see Appendix 1), ideally produced by a single model. Starting from these standardised concentration datasets, forthcoming CMIP5 intercomparisons will allow our understanding of the relationship between emissions and concentrations to be re-defined.

This study describes how the IAM emissions were processed to produce the RCP GHG concentration values, including the compilation of historical GHG concentrations, the harmonization of emissions towards common 2000–2005 emission levels, the projection of best-estimate future GHG concentrations, and their extension beyond 2100. These concentration pathways lead to radiative forcing values that span a range larger than that of the SRES scenarios. In addition to the central contribution of the IAMs, this process was only possible due to the wide range of contributions from the scientific community, in particular regarding historical emissions, observed concentrations, and emission scenarios for ozone depleting substances (ODSs) (see references in Table 1). An overview of the multi-year process to develop the RCPs can be found in van Vuuren et al. (2011a).

The harmonized GHG concentration and emissions time series recommended for CMIP5 (Taylor et al. 2009) can be obtained from the RCP database website (RCP Database 2009) available at http://www.iiasa.ac.at/web-apps/tnt/RcpDb and the CMIP5 portal (PCMDI 2009) at http://cmip-pcmdi.llnl.gov/cmip5/. Extended GHG datasets until 2500 (for use in very long-term experiments), and further background information on the generation of the harmonized GHG concentration time series are provided at: http://www.pik-potsdam.de/`mmalte/rcps/.

This paper is structured as follows. First, we discuss the general approach taken to derive GHG concentration data for the RCPs in Section 2.1. Historical GHG concentrations from 1765 to 2005 are discussed in Section 2.2. The harmonization of the emissions from the IAMs is covered in Section 2.3, the assumptions used to calculate concentrations and forcing time series for the RCPs over the 21st century are discussed in Section 2.4. The extension of the RCPs beyond 2100 is discussed in Section 3. Section 4 presents the resulting GHG concentration time series for the RCPs. Section 5 discusses the results, including the inverse emission calculations for the extensions, and Section 6 concludes.

2 Methods

2.1 General approach

Each of the IAM teams can, in principle, provide both emissions and concentration data. However, each of the models uses different historical and base year data for the recent past (years 2000–2005). In order to ensure a smooth transition in the climate model runs from the historical period into the future, a harmonization step for emissions was performed here. Furthermore, it was decided that a single model version of MAGICC (e.g. Wigley and Raper 2001; Wigley et al. 2009; Meinshausen et al. 2011a) should be used to produce a more consistent estimate of concentrations and carbon feedbacks, rather than basing the RCPs on a variety of different model versions. GCAM that produced RCP4.5 (Thomson et al. 2011), for example, uses MAGICC5.3, as does AIM that contributed RCP6 (Masui et al. 2011). MESSAGE that produced RCP8.5 (Riahi et al. 2011) uses an updated version of MAGICC4.2, and IMAGE that produced RCP2.6 (Van Vuuren et al. 2011b)[1] uses

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[1] A note on the naming of the lower RCP pathway: In the literature, this lower pathway is both called RCP3-PD and RCP2.6. “PD” reflects the unique characteristic of this pathway, i.e., its “Peak & Decline” shape—in contrast to other mere stabilization scenarios. Historically, two candidates were discussed for this lower RCP, RCP2.6 and RCP2.9 with RCP2.6 being finally chosen. Hence, both names, RCP3-PD and RCP2.6, can be used interchangeably.

Table 1 Historical mixing ratios of GHG concentrations used to extend RCP concentrations back in time

Historical mixing ratios	Description
CO_2	Data up to 1832 from Law Dome Ice Core data (Etheridge et al. 1998b) in its 75 year smoothed version [a]. For 1832 through 1958 the Law Dome 20-year smoothed data are used. This Keeling MLO record (Keeling and Whorf 2004) [b] is used over 1959 to 1981 with 0.59 ppm subtracted. 0.59 ppm is the mean difference between the Keeling MLO dataseries and the NOAA/ESRL/GMD global estimates over 1982–1986 (Conway et al. 1994)[c]. The global NOAA/ESRL/GMD data in 1982 and adjusted MLO values are the same at 340.56 ppm. Global NOAA data for 1980 and 1981, but these are not used because they are less consistent with MLO than for subsequent years. From 1982 to 2008, CO_2 concentrations were extended with NOAA global-mean datapoints (Conway et al. 1994)[c].
CH_4	Observations up to 1850 are taken from the Law Dome Ice Core data (Etheridge et al. 1998a)[d]; beyond 1850, the data compilation for the NASA GISS model was used[e]: this data compilation uses concentration estimates over 1850–1980 from Etheridge et al. (1998a) followed thereafter by data from: NOAA/ESRL/GMD (Dlugokencky et al. 1994) for the period 1984 to 2003. From 2004 to 2008, the mixing ratios are taken from the flask data results from the NOAA ESRL Global Monitoring Division[f].
N_2O	Nitrous Oxide (N_2O) average mixing ratio data up to 1850 data is taken from Flückiger et al. (2002) in its smoothed version using a 300 year cutoff spline; thereafter, from 1850 onwards, the data compilation by NASA GISS team is used[g]. This includes the N_2O measurements by Machida et al. (1995) from 1850 to 1977 and NOAA/ESRL/GMD Flask Data[h] over 1978–1999. From 2000 to 2008, our historical dataseries are sourced from the NOAA/ESRL/GMD In-Situ measurement data provided by G.S. Dutton, T.M. Thompson, J.W. Elkins and B.D. Hall[i]
C_2F_6	Historical C_2F_6 mixing ratios are determined from firn air as presented n Worton et al. (2007), Fig. 2b, which includes model results over 1940 to 2001; before 1940, we linearly interpolated to zero levels in 1900.
CF_4	An initial pre-industrial mixing ratio of 35 ppt is assumed until 1922, based on Worton et al. (2007) and Deeds et al. (2008). From 1940 to 2003, the mixing ratio is determined from firn air, as provided in Worton et al. (2007). In between, from 1922 to 1940 estimates are based on model results which assume a constant rate of increase.
HFC-125	Our data is based on Oram et al. (1998) and Fig. 1–23 in WMO (2006), linearly interpolated back to zero from 1980 to 1970.
HFC-134a	Based on NOAA/ESRL/GMD data (Montzka et al. 1996a; Montzka et al. 1996b)[j] extended to July, 2008.
HFC-143a	Based on Culbertson et al. (2004), Table 1 (interpolated end-of-year values between 1978 and 1996); linear interpolation to zero from 1978 to 1970 and linear extrapolation from 1996 to 2000 to attain the average RCP value.
HFC-23	Based on Oram et al. (1998) with extension until 2004 as provided in WMO (2007) Fig. 1–23 and using average 1977–1987 growth rate of concentrations (8.7%/year) for extending back to 1930.
SF6	SF_6 is regularly measured at multiple NOAA/ESRL/GMD sites and by different techniques. We base our 1961–2008 estimate on a record from firn air, flasks, and in situ instruments from Butler et al. (1999); Geller et al. (1997), and from Peters et al. (2004), linearly interpolated back to zero from 1960 to 1950.

Table 1 (continued)

Historical mixing ratios	Description
ODSs	Taken directly from the WMO Stratospheric Ozone Assessment A1 scenario, starting in 1950 (Daniel et al. 2007). These mixing ratio histories are derived using results from global atmospheric measurements, analyses from firn air, archived air, and industrial production and bank data (Montzka et al. 1996a; Butler et al. 1999; Prinn et al. 2000; Metz et al. 2005; Clerbaux et al. 2007). Pre-1950 estimates were loosely based on AFEAS production data and consistent with the 1950 values for CFC-11, CFC-12, CFC-114, and CCl_4. Pre-1950 emissions were designed such that 1950 concentration values are matched under the default lifetimes. For example, a linear ramp up of emissions from 1938 to 1950 of HCFC-22 emissions has been assumed to match 1950 concentration value (0.95 ppt). For CH_3Br and CH_3Cl, a pre-industrial value of 5.8 and 480 ppt is assumed, respectively.

[a] ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/law/law_co2.txt

[b] http://cdiac.ornl.gov/ftp/trends/co2/maunaloa.co2

[c] ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_gl.txt

[d] ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/law/law_ch4.txt

[e] http://data.giss.nasa.gov/modelforce/ghgases/Fig1B.ext.txt

[f] ftp://ftp.cmdl.noaa.gov/ccg/ch4/flask/month/

[g] http://data.giss.nasa.gov/modelforce/ghgases//Fig1C.ext.txt

[h] ftp://ftp.cmdl.noaa.gov/hats/n2o/flasks

[i] ftp://ftp.cmdl.noaa.gov/hats/n2o/insituGCs/CATS/global/insitu_global_N2O

[j] ftp://ftp.cmdl.noaa.gov/hats/hfcs/

MAGICC6 except for its carbon cycle. Thus, as a second harmonization step, we apply a single climate and carbon cycle treatment, using the latest version 6 of MAGICC (Meinshausen et al. 2011a, b)[2] to derive concentrations and inverse emissions for the RCPs.

By design, this study is concerned with providing a 'reference' starting point for further analysis in model intercomparison exercises rather than providing a detailed uncertainty analysis of the cause-effect chain from emissions to concentrations and global-mean temperatures. We hence limited this documentation to a detailed description of the chosen assumptions in deriving the RCP's GHG concentrations, which can serve as the starting point for multi-model ensemble analysis in the future. A detailed description of the cause-effect chain as included in MAGICC6 can be found elsewhere (Meinshausen et al. 2011a), including a representation of uncertainties (Wigley and Raper 2002; Meinshausen et al. 2009).

The following subsections describe our four steps to yield harmonized GHG concentrations and emissions for the RCPs from the native output of the four IAM scenarios (see Fig. 1 below).

2.2 Historical concentrations

For comparing climate model outcomes with historical climate observations, it is ideal if atmosphere-ocean general circulation models (AOGCMs) are driven with observations of

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[2] A research version of MAGICC6 with RCP default settings used in this study will be available from www.magicc.org for the wider scientific community.

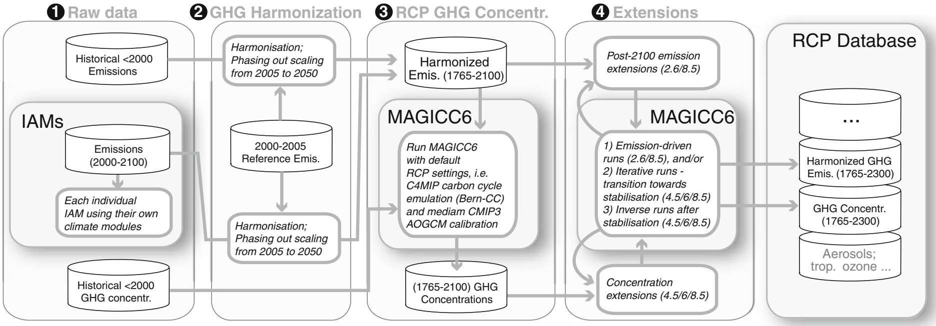

Fig. 1 Overview of methods to harmonize emissions, derive GHG concentrations and create the extensions for the RCPs. See text for further details

the historical atmospheric composition. Such a comparison can be helpful for assessing the skill of climate models, or to determine the human-contribution to climate change. Building on current literature, and with the help of a number of experts, we compiled a consolidated set of 20th century global and annual mean GHG concentrations. Specifically, we compiled concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), eight different hydrofluorocarbons (HFCs, namely HFC-23, HFC-32, HFC-43-10mee, HFC-125, HFC-134a, HFC-143a, HFC-227ea, and HFC-245fa), three perfluorocarbons (PFCs, namely CF_4, C_2F_6, and C_6F_{14}), and SF_6, as well as concentrations of 16 ODSs (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, Carbon Tetrachloride, Methyl chloroform, HCFC-22, HCFC-141b, HCFC-142b, Halon-1211, Halon-1202, Halon-1301, Halon-2402, CH_3Br, CH_3Cl). Building on this database of historical observations, we recommend sets of pre-industrial control run concentrations, depending on whether the historical '20th century' run starts in 1765, or 1850 (or any year in between). Concentrations over this 1765 to 1850 period are constant for the halogenated gases with natural sources, i.e., CF_4, CH_3Br and CH_3Cl, with 35 ppt, 5.8 ppt and 480 ppt, respectively. However, the recommended concentrations for the long-lived GHGs, CO_2, CH_4, and N_2O show a small increase over that period, starting from the levels 278.1 ppm, 721.9 ppb, and 273.0 ppb in 1765 and increasing to 284.7 ppm, 791.0 ppb, 275.4 ppb in 1850, respectively. The concentrations were compiled based upon data available as of mid-2009 (see Table 1).

2.3 Harmonization of emissions

The harmonization of GHGs, tropospheric ozone precursors and aerosol emissions to common historical levels is necessary as IAMs do not necessarily start with the same historical emissions inventories, which is a disadvantage for comparisons of the scenarios' future climate effects. There are several reasons that different IAM scenarios do not share the same historical emissions: besides the uncertainty in the historical record, different IAMs 1) do not include the same set of human activities that lead to emissions, 2) smooth short-term fluctuations differently and/or 3) assume different emissions factors from emissive processes. In addition, the actual 'real world' activity levels and emissions factors are inherently uncertain. The most appropriate harmonization method depends on the reasons that underlie the differences in historical emission levels. Given the many different sectors and emissions factors in the IAMs, a simple and transparent approach is followed here.

Reactive gas and aerosol emissions have been harmonized to year 2000 levels in a separate exercise in the RCP creation process (Lamarque et al. 2010; Smith et al. 2011; Granier et al. 2011), namely for sulfate oxides (SOx), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), black carbon (BC), organic carbon (OC), ammonia (NH_3), and also for methane (CH_4) because of its role in atmospheric chemistry. Here, we extend this harmonization of the reactive gas emissions to year 2005 by using the average growth rates in RCP8.5, RCP4.5, and RCP2.6.[3] This harmonization, therefore, enforces consistency among all RCP scenarios over 2000–2005 period.

For other GHGs, i.e. CO_2, N_2O, HFCs, PFCs, and SF_6, we harmonized global and five-region emission levels using simple scaling routines so that by construction, all four harmonized RCPs share the same 2000 to 2005 emissions data. The five regions are essentially the same as the four SRES regions with the 'Africa&Latin America (ALM)' region being split into 'Middle East and Africa (MAF)' and 'Latin America (LAM)' (see http://www.iiasa.ac.at/web-apps/tnt/RcpDb for a country-by-country definition of these regions). For fossil and industrial CO_2 emissions, we used global inventory estimates from Marland et al. (2008) to 2005. Extending the harmonization only to 2005 does not include the substantial emission increase until 2008 or the zero growth rate in 2009 due to the financial crisis (Olivier and Peters 2010). This was a conscious decision, partially because RCPs are not meant to reflect short-term fluctuations. Net land-use CO_2 emissions estimated by the IAMs (on average 1.15 GtC in the year 2000) are lower than some other emission estimates, e.g. the 1.41 GtC in year 2000 by Houghton (2008).[4] To maintain consistency with the underlying land-use patterns (Hurtt et al. 2011), and given the large uncertainty in current global land-use related CO_2 emissions of around ±0.5 GtC/yr (DeFries et al. 2002; Canadell et al. 2007), we harmonized the emissions using the IAM average (RCP2.6, RCP4.5 and RCP8.5). For fluorinated gases that are included in the basket of gases controlled under the Kyoto Protocol (HFCs, PFCs, SF_6), we used observed concentrations, where available, and derived inverse emission estimates using default lifetime assumptions (Table 2.14 in Forster et al. 2007) within the MAGICC6 coupled gas-cycle climate model. For C_6F_{14}, HFC-32, HFC-43-10mee, HFC-227ea, and HFC-245fa, we took available emissions data from either SRES (Nakicenovic and Swart 2000) (HFC-43-10mee), EDGAR4 (EC-JRC and PBL 2009) (C_6F_{14}, HFC-227ea) or the non-harmonized RCPs (HFC-32, HFC-245fa). For HFC-245fa, sparse observations exist (Vollmer et al. 2006), pointing to lower, but much faster increasing, emissions than we used here from the original RCP4.5 estimates. This difference might be due to an overestimation of actual emissions by RCPs and/or due to slower release factors in early applications of this foam blowing agent than assumed by the IAMs. For ODSs, we use the emissions that were used to derive, with a box model, the standard WMO (2007) A1 scenario concentrations. Further details are provided in Table 2.

We employ a harmonization process whereby the original IAM emission data is adjusted to the common 2000–2005 values and these adjustments are phased out afterwards. Specifically, the longer term RCP emission levels are identical to those of the original IAM emissions from 2050 onwards. In between, from 2005 to 2050, a multiplier, i.e., the ratio between RCP harmonized emission levels and original IAM emissions in 2005, is linearly relaxed back to 1 until 2050 (c.f. Van Vuuren et al. 2008).

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[3] RCP6 was harmonized as well, but its values were not used to determine the growth rates (or other averages for harmonization) due to the later finalization date of this data set. Taking into account RCP6 does not substantially change these results relative to other uncertainties.

[4] 1GtC/yr = 44/12 $GtCO_2$/yr

Table 2 Harmonization emission values

Compound	Unit	Harmonized global Emissions		Source	Harmo. method	Remark
		2000	2005			
Fossil & Ind. CO_2	GtC	6.74	7.97	Marland et al. (2008)	Scale until 2050[b]	The recent emission increase until 2008 and stagnation in 2009 have not been used to harmonize RCP emissions, partially because RCPs are not meant to reflect short term fluctuations, partly because 2010 emissions are likely to be close to the harmonized RCP values.
Landuse CO_2	GtC	1.15	1.20	RCP scenarios and Houghton (2008)	Shift until 2030[b]	2000 is average across RCP2.6, RCP4.5, and RCP8.5 with post-2000 growth rates from Houghton (2008)
CH_4	$MtCH_4$	300.21	315.9	Lamarque et al. (2011)	Scale until 2050[b]	For 2001–2005, the average growth rate across the RCP2.6, RCP4.5 and RCP8.5 scenario is assumed
N_2O	MtN	7.46	7.68	RCP IAM emission scenarios	Scale until 2050[b]	Simple average across original IAM emissions for RCP2.6, RCP4.5 and RCP8.5
SOx	MtS	53.84	56.72	Smith et al. (2011)	Scale until 2050[b]	For 2001–2005, the average growth rate across the RCP2.6, RCP4.5 and RCP8.5 scenario is assumed
CO	MtCO	1,068	1,061	Lamarque et al. (2011)		
NMVOC	Mt	210.62	215.46			
NOx	MtN	38.16	38.79			
BC	Mt	7.8	8.25			
OC	Mt	35.54	36.39			
NH_3	MtN	40.02	41.88			
CF_4	kt	12.00	11.61	Inverse emission estimate[a]	Scale until 2100[b]	In order to match the observed mixing ratio record (Worton et al. 2007) a nearly constant 12 kt emission is necessary (as the concentration increase is close to linear). For 2000–2005, using average growth rate of RCP2.6, RCP4.5 and RCP8.5.
C_2F_6	kt	2.38	2.65	Inverse emission estimate[a]		This emission rate is necessary to match the 0.1 ppt constant mixing ratio increase observed by (Worton et al. 2007).
C_6F_{14}	kt	0.46	0.44	EDGAR4 (EC-JRC and PBL 2009)		RCP2.6 is the only RCP reporting C_6F_{14} with 1.6kt in year 2000. The lower EDGAR4 data was assumed for harmonization.
HFC-23	kt	10.39	10.81	Inverse emission estimate[a]		Inverse emissions to match observed record as shown in Fig. 1.23 of WMO (2006) following Oram et al. (1998). Average growth rate of RCP2.6, RCP4.5 and RCP8.5 between 2004 and 2005 assumed.

Table 2 (continued)

Compound	Unit	Harmonized global Emissions		Source	Harmo. method	Remark
		2000	2005			
HFC-32	kt	4.00	10.99	Taken from original RCP2.6		RCP2.6 is the only RCP reporting HFC-32 emissions.
HFC-43-10mee	kt	0.00	3.24	Average of SRES B1 & A2		As no data was reported in RCP scenarios, the average across SRES B1 & A2 emissions have been assumed. RCP2.6, RCP4.5 and RCP6 follow the stabilizing SRES B1 emissions and RCP8.5 follows A2 emissions.
HFC-125	kt	8.81	13.86	Inverse emission estimate[a]		Inverse emissions to match observed record as shown in Fig. 1.23 of WMO (2006) following Oram et al. (1998). Average growth rate of RCP2.6, RCP4.5 and RCP8.5 between 2004 and 2005 assumed.
HFC-134a	kt	75.69	121.93	Inverse emission estimate[a]		Inverse emissions to match observed atmospheric mixing ratios as provided by NOAA ESRL/GMD available here: /ftp://ftp.cmdl.noaa.gov/hats/hfcs/ (Montzka et al. 1996b)
HFC-143a	kt	6.48	12.72	Inverse emission estimate[a]		Inverse emission for 2000 to match observed atmospheric mixing ratios measured by Culbertson et al. (2004) with 2001-2005 emission growth rate taken as average from RCP2.6, RCP4.5 and RCP8.5.
HFC-227ea	kt	1.95	4.89	EDGAR4 (EC-JRC and PBL 2009)	Scale	As for HFC-245fa, recent observations (Laube et al. 2010) suggest smaller actual emissions.
HFC-245fa	kt	17.93	26.89	RCP4.5 original data	Scale	RCP4.5 derived their HFC-245fa emissions based on a later set of EMF-22 data than RCP2.6 or RCP8.5. Note that this is substantially higher than recently observed (Vollmer et al. 2006), although the latter implies higher rates of increase.
SF_6	kt	5.46	6.21	Inverse emission estimate[a]	Scale	Inverse emission estimate based on a constant lifetime of 3200 years and observed mixing ratios. Based on Butler et al. (1999) and Geller et al. (Geller et al. 1997), and Peters et al. (Peters et al. 2004).

[a] Inverse emissions are estimated using the MAGICC6 gas cycle modules (Meinshausen et al. 2011a)

[b] This harmonization by scaling assumes a multiplicative scaling factor that is the ratio between the harmonized and the original IAM emissions in year 2005, and 1 in the year until which the scaling is applied. In between, from 2005 to year X, i.e., 2050 or 2100, the scaling factor is linearly interpolated between its year 2005 value and 1

Exceptions to this approach are applied for land-use related CO_2 emissions and some fluorinated gases. Land-use related CO_2 emissions turn negative in some regions, which is why we chose to apply an additive shift of emissions rather than a multiplier. The difference between original IAM emissions and the harmonized levels in 2005 is added to the original IAM data and this offset is linearly reduced to zero by 2030. A scaling factor rather than an offset until 2050 could have resulted in more pronounced negative emissions even in the case of an upward adjustment in 2005.

For fluorinated gases, the SRES scenarios used an external set of emissions (Fenhann 2000). In contrast, the IAMs producing the RCP scenarios now include fluorinated gas emissions in their modeling frameworks. For some fluorinated gas species, updated information on their trends is available, which causes IAMs to project markedly different future emissions compared to SRES. Some IAMs, however, include only a few aggregate fluorinated gas categories. This leads to somewhat artificially narrowed spreads for some fluorinated gas projections.

For HFC-227ea, current emission levels provided in the RCPs were uncertain as emissions for this gas in both RCP4.5 and RCP8.5 were only available as an aggregate together with HFC-125. Large uncertainties in HFC-227ea emissions result from the fact that there were no ambient air measurements that could constrain anthropogenic emission estimates in mid-2009, a fairly unique situation for a GHG - and only recently remedied (Laube et al. 2010). Bottom-up emission estimates (e.g. EDGAR4 data by EC-JRC and PBL 2009) seem to overestimate actual HFC-227ea emissions estimated from ambient measurements (Laube et al. 2010). The overall radiative forcing contribution of both gases, HFC-245fa (see above) and HFC-227ea, is rather small, so any future revisions will likely have a minor effect on aggregate radiative forcing levels. For the RCP4.5 and RCP8.5 scenarios, a simple approximation has been used to estimate future emissions of HFC-227ea and HFC-125. The reported GWP-weighted aggregate emissions (HFC-227ea plus HFC-125) were multiplied by scaling factors from the RCP2.6 scenario, which was the only scenario with separate projections for these two gases. RCP6 emissions for HFC227ea were taken from RCP2.6. EDGAR4 data (EC-JRC and PBL 2009) were used for historical harmonization values for HFC-227ea and a constant scaling factor was applied. Similarly, for HFC-245fa and SF_6, a 'ramped' scaling until 2050 would have led to a considerable change in growth rates compared to the near-monotonic increase of emissions until 2100 reported for RCP8.5. Thus, a constant scaling factor was applied over time, which led to higher RCP8.5 emissions by 2100 than projected by the original IAM scenario (see Fig. 2).

The net effect of the harmonization procedure for the long-lived GHGs and ODSs is in some years moderate, but is generally small and negligible in the long-term. Over all years, the highest upward shift in GWP-weighted (100 year time horizon) (IPCC 1996) aggregate emission levels is 11.5% for the RCP6 scenario, which is due to a substantial upward shift of landuse CO_2 emissions from 1.3 to 4.4 $GtCO_2$/yr in year 2005 (+226%). A 4.1% upward adjustment of the RCP2.6 scenario in 2005 resulted as well from the harmonization of landuse CO_2 emissions from 2.8 to 4.4 $GtCO_2$/yr in year 2005, in addition to small upward corrections of CH_4 and fluorinated gases (see Fig. 2). Harmonization reduced the RCP8.5 emissions slightly, by 2.1% in 2005. The aggregate emission levels of RCP4.5 faced a small upward shift by 2.1% in 2005. By construction, the harmonization procedure had only negligible effects on post-2050 emission levels (<0.3%) given that only a few fluorinated gases were adjusted after 2050.

Note that these induced shifts of emission levels are within the uncertainty of current emission estimates. Nevertheless, due to the cumulative effect on radiative forcing levels for long-lived gases, the harmonization procedure will result in slightly different concentration

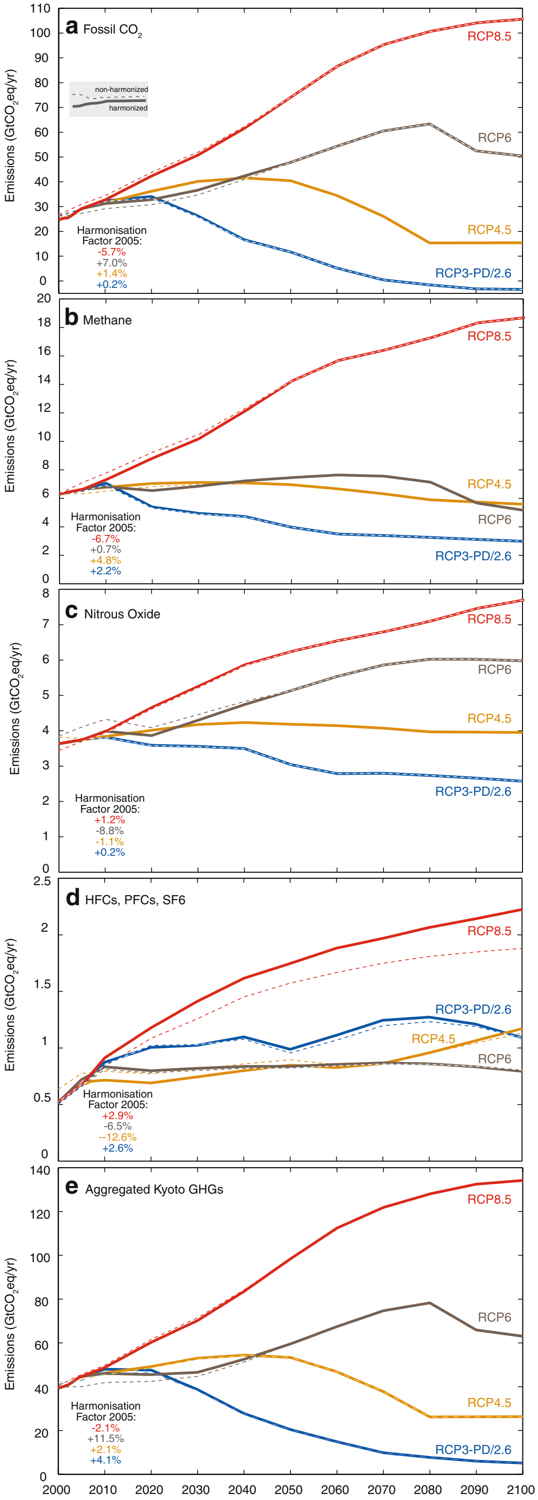

Fig. 2 Harmonized emissions under the four RCP scenarios. The non-harmonized scenarios (*dashed lines*) are in most cases marginally different from the harmonized emissions (*solid lines*). For illustrative purposes, emissions are weighted with IPCC SAR Global Warming Potentials of a 100-year time horizon (IPCC 1996)

and temperature projections (which is intended as part of increasing the comparability between the different scenarios). To ensure a smooth transition of concentrations from historical runs for shorter-lived substances, the harmonization is an essential step for consolidating the scenarios from four different IAMs for a climate model inter-comparison. Otherwise, a consistent comparison of the resulting climate consequences across the scenarios would be hindered.

Some other limitations of the harmonized emissions arose. The ODS projections (WMO 2007) do not incorporate the effects of the accelerated HCFC phase-out accepted by the Parties to the Montreal Protocol in 2007. In the absence of specific mitigation policies, this acceleration would be expected to lead to somewhat lower future HCFC emissions (Velders et al. 2007). and higher HFC emissions (Velders et al. 2009). Furthermore, NF_3 (as well as several less abundant fluorinated gas compounds) are not included in the RCPs even though they may have small positive radiative forcing effects (Prather and Hsu 2008; Prather and Hsu 2010).

2.4 Calculation of GHG concentrations

In most of the experiments for the CMIP5 intercomparison exercise, AOGCMs and ESMs will be driven by historical and future GHG concentrations, not emissions, as shown in Appendix 1 and further described in Taylor et al. (2009). We derive concentrations from the harmonized emissions with a single model, MAGICC6, in order to ensure consistency between and within the different RCPs. Although various versions or parts of MAGICC are used in many IAMs (see above), we chose MAGICC not as a model in its own right, but because of its ability to closely emulate the full range of C^4MIP carbon cycle and CMIP3 AOGCMs (Meinshausen et al. 2011a). We now summarize the various gas-cycle parameterizations, before providing more detail on the chosen carbon cycle and climate response settings. Our assumptions regarding non-GHG forcing agents are detailed in Appendix 2.

MAGICC uses gas-cycle parameterizations of different complexity to project concentrations and radiative forcing for CO_2, CH_4, N_2O,3 PFCs, 8 HFCs, SF_6 and 16 ODSs (see listing of individual species in Section 2.2). For CO_2, MAGICC includes a global carbon cycle model with three land carbon pools, an ocean carbon scheme, and multiple temperature-dependent terrestrial and oceanic fluxes, as well as a parameterization for the CO_2 fertilization effect. The model is designed to closely emulate higher complexity carbon cycle models regarding seven aggregated carbon pools and fluxes, as well as atmospheric CO_2 concentrations, as described in detail in Meinshausen et al. (2011a). The model does not yet include a nitrogen cycle or interactions between the carbon cycle and nitrogen cycle – reflecting the state of carbon cycle models in C^4MIP in 2006 (Friedlingstein et al. 2006). The chosen carbon cycle calibration is further described below.

For projecting CH_4 and N_2O concentrations, parameterizations from Ehhalt et al. (2001) are used—including simplified temperature-dependent tropospheric OH-chemistry parameterizations. Both CH_4 and N_2O lifetime includes a dependency of its lifetime on its own abundance. Further details regarding how these processes are treated in MAGICC6 can be found in Meinshausen et al. (2011a). Stratospheric sinks for all fluorinated gases and ODSs are assumed to become enhanced slightly with rising global mean temperatures (15% per degree Celsius warming) leading to shorter lifetimes at higher warming levels—due to a strengthening Brewer-Dobson circulation (Butchart and Scaife 2001). As the lifetime of CH_4, tropospheric OH-related sinks of flourinated gases are made dependent on the parameterized changes in the OH abundances.

Previous applications of MAGICC6 have not used a single set of best-estimate parameters to calculate concentrations, radiative forcings and global mean temperatures from prescribed emissions, but instead used an array of parameter sets to project a range of climate responses by emulating CMIP3 GCMs (Meehl et al. 2005) and to project a range of CO_2 concentrations by emulating C^4MIP carbon cycle models (Friedlingstein et al. 2006) as described in Meinshausen et al. (2011a). Alternatively, historically constrained joint distributions of parameters were used (Meinshausen et al. 2009). To calculate a single set of concentrations for driving climate models (the motivation for the design of the RCPs), we need a single "best" set of model parameters for MAGICC. Many temperature projections will ultimately be produced by the CMIP5 models. However, the importance of having a 'best-estimate' future temperature projection within MAGICC6 is that many gases' concentrations are influenced by temperature or climate feedbacks.

We chose parameters for MAGICC6 that would closely reflect the median of the distribution in global-mean temperature projections that is spanned when emulating the GCMs and carbon cycle models that took part in CMIP3 and C^4MIP, respectively. Specifically, we chose an emulation of the C^4MIP Bern-CC carbon cycle model (Joos et al. 2001) as 'best-estimate' for the carbon cycle behavior. This is both because the Bern-CC model (and earlier versions of this model) has been used for the consolidated concentrations of IPCC SRES scenarios presented in the Third Assessment Report (see Appendix II in Houghton et al. 2001) and because the projected CO_2 concentrations from the Bern model are roughly in the middle of the range of C^4MIP results (Friedlingstein et al. 2006).

For obtaining a 'best-estimate' climate response (which in turn influences concentrations), the intention is to have a set of climate parameters (such as climate sensitivity, vertical ocean diffusivity, etc.) that resembles the median of the AOGCMs that took part in CMIP3. We first emulated 19 of the CMIP3 AOGCMs by using calibrated MAGICC parameters, which span a climate sensitivity range between 1.9 K and 5.7 K (see Table B3 in Meinshausen et al. 2011a). We ran these emulations for the SRES A1B, B1 and A2 and 'Constant year 2000 concentration' scenarios, taking into account a complete set of radiative forcing agents (including e.g. indirect aerosol effects). In these emulations, we used the default Bern-CC emulation setting for the MAGICC carbon cycle. We then took the median for each scenario across these 19 global mean temperatures and ocean heat uptake time-series. Thereby, we created pseudo-AOGCM datasets, to which a standard least-squares optimization routine could calibrate a "best" set of 10 climate parameters of MAGICC. This is the same procedure as described in Meinshausen et al.(2011a), except that we fix the climate sensitivity at its best-estimate value of 3 K (Meehl et al. 2007; Knutti and Hegerl 2008). This fixed climate sensitivity is very close to the average of 2.88 K from emulating AOGCM CMIP3 models without a fixed climate sensitivity (see Table 4 in Meinshausen et al. 2011a).

Apart from deriving the default MAGICC climate response parameter set for creating the RCPs, one additional amendment has been implemented in MAGICC6 to serve this RCP process. Inverse emissions are now routinely calculated for all 31 considered GHGs (CO_2, CH_4, N_2O, 3 PFCs, 8 HFCs, SF_6 and 16 ODSs). This is of interest when concentration time-series are prescribed for designing the ECPs. For CO_2, these inverse emissions can be compared to the allowable emissions derived from ESMs in the course of CMIP5.

3 Post-2100 extension

The RCP emissions scenarios produced by the IAMs span the period 2005 to 2100. Most IAM research focuses on the 21st century and there is little research addressing comprehensive scenarios beyond 2100. Conducting multi-century climate change analyses, however, requires input data beyond 2100. We designed extensions to the RCPs, the Extended Concentration Pathways (ECPs), using simple rules that have been developed in a series of stakeholder consultations among scientists in the IPCC WG1, WG2 and WG3 communities, including representatives of the IAM groups, representatives of CMIP5, and the wider scientific community. It should be noted that these extensions do not represent fully consistent scenarios, but are simple 'what-if' thought experiments that represent the underlying ideas behind each RCP, which are produced for the purposes of providing a common set of input data for long-term model comparison projects. The rules used for the extension of emissions and/or concentrations of the RCPs are shown in Table 3. No explicit assumptions relating to population or economic development have been made for these stylized 'what-if' extensions.

Generally, there are three options for the design of a simple extension (with multiple combinations of these possible): I) the forcing and concentrations can simply be kept constant (as done for the SRES scenarios in CMIP3 and assessed by the IPCC Forth Assessment Report, AR4), II) emissions can be adapted over time, e.g. to yield a smooth stabilization at another level than where concentrations are in year 2100, or III) emissions can be kept constant. The two intermediate scenarios RCP4.5 and RCP6 are extended by concentration stabilization, albeit with stabilization achieved in 2150 to avoid discontinuities in the implied emissions. For the lowermost RCP, RCP2.6, emissions were kept constant after 2100. The extension of the highest RCP, RCP8.5, represents a mixture of constant emissions until 2150 and constant concentrations after 2250 (see Table 3). As a result of now including a low mitigation pathway RCP2.6 and due to these extension choices, the ECPs span a much wider range of post-2100 forcing pathways than considered in previous studies, such as CMIP3 assessed in IPCC AR4.

Several alternative extensions were considered for each RCP. For RCP8.5, the full range of possible extensions ranged from a constant forcing that results from simply keeping concentrations constant after 2100 to very high levels that result from assuming that emissions stay constant until 2300. After consultations with the respective expert groups an

Table 3 The RCPs and their simple extension rules beyond 2100 assumed for all GHGs.

RCP scenario 2005-2100	Extension 2100 to 2300	Extension rule[a]
RCP2.6/RCP3-PD[b]	ECP3-PD	Constant emissions after 2100.
RCP4.5	ECP4.5	Smooth transition towards concentration stabilization level after 2150 achieved by linear adjustment of emissions between 2100 and 2150.[c]
RCP6	ECP6	
RCP8.5	ECP8.5	Constant emissions after 2100, followed by a smooth transition to stabilized concentrations after 2250 achieved by linear adjustment of emissions after 2150.[b]
RCP6	Supplementary Extension SCP6to4.5	Adjustment of emissions after 2100 to reach RCP4.5 concentrations levels in 2250 and thereafter.

[a] Note that for all extensions, land-use CO_2 emissions are assumed zero consistent with frozen land-use patterns (Hurtt et al. 2011) beyond the 21st century—with a linear interpolation between 2100 and 2125. Reactive gas emissions and aerosols are assumed constant after 2100 (see Lamarque et al. 2011)

[b] See footnote 1 regarding the interchangeably used names RCP2.6 and RCP3-PD

[c] Sudden adjustment of emissions for ODSs in 2150 (ECP6 & ECP4.5) and 2250 (ECP8.5), when concentrations stabilize

intermediate extension was selected. This extension avoids a possible discontinuity in emissions trends (that would arise from keeping concentrations constant), and avoids issues of resource availability that a higher extension might raise. Keeping emissions constant would have resulted in CO_2 concentration of around 3000 ppm by 2300. The adopted RCP8.5 extension (ECP8.5) leads to a CO_2 stabilization after 2250 at roughly 2000 ppm, or more than 7-times pre-industrial CO_2 concentrations. The total forcing of this ECP8.5 is hence approximately twice as high as the next highest ECP (ECP6) (see Fig. 4 below). This high forcing for ECP8.5 is significantly above the highest forcing level that was considered in CMIP3 on the basis of IPCC SRES scenarios (i.e., approximately 700 ppm in A1B).

Another alternative extension was considered for RCP2.6, as one may question whether negative emissions can be sustained over very long time periods (in view of finite CO_2 storage capacity). An alternative extension, in which emissions would converge back to zero between 2,150 and 2,200, would lead to CO_2 concentration of about 380 ppm rather than 360 ppm by 2300. However, in consultation with experts it was concluded that a continuation of the 2100 emission levels cannot be excluded for reasons of physical constraints of sequestration & storage options and would better reflect the character of the RCP2.6 pathway.

In addition to the four standard ECP extensions, we present one supplementary extension, which might be of particular use to investigate irreversibility and the path-dependency of the climate system response to different GHG abundances.[5] This extension starts from RCP6 in 2100 and merges with the concentrations of the next lower scenario, ECP4.5, by 2250. This is similar to other forcing and temperature overshoot scenarios in the literature (Hare and Meinshausen 2006; Wigley et al. 2007; Lowe et al. 2009). Between 2100 and 2250, we adjusted emissions of this supplementary extension (called SCP6to4.5) by following simple linear and continuous trajectories in order to obtain the desired stabilization concentration level of ECP4.5 by 2250. We chose for transparency linear segments of emissions, i.e., a 50-year long phase of stringent reductions (with an annual reduction of fossil CO_2 emissions equivalent to 2.5%/year of 2100 levels) to reach a negative emission floor, which had to be more than twice as negative as under the RCP2.6 scenario (-3.8 GtC/year). Smoother emission trajectories would be possible, although they would imply higher annual reduction rates and/or more negative emission levels than presented here. After 2250, when concentrations are equal by design, the implied inverse CO_2 emission levels of the SCP6to4.5 overshoot pathway are consistently lower than those of ECP4.5 (see Fig. 3). This is because of temperature-induced feedbacks and inertia effects in the carbon cycle. In summary, only by assuming a long period of strong reductions and deeply negative CO_2 emissions, were we able to 'make up' for the higher RCP6 emissions during the 21st century in order to reach ECP4.5 concentration levels by 2250.

Similar to this SCP6to4.5 extension, we considered an alternative ECP6 extension with comparatively less stringent post-2100 emission reductions, basically assuming that the RCP2.6 emissions path is followed 100 years later, i.e., in the 22nd century. Specifically, 2020–2100 RCP2.6 emission trajectories were assumed for 2120 to 2200—with linear interpolation between 2100 RCP6 and the extension by 2120. We kept emissions constant after 2200. Following that alternative, radiative forcing would have declined to 4.5 W/m^2 only 350 years later, i.e., by 2450.

The conclusion from this alternative RCP6 extension and our SCP6to4.5 supplementary extension is that once high 21st century emissions increase radiative forcing levels to 6 W/m^2,

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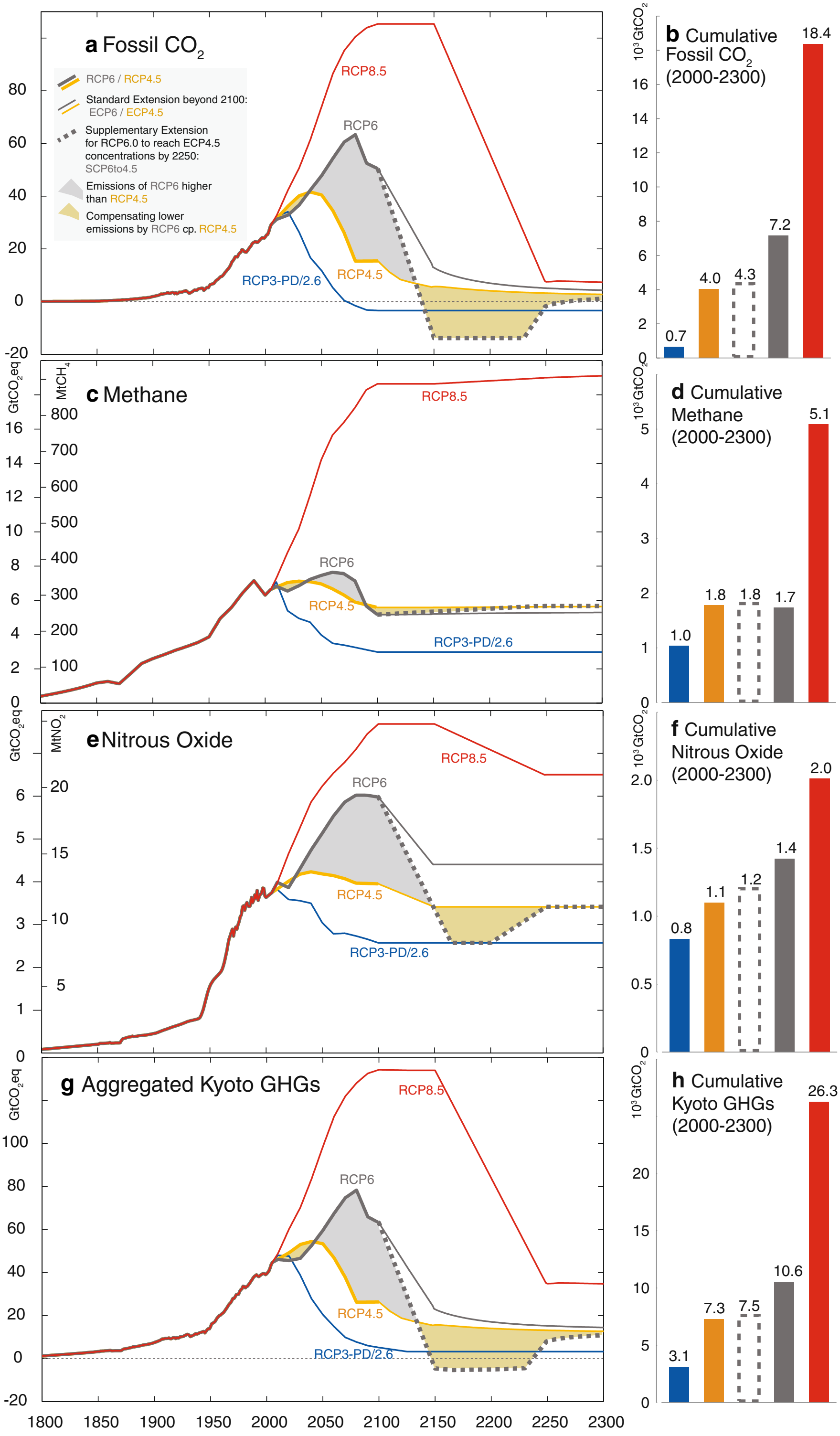
[5] An optional extra extension is provided online as addition to the RCPs and extensions described in this paper, i.e., an extension that brings concentrations back to RCP3-PD levels after 21st century emissions followed RCP4.5. See http://www.pik-potsdam.de/~mmalte/rcps/.


a Fossil CO_2
RCP6 / RCP4.5
Standard Extension beyond 2100:
ECP6 / ECP4.5
Supplementary Extension for RCP6.0 to reach ECP4.5 concentrations by 2250:
SCP6to4.5
Emissions of RCP6 higher than RCP4.5
Compensating lower emissions by RCP6 cp. RCP4.5
RCP8.5
RCP6
RCP4.5
RCP3-PD/2.6
80
60
40
20
0
-20
b Cumulative Fossil CO_2 (2000-2300)
10^3 $GtCO_2$
16
14
12
10
8
6
4
2
0
0.7
4.0
4.3
7.2
18.4
c Methane
$GtCO_2eq$
$MtCH_4$
800
700
600
500
400
300
200
100
16
14
12
10
8
6
4
2
0
RCP8.5
RCP6
RCP4.5
RCP3-PD/2.6
d Cumulative Methane (2000-2300)
10^3 $GtCO_2$
5
4
3
2
1
0
1.0
1.8
1.8
1.7
5.1
e Nitrous Oxide
$GtCO_2eq$
$MtNO_2$
20
15
10
5
6
5
4
3
2
1
0
RCP8.5
RCP6
RCP4.5
RCP3-PD/2.6
f Cumulative Nitrous Oxide (2000-2300)
10^3 $GtCO_2$
2.0
1.5
1.0
0.5
0
0.8
1.1
1.2
1.4
2.0
g Aggregated Kyoto GHGs
$GtCO_2eq$
100
80
60
40
20
0
-20
RCP8.5
RCP6
RCP4.5
RCP3-PD/2.6
h Cumulative Kyoto GHGs (2000-2300)
10^3 $GtCO_2$
20
15
10
5
0
3.1
7.3
7.5
10.6
26.3
1800
1850
1900
1950
2000
2050
2100
2150
2200
2250
2300

◀**Fig. 3** Emissions for the four RCPs and the supplementary extension SCP6to4.5, which starts from the RCP6 scenario and merges with the ECP4.5 concentrations by 2250. The shaded areas denote times of higher emissions (*grey shading*) and compensating lower emissions (*beige shading*)

it seems very difficult to return to lower levels quickly. Any 4.5 W/m^2 overshoot scenario of the sort considered here will imply higher global warming levels for considerable periods of time, i.e., centuries,—and rests on the assumption that stringent post-2100 emission reductions are feasible. A similar conclusion could be drawn for extensions that connect RCP8.5 to ECP6 or RCP4.5 to ECP3-PD long-term concentration levels[5].

For the fluorinated gases within the basket of gases that are controlled under the Kyoto Protocol (HFCs, PFCs, and SF_6), projections are inherently uncertain, as new applications are constantly being developed (apart from the fact that new fluorinated compounds are designed). For the purpose of designing the SCP6to4.5 extension, a question arises how to bridge the gap between the lower ECP6 fluorinated gas concentration levels towards the higher ECP4.5 ones. Partly because this gap is very small, only 2% in terms of the total radiative forcing difference between ECP6 and ECP4.5, and partly for simplicity, we modify only the emissions of the representative forcing agent HFC-134a in order to ramp up the aggregate forcing from HFCs, PFCs, and SF_6.

4 Results: RCP GHG concentrations

This section presents the resulting GHG concentrations for the RCPs and ECPs, as well as the aggregate total radiative forcing. Total radiative forcing here includes all anthropogenic forcing agents as listed in Table 2.12 in IPCC AR4 WG1 (Forster et al. 2007), including—inter alia—direct and indirect aerosol forcings. See Appendix 2 for assumptions in regard to non-GHG forcings.

In the lowest of the four RCPs, the total radiative forcing peaks at approximately 3 W/m^2 and declines thereafter (Fig. 4), (motivating the alternative name for the RCP2.6 pathway, which is RCP3-PD, where PD stands for “Peak&Decline”). CO_2 concentrations reach a maximum level of slightly above 440 ppm in the year 2050, and then decline to below today’s levels by 2300 (~360 ppm) (see Table 4). CO_2-equivalent concentrations (not shown),[6] comprising the net effect of all anthropogenic forcing agents (including aerosols), peak at around 460 ppm just before 2050, declining in tandem with CO_2 towards 360 ppm by 2300, at which time this scenario’s projection for the net effect of non-CO_2 forcing agents is close to zero—similar to the best-estimate non-CO_2 forcing estimate for current times (Forster et al. 2007). The aggregate forcing of all long-lived GHGs controlled under the Kyoto-Protocol, expressed as CO_2 equivalent, declines from 503 ppm CO_2eq in 2050 towards 407 ppm by 2300 in RCP2.6.

RCP8.5’s radiative forcing levels by the end of 2100 are around 8.5 W/m^2 under our ‘best-estimate’ set of model parameters with forcing levels increasing further thereafter—up to 12 W/m^2 by 2250, when concentrations stabilize (Fig. 4). Transient scenarios with such high radiative forcing levels and CO_2 concentrations have never before been investigated in model CMIP intercomparison exercises. Across almost all gases, RCP8.5 concentration levels are by far the highest. For example, CH_4 concentration stabilizes around 3500 ppb—more than twice as high as the next highest scenarios, RCP4.5 and RCP6, which approximately stabilize at 1,500 ppb (slightly below today’s levels of nearly 1800ppb). The only exceptions are ODS concentrations: RCP4.5, RCP6 and RCP8.5 share the same emission assumptions (WMO 2007, A1 Scenario), but the longer-term ODS concentrations are slightly lower in RCP8.5 due to slight decreases in stratospheric ODS lifetimes via expected changes in stratospheric

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[6] available at http://www.pik-potsdam.de/~mmalte/rcps/.

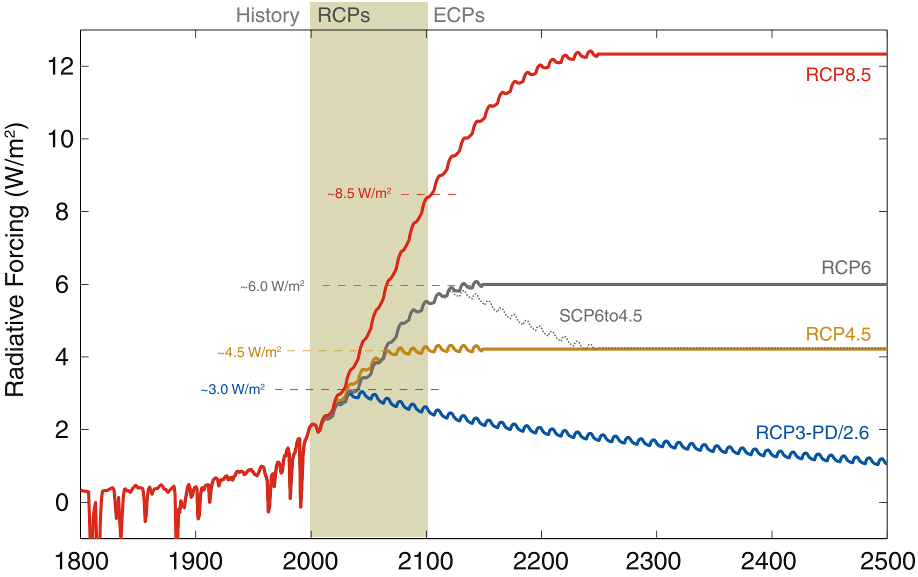


Fig. 4 Total radiative forcing (anthropogenic plus natural) for RCPs,—supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for RCP2.6 (called as well RCP3-PD), RCP4.5 & RCP6, as well as RCP8.5, respectively. Note that the stated radiative forcing levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future radiative forcing levels. Short-term variations in radiative forcing are due to both volcanic forcings in the past (1800–2000) and cyclical solar forcing—assuming a constant 11-year solar cycle (following the CMIP5 recommendation), except at times of stabilization

circulation rates, outweighing initial decreases in tropospheric sinks due to lower OH concentrations (see Section 2.4 and Fig. 5d).

RCP4.5 and RCP6 are both stabilization scenarios, with constant concentrations after 2150. By stabilizing CO_2 concentrations at 543 ppm, RCP4.5 comes very close to a doubling of pre-industrial CO_2 concentration (278 ppm)—and is hence only slightly higher than the SRES B1 scenario and its constant extension after 2100 with 540 ppm CO_2 (see Bern-CC (reference) case in Appendix II.2.1 in Houghton et al. 2001). The RCP6 scenario stabilizes 200 ppm higher, at 752 ppm CO_2 (see Fig. 5).

5 Discussion

5.1 Ensemble results compared to our default concentration and temperature projections

In the above text we selected a specific (‘best-estimate’) set of MAGICC parameters to use in producing a standard set of RCP concentrations. Starting from the harmonized emissions, we can also produce concentrations (and forcing and temperature projections) using 19 individual CMIP3 climate and 9 C^4MIP carbon cycle emulations. How does our default set of results compare with the distribution of results from these 171 (=19×9) cases?

We perform this comparison using the highest and the lowest RCP scenarios. The results are shown in Fig. 6. Not surprisingly, because the responses to external forcings in all climate models are largely linear, the ‘best-estimate’ results are similar to the median of the individual model results, even in the high forcing RCP8.5 case. The ideal test of our projections, although

Table 4 GHG concentrations for pre-industrial, historical, RCP and ECP/SCPs

GHG Forcing Agent (Unit)	Scenario	1765	1800	1850	1900	1950	2000
CO_2 (ppm)	Pre-Ind/Historical	278	283	285	296	311	369
CH_4 (ppb)		722	742	791	880	1,147	1,751
N_2O (ppb)		273	274	275	280	289	316
HFCs, PFCs, SF_6 (ppt HFC-134a-eq) [a]		0	0	0	0	4	81
ODS (ppt CFC-12-eq) [a]		0	0	0	2	22	999
		2005	2050	2100	2150	2250	2300
CO_2 (ppm)	RCP2.6/ECP3PD	379	443	421	399	371	361
	RCP4.5/ECP4.5	379	487	538	543	543	543
	RCP6/ECP6	379	478	670	752	752	752
	SCP6to4.5	379	478	670	689	543	543
	RCP8.5/ECP8.5	379	541	936	1429	1,962	1,962
CH_4 (ppb)	RCP2.6/ECP3PD	1,754	1,452	1,254	1,245	1,253	1,256
	RCP4.5/ECP4.5	1,754	1,833	1,576	1,542	1,542	1,542
	RCP6/ECP6	1,754	1,895	1,649	1,511	1,511	1,511
	SCP6to4.5	1,754	1,895	1,649	1,517	1,542	1,542
	RCP8.5/ECP8.5	1,754	2,740	3,751	3,648	3,481	3,481
N_2O (ppb)	RCP2.6/ECP3PD	319	342	344	342	340	340
	RCP4.5/ECP4.5	319	351	372	379	379	379
	RCP6/ECP6	319	355	406	427	427	427
	SCP6to4.5	319	355	406	418	379	379
	RCP8.5/ECP8.5	319	367	435	490	527	527
HFCs, PFCs, SF_6 (HFC-134a-eq ppt)	RCP2.6/ECP3PD	127	599	862	874	886	888
	RCP4.5/ECP4.5	127	483	654	748	748	748
	RCP6/ECP6	127	426	565	606	606	606
	SCP6to4.5	127	426	565	658	748	748
	RCP8.5/ECP8.5	127	839	1,402	1,614	1,702	1,702
ODS (CFC-12-eq ppt)	RCP2.6/ECP3PD	1,004	567	267	147	53	34
	RCP4.5/ECP4.5	1,004	646	252	128	128	128
	RCP6/ECP6	1,004	653	250	120	120	120
	SCP6to4.5	1,004	653	250	129	129	129
	RCP8.5/ECP8.5	1,004	652	229	94	20	20

[a] Note that the representative gas HFC134a-eq for the group of HFCs, PFCs and SF6 concentrations, and CFC-12 eq for the group of ODS gases are here only given for illustrative reasons and for optional use in GCMs/ESMs. Annual data for individual gas concentrations are provided on http://www.iiasa.ac.at/web-apps/tnt/RcpDb and http://www.pik-potsdam.de/~mmalte/rcps/

impractical, would be for the CMIP3 GCM model ensemble to be run again for the RCP8.5 scenario and ECP8.5 extension. Since the post-2100 ECP8.5 forcing case falls well outside the MAGICC SRES calibration range, it would provide a rather stringent test for MAGICC.

In summary, our default carbon cycle/climate model settings are shown to reflect well the median emulated responses of both the AOGCM and carbon cycle response. The implied relation between emissions and concentrations may, of course, change with the next generation of models. It will be useful to compare the climate and carbon-cycle responses from the next round of climate model experiments with those presented here, which are, necessarily,

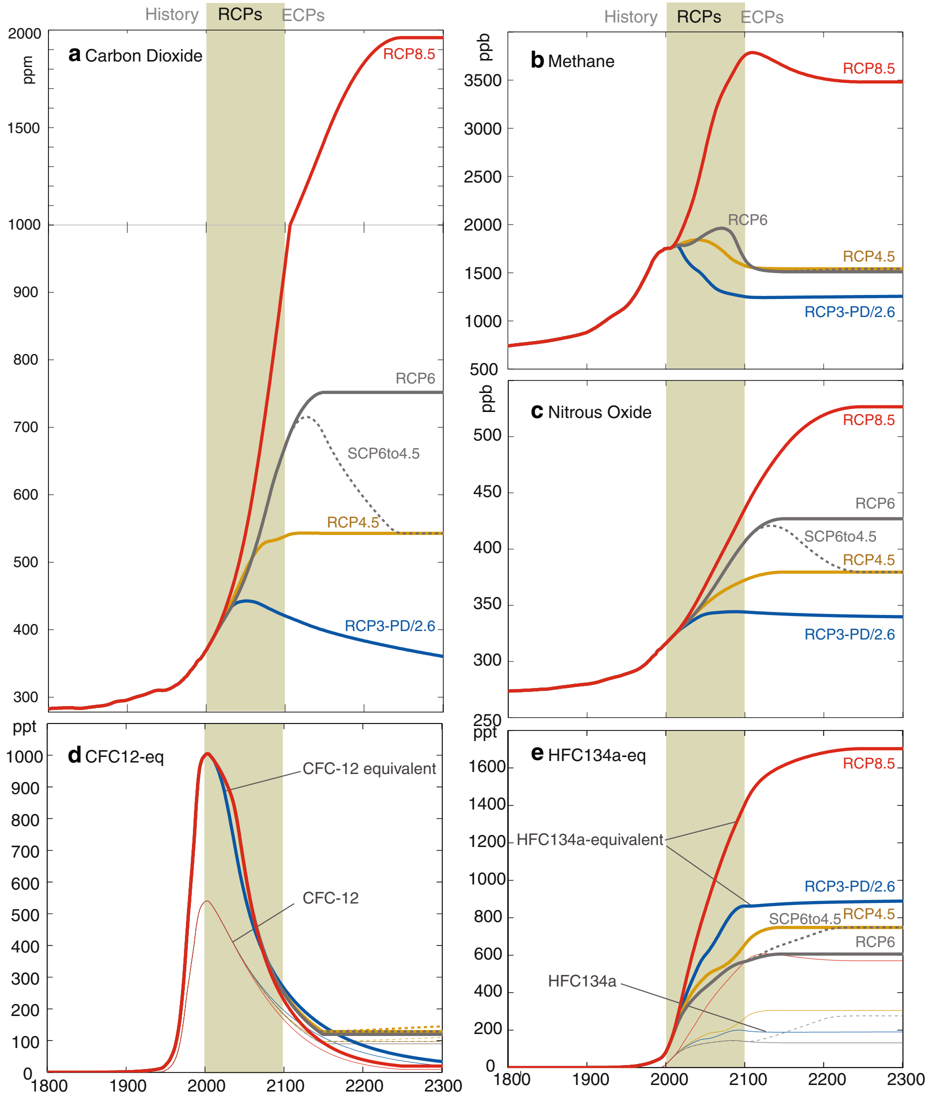
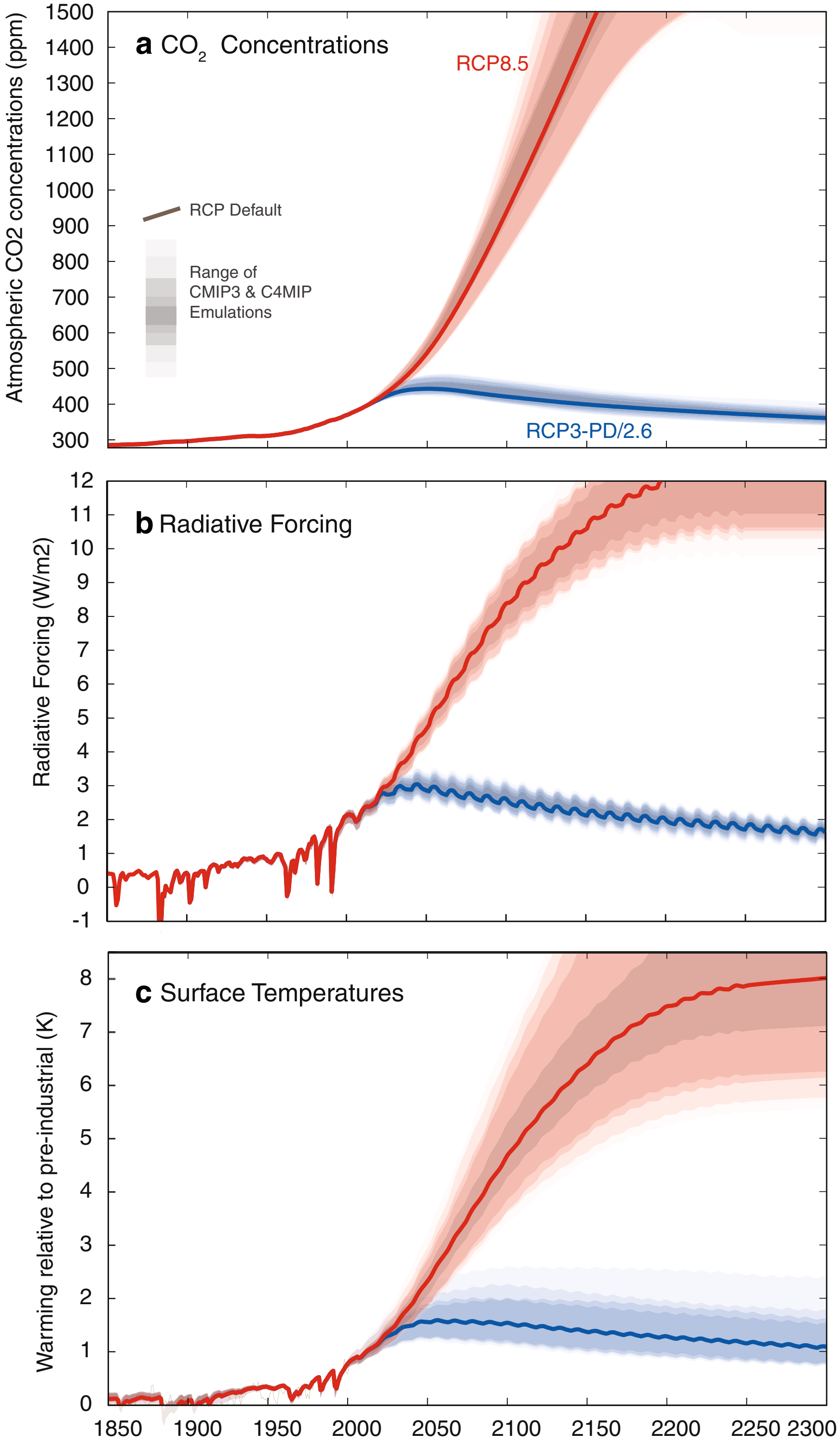


Fig. 5 GHG concentrations recommended for the CMIP5 climate change research studies. Shown are: **a** atmospheric CO_2; **b** methane; **c** nitrous oxide; **d** (equivalent) CFC-12; and **e** (equivalent) HFC134a concentrations. Equivalent concentrations are derived so as to equal the aggregate forcing of the represented forcing agents. For CFC-12, those species that are controlled under the Montreal Protocol are aggregated.. For HFC-134a, the gases aggregated are the fluorinated gases controlled under the Kyoto Protocol. Note that this aggregation is based on radiative forcing equivalence, i.e. aggregation is not based on GWPs (annual data for each individual gas is provided on-line)

Fig. 6 CO_2 concentrations (**a**), total radiative forcing (natural and anthropogenic) (**b**) and global mean surface temperatures (**c**) for RCP2.6 (called as well RCP3-PD) and RCP8.5 (*solid lines*) compared to the full range of CMIP3 GCM and C^4MIP carbon cycle model emulations (*shaded areas*). The small temporal variations in future forcing are caused by the 11-year solar cycle assumption, influencing as well temperature projections

▶


a CO$_2$ Concentrations
Atmospheric CO2 concentrations (ppm)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
RCP8.5
RCP3-PD/2.6
RCP Default
Range of
CMIP3 & C4MIP
Emulations
b Radiative Forcing
Radiative Forcing (W/m2)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
c Surface Temperatures
Warming relative to pre-industrial (K)
8
7
6
5
4
3
2
1
0
1850
1900
1950
2000
2050
2100
2150
2200
2250
2300

calibrated to existing model experiments. The allowable CO_2 emissions for these pathways could, for example, be lower (or higher) than those found here, if positive carbon cycle feedbacks were higher (or lower) in the CMIP5 generations of ESMs compared with C^4MIP models. Similarly, including a nitrogen cycle in the MAGICC and other carbon cycle models will affect future forward and inverse projections (Thornton et al. 2007, 2009).

5.2 Inverse emissions for the long-term extension pathways

The extensions of the RCPs and the generation of the supplementary pathway were made using the simple rules given in Table 3. While these extensions are simply thought experiments, we examine here the implied emissions from the SCP6to4.5 scenario to illustrate some key points relevant to future long-term scenarios. The inverse emissions that correspond to this overshoot scenario imply a period of substantial net negative CO_2 emissions of -13.9 $GtCO_2$/year—between 2150 and 2230 (see Fig. 3). This value is larger in magnitude than the negative emissions level in the RCP2.6 scenario (−0.93 GtC/yr=−3.41$GtCO_2$/yr), but there are scenarios in the literature that imply similarly negative emission levels already by 2100. For example, Calvin et al. (2009) show scenarios with slightly larger negative emissions levels by 2100 of -10 to -15 $GtCO_2$/year in 2095. In addition to sustained net negative emissions in SCP6to4.5, the reduction rates assumed between 2100 and 2150 are rather substantial, similar to the steepest segments of RCP4.5 and RCP2.6 – but extended over a longer time period.

As highlighted in Fig. 3a, CO_2 emissions for the SCP6to4.5 have to be reduced below the RCP4.5 emissions by approximately the same amount as the extra cumulative emissions that were emitted during the 21st century by RCP6. On the timescales of interest here, CO_2 does not have finite lifetime (Archer and Brovkin 2008), but is simply being re-distributed between the different active carbon pools. This is largely why cumulative CO_2 emissions are a crucial quantity for long-term temperature and atmospheric concentration responses (Kheshgi et al. 2005; Allen et al. 2009; Matthews et al. 2009). For this reason, cumulative emissions for the RCP4.5-ECP4.5 pathway and the RCP6-SCP6to4.5 pathway are roughly of the same size (see Fig. 3b).

For other long-lived GHGs such as N_2O, the need to compensate for initially higher emissions with lower emissions later on is still apparent, although cumulative N_2O emissions are a bit higher under the SCP6to4.5 pathway compared to RCP4.5-ECP4.5 — even though both paths ultimately stabilize at the same N_2O concentration levels by design (see Fig. 3 e&f). For CH_4, with its much shorter atmospheric lifetime (Forster et al. 2007), the ultimate concentration depends almost solely on emissions over the final few decades rather than on long-term cumulative emissions.

5.3 Limitations

The challenge this study faces is to synthesize gas-cycle and climate response characteristics from a broad body of literature into a single-best set of data and model parameters to produce a common starting point for future model intercomparison exercises. By design, we therefore do not intend to fully represent uncertainties, but rather seek to produce concentration scenarios that reflect ‘middle-of-the-road’ carbon cycle and climate model responses, representative of the IPCC AR4 state of knowledge. While some parts of our approach can thereby be based on recent intercomparison exercises, in particular C^4MIP and CMIP3, other assumptions relate to earlier community efforts, such as the OxComp workshop (Ehhalt et al. 2001). Uncertainties pertaining to future OH concentrations, CH_4 lifetimes, N_2O concentrations or the effect of the inclusion of a nitrogen cycle will result in different ‘reference’ pathway recommendations if this exercise were to be repeated in a couple of years from now. Furthermore, uncertainties arise as well from second-order effects of tropospheric ozone and aerosols, for example. To the extent that our non-GHG modeling assumptions deviate from current generation chemistry modeling results (see e.g. Lamarque in this issue for a comparison of tropospheric ozone levels), indirect effects via global-mean temperature and gas-cycle feedbacks will impact derived GHG concentrations presented here, although this indirect second-order effect is likely limited.

Regarding the RCP extensions, we reiterate that these ECPs are highly stylized and are not the result of detailed analyses of resource limits, but are instead presented in order to provide a range of concentration and forcing pathways for use in climate model experiments. In contrast to the simple stabilization of concentrations after 2100 used for CMIP3, the current ECPs provide a wider range of forcing pathways in which to test long-term model responses.

6 Conclusions

The historical, 21st century and extended GHG concentration and harmonized emission data presented here are a result of a wide collaboration across scientific communities. In order to obtain a single set of best-estimate projections for future GHG concentrations for the four RCP scenarios, we used an emulation of the median response of both climate and carbon cycle models that took part in the previous climate model inter-comparison exercises CMIP3 (Meehl et al. 2005) and C^4MIP (Friedlingstein et al. 2006). The derived concentration results are generated as the starting point for the CMIP5 inter-comparison exercise (Taylor et al. 2009), which will be evaluated in the forthcoming IPCC Fifth Assessment Report. While the inverse emission results here can also provide a yardstick for comparison, it can be expected that the forthcoming CMIP5 generation of ESMs will diagnose ‘allowable’/inverse emissions that differ from the harmonized emissions presented here. This is because of limitations in the extrapolation of previous model's emulation results, and partly because of new process parameterizations within the new generation of climate and carbon cycle models.

While the provision of concentration pathways for use in model inter-comparison exercises is the end point for the RCP scenario production activity, this is still just the beginning of the overall scientific effort to investigate climate change, its impacts and mitigation options under different scenarios (Moss et al. 2010). With respect to the IPCC WG1 community, the harmonized concentrations and emissions data provided here are a starting point for model experiments that will enable a deeper understanding of the earth systems’ response to the anthropogenic perturbations that are driving climate changes.

Acknowledgements We are deeply thankful to all those in the scientific community, that contributed invaluable assistance, datasets, model code and review comments. Without those contributions, creating the harmonized and consolidated GHG concentrations for the RCP scenarios would not have been possible. We are especially indebted to Tom M. L. Wigley and Karl E. Taylor for helpful in-depth comments on an earlier manuscript version. Furthermore, we thank those, who contributed critical data and assistance, namely Toshihiko Masui, Peter Kolp, Volker Krey, A. Mendoza Beltrán, E. Stehfest, Robert Andres, Greg Marland, Richard Houghton, Judith Lean, David Worton, Makiko Sato, Edward Dlugokencky, Patricia Lang, Kenneth A. Masarie, D.M. Etheridge, J.A. Culbertson, G.S. Dutton, T.M. Thompson, J.W. Elkins, B.D. Hall, J. Flückiger, J. van Aardenne, J. Nabel, K. Markmann, J. Rogelj, and Chris Jones and the contributors to data.giss.nasa.gov.

Appendix 1. RCP GHG data within CMIP5

Table 5

Table 5 Contribution of RCP and ECP GHG data presented in this study to the CMIP5 experiments. For a detailed description of the CMIP5 experiments, see Taylor et al. (2009)

CMIP5 Code	CMIP5 - Experiment	RCP and ECP GHG data (This study)
3.1	Coupled-model, pre-industrial control	Pre-industrial GHG concentration default values.
3.2	Historical (1850–2005) ensemble	Historical mixing ratios (see Section 2.2 and Table 4).
3.3	AMIP (1979–2008) ensemble with imposed SST and sea ice	Historical mixing ratios (see Section 2.2 and Table 4).
7.2, 7.3	Historical runs forced by individual agents	Historical mixing ratios (see Section 2.2 and Table 4).
4.1, 4.2, 4.3, 4.4	Projected responses to concentrations based on RCP2.6, RCP4.5, RCP6 and RCP8.5 (2005–2100)	Consolidated GHG concentration time series; harmonized emission time series for comparison with allowable emissions inferred from ESM runs.
4.1-L, 4.2-L, 4.3-L	Extension of RCP2.6, RCP4.5, and RCP8.5 through year 2300	Consolidated GHG concentration time series for respective ECP scenarios; furthermore, we provide emissions for all extensions for comparison with 'allowable' emissions derived from CMIP5 ESM runs.
Coupled carbon cycle-climate models (ESMs) only		
ESMs only: 5.2 & 5.3	Emission-driven historical and RCP8.5 simulations	Harmonized GHG emission time series.
ESMs only: 5.4 & 5.5	Diagnosis of carbon-climate feedback components in prescribed CO_2 experiments (following "idealized" or more "realistic" pathways) in which CO_2 surface fluxes are saved and allowable emissions computed.	The low RCP2.6 as well as RCP6 and RCP4.5 together with the supplementary extension SCP6to4.5 could offer qualitatively different CO_2 emission behavior compared to emissions derived under continuously increasing CO_2 concentrations of RCP8.5 used in ESM experiments 5.2 & 5.3.
Supplementary data provided for potential use.		
–		The stabilization extension ECP6 of RCP6, currently not envisaged as part of CMIP5 could offer data for additional experiments beyond 2100.
–		The Supplementary extension SCP6to4.5 could offer GHG concentrations for additional post-2100 experiments of potential interest to WGII as well as the 5.4/5.5 ESM experiments.

Appendix 2. Non-GHG forcing agents

Apart from the harmonized global GHG emissions and concentrations presented in this study, the ESMs and the scientific communities of IPCC WG1 and WG2 will be provided with a series of other input data sets: tropospheric & stratospheric ozone and aerosol abundances (Lamarque et al. 2011), land-use patterns (Hurtt et al. 2011), and solar forcing recommendations (Lean and Rind 2009). For the concentration calculations described here, these non-GHG forcings, including aerosols, tropospheric ozone precursors, solar irradiance and volcanic aerosols, were included since temperature and chemical feedbacks have an influence on atmospheric GHG concentrations and their fluxes (see Methods 2.4). To the extent possible, CMIP5-consistent assumptions in regard to the non-GHG forcings were taken, although it should be noted that our IPCC AR4 based forcing parameterizations of different non-GHG compounds differ from chemistry-climate model runs in relation to tropospheric ozone, for example (Lamarque et al. 2011), and will as well differ from new insights generated by CMIP5 set of models. For the emission-driven ESM runs in CMIP5, some of them will generate CO_2 emissions resulting from land-use patterns endogenously, so these emissions will differ from the harmonized IAM emissions used here. For radiative forcing due to solar irradiance changes we followed the CMIP5 recommendation of repeating solar cycle 23 into the future—although we keep solar forcing constant after concentrations are stabilized. Solar irradiance data by Lean and Rind (2009) (see at http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/CMIP5_solar_irradiance.html) is used here as recommended for CMIP5. The irradiance data has been converted into radiative forcing by dividing by 4 (geometrical) and multiplying by 0.7 to take into account albedo. Furthermore, the data is normalized to have an average of zero for the 22 years around 1750.

Concerning volcanic forcings, CMIP5 leaves it to the modeling groups as to how to treat volcanic stratospheric aerosols in the control run and 21st century runs. One problem is that an artificial cooling and reduction of sea level rise will occur in response to the first volcanic events in the historical run (1850), if the control run brought the model in equilibrium without volcanic eruptions. Here, we use a specific setup for volcanic aerosols, which is one—but not the only—option of how GCMs can deal with volcanic forcing for CMIP5. Specifically, we assumed the average volcanic aerosol loadings over the last 100-years (around $-0.2\ W/m^2$) to be applied in both the control run and the future runs from 2006 onwards, or equivalently, to shift the volcanic forcing series such that control run and future forcings, as well as the mean over the historical period are zero (see Taylor et al. 2009 for a further discussion of 2011; Meinshausen et al. 2011a). Analogously, GCMs could apply a stratospheric volcanic aerosol loading in their control runs, as well as in the post-2005 projections.

For the historical 20th century run (1765–2005), we derived monthly volcanic radiative forcing from optical thickness of volcanic stratospheric aerosols as used in the NASA GISS model (available from http://data.giss.nasa.gov/), using an optical thickness τ to radiative forcing conversion of $-23.5\ W/m^2/\tau$. We extended with zero forcing from 2001 to 2005, resulting in a nominal positive forcing of $0.2\ W/m^2$ after being shifted by the 100-year historical mean. Furthermore, we scaled the resulting volcanic forcing by 0.7 in order to obtain a best fit with historical temperature observations using our simple climate model—which compensates for a potential limitation in simple and intermediate complexity models to accurately model responses to volcanic eruptions using the standard forcing assumptions (Tomassini et al. 2007; Meinshausen et al. 2009). Other forcings are assumed according to IPCC AR4, as listed in Table 2.12 in Forster et al. (2007), such as stratospheric water vapour changes due to methane oxidization.

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