

The RCP Greenhouse Gas Concentrations and their Extensions from 1765 to 2300

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27

28 **Abstract**

29 We present the greenhouse gas concentrations for the Representative Concentration Pathways (RCPs)
30 and their extensions beyond 2100, the Extended Concentration Pathways (ECPs). These projections
31 include all major anthropogenic greenhouse gases and are a result of a multi-year effort to produce new
32 scenarios for climate change research. We first compiled a suite of atmospheric concentrations
33 observations and emissions estimates for greenhouse gases (GHGs) through the historical period (1750-
34 2005). For the 21st century, we start from emissions projected by four different Integrated Assessment
35 Models for 2005-2100. We harmonize these emissions to allow inter-comparability of scenarios and to
36 achieve a smooth transition from historical data. These harmonized emissions are then used to derive
37 future GHG concentrations. As concentrations are somewhat dependent on the future climate itself (due
38 to climate feedbacks in the carbon and other gas cycles), we emulate median response characteristics of
39 models assessed in IPCC Fourth Assessment Report using the reduced-complexity carbon cycle climate
40 model MAGICC6. Projected global-mean temperatures range from 1.5°C in the global mean surface
41 temperatures by 2100 for the lowest of the four RCPs, RCP3-PD, to 4.5°C for the highest one, RCP8.5,
42 relative to pre-industrial levels. For times beyond 2100, we present ECPs that are simple extensions of
43 the RCPs: In case of the RCP8.5 scenario, constant emissions are assumed until 2150 and constant
44 concentrations from 2250 onwards, resulting in 'best-estimate' temperature projections around 8°C by
45 2300. The two middle RCPs, RCP6 and RCP4.5 are extended by smoothly stabilizing concentrations
46 from 2150 onwards. The lower RCP3-PD pathway represents a strong mitigation scenario and is
47 extended by assuming constant emissions after 2100 (incl. net negative CO₂ emissions). The slight
48 reduction of radiative forcing levels in RCP3-PD from 2040 onwards is continued to 2300, by which time
49 CO₂ concentrations have decreased to 360 ppm. We also present the GHG concentrations for one
50 supplementary extension, which illustrates the stringent emissions implications of attempting to go back
51 to ECP4.5 concentration levels by 2250 after emissions during the 21st century followed the higher RCP6
52 scenario. Corresponding radiative forcing values are also presented for the RCP and ECPs.

53

54 **1. Introduction**

55 A set of scenarios known as Representative Concentration Pathways (RCPs) have been adopted by
56 climate researchers to provide a range of possible futures for the evolution of atmospheric composition
57 (Moss et al. 2008; Moss et al. 2010). These RCPs complement and, for some purposes, supersede earlier
58 scenario-based projections of atmospheric composition, such as those from the Special Report on
59 Emissions Scenarios (SRES; Nakicenovic and Swart 2000). The RCPs are being used to drive climate
60 model simulations planned as part of the World Climate Research Programme's Fifth Coupled Model
61 Intercomparison Project (CMIP5) (Taylor et al. 2009) and other comparison exercises. The four RCPs are
62 based on multi-gas emission scenarios which were selected from the published literature (Fujino et al.
63 2006; Smith and Wigley 2006; Clarke et al. 2007; Riahi et al. 2007; van Vuuren et al. 2007; Hijioka et al.
64 2008; Wise et al. 2009) and updated for release as RCPs (Masui et al. this issue; Riahi et al. this issue;
65 Thomson et al. this issue; van Vuuren et al. this issue). Since they were produced by four different
66 Integrated Assessment Models (IAMs), there are inconsistencies in the relationships between emissions
67 and concentrations that could impair researcher's ability to interpret the climatic consequences of the
68 four different scenarios. Furthermore, although *concentrations* drive traditional coupled atmosphere-
69 ocean climate models, the fifth phase of CMIP (CMIP5) also includes simulations by Earth System
70 Models (ESMs) with a full representations of the carbon cycle, which are driven by prescribed *emissions*
71 of carbon dioxide. The CMIP5 exercise, therefore, requires a set of historical and future pathways for
72 both concentrations and emissions (see Appendix 1), ideally produced by a single model.

73 This study describes how the IAM emissions were processed to produce the RCP GHG concentration
74 values, including the compilation of historical GHG concentrations, the harmonization of emissions
75 towards common 2000-2005 emission levels, the projection of best-estimate future GHG concentrations,
76 and their extension beyond 2100. These concentration pathways lead to radiative forcing values that span
77 a range larger than that of the SRES scenarios. In addition to the central contribution of the IAMs, this
78 process was only possible due to the wide range of contributions from the scientific community, in

79 particular regarding historical emissions, observed concentrations, and emission scenarios for ozone
80 depleting substances (ODSs) (see references in Table 1).

81 The harmonized GHG concentration and emissions time series recommended for CMIP 5 (Taylor et
82 al. 2009) can be obtained from the RCP database website (RCP Database 2009) available at
83 <http://www.iiasa.ac.at/web-apps/tnt/RcpDb> and the CMIP5 portal (PCMDI 2009) at [http://cmip-
85 pcmdi.llnl.gov/cmip5/](http://cmip-
84 pcmdi.llnl.gov/cmip5/). Extended GHG datasets until 2500 (for use in very long-term experiments), and
86 further background information on the generation of the harmonized GHG concentration time series are
provided at: <http://www.pik-potsdam.de/~mmalte/rcps/>.

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

94

95 **2. Methods**

96 **2.1. General Approach**

97 Each of the IAM teams can, in principle, provide both emissions and concentration data. Each of the
98 models uses different historical and base year data for the recent past (years 2000-2005). In order to
99 ensure a smooth transition in the climate model runs from the historical period into the future, a
100 harmonization step for emissions was performed here. Furthermore, it was decided that a single model
101 version of MAGICC (e.g. Wigley and Raper 2001; Meinshausen et al. 2008; Wigley et al. 2009) should
102 be used to produce a more consistent estimate of concentrations and carbon feedbacks, rather than basing
103 the RCPs on a variety of different model versions. GCAM that produced RCP4.5 (Thomson et al. this
104 issue), for example, uses MAGICC5.3, as does AIM that contributed RCP6. MESSAGE that produced
105 RCP8.5 (Riahi et al. this issue) uses an updated version of MAGICC4.2, and IMAGE that produced
106 RCP3-PD uses MAGICC6 except for its carbon cycle. Thus, as a second harmonization step, we apply a
107 single climate and carbon cycle treatment, using the latest version 6 of MAGICC (Meinshausen et al.
108 2008)¹ to derive concentrations and inverse emissions for the RCPs.

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

111 [INSERT Figure 1 HERE]

112 **2.2. Historical concentrations**

113 For comparing climate model outcomes with historical climate observations, it is ideal if atmosphere-
114 ocean general circulation models (AOGCMs) are driven with observations of the historical atmospheric
115 composition. Such a comparison can be helpful for assessing the skill of climate models, or to determine

¹ 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.

116 the human-contribution to climate change. Building on current literature, and with the help of a number
117 of experts, we compiled a consolidated set of 20th century global and annual mean GHG concentrations.
118 Specifically, we compiled concentrations of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O),
119 eight different hydrofluorocarbons (HFCs, namely HFC-23, HFC-32, HFC-43-10mee, HFC-125, HFC-
120 134a, HFC-143a, HFC-227ea, and HFC-245fa), three perfluorocarbons (PFCs, namely CF₄, C₂F₆, and
121 C₆F₁₄), and SF₆, as well as concentrations of sixteen ODSs (CFC-11, CFC-12, CFC-113, CFC-114, CFC-
122 115, Carbon Tetrachloride, Methyl chloroform, HCFC-22, HCFC-141B, HCFC-142B, HALON-1211,
123 HALON-1202, HALON-1301, HALON-2402, CH₃Br, CH₃Cl). Building on this database of historical
124 observations, we recommend sets of pre-industrial control run concentrations, depending on whether the
125 historical '20th century' run starts in 1765, or 1850 (or any year in between). Concentrations over this
126 1765 to 1850 period are constant for the halogenated gases with natural sources, i.e., CF₄, CH₃Br and
127 CH₃Cl, with 35 ppt, 5.8 ppt and 480 ppt, respectively. However, the recommended concentrations for the
128 long-lived GHGs, CO₂, CH₄, and N₂O show a small increase over that period, starting from the levels
129 278.1 ppm, 721.9 ppb, and 273.0 ppb in 1765 and increasing towards 284.7 ppm, 791.0 ppb, 275.4 ppb in
130 1850, respectively. The concentrations were compiled based upon data available as of mid-2009 (see
131 Table 1).

132 [INSERT Table 1 HERE]

133 **2.3. Harmonization of Emissions**

134 The harmonization of GHG, tropospheric ozone precursor and aerosol emissions to common
135 historical levels is necessary as IAMs do not necessarily start with the same historical emissions
136 inventories, which is a disadvantage for comparisons of the scenarios' future climate effects. There are
137 several reasons that different IAM scenarios do not share the same historical emissions: besides the
138 uncertainty in the historical record, different IAMs 1) do not include the same set of human activities that
139 lead to emissions, 2) smooth short-term fluctuations differently and/or 3) assume different emissions
140 factors from emissive processes. In addition, the actual 'real world' activity levels and emissions factors
141 are inherently uncertain. The most appropriate harmonization method depends on the reasons that

142 underlie the differences in historical emission levels. Given the many different sectors and emissions
143 factors in the IAMs, a simple and transparent approach is followed here.

144 Reactive gas and aerosol emissions have been harmonized to year 2000 levels in a separate exercise
145 in the RCP creation process (Lamarque et al. 2010; Smith et al. 2010; Granier et al. this issue), namely
146 for sulfate oxides (SO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC),
147 nitrogen oxides (NO_x), black carbon (BC), organic carbon (OC), ammonia (NH₃), and also for methane
148 (CH₄) because of its role in atmospheric chemistry. Here, we extend this harmonization of the reactive
149 gas emissions to year 2005 by using the average growth rates in RCP8.5, RCP4.5, and RCP3-PD. RCP6
150 was harmonized as well, but its values were not used to determine the growth rates (or other averages for
151 harmonization) due to the later finalization date of this data set. Taking into account RCP6 does not
152 substantially change these results relative to other uncertainties. This harmonization, therefore, enforces
153 consistency among all RCP scenarios over 2000-2005 period.

154 For other GHGs, i.e. CO₂, N₂O, HFCs, PFCs, and SF₆, we harmonized global and five-region
155 emission levels using simple scaling routines so that by construction, all four harmonized RCPs share the
156 same 2000 to 2005 emissions data. The five regions are basically same as the four SRES regions with the
157 'Africa&Latin America (ALM)' region being split into 'Middle East and Africa (MAF)' and 'Latin
158 America (LAM)' (see <http://www.iiasa.ac.at/web-apps/tnt/RcpDb> for a country-by-country definition of
159 these regions). For fossil and industrial CO₂ emissions, we used global inventory estimates from Marland
160 et al. (2008) to 2005. Extending the harmonization only to 2005 does not include the substantial emission
161 increase until 2008 or the zero growth rate in 2009 due to the financial crisis (Olivier and Peters 2010).
162 This was a conscious decision, partially because RCPs are not meant to reflect short-term fluctuations.
163 Net land-use CO₂ emissions estimated by the IAMs (on average 1.15 GtC in the year 2000) are lower
164 than some other emission estimates, e.g. the 1.41 GtC in year 2000 by Houghton et al. (2008)². To
165 maintain consistency with the underlying land-use patterns (Hurtt et al. this issue), and given the large
166 uncertainty in current global land-use related CO₂ emissions of around ±0.5 GtC/yr (DeFries et al. 2002;
167 Canadell et al. 2007), we harmonized the emissions using the IAM average (RCP3-PD, RCP4.5 and

² 1GtC/yr = 44/12 GtCO₂/yr

168 RCP8.5). For fluorinated gases that are included in the basket of gases controlled under the Kyoto
169 Protocol (HFCs, PFCs, SF₆), we used observed concentrations, where available, and derived inverse
170 emission estimates using default lifetime assumptions (Table 2.14 in Forster et al. 2007) within the
171 MAGICC6 coupled gas-cycle climate model. For C₆F₁₄, HFC-32, HFC-43-10mee, HFC-227ea, and HFC-
172 245fa, we took available emissions data from either SRES (Nakicenovic and Swart 2000) (HFC-43-
173 10mee), EDGAR4 (EC-JRC and PBL 2009) (C₆F₁₄, HFC-227ea) or the non-harmonized RCPs (HFC-32,
174 HFC-245fa). For HFC-245fa, sparse observations exist (Vollmer et al. 2006), pointing to lower, but much
175 faster increasing, emissions than we used here from the original RCP4.5 estimates. This difference might
176 be an overestimation of actual emissions by RCPs and/or due to slower release factors in early
177 applications of this foam blowing agent than assumed by the IAMs. For ODSs, we use the emissions that
178 were used to derive, with a box model, the standard WMO (2007) A1 scenario concentrations. Further
179 details are provided in Table 2.

180 (INSERT Table 2 HERE)

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

186 Exceptions to this approach are applied for land-use related CO₂ emissions and some fluorinated
187 gases. Land-use related CO₂ emissions turn negative in some regions, which is why we chose to apply an
188 additive shift of emissions rather than a multiplier. The difference between original IAM emissions and
189 the harmonized levels in 2005 is added to the original IAM data and this offset is linearly reduced to zero
190 by 2030. A scaling factor rather than an offset until 2050 could have resulted in more pronounced
191 negative emissions even in the case of an upward adjustment in 2005.

192 For fluorinated gases, the SRES scenarios used an external set of emissions (Fenhann 2000). In
193 contrast, the IAMs producing the RCP scenarios now include fluorinated gas emissions in their modeling

194 frameworks. For some fluorinated gas species, updated information on their trends is available, which
195 causes IAMs to project markedly different future emissions compared to SRES. Some IAMs, however,
196 include only a few aggregate fluorinated gas categories. This leads to somewhat artificially narrowed
197 spreads for some fluorinated gas projections.

198 For HFC-227ea, current emission levels provided in the RCPs were uncertain as emissions for this
199 gas in both RCP4.5 and RCP8.5 were only available as an aggregate together with HFC-125. Large
200 uncertainties in HFC-227ea emissions result from the fact that there were no ambient air measurements
201 that could constrain anthropogenic emission estimates in mid-2009, a fairly unique situation for a GHG -
202 only recently revised (Laube et al. 2010). Bottom-up emission estimates (e.g. EDGAR4 data by EC-JRC
203 and PBL 2009) seem to overestimate actual HFC-227ea emissions estimated from ambient measurements
204 (Laube et al. 2010). The overall radiative forcing contribution of both gases, HFC-245fa (see above) and
205 HFC-227ea, is rather small, so any future revisions will likely have a minor effect on aggregate radiative
206 forcing levels. For these two scenarios, RCP4.5 and RCP8.5, a simple approximation has been used to
207 estimate future emissions of HFC-227ea and HFC-125. The reported GWP-weighted aggregate emissions
208 (HFC-227ea plus HFC-125) were multiplied by scaling factors from the RCP3-PD scenario, which was
209 the only scenario with separate projections for these two gases. RCP6 emissions for HFC227ea were
210 taken from RCP3-PD. EDGAR4 data (EC-JRC and PBL 2009) were used for historical harmonization
211 values for HFC-227ea and a constant scaling factor was applied. Similarly, for HFC-245fa and SF₆, a
212 ‘ramped’ scaling until 2050 would have led to a considerable change in growth rates compared to the
213 near-monotonic increase of emissions until 2100 reported for RCP8.5. Thus, a constant scaling factor was
214 applied over time which led to higher RCP8.5 emissions by 2100 than projected by the original IAM
215 scenario (see Figure 2).

216 The net effect of the harmonization procedure for the long-lived GHGs and ODSs is in some years
217 moderate, but is generally small and negligible in the long-term. Over all years, the highest upward shift
218 in GWP-weighted (100 yr time horizon) (IPCC 1996) aggregate emission levels is 11.5% for the RCP6
219 scenario, which is due to a substantial upward shift of landuse CO₂ emissions from 1.3 to 4.4 GtC/yr in
220 year 2005 (+226%). A 4.1% upward adjustment of the RCP3-PD scenario in 2005 resulted as well from

221 the harmonization of landuse CO₂ emissions from 2.8 to 4.4 GtC/yr in year 2005, in addition to small
222 upward corrections of CH₄ and fluorinated gases (see Figure 2). Harmonization reduced the RCP8.5
223 emissions slightly, by 2.1% in 2005. The aggregate emission levels of RCP4.5 faced a small upward shift
224 by 2.1% in 2005. By construction, the harmonization procedure had only negligible effects on post-2050
225 emission levels (<0.3%) given that only a few fluorinated gases were adjusted after 2050.

226 Note that these induced shifts of emission levels are within the uncertainty of current emission
227 estimates. Nevertheless, due to the cumulative effect on radiative forcing levels for long-lived gases, the
228 harmonization procedure will result in slightly different concentration and temperature projections
229 (which is intended as part of increasing the comparability between the different scenarios). To ensure a
230 smooth transition of concentrations from historical runs for shorter-lived substances, the harmonization is
231 an essential step for consolidating the scenarios from four different IAMs for a climate model inter-
232 comparison. Otherwise, a consistent like-with-like comparison of the resulting climate consequences
233 across the scenarios would be hindered.

234 (INSERT Figure 2 HERE)

235 Some other limitations of the harmonized emissions arose. The current ODS projections (WMO
236 2007) do not incorporate the effects of the accelerated HCFC phase-out accepted by the Parties to the
237 Montreal Protocol in 2007. In the absence of specific mitigation policies, this would be expected to lead
238 to somewhat lower future HCFC emissions (Velders et al. 2007). Furthermore, NF₃ (as well several less
239 abundant fluorinated gas compounds) are not included in the RCPs even though they may have small
240 positive radiative forcing effects (Prather and Hsu 2008; Prather and Hsu 2010).

241 **2.4. Calculation of GHG Concentrations**

242 In most of the experiments for the CMIP5 intercomparison exercise, AOGCMs and ESMs will be driven
243 by historical and future GHG concentrations, not emissions, as shown in Appendix 1 and further
244 described in Taylor et al. (2009). We derive concentrations from the harmonized emissions with a single
245 model (MAGICC 6, see Meinshausen et al. 2008), in order to ensure consistency between and within the

246 different RCPs. We now summarize the various gas-cycle parameterizations, before providing more
247 detail on the chosen carbon cycle and climate response settings. Our assumptions regarding non-GHG
248 forcing agents are detailed in Appendix 2.

249 MAGICC uses gas-cycle parameterizations of different complexity to project concentrations and
250 radiative forcing for CO₂, CH₄, N₂O, 3 PFCs, 8 HFCs, SF₆ and 16 ODSs (see listing of individual species
251 in Section 2.2). For CO₂, MAGICC includes a global carbon cycle model with three land carbon pools, an
252 ocean carbon scheme, and multiple temperature dependent terrestrial and oceanic fluxes, as well as a
253 parameterization for the CO₂ fertilization effect. The model does not yet include a nitrogen cycle and
254 interactions between the carbon cycle and nitrogen cycle – reflecting the state of carbon cycle models in
255 C⁴MIP in 2006 (Friedlingstein et al. 2006). The chosen carbon cycle calibration is further described
256 below.

257 For projecting CH₄ and N₂O concentrations, parameterizations from Ehhalt et al. (2001) are used –
258 including simplified temperature-dependent tropospheric OH-chemistry parameterizations. Both CH₄ and
259 N₂O lifetime includes a dependency of its lifetime on its own abundance. Further details regarding how
260 these processes are treated in MAGICC6 can be found in Meinshausen et al. (2008). Stratospheric sinks
261 for all fluorinated gases and ODSs are assumed to become enhanced slightly with rising global mean
262 temperatures (15% per degree Celsius warming) leading to shorter lifetimes at higher warming levels –
263 due to a strengthening Brewer-Dobson circulation (Butchart and Scaife 2001). As for CH₄, tropospheric
264 OH-related sinks of fluorinated gases are dependent on the parameterized changes in the OH abundances.

265

266 Previous applications of MAGICC6 have not used a single set of best-estimate parameters to
267 calculate concentrations, radiative forcings and global mean temperatures from prescribed emissions, but
268 instead used an array of parameter sets to project a range of climate responses by emulating CMIP3
269 GCMs (Meehl et al. 2005) and to project a range of CO₂ concentrations by emulating C⁴MIP carbon
270 cycle models (Friedlingstein et al. 2006) as described in Meinshausen et al. (2008). Alternatively,
271 historically constrained joint distributions of parameters were used (Meinshausen et al. 2009). To

272 calculate a single set of concentrations for driving climate models (the primary reason underlying the
273 RCP concept), we need a single “best” set of model parameters for MAGICC. Temperature projections
274 itself will be ultimately produced by the CMIP5 models. However, the significance of having a ‘best-
275 estimate’ future temperature projection within MAGICC6 is that many gases’ concentrations are
276 influenced by temperature or climate feedbacks.

277 We chose parameters for MAGICC6 that would closely reflect the median of the distribution in
278 global-mean temperature projections that is spanned when emulating the GCMs and carbon cycle models
279 that took part in CMIP3 and C⁴MIP, respectively. Specifically, we chose an emulation of the C⁴MIP
280 Bern-CC carbon cycle model (Joos et al. 2001) as ‘best-estimate’ for the carbon cycle behavior. This is
281 both because the Bern-CC model (and earlier versions of this model) has been used for the consolidated
282 concentrations of IPCC SRES scenarios presented in the Third Assessment Report (see Appendix II in
283 Houghton et al. 2001) and because the projected CO₂ concentrations from the Bern model are roughly in
284 the middle of the range of C⁴MIP results (Friedlingstein et al. 2006).

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

299 Apart from deriving the default MAGICC climate response parameter set for creating the RCPs, one
300 additional amendment has been implemented in MAGICC6 to serve this RCP process. Inverse emissions
301 are now routinely calculated for all 31 considered GHGs (CO₂, CH₄, N₂O, 3 PFCs, 8 HFCs, SF₆ and 16
302 ODSs). This is of interest when concentration time-series are prescribed for designing the ECPs. For
303 CO₂, these inverse emissions can be compared to the allowable emissions derived from ESMs in the
304 course of CMIP5.

305

306 **3. Post-2100 Extension**

307 The RCP emissions scenarios produced by the IAMs span the period 2005 to 2100. Conducting
308 multi-century climate change analyses thus requires extensions beyond 2100. We designed these
309 extensions, the so-called Extended Concentration Pathways (ECPs), using simple rules that have been
310 developed in a series of stakeholder consultations among scientists in the IPCC WG1, WG2 and WG3
311 communities, including representatives of the IAM groups, representatives of CMIP5, and the wider
312 scientific community. It should be noted that these extensions do not represent fully consistent scenarios,
313 but are simple ‘what-if’ thought experiments that represent the underlying ideas behind each RCP. The
314 rules used for the extension of emissions and/or concentrations of the RCPs are shown in Table 3. No
315 explicit assumptions regarding to population or economic development have been made for these stylized
316 “what-if” extensions.

317 Generally, there are three options for the design of a simple extension (with intermediate options
318 possible): I) the forcing and concentrations can simply be kept constant (as done for the SRES scenarios
319 in CMIP3 and assessed by the IPCC Forth Assessment Report, AR4), II) emissions can be adapted over
320 time, e.g. to yield a smooth stabilization at another level than 2100, or III) emissions can be kept constant.
321 The two intermediate scenarios RCP4.5 and RCP6 are extended by concentration stabilization, albeit
322 with stabilization achieved in 2150 to avoid discontinuities in the implied emissions. For the lowermost
323 RCP, RCP3-PD, emissions were kept constant after 2100. The extension of the highest RCP, RCP8.5,
324 represents a mixture of constant emissions until 2150 and constant concentrations after 2250 (see Table
325 3). As a result of now including a low mitigation pathway RCP3-PD and due to these extension choices,
326 the ECPs span a much wider range of post-2100 forcing pathways than considered in previous studies,
327 such as CMIP3 assessed in IPCC AR4.

328 (INSERT Table 3 HERE)

329 Several alternative extensions were considered for each RCP. For RCP8.5, the full range of possible
330 extensions ranged from relatively low forcing levels that result from simply keeping concentrations

331 constant after 2100 to very high levels that result from assuming that emissions stay constant until 2300.
332 After consultations with the respective expert groups an intermediate extension was selected. This
333 extension avoids a possible discontinuity in emissions trends (that would arise from keeping
334 concentrations constant), and avoids issues of resource availability that a higher extension might raise.
335 Keeping emissions constant would have resulted in CO₂ concentration of around 3000 ppm by 2300. The
336 adopted RCP8.5 extension (ECP8.5) leads to a CO₂ stabilization after 2250 at roughly 2000 ppm, or 7-
337 folds of pre-industrial CO₂ concentrations. The total forcing of this ECP8.5 is hence approximately twice
338 as high as the next highest ECP (ECP6) (see Figure 4 below). This high forcing for ECP8.5 is
339 significantly above the highest forcing levels that was considered in CMIP3 on the basis of IPCC SRES
340 scenarios (i.e, approximately 700 ppm in A1B).

341 Another alternative extension was considered for RCP3-PD, as one may question whether negative
342 emissions can be sustained over very long time periods (in view of limited CO₂ storage capacity). An
343 alternative extension, in which emissions would converge back to zero between 2150 and 2200, would
344 lead to CO₂ concentration of about 380 ppm rather than 360 ppm by 2300. However, in consultation with
345 experts it was concluded that a continuation of the 2100 emission levels cannot be excluded for reasons
346 of physical constraints of sequestration & storage options and would better reflect the character of the
347 RCP3-PD pathway.

348 In addition to the four standard ECP extensions, we present one supplementary extension, which
349 might be of particular use to investigate irreversibility and the path-dependency of the climate system
350 response to different GHG abundances³. This extension starts from RCP6 in 2100 and merges with the
351 concentrations of of the next lower scenario, ECP4.5, by 2250. This is similar to other forcing and
352 temperature overshoot scenarios in the literature (Hare and Meinshausen 2006; Wigley et al. 2007; Lowe
353 et al. 2009). Between 2100 and 2250, we adjusted emissions of this supplementary extension (called
354 SCP6to4.5) by following simple linear and continuous trajectories in order to obtain the desired
355 stabilization concentration level of ECP4.5 by 2250. We chose for transparency linear segments of

³ 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/reps/>.

356 emissions, i.e., a 50-yr long phase of stringent reductions (with 2.5%/yr reduction in fossil CO₂ emissions
357 relative to 2100 levels) to reach a negative emission floor, which had to be more than twice as negative as
358 under the RCP3-PD scenario (-3.8GtC/yr). Smoother emission trajectories would be possible, although
359 they would imply higher annual reduction rates and/or more negative emission levels than presented here.
360 After 2250, when concentrations are equal by design, the implied inverse CO₂ emission levels of the
361 SCP6to4.5 overshoot pathway are consistently lower than those of ECP4.5 (see Figure 3). This is because
362 temperature-induced feedbacks and inertia effects in the carbon cycle. In summary, only by assuming a
363 long period of strong reductions and deeply negative CO₂ emissions, we were able to ‘make up’ for the
364 higher RCP6 emissions during the 21st century in order to reach ECP4.5 concentration levels by 2250.

365 Similar to this SCP6to4.5 extension, we considered an alternative ECP6 extension with
366 comparatively less stringent post-2100 emission reductions, basically assuming that the RCP-3PD
367 emissions path is followed 100 years later, i.e., in the 22nd century. Specifically, 2020-2100 RCP3-PD
368 emission trajectories were assumed for 2120 to 2200 – with linear interpolation between 2100 RCP6 and
369 the extension by 2120. We kept emissions constant after 2200. Following that alternative, radiative
370 forcing would have declined to 4.5W/m² only 350 years later, i.e., by 2450.

371 The conclusion from this alternative RCP6 extension and our SCP6to4.5 supplementary extension is
372 that once high 21st century emissions increased radiative forcing levels to 6W/m², it seems practically
373 impossible to return to lower levels quickly. Any 4.5W/m² overshoot scenario of the sort considered here
374 will imply higher global warming levels for considerable periods of time, i.e., centuries, – and rests on
375 the assumption that stringent post-2100 emission reductions are feasible. A similar conclusion could be
376 drawn for extensions that connect RCP8.5 to ECP6 or RCP4.5 to ECP3-PD long-term concentration
377 levels³.

378 (INSERT Figure 3 HERE)

379 For the fluorinated gases within the basket of gases that are controlled under the Kyoto Protocol
380 (HFCs, PFCs, and SF₆), projections are inherently uncertain, as new applications are constantly being
381 developed (apart from the fact that new fluorinated compounds are designed). For the purpose of

382 designing the SCP6to4.5 extension, a question arises how to bridge the gap between the lower ECP6
383 fluorinated gas concentration levels towards the higher ECP4.5 ones. Partly because this gap is very
384 small, only 2% in terms of the total radiative forcing difference between ECP6 and ECP4.5, and partly
385 for simplicity, we modify only the emissions of the representative forcing agent HFC-134a in order to
386 ramp up the aggregate forcing from HFCs, PFCs, and SF₆.

387 **4. Results: RCP GHG concentrations**

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

392 In the lowest of the four RCPs, the total radiative forcing peaks at approximately 3W/m^2 and declines
393 from there (Figure 4), motivating the name RCP3-PD, where PD stands for "Peak&Decline". CO_2
394 concentrations reach a maximum level of slightly above 440 ppm in the year 2050, and then decline to
395 below today's levels by 2300 (~ 360 ppm) (see Table 4). CO_2 -equivalent concentrations (not shown)⁴,
396 comprising the net effect of all anthropogenic forcing agents (including aerosols), peak at around 460
397 ppm just before 2050, declining in tandem with CO_2 towards 360 ppm by 2300, at which time this
398 scenario's projection for the net effect of non- CO_2 forcing agents is again close to zero – similar to the
399 best-estimate non- CO_2 forcing estimate for current times (Forster et al. 2007). The aggregate forcing of
400 all long-lived GHGs controlled under the Kyoto-Protocol, expressed as CO_2 equivalent, declines from
401 503 ppm CO_2eq in 2050 towards 407 ppm by 2300 in RCP3-PD.

402 (INSERT Figure 4 HERE)

403 (INSERT Table 4 HERE)

404 RCP8.5's radiative forcing levels by the end of 2100 are around 8.5W/m^2 under our 'best-estimate'
405 set of model parameters with forcing levels increasing further thereafter – up to 12W/m^2 by 2250, when
406 concentrations are stabilized (Figure 4). Transient scenarios with such high radiative forcing levels and
407 CO_2 concentrations have never before been investigated in model CMIP intercomparison exercises.
408 Across almost all gases, RCP8.5 concentration levels are by far the highest. For example, CH_4
409 concentration peaks around 3500 ppb - more than twice as high as the next highest scenarios, RCP4.5 and
410 RCP6, which approximately stabilize at 1500 ppb. The only exceptions are ODS concentrations: RCP4.5,

⁴ available at <http://www.pik-potsdam.de/~mmalte/rcps/> for illustrative reasons.

411 RCP6 and RCP8.5 share the same emission assumptions (WMO 2007, A1 Scenario), but the longer-term
412 ODS concentrations are slightly lower in RCP8.5 due to slight increases in stratospheric ODS lifetimes
413 via expected changes in stratospheric circulation rates, outweighing initial decreases in tropospheric sinks
414 due to lower OH concentrations (see Section 2.4 and Figure 5d).

415 (INSERT Figure 5 HERE)

416 RCP4.5 and RCP6 are both stabilization scenarios, with constant concentrations after 2150. By
417 stabilizing at 543 ppm CO₂ concentrations, RCP4.5 comes very close to a doubling of pre-industrial CO₂
418 concentrations (556 ppm) – and is hence only slightly higher than the SRES B1 scenario and its constant
419 extension after 2100 with 540 ppm CO₂ (see Bern-CC (reference) case in Appendix II.2.1 in Houghton et
420 al. 2001). The RCP6 scenario stabilizes 200 ppm higher, at 752 ppm CO₂ (see Figure 5).

421

422

423

424 **5. Discussion**

425 **5.1. Ensemble results compared to our default concentration** 426 **and temperature projections.**

427 In the above text we selected a specific ('best-estimate') set of MAGICC parameters to use in
428 producing a standard set of RCP concentrations. Starting from the harmonized emissions, we can also
429 produce concentrations (and forcing and temperature projections) using 19 individual CMIP3 climate and
430 9 C⁴MIP carbon cycle emulations. How does our default set of results compare with the distribution of
431 results from these 171 (=19x9) cases?

432 We perform this comparison using the highest and the lowest RCP scenarios. The results are shown
433 in Figure 6. Not surprisingly, because the responses to external forcings in all climate models are largely
434 linear, the 'best-estimate' results are similar to the median of the individual model results, even in the
435 high forcing RCP8.5 case. The ideal test of our projections, although impractical, would be for the
436 CMIP3 GCM model ensemble to be run again for the RCP8.5 scenario and ECP8.5 extension. Since the
437 post-2100 ECP8.5 forcing case falls well outside the MAGICC SRES calibration range, it would provide
438 a rather stringent test for MAGICC.

439 (INSERT Figure 6 HERE)

440 In summary, our default carbon cycle/climate model settings are shown to reflect well the median
441 emulated responses of both the AOGCM and carbon cycle response. The implied relation between
442 emissions and concentrations may, of course, change with the next generation of models. It will be useful
443 to compare the climate and carbon-cycle responses from the next round of climate model experiments
444 with those presented here, which are, necessarily, calibrated to existing model experiments. The
445 allowable CO₂ emissions for these pathways could, for example, be lower (or higher) than those found
446 here, if for example positive carbon cycle feedbacks were higher (or lower) in the CMIP5 generations of

447 ESMs compared to C⁴MIP models. Including a nitrogen cycle in the MAGICC and other carbon cycle
448 models may also have significant effects on future forward or inverse projections.

449 **5.2. Inverse emissions for the long-term extension pathways**

450 The extensions of the RCPs and the generation of the supplementary pathway were made using the
451 simple rules given in Table 3. While these extensions are simply thought experiments, we examine here
452 the implied emissions from the SCP6to4.5 scenario to illustrate some key points relevant to future long-
453 term scenarios. The inverse emissions that correspond to this overshoot scenario imply a period of
454 substantial net negative emissions for CO₂ of -13.9GtCO₂/yr – between 2150 and 2230 (see Figure 3).
455 This value is larger in magnitude than the negative emissions level in the RCP3-PD scenario (-0.93
456 GtC/yr = -3.41GtCO₂/yr), but there are scenarios in the literature that imply similarly negative emission
457 levels already by 2100. For example, Calvin et al. (2009) show scenarios with slightly larger negative
458 emissions levels by 2100 of -10–15 GtCO₂/yr in 2095. In addition to sustained net negative emissions in
459 SCP6to4.5, the reduction rates assumed between 2100 and 2150 are rather substantial, similar to the
460 steepest segments of RCP4.5 and RCP3PD – but extended over a longer time period.

461 As highlighted in Figure 3a, CO₂ emissions for the SCP6to4.5 have to be reduced below the RCP4.5
462 emissions by approximately the same amount as the extra cumulative emissions that were emitted during
463 the 21st century by RCP6. On the timescales of interest here, CO₂ does not have finite lifetime (Archer
464 and Brovkin 2008), but is simply being re-distributed between the different active carbon pools. This is
465 largely why cumulative CO₂ emissions are a crucial quantity for long-term temperature and atmospheric
466 concentration responses (Kheshgi et al. 2005; Allen et al. 2009; Matthews et al. 2009). For this reason,
467 cumulative emissions for the RCP4.5-ECP4.5 pathway and the RCP6-SCP6to4.5 pathway are roughly of
468 the same size (see Figure 3b).

469 For other long-lived GHGs such as N₂O, the need to compensate for initially higher emissions with
470 lower emissions later on is still apparent, although cumulative N₂O emissions are a bit higher under the
471 SCP6to4.5 pathway compared to RCP4.5-ECP4.5 case - even though both paths ultimately stabilize at

472 the same N₂O concentration levels by design (see Figure 3 e&f). For CH₄, with its much shorter
473 atmospheric lifetime (Forster et al. 2007), the ultimate concentration depends almost solely on emissions
474 over the final few decades rather than on long-term cumulative emissions.

475 We reiterate that the ECP pathways are highly stylized and are not the result of detailed analysis of
476 resource limits, but are instead presented in order to provide a range of concentration and forcing
477 pathways for use in climate model experiments. In contrast to the simple stabilization of concentrations
478 after 2100 used for CMIP3, the current ECPs provide a wider range of forcing pathways in which to test
479 long-term model responses.

480

481 **6. Conclusions**

482 The historical, 21st century and extended GHG concentration and harmonized emission data
483 presented here are a result of a wide collaboration across the scientific communities. In order to obtain a
484 single set of best-estimate projections for future GHG concentrations for the four RCP scenarios, we used
485 an emulation of the median response of both climate and carbon cycle models that took part in the
486 previous climate model inter-comparison exercises CMIP3 (Meehl et al. 2005) and C⁴MIP (Friedlingstein
487 et al. 2006). The derived concentration results are generated as the starting point for the CMIP5 inter-
488 comparison exercise (Taylor et al. 2009), which will be evaluated in the forthcoming IPCC Fifth
489 Assessment Report. While the inverse emission results here can also provide a yardstick for comparison,
490 it can be expected that the forthcoming CMIP5 generation of ESMs will diagnose 'allowable'/inverse
491 emissions that differ from the harmonized emissions presented here. This is because of limitations in the
492 extrapolation of previous model's emulation results, and partly because of new process parameterizations
493 within the new generation of climate and carbon cycle models.

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

500

501

502 **Appendix 1 – RCP GHG data within CMIP5**

503

504

505 [INSERT Table 5 HERE]

506

507

508 **Appendix 2 - Non-GHG forcing agents**

509 Apart from the harmonized global GHG emissions and concentrations presented in this study, the
510 ESMs and the scientific communities of IPCC WG1 and WG2 will be provided with a series of other
511 input data sets: tropospheric & stratospheric ozone and aerosol abundances (Lamarque et al. this issue),
512 land-use patterns (Hurtt et al. this issue), and solar forcing recommendations (Lean and Rind 2009)
513 **(ADD OTHER REFERENCES FROM THIS ISSUE)**. For the concentration calculations described here,
514 these non-GHG forcings, including aerosols, tropospheric ozone precursors, solar irradiance and volcanic
515 aerosols, were included since temperature and chemical feedbacks have an influence on atmospheric
516 GHG concentrations and their fluxes (see Methods 2.4). To the extent possible, CMIP5 consistent
517 assumptions in regard to the non-GHG forcings were taken, although it should be noted that our IPCC
518 AR4 based forcing parameterizations of different non-GHG compounds differ from chemistry-climate
519 model runs in relation to tropospheric ozone, for example (Lamarque et al. this issue), and will as well
520 differ from new insights generated by CMIP5 set of models. For the emission-driven ESM runs in
521 CMIP5, some of them will generate CO₂ emissions resulting from land-use patterns endogenously, so
522 these emissions will differ from the harmonized IAM emissions used here. For radiative forcing due to
523 solar irradiance changes we followed the CMIP5 recommendation of repeating solar cycle 23 into the
524 future – although we keep solar forcing constant after concentrations are stabilized. Solar irradiance data
525 by Lean and Rind (2009) (see at [http://www.geo.fu-](http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/CMIP5_solar_irradiance.html)
526 [berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/CMIP5_solar_irradiance.html](http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/CMIP5_solar_irradiance.html)) is used here as
527 recommended for CMIP5. The irradiance data has been converted into radiative forcing by dividing by 4
528 (geometrical) and multiplying by 0.7 to take into account albedo. Furthermore, the data is normalized to
529 have an average of zero for the 22 years around 1750.

530 Concerning volcanic forcings, CMIP5 leaves it to the modeling groups as to how to treat volcanic
531 stratospheric aerosols in the control run and 21st century runs. One problem is that an artificial cooling
532 and reduction of sea level rise will occur in response to the first volcanic events in the historical run

533 (1850), if the control run brought the model in equilibrium without volcanic eruptions. Here, we use a
534 specific setup for volcanic aerosols, which is one – but not the only – option of how GCMs can deal with
535 volcanic forcing for CMIP5. Specifically, we assumed the average volcanic aerosol loadings over the last
536 100-years (around $-0.2\text{W}/\text{m}^2$) to be applied in both the control run and the future runs from 2006
537 onwards, or equivalently, to shift the volcanic forcing series such that control run and future forcings, as
538 well as the mean over the historical period are zero (see Meinshausen et al. 2008; see Taylor et al. 2009
539 for a further discussion of this issue). Analogously, GCMs could apply a stratospheric volcanic aerosol
540 loading in their control runs, as well as in the post-2005 projections.

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

552

553

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565

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826 **Tables**

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829 **Table 1 - Historical mixing ratios of GHG concentrations used to extend RCP concentrations back in time.**

<i>Historical Mixing Ratios</i>	Description
CO_2	Data up to 1832 from Law Dome Ice Core data (Etheridge et al. 1998) in its 75yr 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 global estimates over 1982-1986 (Conway et al. 1994) ^c . The global NOAA ESRL 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. 1998) ^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. (1998) followed thereafter by data from: NOAA CMDL ESRL (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 300yr 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 1850-1977 and NOAA ESRLCMDL Flask Data ^h over 1978-1999. From 2000 to 2008, our historical dataseries are sourced from the NOAA CMDL ESRL 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 in 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 35ppt 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 figure 1-23 in WMO (2006), linearly interpolated back to zero from 1980 to 1970.

<i>HFC-134a</i>	Based on NOAA/ ESRL/GMD data (Montzka et al. 1996; Montzka et al. 1996) ^j extended to July, 2008.
<i>HFC-143a</i>	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.
<i>HFC-23</i>	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%/yr) for extending back to 1930.
<i>SF₆</i>	SF ₆ is regularly measured at multiple NOAA ESRL sites and by different techniques. We base our 1961-2008 estimate on a record from firm 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.
<i>ODSs</i>	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 firm air, archived air, and industrial production and bank data (Montzka et al. 1996; 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 (0.95ppt). For CH ₃ Br and CH ₃ Cl, a pre-industrial value of 5.8 and 480 ppt is assumed, respectively.

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^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/>

842 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 [#]	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 et al. (2008)	Shift until 2030 [#]	2000 is average across RCP3-PD, RCP45, and RCP8.5 with post-2000 growth rates from Houghton et al. (2008)
CH ₄	MtCH ₄	300.2	315.9	Lamarque et al. (this issue)	Scale until 2050 [#]	For 2001-2005, the average growth rate across the RCP3-PD, RCP45 and RCP85 scenario is assumed
N ₂ O	MtN	7.46	7.68	RCP IAM emission scenarios	Scale until 2050 [#]	Simple average across original IAM emissions for RCP3-PD, RCP45 and RCP85
SO _x	MtS	53.84	56.72	Smith et al. (2010)	Scale until 2050 [#]	For 2001-2005, the average growth rate across the RCP3-PD, RCP45 and RCP85 scenario is assumed
CO	MtCO	1068	1061	Lamarque et al. (this issue)	Scale until 2050 [#]	
NMVOC	Mt	210.6	215.46			
NO _x	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*	Scale until 2100 [#]	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 RCP3-PD, RCP45 and RCP85.
C ₂ F ₆	kt	2.38	2.65	Inverse emission estimate*		This emission rate is necessary to match the 0.1ppt constant mixing ratio increase observed by (Worton et al. 2007).
C ₆ F ₁₄	kt	0.46	0.44	EDGAR4 (EC-JRC and PBL 2009)		RCP3-PD has been the only RCP reporting C ₆ F 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*		Inverse emissions to match observed record as shown in Figure 1.23 of WMO (2006) following Oram et al. (1998). Average growth rate of RCP3-PD, RCP45 and RCP85 between 2004 and 2005 assumed.
HFC-32	kt	4.00	10.99	Taken from original RCP3-PD		RCP3-PD has been 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. RCP3-PD, RCP45 and RCP60 follow the stabilizing SRES B1 emissions and RCP85 follows A2 emissions.
HFC-125	kt	8.81	13.86	Inverse emission estimate*		Inverse emissions to match observed record as shown in Figure 1.23 of WMO (2006) following Oram et al. (1998). Average growth rate of RCP3-PD, RCP45 and RCP85 between 2004 and 2005 assumed.
HFC-134a	kt	75.69	121.93	Inverse emission estimate*		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. 1996)
HFC-143a	kt	6.48	12.72	Inverse emission estimate*		Inverse emission for 2000 to match observed atmospheric mixing ratios measured by Culbertson

HFC-227ea	kt	1.95	4.89	EDGAR4 (EC-JRC and PBL 2009)	Scale	et al. (2004) with 2001-2005 emission growth rate taken as average from RCP3-PD, RCP45 and RCP85.
HFC-245fa	kt	17.93	26.89	RCP4.5 original data	Scale	As for HFC-245fa, recent observations (Laube et al. 2010) suggest smaller actual emissions.
SF ₆	kt	5.46	6.21	Inverse emission estimate*	Scale	RCP4.5 derived their HFC-245fa emissions based on a later set of EMF-22 data than RCP3-PD or RCP85. Note that this is substantially higher than recently observed (Vollmer et al. 2006), although the latter implies higher rates of increase. 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).

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* Inverse emissions are estimated using the MAGICC6 gas cycle modules (Meinshausen et al. 2008).

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, the scaling factor is linearly interpolated between its year 2005 value and 1.

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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⁺
RCP3-PD	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.*
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.*
<i>RCP6</i>	<i>Supplementary Extension SCP6to4.5</i>	<i>Adjustment of emissions after 2100 to reach RCP4.5 concentrations levels in 2250 and thereafter.</i>

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851 ⁺ Note that for all extensions, land-use CO₂ emissions are assumed zero consistent with frozen land-use patterns
852 (Hurtt et al. this issue) beyond the 21st century – with a linear interpolation between 2100 and 2125.
853 Reactive gas emissions and aerosols are assumed constant after 2100 (see Lamarque et al. this issue).

854 * Sudden adjustment of emissions for ODSs in 2150 (ECP6 & ECP4.5) and 2250 (ECP8.5), when concentrations
855 stabilize.

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858 **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	1147	1751
N ₂ O (ppb)		273	274	275	280	289	316
HFCs, PFCs, SF ₆ (ppt HFC-134a-eq) *		0	0	0	0	4	81
ODS (ppt CFC-12-eq) *		0	0	0	2	22	999
		2005	2050	2100	2150	2250	2300
CO ₂ (ppm)	RCP3-PD / 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	1962	1962
CH ₄ (ppb)	RCP3-PD / ECP3PD	1754	1452	1254	1245	1253	1256
	RCP4.5/ECP4.5	1754	1833	1576	1542	1542	1542
	RCP6 / ECP6	1754	1895	1649	1511	1511	1511
	SCP6to4.5	1754	1895	1649	1517	1542	1542
	RCP8.5 / ECP8.5	1754	2740	3751	3648	3481	3481
N ₂ O (ppb)	RCP3-PD / 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)	RCP3-PD / 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	1402	1614	1702	1702
ODS (CFC-12-eq ppt)	RCP3-PD / ECP3PD	1004	567	267	147	53	34
	RCP4.5/ECP4.5	1004	646	252	128	128	128
	RCP6 / ECP6	1004	653	250	120	120	120
	SCP6to4.5	1004	653	250	129	129	129
	RCP8.5 / ECP8.5	1004	652	229	94	20	20

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

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865 *Table for Appendix 1.*

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

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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 RCP3-PD, 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 RCP3-PD, 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 RCP3-PD 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.

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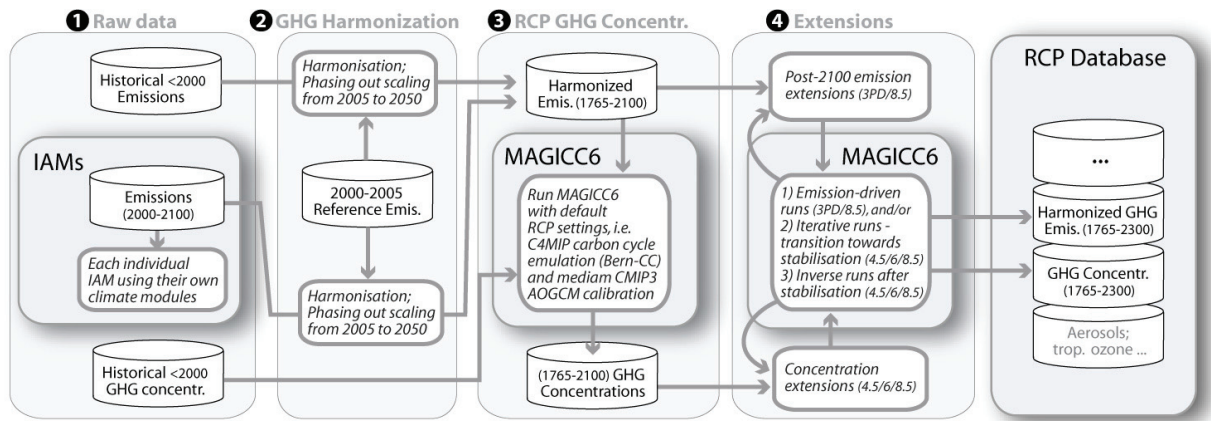
874 **Figures**

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

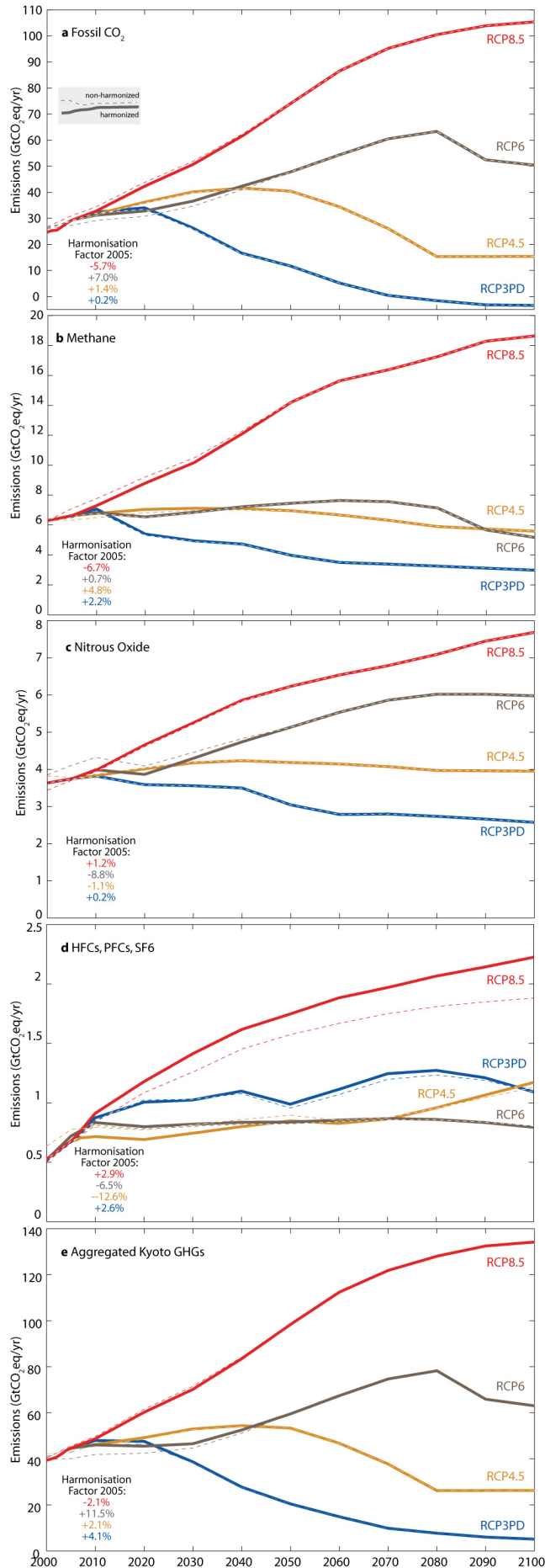
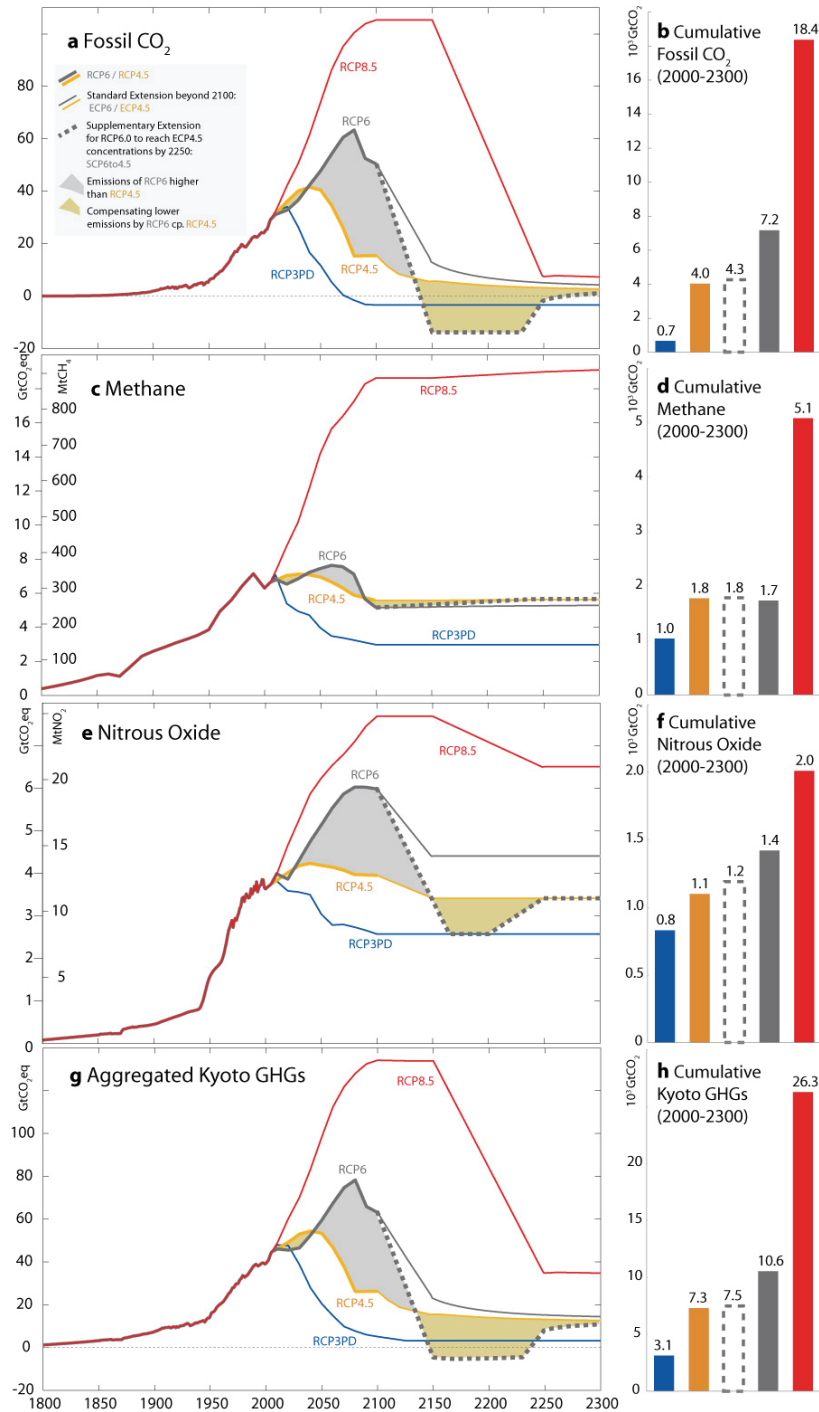


Figure 2 – Harmonized emissions under the four RCP scenarios. The non-harmonized scenarios (dashed lines) are in most cases marginally different from the harmonized emissions (solid lines). For illustrative purposes, emissions are weighted with IPCC SAR Global Warming Potentials of a 100-year time horizon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

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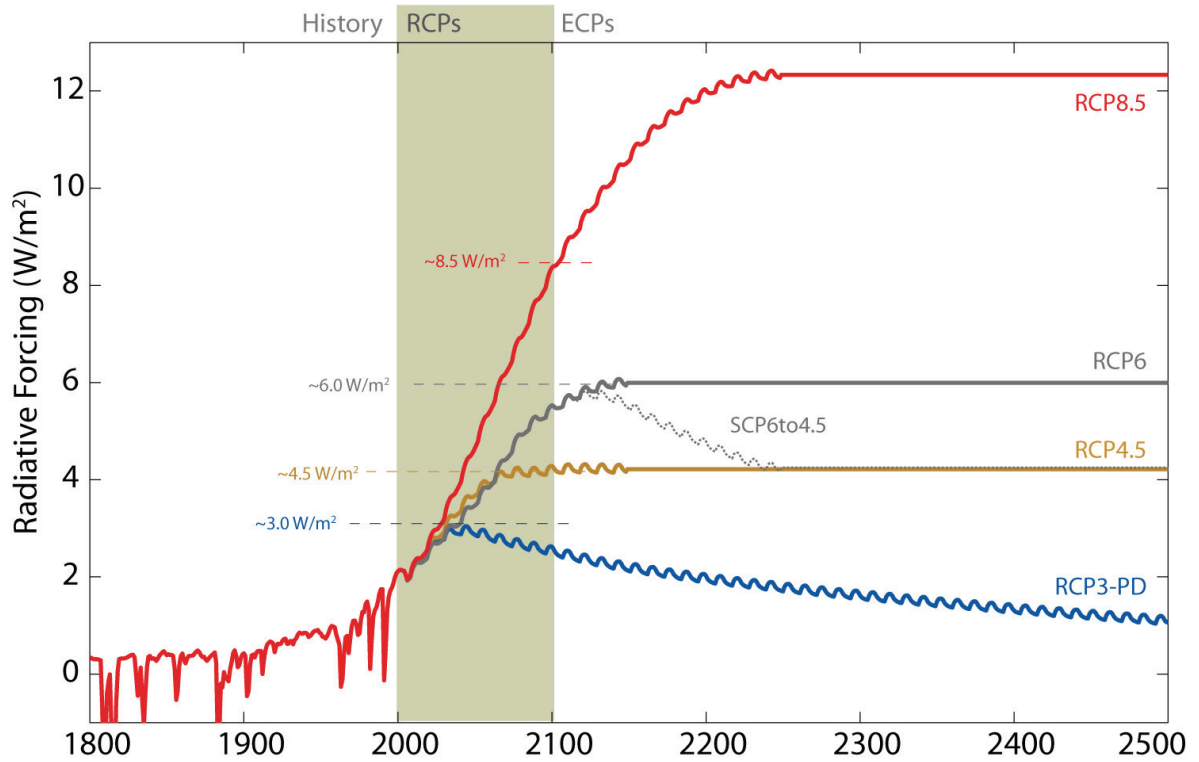
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Figure 3 - Emissions for the four RCPs and the supplementary extension SCP6to4.5, which starts from the RCP6 scenario and merges with the ECP4.5 concentrations by 2250. The shaded areas denote times of higher emissions (grey shading) and compensating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

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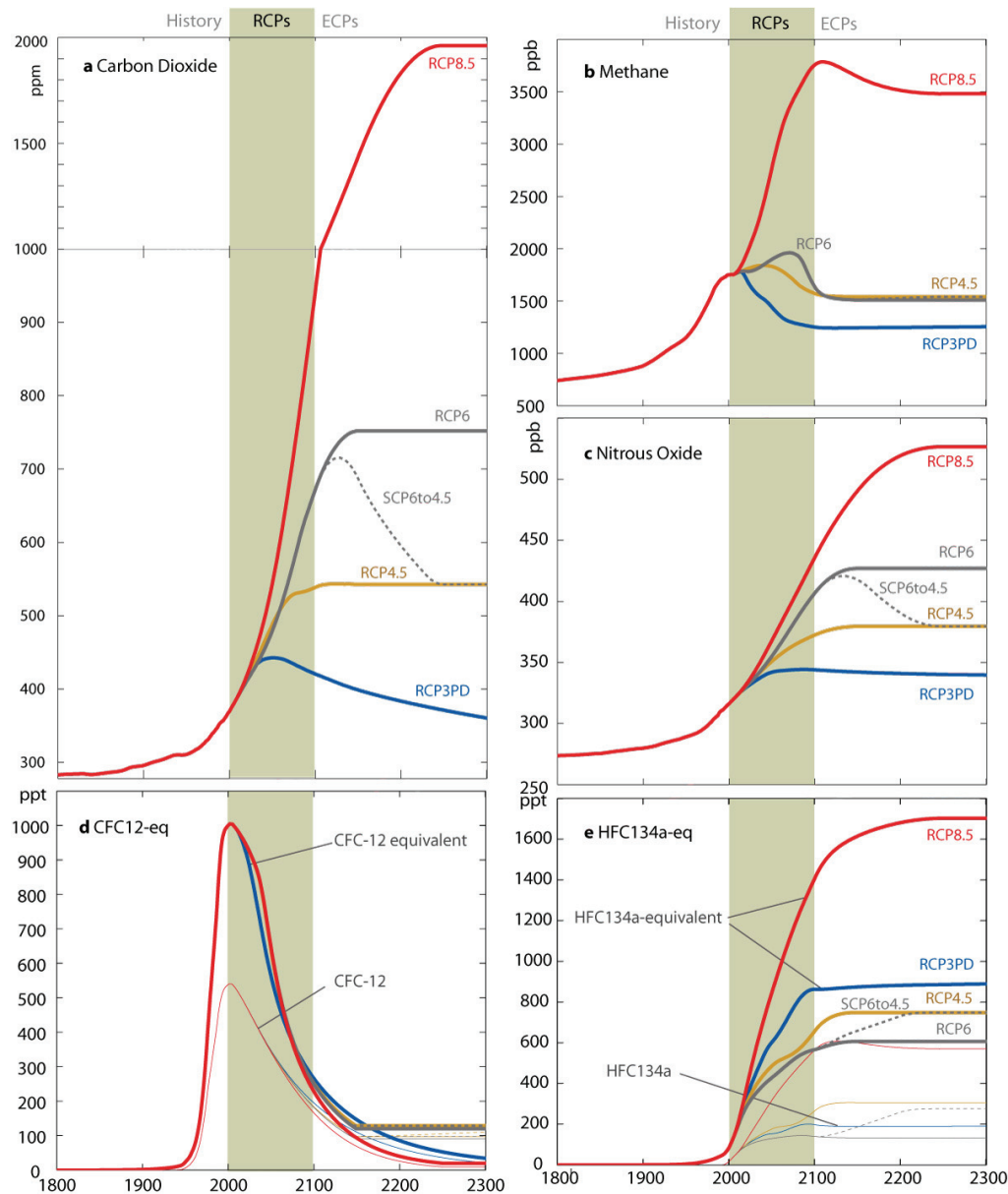
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Figure 4 - Total radiative forcing (anthropogenic plus natural) for RCPs, - supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for RCP3-PD, RCP4.5 & RCP6, as well as RCP8.5, respectively. 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.



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Figure 5 - GHG concentrations recommended for the CMIP5 climate change research studies. Shown are: (a)

atmospheric CO₂; (b), methane; (c), nitrous oxide; (d), (equivalent) CFC-12; and (e) (equivalent) HFC134a

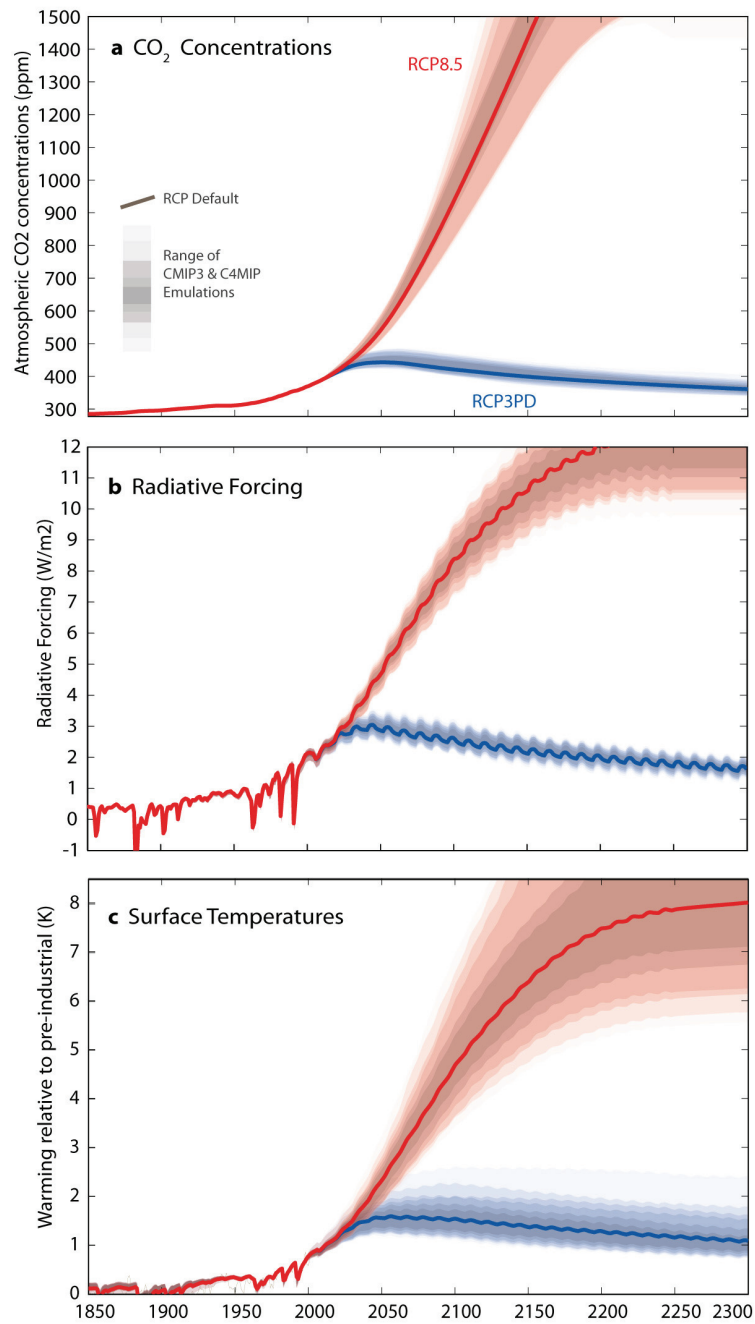
concentrations. Equivalent concentrations are derived so as to equal the aggregate forcing of the represented forcing

agents. For CFC-12, aggregated are those that controlled under the Montreal Protocol. 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).

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917 **Figure 6 - CO₂ concentrations (a,b), total radiative forcing (natural and anthropogenic) (c,d) and global mean**
 918 **surface temperatures (e,f) for RCP3-PD and RCP8.5 (solid lines) compared to the full range of CMIP3 GCM and C⁴MIP**
 919 **carbon cycle model emulations (shaded areas a,c,e). The small temporal variations in forcing are caused by the 11-year**
 920 **solar cycle assumption, influencing as well temperature projections.**