

# *Global warming potentials and radiative efficiencies of halocarbons and related compounds: a comprehensive review*

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1 **Global Warming Potentials and Radiative Efficiencies of**  
2 **Halocarbons and Related Compounds: A Comprehensive**  
3 **Review**

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28 **Abstract**

29 In the mid-1970s it was recognized that, as well as being substances that deplete stratospheric  
30 ozone, chlorofluorocarbons (CFCs) were strong greenhouse gases that could have substantial  
31 impacts on radiative forcing of climate change. Around a decade later, this group of  
32 radiatively active compounds was expanded to include a large number of replacements for  
33 ozone-depleting substances such as chlorocarbons, hydrochlorocarbons,  
34 hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs),  
35 bromofluorocarbons, and bromochlorofluorocarbons.

36 This paper systematically reviews the published literature concerning the radiative  
37 efficiencies (REs) of CFCs, bromofluorocarbons and bromochlorofluorocarbons (halons),  
38 HCFCs, HFCs, PFCs, SF<sub>6</sub>, NF<sub>3</sub>, and related halogen containing compounds. In addition we  
39 provide a comprehensive and self-consistent set of new calculations of REs and global  
40 warming potentials (GWPs) for these compounds, mostly employing atmospheric lifetimes  
41 taken from the available literature. We also present Global Temperature change Potentials  
42 (GTPs) for selected gases. Infrared absorption spectra used in the RE calculations were taken  
43 from databases and individual studies, and from experimental and *ab initio* computational  
44 studies. Evaluations of REs and GWPs are presented for more than 200 compounds. Our  
45 calculations yield REs significantly (> 5%) different from those in the Intergovernmental  
46 Panel on Climate Change Fourth Assessment Report (AR4) for 49 compounds. We present  
47 new RE values for more than 100 gases which were not included in AR4. A widely-used  
48 simple method to calculate REs and GWPs from absorption spectra and atmospheric lifetimes  
49 is assessed and updated. This is the most comprehensive review of the radiative efficiencies  
50 and global warming potentials of halogenated compounds performed to date.

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## 97 1 Introduction

98 Concern was raised in the 1970s that emissions of chlorofluorocarbons (CFCs), a class of  
99 compounds developed for a range of industrial and domestic uses, could lead to stratospheric  
100 ozone depletion [*Molina and Rowland, 1974*]. This concern was realized a decade later with  
101 the discovery of the Antarctic ozone hole [*Farman et al., 1985*] and a less severe but global-  
102 scale stratospheric ozone depletion [e.g., *Stolarski et al., 1992*].

103 At about the same time, it was also recognized that the CFCs were strong absorbers of  
104 infrared radiation and that sustained emissions could lead to accumulations in the atmosphere  
105 which would have significant climate impacts [*Ramanathan, 1975; Wang et al., 1976*]. This  
106 climatic role was re-emphasized during the 1980s, and expanded to more classes of gases,  
107 including chlorocarbons, hydrochlorocarbons, hydrochlorofluorocarbons (HCFCs),  
108 hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and the bromofluorocarbons and  
109 bromochlorofluorocarbons (referred to here as halons) [e.g., *Hansen et al., 1989; Ramanathan*  
110 *et al., 1985; Ramanathan et al., 1987*]. These studies indicated that the increase in  
111 atmospheric concentrations of CFCs and related compounds was contributing a decadal  
112 radiative forcing which was around 30-40% of that due to the increase in carbon dioxide  
113 concentrations. Furthermore, it was noted that this share could increase, if the growth in  
114 emissions of the CFCs and related molecules was unconstrained.

115 The landscape for considering the climate impact of halocarbons (organic compounds  
116 containing one, or more, halogen atom) changed as a result of global environmental  
117 agreements under the auspices of the United Nations. First, the Montreal Protocol on  
118 Substances that Deplete the Ozone Layer  
119 ([http://ozone.unep.org/new\\_site/en/montreal\\_protocol.php](http://ozone.unep.org/new_site/en/montreal_protocol.php)) - signed in 1987 and entered into  
120 force two years later - and its subsequent amendments and adjustments, led to the phasing out  
121 of production and emissions (with some exceptions) of CFCs, chlorocarbons and halons; it  
122 also included a schedule for the phasing out of emissions of HCFCs. Then, the Kyoto  
123 Protocol to the United Nations Framework Convention on Climate Change (UNFCCC)  
124 ([http://unfccc.int/kyoto\\_protocol/items/2830.php](http://unfccc.int/kyoto_protocol/items/2830.php)) - signed in 1997 and entered into force in  
125 2005 - set limits on the emissions of a “basket” of greenhouse gases by developed countries.  
126 The basket of greenhouse gases included a number of PFCs and hydrofluorocarbons (HFCs),  
127 the latter being most commonly used as CFC replacements. The initial Kyoto Protocol  
128 covered emissions in the so-called first commitment period of 2008-2012. The Doha

129 Amendment to the Kyoto Protocol covers emissions in a second commitment period of 2013-  
130 2020, and added nitrogen trifluoride to the basket of greenhouse gases.

131 Some of the issues concerning the halocarbons can be illustrated by reference to  
132 Figure 1 [WMO/GAW, 2011], which shows quasi-global average atmospheric concentrations  
133 of 10 of the more abundant halocarbons. During the 1980s, the halocarbon abundance and  
134 growth was dominated by two CFCs (CFC-11 ( $\text{CCl}_3\text{F}$ ) and CFC-12 ( $\text{CCl}_2\text{F}_2$ )). There were  
135 also significant contributions from CFC-113 ( $\text{CCl}_2\text{FCClF}_2$ ), methyl chloroform, and carbon  
136 tetrachloride. During the 1990s there was a dramatic change in the growth rates of the three  
137 CFCs and methyl chloroform. The changes were driven by the effects of the Montreal  
138 Protocol which led to rapidly declining emissions of these gases. The influence of the  
139 atmospheric lifetime of the different gases is also clear from Figure 1. Methyl chloroform has  
140 a relatively short lifetime (5 years) and its atmospheric concentration responds rapidly to  
141 decreased emissions. In contrast, CFC-12 and CFC-113 have atmospheric lifetimes of 100  
142 and 85 years, respectively, and their atmospheric concentrations respond more slowly to  
143 decreased emissions. CFC-11 has an atmospheric lifetime of 45 years and its atmospheric  
144 concentration is more responsive than CFC-12 but less responsive than methyl chloroform to  
145 decreased emissions. The fact that the atmospheric concentrations of carbon tetrachloride (35  
146 year lifetime) have only declined modestly over the past 30 years reflects continued emissions  
147 from developing nations [WMO, 2011].

148 Figure 1 shows that concentrations of HCFC-22 ( $\text{CHClF}_2$ ), an important interim  
149 replacement for several CFCs, continue to grow, despite being controlled by the Montreal  
150 Protocol – its concentration is now close to that of CFC-11. HFC-134a ( $\text{CH}_2\text{FCF}_3$ ), which is  
151 included within the Kyoto Protocol, has been the fastest growing HFC, mainly because of its  
152 use as a replacement for CFC-12 in refrigeration and vehicle air-conditioning applications. Its  
153 relatively short lifetime (13.4 years) compared to the CFCs means that for the same emission  
154 rate the atmospheric abundance of HFC-134a would be much lower than the CFCs it replaces  
155 (see section 2.4). Estimating future atmospheric concentrations of HCFCs and HFCs is  
156 challenging as it requires estimation of future emissions which are difficult to predict. For  
157 example, future concentrations of HFC-134a will depend on the growth of the global vehicle  
158 fleet and the impact of legislation and improved technology which would limit the use of  
159 HFC-134a or its leakage from that fleet. If the current emission rate ( $149 \pm 27 \text{ kt yr}^{-1}$  in 2008  
160 [WMO, 2011]) were maintained, the tropospheric concentration of HFC-134a would stabilize



161 at  $120 \pm 20$  ppt within a few decades. In addition to the gases shown in Figure 1, there are  
162 other halogenated alkanes (e.g., HFC-125 ( $\text{CF}_3\text{CF}_2\text{H}$ ), HFC-143a ( $\text{CF}_3\text{CH}_3$ ), HFC-152a  
163 ( $\text{CH}_3\text{CHF}_2$ ), HFC-32 ( $\text{CH}_2\text{F}_2$ ), HFC-245fa ( $\text{CHF}_2\text{CH}_2\text{CF}_3$ ),  $\text{C}_2\text{F}_6$ , and  $\text{C}_3\text{F}_8$ ) that have been  
164 detected in the atmosphere at levels of 1-10 ppt.

165 While the Montreal Protocol was designed to protect the ozone layer, its impact on  
166 climate change has been substantial, since it also controlled the atmospheric abundance of  
167 species that are powerful greenhouse gases – indeed it can be argued that it had a greater  
168 influence on the radiative forcing of climate change than the Kyoto Protocol [e.g., *Velders et*  
169 *al.*, 2007].

170 To make the multi-gas approach embedded in the UNFCCC operational, the Kyoto  
171 Protocol from 1997 adopted a framework whereby emissions of non- $\text{CO}_2$  greenhouse gases  
172 were placed on a “ $\text{CO}_2$ -equivalent” scale. As will be discussed in section 2, there is no unique  
173 way of assigning a  $\text{CO}_2$ -equivalence to an emission of a non- $\text{CO}_2$  gas, but the Kyoto Protocol  
174 adopted one available metric, the Global Warming Potential with a 100-year time-horizon  
175 (GWP(100)). The Protocol uses values of GWP(100) for specific gases as reported in the  
176 Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR)  
177 [IPCC, 1995]. It has not, so far, taken into account either revisions to those GWP values (as a  
178 result of improved understanding, and changing background concentrations of gases) or the  
179 expansion of the list to include additional species (including, for example, hydrofluoroethers  
180 (HFEs)) that have been catalogued in subsequent IPCC reports [e.g., IPCC, 2001; 2007] and  
181 World Meteorological Organization (WMO) / United Nations Environment Programme  
182 (UNEP) Scientific Assessment of Ozone Depletion [WMO, 2003; 2007; 2011]. In addition the  
183 parties to the UNFCCC have not considered in any detail and depth the use of alternative  
184 metrics to the GWP(100). For the second commitment period of the Kyoto Protocol, which is  
185 covered by the Doha Amendment, a draft decision (which is described in UNFCCC Decision  
186 2/CMP.8 (<http://unfccc.int/resource/docs/2012/cmp8/eng/13a01.pdf>) which itself refers to  
187 Decision 4/CMP.7 (<http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf>)) has been made  
188 to adopt the GWP(100) values reported by the IPCC's Fourth Assessment Report in the Errata  
189 to Table 2.14 of the Working Group 1 report (see  
190 [http://www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/errataserrata-errata.html#table214](http://www.ipcc.ch/publications_and_data/ar4/wg1/en/errataserrata-errata.html#table214)), but  
191 this decision has not been confirmed at the time of writing.

192           The GWP values for specific gases given in successive IPCC and WMO Ozone  
193 Assessment reports are drawn from a range of sources which use a variety of techniques to  
194 derive the input parameters (and in particular the “radiative efficiency” (RE) – which is,  
195 broadly, the “greenhouse” strength of a particular gas, on a per molecule basis – see section  
196 2.2) needed to calculate the GWP. In addition, rather simplified considerations have  
197 sometimes been adopted to take into account discrepancies between values reported in the  
198 literature (e.g., averaging available values rather than assessing which are likely to be the  
199 more reliable).

200           The primary aim of this review is to provide a comprehensive and consistent analysis  
201 of the input parameters required to calculate values of the GWP and other metrics for a large  
202 number of CFCs, chlorocarbons, hydrochlorocarbons, HCFCs, HFCs, PFCs, HFEs and other  
203 related halogenated substances (including, for example, nitrogen trifluoride (NF<sub>3</sub>) and sulphur  
204 hexafluoride (SF<sub>6</sub>)). The particular emphasis will be on the method of calculation of the  
205 radiative efficiency. The review will also consider, in much less detail, atmospheric lifetimes,  
206 another important input parameter for the calculation of GWPs and other metrics –  
207 atmospheric lifetimes are, for the most part, taken from the existing literature, without  
208 detailed analysis. This then enables us to provide an extensive and self-consistent set of  
209 GWPs for halocarbon gases; we also provide tabulations of values for an alternative metric  
210 (the Global Temperature change Potential (GTP) – see section 4.2) for selected important  
211 gases.

212           In addition to their direct radiative effects, some halocarbons cause additional  
213 (indirect) effects on the climate system by influencing the abundance of other climatically-  
214 important gases – for example, stratospheric ozone, which is influenced by the CFCs and the  
215 halons. Such indirect effects are discussed elsewhere [e.g., *Daniel et al.*, 1995; *WMO*, 2011]  
216 and are not covered here.

217           Section 2 provides the necessary background concepts, section 3 presents the  
218 methodology we adopt to generate a consistent set of REs and lifetimes of the halocarbons,  
219 and related halogenated substances, including a discussion of the sensitivity of these  
220 parameters to uncertainties. Section 4 provides tabulations of the radiative efficiencies,  
221 lifetimes, GWPs and GTPs. Section 5 presents our conclusions.

222

## 223 **2 Background concepts**

224 The computation of GWPs and similar metrics for a particular gas requires various inputs and  
225 model calculations. The two basic input parameters for the GWP calculations are, as will be  
226 described in section 2.5, the RE and the lifetime of the gas. The calculation of these two  
227 parameters requires, in turn, much additional information. Figure 2 summarizes the main  
228 steps required which are discussed in more detail below.

### 229 **2.1 Molecular radiative properties**

230 The first stage in the determination of the RE is knowledge of the fundamental spectroscopic  
231 properties of a molecule. Here we are most concerned with its properties at thermal infrared  
232 (IR) wavelengths (i.e., wavelengths at which the Earth and its atmosphere emit significant  
233 amounts of infrared radiation) of roughly 4 to 200  $\mu\text{m}$  (2500 to 50  $\text{cm}^{-1}$ ). We will mostly work  
234 in terms of the frequency-like variable, wavenumber (the inverse of wavelength, normally  
235 quoted in  $\text{cm}^{-1}$ ). The emission of infrared radiation by the Earth and atmosphere and the  
236 radiative properties of the atmosphere are strong functions of wavenumber. Hence it is  
237 necessary to determine the spectroscopic properties of the target molecule as a function of  
238 wavenumber. A general introduction to atmospheric radiative transfer can be found in *Petty*  
239 [2006] and introductions to general molecular spectroscopy can be found in *Hollas* [2004]  
240 and *Atkins and Friedman* [2010]. Fundamentally, the molecules of interest here absorb and  
241 emit radiation by transitions between their vibrational-rotational energy levels. The  
242 characteristic wavenumber of absorption is determined by the spacing of the vibrational  
243 energy levels, with the transitions between particular vibrational-rotational energy levels  
244 leading to that absorption being spread by typically 50  $\text{cm}^{-1}$  around this characteristic  
245 wavenumber. For example, one of the simplest molecules,  $\text{CF}_4$  absorbs over a narrow range  
246 of wavenumbers near 1300  $\text{cm}^{-1}$  which is associated with the stretching of the carbon-fluorine  
247 bonds in the molecule. Molecules containing the carbon-chlorine bond absorb  
248 characteristically around 800  $\text{cm}^{-1}$ . The more complex the structure of the molecule, the  
249 greater the number of possible modes of vibrations (including different stretching and bending  
250 modes) and hence the more complex the infrared absorption spectrum becomes. Figure 3  
251 shows IR spectra of representative halocarbons and illustrates the increased number of IR  
252 absorption bands observed with larger, more complex and less symmetric molecules.

253 In principle, it would be desirable to characterize the strength of each discrete  
254 vibrational-rotational transition, and indeed this is necessary for some atmospheric  
255 greenhouse gases such as water vapor and carbon dioxide, where the absorption spectrum  
256 consists of many sharp individual spectral lines with rapid variations of absorption with  
257 wavenumber. However, for halocarbons the individual transitions are so close together (as a  
258 result of the large masses of the atoms), and sufficiently broad, that under atmospheric  
259 conditions the individual transitions merge together leading to a spectrum that consists of  
260 broad absorption bands (see Figure 3). The spectrally-resolved absorption cross-sections  
261 (units of  $\text{cm}^2 \text{ molecule}^{-1}$  with typical peak cross-sections of order  $10^{-18}$ - $10^{-17} \text{ cm}^2 \text{ molecule}^{-1}$   
262 for the molecules considered here) can be integrated over infrared wavenumbers to give the  
263 *integrated cross-section* (typical values for halocarbons are of the order of  $10^{-16} \text{ cm}^2$   
264  $\text{ molecule}^{-1} \text{ cm}^{-1}$ ). The integrated cross-section gives a useful measure of the overall strength  
265 of IR absorption but the variation of absorption with wavenumber (i.e., the absorption  
266 spectrum) must be known for calculation of the potential climate impact [e.g., *Pinnock et al.*,  
267 1995; *Wallington et al.*, 2010].

268 The most common way for determining the absorption cross-sections of halocarbons is  
269 via laboratory measurements using Fourier Transform Infrared Spectrometry. Measurements  
270 are made at typically  $0.5 \text{ cm}^{-1}$  or better spectral resolution. In general, the absorption cross-  
271 sections for halocarbons are only rather weakly dependent on temperature and pressure over  
272 the atmospherically relevant range and this dependence is generally neglected in RE  
273 calculations and likely uncertainties are about  $\pm 5\%$  [*Highwood and Shine*, 2000]. The  
274 absorption cross-section measurements are typically assessed to have an accuracy of  
275 approximately  $\pm 5\%$  [e.g., *Ballard et al.*, 2000b; *Clerbaux et al.*, 1993; *Pinnock et al.*, 1995].

276 More recently, absorption cross-sections have begun to be determined by quantum  
277 mechanical electron structure calculations (we will refer to these as *ab initio* methods), which  
278 in principle only rely on the basic laws of nature. In practice, however, *ab initio* calculations  
279 involve approximations to solving the Schrödinger equation and residual errors remain [e.g.,  
280 *Blowers et al.*, 2007; *Bravo et al.*, 2010b; *Papasavva et al.*, 1997]. The *ab initio* methods  
281 show considerable promise, but it has been found that they need empirical corrections  
282 (particularly for the wavenumbers of the main vibrational modes) to agree with laboratory  
283 measurements. In addition, their capabilities have not been assessed for the full range of  
284 molecules considered here. Nevertheless they have already proven to be useful adjuncts to

285 laboratory measurements and can provide data at wavenumbers that are difficult to study in  
286 the laboratory and allow rapid surveying of a broad range of compounds for which laboratory  
287 samples may not be easy to procure.

## 288 **2.2 Radiative forcing and radiative efficiency - concepts**

289 Once the absorption cross-sections have been obtained, the next step is to compute the impact  
290 that the addition of a particular halocarbon to the atmosphere has on the radiation budget. The  
291 resulting change in the radiation budget is generally referred to as “radiative forcing” (RF),  
292 but there are a number of nuances to the definition of RF that need to be elaborated on. Also,  
293 in general, radiative forcing (in units of  $\text{W m}^{-2}$ ) refers to the effect of a specified change in the  
294 concentration of a species, often over some given time period. In this review, we focus on the  
295 radiative forcing per unit change in halocarbon mixing ratio – this is referred to as *radiative*  
296 *efficiency* (RE) ( $\text{W m}^{-2} \text{ppb}^{-1}$ ). RE assumes that the RF is linear in mixing ratio – this is  
297 normally appropriate in the case of small perturbations in mixing ratio about current  
298 concentrations and is also appropriate for gases, such as the ones we consider here, which  
299 have low background concentrations.

300 IPCC Assessment Reports [e.g., *Forster et al.*, 2007] have addressed the rationale for  
301 using RF, outlined caveats in its use, and also defined possible alternative definitions of RF  
302 [see also discussions in e.g., *Fuglestedt et al.*, 2010; *Hansen et al.*, 2005]. Studies using  
303 climate models indicate that there is a direct relationship between global-averaged RF and the  
304 (equilibrium) global-mean surface temperature change, and so RF has been essentially used as  
305 a proxy for surface temperature change. RF is normally defined at the tropopause including  
306 stratospheric temperature adjustment [*Forster et al.*, 2007], the rationale being that the tight  
307 coupling between the surface and troposphere means that they behave as a single  
308 thermodynamic system; hence it is the change in the input of energy into this system that  
309 drives the climate change.

310 Instantaneous RF [e.g., *Forster et al.*, 2007] is defined as the change in net irradiance  
311 at the tropopause, following (for example) a change in a greenhouse gas concentration. Earlier  
312 studies indicated that the instantaneous RF had less utility (i.e., models indicated a less close  
313 relationship between it and the resulting surface temperature change) than RF with  
314 stratospheric temperature adjustment. Part of the rationale for this is that, following a  
315 perturbation, the response time of the stratosphere is fast (around a few months) compared to

316 the decadal time scale for the temperature of the surface-troposphere system to respond. It is  
317 found that for a number of forcings, the RF including stratospheric temperature adjustment  
318 has a closer relationship with modeled surface temperature change, than the instantaneous RF.  
319 For this definition of forcing, stratospheric temperatures are assumed to adjust in response to  
320 the change in greenhouse gas concentration – this change in temperature leads to a further  
321 change in the irradiance, as the downward emission by the stratosphere to the troposphere is  
322 dependent on this temperature. Some gases (notably CO<sub>2</sub>) lead to a cooling of the stratosphere  
323 which makes the stratospheric-adjusted forcing less than the instantaneous forcing. For others  
324 (including many halocarbons) the reverse is true, as the stratosphere warms – see section 3.3.2  
325 for further discussion.

326         Early studies [*Jain et al.*, 2000; *Myhre and Stordal*, 1997; *Naik et al.*, 2000; *Pinnock et*  
327 *al.*, 1995] quantified the difference between the instantaneous and stratospheric-adjusted RF  
328 for a range of halocarbons, indicating that the instantaneous forcing is typically 5-10% lower  
329 than the stratospheric-adjusted RF. One drawback with the stratospheric-adjusted RF is that  
330 its calculation is computationally much more demanding; in this review, because of the large  
331 number of gases involved, we calculated instantaneous RE and then applied a correction,  
332 based on the available literature, to account for the effect of stratospheric adjustment (see  
333 section 3.3.2).

334         More recently, there has been much work investigating alternative definitions of  
335 forcing [e.g., *Andrews and Forster*, 2008; *Forster et al.*, 1997; *Gregory et al.*, 2004; *Hansen*  
336 *et al.*, 2005] – for example, fixing surface temperatures (sometimes sea-surface temperature  
337 only) but allowing tropospheric temperatures, humidity and cloudiness to adjust, in addition  
338 to the stratosphere. The rationale here is that there are so-called “fast feedbacks” or “rapid  
339 adjustments” operating in the troposphere that can change, for example, cloudiness in the  
340 absence of surface temperature change. Hence it is conceptually attractive to separate climate  
341 responses that operate on day-to-month timescales and are independent of changes in surface  
342 temperature from the “traditional” climate feedbacks (for example, water vapor feedback, ice  
343 albedo feedback and various cloud feedbacks) which are mediated by surface temperature  
344 change and hence act on decadal to century timescales.

345         These rapid tropospheric adjustments can be particularly important for other forcings,  
346 such as those resulting from black carbon aerosols. Few model results are available on the  
347 effect of tropospheric adjustments for the gases considered here. Computation of such

348 forcings requires long simulations using sophisticated climate models, and results would  
349 likely depend significantly on the climate model chosen. In addition, because of the inherent  
350 “unforced” natural variability in such climate models, it would be necessary to impose a large  
351 forcing (in excess of  $1 \text{ W m}^{-2}$ ) to easily extract a reliable signal from the model; this is many  
352 times the present-day RF of the most abundant CFC (CFC-12 – about  $0.17 \text{ W m}^{-2}$  [Forster *et*  
353 *al.*, 2007]) and orders of magnitude more than most other gases considered here, raising  
354 concerns about the linearity of the rapid tropospheric adjustments. Since research on these  
355 more advanced definitions of forcing is still at an early stage, and also because of the  
356 computational demands of performing these calculations, we believe it premature to adopt  
357 them here as a framework.

358         An additional and related issue concerns the so-called climate efficacy. An underlying  
359 assumption in early work in this area was that the global-mean surface temperature response  
360 to an RF of, say,  $1 \text{ W m}^{-2}$ , was the same irrespective of the cause of the forcing. Climate  
361 model simulations now indicate that this assumption is not strictly justified. *Efficacy* is a  
362 measure of the ability (per  $\text{W m}^{-2}$ ) of a particular forcing to change surface temperature  
363 relative to, for example, a  $1 \text{ W m}^{-2}$  forcing due to a change in carbon dioxide. Relatively little  
364 research has been performed on the efficacy of the halocarbons. Forster and Joshi [2005]  
365 found an efficacy of CFC-12 (using the stratosphere adjusted forcing) to be 0.94 in their  
366 model. Hansen *et al.* [2005], by contrast, found an equivalent value (for a combination of  
367 CFC-11 and CFC-12) of 1.3, but also demonstrated that the efficacy depends on the definition  
368 of forcing that is adopted. An additional issue for the short-lived halocarbons, is that the  
369 efficacy likely depends on the spatial distribution of the halocarbon [Joshi *et al.*, 2003] which  
370 in turn depends on the halocarbon’s lifetime (see section 2.4) and the distribution of  
371 emissions. Given these uncertainties, we assume an efficacy of 1 throughout this review,  
372 although it is in principle possible to include non-unity values of efficacy within the GWP and  
373 GTP metrics.

### 374 **2.3 Calculation of radiative efficiency**

375 The calculation of radiative efficiency requires, in addition to the absorption spectrum for the  
376 halocarbon in question, a calculation of atmospheric irradiances, accounting for atmospheric  
377 properties, such as the amounts, distributions and radiative properties of other infrared-  
378 absorbing components (water vapor, carbon dioxide, ozone, clouds, etc.), and temperatures.  
379 As the RE is a globally- and annually-averaged quantity, in principle it should be calculated

380 locally and, say, monthly, and then averaged to produce the global and annual mean. In  
381 practice, it is possible, with about 5-10% accuracy, to calculate the RE using a globally-  
382 averaged atmospheric profile or using two or three profiles representative of the tropics and  
383 mid/high latitudes [Freckleton *et al.*, 1998; Myhre and Stordal, 1997]. Myhre *et al.* [2006]  
384 found that for calculations of the CFC-12 RE, the use of two atmospheric profiles (one for  
385 tropics and one extra-tropics) represents global simulations with a horizontal resolution of  
386  $2.5^\circ \times 2.5^\circ$  within 1%. In addition, there are several possible choices of tropopause definition  
387 that impact on the calculated forcing at the 5% level [Freckleton *et al.*, 1998].

388 The radiative transfer models that can be used for such calculations vary in  
389 complexity. The most complex (line-by-line (LBL) models) perform calculations at high  
390 (typically  $0.01 \text{ cm}^{-1}$ ) spectral resolution and resolve explicitly the individual spectral lines of  
391 atmospheric gases such as water vapor, carbon dioxide and ozone. These are computationally  
392 expensive and parameterized models are often used (for example to compute the effect of  
393 stratospheric adjustment). Narrow Band Models resolve the infrared spectrum at typically 10  
394  $\text{cm}^{-1}$  resolution, while computationally-fast Wide Band Models (suitable for use in climate  
395 models) may resolve the thermal infrared region into typically 5 to 10 spectral intervals.  
396 Intercomparisons of such models both for greenhouse gases in general [e.g., Collins *et al.*,  
397 2006; Oreopoulos *et al.*, 2012] and for halocarbons in particular [e.g., Forster *et al.*, 2005;  
398 Gohar *et al.*, 2004; Jain *et al.*, 2000] are of importance in assessing the capabilities of the  
399 parameterized models. When these models are combined with vertical profiles of temperature,  
400 cloudiness and greenhouse gas concentrations, it is necessary to ensure that the model's  
401 global-and-annual outgoing longwave radiation, and the impact of clouds on the outgoing  
402 longwave budget, are in reasonable agreement with satellite observations; otherwise, biases in  
403 the resulting RE calculations can occur.

404 In addition to the direct use of radiative transfer models to calculate REs, it is possible  
405 to use these models to produce simple techniques to compute the radiative forcing directly  
406 from the absorption cross-sections. Pinnock *et al.* [1995] used a narrow-band model to  
407 compute the RE per unit absorption cross-section as a function of wavenumber, using a global  
408 and annual mean atmosphere. This then indicates the spectral regions at which halocarbon  
409 radiative forcing is most effective. As shown in Figure 5 and discussed in section 3.3.1, where  
410 an update to the Pinnock *et al.* [1995] method is presented, molecules are most effective if  
411 they absorb in the  $800\text{-}1200 \text{ cm}^{-1}$  spectral region (a so-called "atmospheric window"), but can



412 remain effective outside this region. If a halogenated compound absorbs at a wavelength  
413 where there is already substantial atmospheric absorption (for example by carbon dioxide near  
414  $670\text{ cm}^{-1}$ ) then the additional absorption by this compound will not contribute significantly to  
415 radiative forcing.

416 Hence, if the spectrally-varying radiative forcings calculated by *Pinnock et al.* [1995]  
417 are multiplied by the absorption cross-sections representing a real halocarbon (averaged to the  
418 same spectral resolution as the radiation calculations) then an estimate of the RE can be  
419 achieved easily by summing over all wavenumbers, using a spreadsheet for example, without  
420 the need for a complex radiation code. *Pinnock et al.* [1995] demonstrated for a wide range of  
421 halocarbons that this simple technique could generate instantaneous REs that were accurate to  
422 within 0.3%, relative to full calculations using the same radiation code that was used to  
423 generate the values in the simple technique, and using the same atmospheric profile. (It is  
424 emphasized that this is not the technique's absolute accuracy, as this is dependent on the  
425 accuracy of the radiation code and its input parameters). Consequently, the method developed  
426 by *Pinnock et al.* is simple and effective, and has been widely used.

427 A further consideration in calculating the RE is that the horizontal and vertical  
428 distribution of the molecule must be specified – often the baseline assumption is that the  
429 molecule is well-mixed within the atmosphere (both horizontally and vertically); corrections  
430 to approximately account for the departure from this assumption are then applied – see section  
431 2.4 and 3.3.4. However, it should be noted that for short-lived gases in particular, there is no  
432 unique value of RE, as its value depends to some extent on the geographical (and seasonal)  
433 distribution of emissions, as these in turn influence the horizontal and vertical distribution of  
434 the gas.

## 435 **2.4 Atmospheric lifetimes**

436 The global atmospheric lifetime (yr) of a gas is defined in the IPCC Third Assessment Report  
437 [IPCC, 2001] as “the burden (Tg) divided by the mean global sink (Tg/yr) for a gas in steady  
438 state (i.e., with unchanging burden).” The report also identifies two important consequences  
439 of this definition, namely that: (i) “when in steady state (i.e., source strength = sink strength)  
440 the atmospheric burden of a gas equals the product of its lifetime and its emissions”; and (ii)  
441 “the integrated atmospheric abundance following a single emission is equal to the product of  
442 the steady-state lifetime for that emission pattern and the amount emitted [*Prather, 1996*]”.

443 As will be discussed in section 2.5, the most frequently used climate metrics consider the  
444 impact of a pulse emission of a gas.

445 The global atmospheric lifetime has also been referred to as simply as “lifetime”, or  
446 ”turnover time” [*Bolin and Rodhe, 1973; IPCC, 1995*] reflecting the fact that it characterizes  
447 the time required to turn over the global atmospheric burden of the gas in question. It is  
448 sometimes thought of as the decay time (e-fold) following a perturbation, with its magnitude  
449 determined by chemical or photolytic loss rates. While conceptually appealing, this approach  
450 applies rigorously only for a gas whose local chemical lifetime is constant in space and time,  
451 such as for the noble gas radon, whose lifetime is fixed by the rate of its radioactive decay  
452 [*IPCC, 2001*]. In reality the chemical losses of pollutants vary in time and space and, if the  
453 magnitude of emissions are sufficient (e.g., for methane), the emissions themselves can  
454 influence the chemistry of the atmosphere and hence the pollutant’s lifetime. As discussed in  
455 sections 3.3.3 and 3.3.4, many halocarbons have short lifetimes, are not well mixed in the  
456 atmosphere, and the spatial and temporal emission pattern needs to be accounted for in  
457 assessments of their radiative efficiencies.

458 Halocarbons are removed from the atmosphere by two main mechanisms; reaction  
459 with OH radicals and photolysis. As a crude guide to understanding how the molecular  
460 structure of a halocarbon affects its reactivity towards OH radicals, for a given carbon  
461 backbone (e.g., C<sub>2</sub>, C<sub>3</sub>, n-C<sub>4</sub>, etc.) the more fluorine atoms in a haloalkane the longer its  
462 lifetime and the more bromine or iodine atoms the shorter its lifetime. For molecules  
463 containing hydrogen such as HCFCs, HFCs, HFEs and hydrochlorocarbons, the primary  
464 removal mechanism in the troposphere is reaction with the hydroxyl radical OH. Lifetimes  
465 range from a few days to millennia, depending on the structure of the molecule – to first  
466 order, the more heavily halogenated a molecule, the longer its lifetime, although the precise  
467 arrangement and nature of those halogens in the molecule plays an important role [*Atkinson et*  
468 *al., 2008; Sander et al., 2010*]. Unsaturated molecules containing >C=C< double bonds react  
469 rapidly with OH radicals. Including one, or more >C=C< double bond is a particularly  
470 effective method of reducing the atmospheric lifetime of halocarbons. For example,  
471 CF<sub>3</sub>CF<sub>2</sub>CH<sub>3</sub> (HFC-245cb) has a lifetime of 47.1 years while CF<sub>3</sub>CF=CH<sub>2</sub> (HFC-1234yf) has a  
472 lifetime of 10.5 days.

473 For CFCs and halons, the primary destruction mechanism is ultraviolet photolysis in  
474 the stratosphere. CFCs are inert in the troposphere as sufficiently short wavelength ultra-

475 violet radiation does not penetrate in to the troposphere. Indeed, it is their chemical inertness  
476 that made the CFCs so attractive in industrial and domestic usages. It is interesting and worth  
477 noting that when detection of CFCs in the atmosphere was first reported, the conclusion  
478 included the comment “The presence of these compounds [CFC-11 and CFC-12] constitutes  
479 no conceivable hazard” [Lovelock and Maggs, 1973]. Halons have atmospheric lifetimes in  
480 the approximate range of 10 to 70 years, while CFCs have atmospheric lifetimes ranging from  
481 about 45 to more than a thousand years. Calvert *et al.* [2008] have reviewed the mechanisms  
482 in the atmospheric photolysis of haloalkanes. Absorption at ultra-violet wavelengths involves  
483 an  $n \rightarrow \sigma^*$  transition with a non-bonding electron of the halogen promoted into an anti-  
484 bonding sigma orbital of the C-X bond. Ultra-violet absorption spectra for haloalkanes (RX)  
485 of similar carbon backbone structure move to lower energy (longer wavelength absorption)  
486 along the series X = F, Cl, Br, to I, reflecting a trend of lower electron affinity of the halogen  
487 atom [Calvert *et al.*, 2008]. Absorption by C-F and C-Cl bonds only occurs at wavelengths  
488 below approximately 240 nm. CFCs, HFCs, HCFCs, chlorocarbons, and hydrochlorocarbons  
489 do not photolyze in the troposphere as sufficiently short wavelength ultra-violet radiation does  
490 not reach the troposphere. In contrast to C-F and C-Cl bonds, C-I bonds absorb strongly at  
491 tropospheric relevant wavelengths and iodine-containing haloalkanes have atmospheric  
492 lifetime of days, or less, with respect to photolysis in the troposphere (e.g., 4.9 days for CH<sub>3</sub>I,  
493 4.3 days for C<sub>2</sub>H<sub>5</sub>I, 4.9 hours for CH<sub>2</sub>ICl, and 4.9 minutes for CH<sub>2</sub>I<sub>2</sub> [Calvert *et al.*, 2008]).  
494 Absorption by C-Br bonds at tropospheric relevant wavelengths is generally weak but  
495 photolysis can contribute to determining the atmospheric lifetime of some bromoalkanes such  
496 as CHBr<sub>3</sub> [Calvert *et al.*, 2008]. Because of the inherent strength of the C-F bond, the PFCs  
497 are chemically inert and, are the longest lived of the halocarbons, with lifetimes ranging from  
498 about a thousand years to approximately 50,000 years for CF<sub>4</sub>.

499 The atmospheric lifetime plays a further role in the determination of the radiative  
500 efficiency, because it helps determine the degree of heterogeneity in the distribution of the  
501 halogenated molecules in the atmosphere. For molecules with lifetimes of less than a few  
502 months, the atmospheric distribution is dependent on where and when the gases are emitted,  
503 reflecting the spatial and temporal distribution of OH radicals which determines the local  
504 atmospheric lifetimes. Since the radiative efficiency of a gas depends on its location (in  
505 general, a gas at low latitudes is more effective, as more radiative energy is available to be  
506 absorbed at high temperatures), a unique radiative efficiency cannot be defined for such short-  
507 lived molecules without a detailed knowledge of the spatial and temporal emission pattern. In

508 addition, the vertical profile of a gas is also influenced by the atmospheric lifetime. Mixing  
509 processes are most efficient within the troposphere with molecules mixed vertically on the  
510 typical timescales of days to weeks. Within the stratosphere the vertical profile of a particular  
511 species depends strongly on the relationship between the timescales for transport within the  
512 stratosphere and the rate at which the molecule is destroyed. *Jain et al.* [2000] and *Naik et al.*  
513 [2000] [see also *Freckleton et al.*, 1998] used chemical transport models to simulate the  
514 distributions of a range of halocarbons, and quantify the difference in the RE between using  
515 these distributions and the assumption that the gases are well mixed. Their results were used  
516 by *Sihra et al.* [2001] to develop a simplistic method to approximately account for the effect  
517 of atmospheric lifetime on the radiative efficiency. This will be further discussed in section  
518 3.3.4. (A non-constant atmospheric profile of a species can also result when the rates of  
519 surface emissions are growing rapidly, because of the multi-year timescale for the molecule to  
520 reach deep into the stratosphere.)

521 The products of the reactions that destroy halocarbons could in principle themselves  
522 be climatically-important gases. However, it is well established that the atmospheric  
523 degradation of halocarbons gives oxygenated compounds which have relatively short  
524 atmospheric lifetimes and are typically removed by wet and dry deposition on a time scale of  
525 days or weeks [*Wallington et al.*, 1994b]. The oxidation products do not accumulate in the  
526 atmosphere and do not contribute significantly to radiative forcing of climate change.

## 527 **2.5 Climate impact metrics**

528 A key objective of this review is to provide values for the GWP and GTP metrics for the  
529 halocarbons. The rationale and challenges in developing climate impact metrics have been  
530 reviewed in detail by *Fuglestedt et al.* [2010] and so only a relatively brief discussion is  
531 given here.

532 One of the prime drivers of the development of emission metrics is the need for their  
533 use in multi-gas climate policies (such as the Kyoto Protocol) where emissions of different  
534 compounds must be placed on a common scale, usually referred to as a “CO<sub>2</sub>-equivalent”  
535 scale. There is no unique method of doing this, and the choice of method should be consistent  
536 with the climate policy that the metric aims to serve [e.g., *Plattner et al.*, 2009]. The Kyoto  
537 Protocol’s choice of the GWP(100) has been a matter of much discussion and debate [e.g.,  
538 *Fuglestedt et al.*, 2003; *Manne and Richels*, 2001; *O’Neill*, 2000; *Shine*, 2009]. One often

539 cited reason for its original use and retention has been the lack of a widely-accepted  
540 alternative, and, latterly, the difficulties that might arise within policymaking if the metric  
541 (more specifically, the numerical value that converts a given emission to a CO<sub>2</sub>-equivalent  
542 emission) was substantially changed.

543         There are a number of elements that have to be considered in metric design. What kind  
544 of emission is considered - for example, a pulse or a sustained emission? What “impact” is  
545 considered – for example, radiative forcing, surface temperature change, sea-level rise,  
546 economic impact, or the rate of change of these quantities? Which indirect effects and  
547 feedbacks should be included? Is the impact considered integrated over some time period, or  
548 at one particular time? Is the impact given as global mean or with a regional resolution? What  
549 time period is considered? And, of significance to their wider acceptability, particularly  
550 within the policymaking community, how transparent are the formulations of the metrics?

551         Here we present results for two metrics. The GWP (with time horizons of 20, 100 and  
552 500 years) is presented to be consistent with reporting in previous IPCC assessments and its  
553 wide usage. The GWP definition we use here is as used in the first IPCC Assessment Report  
554 [IPCC, 1990] which itself was based on then-recent studies suggesting ways of  
555 intercomparing the climate effect of emissions of different gases [Derwent, 1990; Fisher *et*  
556 *al.*, 1990; Lashof and Ahuja, 1990; Wuebbles, 1989]. The GWP represents the time-integrated  
557 radiative forcing due to a pulse emission of a gas. It can be presented as the absolute GWP  
558 (AGWP – with units of, for example, W m<sup>-2</sup> kg<sup>-1</sup> year) or, more normally, as a ratio to the  
559 AGWP of CO<sub>2</sub>. One difficulty is that the AGWP of CO<sub>2</sub> has been subject to periodic revision  
560 in IPCC assessments, as a result of atmospheric changes (the RE of CO<sub>2</sub> decreases as CO<sub>2</sub>  
561 concentrations increase) and changes in understanding of how long CO<sub>2</sub> concentrations  
562 remain perturbed following a pulse emission. Hence the GWP of a halocarbon may change  
563 solely because of a change in AGWP of CO<sub>2</sub> rather than revisions to its own lifetime and  
564 radiative efficiency, as happened, for example, in the IPCC Third Assessment Report IPCC  
565 [2001]. The precise method used here to determine the AGWPs, and hence the GWPs, will be  
566 presented in section 3.5.

567         The GTP [Shine *et al.*, 2005a] is also chosen for presentation here, partly because it  
568 has attracted more attention than other alternative metrics, including at the policymaking level  
569 [e.g., Plattner *et al.*, 2009] and partly because it has a quite different basis from, and hence  
570 provides an alternative perspective to, the GWP. The GTP represents the temperature change

571 due to a pulse emission of a gas, at some time (here 20, 50 and 100 years are chosen) in the  
572 future. Hence it is an “end-point” metric (unlike the GWP, which is a time-integrated metric)  
573 and hence retains less of a memory of the effect of emissions of short-lived species. It has  
574 been suggested that the GTP may be more suitable for target-based climate policies [e.g.,  
575 *Shine et al.*, 2007], such as envisaged under the Copenhagen Accord of the UNFCCC, where  
576 the aim is to keep surface temperature change, relative to pre-industrial times, below 2  
577 degrees C. The GTP method requires, in addition to the lifetime and radiative efficiency,  
578 some model to represent the response of global-mean surface temperature to radiative forcing,  
579 and hence requires the specification of additional parameters compared to the GWP. As with  
580 the GWP it can be presented as an absolute quantity (with units of, for example,  $\text{K kg}^{-1}$ ) or as  
581 a ratio to the absolute Global Temperature change Potential (i.e., AGTP) of  $\text{CO}_2$ .

582 Since *Fuglestvedt et al.* [2010], there has been a significant literature on climate  
583 emission metrics including discussions of how these “physical” metrics relate to metrics  
584 which incorporate, additionally, an economics element [e.g., *Boucher*, 2012; *Johansson*,  
585 2012; *Tol et al.*, 2012], the relationship amongst metrics (for example, *Peters et al.* [2011]  
586 discuss the similarities of the GWP with a time-integrated GTP) and evaluations of the  
587 sensitivities of GWPs and GTPs to uncertainties in input parameters and background  
588 scenarios [e.g., *Reisinger et al.*, 2011; *Reisinger et al.*, 2010].

589

### 590 **3 Data and method**

#### 591 **3.1 Absorption cross-sections**

##### 592 **3.1.1 Laboratory measurements of infrared absorption cross-sections**

593 Analytical infrared instrumentation usually only covers the mid-infrared region, 4000-400  
594  $\text{cm}^{-1}$ , and the majority of available IR absorption spectra — including most of the spectra  
595 covered in this review — were measured within this wavenumber range. As will be shown in  
596 detail in section 3.3.1, the effectiveness of the absorption in contributing to RE varies strongly  
597 with wavenumber, peaking at 300-600 and 750-1000  $\text{cm}^{-1}$ , significant at 1100-1300  $\text{cm}^{-1}$ , and  
598 of minor importance for wavenumbers above 1500  $\text{cm}^{-1}$  [*Pinnock et al.*, 1995].

599 Infrared spectra are measured in transmittance, which is defined as the ratio of spectral  
600 intensity transmitted through the sample at a given wavenumber  $\tilde{\nu}$ ,  $I_{\text{tr}}(\tilde{\nu})$ , to the incoming

601 spectral intensity,  $I_0(\tilde{\nu})$ . Transmittance is related to the wavenumber and temperature  
 602 dependent absorption cross section,  $\sigma(\tilde{\nu}, T)$ , through the Beer-Lambert-Bouguer law:

$$603 \quad \frac{I_{tr}(\tilde{\nu})}{I_0(\tilde{\nu})} = e^{-S(\tilde{\nu}, T)nl}$$

604 where  $n$  is the molecule concentration (molecule  $\text{cm}^{-3}$ ), and  $l$  is the sample optical path length  
 605 (cm). The absorption cross section ( $\text{cm}^2 \text{ molecule}^{-1}$ ) is then given by:

$$606 \quad S(\tilde{\nu}, T) = \frac{1}{n \times l} \times \ln \left[ \frac{I_0(\tilde{\nu})}{I_{tr}(\tilde{\nu})} \right] = \frac{\ln(10)}{n \times l} \times \lg \left[ \frac{I_0(\tilde{\nu})}{I_{tr}(\tilde{\nu})} \right]$$

607 where  $\ln$  is the napierian logarithm and  $\lg$  is the common decadic logarithm.

608 The strength of an absorption band is given by the integral:

$$609 \quad S(\tilde{\nu}_1, \tilde{\nu}_2, T) = \int_{\tilde{\nu}_1}^{\tilde{\nu}_2} S(\tilde{\nu}, T) \times d\tilde{\nu}$$

610 where  $S(\tilde{\nu}_1, \tilde{\nu}_2, T)$  is the integrated absorption intensity (in units of  $\text{cm}^2 \text{ molecule}^{-1} \text{ cm}^{-1}$ ) over  
 611 the wavenumber range  $\tilde{\nu}_1$  to  $\tilde{\nu}_2$ .

612 The absorption cross section depends on temperature for several reasons. First,  
 613 infrared absorption occurs from a range of rotational energy levels, and the relative  
 614 populations of these levels are strongly temperature dependent. Secondly, and particularly for  
 615 molecules containing heavier atoms and in bending vibrations, absorption will not only occur  
 616 from the vibrational ground state but also from vibrationally excited states – so called *hot*  
 617 bands. Since populations depend on the temperature, so will the measured net absorption.  
 618 Further, molecules often have several stable conformations with different energies and  
 619 slightly different infrared spectra. The conformational equilibrium and, consequently, the  
 620 absorption spectrum of such molecules will therefore vary with temperature. While the  
 621 infrared absorption bands of halocarbons narrow with decreasing temperature there is no  
 622 significant change in the integrated infrared absorption over the atmospherically relevant  
 623 range [Ballard et al., 2000b; Le Bris et al., 2011; Orlando et al., 1992]. Changes in  
 624 temperature over the atmospherically relevant range result in narrowing of the absorption  
 625 bands by a few  $\text{cm}^{-1}$  [Orlando et al., 1992]. The error that results from the use of a single  
 626 infrared spectrum measured at, or near, room temperature to calculate the RE of a molecule in  
 627 the whole atmosphere is comparable to, or smaller than, the uncertainties in a single

628 measurement [Ballard *et al.*, 2000b] and so the temperature dependence is often ignored in  
629 RE calculations.

630

### 631 3.1.2 Theoretical calculations of infrared absorption cross sections

632 Theoretical calculations can be used to provide estimates of infrared vibrational band  
633 positions and the intensity of the transitions. The theory underpinning such calculations and  
634 their computational intricacies lie outside the scope of this review, but an introduction to the  
635 background can be found in *Atkins and Friedman* [2010]. Despite the complexities of the  
636 calculational methods, modern software packages are such that the non-specialist can use  
637 them and take advantage of the insights that theoretical calculations offer. Calculations are  
638 carried out using a combination of a calculational method and a basis set. Researchers have  
639 used traditional molecular orbital *ab initio* calculations using the 2nd-order Møller-Plesset  
640 (MP2) perturbation method, and more recently, the Density Functional Theory (DFT) method.  
641 The DFT method is becoming increasingly common, as it provides comparable accuracy to  
642 MP2, but at a considerably reduced computational cost. A commonly used DFT method is the  
643 Becke, 3-parameter, Lee-Yang-Parr method, commonly known as B3LYP. The basis sets  
644 used in modern calculations are comprised of Gaussian-type orbitals, which have  
645 characteristics similar to s-, p-, d-, etc. hydrogenic atomic orbitals. Basis sets are described  
646 with specific notation; common examples are, in order of increasing basis set size, 6-31G, 6-  
647 31G\* and 6-31G\*\*. A calculation might be described as B3LYP/6-31G\*\*, which would mean  
648 that the calculation had been carried out using the B3LYP method combined with the 6-  
649 31G\*\* basis set. There is always a tension between achieving the most accurate description of  
650 a molecule — which requires a large basis set — and the need to reduce the computational  
651 cost of the calculation — which requires a small basis set.

652 In principle, calculations should be carried out for all possible conformers of a  
653 compound, with the final spectrum being a weighted sum of the spectra of the individual  
654 conformers. The contribution of each conformer to the overall spectrum is determined by its  
655 relative population, which is calculated using the Boltzmann distribution. *Bravo et al.* [2010b]  
656 have tested the importance of including the contribution of conformers to the overall spectrum  
657 for *n*-C<sub>4</sub>F<sub>10</sub>. They concluded that the change to the RE of including the higher energy



658 conformers was less than 1%; most calculations use the lowest energy conformer to generate  
659 the spectrum used for RE calculations.

660 Theoretical calculations are subject to quite significant errors, with contributions  
661 arising from the method used and the limited size of the basis set. Fortunately, the outputs  
662 from the calculations generally provide an estimate of the positions of vibrational bands that  
663 differ in a systematic way from the experimentally observed band positions [*Scott and*  
664 *Radom*, 1996]. The extent to which these differences have a significant impact on radiative  
665 forcing efficiency calculations depends on the region of the spectrum where the transitions  
666 occur. For example, compounds containing C-F bonds have strong absorptions at around 1250  
667  $\text{cm}^{-1}$ . In this region of the spectrum, the radiative efficiency function changes rapidly with  
668 wavenumber (see section 3.3.1) and so small errors in the band position can have a relatively  
669 large impact on calculated REs [*Bravo et al.*, 2010b]. Different researchers have dealt with the  
670 systematic errors in different ways; the errors are sometimes ignored [*Blowers and*  
671 *Hollingshead*, 2009], accounted for by using a generic correction formula [*Shine et al.*,  
672 2005b], or corrected using methods specific to the particular class of compounds under  
673 consideration [*Bravo et al.*, 2010b]. Integrated cross sections (over the appropriate  
674 wavenumber range) are generally in good agreement (within 5%) with those determined  
675 experimentally [*Bravo et al.*, 2010b].

676 The output from calculations differs from experimental measurements in that rather  
677 than providing an absorption cross section as a function of wavenumber, an integrated  
678 absorption cross section (IAC) is calculated for each vibrational band. Conversion to a cross  
679 section can be achieved simply by dividing by the appropriate wavenumber interval to get an  
680 average cross section over that interval; for example, *Pinnock et al.* [1995] calculate REs  
681 using a  $10 \text{ cm}^{-1}$  interval, so IACs are simply divided by  $10 \text{ cm}^{-1}$  to get the average cross  
682 section over this interval for use in their calculations [*Bravo et al.*, 2010b]. An alternative  
683 approach is to 'spread' some of the absorption into neighboring wavenumber intervals. *Bravo*  
684 *et al.* [2010b] showed that spreading 50% of absorption equally into regions above and below  
685 the central interval did not have a significant effect on calculated radiative forcing efficiencies  
686 for a number of PFCs using the Pinnock method. However, the impact is likely to be more  
687 significant if a narrower wavenumber interval is chosen for the calculations.

688 For comparison with experiment, the integrated absorption cross sections can be used  
689 to simulate spectra assuming the vibrational bands are Gaussian in shape. Figure 4 shows an

690 experimentally determined spectrum of  $n\text{-C}_4\text{F}_{10}$  from *Bravo et al.* [2010b] along with spectra  
691 calculated using the B3LYP and MP2 methods. The calculated spectra have been corrected  
692 for the systematic errors discussed earlier. The agreement between theory and experiment is  
693 very good, particularly for calculations carried out using the B3LYP method. The spectra  
694 generated in this way can also be used to calculate radiative forcing efficiencies in the normal  
695 way. Again, using the Pinnock method with a  $10\text{ cm}^{-1}$  interval, *Bravo et al.* [2010b] found that  
696 converting the IACs to spectra in this way had only a modest impact on the calculated RE.

697

### 698 3.1.3 Database and sources of cross-section data

699 The main sources of experimental infrared absorption cross-sections are Ford Motor  
700 Company [e.g., *Sihra et al.*, 2001], the SWAGG project (Spectroscopy and Warming  
701 potentials of Atmospheric Greenhouse Gases) [*Ballard et al.*, 2000c; *Highwood and Shine*,  
702 2000], and the two databases HITRAN-2008 (High Resolution Transmission) [*Rothman et al.*,  
703 2009] and GEISA-2009 (which is now referred to as GEISA-2011 on the GEISA website)  
704 (Gestion et Etude des Informations Spectroscopiques Atmosphériques) [*Jacquinet-Husson et*  
705 *al.*, 2011]. Theoretical absorption data from *ab initio* calculations [*Bravo et al.*, 2011a; *Bravo*  
706 *et al.*, 2010b] have also been included here.

707 The HITRAN-2008 database includes IR cross-sections of 31 different gases, many of  
708 which are measured at a range of temperatures and pressures. Updates since the previous  
709 edition, HITRAN-2004, have been described in detail in *Rothman et al.* [2009]. In GEISA-  
710 2009, IR spectra of 39 different gases are included, again for a wide range of temperatures  
711 and pressures. Some of the spectra in GEISA-2009 are from the same source as in HITRAN-  
712 2008, and when this is the case we disregard the spectrum from GEISA-2009 to avoid  
713 duplicates. *Jacquinet-Husson et al.* [2011] describes the GEISA-2009 database and the  
714 updates that have taken place since the 2003 edition.

715 The absorption cross-sections available in the literature have been summarized (Tables  
716 2, 4, 6, 8, 10, 12 and 14) and the spectra which have been used in the calculation of new best  
717 estimate REs are highlighted. Each available spectrum has been evaluated and if several  
718 cross-sections exist from the same laboratory group, only the latest published spectrum has  
719 been used in our calculations. In particular, spectra from *Sihra et al.* [2001] supersede those  
720 from *Pinnock et al.* [1995] and *Christidis et al.* [1997] since the methodology of the Ford

721 laboratory measurements improved over time. Furthermore, cross-sections from laboratory  
722 measurements are favored over theoretical calculations, but the latter have been used if  
723 experimental spectra are not available for a compound and when significant differences in  
724 experimental data exist. The spectrum that was recorded nearest room temperature and  
725 atmospheric pressure was used when more than one spectrum was available from a source, as  
726 described further in section 3.6.1. The format of theoretical *ab initio* data differ from  
727 experimentally measured infrared spectra; theoretical data consist of values of the central  
728 wavenumber and the strength at the vibrational band center. To calculate the radiative  
729 efficiencies from these data, they were spread to the  $1\text{ cm}^{-1}$  bin size of our spectrally-varying  
730 radiative efficiency data (see section 3.3.1). All the cross-sections used in this study have  
731 been converted to the same format as in HITRAN (more information about this format can be  
732 obtained at the HITRAN web site at <http://www.cfa.harvard.edu/hitran>), and many of the  
733 cross-sections are available in the supplementary material.

734

### 735 **3.2 Atmospheric lifetimes**

736 The processes that remove halocarbons from the atmosphere have been described recently  
737 [WMO, 2011]; this publication included a discussion of the rationale for recent changes to the  
738 recommendations for the lifetimes of a number of species. It is outside of the scope of this  
739 review to re-examine these recommendations; we confine ourselves to a summary of the  
740 major atmospheric loss processes for halocarbons, which include chemical reaction and  
741 photolysis, as well as uptake by the oceans and terrestrial ecosystems. In addition, there are  
742 examples of compounds — e.g.,  $\text{SF}_5\text{CF}_3$ , — where dissociative electron attachment may also  
743 be important [Takahashi *et al.*, 2002].

744 The global atmospheric lifetime of a gas was defined in section 2.4 as its burden  
745 divided by its loss rate. Under locally defined conditions, lifetimes can be determined as the  
746 inverse of a (pseudo-)first-order loss process. For loss of compound Y by reaction with X, we  
747 can write the loss rate as:

$$748 \quad -\frac{d[\text{Y}]}{dt} = k_{\text{X}}[\text{Y}][\text{X}].$$

749 In this process, the pseudo-first-order rate constant for the loss of Y is equal to  $k_{\text{X}}[\text{X}]$ , and the  
750 lifetime of Y with respect to reaction with X,  $\tau_{\text{X}}$ , is  $1/(k_{\text{X}}[\text{X}]) = 1/k'_{\text{X}}$ , with an assumption (or

751 approximation) that  $[X]$  is constant. Integration over space and time yields a global and  
752 annual average lifetime of  $Y$  with respect to reaction with  $X$ . In the troposphere, the dominant  
753 oxidant is the hydroxyl radical,  $OH$ . For well-mixed compounds (lifetimes greater than a few  
754 months) lifetimes with respect to  $OH$  are determined relative to the lifetime of methyl  
755 chloroform,  $CH_3CCl_3$ . The lifetime of a gas is given as the product of the  $CH_3CCl_3$  lifetime  
756 and its rate constant for reaction with  $OH$  divided by the  $OH$  rate constant of the gas; see  
757 *WMO* [2011], *Prather and Spivakovsky* [1990], *Spivakovsky et al.* [2000] and *Montzka et al.*  
758 [2011] for further detailed discussion.

759 For photolytic processes, a photolysis rate constant,  $J$ , is defined with units of  $s^{-1}$ , and  
760 is given by the expression:

$$761 \quad J = \int_{\lambda_1}^{\lambda_2} I(\lambda, z) \sigma(\lambda, T) \phi(\lambda, T) d\lambda$$

762 where  $I(\lambda, z)$  is the wavelength-dependent intensity of solar radiation at altitude  $z$  (sometimes  
763 known as the actinic flux),  $\sigma(\lambda, T)$  is the wavelength- and temperature-dependent  
764 ultraviolet/visible absorption cross section of the molecule of interest,  $\phi(\lambda, T)$  is the  
765 wavelength- and temperature-dependent photolysis quantum yield, and  $\lambda_1$  and  $\lambda_2$  define the  
766 wavelength range over which the calculation is carried out. Integration over space and time  
767 yields a global and annual average lifetime with respect to photolysis,  $\tau_J$ .

768 For a molecule destroyed by both chemical reaction and photolysis (and other  
769 processes), the overall global atmospheric lifetime,  $\tau_{total}$  can be written as a combination of the  
770 global and annual average lifetimes with respect to the various loss processes:

$$771 \quad 1/\tau_{total} = 1/\tau_X + 1/\tau_J (+ 1/\tau_{other}).$$

772 As discussed in section 2.4, loss by chemical reaction within the troposphere is dominated by  
773 the reactivity of the hydroxyl radical,  $OH$ . For water soluble compounds such as  
774 perfluorinated esters, uptake by the oceans may also be important [*Kutsuna et al.*, 2005].  
775 Compounds with lifetimes with respect to reaction with  $OH$  that are greater than a few years  
776 will reach the stratosphere, where destruction via photolysis and reaction with  $O(^1D)$  may also  
777 contribute. Fully fluorinated compounds have lifetimes typically of several thousands of years  
778 and their loss is dominated by photolysis in the mesosphere and thermosphere, while CFCs

779 have lifetimes in the range 50-1000 years and are degraded by photolysis and reaction with  
780 O(<sup>1</sup>D) in the stratosphere [Ravishankara *et al.*, 1993].

781 The calculation of atmospheric lifetimes is complicated. Concentrations of reacting  
782 species show strong temporal and spatial variability, and it may be difficult to be confident of  
783 the absolute concentrations of these species. The intensity of solar radiation varies strongly  
784 with altitude, and the absorption cross sections and quantum yields may show significant  
785 dependence on temperature. There are also chemical feedbacks which can affect the lifetime.  
786 Given the spatial and temporal variability of reaction partners and photolysis and the potential  
787 for chemical feedbacks, it is necessary to use atmospheric models to accurately determine  
788 lifetimes, which adds significantly to the complexity of the lifetime determination [Prather,  
789 2007]. There are no unique lifetimes for the shorter lived gases, as their lifetimes depend on  
790 the location of emissions and the chemical and physical conditions of the atmosphere. As  
791 discussed in section 3.6.3, there are often significant uncertainties associated with  
792 atmospheric lifetimes.

793

### 794 **3.3 Radiative forcing efficiency**

#### 795 **3.3.1 Spectrally-varying radiative efficiency**

796 The radiative efficiency calculations carried out here are based on the simple method outlined  
797 by Pinnock *et al.* [1995] in which a radiative transfer code is used to derive a wavelength-  
798 dependent RE for a unit absorption cross-section. With this method the instantaneous REs can  
799 be estimated directly from the absorption spectrum of a molecule without using a radiative  
800 transfer model, as explained in section 2.3. Pinnock *et al.* [1995] showed that results from  
801 their simple method agreed to within 0.3% with results from a narrowband model. This  
802 virtually eliminates the computational time needed and makes it straightforward to perform  
803 RE calculations for a large number of compounds. Additionally, when comparing the  
804 calculated REs between different compounds, uncertainties related to the absorption spectra  
805 are the only factor affecting the comparison, as uncertainties related to the use of different  
806 radiative transfer models can be ruled out. The Pinnock method is derived assuming the  
807 molecule causing the forcing to be well mixed in the atmosphere. The resulting RE has to be  
808 modified to take into account any non-uniformity in the horizontal and vertical distribution;  
809 the method by which this is done here is described in sections 3.3.3 and 3.3.4, and is

810 particularly important for emissions of short-lived gases. In principle, the RE should be  
811 calculated (in a similar manner to the lifetime, as discussed in section 3.2) by calculating the  
812 forcing locally and averaging in space and time to yield the global and annual average RE.

813 The method proposed by *Pinnock et al.* [1995] (plus the lifetime correction) is  
814 applicable for all compounds with low atmospheric concentrations and therefore weak  
815 absorption, such as the halogenated compounds considered here. When this requirement is  
816 met, the compound's radiative forcing per spectral interval is proportional to the product of its  
817 absorption cross section and its number column density. *Pinnock et al.* [1995] included a  
818 weak absorber with the same cross section at all wavelengths in a narrowband model to  
819 calculate the instantaneous, cloudy-sky, RF per unit cross section as a function of  
820 wavenumber.

821 We present here a revised calculation of the instantaneous, cloudy-sky, RF per unit  
822 cross section to reflect improvements in the radiative transfer calculations in the period since  
823 the *Pinnock et al.* [1995] curve was derived. Figure 5 illustrates the progression from the  
824 original to our final revised Pinnock curve. First we employ the same radiative transfer code  
825 (the Reading Narrow Band Model (NBM)) as used in *Pinnock et al.* [1995] to reproduce the  
826 original Pinnock curve, using the (rather dated) global-mean atmospheric profile presented in  
827 that paper – the specification of cloud amount was especially crude. We then recalculated the  
828 Pinnock curve, incorporating many minor updates to the NBM and in particular the use of a  
829 more modern global-mean atmosphere, based on European Centre for Medium-Range  
830 Weather Forecasts (ECWMF) and International Satellite Cloud Climatology Project (ISCCP)  
831 data [*Freckleton et al.*, 1998]. Figure 5 (top) shows in particular a decrease in the Pinnock  
832 curve in the 800-1200  $\text{cm}^{-1}$  region, which mostly reflects an improved characterization of  
833 cloud (the longwave cloud forcing increased from 12 to 21  $\text{W m}^{-2}$  between the old and the  
834 new global-mean atmosphere). At other wavenumbers, the new and old Pinnock curves agree  
835 well. Next, we recalculated the Pinnock curve using area-weighted results using one tropical  
836 and two extratropical profiles [*Freckleton et al.*, 1998], rather than a single global-mean  
837 profile. The most marked effect (see red curve on Figure 5 (top)) of using the new profiles is  
838 an increase in the Pinnock curve between 100 and 500  $\text{cm}^{-1}$ , which reflects the fact that the  
839 extratropical profiles are cooler (moving the peak of the Planck function to lower  
840 wavenumbers) and drier. At wavenumbers greater than 800  $\text{cm}^{-1}$  there are only small  
841 differences between the single and three atmosphere curves. Mixing ratios of other well-

842 mixed gases used in the NBM were 389 ppm for CO<sub>2</sub>, 1800 ppb for CH<sub>4</sub> and 323 ppb for  
843 N<sub>2</sub>O, reflecting contemporary values.

844 Since we wanted our new Pinnock curve to be based on a LBL code (as it is inherently  
845 more accurate and also at higher spectral resolution than the original (10 cm<sup>-1</sup>) curve) we next  
846 generated a Pinnock curve using the Oslo LBL model [Myhre *et al.*, 2006], employing their  
847 two (tropical/extratropical) atmosphere approach. Figure 5 (middle) shows a comparison of  
848 the NBM and LBL (averaged to 10 cm<sup>-1</sup> resolution) Pinnock curves – there is excellent  
849 agreement between the two models. Figure 5 (bottom) shows the final Pinnock curve, using  
850 the LBL but now averaged to 1 cm<sup>-1</sup> resolution. The effect of using the improved spectral  
851 resolution was found to have a negligible impact (<1-2%) on the RE calculations for most of  
852 the compounds presented in section 4. However, for a few compounds, this effect was  
853 stronger, as illustrated in Figure 6. The largest effect was for CF<sub>4</sub> because its main absorption  
854 band is at the edge of the atmospheric window. For this compound the RE was  
855 underestimated by about 8% when using 10 cm<sup>-1</sup> resolution compared to 1 cm<sup>-1</sup> resolution of  
856 the LBL Pinnock curve.

857 An Excel spreadsheet with both the updated 1 and 10 cm<sup>-1</sup> resolution LBL Pinnock  
858 curves is available in the supplementary material.

859

### 860 3.3.2 Stratospheric temperature adjustment

861 Generally, halocarbons warm the lower part of the stratosphere because their strongest  
862 absorption bands normally occur in the atmospheric window region. For these wavelengths, in  
863 the stratosphere, the extra absorption of upwelling radiation by the halocarbon from the  
864 surface and troposphere exceeds the amount of extra radiation emitted by the halocarbon.  
865 Hence, there will be an increased heating rate of the stratosphere. When stratospheric  
866 temperature adjustment is applied, the increased heating rate leads to a warming of the  
867 stratosphere. In the new equilibrium state, the higher stratospheric temperatures lead to an  
868 increase in the amount of radiation emitted downwards into the troposphere so that the  
869 stratosphere-adjusted forcing is higher than the instantaneous forcing. (The reverse is true for  
870 CO<sub>2</sub> forcing, since it acts to cool the stratosphere so that the stratosphere-adjusted forcing is  
871 smaller than the adjusted forcing.)

872 Since the Pinnock *et al.* function used for calculating REs in this study does not take  
873 into account the stratospheric temperature adjustment, we have applied a factor to convert  
874 from instantaneous to adjusted forcing. Based on several studies [Forster *et al.*, 2005; Jain *et*  
875 *al.*, 2000; Myhre and Stordal, 1997; Naik *et al.*, 2000; Pinnock *et al.*, 1995], we have  
876 increased the calculated instantaneous RE for most compounds by 10% to account for  
877 stratospheric temperature adjustment. It should be kept in mind that the effect of stratospheric  
878 temperature adjustment can be quite variable for each compound [e.g., Pinnock *et al.*, 1995],  
879 particularly for gases which absorb outside the atmospheric window. For a few selected gases  
880 (CFC-11, CFC-12, HFC-41 and CF<sub>4</sub>) we have carried out explicit calculations, using the Oslo  
881 LBL model, to estimate the ratio between the RE including stratospheric temperature  
882 adjustment and the instantaneous RE. For CFC-11 and CFC-12, which have their main  
883 absorption bands in the atmospheric window region, the REs were 9.1% and 10.5% higher,  
884 respectively, when taking the stratospheric temperature adjustment into account. HFC-41 is a  
885 special case because its main absorption band overlaps strongly with ozone and our result  
886 from the LBL calculation shows a decrease in RE of 5.0% when accounting for stratospheric  
887 temperature adjustment (some of the radiation which would have been absorbed by ozone in  
888 the stratosphere is instead trapped by CH<sub>3</sub>F in the troposphere leading to a cooling of the  
889 stratosphere). As stated in section 3.3.1, CF<sub>4</sub> absorbs strongly at the edge of the atmospheric  
890 window (near 1,300 cm<sup>-1</sup>), and our results show an increase in RE of 10.5% due to  
891 stratospheric temperature adjustment for this compound. Based on these results and on  
892 previous literature [e.g., Myhre and Stordal, 1997; Pinnock *et al.*, 1995] we consider a 10%  
893 increase a good approximation for most gases.

894

### 895 3.3.3 Simulations of atmospheric distributions and lifetimes

896 The effect of non-uniform vertical profiles on radiative forcing has been investigated in  
897 several studies [e.g., Freckleton *et al.*, 1998; Jain *et al.*, 2000; Naik *et al.*, 2000; Sihra *et al.*,  
898 2001], and is described in section 2.4. To further investigate and reduce the uncertainties  
899 associated with the correction factors for compounds which are mainly lost in the troposphere  
900 through reaction with OH, and normally have a relatively short lifetime, a number of  
901 simulations have been carried out with a 3-D Chemistry-Transport Model (CTM) in  
902 combination with a radiative transfer model. The models chosen for this purpose are the



903 global offline Oslo CTM2 model [Berglen *et al.*, 2004; Søvde *et al.*, 2008] and the Oslo  
904 broadband radiative transfer model [Myhre and Stordal, 1997].

905 The setup of the CTM simulations is similar to the studies of Acerboni *et al.* [2001]  
906 and Sellevag *et al.* [2004b] where a total of 6 short-lived halocarbons were implemented in  
907 the Oslo CTM2. Here we have implemented the following 9 halocarbons in the model, which  
908 were chosen to represent a range of atmospheric lifetimes (~10 days to 5.2 years): HFC-  
909 1234yf ( $\text{CF}_3\text{CF}=\text{CH}_2$ ), HFE-356mmz1 ( $\text{CH}_3\text{OCH}(\text{CF}_3)_2$ ), HFE-254eb2 ( $\text{CH}_3\text{OCHF}(\text{CF}_3)$ ),  
910 HFC-161 ( $\text{CH}_3\text{CH}_2\text{F}$ ),  $\text{CH}_3\text{Br}$ , HCFC-123 ( $\text{CF}_3\text{CCl}_2\text{H}$ ), HFC-152a ( $\text{CH}_3\text{CHF}_2$ ), HFC-143  
911 ( $\text{CH}_2\text{FCHF}_2$ ) and HFC-32 ( $\text{CH}_2\text{F}_2$ ). The compounds were assumed to only react with the  
912 hydroxyl radical (OH), which is the main loss for most short-lived halocarbons, and their  
913 reaction rate coefficients were taken from the NASA/JPL database [Sander *et al.*, 2010]. In a  
914 reference simulation, the geographical distribution of the emissions was the same as for CFC-  
915 11 [McCulloch *et al.*, 1994], while in a sensitivity simulation the emission distribution was set  
916 the same as for black carbon (BC) [Bond *et al.*, 2004; van der Werf *et al.*, 2006] with the  
917 purpose of studying the impact of having a larger share of the emissions occurring at lower  
918 latitudes near the equator. It should be kept in mind that the sensitivity simulation is  
919 considered a rather extreme case as halocarbons are industrial chemicals and their emission  
920 distribution is more likely to follow that for other industrial compounds, such as CFC-11, than  
921 for species like black carbon which has significant non-industry related sources. In both cases,  
922 the anthropogenic emissions of other compounds were taken from the *RETRO* [2006]  
923 database for year 2000. The model was run repeatedly for the meteorological year 2000 with  
924 uniform annual emissions, and a sufficient amount of spin-up time was allowed to obtain  
925 chemical steady-state at levels that yield globally averaged surface mixing ratios of  
926 approximately 1 ppb. The model has been driven by meteorological forecast data from the  
927 ECMWF IFS model cycle 36, as explained by Søvde *et al.* [2011], and run at a horizontal  
928 resolution of approximately  $2.8^\circ \times 2.8^\circ$  (T42) and 60 vertical layers distributed from the  
929 surface to 0.1 hPa.

930 Figure 7 shows the calculated atmospheric distribution of HFC-161, which has a  
931 lifetime with respect to OH of 84 days in the reference simulation. In the sensitivity  
932 simulation with a “BC-like” emission distribution, the global burden is smaller, and hence the  
933 lifetime is shorter (71 days), due to the higher concentrations of OH found near the tropics.  
934 Due to the relatively short lifetime of HFC-161, the distribution of surface concentrations

935 reflects the regions of emissions quite well (Figure 7, top). The reference simulation reveals  
936 large concentrations in the northern hemisphere, and particularly over the industrial areas in  
937 US and Europe, while the sensitivity simulation shows a weaker gradient between the  
938 hemispheres, and with surface maxima over Southeast Asia and the biomass burning regions  
939 in Africa. Furthermore, the vertical profile is different between the two runs with a stronger  
940 decay of mixing ratios with altitude in the simulation with “CFC-11-like” emission  
941 distribution compared to the simulation with “BC-like” emission distribution.

942         The Oslo CTM2 simulated distributions of the halocarbons have been used for RF  
943 calculations with the Oslo broadband model [*Myhre and Stordal, 1997*]. In the radiative  
944 transfer calculations we also use 60-layer meteorological data from the ECMWF-IFS model,  
945 but with a reduced horizontal resolution of  $5.6^\circ \times 5.6^\circ$  (T21). Annual mean cloudy-sky RF  
946 (with stratospheric temperature adjustment included) has been calculated using the radiative  
947 transfer model (based on monthly-mean data), which has been run both with a constant global  
948 and annual mean vertical profile (so that the global and annual mean surface mixing ratio is  
949 used at all heights, latitudes, longitudes and times), and with the monthly mean atmospheric  
950 distribution calculated by Oslo CTM2. A quantification of the importance of using realistic  
951 vertical profiles rather than constant profiles was then obtained by calculating the fractional  
952 difference between the resulting RF from the two radiative transfer simulations.

953         In addition to the model runs explained above, simulations were carried out with the  
954 Oslo LBL model to quantify the effect of a non-uniform vertical profile for compounds which  
955 are mainly lost by photolysis in the stratosphere. Such compounds (i.e., mainly CFCs and  
956 halons) are well-mixed in the troposphere but their mixing ratios decay with increasing  
957 altitude in the stratosphere. Hence, they have a different vertical profile, and their atmospheric  
958 concentrations are also much less influenced by the horizontal distribution of emissions, than  
959 the compounds with lifetimes governed by OH destruction. The three compounds Halon-  
960 1211, CFC-11 and CFC-12 were chosen for the LBL model experiments because they span a  
961 relatively wide range of lifetimes (16 to 100 years [*WMO, 2011*]), and because vertical  
962 profiles of these compounds were available from CTM simulations. The vertical profiles of  
963 the two CFCs were taken from *Myhre and Stordal* [1997] while the Halon-1211 profiles were  
964 fit to the annual mean output from Oslo CTM2, averaged separately over the tropics and the  
965 extra-tropics. For all three compounds the mixing ratios were assumed to decrease  
966 exponentially above the tropopause in the radiation code.

967 To validate the vertical profiles of CFC-11 mixing ratio used in the Oslo radiative  
968 transfer model (results presented in section 3.3.4), we have compared these data with a  
969 recently derived climatology from the MIPAS satellite instrument [Hoffmann *et al.*, 2008] in  
970 Figure 8. This MIPAS data set has been thoroughly validated against several other satellite  
971 observations, as well as airborne and ground-based measurements [Hoffmann *et al.*, 2008].  
972 For comparison the CFC-11 vertical profiles from the Oslo CTM2 simulations are also  
973 included in Figure 8, although these results are not used here directly (only the Halon-1211  
974 profiles were used, as explained above). It should be noted that the mixing ratios of CFC-11  
975 calculated by Oslo CTM2 are largely governed by the top and bottom boundary conditions  
976 taken from the Oslo 2-D stratospheric chemistry model [Stordal *et al.*, 1985] which is based  
977 on WMO recommendations. CFC-11 has a relatively long lifetime of about 45 years [WMO,  
978 2011] and its main loss is photolysis in the stratosphere. As a consequence, CFC-11 is well-  
979 mixed throughout the troposphere, while its concentration decreases with height in the  
980 stratosphere. This reduction with height has a major impact on the compound's radiative  
981 forcing [e.g., Freckleton *et al.*, 1998], and it is therefore important that the models include  
982 realistic vertical profiles. The comparison between the Oslo radiation code and the Oslo  
983 CTM2 model shows that the assumption of an exponential decay of CFC-11 mixing ratios  
984 above the tropopause in the radiation code works relatively well (Figure 8). Furthermore, the  
985 CFC-11 vertical profiles employed in both models are in relatively good agreement with the  
986 climatology derived from MIPAS observations. Some discrepancies can be seen, especially  
987 near the tropical tropopause region, but it should be noted that differences between  
988 climatologies derived from satellite observations are also evident [Hoffmann *et al.*, 2008]  
989 (their Figure 11), and that tropical stratospheric measurements of CFC-11 is a major source of  
990 uncertainty [Minschwaner *et al.*, 2012] (see also their Figure 6). The vertical profiles are  
991 shown separately for the tropics (30°S-30°N) and the extra-tropics (90°S-30°S and 30°N-  
992 90°N) in Figure 8 due to the different tropopause heights. These two regions are also the same  
993 as used in the two-atmosphere setup of the Oslo radiation code.

994

### 995 3.3.4 Fractional correction versus lifetime

996 Results from the experiments described in section 3.3.3 are shown in Figure 9 together with  
997 results from previous studies [Acerboni *et al.*, 2001; Jain *et al.*, 2000; Sellevag *et al.*, 2004b].  
998 Our calculations differ from previous studies in three important respects. First, a number of

999 hypothetical "HFC-1234yf-like" molecules were studied. These compounds all had the  
1000 infrared spectrum of HFC-1234yf but had different atmospheric lifetimes ranging from  
1001 approximately 1 day to 7 years. Variation of the lifetime within the model was achieved by  
1002 assuming rate coefficients for reaction with OH radicals in the range  $4.3 \times 10^{-15} - 3.5 \times 10^{-11}$   
1003  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The results are shown by the filled circles in Figure 9. Second, the  
1004 literature values for the rate coefficients for reactions of OH radicals with the remaining 8  
1005 compounds were used, but this time we did not use the actual absorption spectra for the  
1006 compound for the radiative transfer calculations. Instead, we chose to span the vertical axis,  
1007 representing the fractional correction, by repeating the RE calculation 6 times for each gas,  
1008 using different absorption bands which were either within or at the borders of the atmospheric  
1009 window region. More specifically, these bands were centered at wavenumbers of 631  
1010 (absorption band of  $\text{CF}_4$ ), 714 ( $\text{C}_2\text{F}_6$ ), 948 ( $\text{SF}_6$ ), 1116 ( $\text{C}_2\text{F}_6$ ), 1250 ( $\text{C}_2\text{F}_6$ ), and 1283 ( $\text{CF}_4$ )  
1011  $\text{cm}^{-1}$ . Figure 9 shows the fractional correction for the mean (filled squares) and standard  
1012 deviation (vertical lines) of these 6 bands for each of the 8 gases. It should be noted that the  
1013 fractional correction depends primarily on lifetime, but to some extent also on the position of  
1014 the absorption bands; absorption bands inside the atmospheric window region has the weakest  
1015 correction. Third, the correction factors for compounds with stratospheric photolysis as the  
1016 primary loss mechanism have been calculated using a two-atmosphere approach, and are  
1017 shown by the red symbols in Figure 9.

1018 Several interesting features can be seen in Figure 9. The lifetimes calculated by the  
1019 Oslo CTM2 are shorter when the geographical distribution of emissions was "BC-like" rather  
1020 than "CFC-11-like", especially for lifetimes shorter than approximately 0.5 years. This is not  
1021 surprising as the levels of OH are highest near the tropics (where a large share of the "BC-  
1022 like" emissions takes place) because of higher humidity and more incoming solar radiation at  
1023 low latitudes. Another interesting feature is that the fractional correction is weaker (i.e., closer  
1024 to 1) in the run with "BC-like" emissions than the reference run with "CFC-11-like"  
1025 emissions for lifetimes longer than about 0.003 years, or 1 day, while it is stronger for  
1026 lifetimes shorter than 1 day. One reason for this is the higher RF for well-mixed greenhouse  
1027 gases near the equator than at higher latitudes, because of higher temperatures [*Shine and*  
1028 *Forster, 1999*].

1029 For the compounds with similar lifetimes as in *Jain et al.* [2000], the fractional  
1030 corrections in our reference simulation roughly agree with their corrections, except for the

1031 compound in *Jain et al.* [2000] that has a lifetime of 0.25 years and a fractional correction of  
1032 0.61, which is closer to our results from the simulation with “BC-like” emission distribution.  
1033 Part of the reason is probably that *Jain et al.* [2000] used a 2-D model with geographically  
1034 constant surface mixing ratios, while we use a 3-D model with an assumed (and likely more  
1035 realistic) emission distribution. In fact, another Oslo CTM2 sensitivity simulation with  
1036 surface mixing ratios fixed at 1 ppb globally (results not shown) gives a very similar vertical  
1037 profile and fractional correction factor as the simulation with “BC-like” emission distribution.  
1038 Interestingly, the three compounds studied in *Sellevag et al.* [2004b] have smaller fractional  
1039 correction factors than our results, and they do not always show an increase of fractional  
1040 correction proportional with the lifetime. As the models and simulation setup are quite similar  
1041 to this study, the differences can probably be attributed to the absorption spectra, which are  
1042 different for the various compounds. Figure 9 shows that the spectral position has some  
1043 influence on the fractional correction and causes a maximum deviation from the mean of  
1044  $\pm 10\%$ . On the other hand, the results from *Acerboni et al.* [2001] show slightly higher  
1045 fractional correction factors than in our study, presumably because they used a constant  
1046 surface mixing ratio all over the globe instead of an assumed emission distribution.

1047 *Sihra et al.* [2001] derived an empirical curve fit (see grey curve in Figure 9) to the  
1048 values in *Jain et al.* [2000] and this has been used in later studies [e.g., *Bravo et al.*, 2011a;  
1049 *Gohar et al.*, 2004]. Their fit is given by  $f(\tau) = 1 - 0.241 \tau^{-0.358}$ , where  $f$  is the fractional  
1050 correction and  $\tau$  is the lifetime in years for lifetimes greater than 0.25 years. Here we have  
1051 derived two new empirical curve fits, one for compounds dominated by loss in the  
1052 troposphere through OH reaction, and one for compounds dominated by loss through  
1053 stratospheric photolysis. In the latter case we have used a similar approach as *Sihra et al.*  
1054 [2001] and derived an exponential fit, but this time only results from explicit LBL  
1055 calculations discussed in section 3.3.3 have been used. We further assumed that  $f = 1$  for very  
1056 long lifetimes. The resulting exponential function is given by

$$1057 \quad f(\tau) = 1 - 0.1826 \tau^{-0.3339}, \quad (1)$$

1058 and is shown in Figure 9 by the red curve for  $10 < \tau < 10,000$  years. Equation (1) has been  
1059 used to calculate lifetime-corrected RE for some of the compounds presented in section 4. In  
1060 the case for compounds dominated by tropospheric OH loss, the empirical fit was restricted to  
1061 results from 3-D model experiments where a “CFC-11-like” emission distribution was  
1062 assumed. This means that the results from *Acerboni et al.* [2001] and the 2-D model of *Jain et*

1063 *al.* [2000] were not considered when deriving the fit (but still shown in Figure 9 for  
1064 comparison), while the results of *Sellevag et al.* [2004b] were included along with results  
1065 from the present study. As we now want to include compounds with very short lifetimes, the  
1066 empirical curve fit was constrained to form an *S*-shaped curve in Figure 9 with the following  
1067 formula:

1068 
$$f = \frac{1}{1 + \exp(-a(\tau - b)^c)} \quad (2)$$

1069 where *a*, *b*, *c* and *d* are constants with values of 2.962, 0.9312, 2.994, and 0.9302,  
1070 respectively. The curve was further constrained to give *f* = 0 for very short lifetimes and *f* = 1  
1071 for very long lifetimes. The resulting *S*-shaped function is shown in Figure 9 by the dark blue  
1072 curve for  $10^{-4} < \tau < 10^4$  years, and has been used to calculate lifetime corrected RE values for  
1073 most of the compounds presented in section 4.

1074

### 1075 **3.4 Discussion of impact of functional groups on spectra/radiative forcing**

1076 The infrared spectra of polyatomic molecules are made up of a number of vibrational bands,  
1077 each containing rotational fine structure that may, or may not, be resolved. For a non-linear  
1078 molecule containing *N* atoms, there are 3*N*-6 normal vibrations, although this number of  
1079 bands may not be visible in the spectrum. Bands may overlap with each other, may lie outside  
1080 of the spectral range of the measurements, may be forbidden or the vibrational mode may be  
1081 degenerate. For example, the tetrahedral molecule, CF<sub>4</sub> has a total of 9 normal vibrations, but  
1082 only one band is observed in its infrared spectrum (as illustrated in Figure 3). The molecule  
1083 has stretching and a variety of bending vibrations, but the bending vibrations occur at lower  
1084 wavenumber (ca. 400 cm<sup>-1</sup>) than can usually be observed in an infrared measurement. At the  
1085 same time, as it contains four C-F bonds, it is expected to have four stretching normal  
1086 vibrations. A simple analysis of the symmetry properties of the stretching modes shows that  
1087 one is the totally symmetric (A<sub>1</sub>) stretch, which cannot be accessed in an allowed infrared  
1088 transition. The other three vibrations turn out to be three-fold degenerate (symmetry species  
1089 T<sub>2</sub>) and give rise to a single allowed transition at around 1280 cm<sup>-1</sup>. Molecules with lower  
1090 symmetry will exhibit more bands, as degenerate vibrations are less likely to occur.

1091 In the case of CF<sub>4</sub>, it is clearly possible to identify the T<sub>2</sub> vibration as a C-F stretching  
1092 vibration, which is a specific example of a group vibration. In general, a normal mode of

1093 vibration involves movement of all the atoms in a molecule and it is not always possible to  
1094 assign transitions to particular group vibrations. From the perspective of determining radiative  
1095 efficiencies, the majority of spectral features of importance occur in the region between 1500  
1096 and  $500\text{ cm}^{-1}$ . This region is called the *fingerprint region* and usually contains a complicated  
1097 series of absorptions, and it is often difficult to clearly identify group vibrations within this  
1098 region. Nevertheless, some features may be identified. Molecules containing H atoms will  
1099 have C-H stretching vibrations that produce transitions in the  $3000\text{ cm}^{-1}$  region of the  
1100 spectrum, well outside of the region of interest here. On the other hand, C-H bending  
1101 vibrations are expected at around  $1400\text{ cm}^{-1}$  and are a common feature of many HFCs [e.g.,  
1102 *Sihra et al.*, 2001]. We have already seen that C-F stretching gives rise to a band at  $1280\text{ cm}^{-1}$ ,  
1103 and bands in this region are observed in a wide range of fluorine-containing compounds [e.g.,  
1104 *Bravo et al.*, 2010b; *Sihra et al.*, 2001]. However, it should be noted that the electron-  
1105 withdrawing properties of neighboring groups can have a significant influence on band  
1106 position. While molecules with a relatively high fluorine content show a C-F stretching  
1107 feature at around  $1200\text{-}1300\text{ cm}^{-1}$ , HFC-41 ( $\text{CH}_3\text{F}$ ) shows only a feature at  $1000\text{-}1100\text{ cm}^{-1}$ ,  
1108 which corresponds to the expected position for a C-F group vibration given in standard  
1109 spectroscopy textbooks such as *Hollas* [2004]. For this reason, care must be used when  
1110 assigning observed bands to individual group vibrations in the spectra of heavily halogenated  
1111 molecules.

1112

### 1113 **3.5 Description of metrics**

1114 The motivation for the choice of metrics adopted here (GWP and GTP) was given in section  
1115 2.5.

#### 1116 **3.5.1 The Global Warming Potential (GWP)**

1117 The Global Warming Potential (GWP) is based on the time-integrated radiative forcing due to  
1118 a *pulse* emission of a unit mass of gas. It can be given as an absolute GWP for gas  $i$  ( $\text{AGWP}_i$ )  
1119 (usually in  $\text{W m}^{-2}\text{ kg}^{-1}\text{ year}$ ) or as a dimensionless value by dividing the  $\text{AGWP}_i$  by the  
1120  $\text{AGWP}$  of a reference gas, normally  $\text{CO}_2$ . Thus, the GWP is defined as:

1121 \_\_\_\_\_ .

1122 A user choice is the time horizon ( $H$ ) over which the integration is performed. IPCC has  
1123 usually presented GWP for 20, 100 and 500 years and the Kyoto Protocol has adopted GWPs  
1124 for a time horizon of 100 years.

1125 For a gas  $i$ , if  $A_i$  is the RE,  $\tau_i$  is the lifetime (and assuming its removal from the  
1126 atmosphere can be represented by exponential decay), and  $H$  is the time horizon, then the  
1127 integrated RF up to  $H$  is given by:

1128 
$$-\dots$$

1129 This is an approximation that holds for long-lived gases but is less accurate for shorter  
1130 lived gases whose lifetimes depend on location of emissions and physical and chemical  
1131 conditions of the atmosphere. *Prather* [2007] developed a concept of atmospheric chemistry  
1132 as a coupled system across different trace species with transport between different regions and  
1133 radiative feedbacks. Due to these processes a perturbation to one species in one location will  
1134 lead to a global response on a wide range of time scales, often involving many other chemical  
1135 components. The chemistry-transport system can be linearized and represented by eigenvalue  
1136 decomposition [*Prather*, 2007] that are perturbation patterns of trace gas abundances, also  
1137 known as chemical modes. Any perturbation to atmospheric composition can be expressed as  
1138 a sum of chemical modes, each with a fixed decay term.

1139 The AGWP for  $\text{CO}_2$  is more complicated, because its atmospheric response time (or  
1140 lifetime of a perturbation) cannot be represented by a simple exponential decay. This situation  
1141 arises because  $\text{CO}_2$  is absorbed into the various regions of the oceans (surface water,  
1142 thermocline, deep ocean) on a range of different timescales. As a consequence, following a  
1143 pulse emission of  $\text{CO}_2$  the perturbation of the atmospheric concentration of  $\text{CO}_2$  remains  
1144 significant (>20%) even after 1000 years. The decay of a perturbation of atmospheric  $\text{CO}_2$   
1145 following a pulse emission at time  $t$  is usually approximated by *Joos et al.* [2013]:

1146 
$$-\dots$$

1147 where the parameter values are  $a_0=0.2173$ ,  $a_1=0.2240$ ,  $a_2=0.2824$ ,  $a_3=0.2763$ ,  $\alpha_1=394.4$ ,  
1148  $\alpha_2=36.54$  and  $\alpha_3=4.304$ . The parameter values for the impulse response function (IRF) are  
1149 based on a recent multi-model study [*Joos et al.*, 2013], and these values have been used here.  
1150 For comparison the parameter values from *Forster et al.* [2007] were  $a_0=0.217$ ,  $a_1=0.259$ ,  
1151  $a_2=0.338$ ,  $a_3=0.186$ ,  $\alpha_1=172.9$ ,  $\alpha_2=18.51$  and  $\alpha_3=1.186$  (see footnote a, Table 2.14 in *Forster*  
1152 *et al.* [2007]).



1153 Then the  $AGWP_{CO_2}$  can be given as:

1154 — (3)

1155 Note that the parameters used in calculating the AGWP are dependent on the choice of  
1156 background state, but it is convention to use present-day conditions. While the models used to  
1157 calculate IRF for  $CO_2$  usually include climate carbon cycle feedbacks, usually no climate  
1158 feedbacks are included for the non- $CO_2$  gases.

1159

### 1160 3.5.2 The Global Temperature change Potential (GTP)

1161 GTP is presented as an alternative to the GWP and uses the *change in global mean*  
1162 *temperature for a chosen point in time* as the impact parameter. While GWP is a metric  
1163 integrative in time, the GTP is based on the temperature change per unit emissions for a  
1164 selected year,  $t$ . As for the GWP, the impact of  $CO_2$  is normally used as reference, thus,

$$1165 \quad GTP(t)_i = AGTP(t)_i / AGTP(t)_{CO_2} = \Delta T(t)_i / \Delta T(t)_{CO_2},$$

1166 where  $AGTP$  ( $K \text{ kg}^{-1}$ ) is the absolute GTP. The assumed lifetime of  $CO_2$  is the same as that  
1167 given for the GWP in section 3.5.1.

1168 In the calculations here, we represent the thermal inertia of the climate system  
1169 following the method used by *Fuglestedt et al.* [2010]. This includes a representation of the  
1170 deep ocean as well as the ocean mixed layer based on a temperature response function with  
1171 two time-constants derived from climate model results [*Boucher and Reddy, 2008*]. The  
1172 derived GTPs are dependent on the assumed value of climate sensitivity [*Shine et al., 2005a;*  
1173 *Shine et al., 2007*], which is implicit in the Boucher and Reddy response functions, and is  
1174 equal to about  $1 \text{ K (W m}^{-2}\text{)}^{-1}$ .

1175

### 1176 3.5.3 The reference gas $CO_2$

1177 The metric values need updating due to new scientific knowledge about various properties,  
1178 but also due to changes in lifetimes and radiative efficiencies caused by changing atmospheric  
1179 background conditions.

1180 For the reference gas  $CO_2$ , such changes (i.e., in  $AGWP_{CO_2}$  and  $AGTP_{CO_2}$ ) will affect  
1181 all the other gases. With increasing  $CO_2$  levels in the atmosphere the marginal radiative

1182 forcing is reduced, while at the same time the ocean uptake is reduced and airborne fraction  
1183 increased. These changes (working in opposite directions) lead to changes in  $AGWP_{CO_2}$  and  
1184  $AGTP_{CO_2}$ . Updates to  $AGWP_{CO_2}$  are often presented in IPCC and WMO Ozone assessments.

1185 The radiative forcing for  $CO_2$  can be approximated using the expression based on  
1186 radiative transfer models [Myhre *et al.*, 1998]:

1187  $RF = \alpha \ln((C_0 + \Delta C)/C_0)$ , where  $\alpha = 5.35 \text{ W m}^{-2}$  and  $C$  is the atmospheric mixing ratio  
1188 of  $CO_2$ .

1189 Based on this and for a small  $\Delta C$ , the radiative efficiency of  $CO_2$  can be approximated. The  
1190 RE of  $CO_2$  changed from  $0.0147 \text{ W m}^{-2} \text{ ppm}^{-1}$  to  $0.0141 \text{ W m}^{-2} \text{ ppm}^{-1}$  when atmospheric  
1191  $CO_2$  levels increased from 364 to 378 ppm, as used by IPCC Third Assessment Report (TAR)  
1192 [IPCC, 2001] and IPCC Fourth Assessment Report (AR4) [IPCC, 2007], respectively. At  
1193 current  $CO_2$  levels of  $\sim 391 \text{ ppm}$  [WMO/GAW, 2012], a 1 ppm change in the  $CO_2$   
1194 concentration ( $\Delta C = 1 \text{ ppm}$ ) gives a radiative efficiency for  $CO_2$  of  $0.013665 \text{ W m}^{-2} \text{ ppm}^{-1}$ .

1195 The airborne fraction and the impulse response function have also been updated and  
1196 Figure 10 shows the IRFs from the four IPCC assessment reports together with the updated  
1197 IRF from Joos *et al.* [2013]. In this review we have updated the  $AGWP_{CO_2}$  and  $AGTP_{CO_2}$   
1198 values based on the new IRF and RE of  $CO_2$ . The latter value is converted from per ppb to per  
1199 kg by multiplying with  $(M_A/M_{CO_2}) \times (10^9/T_M)$ , where  $M_A$  and  $M_{CO_2}$  are the molecular weight  
1200 of dry air ( $28.97 \text{ g mol}^{-1}$ ) and  $CO_2$  ( $44.01 \text{ g mol}^{-1}$ ), respectively, and  $T_M$  is the mean dry mass  
1201 of the atmosphere ( $5.135 \times 10^{18} \text{ kg}$  [Trenberth and Smith, 2005]). The RE of  $CO_2$  given per  
1202 mass is then  $1.75 \times 10^{-15} \text{ W m}^{-2} \text{ kg}^{-1}$ , and the resulting AGWPs for  $CO_2$  (using Equation 3) are  
1203  $2.495 \times 10^{-14}$ ,  $9.171 \times 10^{-14}$  and  $32.17 \times 10^{-14} \text{ W m}^{-2} \text{ yr (kgCO}_2\text{)}^{-1}$  for time horizons of 20, 100  
1204 and 500 years, respectively. These values are higher than the  $AGWP_{CO_2}$  used in AR4  
1205 (calculated based on the IRF and RE of  $CO_2$  given in AR4) by approximately 1.4, 6.0 and  
1206 13%, respectively, mainly due to the change in IRF. As a consequence the  $GWP_{100}$  values  
1207 presented for all compounds in section 4 will be about 6% lower than if the  $AGWP_{CO_2}$  from  
1208 AR4 was used. The  $AGTP_{CO_2}$  values used in the calculations of GTPs in section 4.2, have  
1209 been updated (using Equation A3 in Fuglestedt *et al.* [2010]) to  $6.841 \times 10^{-16}$ ,  $6.167 \times 10^{-16}$ ,  
1210  $5.469 \times 10^{-16} \text{ K (kgCO}_2\text{)}^{-1}$  for time horizons of 20, 50 and 100 years, respectively. As for  
1211  $AGWP_{CO_2}$  the new  $AGTP_{CO_2}$  values take into account the updated IRF and radiative  
1212 efficiency of  $CO_2$ , while the remaining parameters are taken from Fuglestedt *et al.* [2010].

1213

## 1214 **3.6 Uncertainty – sensitivity to assumptions**

### 1215 3.6.1 Absorption cross-sections

1216 Uncertainties related to the measurements of IR absorption spectra are dependent on many  
1217 factors, and can differ for each compound. Some compounds have been subject to extensive  
1218 laboratory measurements by several groups, such as for HCFC-22 [*Ballard et al.*, 2000b] and  
1219 HFC-134a [*Forster et al.*, 2005], while others may lack reliable experimental cross-section  
1220 data. Typical sources of uncertainties related to spectra include, but are not limited to,  
1221 temperature and pressure for the measurement and in the sample, spectral range and  
1222 resolution in the measurement, purity of sample, spectrometer and methods used, and noise in  
1223 the measurements. A comprehensive intercomparison of laboratory measurements of  
1224 absorption spectra was reported by *Ballard et al.* [2000b] for HCFC-22. They examined a  
1225 range of sources of uncertainties and identified a limited set of aspects, related both to sample  
1226 and photometric uncertainty sources, which should be given special attention when measuring  
1227 other molecules. Overall, the total error in the absorption cross-section measurements for each  
1228 of the five laboratory groups considered by *Ballard et al.* [2000b] were generally less than 5%  
1229 and for the most part in the range 3-5%.

1230 Integrated absorption cross sections from theoretical calculations are often in good  
1231 agreement with experimentally determined values; for example, *Bravo et al.* [2010b] report  
1232 theoretical integrated absorption cross sections for a range of PFCs that are within 5% of the  
1233 experimentally determined values. Because band overlap often makes it difficult to compare  
1234 individual vibrational bands, agreement at this level may be somewhat worse than for the total  
1235 integrated cross sections. As discussed in section 3.1.2, theoretical calculations generally  
1236 provide infrared absorption band positions that differ systematically from those observed  
1237 experimentally. These differences are wavenumber dependent and are usually only a few  
1238 percent, but because band position is so important in determining radiative efficiencies,  
1239 corrections for these differences are usually made.

1240 The absorption spectra used in this study have for the most part been used as reported  
1241 in the literature when performing the radiative forcing calculations. However, each spectrum  
1242 has been the subject of a visual inspection and in some cases it was necessary to remove noise  
1243 around the baseline. As the noise often does not average out to precisely zero, inclusion of

1244 noise occurring outside the absorption bands may lead to biases in the RE calculations.  
1245 Furthermore, for some compounds measurements were often available for a number of  
1246 different temperatures and pressures, particularly for the HITRAN and GEISA databases.  
1247 When this was the case, we used the data for which temperature and pressure were closest to  
1248 room temperature, 296 K, and surface pressure, 760 Torr. *Forster et al.* [2005] have shown  
1249 that variation of the diluent pressure over the range 0-740 Torr and temperature over the range  
1250 190-296 K has no discernible (<5%) effect on the integrated absorption band intensities of  
1251 HFC-134a. To sum up, we estimate an uncertainty of 5 and 10% for the experimental and ab  
1252 initio absorption cross-sections, respectively.

1253

### 1254 3.6.2 Radiative forcing calculations

1255 Past studies estimating halocarbon radiative forcings have differed significantly for some  
1256 compounds. For instance, a recent RE estimate of the very potent greenhouse gas sulphur  
1257 hexafluoride ( $\text{SF}_6$ ) ( $0.68 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Zhang et al.*, 2011a] was more than 30% higher than  
1258 the IPCC AR4 estimate ( $0.52 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). As noted in section 3.6.1, differences can arise  
1259 due to uncertainties related to the absorption cross-sections, but a large part of the  
1260 uncertainties is usually related to the radiative forcing calculations.

1261 Multi-model studies have proved particularly useful in assessing and reducing  
1262 uncertainties in the RF calculations. *Forster et al.* [2005] applied six detailed radiative  
1263 transfer models (four line-by-line models and two narrowband models) and reduced the  
1264 uncertainty in the radiative forcing of HFC-134a, a compound with a RE estimate that had  
1265 differed significantly in the previous studies. They also concluded that for this compound the  
1266 uncertainties arising from the RF calculations were larger than those caused by using different  
1267 absorption cross-sections - up to 10 and 7%, respectively. Similarly, *Gohar et al.* [2004]  
1268 obtained differences of less than 12% when using two different radiative transfer models to  
1269 calculate REs of four compounds which had differed significantly in the past literature.

1270 The assumptions related to RF calculations includes the choice of radiation scheme,  
1271 temporal and spatial averaging, cloud data, background temperature and concentrations,  
1272 tropopause height, stratospheric temperature adjustment, and accounting for non-uniform  
1273 vertical profile. A wide range of radiative transfer schemes exist, each varying in complexity.  
1274 Broadband schemes are among the simplest and are often used in General Circulation Models

1275 (GCMs) due to the heavy computational requirements of such models. The intercomparison  
1276 study of *Collins et al.* [2006] showed that there are often large differences in the calculated  
1277 radiative forcing by well-mixed greenhouse gases between the various GCM schemes, and  
1278 between the GCM schemes and the much more detailed and computationally expensive line-  
1279 by-line (LBL) codes. However, the LBL codes were in excellent agreement with each other,  
1280 and this type of code has previously been found to agree well with observations, at least in the  
1281 spectral region between 800 and 2600  $\text{cm}^{-1}$  [*Tjemkes et al.*, 2003], which covers the whole  
1282 atmospheric window. Similarly, *Forster et al.* [2011] generally found agreement within 5%  
1283 for four longwave LBL codes (slightly larger range for shortwave LBL codes) in an  
1284 intercomparison study under clear sky conditions for various cases with changes in GHG  
1285 concentrations, whereas differences were substantially larger for radiative transfer codes used  
1286 in GCMs. One exception for the agreement between the LBL codes was for changes in  
1287 stratospheric water vapor [*Maycock and Shine*, 2012]. In a recent study by *Oreopoulos et al.*  
1288 [2012], a LBL model was validated against several high-resolution spectral measurements and  
1289 used as reference when comparing a number of different LBL and GCM radiative transfer  
1290 codes. They concluded that the longwave radiative transfer schemes were generally in  
1291 agreement with the reference results, and that the current generation schemes perform better  
1292 than the GCMs from two decades ago [*Ellingson and Fouquart*, 1991]. The fact that we apply  
1293 a detailed LBL model, should lead to less uncertainty compared to if a narrowband or  
1294 broadband code was used. In *Forster et al.* [2005], the estimated contribution to total RF  
1295 uncertainty for HFC-134a due to radiative transfer scheme was taken to be 3%. Here, we  
1296 consider this value to be too optimistic and estimate an uncertainty of ~5%. We underscore  
1297 that this uncertainty is for detailed radiative transfer codes and codes which have been  
1298 through careful validation in intercomparison studies such as *Forster et al.* [2005] and does  
1299 not apply to radiative transfer codes traditionally used in GCMs.

1300 Different methodologies in how clouds are treated lead to additional uncertainties in  
1301 radiative transfer models [e.g., *Gohar et al.*, 2004]. Clouds lead to reduced upward irradiance  
1302 and therefore the cloudy-sky radiative forcing is normally about 25-35% lower than the clear-  
1303 sky RF [*Jain et al.*, 2000]. Inter-model differences of up to 10% in the cloud radiative effects  
1304 were found by *Oreopoulos et al.* [2012], while *Forster et al.* [2005] estimated an additional  
1305 uncertainty of about 5% in the RE of HFC-134a due to the inclusion of clouds. The detailed  
1306 radiative transfer codes used in *Forster et al.* [2005] all had a global-mean outgoing longwave

1307 radiative flux at the top of the atmosphere close to observations and they span the range of  
1308 realistic longwave cloud radiative effects [*Kiehl and Trenberth, 1997; Trenberth et al., 2009*].

1309         The effect of spectral overlap is important, including in the atmospheric window  
1310 where most of the halocarbons absorb. Spectral overlap with H<sub>2</sub>O is the most important for  
1311 most compounds, and according to *Pinnock et al. [1995]* and *Jain et al. [2000]*, removing all  
1312 water vapor lead to increases in cloudy-sky instantaneous RF typically in the range ~10-30%.  
1313 However, there is less than 1% increase when reducing the water vapor by 10% [*Pinnock et*  
1314 *al., 1995*], indicating that the uncertainty induced by spectral overlap is negligible. On the  
1315 other hand, omitting N<sub>2</sub>O and CH<sub>4</sub>, which was common in some models, could lead to  
1316 substantially larger errors as they increase the instantaneous RF by about 10% for some  
1317 compounds [*Pinnock et al., 1995*]. In *Forster et al. [2005]*, one model was used to test the  
1318 effect of a 0.2 K uncertainty in surface temperature and of using two different climatologies  
1319 for water vapor and pressure, and found approximately 1 and 2% differences in the radiative  
1320 forcings, respectively. Previous studies have also assessed uncertainties associated with  
1321 spectroscopic measurements in new releases of HITRAN data of the greenhouse gases H<sub>2</sub>O,  
1322 CO<sub>2</sub>, O<sub>3</sub>, N<sub>2</sub>O, and CH<sub>4</sub> [*Kratz, 2008; Pinnock and Shine, 1998*]. In general, they found that  
1323 improvements in absorption spectra for these compounds during the preceding couple of  
1324 decades had a relatively small impact on radiative forcing estimates.

1325         Another factor influencing the radiative forcing estimates is the definition of the  
1326 tropopause (recall from section 2.2 that the radiative forcing is normally defined at the  
1327 tropopause). Previous studies have highlighted the role of choosing an appropriate tropopause  
1328 height, and found differences up to 10% in the global mean instantaneous RF when testing  
1329 various tropopause definitions [*Forster et al., 2005; Freckleton et al., 1998; Myhre and*  
1330 *Stordal, 1997*]. The error when using more than one vertical profile to represent the global  
1331 atmosphere is lower, and we have estimated this uncertainty to be ~5%. Furthermore, the  
1332 effect of global and annual averaging may lead to additional errors due to non-linearities in  
1333 the radiative forcing calculations. For well-mixed gases, *Myhre and Stordal [1997]* found  
1334 only small differences (less than 1%) in RF due to temporal averaging, while spatial  
1335 averaging to one global mean profile induced errors up to 10%, partly due to the strong  
1336 sensitivity to tropopause height for the halocarbons. However, the use of three profiles  
1337 representing the tropics and the extra-tropics of each hemisphere was found sufficient by

1338 *Freckleton et al.* [1998]. The RF calculations presented in this study use two or three profiles,  
1339 representing the tropics and the extra-tropics (see section 3.3.1).

1340 As explained in section 3.3.2, stratospheric temperature adjustment typically leads to  
1341 an increase in cloudy-sky RF for the halocarbons of typically about 10%. *Forster et al.* [2005]  
1342 have provided an estimate of the contribution to the RF uncertainty arising from this factor,  
1343 namely ~4%, based on the results of four different radiative transfer models. The two models  
1344 in *Gohar et al.* [2004] differed by a maximum of 3 percentage points when calculating the  
1345 increase in RF due to stratospheric temperature adjustment for four different HFCs.

1346 One of the largest sources of uncertainties in RF estimates is the effect of a non-  
1347 uniform vertical profile caused mainly by reaction with OH in the troposphere and photolysis  
1348 in the stratosphere (section 3.3.4). *Sihra et al.* [2001] estimated this uncertainty to be in the  
1349 order of 5-10%, while we note from Figure 9 that this number is dependent on the lifetime.  
1350 The fractional correction factors for compounds that are reasonably well-mixed in the  
1351 atmosphere, with lifetimes typically longer than about 5 years, show less spread than the  
1352 compounds with shorter lifetimes. One reason for the larger spread is differences caused by  
1353 the various absorption bands, but is also due to uncertainties related to the geographical  
1354 distribution of emissions which influence both the fractional correction and the atmospheric  
1355 lifetime. However, it should be stressed here that for the sensitivity simulation using the “BC-  
1356 like” emission distribution (section 3.3.3) is considered an extreme case and should be given  
1357 less weight. Based on previous literature and the new simulations performed in this study, we  
1358 estimate an uncertainty of ~5% for compounds with lifetimes longer than about 5 years and  
1359 ~20% for compounds with shorter lifetimes.

1360 Each source of uncertainty and their estimated contribution to the total RE uncertainty  
1361 is listed in Table 1. The uncertainty estimates are based on available published studies and on  
1362 subjective judgment, as discussed above. Using the root-sum-square (RSS) method, we find  
1363 an overall uncertainty due to radiative forcing calculations (including uncertainties in the  
1364 experimental absorption spectra described in section 3.6.1) of approximately 13% for  
1365 compounds with lifetimes longer than around 5 years. When using properly corrected  
1366 theoretical absorption spectra the total uncertainty increases to around 15%. We estimate the  
1367 overall uncertainty to be valid for a 5 to 95% (90%) confidence range, which is the same  
1368 confidence range used for the radiative forcing values in IPCC AR4. Our estimate of 13%  
1369 (valid for experimental cross-sections) is only slightly larger than the 10% uncertainty

1370 reported for long-lived greenhouse gases in AR4. Due to the large uncertainties in the  
1371 fractional correction, the total RF uncertainty increases to ~23% for compounds with lifetimes  
1372 shorter than around 5 years. It should also be noted that the radiation schemes used to produce  
1373 our updated “Pinnock curve” is a detailed LBL code and therefore has less uncertainties than  
1374 models with coarser spectral resolution, such as broadband models.

1375

### 1376 3.6.3 Atmospheric lifetimes

1377 Uncertainties in atmospheric lifetimes arise from a range of factors. For short-lived  
1378 compounds, accurate determinations of the temperature-dependent rate coefficients for  
1379 reactions with OH are needed. The NASA Data Evaluation Panel [Chemical Kinetics and  
1380 Photochemical Data for Use in Atmospheric Studies Evaluation Number 17 NASA Panel for  
1381 Data Evaluation:2011] indicates uncertainties in OH rate constants at room temperature of up  
1382 to about 20% for the compounds considered here. Combined with uncertainties in the  
1383 temperature dependence gives an overall uncertainty of about 30% in the rate coefficient of  
1384 the reactions at tropospheric temperatures. It is also important to note that lifetimes with  
1385 respect to reaction with OH are determined relative to the lifetime of methyl chloroform,  
1386 which in turn is dependent on the global OH field (see section 3.4). As an example, *Prather et*  
1387 *al.* [2012] have used a recently published analysis of methyl chloroform data [*Montzka et al.*,  
1388 2011] to estimate a total lifetime for HFC-134a of 14.2 yr as against the WMO [WMO, 2011]  
1389 recommendation of 13.4 yr. While this change is within our stated uncertainty, the important  
1390 point is that changes in our understanding of the methyl chloroform lifetime can have an  
1391 impact on the lifetimes of a great many compounds.

1392 For some longer-lived compounds, photolysis in the stratosphere is the dominant loss  
1393 process. Estimates of lifetimes for such compounds can be made from their ultraviolet  
1394 absorption cross sections and quantum yields, and the altitude-dependent actinic flux. The  
1395 NASA Data Evaluation Panel provides combined cross section/quantum yield uncertainties  
1396 for some of the compounds considered here. For well-studied CFCs (CFC-11 and CFC-12)  
1397 these uncertainties are well-constrained and are quoted at 10%, while for halons, uncertainties  
1398 of a factor of two are quoted. Combined with uncertainties in the actinic flux, it is clear that  
1399 there can be very significant uncertainties in photolysis lifetimes. This can be particularly true  
1400 when considering very long-lived compounds such as the PFCs [*Ravishankara et al.*, 1993].



1401 However, it should be noted that for such long-lived species, GWPs on a one hundred year  
 1402 time horizon are insensitive to atmospheric lifetimes. Uncertainties in other processes such as  
 1403 deposition can be very large, but as *Prather et al.* [2012] point out, these uncertainties often  
 1404 have a relatively small impact on total lifetimes. In general, uncertainties in lifetimes are large  
 1405 compared to uncertainties in other parameters such as cross sections. A follow up study could  
 1406 assess the uncertainties in lifetimes and the combined effect of RE and lifetimes uncertainties  
 1407 on GWP and GTP.

### 1408 3.6.4 GWP

1409 Some studies have investigated uncertainty in GWP and GTP values [*Boucher, 2012; Olivié*  
 1410 *and Peters, 2012; Reisinger et al., 2010; Wuebbles et al., 1995]* and they have been either  
 1411 based on model comparisons or Monte-Carlo approaches. Uncertainty can also be assessed  
 1412 using standard methods of uncertainty propagation. For a general function,  $f$ , with two  
 1413 independent variables,  $x$  and  $y$ , the uncertainty in  $f$  can be approximated as

$$1414 \quad \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2} \quad (4)$$

1415 This allows combination of different pieces of information on uncertainty (e.g., from  
 1416 independent studies) to assess the importance of the different components of metrics (e.g., RE  
 1417 versus lifetime). We use this approach for two chosen gases as examples (HFC-134a and  
 1418 CFC-11) and use uncertainties in RE obtained in this study with uncertainties in lifetimes  
 1419 from the literature. Based on Equation (4) the uncertainty for AGWP is given by

$$1420 \quad \sqrt{\left(\frac{\partial \text{AGWP}}{\partial \text{RE}}\right)^2 \sigma_{\text{RE}}^2 + \left(\frac{\partial \text{AGWP}}{\partial \tau}\right)^2 \sigma_{\tau}^2} \quad (5)$$

1421 assuming Gaussian distributions and no correlation between RE and  $\tau$ . The derivatives of  
 1422 AGWP with respect to RE and  $\tau$  were obtained analytically. For HFC-134a, the relative  
 1423 uncertainty (for the 5–95% (90%) confidence range) is estimated to be  $\pm 18\%$  for  $\tau$  [*Prather et*  
 1424 *al., 2012]* and  $\pm 13\%$  for RE (from Table 1). Using Equation (5) with these uncertainties, the  
 1425 total uncertainty for  $\text{AGWP}_{\text{HFC-134a}}$  is  $\pm 16\%$  for a 20 year time horizon,  $\pm 22\%$  for 100 years,  
 1426 and  $\pm 22\%$  for 500 years. For CFC-11, the relative uncertainty is estimated to be  $\pm 33\%$  for  $\tau$   
 1427 [*Minschwaner et al., 2012]* and  $\pm 13\%$  for RE (from Table 1). Note that uncertainties related  
 1428 to indirect effects caused by e.g., the influence of CFC-11 on stratospheric ozone, are not

1429 taken into account here. The total uncertainty for  $AGWP_{CFC-11}$  is then  $\pm 15\%$  for a 20 year time  
1430 horizon,  $\pm 28\%$  for 100 years, and  $\pm 36\%$  for 500 years.

1431 The uncertainty in the  $AGWP_{CO_2}$  can be obtained using the  $\pm 10\%$  estimated  
1432 uncertainty in RE [IPCC, 2007] and uncertainty in the time-integrated  $IRF_{CO_2}$  (see definition  
1433 of  $IRF_{CO_2}$  in section 3.5.1) of  $\pm 15\%$ ,  $\pm 25\%$ , and  $\pm 28\%$  for a 20, 100, and 500 year time  
1434 horizon [Joos *et al.*, 2013]. The uncertainty for the product  $AGWP_{CO_2}$ , i.e., the  
1435 uncertainty in  $AGWP_{CO_2}$ , is given by

1436 
$$\sqrt{(\text{uncertainty in RE})^2 + (\text{uncertainty in } IRF_{CO_2})^2}$$

1437 leading to an uncertainty of  $AGWP_{CO_2}$  of  $\pm 18\%$ ,  $\pm 26\%$ , and  $\pm 30\%$ , respectively, with the  
1438 uncertainty dominated by the uncertainty in the integrated  $IRF_{CO_2}$ . These estimates are  
1439 different from what is given by IPCC AR4 where it was stated that  $AGWP$  for  $CO_2$  is  
1440 estimated to be  $\pm 15\%$ , with equal contributions from the  $CO_2$  response function and the RF  
1441 calculation [IPCC, 2007]. The main reason for the difference is the new uncertainty range in  
1442 the IRF for  $CO_2$  based on a multi model study [Joos *et al.*, 2013]. Combining the uncertainty  
1443 in the  $AGWP$  values for HFC-134a and CFC-11 with  $AGWP_{CO_2}$  (using the sum of the squares  
1444 uncertainty propagation), the uncertainty in  $GWP_{HFC-134a}$  is estimated to  $\pm 24\%$ ,  $\pm 34\%$ , and  
1445  $\pm 37\%$  for a 20, 100, and 500 year time horizon. For CFC-11 the  $GWP$  uncertainties are  $\pm 23\%$ ,  
1446  $\pm 38\%$  and  $\pm 47\%$  for a 20, 100, and 500 year time horizon.

1447 IPCC [2007] gives  $GWP$  uncertainties of  $\pm 35\%$  for the 5 to 95% (90%) confidence  
1448 range which is based on earlier IPCC assessments; i.e., the Second and Third Assessment  
1449 reports [IPCC, 1995; 2001].

1450 The stated uncertainties for HFC-134a and CFC-11 are probably representative of  
1451 those for most other CFCs, HCFCs, HFCs and perfluorocarbons with similar or longer  
1452 lifetimes and with experimentally determined absorption cross-sections. For shorter-lived  
1453 gases ( $\tau$  less than 5 years), the uncertainties will be considerably greater (we estimate  $AGWP$   
1454 uncertainties about at least a factor of 2 larger than those given above), and the assumption  
1455 that there is no correlation between RE and  $\tau$  will be less valid. In addition, for the shorter-  
1456 lived gases, both RE and  $\tau$  will depend on the location (and time) of emission, and the validity  
1457 of presenting a single globally-representative value of  $GWPs$  is more questionable.

1458

## 1459 **4 Results and Discussion**

### 1460 **4.1 Infrared Spectra, REs and GWPs**

1461 Absorption cross-sections and radiative efficiency estimates in the literature are reviewed in  
1462 this section. In addition we present new calculations of REs and GWPs for a large number of  
1463 gases based on published absorption cross-sections and the updated Pinnock curve described  
1464 in section 3.3. All the REs are given for cloudy-sky and with stratospheric temperature  
1465 adjustment included (see definition of RE in section 2.2), unless explicitly noted in the text.  
1466 When the atmospheric lifetime is available, a correction for non-homogeneous (vertical and  
1467 horizontal) distribution is applied to the calculated REs, following the methods described in  
1468 section 3.3.4. Each available spectrum has been evaluated and the most reliable spectra have  
1469 been used in the calculations of new best estimate REs, as explained in section 3.1.3.

1470 For each compound our results are compared to the values presented in AR4. In a few  
1471 cases, the best estimate RE from AR4 has been retained when new calculations were not  
1472 carried out due to unavailability of reliable absorption cross-section data. Best estimate RE  
1473 and GWP for each compound are indicated in bold in the tables. Additionally, we provide  
1474 best estimate REs and GWPs for a number of compounds which were not included in AR4,  
1475 but where absorption cross-sections were available or where RE values have been published.  
1476 The atmospheric lifetimes necessary for the GWP calculations have been taken from *WMO*  
1477 [2011] unless stated otherwise in the text. Note that indirect effects caused by e.g., the  
1478 influence of CFCs on stratospheric ozone, have not been studied here but are covered  
1479 elsewhere [e.g., *Daniel et al.*, 1995; *WMO*, 2011]. In the following, a brief discussion is given  
1480 for each compound in each of the categories: chlorofluorocarbons, hydrochlorofluorocarbons,  
1481 hydrofluorocarbons, chlorocarbons, bromocarbons and halons, fully fluorinated species, and  
1482 halogenated alcohols and ethers. Additional information, such as the REs reported in each of  
1483 the individual studies, and the calculated REs of all available spectra, is given in Tables S1-S7  
1484 in the supplementary material.

1485 In the following, when we refer to IPCC AR4 [*IPCC*, 2007] it should be noted that a  
1486 number of compounds were inadvertently omitted in the printed version of AR4 WGI Table  
1487 2.14; we have used the erratum to this table which is available at  
1488 [http://www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/errataserrata-errata.html](http://www.ipcc.ch/publications_and_data/ar4/wg1/en/errataserrata-errata.html).

1489

#### 1490 4.1.1 Chlorofluorocarbons (CFCs)

1491 CFCs are long-lived compounds which are mainly removed in the stratosphere by UV  
1492 photolysis or reaction with excited oxygen atoms, O(<sup>1</sup>D). Their GWPs are generally high due  
1493 to long lifetimes, and despite substantial emission reductions of CFCs during the past couple  
1494 of decades, their radiative forcing of climate will remain large for many decades [WMO,  
1495 2011]. The CFCs are relatively homogeneously distributed in the troposphere, but due to  
1496 photolysis their mixing ratios decrease with increasing altitude in the stratosphere. The IR  
1497 absorption by the CFCs occurs to a large extent in the ‘atmospheric window’ from 800 – 1200  
1498 cm<sup>-1</sup>, as illustrated for CFC-11 in Figure 11. Previously published absorption cross-sections  
1499 are listed in Table 2, while updated atmospheric lifetimes, REs, and GWP(100) values for  
1500 CFCs are presented in Table 3 and discussed below. Unless stated otherwise, the exponential  
1501 fit from section 3.3.4 (Equation (1) and red curve in Figure 9) has been used to account for a  
1502 non-uniform vertical profile for the compounds presented in this subsection.

1503

#### 1504 **CFC-11 (CCl<sub>3</sub>F)**

1505 Several studies have calculated the RE of CFC-11 [*Christidis et al.*, 1997; *Fisher et al.*, 1990;  
1506 *Good et al.*, 1998; *Hansen et al.*, 1997; *Heathfield et al.*, 1998; *Jain et al.*, 2000; *Myhre and*  
1507 *Stordal*, 1997; *Myhre et al.*, 1998; *Naik et al.*, 2000; *Ninomiya et al.*, 2000; *Pinnock et al.*,  
1508 1995; *Sihra et al.*, 2001]. Many of these studies report RE equal to, or close to, 0.25 W m<sup>-2</sup>  
1509 ppb<sup>-1</sup>, (range: 0.22-0.29 W m<sup>-2</sup> ppb<sup>-1</sup>, mean: 0.25 W m<sup>-2</sup> ppb<sup>-1</sup>), which is the value that was  
1510 used in AR4. (It should be noted that the RE values for all compounds reported by *Fisher et*  
1511 *al.* [1990] were given relative to CFC-11 in *IPCC* [1990], assuming a RE of 0.22 W m<sup>-2</sup> ppb<sup>-1</sup>  
1512 for CFC-11. *WMO* [1999] scaled the REs from *Fisher et al.* [1990] by a factor 1.14 to account  
1513 for the change in the recommended forcing for CFC-11 (from 0.22 to 0.25 W m<sup>-2</sup> ppb<sup>-1</sup>), and  
1514 these values were then adopted in subsequent IPCC assessments.) *Good et al.* [1998]  
1515 estimated a value of RE using vibrational integrated absorption cross sections calculated using  
1516 *ab initio* methods and obtained a value some 18% larger than those experimentally-derived  
1517 band strengths.

1518 In the present study we have used absorption spectra from several sources [*Heathfield*  
1519 *et al.*, 1998; *Imasu et al.*, 1995; *Li and Varanasi*, 1994; *Orkin et al.*, 2003; *Sihra et al.*, 2001]  
1520 and calculated the RE of CFC-11, assuming it to be well mixed, to be in the range 0.27 – 0.29

1521  $\text{W m}^{-2} \text{ppb}^{-1}$  (mean:  $0.28 \text{ W m}^{-2} \text{ppb}^{-1}$ ) (see Tables 2-3). For CFC-11 we have carried out  
1522 explicit simulations using the Oslo LBL model and derived factors to account for  
1523 stratospheric temperature adjustment and lifetime adjustment (see sections 3.3.3 and 3.3.4 for  
1524 details and validation against satellite observations of CFC-11). The stratospheric adjustment,  
1525 which is accounted for in the mean value of  $0.28 \text{ W m}^{-2} \text{ppb}^{-1}$ , is assumed to increase the  
1526 forcing by 9.1%, while the lifetime correction reduces this value by 7.3%. Our final value,  
1527  $0.26 \text{ W m}^{-2} \text{ppb}^{-1}$  is in relatively good agreement with AR4. As noted above, the RE in some  
1528 studies is given relative to the RE of CFC-11, and have been scaled in previous assessments  
1529 to the former recommended CFC-11 RE of  $0.25 \text{ W m}^{-2} \text{ppb}^{-1}$ . Here we choose to list the  
1530 absolute REs of these studies [mainly *Fisher et al.*, 1990; *Imasu et al.*, 1995] as scaled to our  
1531 new recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ppb}^{-1}$ .

1532 A significant source of uncertainty related to the GWP of CFC-11 is the lifetime. In  
1533 recent assessments [*IPCC*, 2007; *WMO*, 2011] the lifetime has been estimated as 45 years,  
1534 based on observational studies [*Cunnold et al.*, 1997; *Volk et al.*, 1997] and model studies  
1535 [*WMO*, 1999]. However, new studies, based on both models and observations, suggest a  
1536 longer lifetime for CFC-11. *Douglass et al.* [2008] estimated a CFC-11 lifetime of 56-64  
1537 years using models that have realistic age of air and reproduce the observed relationship  
1538 between the mean age and the fractional release. In *Wuebbles et al.* [2009] the lifetime was  
1539 estimated to be 54 and 57 years, using a 3-D and a 2-D atmospheric chemistry model,  
1540 respectively. Recent studies based on satellite and ground-based observations have estimated  
1541 a CFC-11 lifetime of 50 years (range: 34-67 years) [*Minschwaner et al.*, 2012], 52 years  
1542 (range: 40-66 years) [*Rigby et al.*, 2013], and 59 years (range: 53-66 years) [*Laube et al.*,  
1543 2012]. In Table 2 we choose to keep the lifetime of 45 years from *WMO* [2011] as our best  
1544 estimate.

1545

#### 1546 **CFC-12 ( $\text{CCl}_2\text{F}_2$ )**

1547 Literature values for the RE of CFC-12 [*Fisher et al.*, 1990; *Good et al.*, 1998; *Hansen et al.*,  
1548 1997; *Jain et al.*, 2000; *Myhre and Stordal*, 1997; *Myhre et al.*, 1998; *Myhre et al.*, 2006;  
1549 *Orkin et al.*, 2003; *Sihra et al.*, 2001] provide results in the range  $0.30 - 0.33 \text{ W m}^{-2} \text{ppb}^{-1}$   
1550 with a mean of  $0.32 \text{ W m}^{-2} \text{ppb}^{-1}$ , while a value of  $0.32 \text{ W m}^{-2} \text{ppb}^{-1}$  was used in AR4 (based  
1551 on *Myhre and Stordal* [1997]). Differences are caused by differing impact of clouds,  
1552 absorption cross-section data and the vertical profile of decay of the mixing ratio in the

1553 stratosphere [IPCC, 2001]. Detailed LBL calculations were performed by *Myhre et al.* [2006]  
1554 who calculated a RE of  $0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$ . Here we have used absorption cross sections from  
1555 several sources [*Clerbaux et al.*, 1993; *Myhre et al.*, 2006; *Orkin et al.*, 2003; *Sihra et al.*,  
1556 2001; *Varanasi and Nemtchinov*, 1994] to calculate an average RE due to CFC-12 of  $0.32 \text{ W}$   
1557  $\text{m}^{-2} \text{ ppb}^{-1}$  (range:  $0.29 - 0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) (Tables 2-3). As for CFC-11 we have carried out  
1558 explicit simulations of CFC-12 using the Oslo LBL model and derived factors to account for  
1559 stratospheric temperature adjustment and lifetime adjustment. The instantaneous RE is  
1560 increased by 10.5% when stratospheric temperature adjustment is taken into account, while  
1561 the lifetime correction reduces the RE by 3.0%. Our final estimate ( $0.32 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) is in  
1562 excellent agreement with that used in AR4. In contrast to CFC-11, the atmospheric lifetimes  
1563 of CFC-12 derived in the new model study by *Douglass et al.* [2008] are in good agreement  
1564 with those used in previous IPCC and WMO assessments, and we here adopt the lifetime of  
1565 100 years which has been used since the assessment of *WMO* [1999].

1566

#### 1567 **CFC-13 (CCIF<sub>3</sub>)**

1568 A value of  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$  for the RE of CFC-13 has been used in the previous IPCC and  
1569 WMO assessments and is from *Myhre and Stordal* [1997] who used a broadband model. The  
1570 same value was calculated with a narrowband model in *Jain et al.* [2000], and was obtained in  
1571 this study using absorption cross-section data from *McDaniel et al.* [1991].

1572

#### 1573 **CFC-113 (CCl<sub>2</sub>FCCIF<sub>2</sub>)**

1574 Literature measurements of the RE of CFC-113 fall in the range  $0.28 - 0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$  with  
1575 a mean of  $0.31 \text{ W m}^{-2} \text{ ppb}^{-1}$  [*Fisher et al.*, 1990; *Jain et al.*, 2000; *Myhre and Stordal*, 1997],  
1576 which is the same value as in AR4 (based on *Myhre and Stordal* [1997]). We have used  
1577 absorption cross-sections from a recent study by *Le Bris et al.* [2011] and from *McDaniel et*  
1578 *al.* [1991] to obtain values of  $0.31$  and  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$ , respectively. Our average RE ( $0.30$   
1579  $\text{W m}^{-2} \text{ ppb}^{-1}$ ) is in excellent agreement with AR4.

1580

#### 1581 **CFC-114 (CCIF<sub>2</sub>CCIF<sub>2</sub>)**

1582 Literature measurements of the RE of CFC-114 are in the range  $0.29 - 0.38 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1583 (mean:  $0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Fisher *et al.*, 1990; Jain *et al.*, 2000; Myhre and Stordal, 1997].  
1584 AR4 reports a RE of  $0.31 \text{ W m}^{-2} \text{ ppb}^{-1}$  (based on Myhre and Stordal [1997]) which is the  
1585 same as calculated here using absorption cross-section from McDaniel *et al.* [1991]. Although  
1586 our RE estimate is in excellent agreement with AR4, the best estimate GWP of CFC-114 is  
1587 about 15% lower (Table 3) due to the shorter lifetime and higher  $\text{AGWP}_{\text{CO}_2}$  used here. We  
1588 have used the lifetime from WMO [2011] of 190 years, which is based on new model  
1589 calculations by Prather and Hsu [2008; 2010], and is approximately 40% shorter than the  
1590 AR4 estimate of 300 years..

1591

#### 1592 **CFC-115 (CClF<sub>2</sub>CF<sub>3</sub>)**

1593 Literature reports of the RE of CFC-115 fall in the range  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$  to  $0.30 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1594 (mean:  $0.24 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Fisher *et al.*, 1990; Jain *et al.*, 2000; Myhre and Stordal, 1997],  
1595 while the latest assessments (since IPCC [2001]) have used the instantaneous forcing of  $0.18$   
1596  $\text{W m}^{-2} \text{ ppb}^{-1}$  from Myhre and Stordal [1997] (note that the value from AR4 falls outside the  
1597 range quoted for the range of literature values because they reported the instantaneous RE  
1598 while we consider the RE from Myhre and Stordal [1997]). The much higher RE of CFC-115  
1599 calculated by Fisher *et al.* [1990] compared to Myhre and Stordal [1997] and Jain *et al.*  
1600 [2000] is most likely caused by the much higher integrated absorption cross-section in the  
1601 first study compared to the work of McDaniel *et al.* [1991] which has been used in the two  
1602 latter studies (Table 2). We calculate a RE value of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$ , which is in agreement  
1603 with Myhre and Stordal [1997] and close to the RE of  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$  estimated by Jain *et al.*  
1604 [2000]. As for CFC-114, new model calculations [Prather and Hsu, 2008; 2010] suggested  
1605 a significantly shorter lifetime of 1,020 years for CFC-115 (compared to 1,700 years in AR4).  
1606 Nevertheless, the GWP(100) of CFC-115 is still ~4% higher than in AR4 due to the higher  
1607 RE of CFC-115 calculated here (Table 3).

1608

#### 1609 **4.1.2 Hydrochlorofluorocarbons (HCFCs)**

1610 HCFCs are controlled by the Montreal Protocol, but they have been common substitutes for  
1611 CFCs due to their lower potential for ozone depletion. As a consequence, atmospheric  
1612 concentrations of some HCFCs have grown rapidly over the last decade, as illustrated for

1613 HCFC-22 in Figure 1. The atmospheric lifetimes of HCFCs are generally lower than for  
1614 CFCs, but some of these compounds still have sufficiently long lifetimes to yield significant  
1615 global warming potentials. The absorption cross-section of one of the most well-studied  
1616 gases, HCFC-22, is shown in Figure 12. Similarly to the CFCs, most of the absorption from  
1617 HCFCs occurs in the atmospheric window region (800 – 1200  $\text{cm}^{-1}$ ). Previously published  
1618 absorption cross-sections are listed in Table 4, while best estimate lifetimes, radiative  
1619 efficiencies and GWP(100) values for HCFCs are given in Table 5 and discussed below.  
1620 Since the main loss mechanism for HCFCs is through reaction with OH in the troposphere,  
1621 the S-shaped fit from section 3.3.4 (Equation (2) and dark blue curve in Figure 9) has been  
1622 used to account for the non-uniform vertical profile and horizontal distribution of all  
1623 compounds presented in this subsection.

1624

#### 1625 **HCFC-21 ( $\text{CHCl}_2\text{F}$ )**

1626 REs of  $0.19 \text{ W m}^{-2} \text{ ppb}^{-1}$  [Christidis *et al.*, 1997] and  $0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$  [Sihra *et al.*, 2001]  
1627 have been reported for HCFC-21. The difference in the results between the studies reflects  
1628 different vertical profile assumptions; Christidis *et al.* [1997] assumed a constant vertical  
1629 profile while Sihra *et al.* [2001] accounted for the fall-off in concentration of this relatively  
1630 short-lived species (1.7 years atmospheric lifetime) above the troposphere. The RE from Sihra  
1631 *et al.* [2001] is used for the recommended RE in AR4, and the cross-section from that study  
1632 has been used in our RE and GWP calculations. Both the HITRAN 2008 and GEISA 2009  
1633 databases include the spectrum from Massie *et al.* [1985], but this spectrum contains only one  
1634 of the absorption bands (785-840  $\text{cm}^{-1}$ ) and has therefore not been employed in our  
1635 calculations. Our estimate of  $0.15 \text{ W m}^{-2} \text{ ppb}^{-1}$  is in good agreement (3.8% higher prior to  
1636 rounding) with the AR4 (see Table 5).

1637

#### 1638 **HCFC-22 ( $\text{CHClF}_2$ )**

1639 HCFC-22 is one of the most well-studied compounds with RE estimates in the literature  
1640 ranging from 0.18 to  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Fisher *et al.*, 1990; Good *et al.*,  
1641 1998; Highwood and Shine, 2000; Jain *et al.*, 2000; Myhre and Stordal, 1997; Naik *et al.*,  
1642 2000; Orkin *et al.*, 2003; Pinnock *et al.*, 1995; Sihra *et al.*, 2001]. Papasavva *et al.* [1997]  
1643 used an *ab initio* spectrum which is approximately 10% more intense than the experimentally



1644 derived spectra (Table 4) and consequently report a RE of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is 10%  
1645 higher than the average from the experimental studies. AR4 reports a RE of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1646 which is taken from *Highwood and Shine* [2000]. We have based our calculations on the  
1647 spectrum from *Ballard et al.* [2000b] which is a composite of measurements from five  
1648 laboratory groups, and is in good agreement with other reported experimental spectra (see  
1649 Table 4). Our calculations yield a RE value of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$ , which is the same as  
1650 recommended by AR4. We note that calculated RE values using absorption cross-sections  
1651 available from other studies [*Clerbaux et al.*, 1993; *Highwood and Shine*, 2000; *Orkin et al.*,  
1652 2003; *Pinnock et al.*, 1995; *Sihra et al.*, 2001] (see SI Table 2 for individual results) agree to  
1653 within 4% of the RE value calculated using the spectrum from *Ballard et al.* [2000b],  
1654 indicating that the uncertainty in the HCFC-22 spectrum is rather small (the spectrum  
1655 reported by *Varanasi et al.* [1994] was not included in this comparison because one of the  
1656 absorption bands was missing).

1657

#### 1658 **HCFC-122 (CHCl<sub>2</sub>CF<sub>2</sub>Cl)**

1659 One study has estimated the instantaneous RE of HCFC-122 with a value  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1660 [*Orkin et al.*, 2003] (scaled to our recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). We have  
1661 used their absorption spectrum and calculated a RE value of  $0.17 \text{ W m}^{-2} \text{ ppb}^{-1}$ . The main  
1662 reasons for the lower value calculated here are probably that *Orkin et al.* [2003] used a  
1663 simplified approach which were not based on radiative transfer calculations, and that they did  
1664 not account for stratospheric temperature adjustment and inhomogeneous distribution in the  
1665 troposphere. The lifetime of 1.0 year is taken from *Orkin et al.* [2003].

1666

#### 1667 **HCFC-122a (CHFClCFCl<sub>2</sub>)**

1668 One study has estimated instantaneous RE due to HCFC-122a, with a value  $0.24 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1669 [*Orkin et al.*, 2003] (scaled to our recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). We  
1670 calculate a RE value of  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using their absorption cross-section and  
1671 lifetime estimate of 3.4 years.

1672

#### 1673 **HCFC-123 (CHCl<sub>2</sub>CF<sub>3</sub>)**

1674 Literature estimations of the RE of HCFC-123 derived from experimental measurements of  
1675 the IR spectrum lie in the range  $0.14 - 0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.18 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Fisher et al.*, 1990; *Jain et al.*, 2000; *Naik et al.*, 2000; *Orkin et al.*, 2003; *Pinnock et al.*, 1995; *Sihra et al.*, 2001]. As seen from Table 4, the infrared spectrum reported in the *ab initio* study of  
1677 *Papasavva et al.* [1997] is more intense than measured in the experimental studies and  
1678 consequently the instantaneous RE of  $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  is higher than those determined in the  
1679 experimental studies. AR4 report a RE of  $0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is based on both *Sihra et al.*  
1680 [2001] and *Jain et al.* [2000]. We calculate a slightly higher RE value of  $0.15 \text{ W m}^{-2} \text{ ppb}^{-1}$  for  
1681 all three sources of absorption spectra [*Clerbaux et al.*, 1993; *Orkin et al.*, 2003; *Sihra et al.*,  
1682 2001] (Tables 4-5). It should be noted here that for this compound we have applied a  
1683 correction for stratospheric temperature adjustment of 6.5% (the average of the values found  
1684 by *Jain et al.* [2000] (5%) and *Pinnock et al.* [1995] (8%)) rather than the generic 10%  
1685 correction used elsewhere in section 4.1.2.  
1686

1687

#### 1688 **HCFC-123a (CHClCF<sub>2</sub>Cl)**

1689 One study has estimated instantaneous RE of HCFC-123a with a value  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1690 [*Orkin et al.*, 2003] (scaled to our recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). We have  
1691 used their absorption spectrum and calculated a slightly lower RE value of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$ .

1692

#### 1693 **HCFC-124 (CHClCF<sub>3</sub>)**

1694 Previous studies of RE due to HCFC-124 are in relatively good agreement with a range of  
1695  $0.19 - 0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Fisher et al.*, 1990; *Jain et al.*, 2000; *Naik et al.*, 2000; *Pinnock et al.*, 1995; *Sihra et al.*, 2001]. As for HCFC-123, *Papasavva et al.*  
1696 [1997] calculated a higher RE of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  (instantaneous RE) based upon an *ab initio*  
1697 absorption cross-section. IPCC AR4 report a RE of  $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from  
1698 *Fisher et al.* [1990] (note that AR4 scaled the RE value from *Fisher et al.* [1990] to the  
1699 previously recommended CFC-11 RE of  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$  – see the discussion concerning  
1700 CFC-11 in section 4.1.1 – while we refer to the *Fisher et al.* [1990] value as scaled to our  
1701 recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). We have used absorption cross-sections  
1702 from *Sihra et al.* [2001] and *Clerbaux et al.* [1993] to calculate a mean RE value of  $0.20 \text{ W m}^{-2}$   
1703  $\text{ppb}^{-1}$  (range:  $0.19 - 0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) (Tables 4-5), which is lower than in *Fisher et al.*  
1704

1705 [1990]. However, our calculated RE is in agreement with the newer studies of *Sihra et al.*  
1706 [2001], *Jain et al.* [2000] and *Naik et al.* [2000], most likely due to the higher integrated  
1707 absorption cross-section of *Fisher et al.* [1990] (Table 4).

1708

#### 1709 **HCFC-132c (CH<sub>2</sub>FCFCl<sub>2</sub>)**

1710 One study has estimated instantaneous RE due to HCFC-132c, with a value  $0.19 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1711 [*Orkin et al.*, 2003] (scaled to our recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). We  
1712 calculate a RE value of  $0.17 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using their absorption cross-section and  
1713 lifetime estimate of 4.3 years.

1714

#### 1715 **HCFC-141b (CH<sub>3</sub>CCl<sub>2</sub>F)**

1716 Radiative efficiencies for HCFC-141b reported in the published literature are in the range  
1717  $0.12 - 0.18 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.15 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Fisher et al.*, 1990; *Imasu et al.*, 1995; *Jain*  
1718 *et al.*, 2000; *Naik et al.*, 2000; *Orkin et al.*, 2003; *Pinnock et al.*, 1995; *Sihra et al.*, 2001], and  
1719 the value of  $0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Fisher et al.* [1990] has been used by AR4 (scaled to the  
1720 previously recommended CFC-11 RE of  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). *Papasavva et al.* [1997]  
1721 calculated a much higher RE (instantaneous RE of  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) using an *ab initio*  
1722 absorption spectrum. We calculate a slightly higher RE than AR4 with a mean value of  $0.16$   
1723  $\text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.15 - 0.17 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) when using absorption cross-sections from  
1724 several sources [*Clerbaux et al.*, 1993; *Imasu et al.*, 1995; *Orkin et al.*, 2003; *Sihra et al.*,  
1725 2001]. We note that the value of  $0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Fisher et al.* [1990] has been scaled  
1726 by AR4 to account for changes in the recommended RE of CFC-11 (from  $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  in  
1727 *Fisher et al.* [1990] to  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$  in AR4), and that a scaling to our recommended  
1728 CFC-11 forcing of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$  results in a RE of  $0.15 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Fisher et al.*  
1729 [1990] – in better agreement with our calculations.

1730

#### 1731 **HCFC-142b (CH<sub>3</sub>CCIF<sub>2</sub>)**

1732 Previous reports of RE of HCFC-142b are in the range  $0.16 - 0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.18 \text{ W}$   
1733  $\text{ m}^{-2} \text{ ppb}^{-1}$ ) [*Fisher et al.*, 1990; *Jain et al.*, 2000; *Naik et al.*, 2000; *Pinnock et al.*, 1995; *Sihra*  
1734 *et al.*, 2001]. Again, the *ab initio* study of *Papasavva et al.* [1997] is at the higher end of the

1735 range based on experimental studies as they calculate an instantaneous RE of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1736 <sup>1</sup>. AR4 report a RE of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from *Fisher et al.* [1990]. We calculate  
1737 a mean RE value of  $0.19 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.18 - 0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) when using absorption  
1738 cross-sections from *Sihra et al.* [2001] and *Clerbaux et al.* [1993] (Tables 4-5). Our estimate  
1739 is lower than *Fisher et al.* [1990] and *Pinnock et al.* [1995], but higher than the more recent  
1740 studies [*Jain et al.*, 2000; *Naik et al.*, 2000; *Sihra et al.*, 2001].

1741

#### 1742 **HCFC-225ca (CHCl<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)**

1743 A range of  $0.20 - 0.27 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) for the RE of HCFC-225ca has  
1744 been reported in the literature [*Jain et al.*, 2000; *Naik et al.*, 2000; *Pinnock et al.*, 1995; *Sihra*  
1745 *et al.*, 2001]. Three of the studies are in good agreement (<3% difference) while *Pinnock et al.*  
1746 [1995] is an outlier with a value of  $0.27 \text{ W m}^{-2} \text{ ppb}^{-1}$ , despite the lower integrated absorption  
1747 cross-section in their study (Table 4). The reason is that *Pinnock et al.* [1995] did not take into  
1748 account the non-uniform tropospheric distribution, which gives a reduction in the RE of 16%  
1749 when using our fractional correction method described in section 3.3.4 and a lifetime of 1.9  
1750 years [*WMO*, 2011]. AR4 has based their RE recommendation of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$  on *Sihra*  
1751 *et al.* [2001] and *Jain et al.* [2000]. We calculate a mean RE value of  $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  
1752  $0.22 - 0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) when using absorption cross-sections from *Sihra et al.* [2001] and  
1753 *Clerbaux et al.* [1993] (Tables 4-5).

1754

#### 1755 **HCFC-225cb (CHClCF<sub>2</sub>CClF<sub>2</sub>)**

1756 The RE of HCFC-225cb has differed considerably in the past literature with a range of  $0.25 -$   
1757  $0.35 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Imasu et al.*, 1995; *Jain et al.*, 2000; *Naik et al.*,  
1758 2000; *Pinnock et al.*, 1995; *Sihra et al.*, 2001]. A value of  $0.32 \text{ W m}^{-2} \text{ ppb}^{-1}$  has been used in  
1759 previous assessments and is based on Granier (pers. comm.) [*IPCC*, 1994]. We calculate a  
1760 mean RE value of  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.28 - 0.31 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) when using absorption  
1761 cross-sections from *Sihra et al.* [2001], *Clerbaux et al.* [1993] and *Imasu et al.* [1995] (Tables  
1762 4-5). Our result differs by almost 10% from the AR4 recommendation. As the AR4 value is  
1763 not based on published literature it is difficult to assess the reasons to why our estimate is  
1764 significantly lower than their value, but we note that our estimate is in agreement with the

1765 mean of published values and close to the most recent published RE estimate of HCFC-225cb  
1766 of  $0.28 \text{ W m}^{-2} \text{ ppb}^{-1}$  [Sihra *et al.*, 2001].

1767

#### 1768 **(E)-1-Chloro-3,3,3-trifluoroprop-1-ene (CF<sub>3</sub>CH=CHCl(E))**

1769 The radiative efficiency of (E)-1-chloro-3,3,3-trifluoroprop-1-ene has not been assessed in  
1770 AR4, but was estimated by *Andersen et al.* [2008]. They used the original *Pinnock et al.*  
1771 [1995] method and calculated an instantaneous RE of  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$ . Their absorption  
1772 cross-section has been used in this study to calculate a lifetime-corrected RE of  $0.04 \text{ W m}^{-2}$   
1773  $\text{ppb}^{-1}$  (Table 5). The short lifetime of 26 days [WMO, 2011] for this compound leads to a  
1774 strong effect of the fractional correction factor which has been applied to account for non-  
1775 uniform mixing (vertical and horizontal). It should be noted here that the uncertainties  
1776 associated with this correction factor are very large on a percentage basis for such short-lived  
1777 species (see Figure 9 and associated discussion in section 3.3.4), and we further note that our  
1778 calculated RE is in good agreement with *Andersen et al.* [2008] if we assume uniform mixing.

1779

#### 1780 **4.1.3 Hydrofluorocarbons (HFCs)**

1781 HFCs do not destroy stratospheric ozone [Ravishankara *et al.*, 1994; Wallington *et al.*, 1995]  
1782 and have emerged as important replacements for ozone-depleting substances such as the  
1783 CFCs. The main removal mechanism for the HFCs is through reaction with OH. The  
1784 atmospheric lifetime of HFCs depends on their reactivity towards OH radicals and ranges  
1785 from 2.1 days for CH<sub>2</sub>=CHF to 242 years for CF<sub>2</sub>CH<sub>2</sub>CF<sub>3</sub> (HFC-236fa). Compounds with  
1786 lifetimes greater than a decade tend to be well mixed in the troposphere. Compounds with  
1787 lifetimes less than a year are not well mixed and have an inhomogeneous distribution within  
1788 the troposphere and needs to be accounted for in RE estimates. HFCs have strong absorption  
1789 bands within the atmospheric window region ( $800 - 1200 \text{ cm}^{-1}$ ) and hence have the potential  
1790 to be potent greenhouse gases, especially for long-lived gases such as HFC-23 and HFC-  
1791 236fa which have lifetimes greater than 200 years. At the other extreme, fluorinated alkenes  
1792 such as CF<sub>3</sub>CF=CH<sub>2</sub> (HFC-1234yf) have very short atmospheric lifetimes (1-2 weeks) and are  
1793 not significant greenhouse gases. HFC-134a (CF<sub>3</sub>CFH<sub>2</sub>) is the most abundant HFC in the  
1794 atmosphere and is currently present at a concentration of approximately 60 ppt (Figure 1).  
1795 HFC-134a has a lifetime of 13.4 years and its potency as a greenhouse gas lies between those

1796 of the long-lived and short lived HFCs. Figure 13 shows the absorption spectrum of HFC-  
1797 134a which, because of its industrial importance, has been studied extensively and is perhaps  
1798 the best established of all the HFCs. Published absorption cross-sections for HFCs are listed  
1799 in Table 6, atmospheric lifetimes, radiative efficiencies, and GWP(100) values for HFCs are  
1800 presented in Table 7 and discussed below. The S-shaped fit from section 3.3.4 (Equation (2)  
1801 and dark blue curve in Figure 9) has been used to account for a non-uniform vertical profile  
1802 and geographic distribution for all compounds presented in this subsection.

1803

#### 1804 **HFC-23 (CHF<sub>3</sub>)**

1805 Published estimates of the RE of HFC-23 span the range 0.16 – 0.27 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.21  
1806 W m<sup>-2</sup> ppb<sup>-1</sup>) [Gohar *et al.*, 2004; Highwood and Shine, 2000; Jain *et al.*, 2000; Naik *et al.*,  
1807 2000; Pinnock *et al.*, 1995; Sihra *et al.*, 2001]. AR4 adopted the value of 0.19 W m<sup>-2</sup> ppb<sup>-1</sup>  
1808 from Gohar *et al.* [2004], who used two different radiative transfer methods to estimate  
1809 forcings of 0.18 and 0.19 W m<sup>-2</sup> ppb<sup>-1</sup>. The small differences between results from the two  
1810 models used by Gohar *et al.* [2004] were attributed to slight differences in the treatment of  
1811 clouds in the models. The large difference between the results of Gohar *et al.* [2004] and  
1812 those of Jain *et al.* [2000] (0.248 W m<sup>-2</sup> ppb<sup>-1</sup>) and Naik *et al.* [2000] (0.271 W m<sup>-2</sup> ppb<sup>-1</sup>) is  
1813 difficult to explain because all three studies used essentially the same IR spectrum. Two  
1814 studies have used *ab initio* methods to estimate HFC-23 RE to be 0.18 W m<sup>-2</sup> ppb<sup>-1</sup> [Blowers  
1815 and Hollingshead, 2009] and 0.19 W m<sup>-2</sup> ppb<sup>-1</sup> [Papavasava *et al.*, 1997], but these are  
1816 instantaneous REs and must be increased by approximately 11% [Gohar *et al.*, 2004] to be  
1817 comparable with the RE values (including stratospheric temperature adjustment) reported by  
1818 Gohar *et al.* [2004]. We have used absorption cross-sections from Gohar *et al.* [2004] and  
1819 Highwood and Shine [2000] to calculate RE values of 0.19 and 0.16 W m<sup>-2</sup> ppb<sup>-1</sup>,  
1820 respectively, which are in excellent agreement with the REs reported in each of the two  
1821 individual studies. The mean of our calculated REs (0.18 W m<sup>-2</sup> ppb<sup>-1</sup>) is slightly more than  
1822 5% lower than the AR4 recommendation. The relatively large range in the integrated  
1823 absorption cross-sections for HFC-23 (Table 6), and subsequent large range of REs in our  
1824 calculations, indicates that there are uncertainties related to the measurements of the  
1825 absorption cross-section for this compound (the absorption band below 700 cm<sup>-1</sup>, which is  
1826 only taken into account in Gohar *et al.* [2004], has only a negligible contribution to the  
1827 integrated absorption cross-section).

1828

1829 **HFC-32 (CH<sub>2</sub>F<sub>2</sub>)**

1830 Estimates for the RE of HFC-32 based on experimental absorption cross-sections range from  
1831 0.09 to 0.16 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.12 W m<sup>-2</sup> ppb<sup>-1</sup>) [Gohar *et al.*, 2004; Highwood and Shine,  
1832 2000; Jain *et al.*, 2000; Naik *et al.*, 2000; Orkin *et al.*, 2003; Pinnock *et al.*, 1995; Sihra *et al.*,  
1833 2001; Zhang *et al.*, 2011b], while estimates based on absorption cross-sections from *ab initio*  
1834 studies are in the range 0.12 – 0.13 W m<sup>-2</sup> ppb<sup>-1</sup> (instantaneous RE) [Blowers and  
1835 Hollingshead, 2009; Papasavva *et al.*, 1997]. As for HFC-23, the results of Gohar *et al.*  
1836 [2004] were used in AR4 with a value of 0.11 W m<sup>-2</sup> ppb<sup>-1</sup>. We have used absorption spectra  
1837 from Gohar *et al.* [2004], Highwood and Shine [2000] and Orkin *et al.* [2003] and derived a  
1838 RE of HFC-32 of 0.11 W m<sup>-2</sup> ppb<sup>-1</sup> for all these spectra, in excellent agreement with AR4. It  
1839 should be noted that additional absorption cross-sections are available e.g., through the  
1840 HITRAN and GEISA databases (Table 6), but have not been included to avoid double-  
1841 counting of absorption cross-sections from the same laboratory groups (e.g., both Highwood  
1842 and Shine [2000] and Smith *et al.* [1996] are based on spectra from the Molecular  
1843 Spectroscopy Facility / Rutherford Appleton Laboratory [M.S.F./R.A.L.]). The combination  
1844 of a change in the recommended lifetime for this compound (5.2 years in WMO [2011]  
1845 compared to 4.9 years in AR4) and the higher AGWP<sub>CO<sub>2</sub></sub> used here, result in a GWP(100)  
1846 value which is about the same as in AR4 (see Table 7).

1847

1848 **HFC-41 (CH<sub>3</sub>F)**

1849 A radiative efficiency for HFC-41 of 0.02 W m<sup>-2</sup> ppb<sup>-1</sup> has been used in previous assessments  
1850 and is taken from Pinnock *et al.* [1995] (note that stratospheric decay was accounted for in the  
1851 assessments, but not in the original study). A range of 0.02 – 0.03 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.03 W  
1852 m<sup>-2</sup> ppb<sup>-1</sup>) has been reported from studies using measured absorption cross-sections [Pinnock  
1853 *et al.*, 1995; Sihra *et al.*, 2001]. The *ab initio* studies have the same range and mean, but they  
1854 have only reported instantaneous RE [Blowers and Hollingshead, 2009; Papasavva *et al.*,  
1855 1997]. We used the absorption spectrum from Sihra *et al.* [2001] and derived a RE value of  
1856 0.02 W m<sup>-2</sup> ppb<sup>-1</sup>, which is in excellent agreement with AR4. It should be noted that  
1857 stratospheric temperature adjustment normally leads to a stronger forcing compared to  
1858 instantaneous RE (recall from section 3.3.2 that we apply a 10% increase for most  
1859 compounds), while for HFC-41 it leads to a weakening due to the strong overlap with the

1860 absorption spectrum of ozone [Pinnock *et al.*, 1995]. We have carried out explicit LBL model  
1861 calculations and estimated a 5.0% decrease for the stratospheric temperature adjustment for  
1862 HFC-41 (see section 3.3.2), and this result has been used (instead of the 10% increase) to  
1863 calculate the RE of  $0.02 \text{ W m}^{-2} \text{ ppb}^{-1}$  above. Due to a change in the recommended lifetime for  
1864 this compound (2.8 years in *WMO* [2011] compared to 2.4 years in AR4) our recommended  
1865 GWP value is higher than in AR4 (see Table 7).

1866

#### 1867 **HFC-125 (CHF<sub>2</sub>CF<sub>3</sub>)**

1868 Previous studies have reported a fairly wide range of RE values for HFC-125: 0.21 - 0.30 W  
1869  $\text{m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Fisher *et al.*, 1990; Highwood and Shine, 2000; Imasu *et*  
1870 *al.*, 1995; Jain *et al.*, 2000; Naik *et al.*, 2000; Orkin *et al.*, 2003; Pinnock *et al.*, 1995; Sihra *et*  
1871 *al.*, 2001; Young *et al.*, 2009b; Zhang *et al.*, 2011b]. *Ab initio* studies for this compound have  
1872 calculated REs that are at the high end of the range of experimental studies with instantaneous  
1873 RE of  $0.24 \text{ W m}^{-2} \text{ ppb}^{-1}$  [Papavasava *et al.*, 1997] and RE of  $0.28 \text{ W m}^{-2} \text{ ppb}^{-1}$  [Good *et al.*,  
1874 1998]. The recent study by Zhang *et al.* [2011b] is an outlier with a value of  $0.30 \text{ W m}^{-2} \text{ ppb}^{-1}$ ,  
1875 but they did not identify any clear reason for the large difference between their result and the  
1876 results from all other studies. Zhang *et al.* [2011b] calculate their RE from a combination of  
1877 forcings from three standard atmospheres; they do not show to what extent this combination is  
1878 representative of a true global-mean atmosphere, nor do they show how their outgoing  
1879 longwave radiation or cloud forcing, using this combination of atmospheres, compare with  
1880 satellite observed values, which is an important diagnostic of model behavior [e.g., Forster *et*  
1881 *al.*, 2005]. Recent assessments have used the value of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  estimated in  
1882 Highwood and Shine [2000]. We have used absorption cross-sections from several sources  
1883 [Clerbaux *et al.*, 1993; Highwood and Shine, 2000; Imasu *et al.*, 1995; Orkin *et al.*, 2003;  
1884 Young *et al.*, 2009b] (see also Table 6; note that the spectrum from Young *et al.* [2009b]  
1885 supersede that of Sihra *et al.* [2001]) and calculated a mean RE value of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1886 (range:  $0.21 - 0.24 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) (Table 7), which is in excellent agreement with AR4 (note  
1887 that our use of a lifetime of 28.2 years recommended by [WMO, 2011] is shorter than that of  
1888 29 years used in AR4, but this does not affect the GWP(100) value significantly).

1889

#### 1890 **HFC-134 (CHF<sub>2</sub>CHF<sub>2</sub>)**



1891 Studies of the radiative efficiency of HFC-134 have reported values in the range 0.18 – 0.27  
1892  $\text{W m}^{-2} \text{ppb}^{-1}$  (mean:  $0.20 \text{ W m}^{-2} \text{ppb}^{-1}$ ) [*Christidis et al.*, 1997; *Jain et al.*, 2000; *Naik et al.*,  
1893 2000; *Sihra et al.*, 2001; *Zhang et al.*, 2011b]. Again, *Zhang et al.* [2011b] is an outlier with a  
1894 RE value of  $0.27 \text{ W m}^{-2} \text{ppb}^{-1}$ , which is more than 30% higher than reported in any of the  
1895 other studies (see also the HFC-125 section above for a discussion of *Zhang et al.* [2011b]).  
1896 The *ab initio* studies are in good agreement with the mean of experimental studies for this  
1897 compound as both *Papasavva et al.* [1997] and *Good et al.* [1998] calculated REs of  $0.20 \text{ W}$   
1898  $\text{m}^{-2} \text{ppb}^{-1}$  (the first study calculated instantaneous RE). Previous assessments have used the  
1899 value of  $0.18 \text{ W m}^{-2} \text{ppb}^{-1}$  based on *Christidis et al.* [1997] (a scaling factor to account for  
1900 decreased concentrations in the stratosphere was applied). We calculate a mean RE value of  
1901  $0.19 \text{ W m}^{-2} \text{ppb}^{-1}$  (range:  $0.18 - 0.20 \text{ W m}^{-2} \text{ppb}^{-1}$ ) when using absorption cross-sections from  
1902 two sources [*Sihra et al.*, 2001; *Smith et al.*, 1998]. Our GWP(100) estimate is similar to AR4  
1903 due to the combination of a slightly higher RE, a slightly longer lifetime, and a higher  
1904  $\text{AGWP}_{\text{CO}_2}$  used here.

1905

#### 1906 **HFC-134a ( $\text{CH}_2\text{FCF}_3$ )**

1907 Calculations of the RE of HFC-134a are in the range  $0.15 - 0.22 \text{ W m}^{-2} \text{ppb}^{-1}$  (mean:  $0.18 \text{ W}$   
1908  $\text{m}^{-2} \text{ppb}^{-1}$ ) [*Fisher et al.*, 1990; *Forster et al.*, 2005; *Gohar et al.*, 2004; *Highwood and Shine,*  
1909 2000; *Imasu et al.*, 1995; *Jain et al.*, 2000; *Naik et al.*, 2000; *Orkin et al.*, 2003; *Pinnock et*  
1910 *al.*, 1995; *Sihra et al.*, 2001; *Zhang et al.*, 2011b], while one *ab initio* study estimated an  
1911 instantaneous RE of  $0.14 \text{ W m}^{-2} \text{ppb}^{-1}$  [*Papasavva et al.*, 1997]. AR4 adopted a value of  $0.16$   
1912  $\text{W m}^{-2} \text{ppb}^{-1}$  based on the multi-model studies of *Gohar et al.* [2004] and *Forster et al.* [2005].  
1913 Particularly, *Forster et al.* [2005] derived a “recommended” absorption cross section and  
1914 applied four radiative transfer models to yield an average RE with relatively low uncertainty  
1915 ( $0.16 \pm 0.02 \text{ W m}^{-2} \text{ppb}^{-1}$ ), and attributed most of the uncertainty to the radiative forcing  
1916 calculation rather than the absorption cross section. In this study we have used the  
1917 recommended absorption spectrum from *Forster et al.* [2005] (Table 6), which is based on  
1918 measurements from six different laboratory groups, and calculated a radiative forcing of  $0.16$   
1919  $\text{W m}^{-2} \text{ppb}^{-1}$ , the same as used in AR4 (Table 7). The lifetime has been updated to 13.4 years  
1920 from *WMO* [2011] compared to the 14 years used in AR4.

1921

#### 1922 **HFC-143 ( $\text{CH}_2\text{FCHF}_2$ )**

1923 The average RE of HFC-143 reported in the literature based on experimentally measured  
1924 absorption spectra is  $0.12 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.11 - 0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Clerbaux and Colin,*  
1925 *1994; Jain et al., 2000; Naik et al., 2000; Pinnock et al., 1995; Sihra et al., 2001*], while the  
1926 *ab initio* study of [*Papasavva et al., 1997*] estimated an instantaneous RE of  $0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$ .  
1927 AR4 used  $0.13 \text{ W m}^{-2} \text{ ppb}^{-1}$  taken from *Clerbaux and Colin* [1994]. We calculate the same  
1928 mean RE value (range:  $0.12 - 0.13 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) using absorption cross-sections from two  
1929 sources [*M.S.F./R.A.L.; Sihra et al., 2001*].

1930

### 1931 **HFC-143a (CH<sub>3</sub>CF<sub>3</sub>)**

1932 The estimated RE of HFC-143a ranges from  $0.13$  to  $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.16 \text{ W m}^{-2}$   
1933  $\text{ppb}^{-1}$ ) in previous studies [*Fisher et al., 1990; Highwood and Shine, 2000; Jain et al., 2000;*  
1934 *Naik et al., 2000; Pinnock et al., 1995; Sihra et al., 2001; Zhang et al., 2011b*]. *Ab initio*  
1935 studies have calculated RE of  $0.15 \text{ W m}^{-2} \text{ ppb}^{-1}$  [*Good et al., 1998*] and instantaneous RE of  
1936  $0.16 \text{ W m}^{-2} \text{ ppb}^{-1}$  [*Papasavva et al., 1997*]. AR4 adopted the value from *Highwood and Shine*  
1937 [2000] of  $0.13 \text{ W m}^{-2} \text{ ppb}^{-1}$ , which is at the lower end of this range. The recent study of *Zhang*  
1938 *et al.* [2011b] calculated almost 70% higher RE ( $0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) than in AR4, but they did  
1939 not provide adequate reasons for these discrepancies (see also discussion of HFC-125). By  
1940 using absorption cross-sections from three different sources [*Di Lonardo and Masciarelli,*  
1941 *2000; Sihra et al., 2001; Smith et al., 1998*], we calculate a mean RE value of  $0.16 \text{ W m}^{-2} \text{ ppb}^{-1}$   
1942 ( $\text{range: } 0.15 - 0.17 \text{ W m}^{-2} \text{ ppb}^{-1}$ ), which is 22% higher than the AR4 value, but in line with  
1943 the mean of estimates from literature measurements. The low value of RE in the AR4 reflects  
1944 the use of the infrared spectrum from *Highwood and Shine* [2000] which has an integrated  
1945 absorption cross section which is significantly lower than in any of the other studies (Table 6).  
1946 We did not include the *Highwood and Shine* [2000] spectrum here as this was taken from a  
1947 lower temperature (253 K) pure gas measurement of *Di Lonardo and Masciarelli* [2000] who  
1948 note that their lower temperature measurements may be more inaccurate if they fail to  
1949 properly resolve the sharper spectral features at the lower temperature. Another contribution  
1950 to the discrepancy is the use of different factors to correct for a non-uniform vertical profile.  
1951 Whereas we use a fractional correction factor of 0.98 based on the method in section 3.3.4 and  
1952 a lifetime of 47.1 years, *Highwood and Shine* [2000] used the crude factor of 0.95 based on  
1953 *Freckleton et al.* [1998].

1954

1955 **HFC-152 (CH<sub>2</sub>FCH<sub>2</sub>F)**

1956 The *ab initio* study by *Papasavva et al.* [1997] is the only published investigation of the RE  
1957 for HFC-152. An instantaneous RE value of 0.09 W m<sup>-2</sup> ppb<sup>-1</sup> was reported and this value has  
1958 been used in previous IPCC assessments. Using experimentally determined absorption cross-  
1959 sections from *Wallington et al.* [1994a] (Tables 6-7) and accounting for the non-uniform  
1960 distribution we calculate a much lower RE value of 0.04 W m<sup>-2</sup> ppb<sup>-1</sup>. The large difference is  
1961 mainly due to the short lifetime of 146 days for HFC-152 [*WMO*, 2011] which leads to a  
1962 reduction from 0.08 to 0.04 W m<sup>-2</sup> ppb<sup>-1</sup> when taking into account the non-uniform  
1963 distribution (Table 7). Recommended RE and GWP values are updated based on our  
1964 calculations.

1965

1966 **HFC-152a (CH<sub>3</sub>CHF<sub>2</sub>)**

1967 Literature calculations of the RE of HFC-152a, using measured cross-sections, lie in the range  
1968 0.09 - 0.14 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.11 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Fisher et al.*, 1990; *Highwood and Shine*,  
1969 2000; *Jain et al.*, 2000; *Naik et al.*, 2000; *Pinnock et al.*, 1995; *Sihra et al.*, 2001; *Zhang et al.*,  
1970 2011b], while the *ab initio* study of *Papasavva et al.* [1997] estimated an instantaneous RE of  
1971 0.11 W m<sup>-2</sup> ppb<sup>-1</sup>. AR4 reports a RE of 0.09 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Highwood and*  
1972 *Shine* [2000]. We calculated a slightly higher RE value of 0.10 W m<sup>-2</sup> ppb<sup>-1</sup> when using  
1973 absorption cross-sections from either of the three different sources [*Clerbaux et al.*, 1993;  
1974 *Sihra et al.*, 2001; *Vander Auwera*, 2000], showing that the uncertainty associated with  
1975 measurements of the HFC-152a spectrum is low. The higher GWP value calculated here  
1976 reflects the higher RE value, a longer lifetime estimate in the latest review by *WMO* [2011]  
1977 (1.5 years) compared to that used in AR4 (1.4 years), and an updated AGWP<sub>CO<sub>2</sub></sub> value used  
1978 here.

1979

1980 **HFC-161 (CH<sub>3</sub>CH<sub>2</sub>F)**

1981 Values of 0.02 - 0.04 W m<sup>-2</sup> ppb<sup>-1</sup> have been reported for RE of HFC-161 (mean: 0.03 W m<sup>-2</sup>  
1982 ppb<sup>-1</sup>) [*Christidis et al.*, 1997; *Jain et al.*, 2000; *Naik et al.*, 2000; *Sihra et al.*, 2001]. The *ab*  
1983 *initio* study of *Papasavva et al.* [1997] is at the high end of this range with an instantaneous  
1984 RE of 0.04 W m<sup>-2</sup> ppb<sup>-1</sup>. A value of 0.03 W m<sup>-2</sup> ppb<sup>-1</sup> has been used in previous IPCC  
1985 assessments and is based on *Christidis et al.* [1997] (a scaling factor of 0.8 based on

1986 *Freckleton et al.* [1998] was applied to account for decreased concentrations in the  
1987 stratosphere). We calculate a RE value of  $0.02 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using the absorption cross-  
1988 sections from *Sihra et al.* [2001]. The lower RE in our study compared to that in AR4 is  
1989 explained by the different lifetime correction factors used as we use a factor of 0.37 to  
1990 account for the non-homogeneous mixing while a factor 0.8 was applied to the *Christidis et*  
1991 *al.* [1997] result.

1992

1993 **HFC-227ca (CF<sub>3</sub>CF<sub>2</sub>CHF<sub>2</sub>)**

1994 The radiative efficiency of HFC-227ca has not been assessed in AR4. Values in the range  
1995  $0.25 - 0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) are available for this compound [*Christidis*  
1996 *et al.*, 1997; *Sihra et al.*, 2001]. We have used the absorption cross-section from *Sihra et al.*  
1997 [2001] to calculate a RE value of  $0.27 \text{ W m}^{-2} \text{ ppb}^{-1}$ , which is slightly higher than the RE of  
1998  $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$  calculated in their study. The lifetime of 28.2 years is taken from *Christidis*  
1999 *et al.* [1997].

2000

2001 **HFC-227ea (CF<sub>3</sub>CHF<sub>2</sub>CF<sub>3</sub>)**

2002 Published values of the RE of HFC-227ea lie in the range  $0.26$  to  $0.32 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  
2003  $0.28 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Gohar et al.*, 2004; *Jain et al.*, 2000; *Naik et al.*, 2000; *Pinnock et al.*,  
2004 1995; *Sihra et al.*, 2001]. AR4 used a RE value of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is an average  
2005 derived from the two models used in *Gohar et al.* [2004]. The absorption cross-section from  
2006 that study has been used here to calculate a RE value of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ , in agreement with  
2007 that in AR4 (Tables 6-7). Our best estimate GWP value is higher than that in AR4 reflecting  
2008 the latest information on the atmospheric lifetime of HFC-227ea [*WMO*, 2011].

2009

2010 **HFC-236cb (CH<sub>2</sub>FCF<sub>2</sub>CF<sub>3</sub>)**

2011 Two studies have been conducted to determine the RE of HFC-236cb. The average of results  
2012 from the two studies is  $0.24 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.22 - 0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Christidis et al.*,  
2013 1997; *Sihra et al.*, 2001]. Previous assessments have adopted the value of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2014 based on *Christidis et al.* [1997] (a scaling factor to account for decreased concentrations in

2015 the stratosphere was applied). We calculate the same RE value of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  when  
2016 using the absorption cross-section from *Sihra et al.* [2001] (Tables 6-7).

2017

2018 **HFC-236ea ( $\text{CHF}_2\text{CHF CF}_3$ )**

2019 Previous IPCC and WMO assessments have used a value of  $0.30 \text{ W m}^{-2} \text{ ppb}^{-1}$  based on  
2020 *Gierczak et al.* [1996] (a factor 0.8 was applied to yield cloudy-sky adjusted forcing from  
2021 their clear-sky instantaneous forcing), which is the only study that have estimated RE due to  
2022 HFC-236ea. No new calculations have been carried out here for this compound, thus we  
2023 retain the RE from AR4 as our best estimate. The GWP(100) value has been updated,  
2024 however, to account for the change in  $\text{AGWP}_{\text{CO}_2}$  and the updated lifetime (11.0 years in  
2025 *WMO* [2011] compared to 10.7 years in AR4).

2026

2027 **HFC-236fa ( $\text{CF}_3\text{CH}_2\text{CF}_3$ )**

2028 Literature estimates of the RE of HFC-236fa range from  $0.23$  to  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.26$   
2029  $\text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Gierczak et al.*, 1996; *Jain et al.*, 2000; *Naik et al.*, 2000; *Pinnock et al.*, 1995;  
2030 *Sihra et al.*, 2001] (note that the upper estimate of  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Gierczak et al.*  
2031 [1996] have been scaled by a factor 0.8 to convert from clear-sky instantaneous forcing to  
2032 cloudy-sky stratospheric temperature adjusted forcing following *WMO* [1999]). In previous  
2033 assessments, an average of the results from *Pinnock et al.* [1995] and *Gierczak et al.* [1996] of  
2034  $0.28 \text{ W m}^{-2} \text{ ppb}^{-1}$  has been used. Using the absorption spectrum from *Sihra et al.* [2001] we  
2035 calculate a RE value of  $0.24 \text{ W m}^{-2} \text{ ppb}^{-1}$ , 13% lower than the AR4 value (Tables 6-7). We  
2036 note that the estimate of *Gierczak et al.* [1996] was crudely scaled to account for clouds and  
2037 stratospheric temperature adjustment, and that the resulting RE is at the higher end of the  
2038 range of REs from the literature. Furthermore, the difference between our RE estimate and the  
2039 calculation of *Pinnock et al.* [1995] ( $0.27 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) can be partly explained by the higher  
2040 integrated absorption cross-section in their study (Table 6).

2041

2042 **HFC-245ca ( $\text{CH}_2\text{FCF}_2\text{CHF}_2$ )**

2043 An RE estimate of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  for HFC-245ca has been used in all IPCC and WMO  
2044 assessments since *IPCC* [1994] and is based on Fisher (pers. comm.) (original value was 0.20

2045  $\text{W m}^{-2} \text{ppb}^{-1}$ , but it was scaled to  $0.23 \text{ W m}^{-2} \text{ppb}^{-1}$  in *WMO* [1999] because of a change in the  
2046 recommended forcing of CFC-11 – see the discussion of CFC-11 in section 4.1.1), and no  
2047 newer estimates were found in the literature. No new calculations have been carried out here  
2048 for this compound, thus we retain the RE from AR4 as our best estimate, except that we scale  
2049 the value by a factor  $0.26/0.25=1.04$  to account for the update in our recommended RE of  
2050 CFC-11. Our recommended RE of HFC-245ca is then  $0.24 \text{ W m}^{-2} \text{ppb}^{-1}$ . Also, the GWP(100)  
2051 value has been updated to account for the change in  $\text{AGWP}_{\text{CO}_2}$  and the updated lifetime (6.5  
2052 years in *WMO* [2011] compared to 6.2 years in AR4).

2053

#### 2054 **HFC-245cb ( $\text{CF}_3\text{CF}_2\text{CH}_3$ )**

2055 The radiative efficiency of HFC-245cb was not assessed in AR4. Published studies give RE in  
2056 the range  $0.25 - 0.28 \text{ W m}^{-2} \text{ppb}^{-1}$  (mean:  $0.27 \text{ W m}^{-2} \text{ppb}^{-1}$ ) [*Christidis et al.*, 1997; *Sihra et*  
2057 *al.*, 2001]. We used the absorption spectrum from two sources [*Orkin et al.*, 2003; *Sihra et al.*,  
2058 2001] and calculated a mean RE value of  $0.24 \text{ W m}^{-2} \text{ppb}^{-1}$  (range:  $0.23 - 0.25 \text{ W m}^{-2} \text{ppb}^{-1}$ )  
2059 (Tables 6-7), which is slightly lower than the  $0.25 \text{ W m}^{-2} \text{ppb}^{-1}$  reported by *Sihra et al.* [2001].  
2060 However, they assumed a constant vertical profile for this compound, and we note that our  
2061 RE estimate when assuming a constant vertical profile ( $0.25 \text{ W m}^{-2} \text{ppb}^{-1}$ ) is consistent with  
2062 their result. The lifetime of 47.1 years is taken from *Christidis et al.* [1997] who assumed the  
2063 same lifetime as HFC-143a, based on the similar molecular structure of the two compounds.

2064

#### 2065 **HFC-245ea ( $\text{CHF}_2\text{CHFCHF}_2$ ), HFC-245eb ( $\text{CH}_2\text{FCHFCF}_3$ ) and HFC-263fb** 2066 **( $\text{CH}_3\text{CH}_2\text{CF}_3$ )**

2067 The REs of HFC-245ea, HFC-245eb and HFC-263fb have not been assessed in AR4, but  
2068 *Rajakumar et al.* [2006] used a LBL model to calculate REs of 0.18, 0.23 and  $0.13 \text{ W m}^{-2}$   
2069  $\text{ppb}^{-1}$ , respectively. Clouds and stratospheric temperature adjustment were included in their  
2070 study, but they did not include the effect of a non-homogeneous vertical profile. When using  
2071 lifetimes from *WMO* [2011] and our method described in section 3.3.4, the lifetime-corrected  
2072 REs from *Rajakumar et al.* [2006] are 0.16, 0.20 and  $0.10 \text{ W m}^{-2} \text{ppb}^{-1}$  for HFC-245ea, HFC-  
2073 245eb and HFC-263fb, respectively. Using these REs we derive the recommended GWPs  
2074 given in Table 7.

2075

2076 **HFC-245fa (CHF<sub>2</sub>CH<sub>2</sub>CF<sub>3</sub>)**

2077 Published estimates of the RE of HFC-245fa lie in the range 0.24 - 0.29 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2078 0.27 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Jain et al.*, 2000; *Ko et al.*, 1999; *Naik et al.*, 2000; *Orkin et al.*, 2003;  
2079 *Sihra et al.*, 2001], and the value of 0.28 W m<sup>-2</sup> ppb<sup>-1</sup> from *Ko et al.* [1999] has been used in  
2080 recent assessments. We calculate a lower mean RE value of 0.24 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.24 -  
2081 0.25 W m<sup>-2</sup> ppb<sup>-1</sup>) when using the absorption cross-sections from *Sihra et al.* [2001] and  
2082 *Orkin et al.* [2003] (Tables 6-7). Part of the reason for the weaker RE in this study is the  
2083 lower integrated absorption cross-section in *Sihra et al.* [2001] compared to *Ko et al.* [1999]  
2084 (Table 6), but it could also be related to differences in how the non-homogeneous distribution  
2085 is accounted for. We note further that the RE estimate of *Ko et al.* [1999] is at the high end of  
2086 the range of literature REs and that our estimate is in agreement with the 0.24 W m<sup>-2</sup> ppb<sup>-1</sup>  
2087 calculated by *Sihra et al.* [2001]. Our RE estimate of 0.24 W m<sup>-2</sup> ppb<sup>-1</sup> is approximately 13%  
2088 lower than the value of 0.28 W m<sup>-2</sup> ppb<sup>-1</sup> used in AR4 (see Table 7).

2089

2090 **HFC-272ca (CH<sub>3</sub>CF<sub>2</sub>CH<sub>3</sub>)**

2091 Previous studies of RE due to HFC-272ca are in the range 0.08 - 0.09 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2092 0.09 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Pinnock et al.*, 1995; *Sihra et al.*, 2001]. We calculate a RE value of 0.08  
2093 W m<sup>-2</sup> ppb<sup>-1</sup> using the absorption spectrum from *Sihra et al.* [2001] (Tables 6-7). While there  
2094 is no lifetime estimate for CH<sub>3</sub>CF<sub>2</sub>CH<sub>3</sub> in the literature, using the structure activity  
2095 relationship developed by *Calvert et al.* [2008] with  $k(-\text{CH}_3) = 1.35 \times 10^{-13}$  and  $F(-\text{CF}_2-) =$   
2096 0.045 we estimate  $k(\text{OH} + \text{CH}_3\text{CF}_2\text{CH}_3) = 1.21 \times 10^{-14} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  at 298 K. Combining  
2097 this rate coefficient with an average tropospheric OH concentration of  $1 \times 10^6 \text{ cm}^{-3}$  provides  
2098 an estimate for the atmospheric lifetime of 2.6 years. Using this estimated lifetime we derive  
2099 the GWP value given in Table 7.

2100

2101 **HFC-329p (CHF<sub>2</sub>CF<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)**

2102 The RE of HFC-329p has not been assessed by AR4, but was estimated to 0.31 W m<sup>-2</sup> ppb<sup>-1</sup>  
2103 (instantaneous RE) by *Young et al.* [2009b] who used the original *Pinnock et al.* [1995]  
2104 method. We have used the absorption cross-section from *Young et al.* [2009b] and calculated  
2105 the same RE value of 0.31 W m<sup>-2</sup> ppb<sup>-1</sup> (Tables 6-7).

2106

2107 **HFC-365mfc (CH<sub>3</sub>CF<sub>2</sub>CH<sub>2</sub>CF<sub>3</sub>)**

2108 A range of 0.21 – 0.23 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.22 W m<sup>-2</sup> ppb<sup>-1</sup>) is available from literature  
2109 estimations of the RE of HFC-365mfc [Barry *et al.*, 1997; Inoue *et al.*, 2008; Naik *et al.*,  
2110 2000]. AR4 adopted the value of 0.21 W m<sup>-2</sup> ppb<sup>-1</sup> from Barry *et al.* [1997], while WMO  
2111 [2011] used an average of the results from Barry *et al.* [1997] and the more recent study of  
2112 Inoue *et al.* [2008]. The latter study calculated a slightly higher RE of 0.23 W m<sup>-2</sup> ppb<sup>-1</sup>  
2113 (instantaneous RE) reflecting an approximately 10% more intense infrared absorption  
2114 spectrum reported by Inoue *et al.* [2008]. A precise comparison of the spectra recorded by  
2115 Barry *et al.* [1997] and Inoue *et al.* [2008] is not possible because Barry *et al.* [1997] did not  
2116 report an integrated absorption cross section. Here we have used the better documented  
2117 absorption cross-section from Inoue *et al.* [2008] to calculate a radiative forcing of 0.22 W m<sup>-2</sup>  
2118 ppb<sup>-1</sup>. Our RE estimate is approximately 6% higher (prior to rounding) than the value used  
2119 in AR4 (see Table 7).

2120

2121 **HFC-43-10mee (CF<sub>3</sub>CHFCHF<sub>2</sub>CF<sub>3</sub>)**

2122 AR4 reports a RE of HFC-43-10mee of 0.40 W m<sup>-2</sup> ppb<sup>-1</sup> which is based on Fisher (pers.  
2123 comm.) [IPCC, 1994] (original value was scaled in WMO [1999] because of a change in the  
2124 recommended forcing of CFC-11 – see the discussion of CFC-11 in section 4.1.1). No  
2125 published estimates of the RE of this compound exist and no new calculations have been  
2126 carried out here, thus we retain the RE from AR4 as our best estimate, except that we scale  
2127 the value by a factor 0.26/0.25=1.04 to account for the update in our recommended RE of  
2128 CFC-11. Our recommended RE of HFC-43-10mee is then 0.42 W m<sup>-2</sup> ppb<sup>-1</sup>. Also, the  
2129 GWP(100) value has been updated to account for the change in AGWP<sub>CO<sub>2</sub></sub> and the updated  
2130 lifetime (16.1 years in WMO [2011] compared to 15.9 years in AR4).

2131

2132 **HFC-1132a (CH<sub>2</sub>=CF<sub>2</sub>), HFC-1141 (CH<sub>2</sub>=CHF) and (Z)-HFC-1336 (CF<sub>3</sub>CH=CHCF<sub>3</sub>(Z))**

2133 The REs of HFC-1132a, HFC-1141 and (Z)-HFC-1336 were not assessed in AR4.  
2134 Baasandorj *et al.* [2010] have estimated the radiative efficiencies of HFC-1132a and HFC-  
2135 1141 to be 0.09 and 0.08 W m<sup>-2</sup> ppb<sup>-1</sup>, respectively. Baasandorj *et al.* [2011] estimated the  
2136 radiative efficiency of (Z)-HFC-1336 to be 0.38 W m<sup>-2</sup> ppb<sup>-1</sup>. The RE values from both  
2137 studies are instantaneous REs derived using the original Pinnock *et al.* [1995] method for the



2138 forcing calculations. We apply a 10% increase to account for stratospheric temperature  
2139 adjustment, and an additional correction factor to account for the non-homogeneous mixing  
2140 (see section 3.3.4) to derive recommended REs of 0.004, 0.002 and 0.074 W m<sup>-2</sup> ppb<sup>-1</sup> for  
2141 HFC-1132a, HFC-1141 and (Z)-HFC-1336, respectively. Lifetimes necessary for the RE  
2142 lifetime correction and GWP calculation were taken from *WMO* [2011] for HFC-1132a and  
2143 HFC-1141, and from *Baasandorj et al.* [2011] for (Z)-HFC-1336.

2144

#### 2145 **(Z)-HFC-1225ye (CF<sub>3</sub>CF=CHF(Z))**

2146 Literature values of the RE of (Z)-HFC-1225ye are in close agreement with a range 0.25 -  
2147 0.26 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Hurley et al.*, 2007; *Papadimitriou et al.*, 2008a].  
2148 Our RE calculation using the absorption spectrum from *Hurley et al.* [2007] and assuming  
2149 homogeneous mixing throughout the troposphere is 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>, in good agreement with  
2150 the literature data. However, when we account for the substantially non-homogeneous mixing  
2151 of this short-lived species we arrive at the much lower RE value of 0.02 W m<sup>-2</sup> ppb<sup>-1</sup> (Tables  
2152 6-7). Neither of the two literature studies account for the non-homogeneous mixing of  
2153 CF<sub>3</sub>CF=CHF in the troposphere. Our recommended RE and GWP values are given in Table 7.

2154

#### 2155 **(E)-HFC-1225ye (CF<sub>3</sub>CF=CHF(E))**

2156 There has been one published study of the RE of (E)-HFC-1225ye which gave a value 0.24 W  
2157 m<sup>-2</sup> ppb<sup>-1</sup> [*Hurley et al.*, 2007]. We have used the absorption spectrum from *Hurley et al.*  
2158 [2007] and calculated a RE value of 0.01 W m<sup>-2</sup> ppb<sup>-1</sup> (Tables 6-7). As for the (Z)-HFC-  
2159 1225ye compound discussed above, our RE estimate is in close agreement with the published  
2160 value when we assume homogeneous mixing of (E)-HFC-1225ye.

2161

#### 2162 **(Z)-HFC-1234ze (CF<sub>3</sub>CH=CHF(Z))**

2163 There has been one published study of the RE of (Z)-HFC-1234ze which gave a value 0.20 W  
2164 m<sup>-2</sup> ppb<sup>-1</sup> [*Nilsson et al.*, 2009]. We calculate a RE value of 0.02 W m<sup>-2</sup> ppb<sup>-1</sup> using absorption  
2165 spectrum from *Nilsson et al.* [2009] (Tables 6-7). The RE value estimated here is in good  
2166 agreement with the published value when homogeneous distribution is assumed. The lifetime  
2167 of 10 days is taken from *Nilsson et al.* [2009].

2168

2169 **HFC-1234yf (CF<sub>3</sub>CF=CH<sub>2</sub>)**

2170 Literature values for the RE of HFC-1234yf fall in the range 0.22 - 0.24 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2171 0.23 W m<sup>-2</sup> ppb<sup>-1</sup>) [Nielsen *et al.*, 2007; Orkin *et al.*, 2010; Papadimitriou *et al.*, 2008a]. We  
2172 calculate a mean RE value of 0.02 W m<sup>-2</sup> ppb<sup>-1</sup> both when using the absorption cross-section  
2173 from Orkin *et al.* [2010] and from Nielsen *et al.* [2007] (Tables 6-7). Neither of the previous  
2174 studies accounted for the non-homogeneous mixing of this short-lived compound and we note  
2175 that our estimate is in excellent agreement with the mean of published RE values when we  
2176 assume uniform mixing of HFC-1234yf.

2177

2178 **(E)-HFC-1234ze (trans-CF<sub>3</sub>CH=CHF)**

2179 Results from the published studies of the RE of (E)-HFC-1234ze lie in the range 0.24 - 0.27  
2180 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>) [Orkin *et al.*, 2010; Søndergaard *et al.*, 2007]. We  
2181 calculate a RE value of 0.04 W m<sup>-2</sup> ppb<sup>-1</sup> when using absorption cross-sections from both of  
2182 these studies (Tables 6-7). The non-homogeneous mixing of this short-lived compound was  
2183 not accounted for in the two studies; our estimate of RE is consistent with the published  
2184 values if we assume uniform mixing.

2185

2186 **HFC-1243zf, HFC-1345zfc, 3,3,4,4,5,5,6,6,6-nonafluorohex-1-ene,**  
2187 **3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooct-1-ene and 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-**  
2188 **heptadecafluorodec-1-ene (C<sub>x</sub>F<sub>2x+1</sub>CH=CH<sub>2</sub> (x=1, 2, 4, 6 and 8))**

2189 In the recent study by Andersen *et al.* [2012a], REs were calculated for five compounds that  
2190 have not been included in previous assessments. They used the original Pinnock *et al.* [1995]  
2191 method to calculate instantaneous REs of 0.16, 0.18, 0.34, 0.38 and 0.42 W m<sup>-2</sup> ppb<sup>-1</sup> for  
2192 HFC-1243zf, HFC-1345zfc, 3,3,4,4,5,5,6,6,6-nonafluorohex-1-ene, 3,3,4,4,5,5,6,6,7,7,8,8,8-  
2193 tridecafluorooct-1-ene and 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodec-1-ene,  
2194 respectively, assuming uniform mixing of these gases. As can be seen in Table 7, the  
2195 corresponding REs calculated in this study are in close agreement to Andersen *et al.* [2012a],  
2196 while they are substantially lower – in the range 0.01 - 0.03 W m<sup>-2</sup> ppb<sup>-1</sup> – when accounting  
2197 for non-homogeneous mixing. It should be noted here that the uncertainties associated with  
2198 the lifetime correction factor are very large on a percentage basis for such short-lived species

2199 (see Figure 9 and associated discussion in section 3.3.4). The absorption cross-sections used  
2200 here are from *Andersen et al.* [2012a] (Table 6), and the lifetimes necessary for the fractional  
2201 correction and GWP calculation have been taken from *Andersen et al.* [2005].

2202

#### 2203 4.1.4 Chlorocarbons and Hydrochlorocarbons

2204 Chlorocarbons and hydrochlorocarbons are ozone-depleting substances and are therefore  
2205 controlled under the Montreal Protocol. Lifetimes for the chlorocarbons and  
2206 hydrochlorocarbons considered here range from less than a year for  $\text{CH}_2\text{ClCH}_2\text{Cl}$  to 26 years  
2207 for  $\text{CCl}_4$  (carbon tetrachloride). Figure 1 shows the contrasting time-histories of the  
2208 atmospheric concentrations of the most abundant chlorocarbon ( $\text{CCl}_4$ ) and hydrochlorocarbon  
2209 ( $\text{CH}_3\text{CCl}_3$ , methyl chloroform). Methyl chloroform concentrations fell rapidly after  
2210 implementation of the Montreal Protocol, due to a combination of rapidly-decreasing  
2211 emissions and its short (5 year) lifetime. By contrast, due to continued emissions of carbon  
2212 tetrachloride it remains the fourth most abundant of the compounds considered here (about 90  
2213 ppt), with concentrations decreasing only rather slowly (at a rate of about  $1.2 \text{ ppt year}^{-1}$   
2214 [WMO, 2011]). Figure 14 shows the absorption spectrum of carbon tetrachloride – the  
2215 symmetry of this molecule results in a quite simple spectrum, with most of the absorption  
2216 concentrated in the  $750 - 800 \text{ cm}^{-1}$  spectral region. Previously published absorption cross-  
2217 sections are listed in Table 8, while updated atmospheric lifetimes, radiative efficiencies, and  
2218 100-year GWP values for chlorocarbons and hydrochlorocarbons are presented in Table 9 and  
2219 discussed below. With the exception of carbon tetrachloride, which is mainly lost by  
2220 photolysis [WMO, 2011], the S-shaped fit from section 3.3.4 (Equation (2) and dark blue  
2221 curve in Figure 9) has been used to account for a non-uniform vertical profile and geographic  
2222 distribution for all compounds presented in this subsection.

2223

#### 2224 **Methyl chloroform ( $\text{CH}_3\text{CCl}_3$ )**

2225 The studies that have calculated RE of methyl chloroform present values in the range 0.06 -  
2226  $0.10 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.07 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Fisher et al.*, 1990; *Imasu et al.*, 1995; *Jain et al.*,  
2227 2000; *Orkin et al.*, 2003]. Both *Fisher et al.* [1990] and *Jain et al.* [2000] used the same  
2228 absorption cross-section [*Fisher et al.*, 1990]. *Orkin et al.* [2003] presented a 9% larger  
2229 absorption cross-section and, based on the measured spectrum of the Earth's outgoing

2230 radiation obtained by NIMBUS 4 [Kunde *et al.*, 1974], a relative RE to CFC-11 of 0.38. AR4  
2231 adopted the RE value of  $0.06 \text{ W m}^{-2} \text{ ppb}^{-1}$  from Fisher *et al.* [1990]. We have used the  
2232 absorption cross-sections from two sources [Imasu *et al.*, 1995; Orkin *et al.*, 2003] and  
2233 calculated a slightly higher RE value of  $0.07 \text{ W m}^{-2} \text{ ppb}^{-1}$  for both spectra.

2234

#### 2235 **Carbon tetrachloride (CCl<sub>4</sub>)**

2236 Previous studies of carbon tetrachloride RE present values in the range  $0.09 - 0.13 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2237 <sup>1</sup> (mean:  $0.11 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Fisher *et al.*, 1990; Jain *et al.*, 2000; Myhre and Stordal, 1997];  
2238 Fisher *et al.* [1990] and Jain *et al.* [2000] based their calculations on the absorption cross  
2239 section presented by Fisher *et al.* [1990], while Myhre and Stordal [1997] employed the  
2240 absorption cross section of Massie *et al.* [1985]. AR4 adopted the RE of  $0.13 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2241 from Jain *et al.* [2000]. We have used the more recent absorption cross-section from the study  
2242 of Nemtchinov and Varanasi [2003], which includes temperature and pressure dependency  
2243 and an inter-comparison of all previous data, and derive a RE value of  $0.17 \text{ W m}^{-2} \text{ ppb}^{-1}$ . This  
2244 is significantly higher (35% higher) than the AR4 value (Table 9) and entirely due to the  
2245 higher absorption cross-section of the newer data (Table 8) than that was used in the RE  
2246 calculation of Jain *et al.* [2000]. In contrast to the other compounds listed in this section,  
2247 carbon tetrachloride is mainly lost by photolysis rather than reaction with OH [WMO, 2011].  
2248 Hence, we have used the exponential fit from section 3.3.4 (Equation (1) and red curve in  
2249 Figure 9) instead of the S-shaped fit to account for a non-uniform vertical profile, although  
2250 this has only a small impact on the RE because this compound is relatively well-mixed in the  
2251 atmosphere (lifetime of 26.0 years).

2252

#### 2253 **Methyl chloride (CH<sub>3</sub>Cl)**

2254 Only one study has estimated the methyl chloride RE presenting a value of  $0.01 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2255 [Grossman *et al.*, 1997], which is also the value that has been used in the AR4 assessment.  
2256 Grossman and co-workers employed a combination of absorption cross-sections from Brown  
2257 *et al.* [1987] and HITRAN. No new calculations have been carried out here for this  
2258 compound, thus we retain the RE from AR4 as our best estimate. The GWP(100) value has,  
2259 however, been updated to account for the change in  $\text{AGWP}_{\text{CO}_2}$ .

2260

2261 **Methylene chloride (CH<sub>2</sub>Cl<sub>2</sub>)**

2262 No estimate of the methylene chloride RE has been found in the published literature. AR4  
2263 reports a RE of 0.03 W m<sup>-2</sup> ppb<sup>-1</sup> that has been used in all assessments since IPCC [1994] and  
2264 is based on Fisher (pers. comm.) (scaled to the previously recommended CFC-11 RE of 0.25  
2265 W m<sup>-2</sup> ppb<sup>-1</sup>). No new calculations have been carried out here for this compound, thus we  
2266 retain the RE and GWP(100) from AR4 as our best estimate (the GWP(100) for this  
2267 compound rounds to 9 after updating the AGWP<sub>CO2</sub> value).

2268

2269 **Chloroform (CHCl<sub>3</sub>)**

2270 The two previous reports on chloroform RE are in the range 0.09 - 0.11 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2271 0.10 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Highwood and Shine*, 2000; *Sihra et al.*, 2001] and are both based on the  
2272 spectroscopic data from *McPheat and Duxbury* [2000]. AR4 has adopted the RE of 0.11 W m<sup>-2</sup>  
2273 ppb<sup>-1</sup> from *Highwood and Shine* [2000]. We have employed the absorption cross-section  
2274 from *McPheat and Duxbury* [2000], but we derive a substantially lower RE value of 0.08 W  
2275 m<sup>-2</sup> ppb<sup>-1</sup> (Tables 8-9). The reason for the ~30% lower value in the present study is linked to  
2276 the different methods correcting for the non-homogeneous mixing of this short-lived species.  
2277 *Highwood and Shine* [2000] used a factor of 0.8 from *Freckleton et al.* [1998] while we use a  
2278 fractional correction factor of 0.55 based on the method described in section 3.3.4 and a  
2279 lifetime of 0.4 years [*WMO*, 2011]. Recommended RE and GWP values, based on our  
2280 calculations, are presented in Table 9.

2281

2282 **1,2-Dichloroethane (CH<sub>2</sub>ClCH<sub>2</sub>Cl)**

2283 1,2-dichloroethane has a relatively low RE with estimates of 0.02 W m<sup>-2</sup> ppb<sup>-1</sup> in the literature  
2284 [*Highwood and Shine*, 2000; *Sihra et al.*, 2001]; both studies use the absorption cross-section  
2285 of *Vander Auwera* [2000]. The present calculations, employing the same spectroscopic data,  
2286 yield a RE about half the magnitude, 0.01 W m<sup>-2</sup> ppb<sup>-1</sup> (Tables 8-9). As for chloroform, the  
2287 calculated RE value is consistent with the previous studies when a homogeneous distribution  
2288 is assumed.

2289

#### 2290 4.1.5 Bromocarbons, Hydrobromocarbons, and Halons

2291 The bromocarbons, hydrobromocarbons, and halons are ozone-depleting substances on  
2292 account of both presences of bromine, and in some compounds, also chlorine. They are  
2293 controlled under the Montreal Protocol. Lifetimes for the compounds considered here range  
2294 from less than a year in the case of methylene bromide ( $\text{CH}_2\text{Br}_2$ ) to 65 years in the case of  
2295 Halon-1301 ( $\text{CBrF}_3$ ). The most abundant hydrobromocarbon in the atmosphere is methyl  
2296 bromide (about 7.5 ppt, decreasing at  $0.2 \text{ ppt year}^{-1}$  [WMO, 2011]) and the most abundant  
2297 halon is Halon-1211 (about 4.2 ppt, decreasing at  $0.05 \text{ ppt year}^{-1}$  [WMO, 2011]). Figure 15  
2298 shows the absorption spectrum of Halon-1301 ( $\text{CBrF}_3$ ) – the relatively simple structure of this  
2299 molecule is reflected in an absorption spectrum where most of the intensity is concentrated in  
2300 two narrow bands between 1,000 and 1,200  $\text{cm}^{-1}$ .

2301 Previously published absorption cross-sections are listed in Table 10, while updated  
2302 atmospheric lifetimes, radiative efficiencies, and GWP(100) values for bromocarbons,  
2303 hydrobromocarbons, and halons are presented in Table 11 and discussed below. Three of the  
2304 compounds are mainly lost by photolysis in the stratosphere (Halon-1211, Halon-1301 and  
2305 Halon-2402 [WMO, 2011]), and we have therefore used the exponential fit from section 3.3.4  
2306 (Equation (1) and red curve in Figure 9) to account for a non-uniform vertical profile for these  
2307 compounds. The remaining compounds are mainly lost through reaction with OH and we  
2308 have therefore used the S-shaped fit from section 3.3.4 (Equation (2) and dark blue curve in  
2309 Figure 9) to account for a non-uniform vertical profile and geographic distribution for these  
2310 compounds.

2311

#### 2312 **Methyl bromide ( $\text{CH}_3\text{Br}$ )**

2313 The RE of methyl bromide is low with a mean of  $0.006 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.005 - 0.007 \text{ W}$   
2314  $\text{m}^{-2} \text{ ppb}^{-1}$ ) from published estimates [Christidis *et al.*, 1997; Grossman *et al.*, 1997; Jain *et al.*,  
2315 2000; Sihra *et al.*, 2001]. AR4 has adopted a RE of  $0.01 \text{ W m}^{-2} \text{ ppb}^{-1}$  based on the results of  
2316 Grossman *et al.* [1997] and Christidis *et al.* [1997] (rounded to two decimals). Grossman *et*  
2317 *al.* [1997] used the molecular parameters of Anttila *et al.* [1983] and Graner and Blass [1975]  
2318 to model the  $\text{CH}_3\text{Br}$  spectrum. We have used the absorption cross-section from Sihra *et al.*  
2319 [2001] and derive  $\text{RE} = 0.004 \text{ W m}^{-2} \text{ ppb}^{-1}$  (Tables 10-11), which is lower than the AR4 value  
2320 ( $0.006 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). The reason is that the previous studies assumed a constant vertical

2321 profile, while we applied a lifetime correction factor of 0.70 using the method described in  
2322 section 3.3.4 and a lifetime of 0.8 years [WMO, 2011]. The present calculations are in  
2323 excellent agreement with the  $0.007 \text{ W m}^{-2} \text{ ppb}^{-1}$  calculated by *Christidis et al.* [1997] when a  
2324 constant vertical profile of methyl bromide is assumed. The best estimate RE and GWP are  
2325 shown in Table 11.

2326

### 2327 **Methylene bromide ( $\text{CH}_2\text{Br}_2$ )**

2328 Previous studies of RE due to methylene bromide are in the range  $0.011 - 0.021 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2329 (mean:  $0.017 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Christidis et al.*, 1997; *Jain et al.*, 2000; *Sihra et al.*, 2001]; AR4  
2330 recommends RE of  $0.01 \text{ W m}^{-2} \text{ ppb}^{-1}$  (rounded to two decimals) from *Christidis et al.* [1997]  
2331 (note that AR4 accounted for stratospheric decay [WMO, 1999]). When using the absorption  
2332 cross-section from *Sihra et al.* [2001], we calculate a RE value of  $0.008 \text{ W m}^{-2} \text{ ppb}^{-1}$ , which  
2333 leads to a new recommended GWP(100) value of 1 (Tables 10-11).

2334

### 2335 **Halon-1201 ( $\text{CHBrF}_2$ )**

2336 Literature reports of Halon-1201 RE are in the range  $0.15 - 0.18 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.17 \text{ W}$   
2337  $\text{m}^{-2} \text{ ppb}^{-1}$ ) [*Christidis et al.*, 1997; *Jain et al.*, 2000; *Orkin et al.*, 2003; *Sihra et al.*, 2001];  
2338 AR4 adopted a RE of  $0.14 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from *Christidis et al.* [1997] (note that  
2339 AR4 accounted for stratospheric decay [WMO, 1999]). We derive a mean RE of  $0.15 \text{ W m}^{-2}$   
2340  $\text{ppb}^{-1}$  (range:  $0.15 - 0.16 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) when using the absorption cross-sections from *Sihra et*  
2341 *al.* [2001], *Orkin et al.* [2003] and the recent study by *Charmet et al.* [2010] (Tables 10-11).  
2342 Our RE estimate is in agreement with the value from *Sihra et al.* [2001], but it is more than  
2343 5% higher than the AR4 estimate (Table 11). Despite the higher RE, our recommended  
2344 GWP(100) value is lower than in AR4 due to the shorter lifetime recommended by WMO  
2345 [2011] (5.2 years compared to 5.8 years in AR4) and the higher  $\text{AGWP}_{\text{CO}_2}$  used here.

2346

### 2347 **Halon-1202 ( $\text{CBr}_2\text{F}_2$ )**

2348 One study has estimated RE due to Halon-1202 with a value  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$  [*Orkin et al.*,  
2349 2003] (when scaled to our recommended CFC-11 RE of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ). We have used the  
2350 absorption cross-section from the same study and calculated a slightly lower RE of  $0.27 \text{ W m}^{-2}$

2351 <sup>2</sup> ppb<sup>-1</sup>. It should be noted that the recent study by *Papanastasiou et al.* [2013] suggests a  
2352 lifetime of 2.52 years, which is shorter than the 2.9 years [WMO, 2011] used here.

2353

#### 2354 **Halon-1211 (CBrClF<sub>2</sub>)**

2355 Previous reports of the RE of Halon-1211 are in the range 0.25 - 0.33 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2356 0.28 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Christidis et al.*, 1997; *Jain et al.*, 2000; *Sihra et al.*, 2001]. AR4 reports a  
2357 RE of 0.30 W m<sup>-2</sup> ppb<sup>-1</sup>, which is based on the results of *Christidis et al.* [1997] (note that  
2358 AR4 accounted for stratospheric decay [WMO, 1999]). We have used the absorption cross-  
2359 section from *Sihra et al.* [2001] and calculated a RE value of 0.29 W m<sup>-2</sup> ppb<sup>-1</sup>, which is  
2360 consistent (within 5% difference) with the AR4 value (Tables 10-11). For Halon-1211 we  
2361 have carried out explicit simulations using the Oslo LBL model and derived a factor of 0.937  
2362 to account for the non-uniform vertical profile induced by loss through photolysis in the  
2363 stratosphere (see section 3.3.4 for details), and this factor has been used to derive the RE of  
2364 0.29 W m<sup>-2</sup> ppb<sup>-1</sup>. It should be noted that *Papanastasiou et al.* [2013] have recently suggested  
2365 a slightly longer lifetime of 16.4 years compared to the 16.0 years [WMO, 2011] which have  
2366 been used here.

2367

#### 2368 **Halon-1301 (CBrF<sub>3</sub>)**

2369 Estimates of the RE of Halon-1301 in the literatures range from 0.27 to 0.33 W m<sup>-2</sup> ppb<sup>-1</sup>  
2370 (mean: 0.30 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Charmet et al.*, 2008; *Drage et al.*, 2006; *Jain et al.*, 2000; *Orkin et*  
2371 *al.*, 2003; *Ramanathan et al.*, 1985; *Sihra et al.*, 2001]. AR4 used a RE of 0.32 W m<sup>-2</sup> ppb<sup>-1</sup>  
2372 taken from *Ramanathan et al.* [1985]. We have used absorption cross-sections from three  
2373 sources [*Charmet et al.*, 2008; *Orkin et al.*, 2003; *Sihra et al.*, 2001] and calculated a mean  
2374 RE value of 0.30 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.29 - 0.31 W m<sup>-2</sup> ppb<sup>-1</sup>), about 6% lower than AR4.

2375

#### 2376 **Halon-2301 (CH<sub>2</sub>BrCF<sub>3</sub>)**

2377 One study has estimated RE due to Halon-2301 with a value 0.17 W m<sup>-2</sup> ppb<sup>-1</sup> [*Orkin et al.*,  
2378 2003] (scaled to our recommended CFC-11 RE of 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>). We have used their  
2379 absorption cross-section and calculated a lower RE value of 0.14 W m<sup>-2</sup> ppb<sup>-1</sup>. Our value  
2380 includes corrections for stratospheric temperature adjustment and non-homogeneous mixing,



2381 which were not accounted for in the published estimate. The lifetime of 3.4 years is taken  
2382 from *Orkin et al.* [2003].

2383

#### 2384 **Halon-2311 / Halothane (CHBrClCF<sub>3</sub>)**

2385 The RE of Halon-2311 has not been assessed in AR4, but was estimated to be in the range  
2386 0.17 - 0.21 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.19 W m<sup>-2</sup> ppb<sup>-1</sup>) in previous studies [*Andersen et al.*, 2012b;  
2387 *Orkin et al.*, 2003]. Both these studies assumed homogeneous mixing throughout the  
2388 troposphere and used the original *Pinnock et al.* [1995] method to calculate the instantaneous  
2389 RE. We calculate a lower RE with a mean value of 0.13 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.13 - 0.14 W m<sup>-2</sup>  
2390 ppb<sup>-1</sup>) when using the absorption cross-sections from *Andersen et al.* [2012b] and *Orkin et*  
2391 *al.* [2003] (Tables 10-11). The lower value calculated here primarily reflects the correction  
2392 factor we have applied to account for non-homogeneous mixing, but it is also a result of the  
2393 difference between the original Pinnock curve and the new curve presented in section 3.3.1,  
2394 whereas the latter curve generally yields lower REs (in this case ~5% lower).

2395

#### 2396 **Halon-2401 (CHFBrCF<sub>3</sub>)**

2397 *Orkin et al.* [2003] have estimated the RE due to Halon-2401 with a value 0.23 W m<sup>-2</sup> ppb<sup>-1</sup>  
2398 (when scaled to our recommended CFC-11 RE of 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>). We have used their  
2399 absorption cross-section and calculated a RE value of 0.19 W m<sup>-2</sup> ppb<sup>-1</sup>. Again, the lower  
2400 value results mainly from the lifetime correction factor applied here to account for non-  
2401 homogeneous mixing. The lifetime of 2.9 years is taken from *Orkin et al.* [2003].

2402

#### 2403 **Halon-2402 (CBrF<sub>2</sub>CBrF<sub>2</sub>)**

2404 *Sihra et al.* [2001] estimated the RE of Halon-2402 presenting a value of 0.33 W m<sup>-2</sup> ppb<sup>-1</sup>,  
2405 which is also the RE adopted by AR4. We have used the absorption cross-section from *Sihra*  
2406 *et al.* [2001] and calculated a RE value of 0.31 W m<sup>-2</sup> ppb<sup>-1</sup>, about 6% lower than that used in  
2407 AR4. We have used a lifetime of 20.0 years [*WMO*, 2011], but we note that the recent study  
2408 by *Papanastasiou et al.* [2013] has estimated a significantly longer lifetime of 28.3 years, and  
2409 consequently higher GWP values for this compound.

2410

#### 2411 4.1.6 Fully Fluorinated Species

2412 Fully fluorinated compounds are generally long-lived compounds removed by photolysis in  
2413 the stratosphere, although unsaturated compounds may be very short-lived because of their  
2414 reactivity towards OH radicals. Perfluorocarbons (PFCs) usually have strong absorption in the  
2415 1200-1300  $\text{cm}^{-1}$  region of the spectrum (as illustrated for  $\text{CF}_4$  in Figure 16) and so are  
2416 radiatively active in the atmosphere. As a result – and combined with their long lifetimes –  
2417 saturated PFCs have some of the largest GWPs of any compounds detected in the atmosphere.  
2418 These compounds are identified within the Kyoto Protocol as gases whose presence in the  
2419 atmosphere must be controlled, as has sulphur hexafluoride. As noted in section 1, nitrogen  
2420 trifluoride was added to the basket of greenhouse gases in the second commitment period of  
2421 the Kyoto Protocol. Published absorption cross-sections are listed in Table 12, while updated  
2422 atmospheric lifetimes, radiative efficiencies, and GWP(100) values for fully fluorinated  
2423 species are presented in Table 13 and discussed below. For sulfonyl fluoride and six short-  
2424 lived compounds we have used the S-shaped fit from section 3.3.4 (Equation (2) and dark  
2425 blue curve in Figure 9) to account for a non-uniform vertical profile and geographic  
2426 distribution due to their reactivity towards OH. The remaining compounds have very long  
2427 lifetimes (>500 years) and are lost by photolysis in the stratosphere, hence we have used the  
2428 exponential fit from section 3.3.4 (Equation (1) and red curve in Figure 9) to account for a  
2429 non-uniform vertical profile for these compounds.

2430

#### 2431 **Nitrogen trifluoride ( $\text{NF}_3$ )**

2432 There is one study of the RE for nitrogen trifluoride in the literature. *Robson et al.* [2006]  
2433 calculated a cloudy-sky adjusted radiative forcing of  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$  by using a combination  
2434 of line-by-line and narrow band radiative transfer models, and this value has been used in  
2435 IPCC and WMO assessments (since *WMO* [2007]). Earlier assessments reported a much  
2436 lower value of  $0.13 \text{ W m}^{-2} \text{ ppb}^{-1}$  (instantaneous RE), but these calculations were based on  
2437 incomplete cross-section data. We have used the spectrum from *Robson et al.* [2006] and  
2438 calculated a RE value of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$  (Table 12-13), which is consistent (within 5%  
2439 difference) with AR4. Since AR4, the lifetime of  $\text{NF}_3$  has been studied by *Prather and Hsu*  
2440 [2008] who suggest a much shorter lifetime of 550 years, partly due to inclusion of the  $\text{O}(^1\text{D})$   
2441 +  $\text{NF}_3$  reaction, compared to the 740 years recommended in AR4. *WMO* [2011] used an  
2442 updated rate constant for the  $\text{O}(^1\text{D})$  reaction to obtain a lifetime of 500 years, which is the

2443 value we have used here. It should be noted that a very recent study by *Papadimitriou et al.*  
2444 [2013] included temperature dependence of the  $\text{NF}_3$  UV absorption spectrum and suggested a  
2445 longer lifetime for  $\text{NF}_3$  of 585 years ( $\pm 20\%$ ).

2446

#### 2447 **Sulphur hexafluoride ( $\text{SF}_6$ )**

2448 Previous studies of the RE for sulphur hexafluoride are in the range  $0.49 - 0.68 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2449 (mean:  $0.56 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Jain et al.*, 2000; *Myhre and Stordal*, 1997; *Zhang et al.*, 2011a].  
2450 *Zhang et al.* [2011a] estimated a much higher RE than the other studies, and this was also the  
2451 case for several of the HFCs calculated by *Zhang et al.* [2011b] (see discussion of HFC-125  
2452 in section 4.1.3). AR4 adopted a RE of  $0.52 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Myhre and Stordal* [1997],  
2453 while we calculate a 10% higher RE value of  $0.57 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.54 - 0.59 \text{ W m}^{-2} \text{ ppb}^{-1}$ )  
2454 using absorption cross-sections from the GEISA and HITRAN databases (Tables 12-13).

2455

#### 2456 **(Trifluoromethyl)sulfur pentafluoride ( $\text{SF}_5\text{CF}_3$ )**

2457 Previous reports of RE of (trifluoromethyl)sulfur pentafluoride are in the range  $0.57 - 0.59 \text{ W}$   
2458  $\text{m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.58 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Nielsen et al.*, 2002; *Sihra et al.*, 2001; *Sturges et al.*,  
2459 2000], and AR4 adopted the RE of  $0.57 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Sturges et al.* [2000]. We calculate  
2460 a mean RE value of  $0.59 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.58 - 0.61 \text{ W m}^{-2} \text{ ppb}^{-1}$ ), consistent (within 5%  
2461 difference) with the AR4, using absorption cross-sections from two sources [*Nielsen et al.*,  
2462 2002; *Rinsland et al.*, 2003] (Tables 12-13). Both of these spectra include an absorption  
2463 feature at  $612.5 \text{ cm}^{-1}$  which was not included in the measurements of *Sturges et al.* [2000],  
2464 and this explains the slightly higher RE calculated here.

2465

#### 2466 **Sulphuryl fluoride ( $\text{SO}_2\text{F}_2$ )**

2467 Previous reports of RE of sulphuryl fluoride are in the range  $0.20 - 0.22 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  
2468  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Andersen et al.*, 2009; *Papadimitriou et al.*, 2008b]. We calculate a RE  
2469 value of  $0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$  using the absorption spectrum from *Andersen et al.* [2009] (Tables  
2470 12-13) – in good agreement with the previous literature.

2471

#### 2472 **PFC-14 ( $\text{CF}_4$ )**

2473 Previous reports of the RE of PFC-14 are in the range  $0.08 - 0.12 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.10 \text{ W}$   
2474  $\text{m}^{-2} \text{ ppb}^{-1}$ ) [*Bravo et al.*, 2010b; *Hurley et al.*, 2005; *Jain et al.*, 2000; *Myhre and Stordal*,  
2475 1997; *Roehl et al.*, 1995; *Sihra et al.*, 2001; *Zhang et al.*, 2011a]. *Bravo et al.* [2010b] report a  
2476 relatively low RE value of  $0.08 \text{ W m}^{-2} \text{ ppb}^{-1}$  (instantaneous RE) from their B3LYP/6-31G\*\*  
2477 calculations, but it should be noted that  $\text{CF}_4$  was part of the training set used to determine  
2478 corrections to band positions. AR4 adopted a RE of  $0.10 \text{ W m}^{-2} \text{ ppb}^{-1}$  from *Hurley et al.*  
2479 [2005], and we calculate a similar mean RE of  $0.09 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.09 - 0.10 \text{ W m}^{-2}$   
2480  $\text{ppb}^{-1}$ ) when using absorption data from *Hurley et al.* [2005] (only the Ford data, and not the  
2481 M.S.F./R.A.L. data) and from the HITRAN database (Tables 12-13). Interestingly, as PFC-14  
2482 has a very strong and narrow absorption band centered near  $1280 \text{ cm}^{-1}$ , which is close to the  
2483 edge of the atmospheric window region, the spectral resolution is more important for PFC-14  
2484 than for other compounds. When using a  $10 \text{ cm}^{-1}$  resolution instead of  $1 \text{ cm}^{-1}$  in our  
2485 calculations, the RE of PFC-14 is underestimated by  $\sim 8\%$ , as shown in Figure 6 and briefly  
2486 discussed in section 3.3.1. For PFC-14 we have carried out explicit simulations using the Oslo  
2487 LBL model and derived a 10.5% increase to account for stratospheric temperature adjustment  
2488 (see section 3.3.3 for details), and this value has been used (rather than the generic 10%  
2489 increase) in the calculation of the RE value of  $0.09 \text{ W m}^{-2} \text{ ppb}^{-1}$ .

2490

#### 2491 **PFC-116 ( $\text{C}_2\text{F}_6$ )**

2492 Previous reports of RE of PFC-116 are in the range  $0.25 - 0.35 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.27 \text{ W m}^{-2}$   
2493  $\text{ppb}^{-1}$ ) [*Bravo et al.*, 2010b; *Highwood and Shine*, 2000; *Myhre and Stordal*, 1997; *Roehl et*  
2494 *al.*, 1995; *Sihra et al.*, 2001; *Zhang et al.*, 2011a]. *Bravo et al.* [2010b] report a value for RE  
2495 of  $0.23 \text{ W m}^{-2} \text{ ppb}^{-1}$  (instantaneous RE) from their B3LYP/6-31G\*\* calculations, but it should  
2496 be noted that  $\text{C}_2\text{F}_6$  was part the training set used to determine corrections to band positions.  
2497 *Papasavva et al.* [1997] obtained an *ab initio* RE value of  $0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$  using the MP2  
2498 with a wavenumber scaling factor of 0.9427. In AR4 a RE value of  $0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$  was  
2499 used and is taken from *Highwood and Shine* [2000]. We calculate a mean RE value of  $0.25 \text{ W}$   
2500  $\text{m}^{-2} \text{ ppb}^{-1}$  (range:  $0.24 - 0.26 \text{ W m}^{-2} \text{ ppb}^{-1}$ ), which is in good agreement with AR4, and we  
2501 have used absorption cross-sections from three sources [*Bravo et al.*, 2010b; *Sihra et al.*,  
2502 2001; *Zou et al.*, 2004] (Tables 12-13). It should be noted here that as both *Bravo et al.*  
2503 [2010b] and *Highwood and Shine* [2000] present absorption data from M.S.F./R.A.L., we  
2504 here choose the most recent spectrum measurement from *Bravo et al.* [2010b]. Also note that

2505 the *Zou et al.* [2004] spectrum does not include the absorption band located at  $715\text{ cm}^{-1}$  but  
2506 this had negligible impact on the RE, thus we keep this spectrum in our calculation.

2507

#### 2508 **PFC-c216 (c-C<sub>3</sub>F<sub>6</sub>)**

2509 Assessments since *WMO* [1999] have used a RE for PFC-c216 of  $0.42\text{ W m}^{-2}\text{ ppb}^{-1}$  which is  
2510 reported to have been taken from *Papasavva et al.* [1997]. However, *Papasavva et al.* [1997]  
2511 did not report a RE for this compound and so the origin of the value used in AR4 is unclear.  
2512 The only estimate of the RE for c-C<sub>3</sub>F<sub>6</sub> that we are aware of is from a calculation (B3LYP/6-  
2513 31G\*\*), which gives an instantaneous RE of  $0.21\text{ W m}^{-2}\text{ ppb}^{-1}$  [*Bravo et al.*, 2010b]. An  
2514 updated RE (assuming a 10% increase to account for stratospheric temperature adjustment)  
2515 and GWP values for PFC-c216 are given in Table 13.

2516

#### 2517 **PFC-218 (C<sub>3</sub>F<sub>8</sub>)**

2518 Previous reports of RE of PFC-218 are in the range  $0.26 - 0.28\text{ W m}^{-2}\text{ ppb}^{-1}$  (mean:  $0.27\text{ W m}^{-2}$   
2519  $\text{ppb}^{-1}$ ) [*Bravo et al.*, 2010b; *Roehl et al.*, 1995; *Sihra et al.*, 2001]. *Bravo et al.* [2010b] also  
2520 report an instantaneous RE value of  $0.27\text{ W m}^{-2}\text{ ppb}^{-1}$  from their B3LYP/6-31G\*\*  
2521 calculations – consistent with their instantaneous RE derived from experimental cross-  
2522 sections. AR4 reports a RE of  $0.26\text{ W m}^{-2}\text{ ppb}^{-1}$  which is taken from *Roehl et al.* [1995]. We  
2523 calculate a slightly higher mean RE value of  $0.28\text{ W m}^{-2}\text{ ppb}^{-1}$  (range:  $0.27 - 0.28\text{ W m}^{-2}\text{ ppb}^{-1}$   
2524 <sup>1</sup>) using experimental absorption cross-sections from two sources [*Bravo et al.*, 2010b; *Sihra*  
2525 *et al.*, 2001] (Tables 12-13). The higher RE calculated here can be explained by the much  
2526 lower integrated absorption cross-section in the PFC-218 spectrum of *Roehl et al.* [1995]  
2527 compared to other studies (see Table 12).

2528

#### 2529 **PFC-318 (c-C<sub>4</sub>F<sub>8</sub>)**

2530 Previous reports of RE of PFC-318 based on experimentally measured absorption spectra are  
2531 in the range  $0.31 - 0.32\text{ W m}^{-2}\text{ ppb}^{-1}$  (mean:  $0.31\text{ W m}^{-2}\text{ ppb}^{-1}$ ) [*Highwood and Shine*, 2000;  
2532 *Sihra et al.*, 2001; *Vasekova et al.*, 2006] while *Bravo et al.* [2010b] report a value for RE of  
2533  $0.30\text{ W m}^{-2}\text{ ppb}^{-1}$  from their B3LYP/6-31G\*\* calculations, in good agreement with the values  
2534 derived from the experimentally measured spectra. AR4 reports a RE of  $0.32\text{ W m}^{-2}\text{ ppb}^{-1}$

2535 taken from *Highwood and Shine* [2000]. We have used the absorption spectrum from the  
2536 same study and our calculations give a RE value of  $0.32 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is in agreement  
2537 with AR4 (Tables 12-13).

2538

#### 2539 **PFC-31-10 (C<sub>4</sub>F<sub>10</sub>)**

2540 Previous estimates of the RE for PFC-31-10 based on experimentally measured absorption  
2541 spectra are in the range  $0.33 - 0.37 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.36 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Bravo et al.*,  
2542 2010b; *Roehl et al.*, 1995; *Sihra et al.*, 2001]. *Bravo et al.* [2010b] also report an  
2543 instantaneous RE of  $0.34 \text{ W m}^{-2} \text{ ppb}^{-1}$  from their B3LYP/6-31G\*\* calculations – consistent  
2544 with their instantaneous RE derived from experimental cross-sections. AR4 report a RE of  
2545  $0.33 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from *Roehl et al.* [1995]. We calculate a higher RE value of  
2546  $0.36 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using the experimental absorption cross-section from *Bravo et al.*  
2547 [2010b] (Tables 12-13). As for PFC-218, the higher RE calculated here can be explained by  
2548 the lower integrated absorption cross-section in *Roehl et al.* [1995] compared to *Bravo et al.*  
2549 [2010b]. Updated values of recommended RE and GWP for PFC-31-10 are given in Table 13.

2550

#### 2551 **Perfluorocyclopentene (c-C<sub>5</sub>F<sub>8</sub>)**

2552 Previous reports of RE of perfluorocyclopentene are in the range  $0.22 - 0.32 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2553 (mean:  $0.27 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Bravo et al.*, 2010b; *Vasekova et al.*, 2006]. Part of the reason for  
2554 the large difference between these two studies is that *Vasekova et al.* [2006] applied a factor  
2555 of 0.8 to account for non-homogeneous vertical profile, while *Bravo et al.* [2010b] assumed a  
2556 constant vertical profile. No new calculations have been carried out here for this compound  
2557 and to provide recommended RE we therefore use the average of the instantaneous REs  
2558 reported in the literature ( $0.30 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) and account for stratospheric temperature  
2559 adjustment as well as non-homogeneous mixing (see sections 3.3.2 and 3.3.4) and end up with  
2560 a RE value of  $0.08 \text{ W m}^{-2} \text{ ppb}^{-1}$ . The only lifetime reported in the literature for this compound  
2561 is 1.0 year from *Vasekova et al.* [2006] who refer to a non-traceable source. Considering that  
2562 *Cometto et al.* [2010] estimated a lifetime of only 31 days for  $\text{CF}_3\text{CF}=\text{CFCF}_3$ , we think that  
2563 the lifetime from *Vasekova et al.* [2006] may be too long and instead use a value of 31 days  
2564 when applying the lifetime correction and calculating the GWP value.

2565

2566 **PFC-41-12 (*n*-C<sub>5</sub>F<sub>12</sub>)**

2567 Previous reports of RE of PFC-41-12 are in the range 0.40 - 0.41 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.41 W  
2568 m<sup>-2</sup> ppb<sup>-1</sup>) [*Bravo et al.*, 2010b; *Roehl et al.*, 1995]. *Bravo et al.* [2010b] also report an  
2569 instantaneous RE of 0.40 W m<sup>-2</sup> ppb<sup>-1</sup> from their B3LYP/6-31G\*\* calculations – in agreement  
2570 with their instantaneous RE estimate based on experimental absorption cross-sections (it  
2571 should be noted that C<sub>5</sub>F<sub>12</sub> was part the training set used to determine corrections to band  
2572 positions). AR4 has used a value of 0.41 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Roehl et al.* [1995],  
2573 and we calculate the exact same RE value when using the experimental absorption cross-  
2574 section from *Bravo et al.* [2010b] (Tables 12-13).

2575

2576 **PFC-51-14 (*n*-C<sub>6</sub>F<sub>14</sub>)**

2577 Previous reports of RE of PFC-51-14 are in the range 0.43 - 0.49 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.46 W  
2578 m<sup>-2</sup> ppb<sup>-1</sup>) [*Bravo et al.*, 2010b; *Roehl et al.*, 1995]. *Bravo et al.* [2010b] also report an  
2579 instantaneous RE of 0.42 W m<sup>-2</sup> ppb<sup>-1</sup> from their B3LYP/6-31G\*\* calculations, but it should  
2580 be noted that C<sub>6</sub>F<sub>14</sub> was part of the training set used to determine corrections to band  
2581 positions. AR4 report a RE of 0.49 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Roehl et al.* [1995]. We  
2582 calculate a RE value of 0.44 W m<sup>-2</sup> ppb<sup>-1</sup> when using the experimental absorption cross-  
2583 section from *Bravo et al.* [2010b] (Tables 12-13). The lower RE value calculated here is  
2584 presumably due to the lower integrated absorption cross-section in *Bravo et al.* [2010b] than  
2585 in *Roehl et al.* [1995] (Table 12).

2586

2587 **PFC-61-16 (*n*-C<sub>7</sub>F<sub>16</sub>)**

2588 *Ivy et al.* [2012] calculated the RE of PFC-61-16 using experimental absorption data and  
2589 derived a value of 0.48 W m<sup>-2</sup> ppb<sup>-1</sup>. *Bravo et al.* [2010b] reported a value of 0.45 W m<sup>-2</sup> ppb<sup>-1</sup>  
2590 using absorption data from B3LYP/6-31G\*\* calculations, in reasonable agreement with the  
2591 result obtained using experimental absorption data. We have used the absorption spectrum  
2592 from *Ivy et al.* [2012] and calculated a RE value of 0.50 W m<sup>-2</sup> ppb<sup>-1</sup> (Tables 12-13).

2593

2594 **PFC-71-18 (C<sub>8</sub>F<sub>18</sub>)**

2595 Previous experimental results for RE of PFC-71-18 are in the range  $0.50 - 0.57 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2596 (mean:  $0.53 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Bravo et al.*, 2010b; *Ivy et al.*, 2012]. We calculate a mean RE  
2597 value of  $0.55 \text{ W m}^{-2} \text{ ppb}^{-1}$  (range:  $0.51 - 0.59 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) when using absorption cross-  
2598 sections from both of these studies (Tables 12-13). The large range in our calculations is  
2599 caused by the large difference in the integrated absorption cross-sections of *Bravo et al.*  
2600 [2010b] and *Ivy et al.* [2012] (Table 12). The lifetime of 3,000 years is taken from *Bravo et al.*  
2601 [2010b], who also report a value for RE of  $0.50 \text{ W m}^{-2} \text{ ppb}^{-1}$  from their B3LYP/6-31G\*\*  
2602 calculations, but it should be noted that PFC-71-18 was part of the training set used to  
2603 determine corrections to band positions.

2604

#### 2605 **Perfluorodecalin (mixed C<sub>10</sub>F<sub>18</sub>, Z-C<sub>10</sub>F<sub>18</sub>, E-C<sub>10</sub>F<sub>18</sub>)**

2606 The RE of perfluorodecalin has been reported to be  $0.56 \text{ W m}^{-2} \text{ ppb}^{-1}$  [*Shine et al.*, 2005b] and  
2607 this value was adopted by AR4. We calculate a RE value of  $0.55 \text{ W m}^{-2} \text{ ppb}^{-1}$  using the  
2608 absorption cross-section from *Shine et al.* [2005b] (Tables 12-13), which was derived  
2609 experimentally in the wavenumber range  $600 - 1500 \text{ cm}^{-1}$  while the absorption bands were  
2610 calculated in the lower wavenumber range  $0 - 600 \text{ cm}^{-1}$ . Our calculations for the isomers Z-  
2611 C<sub>10</sub>F<sub>18</sub> and E-C<sub>10</sub>F<sub>18</sub> yield REs (in the wavenumber range  $600 - 1500 \text{ cm}^{-1}$ ) of 0.56 and 0.48  
2612  $\text{W m}^{-2} \text{ ppb}^{-1}$ , respectively. *Bravo et al.* [2010b] report instantaneous RE values of 0.58, 0.60  
2613 and  $0.56 \text{ W m}^{-2} \text{ ppb}^{-1}$  for C<sub>10</sub>F<sub>18</sub> (mixed), Z-C<sub>10</sub>F<sub>18</sub>, E-C<sub>10</sub>F<sub>18</sub>, respectively, from their  
2614 B3LYP/6-31G\*\* calculations.

2615

#### 2616 **PFC-1114 (CF<sub>2</sub>=CF<sub>2</sub>)**

2617 Previous results for RE of PFC-1114 are in the range  $0.01 - 0.11 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.06 \text{ W}$   
2618  $\text{m}^{-2} \text{ ppb}^{-1}$ ) [*Acerboni et al.*, 2001; *Drage et al.*, 2006]. (*Acerboni et al.* [2001] used vertical  
2619 profiles from a CTM distribution while *Drage et al.* [2006] assumed a constant profile.) Due  
2620 to the short lifetime of 1.1 days, we calculate a RE value which rounds to  $0.00 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2621 when using the absorption cross-section from *Acerboni et al.* [2001] (Tables 12-13) and the  
2622 correction factor for non-uniform mixing discussed in section 3.3.4.

2623

#### 2624 **PFC-1216 (CF<sub>3</sub>CF=CF<sub>2</sub>)**



2625 Only one study has estimated RE due to PFC-1216, with a value  $0.04 \text{ W m}^{-2} \text{ ppb}^{-1}$  [*Acerboni*  
2626 *et al.*, 2001] (vertical profiles from a CTM distribution were used). We have used their  
2627 spectrum and calculated a RE value of  $0.01 \text{ W m}^{-2} \text{ ppb}^{-1}$  when accounting for the non-  
2628 homogeneous vertical profile (Tables 12-13).

2629

#### 2630 **Perfluorobuta-1,3-diene (CF<sub>2</sub>=CFCF=CF<sub>2</sub>)**

2631 Previous reports of RE of Perfluorobuta-1,3-diene are in the range  $0.01 - 0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2632 (mean:  $0.11 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Acerboni et al.*, 2001; *Bravo et al.*, 2010b]. (*Acerboni et al.* [2001]  
2633 used vertical profiles from a CTM distribution while *Bravo et al.* [2010b] assumed a constant  
2634 profile.) We calculate a RE value which rounds to  $0.00 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using the  
2635 absorption cross-section from *Acerboni et al.* [2001] (Tables 12-13).

2636

#### 2637 **Perfluorobut-1-ene (CF<sub>3</sub>CF<sub>2</sub>CF=CF<sub>2</sub>)**

2638 Only one study has estimated RE due to perfluorobut-1-ene, with a value  $0.29 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2639 *Young et al.* [2009a]. We calculate a RE value of  $0.02 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using their  
2640 absorption cross-section, and account for stratospheric temperature adjustment and non-  
2641 homogeneous distribution. A lifetime of 6 days has been used in the RE and GWP calculation  
2642 for this compound, assuming that its lifetime is comparable to the lifetime of PFC-1216.

2643

#### 2644 **Perfluorobut-2-ene (CF<sub>3</sub>CF=CFCF<sub>3</sub>)**

2645 Previous reports of RE of perfluorobut-2-ene are in the range  $0.30 - 0.32 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  
2646  $0.31 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Cometto et al.*, 2010; *Young et al.*, 2009a]. We calculate a RE value of  
2647  $0.07 \text{ W m}^{-2} \text{ ppb}^{-1}$  when using the absorption spectra and lifetime estimate (31 days) from  
2648 *Cometto et al.* [2010], and accounting for stratospheric temperature adjustment and non-  
2649 homogeneous distribution.

2650

#### 2651 **Other PFCs**

2652 In the sections above, recommended values of RE have been presented for the range of fully  
2653 fluorinated compounds considered in AR4, along with a small number of others, where

2654 experimental data are available. In addition, *Bravo et al.* [2010b] report estimates of RE for a  
2655 range of other PFCs, based on theoretical calculations.

2656

#### 2657 4.1.7 Halogenated Alcohols and Ethers

2658 This is a very broad range of compounds with lifetimes stretching from days to centuries. The  
2659 generally complex structure, compared to other compounds considered here, leads to a rich  
2660 infrared absorption spectrum – Figure 17 shows the spectrum of isoflurane ( $\text{CHF}_2\text{OCHClCF}$ )  
2661 a molecule used as an inhalation anesthetic, which has absorption bands stretching across  
2662 much of the infrared.

2663 Previously published absorption cross-sections are listed in Table 14, while updated  
2664 atmospheric lifetimes, radiative efficiencies, and 100-year GWP values for halogenated  
2665 alcohols and ethers are presented in Table 15 and discussed below. In contrast to sections  
2666 4.1.1 – 4.1.6, not all compounds have their own individual piece of text in this section. For the  
2667 purpose of presentation quality and brevity, some compounds are grouped together where we  
2668 found it appropriate. However, all the information about previously published estimates (both  
2669 based on experimental and *ab initio* absorption spectra) and results from our calculations can  
2670 be found in Tables 14-15, and in Table S7 in the supplementary material. With the exception  
2671 of PFPME, which is lost by photolysis in the upper atmosphere [*Young et al.*, 2006], the *S*-  
2672 shaped fit from section 3.3.4 (Equation (2) and dark blue curve in Figure 9) has been used to  
2673 account for a non-uniform vertical profile and geographic distribution for all compounds  
2674 presented in this subsection.

2675 In what follows, we focus particularly on the experimental studies. There have been *ab*  
2676 *initio* studies from three groups [*Blowers et al.*, 2007; 2008b; *Bravo et al.*, 2011a; *Good et al.*,  
2677 1998]. We can make the following general observations about these studies. The work from  
2678 the group of Blowers tends to calculate REs that are significantly higher than those obtained  
2679 from experimentally determined values. Differences are around 25%, but can be as high as  
2680 40%. This group does not adjust for atmospheric lifetimes, so the differences can appear  
2681 greater. The calculations from *Bravo et al.* [2011a] tend to agree with experimental values  
2682 within about 10-15%, although the more sophisticated lifetime adjustment applied here can  
2683 make the differences appear larger. However, REs calculated for the HG' HFPEs are some  
2684 35% higher than experimental values, although it should be noted that only one group has

2685 studied these compounds experimentally [Stevenson *et al.*, 2004]. Good *et al.* [1998]  
2686 examined only three compounds using a narrow band model; they obtain values that are  
2687 somewhat higher than those using experimentally determined cross-sections. In the text  
2688 below, we do not discuss the *ab initio* calculations except where they provide the only RE  
2689 values, or are of special note. Whenever RE values based on *ab initio* calculations are  
2690 presented, this has been clearly marked in the text.

2691 A large number of the compounds in this section were examined by Imasu *et al.*  
2692 [1995], who reported both laboratory spectroscopy measurements and REs, calculated for a  
2693 clear-sky mid-latitude atmosphere. In WMO [1999] (which became a source for REs used in  
2694 many subsequent IPCC and WMO Ozone assessments), these were approximately converted  
2695 to global-mean all-sky adjusted RE by taking their RE relative to Imasu *et al.*'s [1995] own  
2696 CFC-11 calculation and then multiplying by the CFC-11 RE ( $0.25 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) used in WMO  
2697 [1999] (see footnote i of Table 10-6 of WMO [1999]). Henceforth in this section, we refer to  
2698 these forcings as “Imasu *et al.* [1995] as modified by WMO [1999]”. When referring to the  
2699 Imasu *et al.* [1995] REs we renormalize the WMO [1999] forcings to account for our  
2700 recommended 4% increase in the CFC-11 RE (see section 4.1.1).

2701

#### 2702 **HFE-125 (CHF<sub>2</sub>OCF<sub>3</sub>)**

2703 Previous reports of RE due to HFE-125 are in the range  $0.41 - 0.44 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.42$   
2704  $\text{W m}^{-2} \text{ ppb}^{-1}$ ) [Christidis *et al.*, 1997; Heathfield *et al.*, 1998; Sihra *et al.*, 2001]. IPCC AR4  
2705 uses a RE of  $0.44 \text{ W m}^{-2} \text{ ppb}^{-1}$  taken from Christidis *et al.* [1997], Good *et al.* [1998] and  
2706 Heathfield *et al.* [1998] (the latter two after rescaling as reported in WMO [1999]). We have  
2707 used the absorption cross-sections from Sihra *et al.* [2001] and calculated a RE of  $0.41 \text{ W m}^{-2}$   
2708  $\text{ppb}^{-1}$  – 8% lower than that in AR4.

2709

#### 2710 **HFE-134 (HG-00) (CHF<sub>2</sub>OCHF<sub>2</sub>)**

2711 Previous reports of RE of HFE-134 (HG-00) are in the range  $0.40 - 0.44 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  
2712  $0.43 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Andersen *et al.*, 2010a; Heathfield *et al.*, 1998; Imasu *et al.*, 1995; Myhre  
2713 *et al.*, 1999]. IPCC AR4 used a RE value of  $0.45 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from Good *et al.*  
2714 [1998] and Heathfield *et al.* [1998] after rescaling in WMO [1999]. Here we have used the  
2715 absorption cross-section from Imasu *et al.* [1995] and calculated a RE value of  $0.44 \text{ W m}^{-2}$

2716 ppb<sup>-1</sup>, which is in good agreement with AR4. Due to an update in the lifetime for this  
2717 compound (24.4 years in WMO [2011] compared to 26 years in AR4), and a higher AGWP<sub>CO2</sub>  
2718 value, the GWP(100) value is significantly lower than that in AR4 (see Table 15).

2719

2720 **HFE-143a (CH<sub>3</sub>OCF<sub>3</sub>)**

2721 Previous reports of RE of HFE-143a are in the range 0.17 - 0.19 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.18 W  
2722 m<sup>-2</sup> ppb<sup>-1</sup>) [Christensen *et al.*, 1999; Sihra *et al.*, 2001]. IPCC AR4 reports a RE of 0.27 W m<sup>-2</sup>  
2723 ppb<sup>-1</sup> which is taken from the *ab initio* study of Good *et al.* [1998] after rescaling assuming  
2724 CFC-11 RE = 0.25 W m<sup>-2</sup> ppb<sup>-1</sup> in WMO [1999]. We calculate a RE value of 0.18 W m<sup>-2</sup> ppb<sup>-1</sup>  
2725 using absorption cross-section from Sihra *et al.* [2001]. Our estimate is much lower (34%  
2726 lower) than the AR4 value, which is based on an *ab initio* study, but in good agreement with  
2727 experimental studies.

2728

2729 **HFE-227ea (CF<sub>3</sub>CHFOCF<sub>3</sub>)**

2730 Previous reports of RE of HFE-227ea are in the range 0.31 - 0.42 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.37 W  
2731 m<sup>-2</sup> ppb<sup>-1</sup>) [Imasu *et al.*, 1995; Jain *et al.*, 2001; Oyaro *et al.*, 2005; Takahashi *et al.*, 2002].  
2732 IPCC AR4 reports a RE of 0.40 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from Imasu *et al.* [1995] as  
2733 modified by WMO [1999]. We calculate a RE value of 0.44 W m<sup>-2</sup> ppb<sup>-1</sup> both when using  
2734 absorption cross-sections from Oyaro *et al.* [2005] and Imasu *et al.* [1995]. Our estimate is  
2735 10% higher than in AR4.

2736

2737 **HCFE-235ca2 (enflurane) (CHF<sub>2</sub>OCF<sub>2</sub>CHFCl)**

2738 Previous studies of RE due to HCFE-235ca2 (enflurane) are in the range 0.42 - 0.45 W m<sup>-2</sup>  
2739 ppb<sup>-1</sup> (mean: 0.43 W m<sup>-2</sup> ppb<sup>-1</sup>) [Andersen *et al.*, 2012b; Dalmaso *et al.*, 2006]. We have  
2740 used the absorption cross-sections from these two studies and calculated a mean RE value of  
2741 0.41 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.39 - 0.42 W m<sup>-2</sup> ppb<sup>-1</sup>).

2742

2743 **HCFE-235da2 (isoflurane) (CHF<sub>2</sub>OCHClCF<sub>3</sub>)**

2744 Previous reports of RE due to HCFE-235da2 (isoflurane) are in the range 0.37 - 0.48 W m<sup>-2</sup>  
2745 ppb<sup>-1</sup> (mean: 0.44 W m<sup>-2</sup> ppb<sup>-1</sup>) [Andersen *et al.*, 2010b; Christidis *et al.*, 1997; Ryan and

2746 *Nielsen, 2010; Sihra et al., 2001*]. IPCC AR4 accounted for stratospheric decay and reports a  
2747 RE of  $0.38 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from *Christidis et al. [1997]*. We calculate a RE value  
2748 of  $0.42 \text{ W m}^{-2} \text{ ppb}^{-1}$  both when using absorption cross-sections from *Andersen et al. [2010c]*  
2749 and from *Ryan and Nielsen [2010]*. Our estimate is about 10% higher than in AR4.

2750

2751 **HFEs studied theoretically by *Blowers et al. [2007]* and *Blowers et al. [2008a]***

2752 For some HFE compounds, no RE estimates based on experimental absorption cross-sections  
2753 exist, and the *ab initio* studies of *Blowers et al. [2007]* and *Blowers et al. [2008a]* provide the  
2754 only RE estimates of these HFEs. These compounds are:

2755 HFE-236ca ( $\text{CHF}_2\text{OCF}_2\text{CHF}_2$ )

2756 Fluoro(methoxy)methane ( $\text{CH}_3\text{OCH}_2\text{F}$ )

2757 Difluoro(methoxy)methane ( $\text{CH}_3\text{OCHF}_2$ )

2758 Fluoro(fluoromethoxy)methane ( $\text{CH}_2\text{FOCH}_2\text{F}$ )

2759 Difluoro(fluoromethoxy)methane ( $\text{CH}_2\text{FOCHF}_2$ )

2760 Trifluoro(fluoromethoxy)methane ( $\text{CH}_2\text{FOCF}_3$ )

2761 Trifluoro(trifluoromethoxy)methane ( $\text{CF}_3\text{OCF}_3$ )

2762

2763 Note that *Blowers et al. [2007]* estimated REs for some hydrofluoroethers not listed in  
2764 this section. *Blowers et al. [2007]* and *Blowers et al. [2008a]* calculated instantaneous REs by  
2765 using the theoretical procedure described by *Papasavva et al. [1997]* combined with the  
2766 *Pinnock et al. [1995]* method (their RE estimates are listed in Table S7 in the supplementary  
2767 material). Since absorption spectra were unavailable for the seven compounds listed above, no  
2768 new calculations have been carried out here. Thus, we use the REs from *Blowers et al. [2007]*  
2769 and *Blowers et al. [2008a]*, accounting for stratospheric temperature adjustment and lifetime  
2770 correction (see sections 3.3.2 and 3.3.4, respectively), and present new best estimate RE and  
2771 GWP values in Table 15. The lifetime of HFE-236ca is from *WMO [2011]*, the lifetime of  
2772 fluoro(methoxy)methane is from *Urata et al. [2003]*, while a lifetime estimate could not be  
2773 found for trifluoro(trifluoromethoxy)methane and thus we only present RE assuming a  
2774 uniform distribution for this compound. The lifetimes of the remaining compounds are taken

2775 from *Blowers et al.* [2008a]. The resulting REs are 0.56, 0.07, 0.17, 0.19, 0.30, 0.33 and 0.53  
2776  $\text{W m}^{-2} \text{ppb}^{-1}$  for HFE-236ca, fluoro(methoxy)methane, difluoro(methoxy)methane,  
2777 fluoro(fluoromethoxy)methane, difluoro(fluoromethoxy)methane,  
2778 trifluoro(fluoromethoxy)methane and trifluoro(trifluoromethoxy)methane, respectively.  
2779 However, it should be stressed that these REs are based on *ab initio* studies, and the  
2780 uncertainties are therefore larger than for REs based on experimental absorption spectra, as  
2781 discussed in section 3.6.1.

2782

### 2783 **HFE-236ea2 (desflurane) ( $\text{CHF}_2\text{OCHF}_2\text{CF}_3$ )**

2784 Previous studies of RE of HFE-236ea2 (desflurane) are in the range 0.45 - 0.47  $\text{W m}^{-2} \text{ppb}^{-1}$   
2785 (mean: 0.46  $\text{W m}^{-2} \text{ppb}^{-1}$ ) [*Andersen et al.*, 2010b; *Imasu et al.*, 1995; *Oyaro et al.*, 2005].  
2786 IPCC AR4 used a RE of 0.44  $\text{W m}^{-2} \text{ppb}^{-1}$  which is taken from *Imasu et al.* [1995] as  
2787 modified by *WMO* [1999]. We calculate a mean RE value of 0.45  $\text{W m}^{-2} \text{ppb}^{-1}$  (range: 0.45 -  
2788 0.46  $\text{W m}^{-2} \text{ppb}^{-1}$ ) using absorption cross-sections from three sources [*Andersen et al.*, 2010c;  
2789 *Imasu et al.*, 1995; *Oyaro et al.*, 2005]. Our RE estimate is in good agreement with AR4, but  
2790 due to an updated lifetime estimate (10.8 years in *WMO* [2011] compared to 5.8 years in  
2791 AR4), our GWP(100) value is much higher, despite the higher AGWP<sub>CO2</sub> value used here.

2792

### 2793 **HFEs studied by *Imasu et al.* [1995]**

2794 For a number of HFE compounds, *Imasu et al.* [1995] is the only study providing REs based  
2795 on experimental absorption cross-sections:

2796 HFE-236fa ( $\text{CF}_3\text{CH}_2\text{OCF}_3$ )

2797 HFE-245cb2 ( $\text{CF}_3\text{CF}_2\text{OCH}_3$ )

2798 HFE-245fa1 ( $\text{CHF}_2\text{CH}_2\text{OCF}_3$ )

2799 HFE-329mcc2 ( $\text{CHF}_2\text{CF}_2\text{OCF}_2\text{CF}_3$ )

2800 HFE-338mmz1 ( $(\text{CF}_3)_2\text{CHOCHF}_2$ )

2801 HFE-338mcf2 ( $\text{CF}_3\text{CH}_2\text{OCF}_2\text{CF}_3$ )

2802 HFE-347mcf2 ( $\text{CHF}_2\text{CH}_2\text{OCF}_2\text{CF}_3$ )

- 2803 HFE-347mmy1 ((CF<sub>3</sub>)<sub>2</sub>CFOCH<sub>3</sub>)
- 2804 HFE-356mec3 (CH<sub>3</sub>OCF<sub>2</sub>CHF<sub>2</sub>CF<sub>3</sub>)
- 2805 HFE-356pcf2 (CHF<sub>2</sub>CH<sub>2</sub>OCF<sub>2</sub>CHF<sub>2</sub>)
- 2806 HFE-356pcf3 (CHF<sub>2</sub>OCH<sub>2</sub>CF<sub>2</sub>CHF<sub>2</sub>)
- 2807 HFE-356pcc3 (CH<sub>3</sub>OCF<sub>2</sub>CF<sub>2</sub>CHF<sub>2</sub>)
- 2808 1,1,1,3,3,3-Hexafluoro-2-(trifluoromethyl)-2-propanol ((CF<sub>3</sub>)<sub>3</sub>COH)
- 2809 2,2,3,3,4,4,5,5-Octafluorocyclopentanol (-(CF<sub>2</sub>)<sub>4</sub>CH(OH)-)
- 2810 1,1,1,3,3,3-Hexafluoropropan-2-ol ((CF<sub>3</sub>)<sub>2</sub>CHOH)

2811

2812 Many of the compounds listed above have also been studied using *ab initio* methods in  
 2813 *Blowers et al.* [2007] and *Bravo et al.* [2011a] (see Table 14). As previously mentioned, the  
 2814 uncertainties are larger for theoretical studies and we choose to focus on the experimental  
 2815 studies when these are available. With the exception of 1,1,1,3,3,3-hexafluoro-2-  
 2816 (trifluoromethyl)-2-propanol, for which no lifetime estimate is available in the literature, all  
 2817 the 15 compounds listed above, and their REs, have been reported in AR4 based on *Imasu et*  
 2818 *al.* [1995] as modified by *WMO* [1999]. We have used the *Imasu et al.* [1995] cross-sections  
 2819 to calculate new estimates of RE, taking into account both stratospheric temperature  
 2820 adjustment (by increasing the instantaneous RE by 10% as described in section 3.3.2) and  
 2821 fractional correction (by using the method described in section 3.3.4). Table 15 presents the  
 2822 results of our calculations and highlights the best estimate RE and GWP(100) values for each  
 2823 compound. For 5 of the 14 compounds which are listed above and included in AR4, our  
 2824 calculation of RE differed by more than 5% compared to AR4. The differences in RE between  
 2825 our calculation and AR4 were larger for compounds which were not well-mixed in the  
 2826 atmosphere (with lifetimes typically less than a few years), because lifetime corrections were  
 2827 not considered in AR4 (recall from the introduction to section 4.1.7 that the *Imasu et al.*  
 2828 [1995] results were scaled to a CFC-11 value of 0.25 W m<sup>-2</sup> ppb<sup>-1</sup> as explained in *WMO*  
 2829 [1999]). In many of the cases the REs in our calculation were in good agreement with AR4,  
 2830 but the updated lifetimes, which we take from *WMO* [2011], led to a change in the GWP(100)  
 2831 compared to AR4 (note also that the updated AGWP<sub>CO<sub>2</sub></sub> lead to ~5% lower GWP(100) for all  
 2832 compounds compared to AR4).

2833

2834 **HFE-245fa2 (CHF<sub>2</sub>OCH<sub>2</sub>CF<sub>3</sub>)**

2835 Previous calculations of RE of HFE-245fa2 are in the range 0.33 - 0.39 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2836 0.37 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Christidis et al.*, 1997; *Imasu et al.*, 1995; *Oyaro et al.*, 2005; *Sihra et al.*,  
2837 2001]. IPCC AR4 reports a RE of 0.31 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Christidis et al.*  
2838 [1997], but modified to approximately account for stratospheric decay as described in *WMO*  
2839 [1999]. We have used absorption cross-sections from *Oyaro et al.* [2005], *Sihra et al.* [2001]  
2840 and *Imasu et al.* [1995] and calculated a RE value of 0.36 W m<sup>-2</sup> ppb<sup>-1</sup> for all three absorption  
2841 spectra. The reason for the 16% higher RE value calculated here compared to AR4 is related  
2842 to the different factors to account for the non-uniform distribution in the atmosphere. AR4  
2843 used a crude factor of 0.8 from *Freckleton et al.* [1998] while our method (see section 3.3.4)  
2844 yields a factor of 0.93 for a lifetime of 5.5 years.

2845

2846 **2,2,3,3,3-Pentafluoropropan-1-ol (CF<sub>3</sub>CF<sub>2</sub>CH<sub>2</sub>OH)**

2847 Previous studies of RE due to 2,2,3,3,3-pentafluoropropan-1-ol are in the range 0.25 - 0.26 W  
2848 m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.25 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Antiñolo et al.*, 2012b; *Imasu et al.*, 1995; *Sellevåg et al.*,  
2849 2007]. IPCC AR4 reports a RE of 0.24 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Imasu et al.* [1995] as  
2850 modified by *WMO* [1999]. We calculate a mean RE value of 0.14 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.13 -  
2851 0.15 W m<sup>-2</sup> ppb<sup>-1</sup>) using absorption cross-sections from three sources [*Antiñolo et al.*, 2012b;  
2852 *Imasu et al.*, 1995; *Sellevåg et al.*, 2007]. Our estimate is much lower (42% different) than  
2853 that in AR4. The short lifetime of 0.3 years [*Antiñolo et al.*, 2012b] for this compound leads  
2854 to a strong effect of the fractional correction factor which has been applied to account for non-  
2855 uniform mixing (vertical and horizontal). It should be noted here that the uncertainties  
2856 associated with this correction factor are very large on a percentage basis for such short-lived  
2857 species (see Figure 9 and associated discussion in section 3.3.4), and we further note that our  
2858 calculated instantaneous RE (i.e., without applying corrections for stratospheric temperature  
2859 adjustment and lifetime correction) is in good agreement with the published instantaneous RE  
2860 estimates (Table 7 in supplementary material).

2861

2862 **HFE-254cb1 (CH<sub>3</sub>OCF<sub>2</sub>CHF<sub>2</sub>)**



2863 Previous calculations of RE of HFE-254cb1 are in the range 0.29 - 0.30 W m<sup>-2</sup> ppb<sup>-1</sup> (mean:  
2864 0.29 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Heathfield et al.*, 1998; *Imasu et al.*, 1995]. IPCC AR4 used a RE of 0.28  
2865 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Imasu et al.* [1995] as modified by *WMO* [1999]. We  
2866 calculate an 8% lower RE value of 0.26 W m<sup>-2</sup> ppb<sup>-1</sup> using absorption cross-section from  
2867 *Imasu et al.* [1995].

2868

#### 2869 **HFE-263fb1 (CF<sub>3</sub>CH<sub>2</sub>OCH<sub>3</sub>)**

2870 Previous reports of RE of HFE-263fb2 are in the range 0.19 - 0.21 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.20  
2871 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Imasu et al.*, 1995; *Osterstrom et al.*, 2012; *Oyaro et al.*, 2005]. IPCC AR4  
2872 gives a RE of 0.20 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from *Imasu et al.* [1995] as modified by *WMO*  
2873 [1999]. Using absorption cross-sections from three studies [*Imasu et al.*, 1995; *Osterstrom et*  
2874 *al.*, 2012; *Oyaro et al.*, 2005] that give the same results we calculate a much lower (81%)  
2875 mean RE value of 0.04 W m<sup>-2</sup> ppb<sup>-1</sup>. The reason for the large differences between our estimate  
2876 and the AR4 is the lifetime correction factor of 0.18 (for a lifetime of 23 days [*WMO*, 2011])  
2877 which has been applied here to account for non-uniform distribution (vertical and horizontal).  
2878 It should be noted here that the uncertainties associated with this correction factor are very  
2879 large on a percentage basis for such short-lived species (see Figure 9 and associated  
2880 discussion in section 3.3.4). Our calculated RE is, however, in good agreement with the  
2881 results from *Imasu et al.* [1995], and hence AR4, if we compare instantaneous RE (i.e.,  
2882 without applying corrections for stratospheric temperature adjustment and lifetime correction)  
2883 (Table 7 in supplementary material).

2884

#### 2885 **HFEs studied by *Oyaro et al.* [2005]**

2886 For the following HFE compounds, *Oyaro et al.* [2005] is the only study providing REs based  
2887 on experimental absorption cross-sections:

2888 HFE-263m1 (CF<sub>3</sub>OCH<sub>2</sub>CH<sub>3</sub>)

2889 1,1,2-Trifluoro-2-(trifluoromethoxy)-ethane (CHF<sub>2</sub>CHFOCF<sub>3</sub>)

2890 1-Ethoxy-1,1,2,3,3,3-hexafluoropropane (CF<sub>3</sub>CHF<sub>2</sub>CF<sub>2</sub>OCH<sub>2</sub>CH<sub>3</sub>)

2891 1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane (CF<sub>3</sub>CF<sub>2</sub>CF<sub>2</sub>OCHF<sub>2</sub>CF<sub>3</sub>)

2892

2893 *Ab initio* studies are available for these compounds [Blowers *et al.*, 2007; Bravo *et al.*,  
2894 2011a] (Table 14), but we focus here on the experimental data from Oyaró *et al.* [2005]. They  
2895 used the Pinnock *et al.* [1995] method to estimate instantaneous REs of 0.21, 0.35, 0.33 and  
2896  $0.56 \text{ W m}^{-2} \text{ ppb}^{-1}$  for HFE-263m1, 1,1,2-Trifluoro-2-(trifluoromethoxy)-ethane, 1-Ethoxy-  
2897 1,1,2,3,3,3-hexafluoropropane, and 1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-  
2898 propane, respectively. The corresponding RE estimates from our calculations (now taking  
2899 into account stratospheric temperature adjustment and inhomogeneous distribution in the  
2900 troposphere) are 0.13, 0.35, 0.33 and  $0.58 \text{ W m}^{-2} \text{ ppb}^{-1}$ , respectively, when using absorption  
2901 cross-sections from Oyaró *et al.* [2005] and lifetime estimates of 0.4 [Bravo *et al.*, 2011a],  
2902 9.8, 0.4 and 67.0 years [Oyaró *et al.*, 2005], respectively. None of these compounds are  
2903 included in AR4, thus we provide new best estimates of RE and GWP for all these  
2904 compounds.

2905

### 2906 **3,3,3-Trifluoropropan-1-ol (CF<sub>3</sub>CH<sub>2</sub>CH<sub>2</sub>OH)**

2907 Previous experimental studies of 3,3,3-trifluoropropan-1-ol have reported values for RE in the  
2908 range  $0.17 - 0.20 \text{ W m}^{-2} \text{ ppb}^{-1}$  (mean:  $0.19 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Jimenez *et al.*, 2010; Sellevåg *et al.*,  
2909 2007]. We have used absorption cross-sections from Jimenez *et al.* [2010], Sellevåg *et al.*  
2910 [2007] and Waterland *et al.* [2005] and calculated the same RE of  $0.02 \text{ W m}^{-2} \text{ ppb}^{-1}$  for all  
2911 three spectra. Our calculated instantaneous REs of  $0.21 \text{ W m}^{-2} \text{ ppb}^{-1}$  and  $0.17 \text{ W m}^{-2} \text{ ppb}^{-1}$   
2912 using spectra from Jimenez *et al.* [2010] and Sellevåg *et al.* [2007], respectively, compare  
2913 well with the previously published REs (which did not account for stratospheric temperature  
2914 adjustment and lifetime correction). The lifetime of 12.0 days is taken from Jimenez *et al.*  
2915 [2010].

2916

### 2917 **Sevoflurane, HFE-347mmz1 ((CF<sub>3</sub>)<sub>2</sub>CHOCH<sub>2</sub>F)**

2918 Experimental studies have reported RE values for sevoflurane in the range  $0.35 - 0.37 \text{ W m}^{-2}$   
2919  $\text{ppb}^{-1}$  (mean:  $0.36 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [Andersen *et al.*, 2010c; Ryan and Nielsen, 2010]. We have  
2920 used the absorption cross-sections from these two studies and calculated a RE value of  $0.32$   
2921  $\text{W m}^{-2} \text{ ppb}^{-1}$  for both spectra. It should be noted here that Andersen *et al.* [2010c] and Ryan  
2922 and Nielsen [2010] calculated the instantaneous RE using the Pinnock *et al.* [1995] method

2923 while we have accounted for stratospheric temperature adjustment and non-uniform  
2924 distribution in the troposphere.

2925

2926 **HFE-347mcc3 (HFE-7000) (CH<sub>3</sub>OCF<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)**

2927 Previous experimental studies of HFE-347mcc3 (HFE-7000) have reported values for RE in  
2928 the range 0.32 - 0.35 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.34 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Bravo et al.*, 2010a; *Imasu et al.*,  
2929 1995; *Ninomiya et al.*, 2000]. We have used the absorption cross-sections from all these three  
2930 studies and calculated a mean RE value of 0.35 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.33 - 0.36 W m<sup>-2</sup> ppb<sup>-1</sup>).  
2931 Our estimate is in reasonable agreement with the RE of 0.34 W m<sup>-2</sup> ppb<sup>-1</sup> in AR4 (which  
2932 originated from *Imasu et al.* [1995] as modified by *WMO* [1999]).

2933

2934 **HFE-347pcf2 (CHF<sub>2</sub>CF<sub>2</sub>OCH<sub>2</sub>CF<sub>3</sub>)**

2935 One experimental study has reported a value of RE for this HFE-347pcf2 [*Heathfield et al.*,  
2936 1998]. The original value (0.47 W m<sup>-2</sup> ppb<sup>-1</sup>) was determined using the *Pinnock et al.* [1995]  
2937 method. There is some confusion regarding the RE of this molecule. *WMO* [1999] (where it is  
2938 referred to as HFE-347mfc2) use the *Heathfield et al.* [1998] value - this molecule then does  
2939 not seem to appear in IPCC or WMO/UNEP ozone assessments tabulations until *IPCC* [2007]  
2940 which recommends a value of 0.25 W m<sup>-2</sup> ppb<sup>-1</sup> – this is perhaps a lifetime-corrected version  
2941 of the earlier value, although no reference is given. We recommend instead, using the original  
2942 *Heathfield et al.* [1998] value, applying our generic correction of a 10% increase to account  
2943 for stratospheric temperature adjustment and applying the lifetime correction (assuming a  
2944 lifetime of 6 years) from section 3.3.4 of 0.93. This yields our recommended value of 0.48 W  
2945 m<sup>-2</sup> ppbv<sup>-1</sup>.

2946

2947 **HFE-356mff2 (CF<sub>3</sub>CH<sub>2</sub>OCH<sub>2</sub>CF<sub>3</sub>)**

2948 Previous experimental studies of HFE-356mff2 have reported values for RE in the range 0.33  
2949 - 0.35 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.35 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Oyaro et al.*, 2004; *Sihra et al.*, 2001;  
2950 *Wallington et al.*, 1998]. We calculate a mean RE value of 0.17 W m<sup>-2</sup> ppb<sup>-1</sup> (range: 0.17 -  
2951 0.18 W m<sup>-2</sup> ppb<sup>-1</sup>) using absorption cross-sections from two sources [*Oyaro et al.*, 2004; *Sihra*  
2952 *et al.*, 2001]. The non-homogeneous mixing of this short-lived compound was not accounted

2953 for in the three previous studies; our estimate of RE is consistent with the published values if  
2954 we assume uniform mixing.

2955

#### 2956 **HFE-356mmz1 ((CF<sub>3</sub>)<sub>2</sub>CHOCH<sub>3</sub>)**

2957 Previous experimental studies of HFE-356mmz1 have both reported values for RE of 0.31 W  
2958 m<sup>-2</sup> ppb<sup>-1</sup> [*Imasu et al.*, 1995; *Oyaro et al.*, 2004] (note that the *Imasu et al.* [1995] value is  
2959 here scaled to our recommended CFC-11 RE of 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>). The *Imasu et al.* [1995]  
2960 value (as modified by *WMO* [1999]) of 0.30 W m<sup>-2</sup> ppb<sup>-1</sup> was used by IPCC AR4. We have  
2961 used the absorption cross-sections from *Imasu et al.* [1995] and *Oyaro et al.* [2004] and  
2962 calculated a RE value of 0.15 W m<sup>-2</sup> ppb<sup>-1</sup> for both of these spectra. Our estimate is 50%  
2963 lower than AR4, and this is almost entirely due to the factor applied here to account for non-  
2964 homogeneous mixing for this short-lived species (lifetime of 97.1 days [*Oyaro et al.*, 2004]).  
2965 The best estimate RE and GWP values are shown in Table 15.

2966

#### 2967 **HFE-365mcf3 (CF<sub>3</sub>CF<sub>2</sub>CH<sub>2</sub>OCH<sub>3</sub>)**

2968 Previous experimental studies of HFE-365mcf3 have reported values for RE in the range 0.28  
2969 - 0.33 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.30 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Imasu et al.*, 1995; *Oyaro et al.*, 2004; *Thomsen*  
2970 *et al.*, 2011] (note that the *Imasu et al.* [1995] value is here scaled to our recommended CFC-  
2971 11 RE of 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>). The *Imasu et al.* [1995] value (as modified by *WMO* [1999]) of  
2972 0.27 W m<sup>-2</sup> ppb<sup>-1</sup> was used by IPCC AR4. In contrast to the published values we have  
2973 accounted for stratospheric temperature adjustment and non-homogeneous mixing in the  
2974 troposphere (assuming a lifetime of 19.3 days [*Oyaro et al.*, 2004]), and calculated a RE value  
2975 of 0.05 W m<sup>-2</sup> ppb<sup>-1</sup> when using absorption cross-sections from both *Oyaro et al.* [2004] and  
2976 *Imasu et al.* [1995]. Our estimate is ~80% lower than that in AR4, but it should be noted here  
2977 that the uncertainties associated with the lifetime correction factors are very large on a  
2978 percentage basis for such short-lived species (see Figure 9 and associated discussion in  
2979 section 3.3.4), and we further note that our calculated instantaneous RE is consistent with the  
2980 published estimates.

2981

#### 2982 **HFEs studied theoretically by *Bravo et al.* [2011a]**

2983 For a number of HFE compounds, no RE estimates based on experimental absorption cross-  
2984 sections exist and the *ab initio* study of *Bravo et al.* [2011a] provides the only RE estimate of  
2985 these HFEs. These compounds are:

2986 HFE-365mcf2 ( $\text{CF}_3\text{CF}_2\text{OCH}_2\text{CH}_3$ )

2987 HG-02 ( $\text{HF}_2\text{C}-(\text{OCF}_2\text{CF}_2)_2-\text{OCF}_2\text{H}$ )

2988 HG-03 ( $\text{HF}_2\text{C}-(\text{OCF}_2\text{CF}_2)_3-\text{OCF}_2\text{H}$ )

2989 HG-20 ( $\text{HF}_2\text{C}-(\text{OCF}_2)_2-\text{OCF}_2\text{H}$ )

2990 HG-21 ( $\text{HF}_2\text{C}-\text{OCF}_2\text{CF}_2\text{OCF}_2\text{OCF}_2\text{O}-\text{CF}_2\text{H}$ )

2991 HG-30 ( $\text{HF}_2\text{C}-(\text{OCF}_2)_3-\text{OCF}_2\text{H}$ )

2992 1-Ethoxy-1,1,2,2,3,3,3-heptafluoropropane ( $\text{CF}_3\text{CF}_2\text{CF}_2\text{OCH}_2\text{CH}_3$ )

2993 Fluoroxene ( $\text{CF}_3\text{CH}_2\text{OCH}=\text{CH}_2$ )

2994 1,1,2,2-Tetrafluoro-1-(fluoromethoxy)ethane ( $\text{CH}_2\text{FOCF}_2\text{CF}_2\text{H}$ )

2995 HG'-10 ( $\text{CH}_3\text{OCF}_2\text{OCH}_3$ )

2996 HG'-20 ( $\text{CH}_3\text{O}(\text{CF}_2\text{O})_2\text{CH}_3$ )

2997 HG'-30 ( $\text{CH}_3\text{O}(\text{CF}_2\text{O})_3\text{CH}_3$ )

2998

2999 For all of the compounds listed above we have used the theoretical absorption cross-  
3000 sections from *Bravo et al.* [2011a] to calculate estimates of RE, taking into account both  
3001 stratospheric temperature adjustment (by increasing the instantaneous RE by 10% as  
3002 described in section 3.3.2) and fractional correction (by using the method described in section  
3003 3.3.4). For three of these compounds (HG'-10, HG'-20, HG'-30), no lifetime estimates were  
3004 found in the literature, and hence the RE estimates for these compounds assumes a uniform  
3005 vertical and horizontal distribution in the atmosphere. Lifetimes for the remaining nine  
3006 compounds were taken from *Bravo et al.* [2011a]. The study of *Bravo et al.* [2011a] used the  
3007 *Pinnock et al.* [1995] method to estimate instantaneous REs, and accounted for non-  
3008 homogeneous mixing by applying the exponential function from *Sihra et al.* [2001] (see  
3009 section 3.3.4) for compounds where lifetime estimates were known. The RE estimates of  
3010 *Bravo et al.* [2011a] are listed in Table S7 in the supplementary material, while our results are  
3011 presented in Table 15. In general, differences are small but reflect the use of an updated

3012 *Pinnock et al.* [1995] curve in this study, and that the stratospheric temperature adjustment  
3013 was not taken into account in *Bravo et al.* [2011a]. None of the compounds listed above are  
3014 included in AR4, thus we provide new best estimates of RE and GWP for all these  
3015 compounds. It should, however, be kept in mind that RE estimates based on *ab initio*  
3016 calculations are associated with larger uncertainties than estimates based on experimental  
3017 cross-sections, as discussed in section 3.6.1 (see also Table 1).

3018

#### 3019 **HFE-374pc2 (CHF<sub>2</sub>CF<sub>2</sub>OCH<sub>2</sub>CH<sub>3</sub>)**

3020 Previous experimental studies of HFE-374pc2 have reported values for RE in the range 0.31 -  
3021 0.32 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.31 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Heathfield et al.*, 1998; *Imasu et al.*, 1995]. AR4  
3022 uses a RE of 0.25 W m<sup>-2</sup> ppb<sup>-1</sup> taken from *Heathfield et al.* [1998], but modified in *WMO*  
3023 [1999] to crudely account for non-homogeneous mixing by applying a factor of 0.8 based on  
3024 *Freckleton et al.* [1998]. We calculate a RE value of 0.30 W m<sup>-2</sup> ppb<sup>-1</sup> using absorption cross-  
3025 sections from *Imasu et al.* [1995]. Due to the different methods used to account for non-  
3026 homogeneous mixing, our estimate is 19% higher than in AR4. The lifetime of 5.0 years is  
3027 taken from AR4.

3028

#### 3029 **4,4,4-Trifluorobutan-1-ol (CF<sub>3</sub>(CH<sub>2</sub>)<sub>2</sub>CH<sub>2</sub>OH)**

3030 *Jimenez et al.* [2010] used the *Pinnock et al.* [1995] method and report an instantaneous RE  
3031 value for 4,4,4-trifluorobutan-1-ol of 0.11 W m<sup>-2</sup> ppb<sup>-1</sup>. We have used their absorption cross-  
3032 section and calculated the same instantaneous RE. When taking into account stratospheric  
3033 temperature adjustment and non-homogeneous mixing in the troposphere (assuming a lifetime  
3034 of 4.0 days [*Jimenez et al.*, 2010]), our calculation yield a RE value of 0.01 W m<sup>-2</sup> ppb<sup>-1</sup>.

3035

#### 3036 **HFE-43-10pccc124 (H-Galden 1040x, HG-11) (CHF<sub>2</sub>OCF<sub>2</sub>OC<sub>2</sub>F<sub>4</sub>OCHF<sub>2</sub>)**

3037 Previous experimental studies of HFE-43-10pccc124 (H-Galden 1040x, HG-11) have  
3038 reported values for RE in the range 0.99 – 1.37 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 1.12 W m<sup>-2</sup> ppb<sup>-1</sup>)  
3039 [*Christidis et al.*, 1997; *Myhre et al.*, 1999; *Sihra et al.*, 2001; *Wallington et al.*, 2009]. IPCC  
3040 AR4 use a RE of 1.37 W m<sup>-2</sup> ppb<sup>-1</sup> taken from *Myhre et al.* [1999]. We have used the  
3041 absorption cross-section from *Wallington et al.* [2009] and calculated a 26% lower RE value

3042 of  $1.02 \text{ W m}^{-2} \text{ ppb}^{-1}$ , which is the same as the estimate in *Wallington et al.* [2009]. It should  
3043 be noted here that the spectrum from *Wallington et al.* [2009] supersedes previous Ford  
3044 measurements of HG-11 [*Christidis et al.*, 1997; *Sihra et al.*, 2001] and that the cross-section  
3045 from *Cavalli et al.* [1998], which has been used in *Myhre et al.* [1999], is an overestimate  
3046 [*Wallington et al.*, 2009].

3047

#### 3048 **HFE-449s1 (HFE-7100) ( $\text{C}_4\text{F}_9\text{OCH}_3$ )**

3049 Previous studies of RE due to HFE-449s1 (HFE-7100) are in the range  $0.31 - 0.37 \text{ W m}^{-2} \text{ ppb}^{-1}$   
3050 <sup>1</sup> (mean:  $0.34 \text{ W m}^{-2} \text{ ppb}^{-1}$ ) [*Bravo et al.*, 2010a; *Sihra et al.*, 2001; *Wallington et al.*, 1997].  
3051 IPCC AR4 report a RE of  $0.31 \text{ W m}^{-2} \text{ ppb}^{-1}$  which is taken from *Wallington et al.* [1997] as  
3052 modified by *WMO* [1999]. We estimate a 17% higher RE of  $0.36 \text{ W m}^{-2} \text{ ppb}^{-1}$  using the  
3053 absorption cross-sections from two sources [*Bravo et al.*, 2010a; *Sihra et al.*, 2001] and  
3054 applying our lifetime correction. The main reason for the higher estimate is due to lower  
3055 lifetime correction with a factor of 0.92 instead of 0.8 applied in *WMO* [1999].

3056

#### 3057 **HFEs studied by *Sihra et al.* [2001]**

3058 For the following HFE compounds, *Sihra et al.* [2001] is the only study providing REs based  
3059 on experimental absorption cross-sections:

3060 *n*-HFE-7100 (*n*- $\text{C}_4\text{F}_9\text{OCH}_3$ )

3061 *i*-HFE-7100 (*i*- $\text{C}_4\text{F}_9\text{OCH}_3$ )

3062 *i*-HFE-7200 (*i*- $\text{C}_4\text{F}_9\text{OC}_2\text{H}_5$ )

3063

3064 *Ab initio* studies are available for these compounds [*Blowers et al.*, 2007; *Bravo et al.*,  
3065 2011a] (Table 14), but we focus here on the experimental data from *Sihra et al.* [2001]. They  
3066 assumed homogeneous distribution in the atmosphere and estimated REs of 0.47, 0.37 and  
3067  $0.34 \text{ W m}^{-2} \text{ ppb}^{-1}$  for *n*-HFE-7100, *i*-HFE-7100 and *i*-HFE-7200, respectively. Our  
3068 calculations are consistent with the *Sihra et al.* [2001] results if we make the same assumption  
3069 and use their absorption cross-sections. When accounting for non-homogeneous vertical and  
3070 horizontal distribution, our calculations yield lower REs with values of 0.42, 0.35 and  $0.24 \text{ W}$   
3071  $\text{m}^{-2} \text{ ppb}^{-1}$  for *n*-HFE-7100, *i*-HFE-7100 and *i*-HFE-7200, respectively. We have then assumed

3072 that the lifetime of *n*-HFE-7100 and *i*-HFE-7100 are the same as for HFE-7100 (4.7 years  
3073 [WMO, 2011]), and that *i*-HFE-7200 has the same lifetime as HFE-7200 (0.8 years [WMO,  
3074 2011]). None of these compounds are included in AR4, thus we provide new best estimates of  
3075 RE and GWP for all these compounds.

3076

#### 3077 **HFE-569sf2 (HFE-7200) (C<sub>4</sub>F<sub>9</sub>OC<sub>2</sub>H<sub>5</sub>)**

3078 Previous studies of RE due to HFE-569sf2 (HFE-7200) are in the range 0.30 - 0.39 W m<sup>-2</sup>  
3079 ppb<sup>-1</sup> (mean: 0.33 W m<sup>-2</sup> ppb<sup>-1</sup>) [Bravo *et al.*, 2010a; Christensen *et al.*, 1998; Sihra *et al.*,  
3080 2001]. IPCC AR4 report a RE of 0.30 W m<sup>-2</sup> ppb<sup>-1</sup> which is taken from Christensen *et al.*  
3081 [1998] as modified by WMO [1999]. We have used absorption cross-sections from two  
3082 sources [Bravo *et al.*, 2010a; Sihra *et al.*, 2001] and calculated a mean RE value of 0.30 W m<sup>-2</sup>  
3083 ppb<sup>-1</sup> (range: 0.29 - 0.32 W m<sup>-2</sup> ppb<sup>-1</sup>) – in agreement with AR4.

3084

#### 3085 ***n*-HFE-7200 (*n*-C<sub>4</sub>F<sub>9</sub>OC<sub>2</sub>H<sub>5</sub>)**

3086 The only estimates of the RE of *n*-HFE-7200 are from the *ab initio* studies of Bravo *et al.*  
3087 [2011a] and Blowers *et al.* [2007] who both used the Pinnock *et al.* [1995] method to  
3088 calculate instantaneous REs of 0.47 and 0.55 W m<sup>-2</sup> ppb<sup>-1</sup>, respectively. We have used the  
3089 theoretical absorption spectrum from Bravo *et al.* [2011a] and calculated a similar  
3090 instantaneous RE (0.45 W m<sup>-2</sup> ppb<sup>-1</sup>). When accounting for stratospheric temperature  
3091 adjustment and non-homogeneous tropospheric distribution, our RE estimate is 0.35 W m<sup>-2</sup>  
3092 ppb<sup>-1</sup>. We have then assumed that *n*-HFE-7200 has the same lifetime as HFE-7200 (0.8 years  
3093 [WMO, 2011]).

3094

#### 3095 **HFE-236ca12 (HG-10) (CHF<sub>2</sub>OCF<sub>2</sub>OCHF<sub>2</sub>)**

3096 The RE of HFE-236ca12 (HG-10) has been estimated to be 0.66 W m<sup>-2</sup> ppb<sup>-1</sup> in Myhre *et al.*  
3097 [1999], and this value was used in the AR4 report. We have used the absorption cross-section  
3098 from the same study and calculated a RE value of 0.65 W m<sup>-2</sup> ppb<sup>-1</sup> – in good agreement with  
3099 AR4. Due to an updated lifetime for this compound, from 12.1 years in AR4 to 25.0 years in  
3100 WMO [2011], our calculated GWP(100) value is considerably higher than in AR4, despite the  
3101 higher AGWP<sub>CO2</sub> value used here.



3102

3103 **HFE-338pcc13 (HG-01) (CHF<sub>2</sub>OCF<sub>2</sub>CF<sub>2</sub>OCHF<sub>2</sub>)**

3104 *Myhre et al.* [1999] have estimated a RE due to HFE-338pcc13 (HG-01) of 0.87 W m<sup>-2</sup> ppb<sup>-1</sup>,  
3105 which is the value adopted by AR4. We have used the *Myhre et al.* [1999] absorption cross-  
3106 section and calculated a similar RE value of 0.86 W m<sup>-2</sup> ppb<sup>-1</sup>. We use an updated lifetime of  
3107 12.9 years [*WMO*, 2011], compared to 6.2 years in AR4, and this leads to a GWP(100) value  
3108 which is about a factor 2 higher than in AR4.

3109

3110 **2-Ethoxy-3,3,4,4,5-pentafluorotetrahydro-2,5-bis[1,2,2,2-tetrafluoro-1-**  
3111 **(trifluoromethyl)ethyl]-furan (C<sub>12</sub>H<sub>5</sub>F<sub>19</sub>O<sub>2</sub>)**

3112 *Javadi et al.* [2007] used the *Pinnock et al.* [1995] method to estimate an instantaneous RE  
3113 due to 2-ethoxy-3,3,4,4,5-pentafluorotetrahydro-2,5-bis[1,2,2,2-tetrafluoro-1-  
3114 (trifluoromethyl)ethyl]-furan of 0.60 W m<sup>-2</sup> ppb<sup>-1</sup>. Since no new calculations have been  
3115 carried out here for this compound, we apply our generic correction of a 10% increase to  
3116 account for stratospheric temperature adjustment, and our lifetime correction factor (assuming  
3117 a lifetime of 1.0 year [*Javadi et al.*, 2007]) from section 3.3.4 of 0.74, and recommend a RE  
3118 value of 0.49 W m<sup>-2</sup> ppbv<sup>-1</sup>.

3119

3120 **HFEs studied by Andersen et al. [2004]**

3121 For the following HFE compounds, *Andersen et al.* [2004] is the only study providing REs  
3122 based on experimental absorption cross-sections:

3123 HG'-01 (CH<sub>3</sub>OCF<sub>2</sub>CF<sub>2</sub>OCH<sub>3</sub>)

3124 HG'-02 (CH<sub>3</sub>O(CF<sub>2</sub>CF<sub>2</sub>O)<sub>2</sub>CH<sub>3</sub>)

3125 HG'-03 (CH<sub>3</sub>O(CF<sub>2</sub>CF<sub>2</sub>O)<sub>3</sub>CH<sub>3</sub>)

3126

3127 RE estimates using *ab initio* calculations are available for these compounds [*Bravo et*  
3128 *al.*, 2011a] (Table S7 in the supplementary material), but we focus here on the experimental  
3129 data from *Andersen et al.* [2004]. They used the *Pinnock et al.* [1995] method to estimate  
3130 instantaneous REs of 0.32, 0.61 and 0.83 W m<sup>-2</sup> ppb<sup>-1</sup> for HG'-01, HG'-02 and HG'-03,

3131 respectively. The corresponding RE estimates from our calculations (now taking into account  
3132 stratospheric temperature adjustment and inhomogeneous distribution in the troposphere) are  
3133 0.29, 0.56 and 0.76  $W m^{-2} ppb^{-1}$ , respectively, when using absorption cross-sections and  
3134 lifetimes from *Andersen et al.* [2004]. None of these compounds are included in AR4, thus we  
3135 provide new best estimates of RE and GWP for all these compounds.

3136

3137 **HFE-329me3 (CF<sub>3</sub>CFHCF<sub>2</sub>OCF<sub>3</sub>)**

3138 *Wallington et al.* [2004] have calculated an instantaneous RE value of HFE-329me3 of 0.48  
3139  $W m^{-2} ppb^{-1}$  by using experimental absorption cross-section and the *Pinnock et al.* [1995]  
3140 method. We have used the absorption spectrum from the same study and calculated the same  
3141 RE value when accounting for stratospheric temperature adjustment. Due to the relatively  
3142 long lifetime of 40 years [*Wallington et al.*, 2004], the compound is well-mixed in the  
3143 troposphere and the lifetime correction factor does not impact the RE value.

3144

3145 **HFE-338mec3 (CF<sub>3</sub>CFHCF<sub>2</sub>OCF<sub>2</sub>H)**

3146 Previous experimental studies of RE due to HFE-338mec3 are in the range 0.49 - 0.51  $W m^{-2}$   
3147  $ppb^{-1}$  (mean: 0.50  $W m^{-2} ppb^{-1}$ ) [*Oyaro et al.*, 2005; *Wallington et al.*, 2004]. We have used  
3148 the absorption cross-sections from both these studies and calculated a mean RE value of 0.51  
3149  $W m^{-2} ppb^{-1}$  (range: 0.51 - 0.52  $W m^{-2} ppb^{-1}$ ) when assuming a uniform distribution in the  
3150 atmosphere. This is probably an upper estimate as no fractional correction factor has been  
3151 applied because of the large disagreement found in the literature of the lifetime for this  
3152 compound [*Oyaro et al.*, 2005; *Wallington et al.*, 2004].

3153

3154 **HFEs studied by *Waterland et al.* [2005]**

3155 For the following HFE compounds, *Waterland et al.* [2005] is the only study providing  
3156 experimental absorption cross-sections:

3157 3,3,4,4,5,5,6,6,7,7,7-Undecafluoroheptan-1-ol (CF<sub>3</sub>(CF<sub>2</sub>)<sub>4</sub>CH<sub>2</sub>CH<sub>2</sub>OH)

3158 3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-Pentadecafluorononan-1-ol (CF<sub>3</sub>(CF<sub>2</sub>)<sub>6</sub>CH<sub>2</sub>CH<sub>2</sub>OH)

3159 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-Nonadecafluoroundecan-1-ol  
3160 ( $\text{CF}_3(\text{CF}_2)_8\text{CH}_2\text{CH}_2\text{OH}$ )

3161

3162 *Waterland et al.* [2005] did not estimate REs of the compounds listed above, but we  
3163 have used their absorption cross-sections to calculate REs of 0.06, 0.07 and 0.05  $\text{W m}^{-2} \text{ppb}^{-1}$   
3164 for 3,3,4,4,5,5,6,6,7,7,7-undecafluoroheptan-1-ol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-  
3165 pentadecafluorononan-1-ol and 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-  
3166 nonadecafluoroundecan-1-ol, respectively. The lifetimes for all three compounds were  
3167 assumed to be 20 days based on *Ellis et al.* [2003].

3168

3169 **2-Chloro-1,1,2-trifluoro-1-methoxyethane ( $\text{CH}_3\text{OCF}_2\text{CHFCl}$ )**

3170 One experimental study has used the *Pinnock et al.* [1995] method to estimate an  
3171 instantaneous RE due to 2-chloro-1,1,2-trifluoro-1-methoxyethane of 0.26  $\text{W m}^{-2} \text{ppb}^{-1}$   
3172 [*Dalmasso et al.*, 2006]. We have used their absorption cross-section to calculate a slightly  
3173 lower RE value of 0.21  $\text{W m}^{-2} \text{ppb}^{-1}$  (now taking into account stratospheric temperature  
3174 adjustment and inhomogeneous distribution in the troposphere). The lifetime of 1.4 years is  
3175 taken from *Dalmasso et al.* [2006].

3176

3177 **PFFMIE (perfluoropolymethylisopropyl) ( $\text{CF}_3\text{OCF}(\text{CF}_3)\text{CF}_2\text{OCF}_2\text{OCF}_3$ )**

3178 One experimental study has estimated RE due to PFFMIE (perfluoropolymethylisopropyl),  
3179 with a value 0.65  $\text{W m}^{-2} \text{ppb}^{-1}$  [*Young et al.*, 2006] which is used in IPCC AR4. We have used  
3180 the same absorption cross-section and calculated the same RE value. In contrast to the other  
3181 compounds listed in this section, PFFMIE is lost by photolysis in the upper atmosphere and  
3182 this results in a long lifetime of approximately 800 years [*Young et al.*, 2006]. Hence, we have  
3183 used the exponential fit from section 3.3.4 (Equation (1) and red curve in Figure 9) rather than  
3184 the S-shaped fit to account for a non-uniform vertical profile, although this has almost a  
3185 negligible impact on the RE because such long-lived compounds are relatively well-mixed  
3186 throughout the atmosphere.

3187

3188 **HFE-216 ( $\text{CF}_3\text{OCF}=\text{CF}_2$ )**

3189 *Mashino et al.* [2000] have estimated the instantaneous RE of HFE-216 by using the *Pinnock*  
3190 *et al.* [1995] method and report a value of  $0.28 \text{ W m}^{-2} \text{ ppb}^{-1}$ . We have used their absorption  
3191 cross-section, accounted for stratospheric temperature adjustment and lifetime correction, and  
3192 calculated a much lower RE value of  $0.02 \text{ W m}^{-2} \text{ ppb}^{-1}$ . The reason for the large difference is  
3193 the short lifetime of 8.4 days [*Mashino et al.*, 2000] which leads to a strong correction when  
3194 accounting for non-homogeneous horizontal and vertical distribution in the troposphere. It  
3195 should be noted here that the uncertainties associated with the lifetime correction factors are  
3196 very large on a percentage basis for such short-lived species (see Figure 9 and associated  
3197 discussion in section 3.3.4).

3198

3199 **HFEs studied theoretically by *Bravo et al.* [2011b]**

3200 For a number of HFE compounds, no RE estimates based on experimental absorption cross-  
3201 sections exist and the *ab initio* study of *Bravo et al.* [2011b] provides the only RE estimate of  
3202 these HFEs. These compounds are:

3203 Trifluoromethyl formate ( $\text{HCOOCF}_3$ )

3204 Perfluoroethyl formate ( $\text{HCOOCF}_2\text{CF}_3$ )

3205 Perfluoropropyl formate ( $\text{HCOOCF}_2\text{CF}_2\text{CF}_3$ )

3206 Perfluorobutyl formate ( $\text{HCOOCF}_2\text{CF}_2\text{CF}_2\text{CF}_3$ )

3207 2,2,2-Trifluoroethyl formate ( $\text{HCOOCH}_2\text{CF}_3$ )

3208 3,3,3-Trifluoropropyl formate ( $\text{HCOOCH}_2\text{CH}_2\text{CF}_3$ )

3209 1,2,2,2-Tetrafluoroethyl formate ( $\text{HCOOCHF}_2\text{CF}_3$ )

3210 1,1,1,3,3,3-Hexafluoropropan-2-yl formate ( $\text{HCOOCH}(\text{CF}_3)_2$ )

3211 Perfluorobutyl acetate ( $\text{CH}_3\text{COOCF}_2\text{CF}_2\text{CF}_2\text{CF}_3$ )

3212 Perfluoropropyl acetate ( $\text{CH}_3\text{COOCF}_2\text{CF}_2\text{CF}_3$ )

3213 Perfluoroethyl acetate ( $\text{CH}_3\text{COOCF}_2\text{CF}_3$ )

3214 Trifluoromethyl acetate ( $\text{CH}_3\text{COOCF}_3$ )

3215 Methyl carbonofluoridate ( $\text{FCOOCH}_3$ )

3216 Fluoromethyl carbonofluoridate ( $\text{FCOOCFH}_2$ )

- 3217 Difluoromethyl carbonofluoridate (FCOOCF<sub>2</sub>H)
- 3218 Trifluoromethyl carbonofluoridate (FCOOCF<sub>3</sub>)
- 3219 Perfluoroethyl carbonofluoridate (FCOOCF<sub>2</sub>CF<sub>3</sub>)
- 3220 2,2,2-Trifluoroethyl carbonofluoridate (FCOOCH<sub>2</sub>CF<sub>3</sub>)
- 3221 1,1-Difluoroethyl carbonofluoridate (FCOOCF<sub>2</sub>CH<sub>3</sub>)
- 3222 Perfluoropropyl carbonofluoridate (FCOOCF<sub>2</sub>CF<sub>2</sub>CF<sub>3</sub>)
- 3223 Trifluoromethyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCF<sub>3</sub>)
- 3224 Perfluoroethyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCF<sub>2</sub>CF<sub>3</sub>)
- 3225 1,1-Difluoroethyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCF<sub>2</sub>CH<sub>3</sub>)
- 3226 1,1,1,3,3,3-Hexafluoropropan-2-yl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCH(CF<sub>3</sub>)<sub>2</sub>)
- 3227 Vinyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCH=CH<sub>2</sub>)
- 3228 Ethyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCH<sub>2</sub>CH<sub>3</sub>)
- 3229 2,2,2-Trifluoroethyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCH<sub>2</sub>CF<sub>3</sub>)
- 3230 Allyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCH<sub>2</sub>CHCH<sub>2</sub>)
- 3231 Methyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCH<sub>3</sub>)
- 3232 Phenyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOPh)
- 3233 Methyl 2-fluoroacetate (H<sub>2</sub>CF<sub>2</sub>COOCH<sub>3</sub>)
- 3234 Difluoromethyl 2,2-difluoroacetate (HCF<sub>2</sub>COOCHF<sub>2</sub>)
- 3235 Methyl 2,2-difluoroacetate (HCF<sub>2</sub>COOCH<sub>3</sub>)
- 3236 Difluoromethyl 2,2,2-trifluoroacetate (CF<sub>3</sub>COOCHF<sub>2</sub>)

3237

3238 For all of the compounds listed above we have used the theoretical absorption cross-  
 3239 sections from *Bravo et al.* [2011b] to calculate estimates of RE, taking into account both  
 3240 stratospheric temperature adjustment (by increasing the instantaneous RE by 10% as  
 3241 described in section 3.3.2) and the fractional correction (by using the method described in  
 3242 section 3.3.4). For 14 of the 34 compounds listed above, no lifetime estimates were found in  
 3243 the literature, hence the RE estimates for these compounds assume a uniform vertical and

3244 horizontal distribution in the atmosphere. Lifetimes for the remaining 20 compounds were  
3245 taken from various sources [*Blanco and Teruel*, 2007; *Bravo et al.*, 2011b; *Chen et al.*, 2006;  
3246 *Christensen et al.*, 1998; *Oyaro et al.*, 2004; *Wallington et al.*, 1988; *Wallington et al.*, 1997;  
3247 *WMO*, 2011] (see Table S7 in the supplementary material for details). The *Bravo et al.*  
3248 [2011b] study used the *Pinnock et al.* [1995] method to estimate instantaneous REs, but they  
3249 did not account for non-homogeneous mixing. The RE estimates of *Bravo et al.* [2011b] are  
3250 listed in Table S7 in the supplementary material, while our results are presented in Table 15.  
3251 In general, differences reflect the use of an updated *Pinnock et al.* [1995] curve in this study,  
3252 and that stratospheric temperature adjustment and lifetime correction were not taken into  
3253 account in *Bravo et al.* [2011b]. None of the compounds listed above are included in AR4,  
3254 thus we provide new best estimates of RE and GWP for all these compounds. It should,  
3255 however, be kept in mind that RE estimates based on *ab initio* calculations are associated with  
3256 larger uncertainties than estimates based on experimental cross-sections, as discussed in  
3257 section 3.6.1 (see also Table 1).

3258

#### 3259 **2,2,3,3,4,4,4-Heptafluorobutan-1-ol (C<sub>3</sub>F<sub>7</sub>CH<sub>2</sub>OH)**

3260 One experimental study has estimated the instantaneous lifetime-corrected RE due to  
3261 2,2,3,3,4,4,4-heptafluorobutan-1-ol with a value 0.20 W m<sup>-2</sup> ppb<sup>-1</sup> [*Bravo et al.*, 2010a]. We  
3262 have used their absorption cross-section and calculated the same RE value when also taking  
3263 into account stratospheric temperature adjustment and when using our own lifetime correction  
3264 method (*Bravo et al.* [2010a] used the exponential function of *Sihra et al.* [2001]). The  
3265 lifetime of 0.6 years is taken from *Bravo et al.* [2010a].

3266

#### 3267 **2,2,3,3-Tetrafluoro-1-propanol (CHF<sub>2</sub>CF<sub>2</sub>CH<sub>2</sub>OH)**

3268 Previous experimental studies of RE due to 2,2,3,3-tetrafluoro-1-propanol are in the range  
3269 0.20 - 0.23 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.22 W m<sup>-2</sup> ppb<sup>-1</sup>) [*Antiñolo et al.*, 2012b; *Sellevåg et al.*,  
3270 2007]. We have used the absorption cross-sections from these two studies and calculated a RE  
3271 value of 0.11 W m<sup>-2</sup> ppb<sup>-1</sup> for both sources. The lifetime correction applied here is the main  
3272 reason for the lower value compared to earlier work where the instantaneous RE assuming  
3273 constant distribution was estimated. The lifetime of 91.2 days is taken from *Antiñolo et al.*  
3274 [2012b].

3275

3276 **2,2,3,4,4,4-Hexafluoro-1-butanol (CF<sub>3</sub>CHF<sub>2</sub>CF<sub>2</sub>CH<sub>2</sub>OH)**

3277 The experimental study of *Sellevåg et al.* [2007] has used the *Pinnock et al.* [1995] method to  
3278 estimate an instantaneous RE due to 2,2,3,4,4,4-hexafluoro-1-butanol of 0.37 W m<sup>-2</sup> ppb<sup>-1</sup>.  
3279 We have used their absorption cross-section and calculated a RE value of 0.19 W m<sup>-2</sup> ppb<sup>-1</sup>  
3280 when taking into account stratospheric temperature adjustment and lifetime correction. The  
3281 lifetime of 94.9 days is taken from *Sellevåg et al.* [2007].

3282

3283 **2,2,3,3,4,4,4-Heptafluoro-1-butanol (CF<sub>3</sub>CF<sub>2</sub>CF<sub>2</sub>CH<sub>2</sub>OH)**

3284 One experimental study has estimated the instantaneous RE due to 2,2,3,3,4,4,4-heptafluoro-  
3285 1-butanol, with a value 0.30 W m<sup>-2</sup> ppb<sup>-1</sup> [*Sellevåg et al.*, 2007]. We calculate a RE value of  
3286 0.16 W m<sup>-2</sup> ppb<sup>-1</sup> using the absorption cross-section from the same study. Our RE estimate  
3287 accounts for stratospheric temperature adjustment and lifetime correction; the latter factor  
3288 explains the lower RE calculated here. The lifetime of 0.3 years is taken from *Sellevåg et al.*  
3289 [2007].

3290

3291 **1,1,2,2-Tetrafluoro-3-methoxy-propane (CHF<sub>2</sub>CF<sub>2</sub>CH<sub>2</sub>OCH<sub>3</sub>)**

3292 One experimental study has estimated the instantaneous RE due to 1,1,2,2-tetrafluoro-3-  
3293 methoxy-propane with a value 0.24 W m<sup>-2</sup> ppb<sup>-1</sup> [*Oyaro et al.*, 2004]. We have used their  
3294 absorption cross-section and calculated a much lower RE value of 0.04 W m<sup>-2</sup> ppb<sup>-1</sup> when  
3295 taking into account stratospheric temperature adjustment and non-homogeneous distribution  
3296 in the troposphere (these factors were not taken into account in the published RE estimate).  
3297 The lifetime of 14.2 days is taken from *Oyaro et al.* [2004], and it should be noted here that  
3298 the uncertainties associated with the lifetime correction factor are very large on a percentage  
3299 basis for such short-lived species (see Figure 9 and associated discussion in section 3.3.4),

3300

3301 **Perfluoro-2-methyl-3-pentanone (CF<sub>3</sub>CF<sub>2</sub>C(O)CF(CF<sub>3</sub>)<sub>2</sub>)**

3302 No RE estimates of perfluoro-2-methyl-3-pentanone exist in the literature. Here we have used  
3303 the absorption cross-section from *D'Anna et al.* [2005] and calculate a RE value of 0.03 W m<sup>-2</sup>  
3304 ppb<sup>-1</sup> assuming a lifetime of 7.0 days [*D'Anna et al.*, 2005].

3305

3306 **3,3,3-Trifluoro-propanal (CF<sub>3</sub>CH<sub>2</sub>CHO)**

3307 No RE estimates of 3,3,3-trifluoro-propanal can be found in the literature, but here we have  
3308 calculated its RE by using the absorption cross-sections of *Antiñolo et al.* [2011] and *Sellevag*  
3309 *et al.* [2004a]. Due to the very short lifetime of only 2.0 days for this compound [*Antiñolo et*  
3310 *al.*, 2011], our calculated RE rounds to 0.00 W m<sup>-2</sup> ppb<sup>-1</sup> when applying the lifetime  
3311 correction (section 3.3.4). Uncertainties related to the fractional correction are large for  
3312 compounds with such short lifetimes. The mean RE calculated here when assuming a uniform  
3313 horizontal and vertical distribution is 0.16 W m<sup>-2</sup> ppb<sup>-1</sup>, and should be considered an upper  
3314 estimate.

3315

3316 **4,4,4-Trifluorobutanal (CF<sub>3</sub>(CH<sub>2</sub>)<sub>2</sub>CHO)**

3317 No RE or lifetime estimates of 4,4,4-trifluorobutanal can be found in the literature. Here we  
3318 have used the absorption cross-section from *Antiñolo et al.* [2012a] and calculated a RE value  
3319 of 0.16 W m<sup>-2</sup> ppb<sup>-1</sup> assuming a constant horizontal and vertical distribution in the  
3320 troposphere. Hence, this RE value should be considered an upper estimate.

3321

3322 **2-Fluoroethanol (CH<sub>2</sub>FCH<sub>2</sub>OH)**

3323 In the experimental study of *Sellevag et al.* [2004b] a broadband model and a CTM were used  
3324 to estimate the RE due to 2-fluoroethanol with a value 0.02 W m<sup>-2</sup> ppb<sup>-1</sup>. We have used their  
3325 absorption cross-section and calculated the same RE value. The lifetime of 20.4 days is taken  
3326 from *Sellevag et al.* [2004b].

3327

3328 **2,2-Difluoroethanol (CHF<sub>2</sub>CH<sub>2</sub>OH)**

3329 One experimental study has estimated RE due to 2,2-difluoroethanol, with a value 0.02 W m<sup>-2</sup>  
3330 ppb<sup>-1</sup> [*Sellevag et al.*, 2004b]. We used their absorption cross-section and calculated a higher  
3331 RE value of 0.04 W m<sup>-2</sup> ppb<sup>-1</sup>. As discussed in section 3.3.4 and illustrated in Figure 9, the  
3332 uncertainties when applying lifetime corrections are large for such short-lived compounds  
3333 (lifetime of 40.0 days [*Sellevag et al.*, 2004b]).



3334

3335 **2,2,2-Trifluoroethanol (CF<sub>3</sub>CH<sub>2</sub>OH)**

3336 Previous experimental studies of RE due to 2,2,2-trifluoroethanol are in the range 0.09 - 0.19  
3337 W m<sup>-2</sup> ppb<sup>-1</sup> (mean: 0.14 W m<sup>-2</sup> ppb<sup>-1</sup>) and stem from the work of *Sellevag et al.* [2004b] and  
3338 *Imasu et al.* [1995] (note that the RE from the latter study has been scaled to our  
3339 recommended CFC-11 RE of 0.26 W m<sup>-2</sup> ppb<sup>-1</sup>). We calculate a RE value of 0.10 W m<sup>-2</sup> ppb<sup>-1</sup>  
3340 when using the absorption cross-sections from both these sources. Our value is close to the  
3341 RE of 0.09 W m<sup>-2</sup> ppb<sup>-1</sup> from *Sellevag et al.* [2004b] who used a CTM to account for the non-  
3342 homogeneous tropospheric distribution. The lifetime of 0.3 years is taken from *Sellevag et al.*  
3343 [2004b].

3344

3345 **HFEs studied by *Andersen et al.* [2010b]**

3346 For the following HFE compounds, *Andersen et al.* [2010b] is the only study providing REs  
3347 based on experimental absorption cross-sections:

3348 1,1'-Oxybis[2-(difluoromethoxy)-1,1,2,2-tetrafluoroethane (HCF<sub>2</sub>O(CF<sub>2</sub>CF<sub>2</sub>O)<sub>2</sub>CF<sub>2</sub>H)

3349 1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-hexadecafluoro-2,5,8,11-Tetraoxadodecane  
3350 (HCF<sub>2</sub>O(CF<sub>2</sub>CF<sub>2</sub>O)<sub>3</sub>CF<sub>2</sub>H)

3351 1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12,13,13,15,15-eicosafuoro-2,5,8,11,14-  
3352 Pentaoxapentadecane (HCF<sub>2</sub>O(CF<sub>2</sub>CF<sub>2</sub>O)<sub>4</sub>CF<sub>2</sub>H)

3353

3354 *Andersen et al.* [2010b] used the *Pinnock et al.* [1995] method to estimate  
3355 instantaneous REs of these compounds. Since absorption spectra were unavailable for the  
3356 three compounds listed above, no new calculations have been carried out here. Thus, we use  
3357 the REs from *Andersen et al.* [2010b], accounting for stratospheric temperature adjustment  
3358 and lifetime correction (see sections 3.3.2 and 3.3.4, respectively), and present new best  
3359 estimate REs of 1.15, 1.43 and 1.46 W m<sup>-2</sup> ppb<sup>-1</sup> for 1,1'-oxybis[2-(difluoromethoxy)-1,1,2,2-  
3360 tetrafluoroethane, 1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-hexadecafluoro-2,5,8,11-  
3361 tetraoxadodecane and 1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12,13,13,15,15-eicosafuoro-  
3362 2,5,8,11,14-pentaoxapentadecane, respectively. We have used the same assumption as in  
3363 *Andersen et al.* [2010b] of a lifetime for all three compounds of 26 years.

3364

3365 **4.2 Additional metrics for most important gases: GTPs and GWPs for other**  
3366 **time horizons**

3367 While we have used a time horizon of 100 years in the main tables we also show GWP values  
3368 for 20 and 500 years for a selection of gases together with GTP values for the same gases in  
3369 Table 16. The GTP values vary with time horizon in a way that depends on adjustment time  
3370 and how this compares with the time scale for the response of CO<sub>2</sub>. For gases with short and  
3371 medium lifetimes (e.g., HFC-152a and HCFC-22), the GTP falls rapidly with time horizon  
3372 from 20 to 100 years. By contrast, the longer-lived gases, such as HFC-23 and CFC-12, show  
3373 GTPs that increase from time horizons of 20 to 50 years, before decreasing, while for the very  
3374 long-lived gases (SF<sub>6</sub> and PFC-14), the GTP values continue to increase out to 100 years. The  
3375 contrast between the GWP and GTP values in Table 16 is particularly noticeable for gases  
3376 with short and medium lifetimes – for example, for HCFC-22, the GWP drops by an about a  
3377 factor of 3 between time horizons of 20 and 100 years, whereas the GTP drops by more than  
3378 an order of magnitude. This reflects the fact that the integral nature of the GWP means that it  
3379 keeps the memory of the strong short-lived forcing, while the GTP, being an end-point metric,  
3380 retains less of a memory, and the impact of the forcing pulse on temperature has largely  
3381 disappeared after 100 years.

3382 Compared to *Fuglestad et al.* [2010], the GWP and GTPs for CCl<sub>4</sub> are higher due to  
3383 the higher RE calculated in this study compared to the recommended RE in AR4 (see  
3384 discussion of CCl<sub>4</sub> in section 4.1.4 for details). The metric values for SF<sub>6</sub> have also increased  
3385 (except for GWP 500-yr) due to the increase of the best estimate RE for this compound (see  
3386 section 4.1.6).

3387 It should be noted that while the impulse response function for CO<sub>2</sub> includes climate-  
3388 carbon cycle feedbacks, no feedbacks are included for the non-CO<sub>2</sub> gases. The magnitude of  
3389 this bias has not been assessed for the gases addressed here. However, *Gillett and Matthews*  
3390 [2010] found that for N<sub>2</sub>O and CH<sub>4</sub> the GWP-100 values increased by 20% when climate-  
3391 carbon feedbacks were included; which gives some indication of the bias in the GWP values  
3392 presented here.

3393

## 3394 5 Summary and conclusions

3395 We present a comprehensive assessment of the radiative efficiencies (REs) for a large number  
3396 of halocarbons and related radiatively-active compounds including CFCs, HCFCs,  
3397 bromofluorocarbons and bromochlorofluorocarbons (halons), HFCs, PFCs, SF<sub>6</sub>, NF<sub>3</sub>, and  
3398 related halogen containing compounds. A consistent method for calculating RE has been used  
3399 for all compounds ruling out any differences related to the radiative transfer method. Further,  
3400 our results have been compared with previously published literature and new best estimates  
3401 have been presented for lifetimes, REs, and GWPs. A total of 223 compounds were included  
3402 in this study. Here we summarize our main findings:

- 3403 1. Absorption cross-sections have been collected from various sources including freely-  
3404 available databases and requests to authors of individual studies. The absorption cross-  
3405 section data used include experimental data and *ab initio* calculations. For most of the  
3406 important halocarbons, several independent sources are available for absorption cross  
3407 sections. However, we find insufficient data available (and hence encourage further  
3408 studies) for HFC-23, HFC-236ea, HFC-245ca, CCl<sub>4</sub>, and several HFEs.
- 3409 2. An updated version of the simplified method presented in *Pinnock et al.* [1995] to  
3410 calculate REs was developed and is presented. In the updated version an improved  
3411 representation of clouds and the spatial distribution of temperature and water vapor  
3412 leads to changes in the estimated REs of up to 10% from those estimated using the  
3413 values given by *Pinnock et al.* [1995]. For most compounds we apply a generic  
3414 correction to account for the effect of stratospheric temperature adjustment. The  
3415 simulations by the simplified method are performed with a LBL model and results are  
3416 presented on a 1 cm<sup>-1</sup> resolution. There was very little (1-2%) difference between REs  
3417 calculated using 1 cm<sup>-1</sup> or 10 cm<sup>-1</sup> resolution, but it is greater for some compounds,  
3418 most notably CF<sub>4</sub> where the difference is 8%.
- 3419 3. Simulations using a chemical transport model and results from the existing literature  
3420 were used to develop simple lifetime-dependent correction factors to account for  
3421 inhomogeneous mixing in the atmosphere. Application of these correction factors is  
3422 shown to be particularly important for very short-lived compounds and leads to  
3423 substantially lower REs than generally reported in the literature.
- 3424 4. We estimate that the uncertainty (5-95% confidence range) in RE of compounds for  
3425 which we have experimental absorption cross-sections is approximately 13% for gases  
3426 with atmospheric lifetimes greater than 5 years, and approximately 23% for gases with  
3427 lifetimes less than 5 years. For compounds for which only *ab initio* cross-sections are  
3428 available, the estimated uncertainties are 16% and 25% for compounds with lifetimes  
3429 greater and less than 5 years, respectively. These estimates assume that empirical  
3430 corrections based on knowledge of the spectra of related compounds have been  
3431 applied to the *ab initio* cross-sections to account for systematic errors in the

3432 calculation of the wavenumbers of the vibrational modes. Where more generic  
3433 corrections have been made, the errors can be somewhat larger. Our estimated  
3434 uncertainties are larger than the value of 10% given in IPCC AR4 for the RE of the  
3435 long-lived greenhouse gases. The uncertainty in  $GWP_{HFC-134a}$  is estimated to 24%,  
3436 34% and 37% for a 20, 100, and 500 year time horizon. For CFC-11 the GWP  
3437 uncertainties are 23%, 38% and 47% for a 20, 100, and 500 year time horizon.

3438 5. Compared to AR4, the REs presented here differed significantly (by more than 5%)  
3439 for 49 compounds, while 42 compounds had similar (<5% difference) RE as in AR4.  
3440 For 7 of the compounds included in AR4 we have not carried out calculations because  
3441 spectrally-resolved absorption cross-section data were not available, but for 2 of these  
3442 compounds we have updated the recommended RE based on values from the  
3443 literature. Best estimate REs and GWPs have also been presented for 112 compounds  
3444 which were not included in AR4. For 20 additional compounds we have only  
3445 presented new REs and not GWPs due to missing lifetime estimates.

3446 6. Substantial updates in REs are made for several important gases: CFC-11, CFC-115,  
3447 HCFC-124, HCFC-225cb, HFC-143a, HFC-245fa,  $CCl_4$ ,  $CHCl_3$ , and  $SF_6$ .

3448 7. As shown in Figure 18, where there are substantial differences between the REs  
3449 evaluated in the present work and those given in AR4, the values evaluated here tend  
3450 to be lower than those given in AR4. This trend largely reflects an improvement in the  
3451 methodology used to correct for the inhomogeneous mixing of shorter lived species  
3452 (see section 3.3.4).

3453 8.  $SF_6$  has the highest  $GWP(100)$  with a value of 23,500 (relative to  $CO_2$ ) as a result of  
3454 its high RE and very long lifetime. A majority of the compounds considered here have  
3455 a  $GWP(100)$  below 1,000 and almost half of the compounds have a  $GWP(100)$  below  
3456 100. (See Figure 19 showing  $GWP(100)$  values in ordered ranking for all the  
3457 compounds investigated in this study.) The AGWPs for  $CO_2$  have been updated and  
3458 this leads to a lowering of the  $GWP(100)$  values of approximately 6% compared to  
3459 AR4.

3460 9. We have calculated GWPs for 20, 100, and 500 year time horizons and Global  
3461 Temperature change Potentials (GTP) for 20, 50 and 100 years. The contrast between  
3462 the GWP and GTP values is particularly noticeable for gases with short and medium  
3463 lifetimes and reflects the integral nature of the GWP which retains memory of the  
3464 strong short-lived forcing, while the GTP, being an end-point metric, has less of a  
3465 memory.

3466 The GWP and GTP values are expected to change in the future, reflecting changes related to  
3467 the reference gas  $CO_2$  (i.e.,  $AGWP_{CO_2}$  and  $AGTP_{CO_2}$  will be updated as background  
3468 conditions change and models improve) and as our understanding of the RE and lifetimes of  
3469 the compounds improve. In future reviews it will be important to distinguish between changes

3470 in GWP and GTP values that are due to changes in RE and/or lifetime of the non-CO<sub>2</sub> gas and  
3471 those that are due to the changes related to the reference gas CO<sub>2</sub> (i.e., AGWP<sub>CO2</sub> and  
3472 AGTP<sub>CO2</sub>). Updated GWPs and GTPs can be obtained by multiplying old values with the ratio  
3473 between old and new AGWP<sub>CO2</sub> and AGTP<sub>CO2</sub> values, respectively.

3474 Our main focus has been on providing a comprehensive and self-consistent set of new  
3475 calculations of REs. A follow up study could be a detailed assessment of lifetimes with  
3476 calculations of how uncertainties in lifetimes together with uncertainties in RE propagate to  
3477 GWPs and GTPs.

3478 There are several important impacts of our new results. First of all, the large number  
3479 of compounds included in the review, and the high degree of consistency in the method of  
3480 calculating REs of each compound, make it a lot easier for researchers, industry and others to  
3481 compare the potential climate impacts (i.e., the GWPs and GTPs) of molecules, and this may  
3482 be helpful in choosing compounds that are more climate-friendly. Such a consistent set of RE  
3483 values may also be relevant for future assessment reports and could in turn have policy  
3484 implications. Second, the contribution from halocarbons to the present-day total radiative  
3485 forcing of anthropogenic greenhouse gases is also expected to change slightly as a result of  
3486 our updated RE numbers. In particular, carbon tetrachloride (CCl<sub>4</sub>) has a high atmospheric  
3487 concentration and the RE for this compound is much higher in our study (0.17 W m<sup>-2</sup> ppb<sup>-1</sup>)  
3488 than in AR4 (0.13 W m<sup>-2</sup> ppb<sup>-1</sup>). Finally, we provide the research community with an  
3489 improved tool for calculating the RE, GWP and GTP of a compound in a relatively simple  
3490 manner.

3491

## 3492 **Supplementary Material**

3493 Supplementary Material is available and includes additional tables, the updated Pinnock et al.  
3494 curve, and a large number of absorption cross-sections (see SM\_Readme.txt for more  
3495 information).

3496

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3515 **References**

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4326 **Table 1.** Estimated contributions to the total radiative forcing uncertainty.

Source of uncertainty	Estimated contribution to total RF uncertainty	References used as basis for uncertainty estimates
Absorption cross-sections	~5% for experimentally determined spectra, ~10% for ab initio spectra	[ <i>Ballard et al.</i> , 2000b; <i>Bravo et al.</i> , 2010b; <i>Forster et al.</i> , 2005]
Radiation scheme	~5%	[ <i>Collins et al.</i> , 2006; <i>Forster et al.</i> , 2005; <i>Oreopoulos et al.</i> , 2012]
Clouds	~5%	[ <i>Forster et al.</i> , 2005; <i>Gohar et al.</i> , 2004]
Spectral overlap and water vapor distribution	~3%	[ <i>Forster et al.</i> , 2005; <i>Jain et al.</i> , 2000; <i>Pinnock et al.</i> , 1995]
Surface temperature and atmospheric temperature	~3%	[ <i>Forster et al.</i> , 2005]
Tropopause level	~5%	[ <i>Forster et al.</i> , 2005; <i>Freckleton et al.</i> , 1998; <i>Myhre and Stordal</i> , 1997]
Temporal and spatial averaging	~1%	[ <i>Freckleton et al.</i> , 1998; <i>Myhre and Stordal</i> , 1997]
Stratospheric temperature adjustment	~4%	[ <i>Forster et al.</i> , 2005; <i>Gohar et al.</i> , 2004]
Non-uniform vertical profile	~5% for lifetimes > ~5 years, ~20% for lifetimes < ~5 years	[ <i>Sihra et al.</i> , 2001] + this study
Total (RSS) (experimental)	~13% for lifetimes > ~5 years ~23% for lifetimes < ~5 years	
Total (RSS) (ab initio)	~15% for lifetimes > ~5 years	

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4329 **Table 2.** Integrated absorption cross-sections ( $S$ ) for chlorofluorocarbons (CFCs) from the literature. Spectra used in RE calculations in the present study are indicated in  
 4330 bold.

Name	CAS#	Acronym	Formula	Data <sup>1</sup>	$T/K$	Wn. range /cm <sup>-1</sup>	$S^2$	Reference	Database <sup>3</sup>	
Trichlorofluoromethane	75-69-4	CFC-11	CCl <sub>3</sub> F	E	295	820 - 1120	9.3	<b>[Orkin et al., 2003]</b>		
				E	296	650 - 1500	9.3	<b>[Sihra et al., 2001]</b>		
				E					[Naik et al., 2000]	
				E					[Ninomiya et al., 2000]	
				E	296	810 - 1120	9.5	[Varanasi-priv.com., 2000]	H	
				A					[Good et al., 1998]	
				E	298	800 - 1120	9.4	<b>[Heathfield et al., 1998]</b>	G	
				E	296	810 - 1120	9.0	[Christidis et al., 1997]	G	
				E	296	700 - 1500	9.8	<b>[Imasu et al., 1995]</b>		
				E	296	810 - 1120	9.5	<b>[Li and Varanasi, 1994]</b>	G	
				E	293	800 - 1120	9.2	[McDaniel et al., 1991]		
				E		810 - 1120	8.9	[Fisher et al., 1990]		
				E		800 - 1120	9.8	[Varanasi and Chudamani, 1988a]		
				E		800 - 1120	8.4	[Massie et al., 1985]		
				E		800 - 1120	10.3	[Kagann et al., 1983]		
				Dichlorodifluoromethane	75-71-8	CFC-12	CCl <sub>2</sub> F <sub>2</sub>	E	295	850 - 1190
E	296	640 - 1200	12.2					[Hurley-priv.com., 2003]	G	
E	295	850 - 1190	12.9					<b>[Orkin et al., 2003]</b>		
E	296	500 - 1500	12.2					<b>[Sihra et al., 2001]</b>		
E	296	850 - 1200	13.6					[Varanasi-priv.com., 2000]	H	
A									[Good et al., 1998]	
E	296	850 - 1200	13.6					<b>[Varanasi and Nemtchinov, 1994]</b>	G	
E	287	850 - 1190	13.5					<b>[Clerbaux et al., 1993]</b>	G	
E	293	850 - 1190	12.6					[McDaniel et al., 1991]		
E	296	850 - 1190	12.1					[Fisher et al., 1990]		
E	300	850 - 1190	13.4					[Varanasi and Chudamani, 1988a]		
E	298	800 - 1200	12.7					[Vanthanh et al., 1986]		

				E	296	850 - 1190	13.3	[ <i>Massie et al.</i> , 1985]	
				E	296	850 - 1190	13.6	[ <i>Kagann et al.</i> , 1983]	
				E	300	850 - 1190	12.9	[ <i>Varanasi and Ko</i> , 1977]	
				E				[ <i>Morcillo et al.</i> , 1966]	
Chlorotrifluoromethane	75-72-9	CFC-13	CClF <sub>3</sub>	E	293	765 - 1235	14.8	[ <b>McDaniel et al.</b> , 1991]	H
				E		1050 - 1291	16.3	[ <i>Varanasi and Chudamani</i> , 1988b]	
				E		755 - 1291	16.1	[ <i>Golden et al.</i> , 1978]	
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1	CFC-113	CCl <sub>2</sub> CClF <sub>2</sub>	E	283	600 - 1250	13.7	[ <b>Le Bris et al.</b> , 2011]	
				E	293	780 - 1232	12.7	[ <b>McDaniel et al.</b> , 1991]	H
				E		618 - 1397	12.7	[ <i>Fisher et al.</i> , 1990]	
				E		780 - 1235	19.4	[ <i>Rogers and Stephens</i> , 1988]	
				E		780 - 1235	14.1	[ <i>Varanasi and Chudamani</i> , 1988b]	
1,2-Dichloro-1,1,2,2-tetrafluoroethane	76-14-2	CFC-114	CClF <sub>2</sub> CClF <sub>2</sub>	E	293	815 - 1285	15.2	[ <b>McDaniel et al.</b> , 1991]	H
				E		555 - 1397	15.4	[ <i>Fisher et al.</i> , 1990]	
				E		820 - 1310	23.9	[ <i>Rogers and Stephens</i> , 1988]	
				E		820 - 1310	15.8	[ <i>Varanasi and Chudamani</i> , 1988b]	
				E		1025 - 1310	12.0	[ <i>Massie et al.</i> , 1985]	
1-Chloro-1,1,2,2,2-pentafluoroethane	76-15-3	CFC-115	CClF <sub>2</sub> CF <sub>3</sub>	E	293	955 - 1260	12.1	[ <b>McDaniel et al.</b> , 1991]	H
				E		618 - 1397	17.4	[ <i>Fisher et al.</i> , 1990]	

4331 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.

4332 <sup>2</sup> Integrated absorption cross-section in units of 10<sup>-17</sup> cm<sup>2</sup> molecule<sup>-1</sup> cm<sup>-1</sup> for the wavenumber interval specified.

4333 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009

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4337 **Table 3.** Lifetimes, radiative efficiencies and direct GWPs (relative to CO<sub>2</sub>) for chlorofluorocarbons (CFCs).  
 4338 Compounds in bold either have significant current atmospheric concentrations or a clear potential for future  
 4339 emissions. Recommended RE and GWP(100) values are indicated in bold. Lifetimes are from *WMO* [2011].

Acronym	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP(100)	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>CFC-11</b>	CCl <sub>3</sub> F	45.0	0.25	0.28	<b>0.26</b>	4,750	<b>4,660</b>
<b>CFC-12</b>	CCl <sub>2</sub> F <sub>2</sub>	100.0	0.32	0.33	<b>0.32</b>	10,900	<b>10,200</b>
<b>CFC-13</b>	CClF <sub>3</sub>	640.0	0.25	0.26	<b>0.25</b>	14,400	<b>13,900</b>
<b>CFC-113</b>	CCl <sub>2</sub> FCClF <sub>2</sub>	85.0	0.30	0.31	<b>0.30</b>	6,130	<b>5,820</b>
<b>CFC-114</b>	CClF <sub>2</sub> CClF <sub>2</sub>	190.0	0.31	0.32	<b>0.31</b>	10,000	<b>8,590</b>
<b>CFC-115</b>	CClF <sub>2</sub> CF <sub>3</sub>	1,020.0	0.18	0.21	<b>0.20</b>	7,370	<b>7,670</b>

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4342 **Table 4.** Integrated absorption cross-sections ( $S$ ) for hydrochlorofluorocarbons (HCFCs) from the literature. Spectra used in RE calculations in the present study are  
 4343 indicated in bold.

Name	CAS#	Acronym	Formula	Data <sup>1</sup>	$T/K$	Wn. range /cm <sup>-1</sup>	$S^2$	Reference	Database <sup>3</sup>
Dichlorofluoromethane	75-43-4	HCFC-21	CHCl <sub>2</sub> F	E	296	600 - 1500	7.4	<b>[Sihra et al., 2001]</b>	
				E	296	450 - 2000	6.8	[Christidis et al., 1997]	
				E	296	785 - 840	2.7	[Massie et al., 1985]	H
Chlorodifluoromethane	75-45-6	HCFC-22	CHClF <sub>2</sub>	E	295	750 - 1380	10.0	[Orkin et al., 2003]	
				E	296	700 - 1400	10.1	[Sihra et al., 2001]	
				E	293	775 - 1375	10.1	<b>[Ballard et al., 2000b]</b>	G
				E	273	750 - 1400	10.2	[Highwood and Shine, 2000]	
				E				[Naik et al., 2000]	
				A		600 - 1500	11.6	[Papasavva et al., 1997]	
				E	296	765 - 1390	10.2	[Pinnock et al., 1995]	G
				E	296	735 - 1380	9.7	[Anastasi et al., 1994]	
				E	296	1070 - 1195	6.9	[Varanasi et al., 1994]	G
				E	287	765 - 1380	10.3	[Clerbaux et al., 1993]	H
				E	293	755 - 1390	10.3	[Cappellani and Restelli, 1992]	
				E	293	775 - 1375	9.0	[McDaniel et al., 1991]	
E		775 - 1397	9.5	[Fisher et al., 1990]					
E		775 - 1170	9.4	[Varanasi and Chudamani, 1988b]					
1,1,2-Trichloro-2,2-difluoroethane	354-21-2	HCFC-122	CHCl <sub>2</sub> CF <sub>2</sub> Cl	E	295	560 - 1360	10.4	<b>[Orkin et al., 2003]</b>	
1,1,2-Trichloro-1,2-difluoroethane	354-15-4	HCFC-122a	CHFClCFCl <sub>2</sub>	E	295	590 - 1380	9.9	<b>[Orkin et al., 2003]</b>	
2,2-Dichloro-1,1,1-trifluoroethane	306-83-2	HCFC-123	CHCl <sub>2</sub> CF <sub>3</sub>	E	295	480 - 1430	13.1	<b>[Orkin et al., 2003]</b>	
				E	296	700 - 1500	11.9	<b>[Sihra et al., 2001]</b>	
				E				[Naik et al., 2000]	
				A		600 - 1500	14.1	[Papasavva et al., 1997]	
				E	296	700 - 1400	12.0	[Pinnock et al., 1995]	G
E		480 - 1430	12.7	[Olliff and Fischer, 1994]					

				E	287	740 - 1450	12.9	[Clerbaux et al., 1993]	H
				E	293	648 - 1440	12.7	[Cappellani and Restelli, 1992]	
				E		649 - 1307	10.6	[Fisher et al., 1990]	
1,2-Dichloro-1,1,2-trifluoroethane	354-23-4	HCFC-123a	CHClFCF <sub>2</sub> Cl	E	295	450 - 1400	12.3	[Orkin et al., 2003]	
2-Chloro-1,1,1,2-tetrafluoroethane	2837-89-0	HCFC-124	CHClFCF <sub>3</sub>	E	296	700 - 1500	13.4	[Sihra et al., 2001]	
				E				[Naik et al., 2000]	
				A		600 - 1500	15.7	[Papasavva et al., 1997]	
				E	296	670 - 1435	13.8	[Pinnock et al., 1995]	G
				E	287	675 - 1430	14.4	[Clerbaux et al., 1993]	H
				E		440 - 1420	15.0	[Fisher et al., 1990]	
1,1-Dichloro-1,2-difluoroethane	1842-05-3	HCFC-132c	CH <sub>2</sub> FCFCl <sub>2</sub>	E	295	425 - 1490	8.4	[Orkin et al., 2003]	
1,1-Dichloro-1-fluoroethane	1717-00-6	HCFC-141b	CH <sub>3</sub> CCl <sub>2</sub> F	E	283	570 - 3100	8.1	[Le Bris et al., 2012]	
				E	295	540 - 1540	8.0	[Orkin et al., 2003]	
				E	296	700 - 1500	7.1	[Sihra et al., 2001]	
				E				[Naik et al., 2000]	
				A		600 - 1500	9.1	[Papasavva et al., 1997]	
				E	296	700 - 1500	8.3	[Imasu et al., 1995]	
				E	296	700 - 1470	7.2	[Pinnock et al., 1995]	G
				E		540 - 1480	7.6	[Olliff and Fischer, 1994]	
				E	287	710 - 1470	7.8	[Clerbaux et al., 1993]	H
				E		555 - 1420	7.1	[Fisher et al., 1990]	
1-Chloro-1,1-difluoroethane	75-68-3	HCFC-142b	CH <sub>3</sub> CClF <sub>2</sub>	E	283	650 - 3500	10.8	[Le Bris and Strong, 2010]	
				E	296	700 - 1500	9.6	[Sihra et al., 2001]	
				E				[Naik et al., 2000]	
				A		600 - 1500	11.8	[Papasavva et al., 1997]	
				E	296	650 - 1425	10.1	[Pinnock et al., 1995]	G
				E	287	650 - 1469	11.1	[Clerbaux et al., 1993]	H
				E				[Cappellani and Restelli, 1992]	
				E	293	647 - 1485	10.7		
				E		649 - 1397	9.6	[Fisher et al., 1990]	
3,3-Dichloro-1,1,1,2,2-	422-56-0	HCFC-	CHCl <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	E	296	700 - 1400	18.0	[Sihra et al., 2001]	



pentafluoropropane		225ca		E					[Naik <i>et al.</i> , 2000]	
				E	296	700 - 1400	14.6		[Pinnock <i>et al.</i> , 1995]	
				E	287	695 - 1420	17.7		[Clerbaux <i>et al.</i> , 1993]	H
1,3-Dichloro-1,1,2,2,3-pentafluoropropane	507-55-1	HCFC-225cb	CHClFCF <sub>2</sub> CClF <sub>2</sub>	E	296	700 - 1400	15.2		[Sihra <i>et al.</i> , 2001]	
				E					[Naik <i>et al.</i> , 2000]	
				E	296	700 - 1500	16.6		[Imasu <i>et al.</i> , 1995]	
				E	296	700 - 1400	15.1		[Pinnock <i>et al.</i> , 1995]	
				E	287	715 - 1375	15.6		[Clerbaux <i>et al.</i> , 1993]	H
(E)-1-Chloro-3,3,3-trifluoroprop-1-ene	102687-65-0		trans-CF <sub>3</sub> CH=CHCl	E	295	600 - 1800	17.4		[Andersen <i>et al.</i> , 2008]	

4344 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.

4345 <sup>2</sup> Integrated absorption cross-section in units of 10<sup>-17</sup> cm<sup>2</sup> molecule<sup>-1</sup> cm<sup>-1</sup> for the wavenumber interval specified.

4346 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009.

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4349 **Table 5.** Lifetimes, radiative efficiencies (RE) and direct GWPs (relative to CO<sub>2</sub>) for hydrochlorofluorocarbons  
 4350 (HCFCs). Compounds in bold either have significant current atmospheric concentrations or a clear potential for  
 4351 future emissions. Recommended RE and GWP 100-yr values are indicated in bold. Lifetimes are from *WMO*  
 4352 [2011] except those in italic (see text for details).

Acronym / name	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP 100-yr	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>HCFC-21</b>	CHCl <sub>2</sub> F	1.7	0.14	0.18	<b>0.15</b>	151	<b>148</b>
<b>HCFC-22</b>	CHClF <sub>2</sub>	11.9	0.20	0.22	<b>0.21</b>	1,810	<b>1,760</b>
HCFC-122	CHCl <sub>2</sub> CF <sub>2</sub> Cl	<i>1.0</i>		0.23	<b>0.17</b>		<b>59</b>
HCFC-122a	CHFCICFCI <sub>2</sub>	<i>3.4</i>		0.23	<b>0.21</b>		<b>258</b>
<b>HCFC-123</b>	CHCl <sub>2</sub> CF <sub>3</sub>	1.3	0.14	0.19	<b>0.15</b>	77	<b>79</b>
HCFC-123a	CHClFCF <sub>2</sub> Cl	4.0		0.25	<b>0.23</b>		<b>370</b>
<b>HCFC-124</b>	CHClFCF <sub>3</sub>	5.9	0.22	0.21	<b>0.20</b>	609	<b>527</b>
HCFC-132c	CH <sub>2</sub> FCFCI <sub>2</sub>	<i>4.3</i>		0.19	<b>0.17</b>		<b>338</b>
<b>HCFC-141b</b>	CH <sub>3</sub> CCl <sub>2</sub> F	9.2	0.14	0.17	<b>0.16</b>	725	<b>782</b>
<b>HCFC-142b</b>	CH <sub>3</sub> CClF <sub>2</sub>	17.2	0.20	0.19	<b>0.19</b>	2,310	<b>1,980</b>
<b>HCFC-225ca</b>	CHCl <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	1.9	0.20	0.26	<b>0.22</b>	122	<b>127</b>
<b>HCFC-225cb</b>	CHClFCF <sub>2</sub> CClF <sub>2</sub>	5.9	0.32	0.32	<b>0.29</b>	595	<b>525</b>
<b>(E)-1-Chloro-3,3,3-trifluoroprop-1-ene</b>	trans-CF <sub>3</sub> CH=CHCl	26.0 days		0.22	<b>0.04</b>		<b>1</b>

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4354

4355 **Table 6.** Integrated absorption cross-sections ( $S$ ) for hydrofluorocarbons (HFCs) from the literature. Spectra used in RE calculations in the present study are indicated in  
 4356 bold.

Name	CAS#	Acronym	Formula	Data <sup>1</sup>	$T/K$	Wn. range /cm <sup>-1</sup>	$S^2$	Reference	Database <sup>3</sup>
Trifluoromethane	75-46-7	HFC-23	CHF <sub>3</sub>	A	298			[Blowers and Hollingshead, 2009]	
				E	296	400 - 1500	11.8	[Gohar et al., 2004]	
				E	296	700 - 1500	11.7	[Sihra et al., 2001]	
				E	253	655 - 1415	10.1	[Highwood and Shine, 2000]	
				E				[Naik et al., 2000]	
				A		600 - 1500	12.9	[Papasavva et al., 1997]	
				E	296	700 - 1400	12.7	[Pinnock et al., 1995]	
Difluoromethane	75-10-5	HFC-32	CH <sub>2</sub> F <sub>2</sub>	A	298			[Blowers and Hollingshead, 2009]	
				E	296	400 - 1550	5.8	[Gohar et al., 2004]	
				E	295	450 - 1480	5.9	[Orkin et al., 2003]	
				E	296	700 - 1500	5.7	[Sihra et al., 2001]	
				E	253	450 - 1475	5.6	[Highwood and Shine, 2000]	
				E				[Naik et al., 2000]	
				A		600 - 1500	6.1	[Papasavva et al., 1997]	
				E	297	995 - 1475	5.2	[Smith et al., 1996]	H
				E	296	700 - 1400	6.3	[Pinnock et al., 1995]	G
Fluoromethane	593-53-3	HFC-41	CH <sub>3</sub> F	E	297	995 - 1475	5.2	[M.S.F./R.A.L.]	G
				A	298			[Blowers and Hollingshead, 2009]	
				E	296	700 - 1400	1.5	[Sihra et al., 2001]	
				A		600 - 1500	1.7	[Papasavva et al., 1997]	
				E	296	700 - 1400	1.8	[Pinnock et al., 1995]	
1,1,1,2,2-Pentafluoroethane	354-33-6	HFC-125	CHF <sub>2</sub> CF <sub>3</sub>	E	296	700 - 1480	15.5	[Young et al., 2009b]	
				E	295	460 - 1480	16.6	[Orkin et al., 2003]	
				E	296	700 - 1500	16.5	[Sihra et al., 2001]	
				E	293	550 - 1480	17.2	[Di Lonardo and Masciarelli, 2000]	G

				E	253	550 - 1480	16.6	[ <b>Highwood and Shine, 2000</b> ]	
				E				[ <i>Naik et al., 2000</i> ]	
				A				[ <i>Good et al., 1998</i> ]	
				A		600 - 1500	16.8	[ <i>Papasavva et al., 1997</i> ]	
				E	296	700 - 1500	17.0	[ <b>Imasu et al., 1995</b> ]	
				E	296	700 - 1400	16.1	[ <i>Pinnock et al., 1995</i> ]	G
				E		460 - 1480	16.0	[ <i>Olliff and Fischer, 1994</i> ]	
				E	287	700 - 1465	16.1	[ <b>Clerbaux et al., 1993</b> ]	G
				E		500 - 1307	14.5	[ <i>Fisher et al., 1990</i> ]	
1,1,2,2-Tetrafluoroethane	359-35-3	HFC-134	CHF <sub>2</sub> CHF <sub>2</sub>	E	296	450 - 1550	10.5	[ <b>Sihra et al., 2001</b> ]	
				E				[ <i>Naik et al., 2000</i> ]	
				A				[ <i>Good et al., 1998</i> ]	
				E	296	450 - 2000	9.7	[ <i>Christidis et al., 1997</i> ]	
				A		600 - 1500	10.6	[ <i>Papasavva et al., 1997</i> ]	
				E	297	600 - 1700	11.4	[ <b>Smith et al., 1998</b> ]	H
				E	296	450 - 1420	10.5	[ <i>Hurley-priv.com., 2003</i> ]	G
				E	297	600 - 1700	11.4	[ <i>M.S.F./R.A.L.</i> ]	G
1,1,1,2-Tetrafluoroethane	811-97-2	HFC-134a	CH <sub>2</sub> FCF <sub>3</sub>	E	296	250 - 2000	13.2	[ <b>Forster et al., 2005</b> ]	
				E	296	300 - 1550	13.1	[ <i>Gohar et al., 2004</i> ]	
				E	296	1035 - 1340	11.4	[ <i>Nemtchinov and Varanasi, 2004</i> ]	H
				E	296	700 - 1500	12.4	[ <i>Hurley-priv.com., 2003</i> ]	G
				E	295	490 - 1550	13.6	[ <b>Orkin et al., 2003</b> ]	
				E	296	700 - 1550	12.4	[ <i>Sihra et al., 2001</i> ]	
				E	253	75 - 1540	13.6	[ <b>Highwood and Shine, 2000</b> ]	
				E				[ <i>Naik et al., 2000</i> ]	
				A		600 - 1500	13.6	[ <i>Papasavva et al., 1997</i> ]	
				E		600 - 1448	13.5	[ <i>Newnham et al., 1996</i> ]	
				E	296	700 - 1500	13.5	[ <i>Imasu et al., 1995</i> ]	
				E	296	700 - 1400	13.1	[ <i>Pinnock et al., 1995</i> ]	
				E		490 - 1510	13.4	[ <i>Olliff and Fischer, 1994</i> ]	
				E	287	815 - 1485	12.6	[ <b>Clerbaux et al., 1993</b> ]	H
				E	293	610 - 1490	13.2	[ <i>Cappellani and Restelli, 1992</i> ]	
				E		618 - 1420	12.2	[ <i>Fisher et al., 1990</i> ]	

1,1,2-Trifluoroethane	430-66-0	HFC-143	CH <sub>2</sub> FCHF <sub>2</sub>	E	296	600 - 1600	12.5	[M.S.F./R.A.L.]	G
				E	296	700 - 1550	7.1	[Sihra et al., 2001]	
				E				[Naik et al., 2000]	
				A		600 - 1500	7.2	[Papasavva et al., 1997]	
				E	296	700 - 1400	6.9	[Pinnock et al., 1995]	
1,1,1-Trifluoroethane	420-46-2	HFC-143a	CH <sub>3</sub> CF <sub>3</sub>	E	287	700 - 1500	6.9	[Clerbaux and Colin, 1994]	G
				E	296	400 - 1500	7.6	[M.S.F./R.A.L.]	
				E	296	700 - 1500	12.7	[Sihra et al., 2001]	
				E	293	797 - 1460	12.8	[Di Lonardo and Masciarelli, 2000]	
				E	253	800 - 1470	12.0	[Highwood and Shine, 2000]	
				E				[Naik et al., 2000]	
				A				[Good et al., 1998]	
1,2-Difluoroethane	624-72-6	HFC-152	CH <sub>2</sub> FCH <sub>2</sub> F	E	297	700 - 1500	13.6	[Smith et al., 1998]	H, G
				A		600 - 1500	13.7	[Papasavva et al., 1997]	
				E	296	500 - 1500	12.3	[Pinnock et al., 1995]	
				E	293	796 - 1474	12.8	[Olliff and Fischer, 1994]	
				E		555 - 1535	12.7	[Fisher et al., 1990]	
				A		600 - 1500	4.2	[Papasavva et al., 1997]	
				E		810 - 1510	3.7	[Wallington et al., 1994a]	
1,1-Difluoroethane	75-37-6	HFC-152a	CH <sub>3</sub> CHF <sub>2</sub>	E	296	700 - 1500	6.8	[Sihra et al., 2001]	G
				E	253	830 - 1500	6.7	[Highwood and Shine, 2000]	
				E				[Naik et al., 2000]	
				E	293	840 - 1490	6.9	[Vander Auwera, 2000]	
				A		600 - 1500	7.1	[Papasavva et al., 1997]	
				E	296	700 - 1400	7.4	[Pinnock et al., 1995]	
				E	287	840 - 1490	6.9	[Clerbaux et al., 1993]	
Fluoroethane	353-36-6	HFC-161	CH <sub>3</sub> CH <sub>2</sub> F	E	293	830 - 1485	6.9	[Cappellani and Restelli, 1992]	H
				E		775 - 1420	6.1	[Fisher et al., 1990]	
				E	296	450 - 1600	2.4	[Sihra et al., 2001]	
				E	296	450 - 2000	2.2	[Christidis et al., 1997]	

1,1,1,2,2,3,3-Heptafluoropropane	2252-84-8	HFC-227ca	CF <sub>3</sub> CF <sub>2</sub> CHF <sub>2</sub>	A	600 - 1500	2.4	[Papasavva et al., 1997]
				E	296	450 - 1550	19.9
1,1,1,2,3,3,3-Heptafluoropropane	431-89-0	HFC-227ea	CF <sub>3</sub> CHF <sub>2</sub> CF <sub>3</sub>	E	296	450 - 2000	20.9 [Christidis et al., 1997]
				E	296	400 - 1550	23.3 [Gohar et al., 2004]
				E	296	700 - 1500	22.3 [Sihra et al., 2001]
				E			[Naik et al., 2000]
1,1,1,2,2,3-Hexafluoropropane	677-56-5	HFC-236cb	CH <sub>2</sub> FCF <sub>2</sub> CF <sub>3</sub>	E	296	700 - 1400	23.0 [Pinnock et al., 1995]
				E	296	450 - 1550	17.0 [Sihra et al., 2001]
1,1,1,2,3,3-Hexafluoropropane	431-63-0	HFC-236ea	CHF <sub>2</sub> CHF <sub>2</sub> CF <sub>3</sub>	E	296	450 - 2000	16.5 [Christidis et al., 1997]
1,1,1,3,3,3-Hexafluoropropane	690-39-1	HFC-236fa	CF <sub>3</sub> CH <sub>2</sub> CF <sub>3</sub>	E	296	680 - 1320	17.2 [Gierczak et al., 1996]
1,1,1,2,2-Pentafluoropropane	1814-88-6	HFC-245cb	CF <sub>3</sub> CF <sub>2</sub> CH <sub>3</sub>	E	296	700 - 1500	22.8 [Sihra et al., 2001]
				E			[Naik et al., 2000]
				E	296	600 - 1350	22.6 [Gierczak et al., 1996]
				E	296	700 - 1400	23.3 [Pinnock et al., 1995]
1,1,1,2,3-Pentafluoropropane	24270-66-4	HFC-245ea	CHF <sub>2</sub> CHF <sub>2</sub> CHF <sub>2</sub>	E	295	472 - 1490	18.1 [Orkin et al., 2003]
				E	296	450 - 1550	16.5 [Sihra et al., 2001]
1,1,1,2,3-Pentafluoropropane	431-31-2	HFC-245eb	CH <sub>2</sub> FCHF <sub>2</sub> CF <sub>3</sub>	E	296	450 - 2000	15.8 [Christidis et al., 1997]
				E			[Rajakumar et al., 2006]
1,1,1,3,3-Pentafluoropropane	460-73-1	HFC-245fa	CHF <sub>2</sub> CH <sub>2</sub> CF <sub>3</sub>	E	298	500 - 4000	[Rajakumar et al., 2006]
1,1,1-Trifluoropropane	421-07-8	HFC-263fb	CH <sub>3</sub> CH <sub>2</sub> CF <sub>3</sub>	E	295	455 - 1485	19.8 [Orkin et al., 2003]
				E	296	640 - 1500	19.6 [Sihra et al., 2001]
				E			[Jain et al., 2000]
				E			[Naik et al., 2000]
2,2-Difluoropropane	420-45-1	HFC-272ca	CH <sub>3</sub> CF <sub>2</sub> CH <sub>3</sub>	E		450 - 2325	20.6 [Ko et al., 1999]
				E	298	500 - 4000	[Rajakumar et al., 2006]
1,1,1,2,2,3,3,4,4-Nonafluorobutane	375-17-7	HFC-329p	CHF <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	E	296	700 - 1500	5.7 [Sihra et al., 2001]
1,1,1,3,3-Pentafluorobutane	406-58-6	HFC-365mfc	CH <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> CF <sub>3</sub>	E	296	700 - 1400	5.6 [Pinnock et al., 1995]
				E	296	700 - 1435	22.2 [Young et al., 2009b]
1,1-Difluoroethene	75-38-7	HFC-	CH <sub>2</sub> =CF <sub>2</sub>	E	296	665 - 1500	18.8 [Inoue et al., 2008]
				E			[Naik et al., 2000]
				E	298	600 - 1500	[Barry et al., 1997]
				E	296	745 - 1820	10.1 [Baasandorj et al., 2010]

Fluoroethene	75-02-5	1132a HFC-1141	CH <sub>2</sub> =CHF	E	296	770 - 1740	4.8	[Baasandorj et al., 2010]
(Z)-1,2,3,3,3-Pentafluoroprop-1-ene	5528-43-8	(Z)-HFC-1225ye	CF <sub>3</sub> CF=CHF(Z)	E	296	770 - 1740	4.5	[Stoppa et al., 2009]
(E)-1,2,3,3,3-Pentafluoroprop-1-ene	5595-10-8	(E)-HFC-1225ye	CF <sub>3</sub> CF=CHF(E)	E	296	706 - 1812	19.3	[Papadimitriou et al., 2008a]
(Z)-1,3,3,3-Tetrafluoroprop-1-ene	29118-25-0	(Z)-HFC-1234ze	CF <sub>3</sub> CH=CHF(Z)	E	296	710 - 2000	18.3	[Hurley et al., 2007]
2,3,3,3-Tetrafluoroprop-1-ene	754-12-1	HFC-1234yf	CF <sub>3</sub> CF=CH <sub>2</sub>	E	295	810 - 2000	18.4	[Hurley et al., 2007]
				E	296	500 - 1900	17.2	[Orkin et al., 2010]
				E	296	540 - 1810	16.9	[Papadimitriou et al., 2008a]
(E)-1,3,3,3-Tetrafluoroprop-1-ene	1645-83-6	(E)-HFC-1234ze	trans-CF <sub>3</sub> CH=CHF	E	295	863 - 1745	16.1	[Nielsen et al., 2007]
				E	296	500 - 1900	19.9	[Orkin et al., 2010]
				E	296	680 - 2000	19.4	[Søndergaard et al., 2007]
(Z)-1,1,1,4,4,4-Hexafluorobut-2-ene	692-49-9	(Z)-HFC-1336	CF <sub>3</sub> CH=CHCF <sub>3</sub> (Z)	E	296	1100 - 1500	27.8	[Baasandorj et al., 2011]
3,3,3-Trifluoroprop-1-ene	677-21-4	HFC-1243zf	CF <sub>3</sub> CH=CH <sub>2</sub>	E	298	650 - 2000	12.5	[Andersen et al., 2012a]
3,3,4,4,4-Pentafluorobut-1-ene	374-27-6	HFC-1345zfc	C <sub>2</sub> F <sub>5</sub> CH=CH <sub>2</sub>	E	298	650 - 2000	13.6	[Andersen et al., 2012a]
3,3,4,4,5,5,6,6,6-Nonafluorohex-1-ene	19430-93-4		C <sub>4</sub> F <sub>9</sub> CH=CH <sub>2</sub>	E	298	650 - 2000	24.1	[Andersen et al., 2012a]
3,3,4,4,5,5,6,6,7,7,8,8,8-Tridecafluorooct-1-ene	25291-17-2		C <sub>6</sub> F <sub>13</sub> CH=CH <sub>2</sub>	E	298	650 - 2000	29.6	[Andersen et al., 2012a]
3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-Heptafluorodec-1-ene	21652-58-4		C <sub>8</sub> F <sub>17</sub> CH=CH <sub>2</sub>	E	298	650 - 2000	33.7	[Andersen et al., 2012a]

4357 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.

4358 <sup>2</sup> Integrated absorption cross-section in units of 10<sup>-17</sup> cm<sup>2</sup> molecule<sup>-1</sup> cm<sup>-1</sup> for the wavenumber interval specified.

4359 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009.

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4361 **Table 7.** Lifetimes, radiative efficiencies and direct GWPs (relative to CO<sub>2</sub>) for hydrofluorocarbons (HFCs).  
 4362 Compounds in bold either have significant current atmospheric concentrations or a clear potential for future  
 4363 emissions. Recommended RE and GWP 100-yr values are indicated in bold. Lifetimes are from *WMO* [2011]  
 4364 except those in italic (see text for details). RE and GWP values in italic are based on previous publications (see  
 4365 text for details).

Acronym / name	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP 100-yr	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>HFC-23</b>	CHF <sub>3</sub>	222.0	0.19	0.18	<b>0.18</b>	14,800	<b>12,400</b>
<b>HFC-32</b>	CH <sub>2</sub> F <sub>2</sub>	5.2	0.11	0.12	<b>0.11</b>	675	<b>677</b>
<b>HFC-41</b>	CH <sub>3</sub> F	2.8	0.02	0.03	<b>0.02</b>	92	<b>116</b>
<b>HFC-125</b>	CHF <sub>2</sub> CF <sub>3</sub>	28.2	0.23	0.23	<b>0.23</b>	3,500	<b>3,170</b>
<b>HFC-134</b>	CHF <sub>2</sub> CHF <sub>2</sub>	9.7	0.18	0.20	<b>0.19</b>	1,100	<b>1,120</b>
<b>HFC-134a</b>	CH <sub>2</sub> FCF <sub>3</sub>	13.4	0.16	0.17	<b>0.16</b>	1,430	<b>1,300</b>
<b>HFC-143</b>	CH <sub>2</sub> FCHF <sub>2</sub>	3.5	0.13	0.14	<b>0.13</b>	353	<b>328</b>
<b>HFC-143a</b>	CH <sub>3</sub> CF <sub>3</sub>	47.1	0.13	0.16	<b>0.16</b>	4,470	<b>4,800</b>
<b>HFC-152</b>	CH <sub>2</sub> FCH <sub>2</sub> F	0.4	0.09	0.08	<b>0.04</b>	53	<b>16</b>
<b>HFC-152a</b>	CH <sub>3</sub> CHF <sub>2</sub>	1.5	0.09	0.12	<b>0.10</b>	124	<b>138</b>
<b>HFC-161</b>	CH <sub>3</sub> CH <sub>2</sub> F	66.0 days	0.03	0.04	<b>0.02</b>	12	<b>4</b>
HFC-227ca	CF <sub>3</sub> CF <sub>2</sub> CHF <sub>2</sub>	28.2		0.27	<b>0.27</b>		<b>2,640</b>
<b>HFC-227ea</b>	CF <sub>3</sub> CHFCF <sub>3</sub>	38.9	0.26	0.26	<b>0.26</b>	3,220	<b>3,350</b>
<b>HFC-236cb</b>	CH <sub>2</sub> FCF <sub>2</sub> CF <sub>3</sub>	13.1	0.23	0.24	<b>0.23</b>	1,340	<b>1,210</b>
<b>HFC-236ea</b>	CHF <sub>2</sub> CHFCF <sub>3</sub>	11.0	<b>0.30</b>			1,370	<b>1,330</b>
<b>HFC-236fa</b>	CF <sub>3</sub> CH <sub>2</sub> CF <sub>3</sub>	242.0	0.28	0.24	<b>0.24</b>	9,810	<b>8,060</b>
<b>HFC-245ca</b>	CH <sub>2</sub> FCF <sub>2</sub> CHF <sub>2</sub>	6.5	0.23		<b>0.24</b>	693	<b>716</b>
HFC-245cb	CF <sub>3</sub> CF <sub>2</sub> CH <sub>3</sub>	47.1		0.25	<b>0.24</b>		<b>4,620</b>
HFC-245ea	CHF <sub>2</sub> CHFCHF <sub>2</sub>	3.2		0.18	<b>0.16</b>		<b>235</b>
HFC-245eb	CH <sub>2</sub> FCHFCF <sub>3</sub>	3.1		0.23	<b>0.20</b>		<b>290</b>
<b>HFC-245fa</b>	CHF <sub>2</sub> CH <sub>2</sub> CF <sub>3</sub>	7.7	0.28	0.26	<b>0.24</b>	1,030	<b>858</b>
HFC-263fb	CH <sub>3</sub> CH <sub>2</sub> CF <sub>3</sub>	1.2		0.13	<b>0.10</b>		<b>76</b>
HFC-272ca	CH <sub>3</sub> CF <sub>2</sub> CH <sub>3</sub>	2.6		0.08	<b>0.07</b>		<b>144</b>
HFC-329p	CHF <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	28.4		0.31	<b>0.31</b>		<b>2,360</b>
<b>HFC-365mfc</b>	CH <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> CF <sub>3</sub>	8.7	0.21	0.23	<b>0.22</b>	794	<b>804</b>
<b>HFC-43-10mee</b>	CF <sub>3</sub> CHFCF <sub>2</sub> CF <sub>3</sub>	16.1	0.40		<b>0.42</b>	1,640	<b>1,650</b>
HFC-1132a	CH <sub>2</sub> =CF <sub>2</sub>	4.0 days		0.10	<b>0.00</b>		<b>0</b>
HFC-1141	CH <sub>2</sub> =CHF	2.1 days		0.09	<b>0.00</b>		<b>0</b>
(Z)-HFC-1225ye	CF <sub>3</sub> CF=CHF(Z)	8.5 days		0.26	<b>0.02</b>		<b>0</b>
(E)-HFC-1225ye	CF <sub>3</sub> CF=CHF(E)	4.9 days		0.25	<b>0.01</b>		<b>0</b>
(Z)-HFC-1234ze	CF <sub>3</sub> CH=CHF(Z)	10.0 days		0.20	<b>0.02</b>		<b>0</b>
HFC-1234yf	CF <sub>3</sub> CF=CH <sub>2</sub>	10.5 days		0.23	<b>0.02</b>		<b>0</b>
(E)-HFC-1234ze	trans-CF <sub>3</sub> CH=CHF	16.4 days		0.28	<b>0.04</b>		<b>1</b>
(Z)-HFC-1336	CF <sub>3</sub> CH=CHCF <sub>3</sub> (Z)	22.0 days		0.42	<b>0.07</b>		<b>2</b>
HFC-1243zf	CF <sub>3</sub> CH=CH <sub>2</sub>	7.0 days		0.17	<b>0.01</b>		<b>0</b>
HFC-1345zfc	C <sub>2</sub> F <sub>5</sub> CH=CH <sub>2</sub>	7.6 days		0.19	<b>0.01</b>		<b>0</b>
3,3,4,4,5,5,6,6,6- Nonafluorohex-1-ene	C <sub>4</sub> F <sub>9</sub> CH=CH <sub>2</sub>	7.6 days		0.35	<b>0.03</b>		<b>0</b>
3,3,4,4,5,5,6,6,7,7,8,8, 8-Tridecafluorooct-1- ene	C <sub>6</sub> F <sub>13</sub> CH=CH <sub>2</sub>	7.6 days		0.39	<b>0.03</b>		<b>0</b>
3,3,4,4,5,5,6,6,7,7,8,8, 8-Tridecafluorooct-1- ene	C <sub>8</sub> F <sub>17</sub> CH=CH <sub>2</sub>	7.6 days		0.44	<b>0.03</b>		<b>0</b>



9,9,10,10,10-  
Heptafluorodec-1-  
ene

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4368 **Table 8.** Integrated absorption cross-sections ( $S$ ) for chlorocarbons and hydrochlorocarbons from the literature. Spectra used in RE calculations in the present study are  
 4369 indicated in bold.

Name	CAS#	Trivial name	Formula	Data <sup>1</sup>	$T/K$	Wn. range /cm <sup>-1</sup>	$S^2$	Reference	Database <sup>3</sup>
1,1,1-Trichloroethane	71-55-6	Methyl chloroform	CH <sub>3</sub> CCl <sub>3</sub>	E	295	480 - 1490	5.1	<b>[Orkin et al., 2003]</b>	
				E	296	700 - 1500	5.0	<b>[Imasu et al., 1995]</b>	
				E		669 - 1397	4.5	[Fisher et al., 1990]	
Perchloromethane, tetrachloromethane	56-23-5	Carbon tetrachloride	CCl <sub>4</sub>	E	297	750 - 812	6.2	<b>[Nemtchinov and Varanasi, 2003]</b>	G
				E	297	750 - 812	6.2	[Varanasi-priv.com., 2000]	H
				E	298	730 - 825	5.9	[Orlando et al., 1992]	
				E	298	773 - 802	3.7	[Brown et al., 1987]	
				E	298	786 - 806	3.6	[Massie et al., 1985]	
Chloromethane	74-87-3	Methyl chloride	CH <sub>3</sub> Cl	E		616 - 934	4.5	[Fisher et al., 1990]	
				E		661 - 1646	1.4	[Grossman et al., 1997]	
Dichloromethane	75-09-2	Methylene chloride	CH <sub>2</sub> Cl <sub>2</sub>	A		250 - 3300	3.3	[Bera et al., 2009]	
Trichloromethane	67-66-3	Chloroform	CHCl <sub>3</sub>	E	295	540 - 1600	5.6	<b>[McPheat and Duxbury, 2000]</b>	
1,2-Dichloroethane	107-06-2		CH <sub>2</sub> ClCH <sub>2</sub> Cl	E	293	600 - 1700	2.1	<b>[Vander Auwera, 2000]</b>	

4370 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.

4371 <sup>2</sup> Integrated absorption cross-section in units of 10<sup>-17</sup> cm<sup>2</sup> molecule<sup>-1</sup> cm<sup>-1</sup> for the wavenumber interval specified.

4372 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009.

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4376 **Table 9.** Lifetimes, radiative efficiencies and direct GWPs (relative to CO<sub>2</sub>) for chlorocarbons and  
 4377 hydrochlorocarbons. Compounds in bold either have significant current atmospheric concentrations or a clear  
 4378 potential for future emissions. Recommended RE and GWP 100-yr values are indicated in bold. Lifetimes are  
 4379 from *WMO* [2011].

Acronym / name	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP 100-yr	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>Methyl chloroform</b>	CH <sub>3</sub> CCl <sub>3</sub>	5.0	0.06	0.08	<b>0.07</b>	146	<b>160</b>
<b>Carbon tetrachloride</b>	CCl <sub>4</sub>	26.0	0.13	0.18	<b>0.17</b>	1,400	<b>1,730</b>
<b>Methyl chloride</b>	CH <sub>3</sub> Cl	1.0	<b>0.01</b>			13	<b>12</b>
<b>Methylene chloride</b>	CH <sub>2</sub> Cl <sub>2</sub>	0.4	<b>0.03</b>			9	<b>9</b>
<b>Chloroform</b>	CHCl <sub>3</sub>	0.4	0.11	0.14	<b>0.08</b>	31	<b>16</b>
1,2-Dichloroethane	CH <sub>2</sub> ClCH <sub>2</sub> Cl	65.0 days		0.02	<b>0.01</b>		<b>1</b>

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4382 **Table 10.** Integrated absorption cross-sections (*S*) for bromocarbons, hydrobromocarbons and halons from the literature. Spectra used in RE calculations in the present  
4383 study are indicated in bold.

Name	CAS#	Acronym / trivial name	Formula	Data <sup>1</sup>	<i>T</i> /K	Wn. range /cm <sup>-1</sup>	<i>S</i> <sup>2</sup>	Reference	Database <sup>3</sup>
Bromomethane	74-83-9	Methyl bromide	CH <sub>3</sub> Br	E	296	450 - 2000	0.7	<b>[Sihra et al., 2001]</b>	
				E	296	450 - 2000	0.8	[Christidis et al., 1997]	
				E		550 - 1600	1.2	[Grossman et al., 1997]	
				E				[Graner, 1981]	
Dibromomethane	74-95-3	Methylene bromide	CH <sub>2</sub> Br <sub>2</sub>	E	296	450 - 2000	2.1	<b>[Sihra et al., 2001]</b>	
				E	296	450 - 2000	2.0	[Christidis et al., 1997]	
Bromodifluoromethane	1511-62-2	Halon-1201	CHBrF <sub>2</sub>	E,A	298	530 - 1460	10.2	<b>[Charmet et al., 2010]</b>	
				E	295	530 - 1400	10.1	<b>[Orkin et al., 2003]</b>	
				E	296	450 - 2000	10.0	<b>[Sihra et al., 2001]</b>	
				E	296	450 - 2000	9.9	[Christidis et al., 1997]	
Dibromodifluoromethane	75-61-6	Halon-1202	CBr <sub>2</sub> F <sub>2</sub>	E	295	400 - 1600	11.8	<b>[Orkin et al., 2003]</b>	
Bromochlorodifluoromethane	353-59-3	Halon-1211	CBrClF <sub>2</sub>	E	296	450 - 2000	12.4	<b>[Sihra et al., 2001]</b>	
				E	296	450 - 2000	11.5	[Christidis et al., 1997]	
Bromotrifluoromethane	75-63-8	Halon-1301	CBrF <sub>3</sub>	E	298	461 - 2500	16.7	<b>[Charmet et al., 2008]</b>	
				E	298	720 - 1250	15.4	[Drage et al., 2006]	
				E	295	720 - 1250	16.4	<b>[Orkin et al., 2003]</b>	
				E	296	450 - 2000	17.0	<b>[Sihra et al., 2001]</b>	
				E		1040 - 1250	16.0	[Varanasi and Chudamani, 1988b]	
				E		1040 - 1250	16.1	[Ramanathan et al., 1985]	
				E		720 - 1250	15.9	[Person and Polo, 1961]	
2-Bromo-1,1,1-trifluoroethane	421-06-7	Halon-2301	CH <sub>2</sub> BrCF <sub>3</sub>	E	295	590 - 1510	12.8	<b>[Orkin et al., 2003]</b>	
2-Bromo-2-chloro-1,1,1-trifluoroethane	151-67-7	Halon-2311 / Halothane	CHBrClCF <sub>3</sub>	E	298	650 - 1500	12.2	<b>[Andersen et al., 2012b]</b>	
				E	295	480 - 1370	13.0	<b>[Orkin et al., 2003]</b>	
2-Bromo-1,1,1,2-tetrafluoroethane	124-72-1	Halon-2401	CHFBrcF <sub>3</sub>	E	295	490 - 1480	14.6	<b>[Orkin et al., 2003]</b>	
1,2-Dibromo-1,1,2,2-tetrafluoroethane	124-73-2	Halon-2402	CBrF <sub>2</sub> CBrF <sub>2</sub>	E	296	450 - 2000	15.4	<b>[Sihra et al., 2001]</b>	

- 4384 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.
- 4385 <sup>2</sup> Integrated absorption cross-section in units of  $10^{-17} \text{ cm}^2 \text{ molecule}^{-1} \text{ cm}^{-1}$  for the wavenumber interval specified.
- 4386 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009.
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4389 **Table 11.** Lifetimes, radiative efficiencies and direct GWPs (relative to CO<sub>2</sub>) for bromocarbons,  
 4390 hydrobromocarbons and halons. Compounds in bold either have significant current atmospheric concentrations  
 4391 or a clear potential for future emissions. Recommended RE and GWP 100-yr values are indicated in bold.  
 4392 Lifetimes are from *WMO* [2011].

Acronym / name	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP 100-yr	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>Methyl bromide</b>	CH <sub>3</sub> Br	0.8	0.01	0.01	<b>0.00</b>	5	<b>2</b>
<b>Methylene bromide</b>	CH <sub>2</sub> Br <sub>2</sub>	0.3	0.01	0.02	<b>0.01</b>	2	<b>1</b>
<b>Halon-1201</b>	CHBrF <sub>2</sub>	5.2	0.14	0.17	<b>0.15</b>	404	<b>376</b>
Halon-1202	CBr <sub>2</sub> F <sub>2</sub>	2.9		0.31	<b>0.27</b>		<b>231</b>
<b>Halon-1211</b>	CBrClF <sub>2</sub>	16.0	0.30	0.31	<b>0.29</b>	1,890	<b>1,750</b>
<b>Halon-1301</b>	CBrF <sub>3</sub>	65.0	0.32	0.31	<b>0.30</b>	7,140	<b>6,290</b>
Halon-2301	CH <sub>2</sub> BrCF <sub>3</sub>	3.4		0.15	<b>0.14</b>		<b>173</b>
Halon-2311 / Halothane	CHBrClCF <sub>3</sub>	1.0		0.18	<b>0.13</b>		<b>41</b>
Halon-2401	CHFBrcF <sub>3</sub>	2.9		0.21	<b>0.19</b>		<b>184</b>
<b>Halon-2402</b>	CBrF <sub>2</sub> CBrF <sub>2</sub>	20.0	0.33	0.34	<b>0.31</b>	1,640	<b>1,470</b>

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4395 **Table 12.** Integrated absorption cross-sections (*S*) for fully fluorinated species from the literature. Spectra used in RE calculations in the present study are indicated in  
 4396 bold.

Name	CAS#	Acronym	Formula	Data <sup>1</sup>	<i>T</i> /K	Wn. range /cm <sup>-1</sup>	<i>S</i> <sup>2</sup>	Reference	Database <sup>3</sup>
Nitrogen trifluoride	7783-54-2		NF <sub>3</sub>	E	296	400 - 2000	7.0	<b>[Robson et al., 2006]</b>	
Sulphur hexafluoride	2551-62-4		SF <sub>6</sub>	E				[Vlachogiannis et al., 2005]	
				E	296	900 - 1000	20.7	<b>[Hurley-priv.com., 2003]</b>	G
				E				[Jain et al., 2000]	
				E	295	925 - 955	18.8	<b>[Varanasi-priv.com., 2000]</b>	H
				E	216	925 - 955	18.9	[Varanasi et al., 1994]	H
				E		640 - 1225	20.2	[Ko et al., 1993]	
				E			18.0	[Chapados, 1988]	
				E			17.6	[McDowell et al., 1986]	
				E			17.6	[Dunn et al., 1982]	
				E			18.3	[Brodbeck et al., 1980]	
(Trifluoromethyl)sulfur pentafluoride	373-80-8		SF <sub>5</sub> CF <sub>3</sub>	E	298	599 - 2500	28.6	<b>[Rinsland et al., 2003]</b>	H
				E	296	670 - 1325	25.2	[Hurley-priv.com., 2003]	G
				E	296	400 - 1330	26.5	<b>[Nielsen et al., 2002]</b>	
				E	296	700 - 2000	25.4	[Sihra et al., 2001]	
				E	296	670 - 1325	25.4	[Sturges et al., 2000]	
Sulfuryl fluoride	2699-79-8		SO <sub>2</sub> F <sub>2</sub>	E	296	805 - 1760	13.0	<b>[Andersen et al., 2009]</b>	
				E		500 - 1542	13.6	[Dillon et al., 2008]	
				E,A	296	500 - 1542	14.0	[Papadimitriou et al., 2008b]	
Perfluoromethane, tetrafluoromethane	75-73-0	PFC-14	CF <sub>4</sub>	A		700 - 1400	19.3	[Bravo et al., 2010b]	
				E	296	1230 - 1300	19.0	<b>[Hurley et al., 2005]</b>	
				E	296	1230 - 1300	21.9	[Hurley-priv.com., 2003]	G
				E	296	500 - 1400	21.9	[Sihra et al., 2001]	
				E	296	1250 - 1290	19.1	<b>[Varanasi-priv.com., 2000]</b>	H

				A		600 - 1500	20.1	[Papasavva et al., 1997]	
				E	300	590 - 1320	18.5	[Roehl et al., 1995]	
				E	293	1255 - 1310	17.3	[McDaniel et al., 1991]	
				E		1255 - 1310	14.0	[Varanasi and Chudamani, 1988b]	
				E		1255 - 1310	16.9	[Golden et al., 1978]	
Perfluoroethane	76-16-4	PFC-116	C <sub>2</sub> F <sub>6</sub>	A			26.3	[Bera et al., 2010]	
				E	297	700 - 1400	23.0	[Bravo et al., 2010b]	
				A		700 - 1400	22.5	[Bravo et al., 2010b]	
				E	296	1061 - 1285	21.0	[Zou et al., 2004]	H
				E	296	450 - 1500	21.6	[Sihra et al., 2001]	
				E	293	675 - 1400	22.8	[Ballard et al., 2000a]	
				E	253	680 - 1380	22.8	[Highwood and Shine, 2000]	
				E	296	690 - 1360	21.5	[Highwood et al., 1999]	G
				A		600 - 1500	22.7	[Papasavva et al., 1997]	
				E	300	480 - 1385	21.6	[Roehl et al., 1995]	
				E				[Varanasi and Chudamani, 1988b]	
				E				[Mills et al., 1958]	
				E	293	690 - 1360	22.2	[M.S.F./R.A.L.]	G
Perfluorocyclopropane	931-91-9	PFC-c216	c-C <sub>3</sub> F <sub>6</sub>	A		0 - 2500	16.9	[Bravo et al., 2010b]	
Perfluoropropane	76-19-7	PFC-218	C <sub>3</sub> F <sub>8</sub>	A			30.4	[Bera et al., 2010]	
				E	297	700 - 1400	26.8	[Bravo et al., 2010b]	
				A		700 - 1400	27.6	[Bravo et al., 2010b]	
				E	296	500 - 1500	27.5	[Sihra et al., 2001]	
				E	300	500 - 1550	22.0	[Roehl et al., 1995]	
Perfluorocyclobutane	115-25-3	PFC-318	c-C <sub>4</sub> F <sub>8</sub>	A		0 - 2500	22.1	[Bravo et al., 2010b]	
				E	297	550 - 1500	21.7	[Vasekova et al., 2006]	
				E	297	550 - 1500	22.2	[Ballard et al., 2000a]	
				E	253	555 - 1460	21.6	[Highwood and Shine, 2000]	
				E	297	555 - 1430	21.8	[M.S.F./R.A.L.]	G
Perfluorobutane	355-25-9	PFC-31-10	C <sub>4</sub> F <sub>10</sub>	A			36.0	[Bera et al., 2010]	
				E	297	450 - 1500	31.7	[Bravo et al., 2010b]	
				A		0 - 2500	32.5	[Bravo et al., 2010b]	
				E	296	450 - 1500	31.7	[Sihra et al., 2001]	
				E	300	500 - 1550	27.2	[Roehl et al., 1995]	
Perfluorocyclopentene	559-40-0		c-C <sub>5</sub> F <sub>8</sub>	E			24.0	[Bravo et al., 2010b]	



Perfluoropentane	678-26-2	PFC-41-12	n-C <sub>5</sub> F <sub>12</sub>	E	297	550 - 1800	20.9	[Vasekova et al., 2006]
				E	297	210 - 2000	36.3	[Bravo et al., 2010b]
				A		0 - 2500	37.2	[Bravo et al., 2010b]
Perfluorohexane	355-42-0	PFC-51-14	n-C <sub>6</sub> F <sub>14</sub>	E	300	500 - 1550	34.6	[Roehl et al., 1995]
				E	297	210 - 2000	38.5	[Bravo et al., 2010b]
				A		0 - 2500	41.8	[Bravo et al., 2010b]
Perfluoroheptane	335-57-9	PFC-61-16	n-C <sub>7</sub> F <sub>16</sub>	E	300	500 - 1550	39.6	[Roehl et al., 1995]
				E	296	500 - 4000	44.7	[Ivy et al., 2012]
		PFC-71-18	C <sub>8</sub> F <sub>18</sub>	E	296	500 - 4000	52.3	[Ivy et al., 2012]
				E	297	700 - 1400	45.6	[Bravo et al., 2010b]
Perfluorodecalin (mixed)	306-94-5	PFC-91-18	C <sub>10</sub> F <sub>18</sub>	A		700 - 1400	50.9	[Bravo et al., 2010b]
				A		0 - 2500	43.2	[Bravo et al., 2010b]
				E	296	0 - 1500	39.1	[Shine et al., 2005b]
Perfluorodecalin (cis)	60433-11-6		cis-C <sub>10</sub> F <sub>18</sub>	A		0 - 2500	43.4	[Bravo et al., 2010b]
				E	296	655 - 1370	37.9	[Shine et al., 2005b]
Perfluorodecalin (trans)	60433-12-7		trans-C <sub>10</sub> F <sub>18</sub>	A		0 - 2500	43.0	[Bravo et al., 2010b]
				E	296	655 - 1360	35.6	[Shine et al., 2005b]
Perfluoroethene	116-14-3	PFC-1114	CF <sub>2</sub> =CF <sub>2</sub>	E	296	1080 - 1400	12.0	[Drage et al., 2006]
				E	298	1080 - 1400	12.9	[Acerboni et al., 2001]
Perfluoropropene	116-15-4	PFC-1216	CF <sub>3</sub> CF=CF <sub>2</sub>	E	298	970 - 1850	23.5	[Acerboni et al., 2001]
				Perfluorobuta-1,3-diene	685-63-2	CF <sub>2</sub> =CFCF=CF <sub>2</sub>	E	
A			21.9				[Bravo et al., 2010b]	
E	298	900 - 1850	21.8				[Acerboni et al., 2001]	
Perfluorobut-1-ene	357-26-6		CF <sub>3</sub> CF <sub>2</sub> CF=CF <sub>2</sub>	E	296	635 - 1830	24.0	[Young et al., 2009a]
Perfluorobut-2-ene	360-89-4		CF <sub>3</sub> CF=CFCF <sub>3</sub>	E	298	500 - 1410	25.3	[Cometto et al., 2010]
				E	296	650 - 1500	28.8	[Young et al., 2009a]

4397 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.

4398 <sup>2</sup> Integrated absorption cross-section in units of 10<sup>-17</sup> cm<sup>2</sup> molecule<sup>-1</sup> cm<sup>-1</sup> for the wavenumber interval specified.

4399 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009.

4400

4401 **Table 13.** Lifetimes, radiative efficiencies and direct GWPs (relative to CO<sub>2</sub>) for fully fluorinated species.  
 4402 Compounds in bold either have significant current atmospheric concentrations or a clear potential for future  
 4403 emissions. Recommended RE and GWP 100-yr values are indicated in bold. Lifetimes are from WMO [2011]  
 4404 except those in italic (see text for details). RE and GWP values in italic are based on previous publications (see  
 4405 text for details).

Acronym / name	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP 100-yr	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>Nitrogen trifluoride</b>	NF <sub>3</sub>	500.0	0.21	0.21	<b>0.20</b>	17,200	<b>16,100</b>
<b>Sulphur hexafluoride</b>	SF <sub>6</sub>	3,200.0	0.52	0.57	<b>0.57</b>	22,800	<b>23,500</b>
<b>(Trifluoromethyl)sulfur pentafluoride</b>	SF <sub>5</sub> CF <sub>3</sub>	800.0	0.57	0.60	<b>0.59</b>	17,700	<b>17,400</b>
Sulfuryl fluoride	SO <sub>2</sub> F <sub>2</sub>	36.0		0.21	<b>0.20</b>		<b>4,090</b>
<b>PFC-14</b>	CF <sub>4</sub>	50,000.0	0.10	0.09	<b>0.09</b>	7,390	<b>6,630</b>
<b>PFC-116</b>	C <sub>2</sub> F <sub>6</sub>	10,000.0	0.26	0.25	<b>0.25</b>	12,200	<b>11,100</b>
<b>PFC-c216</b>	c-C <sub>3</sub> F <sub>6</sub>	3,000.0	0.42	<i>0.23</i>	<b>0.23</b>	17,300	<b>9,200</b>
<b>PFC-218</b>	C <sub>3</sub> F <sub>8</sub>	2,600.0	0.26	0.28	<b>0.28</b>	8,830	<b>8,900</b>
<b>PFC-318</b>	c-C <sub>4</sub> F <sub>8</sub>	3,200.0	0.32	0.32	<b>0.32</b>	10,300	<b>9,540</b>
<b>PFC-31-10</b>	C <sub>4</sub> F <sub>10</sub>	2,600.0	0.33	0.37	<b>0.36</b>	8,860	<b>9,200</b>
Perfluorocyclopentene	c-C <sub>5</sub> F <sub>8</sub>	<i>31.0 days</i>		<i>0.33</i>	<b>0.08</b>		<b>2</b>
<b>PFC-41-12</b>	n-C <sub>5</sub> F <sub>12</sub>	4,100.0	0.41	0.41	<b>0.41</b>	9,160	<b>8,550</b>
<b>PFC-51-14</b>	n-C <sub>6</sub> F <sub>14</sub>	3,100.0	0.49	0.45	<b>0.44</b>	9,300	<b>7,910</b>
PFC-61-16	n-C <sub>7</sub> F <sub>16</sub>	3,000.0		0.51	<b>0.50</b>		<b>7,820</b>
PFC-71-18	C <sub>8</sub> F <sub>18</sub>	<i>3,000.0</i>		0.56	<b>0.55</b>		<b>7,620</b>
<b>Perfluorodecalin (mixed)</b>	C <sub>10</sub> F <sub>18</sub>	2,000.0	0.56	0.56	<b>0.55</b>	7,500	<b>7,190</b>
<b>Perfluorodecalin (cis)</b>	cis-C <sub>10</sub> F <sub>18</sub>	2,000.0		0.57	<b>0.56</b>		<b>7,240</b>
<b>Perfluorodecalin (trans)</b>	trans-C <sub>10</sub> F <sub>18</sub>	2,000.0		0.49	<b>0.48</b>		<b>6,290</b>
PFC-1114	CF <sub>2</sub> =CF <sub>2</sub>	1.1 days		0.12	<b>0.00</b>		<b>0</b>
PFC-1216	CF <sub>3</sub> CF=CF <sub>2</sub>	4.9 days		0.25	<b>0.01</b>		<b>0</b>
Perfluorobuta-1,3-diene	CF <sub>2</sub> =CFCF=CF <sub>2</sub>	1.1 days		0.24	<b>0.00</b>		<b>0</b>
Perfluorobut-1-ene	CF <sub>3</sub> CF <sub>2</sub> CF=CF <sub>2</sub>	<i>6.0 days</i>		0.30	<b>0.02</b>		<b>0</b>
Perfluorobut-2-ene	CF <sub>3</sub> CF=CFCF <sub>3</sub>	<i>31.0 days</i>		0.29	<b>0.07</b>		<b>2</b>

4406

4407

4408 **Table 14.** Integrated absorption cross-sections ( $S$ ) for halogenated alcohols and ethers from the literature. Spectra used in RE calculations in the present study are indicated  
4409 in bold.

Name	CAS#	Acronym	Formula	Data <sup>1</sup>	T/K	Wn. range /cm <sup>-1</sup>	$S^2$	Reference	Data base <sup>3</sup>
(Difluoromethoxy)trifluoromethane	3822-68-2	HFE-125	CHF <sub>2</sub> OCF <sub>3</sub>	A	277	0 - 1500		[Blowers <i>et al.</i> , 2008a]	
				A				[Blowers <i>et al.</i> , 2007]	
				E	296	450 - 1650	31.7	[Sihra <i>et al.</i> , 2001]	
				E	295	980 - 1510	31.2	[Orkin <i>et al.</i> , 1999]	
				A				[Good <i>et al.</i> , 1998]	
				E	298	475 - 1590	32.9	[Heathfield <i>et al.</i> , 1998]	
(Difluoromethoxy)difluoromethane	1691-17-4	HFE-134 (HG-00)	CHF <sub>2</sub> OCHF <sub>2</sub>	E	296	450 - 2000	29.2	[Christidis <i>et al.</i> , 1997]	
				A		31 - 2500	26.5	[Bravo <i>et al.</i> , 2011a]	
				E	296	700 - 1500	25.7	[Andersen <i>et al.</i> , 2010a]	
				A	277	0 - 1500		[Blowers <i>et al.</i> , 2008a]	
				A				[Blowers <i>et al.</i> , 2007]	
				E	298	25 - 3250	25.0	[Myhre <i>et al.</i> , 1999]	
				E	295	741 - 1443	25.4	[Orkin <i>et al.</i> , 1999]	
				A				[Good <i>et al.</i> , 1998]	
				E	298	750 - 1480	25.6	[Heathfield <i>et al.</i> , 1998]	
				E	296	700 - 1500	25.5	[Imasu <i>et al.</i> , 1995]	
Trifluoro(methoxy)methane	421-14-7	HFE-143a	CH <sub>3</sub> OCF <sub>3</sub>	E		770 - 1430	25.3	[Garland <i>et al.</i> , 1993]	
				A		78 - 1503	22.3	[Bravo <i>et al.</i> , 2011a]	
				A	277	0 - 1500		[Blowers <i>et al.</i> , 2008a]	
				A				[Blowers <i>et al.</i> , 2007]	
				E	296	550 - 1520	19.9	[Sihra <i>et al.</i> , 2001]	
				E				[Christensen <i>et al.</i> , 1999]	
1,1,1,2-Tetrafluoro-2-(trifluoromethoxy)ethane	2356-62-9	HFE-227ea	CF <sub>3</sub> CHFOCF <sub>3</sub>	A				[Good <i>et al.</i> , 1998]	
								[Blowers <i>et al.</i> , 2007]	
				E	298	485 - 1600	37.0	[Oyaro <i>et al.</i> , 2005]	
				E	296	645 - 1460	33.3	[Takahashi <i>et al.</i> , 2002]	
				E	298	700 - 1500	41.0	[Jain <i>et al.</i> , 2001]	
				E	296	700 - 1500	36.9	[Imasu <i>et al.</i> , 1995]	
2-Chloro-1-(difluoromethoxy)-1,1,2-trifluoroethane	13838-16-9	HCFE-235ca2 (enflurane)	CHF <sub>2</sub> OCF <sub>2</sub> CHFCl	E,A	296	500 - 2000	38.4	[Suga <i>et al.</i> , 1994]	
				E	298	650 - 1500	26.8	[Andersen <i>et al.</i> , 2012b]	
						800 - 1500	25.1	[Dalmasso <i>et al.</i> , 2006]	
2-Chloro-2-(difluoromethoxy)-1,1,1-trifluoroethane	26675-46-7	HCFE-235da2 (isoflurane)	CHF <sub>2</sub> OCHClCF <sub>3</sub>	E	298	650 - 1500	29.1	[Andersen <i>et al.</i> , 2010c]	
				E		400 - 1500	28.5	[Ryan and Nielsen, 2010]	
				E	296	450 - 1650	27.5	[Sihra <i>et al.</i> , 2001]	
				E	296	450 - 2000	26.3	[Christidis <i>et al.</i> , 1997]	
1-(Difluoromethoxy)-1,1,2,2-tetrafluoroethane	32778-11-3	HFE-236ca	CHF <sub>2</sub> OCF <sub>2</sub> CHF <sub>2</sub>	A				[Blowers <i>et al.</i> , 2007]	

2-(Difluoromethoxy)-1,1,1,2-tetrafluoroethane	57041-67-5	HFE-236ea2 (desflurane)	CHF <sub>2</sub> OCHF <sub>2</sub> CF <sub>3</sub>	A		43 - 2500	31.9	[Bravo et al., 2011a]
				E	298	650 - 1500	31.3	[Andersen et al., 2010c]
				A				[Blowers et al., 2007]
				E	298	485 - 1530	30.3	[Oyaro et al., 2005]
1,1,1-Trifluoro-2-(trifluoromethoxy)ethane	20193-67-3	HFE-236fa	CF <sub>3</sub> CH <sub>2</sub> OCF <sub>3</sub>	E	296	700 - 1500	29.9	[Imasu et al., 1995]
				A				[Blowers et al., 2007]
1,1,1,2,2-Pentafluoro-2-methoxy-ethane	22410-44-2	HFE-245cb2	CF <sub>3</sub> CF <sub>2</sub> OCH <sub>3</sub>	E	296	700 - 1500	33.5	[Imasu et al., 1995]
				A		45 - 1501	26.0	[Bravo et al., 2011a]
1,1-Difluoro-2-(trifluoromethoxy)ethane	84011-15-4	HFE-245fa1	CHF <sub>2</sub> CH <sub>2</sub> OCF <sub>3</sub>	A				[Blowers et al., 2007]
				E	296	700 - 1500	24.6	[Imasu et al., 1995]
				A				[Blowers et al., 2007]
2-(Difluoromethoxy)-1,1,1-trifluoroethane	1885-48-9	HFE-245fa2	CHF <sub>2</sub> OCH <sub>2</sub> CF <sub>3</sub>	A				[Blowers et al., 2007]
				E	298	470 - 1550	26.5	[Oyaro et al., 2005]
				E	296	450 - 1550	26.3	[Sihra et al., 2001]
				E	296	450 - 2000	25.1	[Christidis et al., 1997]
2,2,3,3,3-Pentafluoropropan-1-ol	422-05-9		CF <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> OH	E	296	700 - 1500	26.3	[Imasu et al., 1995]
				E	298	600 - 4000	20.5	[Antiñolo et al., 2012b]
				E	298	490 - 1500	18.0	[Sellevåg et al., 2007]
				E	296	700 - 1500	17.9	[Imasu et al., 1995]
1,1,2,2-Tetrafluoro-1-methoxyethane	425-88-7	HFE-254cb1	CH <sub>3</sub> OCF <sub>2</sub> CHF <sub>2</sub>	A		66 - 2500	20.1	[Bravo et al., 2011a]
				A				[Blowers et al., 2007]
				E	298	500 - 1600	19.6	[Heathfield et al., 1998]
				E	296	700 - 1500	19.1	[Imasu et al., 1995]
1,1,1-Trifluoro-2-methoxyethane	460-43-5	HFE-263fb1	CF <sub>3</sub> CH <sub>2</sub> OCH <sub>3</sub>	E	296	600 - 1600	15.5	[Osterstrom et al., 2012]
				A				[Bravo et al., 2011a]
				A				[Blowers et al., 2007]
				E	298	500 - 1525	15.3	[Oyaro et al., 2005]
1,1,2,2-Tetrafluoro-1-(trifluoromethoxy)ethane	690-22-2	HFE-263m1	CF <sub>3</sub> OCH <sub>2</sub> CH <sub>3</sub>	E	296	700 - 1500	15.2	[Imasu et al., 1995]
				A		42 - 1562	22.9	[Bravo et al., 2011a]
				A				[Blowers et al., 2007]
				E	298	550 - 1550	22.0	[Oyaro et al., 2005]
3,3,3-Trifluoropropan-1-ol	2240-88-2		CF <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> OH	E	298	500 - 4000	16.6	[Jimenez et al., 2010]
				E	298	515 - 1550	13.8	[Sellevåg et al., 2007]
				E	296	650 - 1530	14.6	[Waterland et al., 2005]
				E	296	650 - 1530	14.6	[Waterland et al., 2005]
1,1,1,2,2-Pentafluoro-2-(1,1,2,2-tetrafluoroethoxy)ethane	134769-21-4	HFE-329mcc2	CHF <sub>2</sub> CF <sub>2</sub> OCF <sub>2</sub> CF <sub>3</sub>	A				[Blowers et al., 2007]
				E	296	700 - 1500	39.2	[Imasu et al., 1995]
2-(Difluoromethoxy)-1,1,1,3,3,3-hexafluoropropane	26103-08-2	HFE-338mmz1	(CF <sub>3</sub> ) <sub>2</sub> CHOCHF <sub>2</sub>	A				[Blowers et al., 2007]
				E	296	700 - 1500	35.4	[Imasu et al., 1995]
1,1,1,2,2-Pentafluoro-2-(2,2,2-trifluoroethoxy)ethane	156053-88-2	HFE-338mcf2	CF <sub>3</sub> CH <sub>2</sub> OCF <sub>2</sub> CF <sub>3</sub>	A				[Blowers et al., 2007]
				E	296	700 - 1500	34.7	[Imasu et al., 1995]
1,1,1,3,3,3-Hexafluoro-2-	28523-86-6	Sevoflurane (HFE-	(CF <sub>3</sub> ) <sub>2</sub> CHOCH <sub>2</sub> F	A		39 - 2500	32.2	[Bravo et al., 2011a]

(fluoromethoxy)propane		347mmz1)								
				E	298	650 - 1500	30.2	[Andersen et al., 2010c]		
				E		650 - 1500	30.6	[Ryan and Nielsen, 2010]		
1,1,1,2,2,3,3-Heptafluoro-3-methoxypropane	375-03-1	HFE-347mcc3 (HFE-7000)	CH <sub>3</sub> OCF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	A		51 - 2500	31.1	[Bravo et al., 2011a]		
				E		700 - 1400	28.2	[Bravo et al., 2010a]		
				A				[Blowers et al., 2007]		
				E		700 - 1500	27.4	[Ninomiya et al., 2000]		
				E	296	700 - 1500	29.5	[Imasu et al., 1995]		
1-(2,2-Difluoroethoxy)-1,1,2,2,2-pentafluoroethane	171182-95-9	HFE-347mcf2	CHF <sub>2</sub> CH <sub>2</sub> OCF <sub>2</sub> CF <sub>3</sub>	A				[Blowers et al., 2007]		
				E	296	700 - 1500	30.2	[Imasu et al., 1995]		
1,1,2,2-Tetrafluoro-1-(2,2,2-trifluoroethoxy)ethane	406-78-0	HFE-347pcf2	CHF <sub>2</sub> CF <sub>2</sub> OCH <sub>2</sub> CF <sub>3</sub>	A				[Blowers et al., 2007]		
				E	298	500 - 1600	32.2	[Heathfield et al., 1998]		
1,1,1,2,3,3,3-Heptafluoro-2-methoxypropane	22052-84-2	HFE-347mmy1	(CF <sub>3</sub> ) <sub>2</sub> CFOCH <sub>3</sub>	A				[Blowers et al., 2007]		
				E	296	700 - 1500	28.6	[Imasu et al., 1995]		
1,1,1,2,3,3,3-Hexafluoro-3-methoxypropane	382-34-3	HFE-356mec3	CH <sub>3</sub> OCF <sub>2</sub> CHFCF <sub>3</sub>	A				[Blowers et al., 2007]		
				E	296	700 - 1500	25.8	[Imasu et al., 1995]		
				A				[Blowers et al., 2007]		
				E	298	500 - 1600	27.2	[Oyaro et al., 2004]		
				E	296	500 - 1500	28.1	[Sihra et al., 2001]		
				E	295	500 - 1600	27.7	[Orkin et al., 1999]		
				E				[Wallington et al., 1998]		
1-(2,2-Difluoroethoxy)-1,1,2,2-tetrafluoroethane	50807-77-7	HFE-356pcf2	CHF <sub>2</sub> CH <sub>2</sub> OCF <sub>2</sub> CHF <sub>2</sub>	A				[Blowers et al., 2007]		
				E	296	700 - 1500	24.9	[Imasu et al., 1995]		
3-(Difluoromethoxy)-1,1,2,2-tetrafluoropropane	35042-99-0	HFE-356pcf3	CHF <sub>2</sub> OCH <sub>2</sub> CF <sub>2</sub> CHF <sub>2</sub>	A				[Blowers et al., 2007]		
				E	296	700 - 1500	24.8	[Imasu et al., 1995]		
1,1,2,2,3,3-Hexafluoro-1-methoxypropane	160620-20-2	HFE-356pcc3	CH <sub>3</sub> OCF <sub>2</sub> CF <sub>2</sub> CHF <sub>2</sub>	A				[Blowers et al., 2007]		
				E	296	700 - 1500	23.4	[Imasu et al., 1995]		
1,1,1,3,3,3-Hexafluoro-2-methoxypropane	13171-18-1	HFE-356mmz1	(CF <sub>3</sub> ) <sub>2</sub> CHOCH <sub>3</sub>	A				[Blowers et al., 2007]		
				E	298	475 - 1550	25.8	[Oyaro et al., 2004]		
				E	296	700 - 1500	25.7	[Imasu et al., 1995]		
1,1,1,2,2-Pentafluoro-3-methoxypropane	378-16-5	HFE-365mcf3	CF <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> OCH <sub>3</sub>	E	296	650 - 1500	20.7	[Thomsen et al., 2011]		
				A				[Blowers et al., 2007]		
				E	298	490 - 1525	19.5	[Oyaro et al., 2004]		
				E	296	700 - 1500	19.6	[Imasu et al., 1995]		
1-Ethoxy-1,1,2,2,2-pentafluoroethane	22052-81-9	HFE-365mcf2	CF <sub>3</sub> CF <sub>2</sub> OCH <sub>2</sub> CH <sub>3</sub>	A		96 - 1520	27.8	[Bravo et al., 2011a]		
1-Ethoxy-1,1,2,2-tetrafluoroethane	512-51-6	HFE-374pc2	CHF <sub>2</sub> CF <sub>2</sub> OCH <sub>2</sub> CH <sub>3</sub>	A				[Blowers et al., 2007]		
				E	298	500 - 1600	20.9	[Heathfield et al., 1998]		
				E	296	700 - 1500	20.7	[Imasu et al., 1995]		
4,4,4-Trifluorobutan-1-ol	461-18-7		CF <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CH <sub>2</sub> OH	E	298	500 - 4000	10.6	[Jimenez et al., 2010]		
1,1,1,3,3,3-Hexafluoro-2-(trifluoromethyl)-2-propanol	2378-02-1		(CF <sub>3</sub> ) <sub>3</sub> COH	E	296	700 - 1500	37.4	[Imasu et al., 1995]		
2,2,3,3,4,4,5,5-Octafluorocyclopentanol	16621-87-7		-(CF <sub>2</sub> ) <sub>4</sub> CH(OH)-	E	296	700 - 1500	21.1	[Imasu et al., 1995]		

1-(Difluoromethoxy)-2-(difluoromethoxy)difluoromethoxy-1,1,2,2-tetrafluoroethane	188690-77-9	HFE-43-10pccc124 (H-Galden 1040x, HG-11)	CHF <sub>2</sub> OCF <sub>2</sub> OC <sub>2</sub> F <sub>4</sub> OCHF <sub>2</sub>	A	21 - 2500	80.9	[Bravo et al., 2011a]	
				E	296	700 - 1440	67.9	[Wallington et al., 2009]
				E	296	450 - 1600	66.5	[Sihra et al., 2001]
				E	295	963 - 1587	84.9	[Cavalli et al., 1998]
1,1,1,2,2,3,3,4,4-Nonafluoro-4-methoxybutane	163702-07-6	HFE-449s1 (HFE-7100)	C <sub>4</sub> F <sub>9</sub> OCH <sub>3</sub>	E	296	450 - 2000	65.5	[Christidis et al., 1997]
				A				[Bravo et al., 2011a]
				E	296	450 - 1550	36.0	[Sihra et al., 2001]
	163702-07-6	<i>n</i> -HFE-7100	<i>n</i> -C <sub>4</sub> F <sub>9</sub> OCH <sub>3</sub>	E	295	700 - 1400	34.4	[Bravo et al., 2010a]
				E				[Wallington et al., 1997]
				A		35 - 1501	36.0	[Bravo et al., 2011a]
163702-08-7	<i>i</i> -HFE-7100	<i>i</i> -C <sub>4</sub> F <sub>9</sub> OCH <sub>3</sub>	A	296	450 - 1520	33.7	[Sihra et al., 2001]	
			A		59 - 1501	39.3	[Bravo et al., 2011a]	
			E				[Blowers et al., 2007]	
1-Ethoxy-1,1,2,2,3,3,4,4,4-nonafluorobutane	163702-05-4	HFE-569sf2 (HFE-7200)	C <sub>4</sub> F <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	A	296	450 - 1500	37.6	[Sihra et al., 2001]
				E				[Bravo et al., 2011a]
				E	296	500 - 1500	37.1	[Sihra et al., 2001]
	163702-05-4	<i>n</i> -HFE-7200	<i>n</i> -C <sub>4</sub> F <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	E		700 - 1400	38.5	[Bravo et al., 2010a]
				E				[Christensen et al., 1998]
				A		31 - 1519	38.1	[Bravo et al., 2011a]
163702-06-5	<i>i</i> -HFE-7200	<i>i</i> -C <sub>4</sub> F <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	A				[Blowers et al., 2007]	
			A		37 - 1519	41.4	[Bravo et al., 2011a]	
			E				[Blowers et al., 2007]	
Bis(difluoromethoxy)difluoromethane	78522-47-1	HFE-236ca12 (HG-10)	CHF <sub>2</sub> OCF <sub>2</sub> OCHF <sub>2</sub>	E	296	450 - 1400	32.7	[Sihra et al., 2001]
				A		36 - 2500	47.1	[Bravo et al., 2011a]
				E	298	25 - 3250	44.9	[Myhre et al., 1999]
				E	295	978 - 1584	51.9	[Cavalli et al., 1998]
1,2-Bis(difluoromethoxy)-1,1,2,2-tetrafluoroethane	188690-78-0	HFE-338pcc13 (HG-01)	CHF <sub>2</sub> OCF <sub>2</sub> CF <sub>2</sub> OCHF <sub>2</sub>	A		28 - 2500	53.6	[Bravo et al., 2011a]
				E	298	25 - 3250	54.7	[Myhre et al., 1999]
				E	295	930 - 1501	60.4	[Cavalli et al., 1998]
				E	296	700 - 1500	25.4	[Imasu et al., 1995]
1,1,1,3,3,3-Hexafluoropropan-2-ol	920-66-1		(CF <sub>3</sub> ) <sub>2</sub> CHOH					
1-(Difluoromethoxy)-2-(2-(difluoromethoxy)-1,1,2,2-tetrafluoroethoxy)-1,1,2,2-tetrafluoroethane	205367-61-9	HG-02	HF <sub>2</sub> C-(OCF <sub>2</sub> CF <sub>2</sub> ) <sub>2</sub> -OCF <sub>2</sub> H	A		20 - 2500	80.4	[Bravo et al., 2011a]
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-Hexadecafluoro-2,5,8,11-tetraoxadodecane	173350-37-3	HG-03	HF <sub>2</sub> C-(OCF <sub>2</sub> CF <sub>2</sub> ) <sub>3</sub> -OCF <sub>2</sub> H	A		17 - 2500	114.1	[Bravo et al., 2011a]
(Difluoromethoxy)((difluoromethoxy)difluoromethoxy)difluoromethane	249932-25-0	HG-20	HF <sub>2</sub> C-(OCF <sub>2</sub> ) <sub>2</sub> -OCF <sub>2</sub> H	A		35 - 2500	70.3	[Bravo et al., 2011a]
1,1,3,3,5,5,7,7,8,8,10,10-Dodecafluoro-2,4,6,9-tetraoxadecane	249932-26-1	HG-21	HF <sub>2</sub> C-OCF <sub>2</sub> CF <sub>2</sub> OCF <sub>2</sub> OCF <sub>2</sub> O-CF <sub>2</sub> H	A		24 - 2500	108.0	[Bravo et al., 2011a]
1,1,3,3,5,5,7,7,9,9-Decafluoro-2,4,6,8-tetraoxanonane	188690-77-9	HG-30	HF <sub>2</sub> C-(OCF <sub>2</sub> ) <sub>3</sub> -OCF <sub>2</sub> H	A		30 - 2500	103.3	[Bravo et al., 2011a]

1-Ethoxy-1,1,2,2,3,3,3-heptafluoropropane	22052-86-4		CF <sub>3</sub> CF <sub>2</sub> CF <sub>2</sub> OCH <sub>2</sub> CH <sub>3</sub>	A		67 - 1519	33.0	[Bravo et al., 2011a]
(2,2,2-Trifluoroethoxy)ethene	406-90-6	Fluoroxene	CF <sub>3</sub> CH <sub>2</sub> OCH=CH <sub>2</sub>	A		47 - 2500	23.5	[Bravo et al., 2011a]
1,1,2,2-Tetrafluoro-1-(fluoromethoxy)ethane	37031-31-5		CH <sub>2</sub> FOCF <sub>2</sub> CF <sub>2</sub> H	A		43 - 2500	25.0	[Bravo et al., 2011a]
2-Ethoxy-3,3,4,4,5-pentafluorotetrahydro-2,5-bis[1,2,2,2-tetrafluoro-1-(trifluoromethyl)ethyl]-furan	920979-28-8		C <sub>12</sub> H <sub>5</sub> F <sub>19</sub> O <sub>2</sub>	E	294	700 - 1400	55.9	[Javadi et al., 2007]
Fluoro(methoxy)methane	460-22-0		CH <sub>3</sub> OCH <sub>2</sub> F	A				[Blowers et al., 2008a]
Difluoro(methoxy)methane	359-15-9		CH <sub>3</sub> OCHF <sub>2</sub>	A				[Blowers et al., 2008a]
				A				[Blowers et al., 2007]
Fluoro(fluoromethoxy)methane	462-51-1		CH <sub>2</sub> FOCH <sub>2</sub> F	A				[Blowers et al., 2008a]
Difluoro(fluoromethoxy)methane	461-63-2		CH <sub>2</sub> FOCHF <sub>2</sub>	A				[Blowers et al., 2008a]
Trifluoro(fluoromethoxy)methane	2261-01-0		CH <sub>2</sub> FOCF <sub>3</sub>	A				[Blowers et al., 2008a]
1,1,2,2-Tetrafluoro-1,2-dimethoxyethane	73287-23-7	HG <sup>1</sup> -01	CH <sub>3</sub> OCF <sub>2</sub> CF <sub>2</sub> OCH <sub>3</sub>	A		16 - 2500	29.5	[Bravo et al., 2011a]
				E	296	200 - 1800	23.0	[Andersen et al., 2004]
1,1,2,2-Tetrafluoro-1-methoxy-2-(1,1,2,2-tetrafluoro-2-methoxyethoxy)ethane	485399-46-0	HG <sup>1</sup> -02	CH <sub>3</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>2</sub> CH <sub>3</sub>	A		29 - 2500	58.2	[Bravo et al., 2011a]
				E	296	200 - 1800	45.5	[Andersen et al., 2004]
3,3,4,4,6,6,7,7,9,9,10,10-Dodecafluoro-2,5,8,11-tetraoxadodecane	485399-48-2	HG <sup>1</sup> -03	CH <sub>3</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>3</sub> CH <sub>3</sub>	A		20 - 2500	82.7	[Bravo et al., 2011a]
				E	296	200 - 1800	63.4	[Andersen et al., 2004]
Difluorodimethoxymethane	54796-90-6	HG <sup>1</sup> -10	CH <sub>3</sub> OCF <sub>2</sub> OCH <sub>3</sub>	A		64 - 2500	26.1	[Bravo et al., 2011a]
		HG <sup>1</sup> -20	CH <sub>3</sub> O(CF <sub>2</sub> O) <sub>2</sub> CH <sub>3</sub>	A		49 - 2500	51.8	[Bravo et al., 2011a]
		HG <sup>1</sup> -30	CH <sub>3</sub> O(CF <sub>2</sub> O) <sub>3</sub> CH <sub>3</sub>	A		41 - 2500	78.8	[Bravo et al., 2011a]
1,1,1,2,3,3-Hexafluoro-3-(trifluoromethoxy)propane	428454-68-6	HFE-329me3	CF <sub>3</sub> CFHCF <sub>2</sub> OCF <sub>3</sub>	A				[Blowers et al., 2007]
				E	296	670 - 1450	42.4	[Wallington et al., 2004]
1-(Difluoromethoxy)-1,1,2,3,3,3-hexafluoropropane	56860-85-6	HFE-338mec3	CF <sub>3</sub> CFHCF <sub>2</sub> OCF <sub>2</sub> H	A				[Blowers et al., 2007]
				E	298	620 - 1450	34.2	[Oyaro et al., 2005]
				E	296	680 - 1450	36.3	[Wallington et al., 2004]
3,3,4,4,5,5,6,6,7,7,7-Undecafluoroheptan-1-ol	185689-57-0		CF <sub>3</sub> (CF <sub>2</sub> ) <sub>4</sub> CH <sub>2</sub> CH <sub>2</sub> OH	E	296	670 - 1510	26.8	[Waterland et al., 2005]
3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-Pentadecafluorononan-1-ol	755-02-2		CF <sub>3</sub> (CF <sub>2</sub> ) <sub>6</sub> CH <sub>2</sub> CH <sub>2</sub> OH	E	296	600 - 1480	30.9	[Waterland et al., 2005]
3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-Nonadecafluoroundecan-1-ol	87017-97-8		CF <sub>3</sub> (CF <sub>2</sub> ) <sub>8</sub> CH <sub>2</sub> CH <sub>2</sub> OH	E	296	645 - 1450	24.7	[Waterland et al., 2005]
2-Chloro-1,1,2-trifluoro-1-methoxyethane	425-87-6		CH <sub>3</sub> OCF <sub>2</sub> CHFCI	E	298	800 - 1500	17.0	[Dalmaso et al., 2006]
1-(Difluoro(trifluoromethoxy)methoxy)-1,1,2,3,3,3-hexafluoro-2-(trifluoromethoxy)propane	1309353-34-1	PFPME (perfluoropolymethylisopropyl)	CF <sub>3</sub> OCF(CF <sub>3</sub> )CF <sub>2</sub> OCF <sub>2</sub> OCF <sub>3</sub>	E	296	650 - 1500	59.2	[Young et al., 2006]
1,1,2-Trifluoro-2-(trifluoromethoxy)ethene	1187-93-5	HFE-216	CF <sub>3</sub> OCF=CF <sub>2</sub>	E		890 - 1865	29.8	[Mashino et al., 2000]
Trifluoro(trifluoromethoxy)methane	1479-49-8		CF <sub>3</sub> OCF <sub>3</sub>	A				[Blowers et al., 2008a]
Trifluoromethyl formate	85358-65-2		HCOOCF <sub>3</sub>	A		89 - 2500	30.9	[Bravo et al., 2011b]
Perfluoroethyl formate	313064-40-3		HCOOCF <sub>2</sub> CF <sub>3</sub>	A		59 - 1847	35.6	[Bravo et al., 2011b]
Perfluoropropyl formate	271257-42-2		HCOOCF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	A		64 - 1847	41.2	[Bravo et al., 2011b]
Perfluorobutyl formate	197218-56-7		HCOOCF <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	A		37 - 1847	46.6	[Bravo et al., 2011b]
2,2,2-Trifluoroethyl formate	32042-38-9		HCOOCH <sub>2</sub> CF <sub>3</sub>	A		24 - 1808	25.0	[Bravo et al., 2011b]

3,3,3-Trifluoropropyl formate	1344118-09-7		HCOOCH <sub>2</sub> CH <sub>2</sub> CF <sub>3</sub>	A	37 - 1806	26.1	[Bravo et al., 2011b]	
1,2,2,2-Tetrafluoroethyl formate	481631-19-0		HCOOCHF <sub>2</sub> CF <sub>3</sub>	A	41 - 2500	29.2	[Bravo et al., 2011b]	
1,1,1,3,3,3-Hexafluoropropan-2-yl formate	856766-70-6		HCOOCH(CF <sub>3</sub> ) <sub>2</sub>	A	37 - 2500	36.5	[Bravo et al., 2011b]	
Perfluorobutyl acetate	209597-28-4		CH <sub>3</sub> COOCF <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	A	35 - 2500	49.8	[Bravo et al., 2011b]	
Perfluoropropyl acetate	1344118-10-0		CH <sub>3</sub> COOCF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	A	60 - 2500	44.4	[Bravo et al., 2011b]	
Perfluoroethyl acetate	343269-97-6		CH <sub>3</sub> COOCF <sub>2</sub> CF <sub>3</sub>	A	52 - 2500	38.6	[Bravo et al., 2011b]	
Trifluoromethyl acetate	74123-20-9		CH <sub>3</sub> COOCF <sub>3</sub>	A	71 - 2500	34.0	[Bravo et al., 2011b]	
Methyl carbonofluoridate	1538-06-3		FCOOCH <sub>3</sub>	A	118 - 2500	18.3	[Bravo et al., 2011b]	
Fluoromethyl carbonofluoridate	2838-04-2		FCOOCFH <sub>2</sub>	A	29 - 2500	23.5	[Bravo et al., 2011b]	
Difluoromethyl carbonofluoridate	70411-09-5		FCOOCF <sub>2</sub> H	A	37 - 2500	30.5	[Bravo et al., 2011b]	
Trifluoromethyl carbonofluoridate	3299-24-9		FCOOCF <sub>3</sub>	A	77 - 1928	37.1	[Bravo et al., 2011b]	
Perfluoroethyl carbonofluoridate	623950-74-3		FCOOCF <sub>2</sub> CF <sub>3</sub>	A	49 - 1928	41.7	[Bravo et al., 2011b]	
2,2,2-Trifluoroethyl carbonofluoridate	112915-23-8		FCOOCH <sub>2</sub> CF <sub>3</sub>	A	0 - 2500	29.9	[Bravo et al., 2011b]	
1,1-Difluoroethyl carbonofluoridate	1344118-11-1		FCOOCF <sub>2</sub> CH <sub>3</sub>	A	76 - 2500	32.2	[Bravo et al., 2011b]	
Perfluoropropyl carbonofluoridate	1344118-12-2		FCOOCF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>	A	0 - 1928	47.4	[Bravo et al., 2011b]	
Trifluoromethyl 2,2,2-trifluoroacetate	30410-93-6		CF <sub>3</sub> COOCF <sub>3</sub>	A	22 - 1883	43.2	[Bravo et al., 2011b]	
Perfluoroethyl 2,2,2-trifluoroacetate	206436-37-5		CF <sub>3</sub> COOCF <sub>2</sub> CF <sub>3</sub>	A	19 - 1883	47.5	[Bravo et al., 2011b]	
1,1-Difluoroethyl 2,2,2-trifluoroacetate	1344118-13-3		CF <sub>3</sub> COOCF <sub>2</sub> CH <sub>3</sub>	A	21 - 1873	38.0	[Bravo et al., 2011b]	
1,1,1,3,3,3-Hexafluoropropan-2-yl 2,2,2-trifluoroacetate	42031-15-2		CF <sub>3</sub> COOCH(CF <sub>3</sub> ) <sub>2</sub>	A	24 - 1858	48.5	[Bravo et al., 2011b]	
Vinyl 2,2,2-trifluoroacetate	433-28-3		CF <sub>3</sub> COOCH=CH <sub>2</sub>	A	35 - 1734	27.6	[Bravo et al., 2011b]	
Ethyl 2,2,2-trifluoroacetate	383-63-1		CF <sub>3</sub> COOCH <sub>2</sub> CH <sub>3</sub>	A	49 - 1834	25.5	[Bravo et al., 2011b]	
2,2,2-Trifluoroethyl 2,2,2-trifluoroacetate	407-38-5		CF <sub>3</sub> COOCH <sub>2</sub> CF <sub>3</sub>	A	23 - 1844	37.0	[Bravo et al., 2011b]	
Allyl 2,2,2-trifluoroacetate	383-67-5		CF <sub>3</sub> COOCH <sub>2</sub> CHCH <sub>2</sub>	A	22 - 1833	28.0	[Bravo et al., 2011b]	
Methyl 2,2,2-trifluoroacetate	431-47-0		CF <sub>3</sub> COOCH <sub>3</sub>	A	24 - 1839	23.2	[Bravo et al., 2011b]	
Phenyl 2,2,2-trifluoroacetate	500-73-2		CF <sub>3</sub> COOPh	A	23 - 1842	31.9	[Bravo et al., 2011b]	
Methyl 2-fluoroacetate	453-18-9		H <sub>2</sub> CF <sub>2</sub> COOCH <sub>3</sub>	A	63 - 1805	14.0	[Bravo et al., 2011b]	
Difluoromethyl 2,2-difluoroacetate	2002-63-3		HCF <sub>2</sub> COOCHF <sub>2</sub>	A	31 - 1855	30.2	[Bravo et al., 2011b]	
Methyl 2,2-difluoroacetate	433-53-4		HCF <sub>2</sub> COOCH <sub>3</sub>	A	21 - 1836	17.2	[Bravo et al., 2011b]	
Difluoromethyl 2,2,2-trifluoroacetate	2024-86-4		CF <sub>3</sub> COOCHF <sub>2</sub>	A	27 - 1857	36.1	[Bravo et al., 2011b]	
2,2,3,3,4,4,4-Heptafluorobutan-1-ol	375-01-9		C <sub>3</sub> F <sub>7</sub> CH <sub>2</sub> OH	E	700 - 1400	21.4	[Bravo et al., 2010a]	
1,1,2-Trifluoro-2-(trifluoromethoxy)-ethane	84011-06-3		CHF <sub>2</sub> CHFOCF <sub>3</sub>	A			[Blowers et al., 2007]	
				E	298	465 - 1600	28.2	[Oyaro et al., 2005]
1-Ethoxy-1,1,2,3,3,3-hexafluoropropane	380-34-7		CF <sub>3</sub> CHFCF <sub>2</sub> OCH <sub>2</sub> CH <sub>3</sub>	A			[Blowers et al., 2007]	
				E	298	675 - 1450	27.4	[Oyaro et al., 2005]
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3330-15-2		CF <sub>3</sub> CF <sub>2</sub> CF <sub>2</sub> OCHFCF <sub>3</sub>	A			[Blowers et al., 2007]	
				E	298	500 - 1450	43.7	[Oyaro et al., 2005]
2,2,3,3-Tetrafluoro-1-propanol	76-37-9		CHF <sub>2</sub> CF <sub>2</sub> CH <sub>2</sub> OH	E	298	600 - 4000	19.2	[Antiñolo et al., 2012b]
				E	298	505 - 1500	13.6	[Sellevåg et al., 2007]
2,2,3,4,4,4-Hexafluoro-1-butanol	382-31-0		CF <sub>3</sub> CHFCF <sub>2</sub> CH <sub>2</sub> OH	E	298	450 - 1500	29.2	[Sellevåg et al., 2007]
2,2,3,3,4,4,4-Heptafluoro-1-butanol	375-01-9		CF <sub>3</sub> CF <sub>2</sub> CF <sub>2</sub> CH <sub>2</sub> OH	E	298	450 - 1500	21.4	[Sellevåg et al., 2007]
1,1,2,2-Tetrafluoro-3-methoxy-propane	60598-17-6		CHF <sub>2</sub> CF <sub>2</sub> CH <sub>2</sub> OCH <sub>3</sub>	A			[Blowers et al., 2007]	
				E	298	500 - 1520	13.9	[Oyaro et al., 2004]
1,1,1,2,2,4,5,5,5-Nonafluoro-4-(trifluoromethyl)-3-pentanone	756-13-8	perfluoro-2-methyl-3-pentanone	CF <sub>3</sub> CF <sub>2</sub> C(O)CF(CF <sub>3</sub> ) <sub>2</sub>	E	298	480 - 1880	40.5	[D'Anna et al., 2005]



3,3,3-Trifluoro-propanal	460-40-2	CF <sub>3</sub> CH <sub>2</sub> CHO	E	298	600 - 1850	16.7	[Antiñolo et al., 2011]
			E	298	400 - 1900	14.2	[Sellevag et al., 2004a]
4,4,4-Trifluorobutanal	406-87-1	CF <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CHO	E		1000 - 1850	17.0	[Antiñolo et al., 2012a]
2-Fluoroethanol	371-62-0	CH <sub>2</sub> FCH <sub>2</sub> OH	E	293	100 - 1600	6.2	[Sellevag et al., 2004b]
2,2-Difluoroethanol	359-13-7	CHF <sub>2</sub> CH <sub>2</sub> OH	E	293	100 - 1600	8.0	[Sellevag et al., 2004b]
2,2,2-Trifluoroethanol	75-89-8	CF <sub>3</sub> CH <sub>2</sub> OH	E	293	100 - 1600	15.9	[Sellevag et al., 2004b]
			E	296	700 - 1500	14.3	[Imasu et al., 1995]
1,1'-Oxybis[2-(difluoromethoxy)-1,1,2,2-tetrafluoroethane	205367-61-9	HCF <sub>2</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>2</sub> CF <sub>2</sub> H	E	295	650 - 1500	92.5	[Andersen et al., 2010b]
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-hexadecafluoro-2,5,8,11-Tetraoxadecane	173350-37-3	HCF <sub>2</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>3</sub> CF <sub>2</sub> H	E	295	650 - 1500	85.2	[Andersen et al., 2010b]
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12,13,13,15,15-eicosafluoro-2,5,8,11,14-Pentaaxapentadecane	173350-38-4	HCF <sub>2</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>4</sub> CF <sub>2</sub> H	E	295	650 - 1500	70.2	[Andersen et al., 2010b]

4410 <sup>1</sup> Type of data: E, Experimental; A, Ab initio.

4411 <sup>2</sup> Integrated absorption cross-section in units of 10<sup>-17</sup> cm<sup>2</sup> molecule<sup>-1</sup> cm<sup>-1</sup> for the wavenumber interval specified.

4412 <sup>3</sup> Database: H, HITRAN 2008; G, GEISA 2009.

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4416 **Table 15.** Lifetimes, radiative efficiencies and direct GWPs (relative to CO<sub>2</sub>) for halogenated alcohols and  
 4417 ethers. Compounds in bold either have significant current atmospheric concentrations or a clear potential for  
 4418 future emissions. Recommended RE and GWP 100-yr values are indicated in bold. Lifetimes are from *WMO*  
 4419 [2011] except those in italic (see text for details). RE and GWP values in italic are based on previous  
 4420 publications (see text for details).

Acronym / name	Formula	Lifetime (yr)	Radiative Efficiency (W m <sup>-2</sup> ppb <sup>-1</sup> )			GWP 100-yr	
			AR4	This study – const. profile	This study – lifetime corr.	AR4	This study – lifetime corr.
<b>HFE-125</b>	CHF <sub>2</sub> OCF <sub>3</sub>	119.0	0.44	0.41	<b>0.41</b>	14,900	<b>12,400</b>
<b>HFE-134 (HG-00)</b>	CHF <sub>2</sub> OCHF <sub>2</sub>	24.4	0.45	0.46	<b>0.44</b>	6,320	<b>5,560</b>
<b>HFE-143a</b>	CH <sub>3</sub> OCF <sub>3</sub>	4.8	0.27	0.19	<b>0.18</b>	756	<b>523</b>
<b>HFE-227ea</b>	CF <sub>3</sub> CHFOCF <sub>3</sub>	51.6	0.40	0.45	<b>0.44</b>	1,540	<b>6,450</b>
HCFE-235ca2 (enflurane)	CHF <sub>2</sub> OCF <sub>2</sub> CHF Cl	4.3		0.45	<b>0.41</b>		<b>583</b>
<b>HCFE-235da2 (isoflurane)</b>	CHF <sub>2</sub> OCHClCF <sub>3</sub>	3.5	0.38	0.47	<b>0.42</b>	350	<b>491</b>
HFE-236ca	CHF <sub>2</sub> OCF <sub>2</sub> CHF <sub>2</sub>	20.8		<i>0.58</i>	<i>0.56</i>		<i>4,240</i>
<b>HFE-236ea2 (desflurane)</b>	CHF <sub>2</sub> OCHF <sub>2</sub> CF <sub>3</sub>	10.8	0.44	0.47	<b>0.45</b>	989	<b>1,790</b>
<b>HFE-236fa</b>	CF <sub>3</sub> CH <sub>2</sub> OCF <sub>3</sub>	7.5	0.34	0.38	<b>0.36</b>	487	<b>979</b>
<b>HFE-245cb2</b>	CF <sub>3</sub> CF <sub>2</sub> OCH <sub>3</sub>	4.9	0.32	0.36	<b>0.33</b>	708	<b>654</b>
<b>HFE-245fa1</b>	CHF <sub>2</sub> CH <sub>2</sub> OCF <sub>3</sub>	6.6	0.30	0.33	<b>0.31</b>	286	<b>828</b>
<b>HFE-245fa2</b>	CHF <sub>2</sub> OCH <sub>2</sub> CF <sub>3</sub>	5.5	0.31	0.39	<b>0.36</b>	659	<b>812</b>
<b>2,2,3,3,3-Pentafluoropropan-1-ol</b>	CF <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> OH	0.3	0.24	0.27	<b>0.14</b>	42	<b>19</b>
<b>HFE-254cb1</b>	CH <sub>3</sub> OCF <sub>2</sub> CHF <sub>2</sub>	2.5	0.28	0.30	<b>0.26</b>	359	<b>301</b>
<b>HFE-263fb1</b>	CF <sub>3</sub> CH <sub>2</sub> OCH <sub>3</sub>	23.0 days	0.20	0.21	<b>0.04</b>	11	<b>1</b>
HFE-263ml	CF <sub>3</sub> OCH <sub>2</sub> CH <sub>3</sub>	<i>0.4</i>		0.22	<b>0.13</b>		<b>29</b>
3,3,3-Trifluoropropan-1-ol	CF <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> OH	<i>12.0 days</i>		0.20	<b>0.02</b>		<b>0</b>
<b>HFE-329mcc2</b>	CHF <sub>2</sub> CF <sub>2</sub> OCF <sub>2</sub> CF <sub>3</sub>	22.5	0.49	0.54	<b>0.53</b>	919	<b>3,070</b>
<b>HFE-338mmz1</b>	(CF <sub>3</sub> ) <sub>2</sub> CHOCHF <sub>2</sub>	21.2	0.41	0.45	<b>0.44</b>	380	<b>2,620</b>
<b>HFE-338mcf2</b>	CF <sub>3</sub> CH <sub>2</sub> OCF <sub>2</sub> C F <sub>3</sub>	7.5	0.43	0.47	<b>0.44</b>	552	<b>929</b>
Sevoflurane (HFE-347mmz1)	(CF <sub>3</sub> ) <sub>2</sub> CHOCH <sub>2</sub> F	2.2		0.37	<b>0.32</b>		<b>216</b>
<b>HFE-347mcc3 (HFE-7000)</b>	CH <sub>3</sub> OCF <sub>2</sub> CF <sub>2</sub> C F <sub>3</sub>	5.0	0.34	0.37	<b>0.35</b>	575	<b>530</b>
<b>HFE-347mcf2</b>	CHF <sub>2</sub> CH <sub>2</sub> OCF <sub>2</sub> CF <sub>3</sub>	6.6	0.41	0.45	<b>0.42</b>	374	<b>854</b>
<b>HFE-347pcf2</b>	CHF <sub>2</sub> CF <sub>2</sub> OCH <sub>2</sub> CF <sub>3</sub>	6.0	0.25	<i>0.52</i>	<i>0.48</i>	580	<i>889</i>
<b>HFE-347mmy1</b>	(CF <sub>3</sub> ) <sub>2</sub> CFOCH <sub>3</sub>	3.7	0.31	0.35	<b>0.32</b>	343	<b>363</b>
<b>HFE-356mec3</b>	CH <sub>3</sub> OCF <sub>2</sub> CHFC F <sub>3</sub>	3.8	0.30	0.33	<b>0.30</b>	101	<b>387</b>
HFE-356mff2	CF <sub>3</sub> CH <sub>2</sub> OCH <sub>2</sub> C F <sub>3</sub>	105.0 days		0.36	<b>0.17</b>		<b>17</b>
<b>HFE-356pcf2</b>	CHF <sub>2</sub> CH <sub>2</sub> OCF <sub>2</sub> CHF <sub>2</sub>	5.7	0.37	0.40	<b>0.37</b>	265	<b>719</b>
<b>HFE-356pcf3</b>	CHF <sub>2</sub> OCH <sub>2</sub> CF <sub>2</sub> CHF <sub>2</sub>	3.5	0.39	0.42	<b>0.38</b>	502	<b>446</b>
<b>HFE-356pcc3</b>	CH <sub>3</sub> OCF <sub>2</sub> CF <sub>2</sub> C	3.8	0.33	0.36	<b>0.32</b>	110	<b>413</b>

<b>HFE-356mmz1</b>	HF <sub>2</sub> (CF <sub>3</sub> ) <sub>2</sub> CHOCH <sub>3</sub>	97.1 days	0.30	0.33	<b>0.15</b>	27	<b>14</b>
<b>HFE-365mcf3</b>	CF <sub>3</sub> CF <sub>2</sub> CH <sub>2</sub> OC H <sub>3</sub>	19.3 days	0.27	0.29	<b>0.05</b>	11	<b>1</b>
HFE-365mcf2	CF <sub>3</sub> CF <sub>2</sub> OCH <sub>2</sub> C H <sub>3</sub>	0.6		0.41	<b>0.26</b>		<b>58</b>
<b>HFE-374pc2</b>	CHF <sub>2</sub> CF <sub>2</sub> OCH <sub>2</sub> CH <sub>3</sub>	5.0	0.25	0.32	<b>0.30</b>	557	<b>627</b>
4,4,4-Trifluorobutan-1-ol	CF <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CH <sub>2</sub> O H	4.0 days		0.12	<b>0.01</b>		<b>0</b>
1,1,1,3,3,3-Hexafluoro-2- (trifluoromethyl)-2- propanol	(CF <sub>3</sub> ) <sub>3</sub> COH			<b>0.38</b>			
<b>2,2,3,3,4,4,5,5- Octafluorocyclopentanol</b>	-(CF <sub>2</sub> ) <sub>4</sub> CH(OH)-	0.3	0.30	0.33	<b>0.16</b>	73	<b>13</b>
<b>HFE-43-10pccc124 (H- Galden 1040x, HG-11)</b>	CHF <sub>2</sub> OCF <sub>2</sub> OC <sub>2</sub> F <sub>4</sub> OCHF <sub>2</sub>	13.5	1.37	1.06	<b>1.02</b>	1,870	<b>2,820</b>
<b>HFE-449s1 (HFE-7100)</b>	C <sub>4</sub> F <sub>9</sub> OCH <sub>3</sub>	4.7	0.31	0.40	<b>0.36</b>	297	<b>421</b>
<i>n</i> -HFE-7100	<i>n</i> -C <sub>4</sub> F <sub>9</sub> OCH <sub>3</sub>	4.7		0.46	<b>0.42</b>		<b>486</b>
<i>i</i> -HFE-7100	<i>i</i> -C <sub>4</sub> F <sub>9</sub> OCH <sub>3</sub>	4.7		0.38	<b>0.35</b>		<b>407</b>
<b>HFE-569sf2 (HFE-7200)</b>	C <sub>4</sub> F <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	0.8	0.30	0.44	<b>0.30</b>	59	<b>57</b>
<i>n</i> -HFE-7200	<i>n</i> -C <sub>4</sub> F <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	0.8		0.49	<b>0.35</b>		<b>65</b>
<i>i</i> -HFE-7200	<i>i</i> -C <sub>4</sub> F <sub>9</sub> OC <sub>2</sub> H <sub>5</sub>	0.8		0.36	<b>0.25</b>		<b>44</b>
<b>HFE-236ca12 (HG-10)</b>	CHF <sub>2</sub> OCF <sub>2</sub> OCH F <sub>2</sub>	25.0	0.66	0.67	<b>0.65</b>	2,800	<b>5,350</b>
<b>HFE-338pcc13 (HG-01)</b>	CHF <sub>2</sub> OCF <sub>2</sub> CF <sub>2</sub> OCHF <sub>2</sub>	12.9	0.87	0.89	<b>0.86</b>	1,500	<b>2,910</b>
<b>1,1,1,3,3,3- Hexafluoropropan-2-ol</b>	(CF <sub>3</sub> ) <sub>2</sub> CHOH	1.9	0.28	0.31	<b>0.26</b>	195	<b>182</b>
HG-02	HF <sub>2</sub> C- (OCF <sub>2</sub> CF <sub>2</sub> ) <sub>2</sub> - OCF <sub>2</sub> H	12.9		1.29	<b>1.24</b>		<b>2,730</b>
HG-03	HF <sub>2</sub> C- (OCF <sub>2</sub> CF <sub>2</sub> ) <sub>3</sub> - OCF <sub>2</sub> H	12.9		1.83	<b>1.76</b>		<b>2,850</b>
HG-20	HF <sub>2</sub> C-(OCF <sub>2</sub> ) <sub>2</sub> - OCF <sub>2</sub> H	25.0		0.94	<b>0.92</b>		<b>5,300</b>
HG-21	HF <sub>2</sub> C- OCF <sub>2</sub> CF <sub>2</sub> OCF <sub>2</sub> OCF <sub>2</sub> O-CF <sub>2</sub> H	13.5		1.78	<b>1.71</b>		<b>3,890</b>
HG-30	HF <sub>2</sub> C-(OCF <sub>2</sub> ) <sub>3</sub> - OCF <sub>2</sub> H	25.0		1.69	<b>1.65</b>		<b>7,330</b>
1-Ethoxy-1,1,2,2,3,3,3- heptafluoropropane	CF <sub>3</sub> CF <sub>2</sub> CF <sub>2</sub> OC H <sub>2</sub> CH <sub>3</sub>	0.8		0.41	<b>0.28</b>		<b>61</b>
Fluoroxene	CF <sub>3</sub> CH <sub>2</sub> OCH=C H <sub>2</sub>	3.6 days		0.28	<b>0.01</b>		<b>0</b>
1,1,2,2-Tetrafluoro-1- (fluoromethoxy)ethane	CH <sub>2</sub> FOCF <sub>2</sub> CF <sub>2</sub> H	6.2		0.37	<b>0.34</b>		<b>871</b>
2-Ethoxy-3,3,4,4,5- pentafluorotetrahydro-2,5- bis[1,2,2,2-tetrafluoro-1- (trifluoromethyl)ethyl]- furan	C <sub>12</sub> H <sub>5</sub> F <sub>19</sub> O <sub>2</sub>	1.0		0.66	<b>0.49</b>		<b>56</b>
Fluoro(methoxy)methane	CH <sub>3</sub> OCH <sub>2</sub> F	73.0 days		0.165	<b>0.07</b>		<b>13</b>
Difluoro(methoxy)methan e	CH <sub>3</sub> OCHF <sub>2</sub>	1.1		0.23	<b>0.17</b>		<b>144</b>
Fluoro(fluoromethoxy)me thane	CH <sub>2</sub> FOCH <sub>2</sub> F	0.9		0.27	<b>0.19</b>		<b>130</b>
Difluoro(fluoromethoxy)	CH <sub>2</sub> FOCHF <sub>2</sub>	3.3		0.34	<b>0.30</b>		<b>617</b>

methane								
Trifluoro(fluoromethoxy)	CH <sub>2</sub> FOCF <sub>3</sub>	4.4		0.36	0.33			751
methane								
HG'-01	CH <sub>3</sub> OCF <sub>2</sub> CF <sub>2</sub> O CH <sub>3</sub>	2.0		0.35	0.29			222
HG'-02	CH <sub>3</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) ) <sub>2</sub> CH <sub>3</sub>	2.0		0.67	0.56			236
HG'-03	CH <sub>3</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) ) <sub>3</sub> CH <sub>3</sub>	2.0		0.91	0.76			221
HG'-10	CH <sub>3</sub> OCF <sub>2</sub> OCH <sub>3</sub>				0.26			
HG'-20	CH <sub>3</sub> O(CF <sub>2</sub> O) <sub>2</sub> C H <sub>3</sub>				0.72			
HG'-30	CH <sub>3</sub> O(CF <sub>2</sub> O) <sub>3</sub> C H <sub>3</sub>				1.14			
HFE-329me3	CF <sub>3</sub> CFHCF <sub>2</sub> OC F <sub>3</sub>	40.0		0.48	0.48			4,550
HFE-338mec3	CF <sub>3</sub> CFHCF <sub>2</sub> OC F <sub>2</sub> H				0.51			
3,3,4,4,5,5,6,6,7,7,7- Undecafluoroheptan-1-ol	CF <sub>3</sub> (CF <sub>2</sub> ) <sub>4</sub> CH <sub>2</sub> C H <sub>2</sub> OH	20.0 days		0.37	0.06			0
3,3,4,4,5,5,6,6,7,7,8,8,9,9, 9-Pentadecafluorononan- 1-ol	CF <sub>3</sub> (CF <sub>2</sub> ) <sub>6</sub> CH <sub>2</sub> C H <sub>2</sub> OH	20.0 days		0.41	0.07			0
3,3,4,4,5,5,6,6,7,7,8,8,9,9, 10,10,11,11,11- Nonadecafluoroundecan- 1-ol	CF <sub>3</sub> (CF <sub>2</sub> ) <sub>8</sub> CH <sub>2</sub> C H <sub>2</sub> OH	20.0 days		0.31	0.05			0
2-Chloro-1,1,2-trifluoro- 1-methoxyethane	CH <sub>3</sub> OCF <sub>2</sub> CHFC 1	1.4		0.27	0.21			122
<b>PFPME</b> <b>(perfluoropolymethyliso</b> <b>propyl)</b>	CF <sub>3</sub> OCF(CF <sub>3</sub> )C F <sub>2</sub> OCF <sub>2</sub> OCF <sub>3</sub>	800.0	0.65	0.66	0.65	10,300		9,710
HFE-216	CF <sub>3</sub> OCF=CF <sub>2</sub>	8.4 days		0.30	0.02			0
Trifluoro(trifluoromethox y)methane	CF <sub>3</sub> OCF <sub>3</sub>				0.53			
Trifluoromethyl formate	HCOOCF <sub>3</sub>	3.5		0.35	0.31			588
Perfluoroethyl formate	HCOOCF <sub>2</sub> CF <sub>3</sub>	3.5		0.49	0.44			580
Perfluoropropyl formate	HCOOCF <sub>2</sub> CF <sub>2</sub> C F <sub>3</sub>	2.6		0.58	0.50			376
Perfluorobutyl formate	HCOOCF <sub>2</sub> CF <sub>2</sub> C F <sub>2</sub> CF <sub>3</sub>	3.0		0.63	0.56			392
2,2,2-Trifluoroethyl formate	HCOOCH <sub>2</sub> CF <sub>3</sub>	0.4		0.27	0.16			33
3,3,3-Trifluoropropyl formate	HCOOCH <sub>2</sub> CH <sub>2</sub> CF <sub>3</sub>	0.3		0.27	0.13			17
1,2,2,2-Tetrafluoroethyl formate	HCOOCHFCF <sub>3</sub>	3.2		0.39	0.35			470
1,1,1,3,3,3- Hexafluoropropan-2-yl formate	HCOOCH(CF <sub>3</sub> ) 2	3.2		0.37	0.33			333
Perfluorobutyl acetate	CH <sub>3</sub> COOCF <sub>2</sub> CF 2CF <sub>2</sub> CF <sub>3</sub>	21.9 days		0.70	0.12			2
Perfluoropropyl acetate	CH <sub>3</sub> COOCF <sub>2</sub> CF 2CF <sub>3</sub>	21.9 days		0.60	0.11			2
Perfluoroethyl acetate	CH <sub>3</sub> COOCF <sub>2</sub> CF 3	21.9 days		0.56	0.10			2
Trifluoromethyl acetate	CH <sub>3</sub> COOCF <sub>3</sub>	21.9 days		0.41	0.07			2
Methyl carbonofluoridate	FCOOCH <sub>3</sub>	1.8		0.08	0.07			95
Fluoromethyl	FCOOCHF <sub>2</sub>				0.19			

carbonofluoride					
Difluoromethyl carbonofluoride	FCOOCF <sub>2</sub> H		<b>0.33</b>		
Trifluoromethyl carbonofluoride	FCOOCF <sub>3</sub>		<b>0.32</b>		
Perfluoroethyl carbonofluoride	FCOOCF <sub>2</sub> CF <sub>3</sub>		<b>0.48</b>		
2,2,2-Trifluoroethyl carbonofluoride	FCOOCH <sub>2</sub> CF <sub>3</sub>		<b>0.33</b>		
1,1-Difluoroethyl carbonofluoride	FCOOCF <sub>2</sub> CH <sub>3</sub>	0.3	0.33	<b>0.17</b>	<b>27</b>
Perfluoropropyl carbonofluoride	FCOOCF <sub>2</sub> CF <sub>2</sub> CF <sub>3</sub>		<b>0.53</b>		
Trifluoromethyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCF <sub>3</sub>		<b>0.49</b>		
Perfluoroethyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCF <sub>2</sub> CF <sub>3</sub>		<b>0.62</b>		
1,1-Difluoroethyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCF <sub>2</sub> CH <sub>3</sub>	0.3	0.53	<b>0.27</b>	<b>31</b>
1,1,1,3,3,3-Hexafluoropropan-2-yl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCH(CF <sub>3</sub> ) <sub>2</sub>		<b>0.49</b>		
Vinyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCH=C		<b>0.39</b>		
Ethyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCH <sub>2</sub> CH <sub>3</sub>	21.9 days	0.30	<b>0.05</b>	<b>1</b>
2,2,2-Trifluoroethyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCH <sub>2</sub> CF <sub>3</sub>	54.8 days	0.43	<b>0.15</b>	<b>7</b>
Allyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub>		<b>0.35</b>		
Methyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCH <sub>3</sub>	0.6	0.28	<b>0.18</b>	<b>52</b>
Phenyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOPh		<b>0.39</b>		
Methyl 2-fluoroacetate	H <sub>2</sub> CF <sub>2</sub> COOCH <sub>3</sub>		<b>0.08</b>		
Difluoromethyl 2,2-difluoroacetate	HCF <sub>2</sub> COOCHF <sub>2</sub>		<b>0.44</b>		
Methyl 2,2-difluoroacetate	HCF <sub>2</sub> COOCH <sub>3</sub>	40.1 days	0.19	<b>0.05</b>	<b>3</b>
Difluoromethyl 2,2,2-trifluoroacetate	CF <sub>3</sub> COOCHF <sub>2</sub>	0.3	0.49	<b>0.24</b>	<b>27</b>
2,2,3,3,4,4,4-Heptafluorobutan-1-ol	C <sub>3</sub> F <sub>7</sub> CH <sub>2</sub> OH	0.6	0.32	<b>0.20</b>	<b>34</b>
1,1,2-Trifluoro-2-(trifluoromethoxy)-ethane	CHF <sub>2</sub> CHFOCF <sub>3</sub>	9.8	0.36	<b>0.35</b>	<b>1,240</b>
1-Ethoxy-1,1,2,3,3,3-hexafluoropropane	CF <sub>3</sub> CHFCF <sub>2</sub> OC <sub>2</sub> H <sub>5</sub>	0.4	0.35	<b>0.19</b>	<b>23</b>
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	CF <sub>3</sub> CF <sub>2</sub> CF <sub>2</sub> OC <sub>2</sub> H <sub>4</sub> CF <sub>3</sub>	67.0	0.59	<b>0.58</b>	<b>6,490</b>
2,2,3,3-Tetrafluoro-1-propanol	CHF <sub>2</sub> CF <sub>2</sub> CH <sub>2</sub> OH	91.3 days	0.25	<b>0.11</b>	<b>13</b>
2,2,3,4,4,4-Hexafluoro-1-butanol	CF <sub>3</sub> CHFCF <sub>2</sub> CH <sub>2</sub> OH	94.9 days	0.43	<b>0.19</b>	<b>17</b>
2,2,3,3,4,4,4-Heptafluoro-1-butanol	CF <sub>3</sub> CF <sub>2</sub> CF <sub>2</sub> CH <sub>2</sub> OH	0.3	0.31	<b>0.16</b>	<b>16</b>
1,1,2,2-Tetrafluoro-3-methoxy-propane	CHF <sub>2</sub> CF <sub>2</sub> CH <sub>2</sub> OC <sub>2</sub> H <sub>5</sub>	14.2 days	0.25	<b>0.03</b>	<b>1</b>
<b>Perfluoro-2-methyl-3-</b>	CF <sub>3</sub> CF <sub>2</sub> C(O)CF <sub>3</sub>	7.0 days	0.41	<b>0.03</b>	<b>0</b>

<b>pentanone</b>	CF <sub>3</sub> ) <sub>2</sub>					
3,3,3-Trifluoro-propanal	CF <sub>3</sub> CH <sub>2</sub> CHO	2.0 days	0.16	<b>0.00</b>		<b>0</b>
4,4,4-Trifluorobutanal	CF <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CHO		<b>0.16</b>			
2-Fluoroethanol	CH <sub>2</sub> FCH <sub>2</sub> OH	20.4 days	0.10	<b>0.02</b>		<b>1</b>
2,2-Difluoroethanol	CHF <sub>2</sub> CH <sub>2</sub> OH	40.0 days	0.13	<b>0.04</b>		<b>3</b>
2,2,2-Trifluoroethanol	CF <sub>3</sub> CH <sub>2</sub> OH	0.3	0.20	<b>0.10</b>		<b>20</b>
1,1'-Oxybis[2-(difluoromethoxy)-1,1,2,2-tetrafluoroethane]	HCF <sub>2</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>2</sub> CF <sub>2</sub> H	26.0	1.18	<b>1.15</b>		<b>4,920</b>
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-hexadecafluoro-2,5,8,11-Tetraoxadodecane	HCF <sub>2</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>3</sub> CF <sub>2</sub> H	26.0	1.46	<b>1.43</b>		<b>4,490</b>
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12,13,13,15,15-eicosafuoro-2,5,8,11,14-Pentaoxapentadecane	HCF <sub>2</sub> O(CF <sub>2</sub> CF <sub>2</sub> O) <sub>4</sub> CF <sub>2</sub> H	26.0	1.50	<b>1.46</b>		<b>3,630</b>

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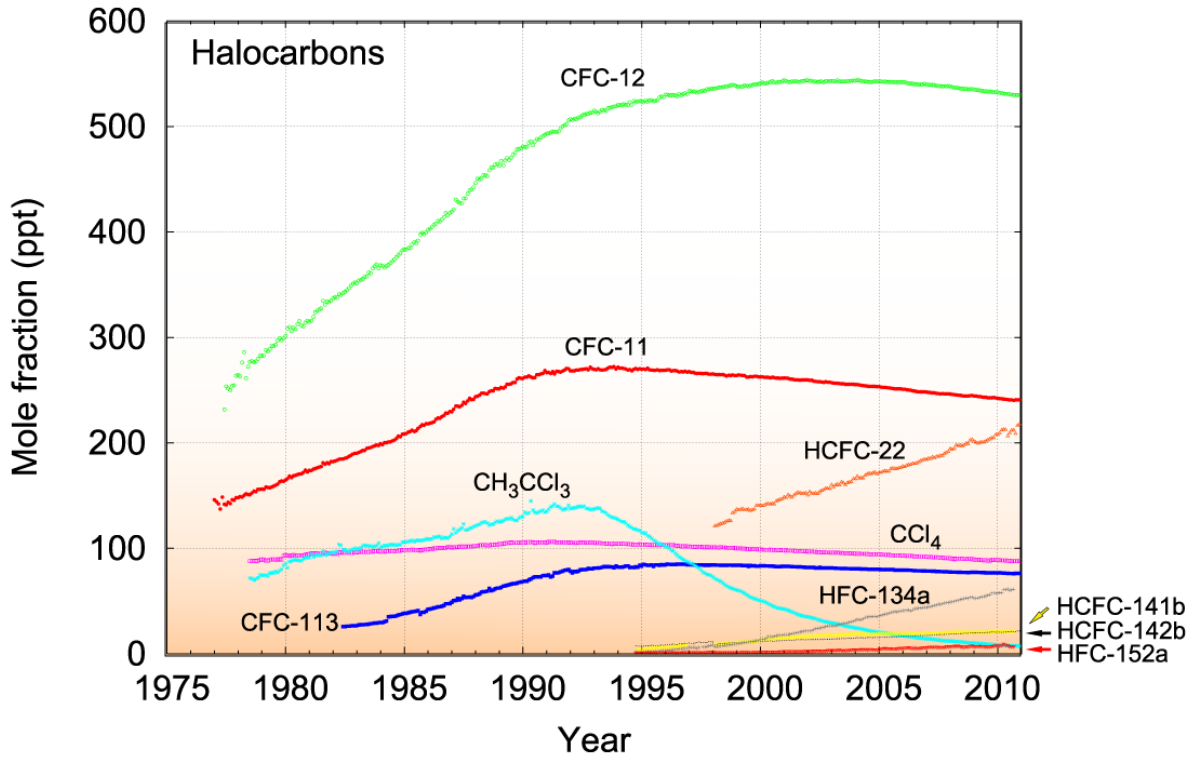
4425 **Table 16.** GWP and GTP for selected gases.

Acronym / name	Formula	Lifetime (yr)	RE (W m <sup>-2</sup> ppb <sup>-1</sup> )	GWP			GTP		
				20-yr	100-yr	500-yr	20-yr	50-yr	100-yr
CFC-11	CCl <sub>3</sub> F	45.0	0.26	6,900	4,660	1,490	6,890	4,890	2,340
CFC-12	CCl <sub>2</sub> F <sub>2</sub>	100.0	0.32	10,800	10,200	4,590	11,300	11,000	8,450
CFC-113	CCl <sub>2</sub> FCClF <sub>2</sub>	85.0	0.30	6,490	5,820	2,390	6,730	6,250	4,470
HCFC-22	CHClF <sub>2</sub>	11.9	0.21	5,280	1,760	503	4,200	832	262
HCFC-141b	CH <sub>3</sub> CCl <sub>2</sub> F	9.2	0.16	2,550	782	223	1,850	271	111
HCFC-142b	CH <sub>3</sub> CClF <sub>2</sub>	17.2	0.19	5,020	1,980	567	4,390	1,370	356
HFC-23	CHF <sub>3</sub>	222.0	0.18	10,800	12,400	8,720	11,500	13,000	12,700
HFC-134a	CH <sub>2</sub> FCF <sub>3</sub>	13.4	0.16	3,710	1,300	371	3,050	703	201
HFC-152a	CH <sub>3</sub> CHF <sub>2</sub>	1.5	0.10	506	138	39	174	24	19
Methyl chloroform	CH <sub>3</sub> CCl <sub>3</sub>	5.0	0.07	578	160	46	317	34	22
Carbon tetrachloride	CCl <sub>4</sub>	26.0	0.17	3,480	1,730	504	3,280	1,570	479
Sulphur hexafluoride	SF <sub>6</sub>	3,200.0	0.57	17,500	23,500	31,500	18,900	23,800	28,200
PFC-14	CF <sub>4</sub>	50,000.0	0.09	4,880	6,630	9,410	5,270	6,690	8,040

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4430 **Figure 1.** Atmospheric concentrations of 10 halocarbons from 1977-2010 averaged over the  
4431 greenhouse gas monitoring network (between 7 and 10 stations) [from *WMO/GAW*, 2011].

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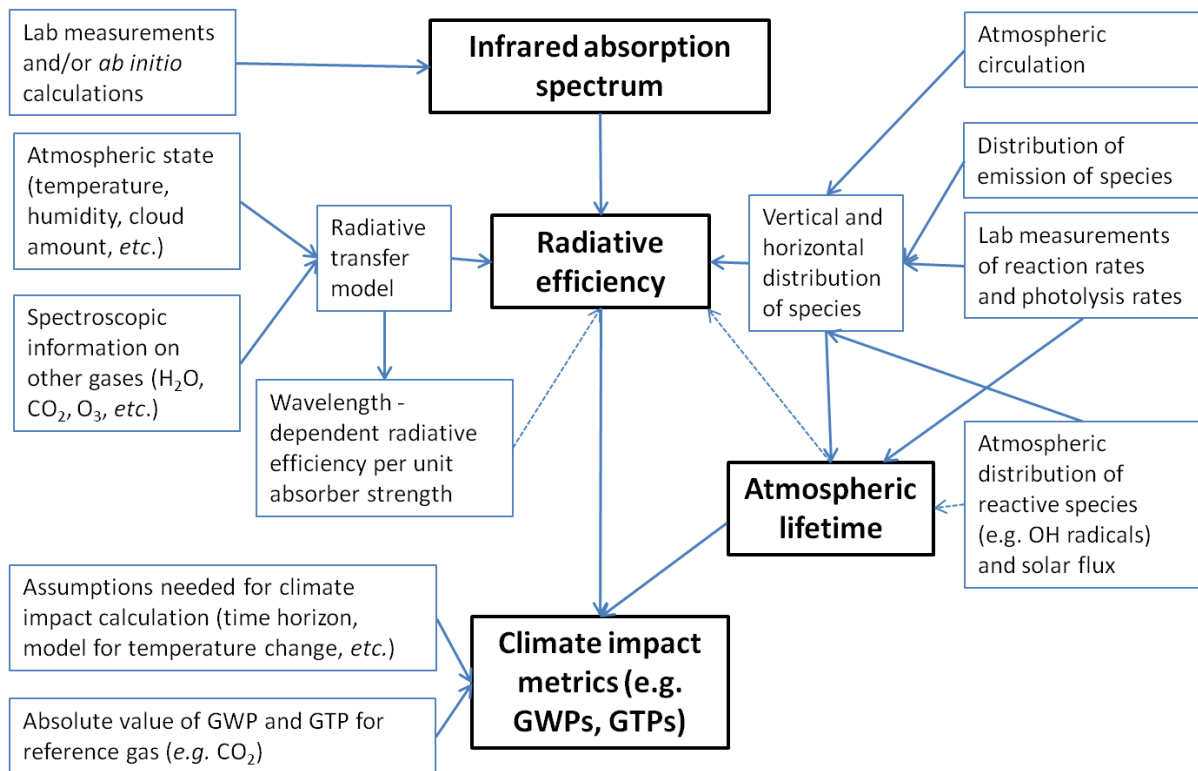
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4443 **Figure 2.** Schematic figure showing the main parameters required to compute climate impact  
 4444 metrics, and the additional inputs required in the calculation of those parameters. Dashed lines  
 4445 show where simpler techniques (based on the more complex models) are often employed (as  
 4446 is the case in this review).

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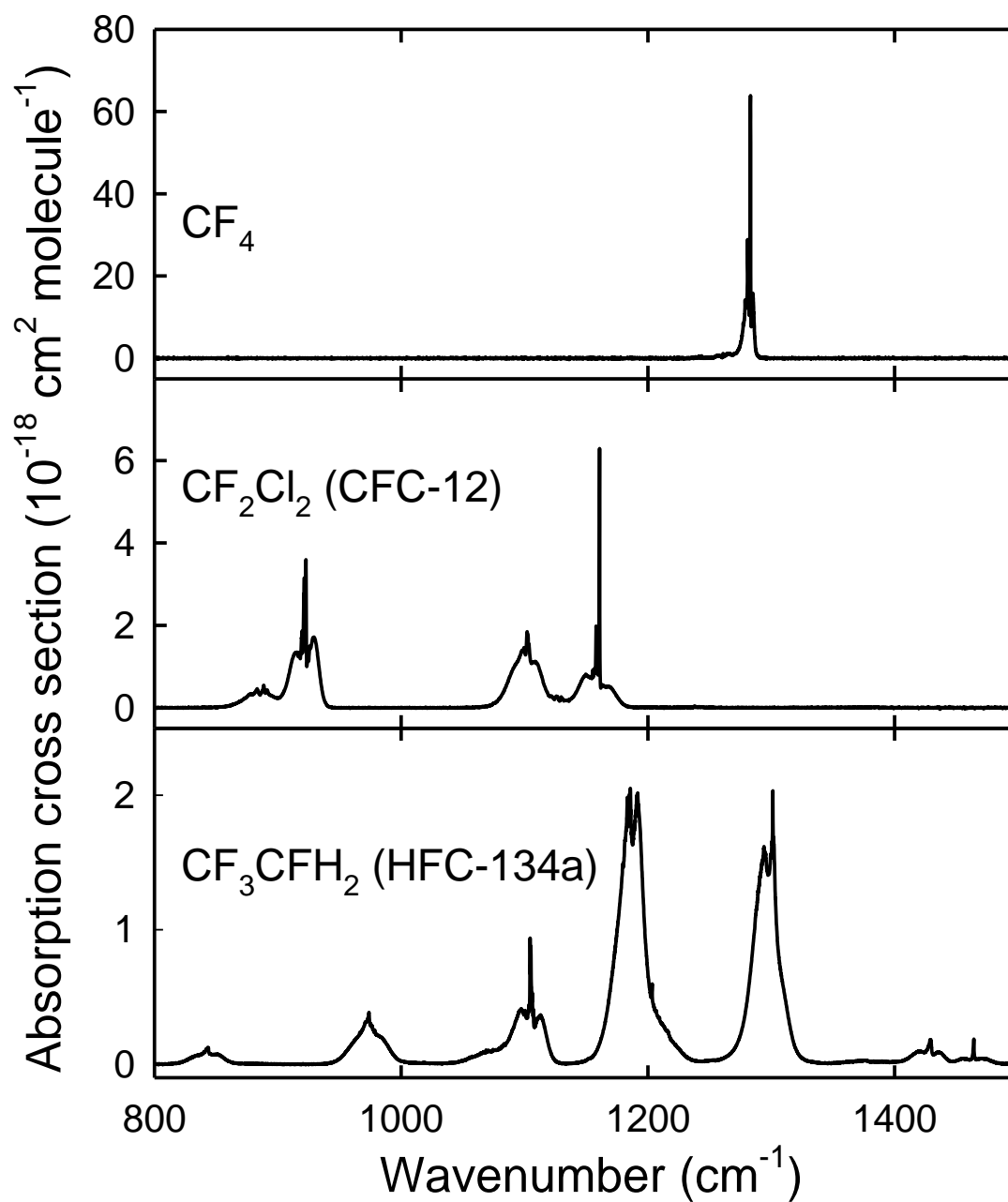
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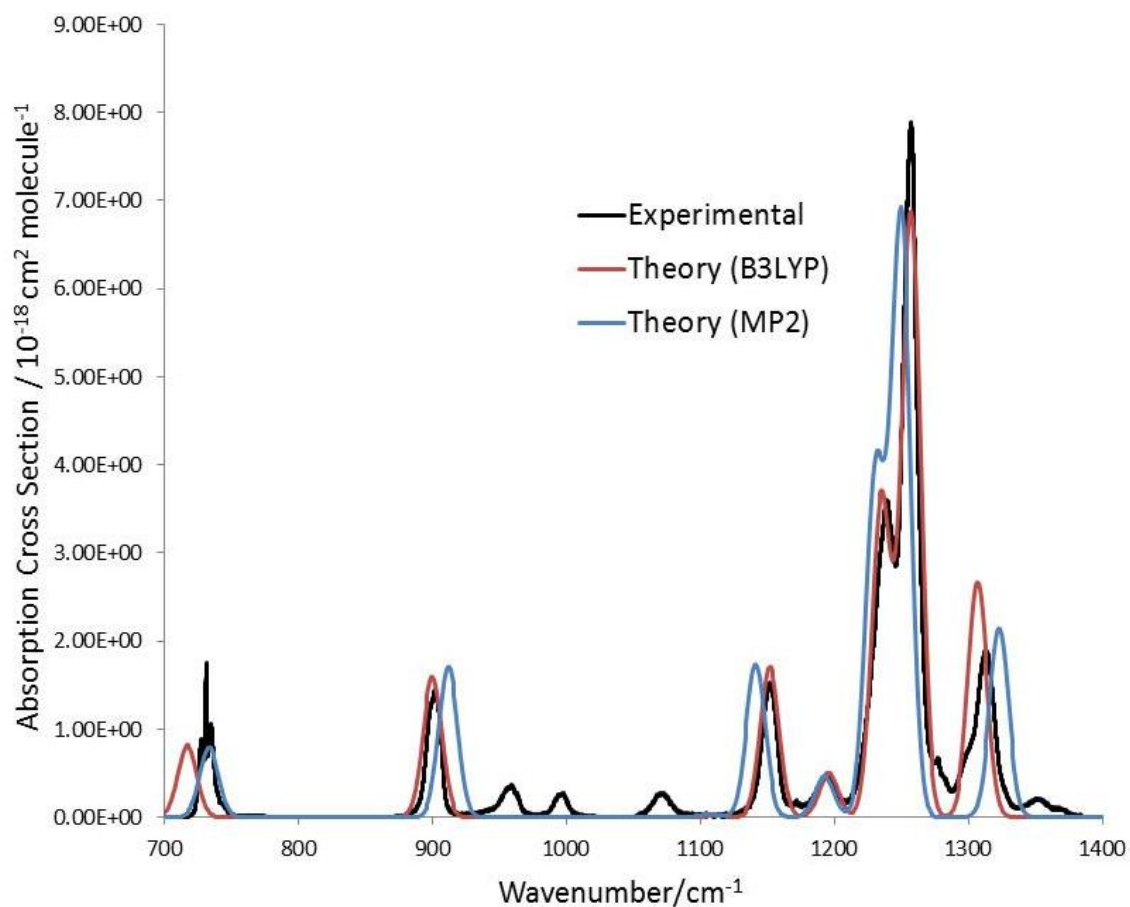
4460 **Figure 3.** IR spectra of  $\text{CF}_4$  (top panel),  $\text{CF}_2\text{Cl}_2$  (middle panel), and  $\text{CF}_3\text{CFH}_2$  (bottom panel)  
4461 measured using  $0.5 \text{ cm}^{-1}$  spectral resolution in 700 Torr of air diluent at 296 K [Forster *et al.*,  
4462 2005; Hurley *et al.*, 2005; Sihra *et al.*, 2001].

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4468 **Figure 4.** Comparison of experimental and theoretical (B3LYP/6-31G\*\*, MP2/6-31G\*\*) spectra for *n*-C<sub>4</sub>F<sub>10</sub>. The theoretical spectra were modeled using Gaussian functions of 14 cm<sup>-1</sup>  
4469 full width. Data taken from *Bravo et al.* [2010b].

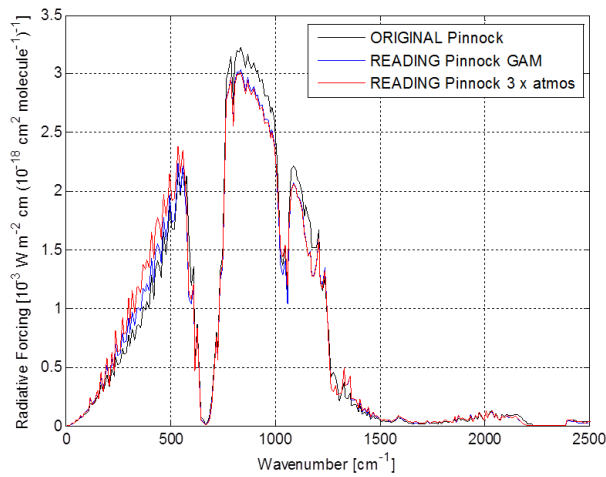
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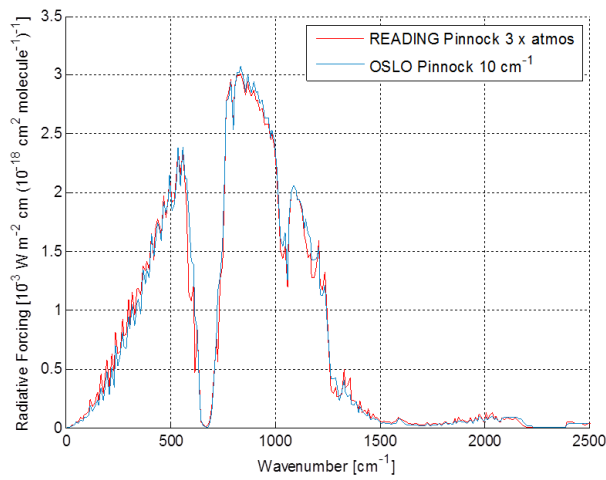
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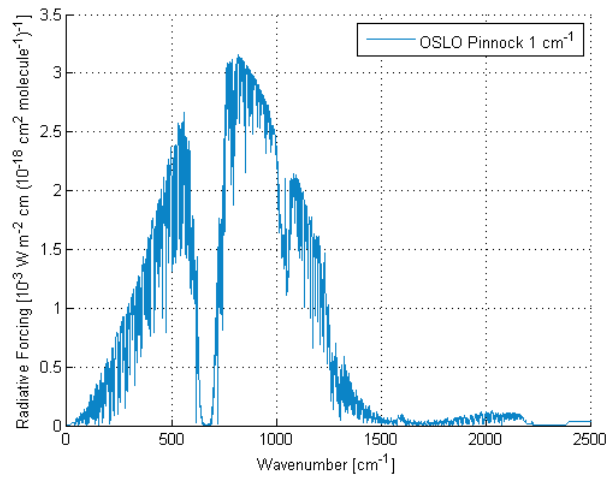
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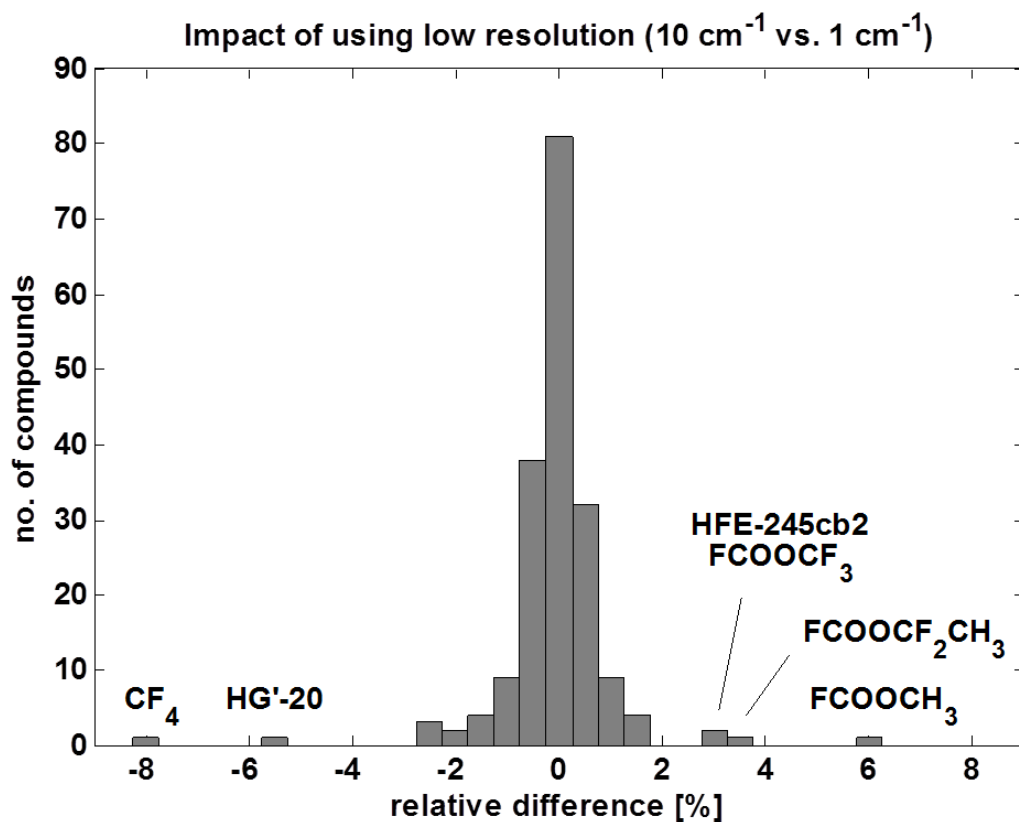


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4479 **Figure 5.** Radiative forcing efficiency (for a 0-1 ppb increase in mixing ratio) per unit cross section compared  
 4480 between the *Pinnock et al.* [1995] study and this study. The top panel shows the progression from the original  
 4481 Pinnock plot (using the Reading Narrow Band Model (NBM)) on incorporating an updated global-annual mean  
 4482 atmosphere (GAM) and then incorporating three atmospheres representing the tropics and extra-tropics, all at a

4483 resolution of  $10\text{ cm}^{-1}$ . The middle panel shows a comparison of the Reading NBM and the Oslo Line-by-Line  
4484 (LBL) model averaged to  $10\text{ cm}^{-1}$  resolution, using atmospheres representing the tropics and extra-tropics. The  
4485 bottom panel shows the results from the Oslo LBL model at a resolution of  $1\text{ cm}^{-1}$ .

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4488 **Figure 6.** Relative difference in calculation of RE using  $1\text{ cm}^{-1}$  and  $10\text{ cm}^{-1}$  with the Pinnock  
4489 plot shown in Figure 5 of the compounds investigated in this study. The original LBL  
4490 calculations are performed with  $0.2\text{ cm}^{-1}$  and then converted to  $1\text{ cm}^{-1}$  and  $10\text{ cm}^{-1}$ .

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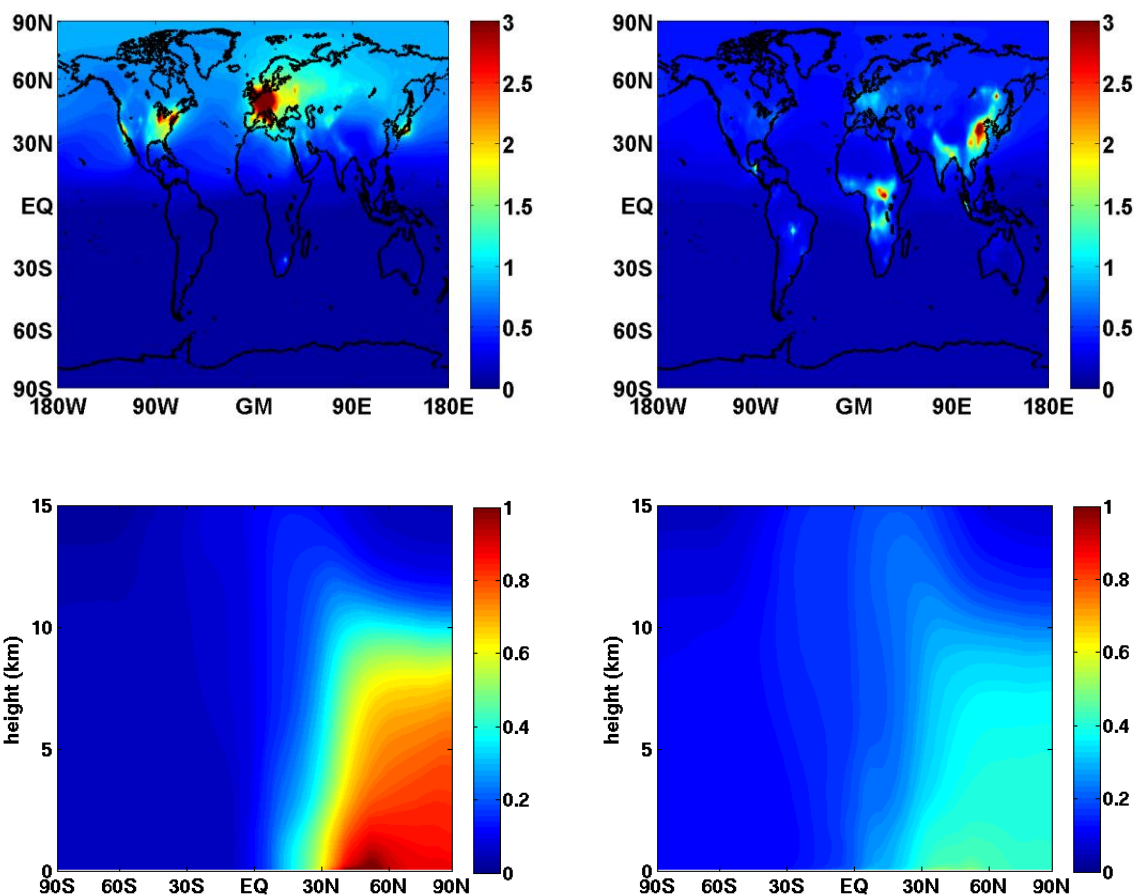
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4502 **Figure 7.** Annual average distribution of HFC-161 mixing ratio (ppb) at the surface (top panels) and averaged  
4503 zonally (bottom) for the reference simulation with emission distribution as for CFC-11 (left) and the sensitivity  
4504 simulation with emission distribution as for BC (right) calculated with the Oslo CTM2 model (see text for  
4505 details).

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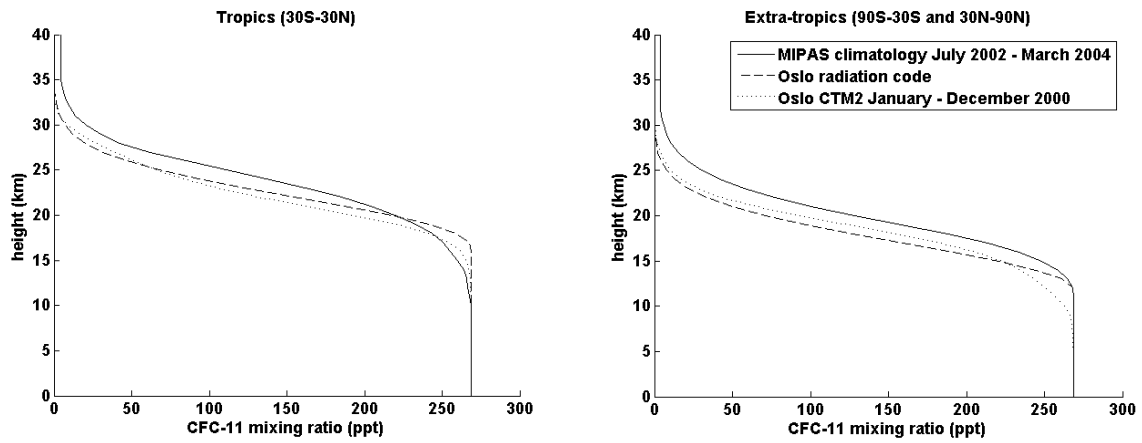
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4515 **Figure 8.** Vertical profiles of CFC-11 mixing ratio (ppt) in the tropics (left) and the extra-  
 4516 tropics (right) from MIPAS observations [*Hoffmann et al.*, 2008], the Oslo radiation code, and  
 4517 the Oslo CTM2 model. The profiles have been scaled to the year 1994 tropospheric mixing  
 4518 ratio of 269 ppt as in *Minschwaner et al.* [2012].

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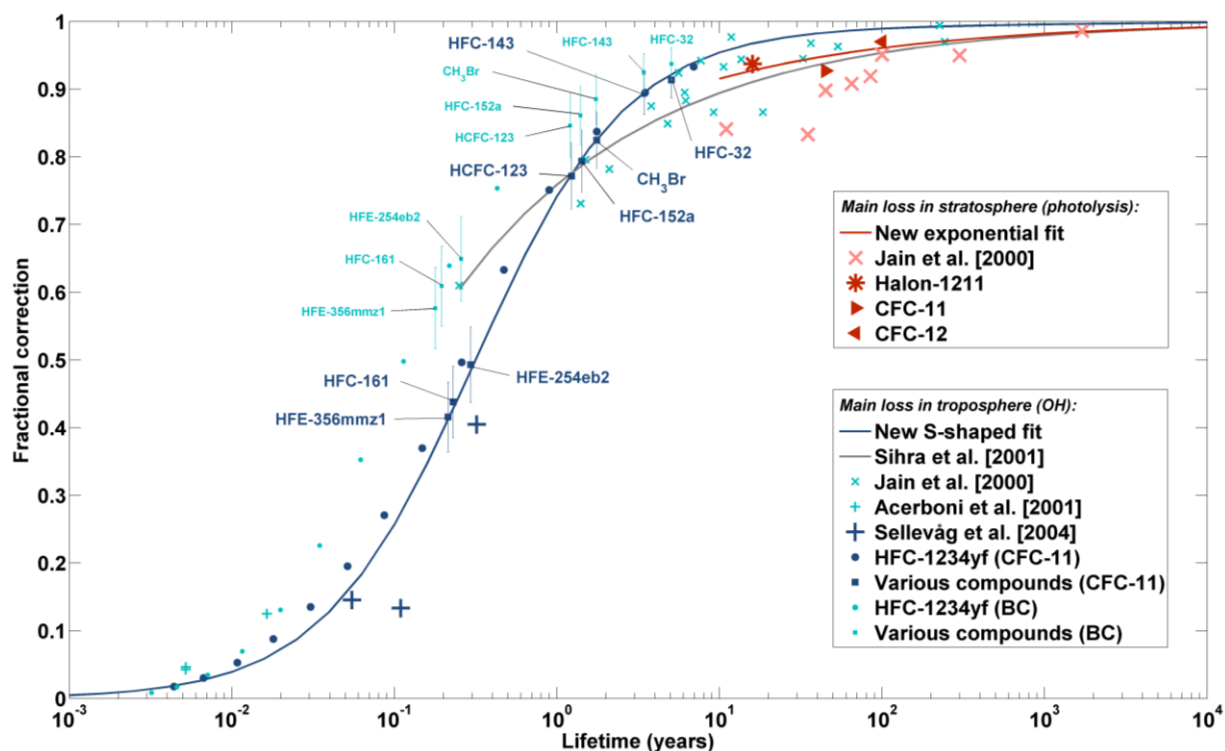
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4537 **Figure 9.** Factor needed to correct RE to account for non-uniform vertical and horizontal distribution versus  
 4538 atmospheric lifetime. The red symbols are for compounds whose main loss mechanism is stratospheric  
 4539 photolysis while the blue symbols are for compounds which are mainly lost in the troposphere by reaction with  
 4540 OH. Dark blue symbols have been used in the calculation of the S-shaped fit and dark red symbols have been  
 4541 used in the calculation of the exponential fit. Light blue and light red symbols are shown for comparison. The  
 4542 curve from Sihra et al. [2001] represents an empirical least squares fit to the fractional correction factors from  
 4543 Jain et al. [2000]. The parentheses designate whether the results are from the simulations with "CFC-11-like" or  
 4544 "BC-like" emission distribution. For the compounds where several different absorption bands have been used in  
 4545 the RF calculations, both the mean and the standard deviation of the fractional corrections are shown.

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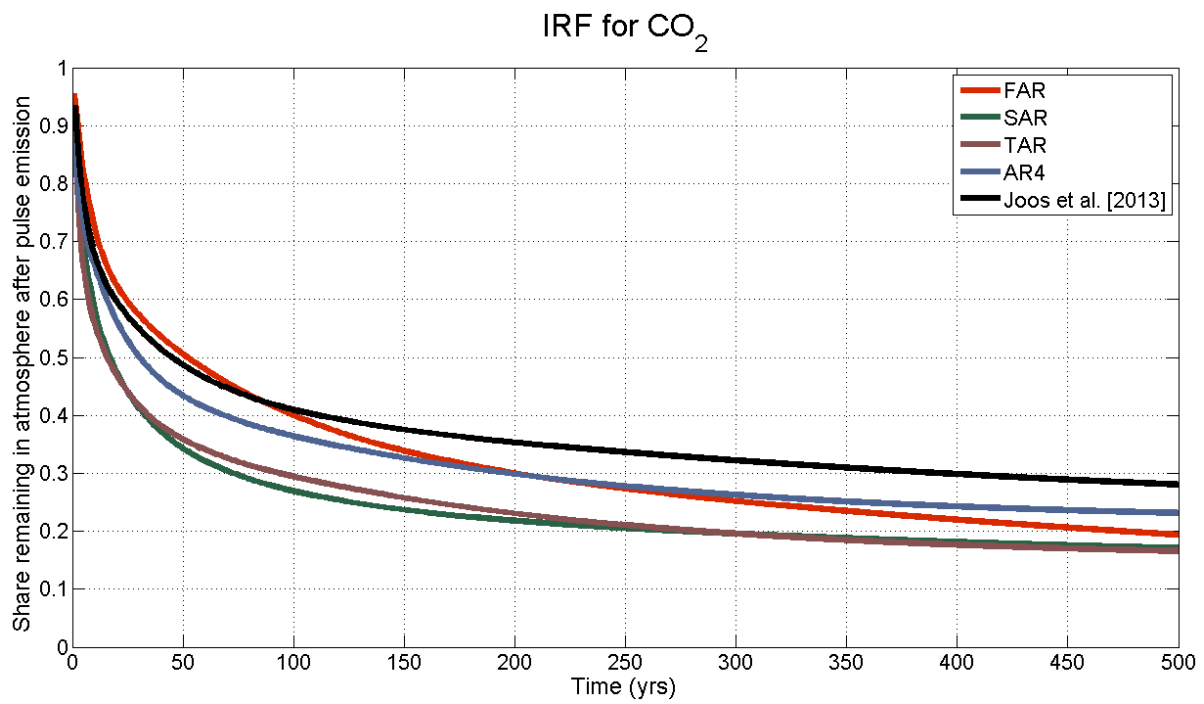
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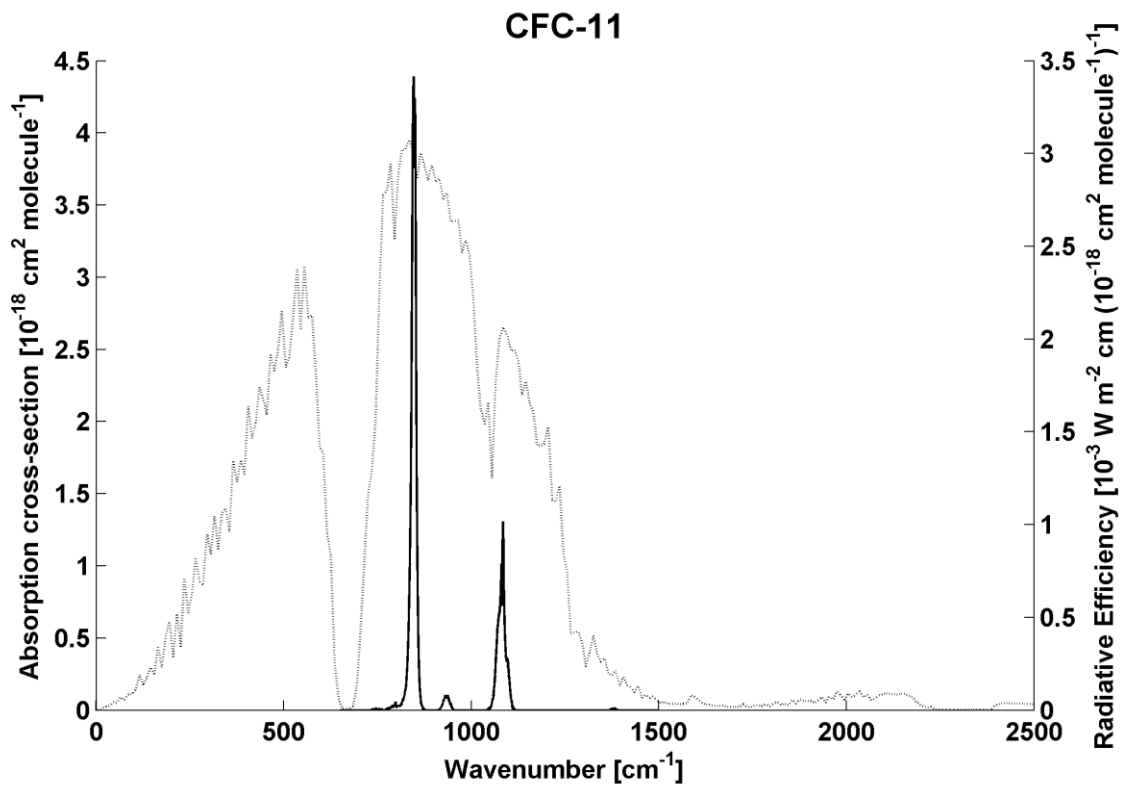
4555 **Figure 10.** Impulse response functions from the four IPCC assessments and from the recent  
 4556 multi-model study of *Joos et al.* [2013]. Note that the IRF from FAR [IPCC, 1990] and SAR  
 4557 [IPCC, 1995] did not include climate-carbon cycle feedbacks, while these are included in  
 4558 IRFs from TAR [IPCC, 2001], AR4 [IPCC, 2007] and *Joos et al.* [2013].

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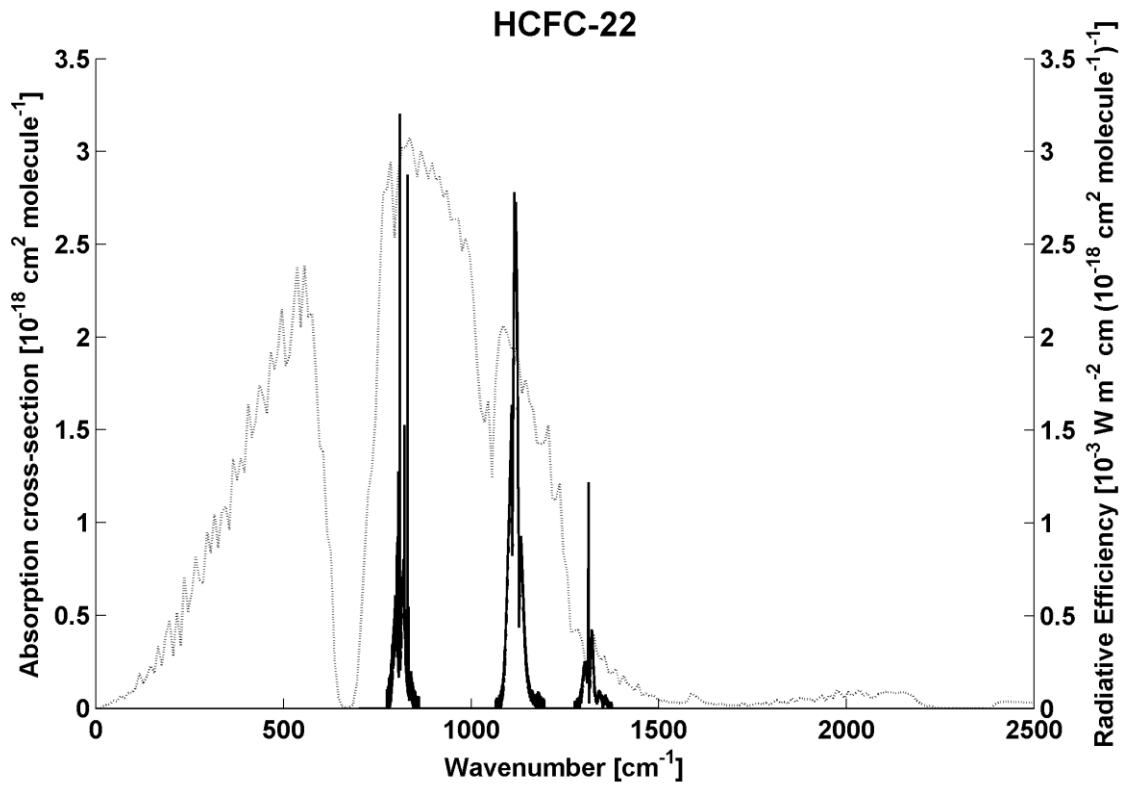
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4564 **Figure 11.** Absorption spectrum of CFC-11 at 296 K in 933 hPa (700 Torr) air diluent from  
 4565 *Sihra et al.* [2001] (solid line) and Oslo simulation of Pinnock curve (dotted line).

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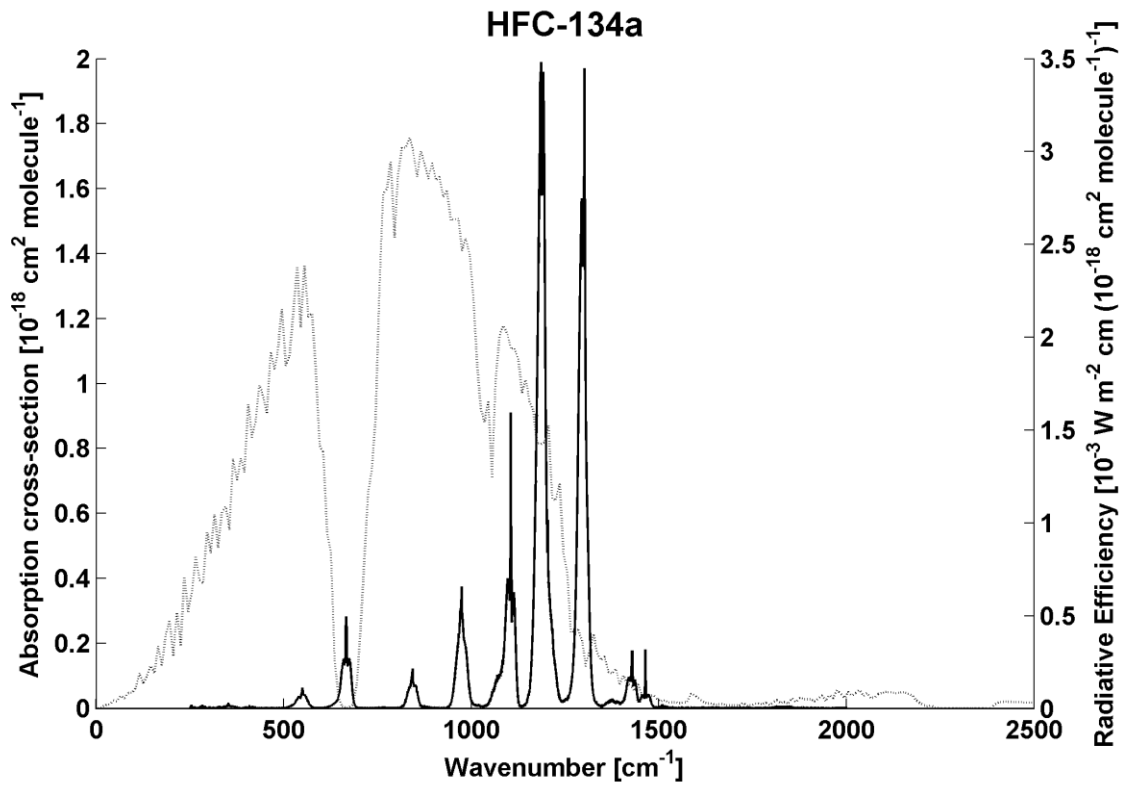
4570 **Figure 12.** Absorption spectrum of HCFC-22 at 293 K in 800 hPa air diluent from *Ballard et*  
4571 *al.* [2000b] (solid line) and Oslo simulation of Pinnock curve (dotted line).

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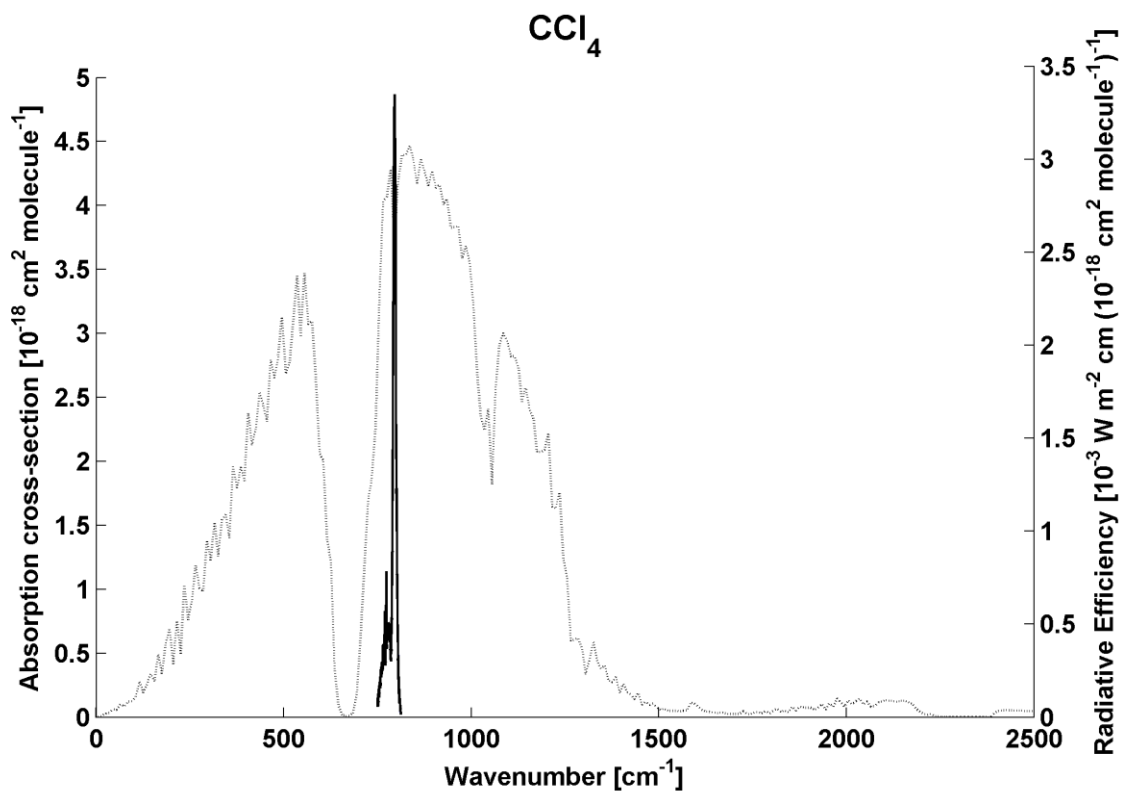


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4577 **Figure 13.** Absorption cross-section of HFC-134a from *Forster et al.* [2005] (solid line) and  
 4578 Oslo simulation of Pinnock curve (dotted line). The spectrum is a composite of measurements  
 4579 from five laboratory groups and has been measured under various temperatures and diluent  
 4580 gas pressures.

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4584 **Figure 14.** Absorption spectrum of CCl<sub>4</sub> at 296 K from *Nemtchinov and Varanasi* [2003]  
4585 (solid line) and Oslo simulation of Pinnock curve (dotted line).

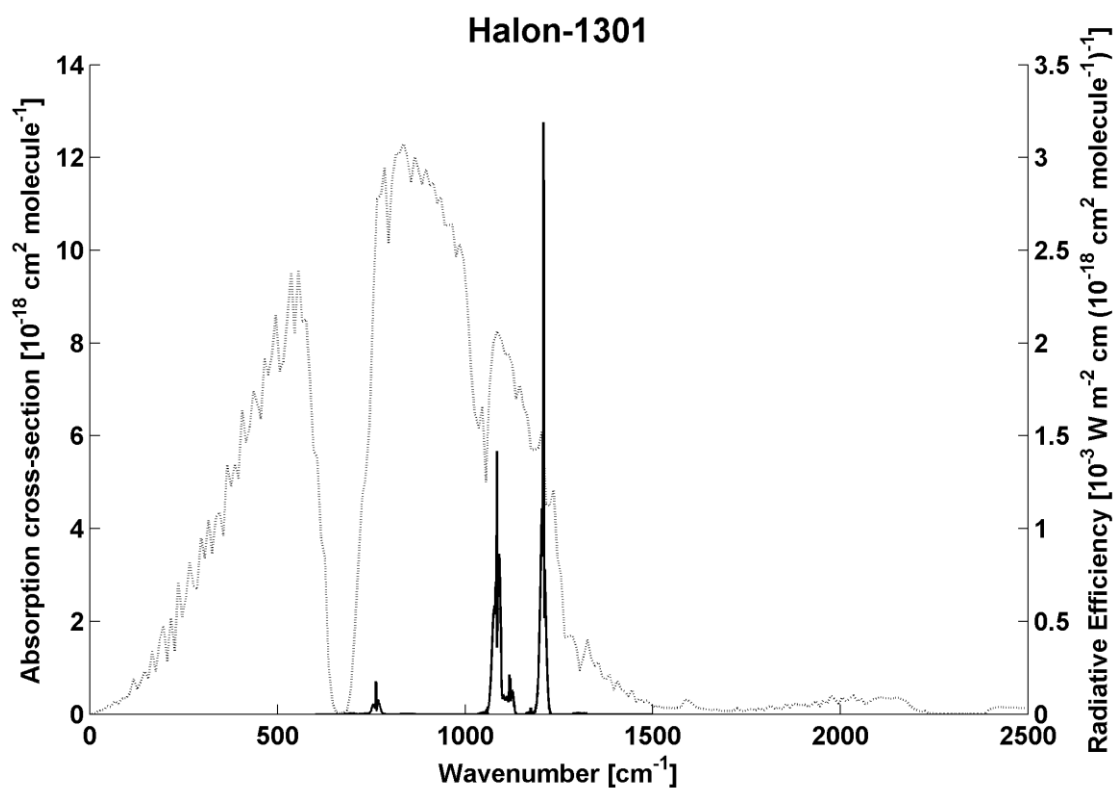
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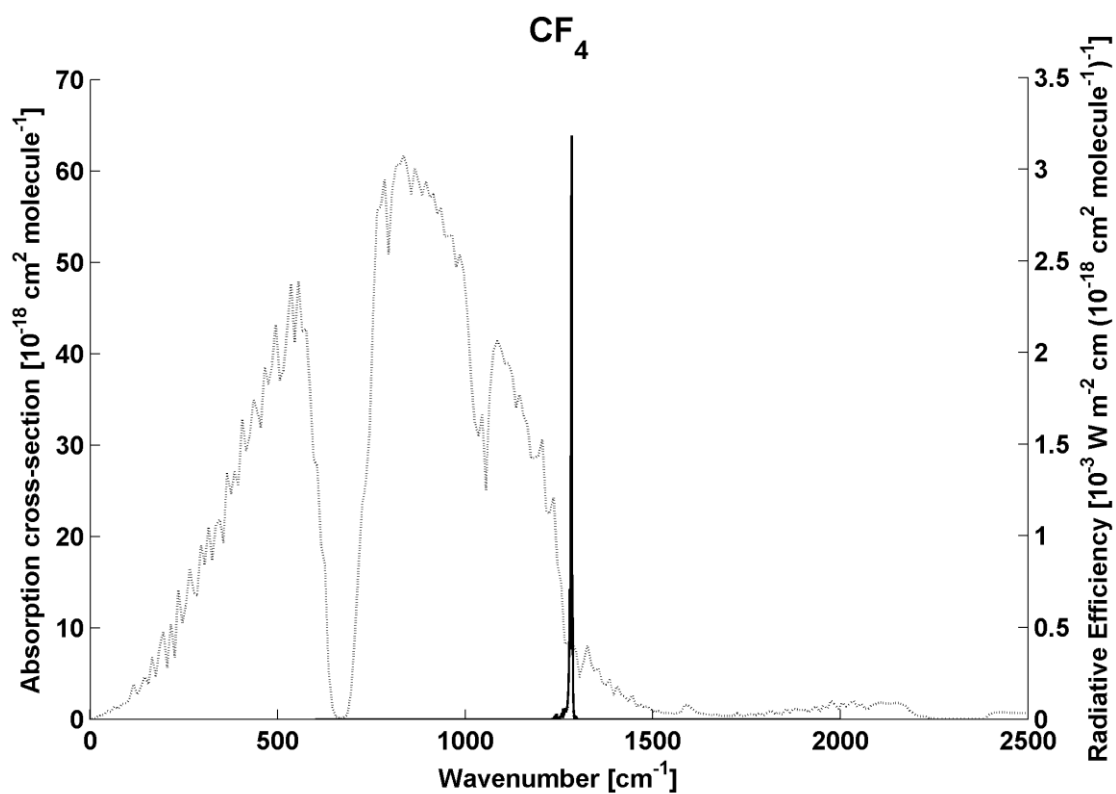
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4592 **Figure 15.** Absorption spectrum of Halon-1301 at 296 K in 933 hPa (700 Torr) air diluent  
4593 from Sihra *et al.* [2001] (solid line) and Oslo simulation of Pinnock curve (dotted line).

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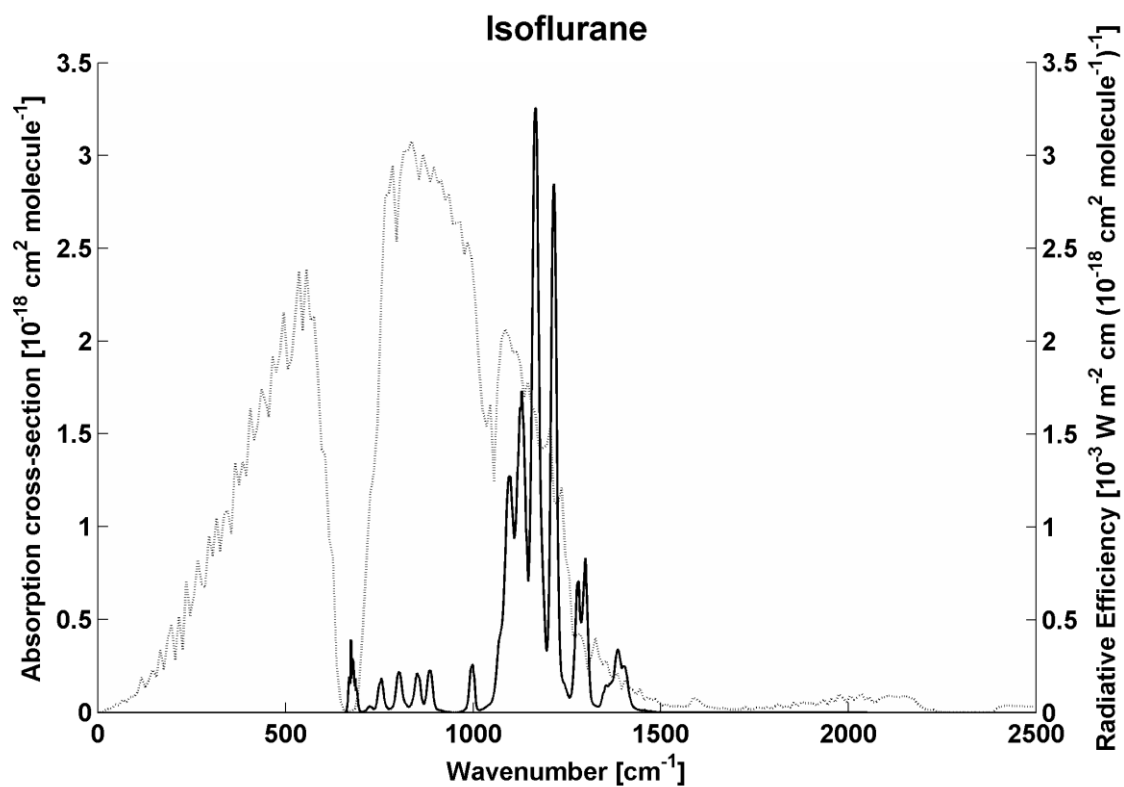


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4598 **Figure 16.** Absorption spectrum of CF<sub>4</sub> at 296 K in 933 hPa (700 Torr) air diluent from *Sihra*  
4599 *et al.* [2001] (solid line) and Oslo simulation of Pinnock curve (dotted line).

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4604 **Figure 17.** Absorption spectrum of isoflurane at 296 K in 933 mbar (700 Torr) air diluent  
4605 from Andersen *et al.* [2010c] (solid line) and Oslo simulation of Pinnock curve (dotted line).

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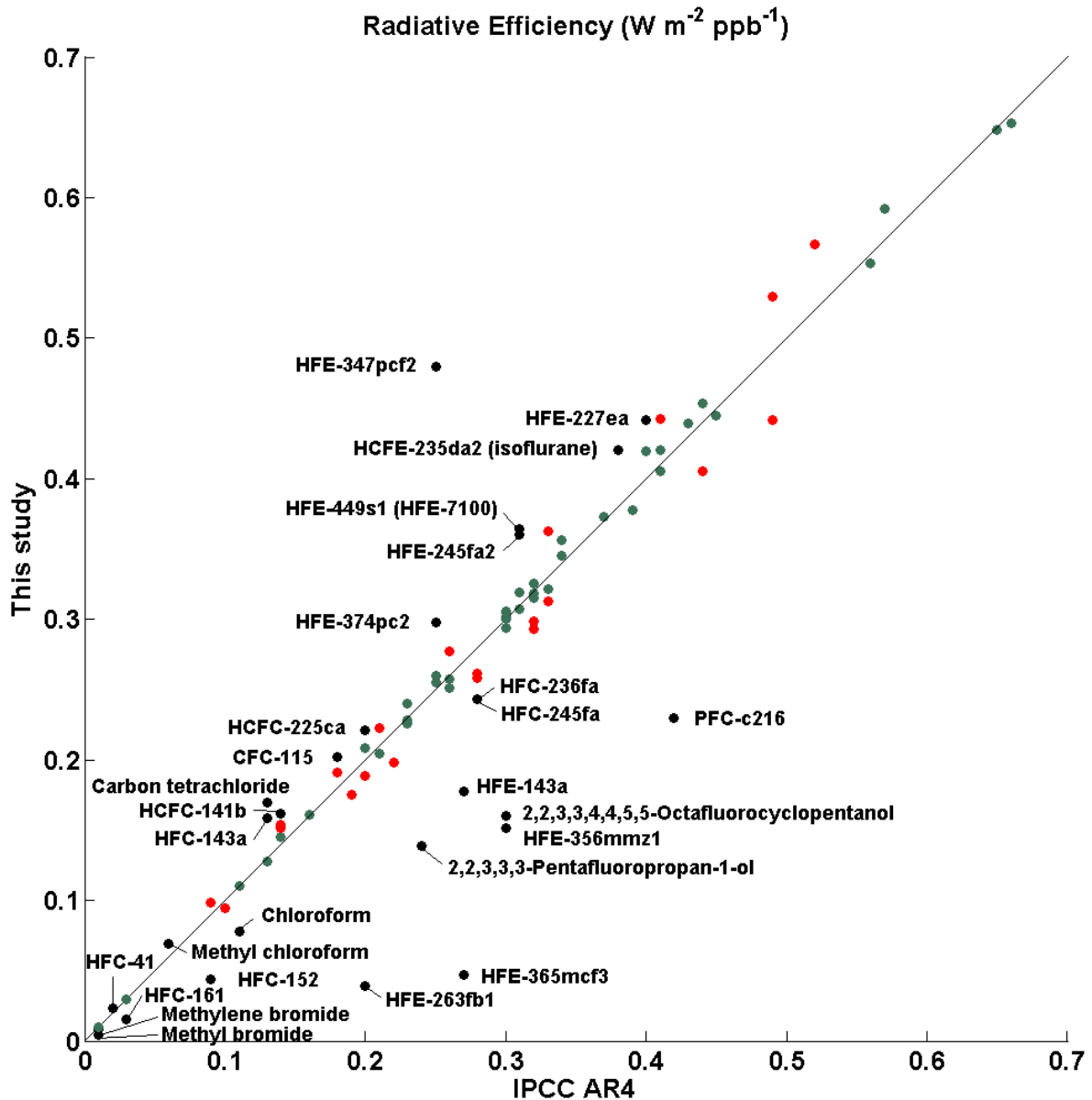
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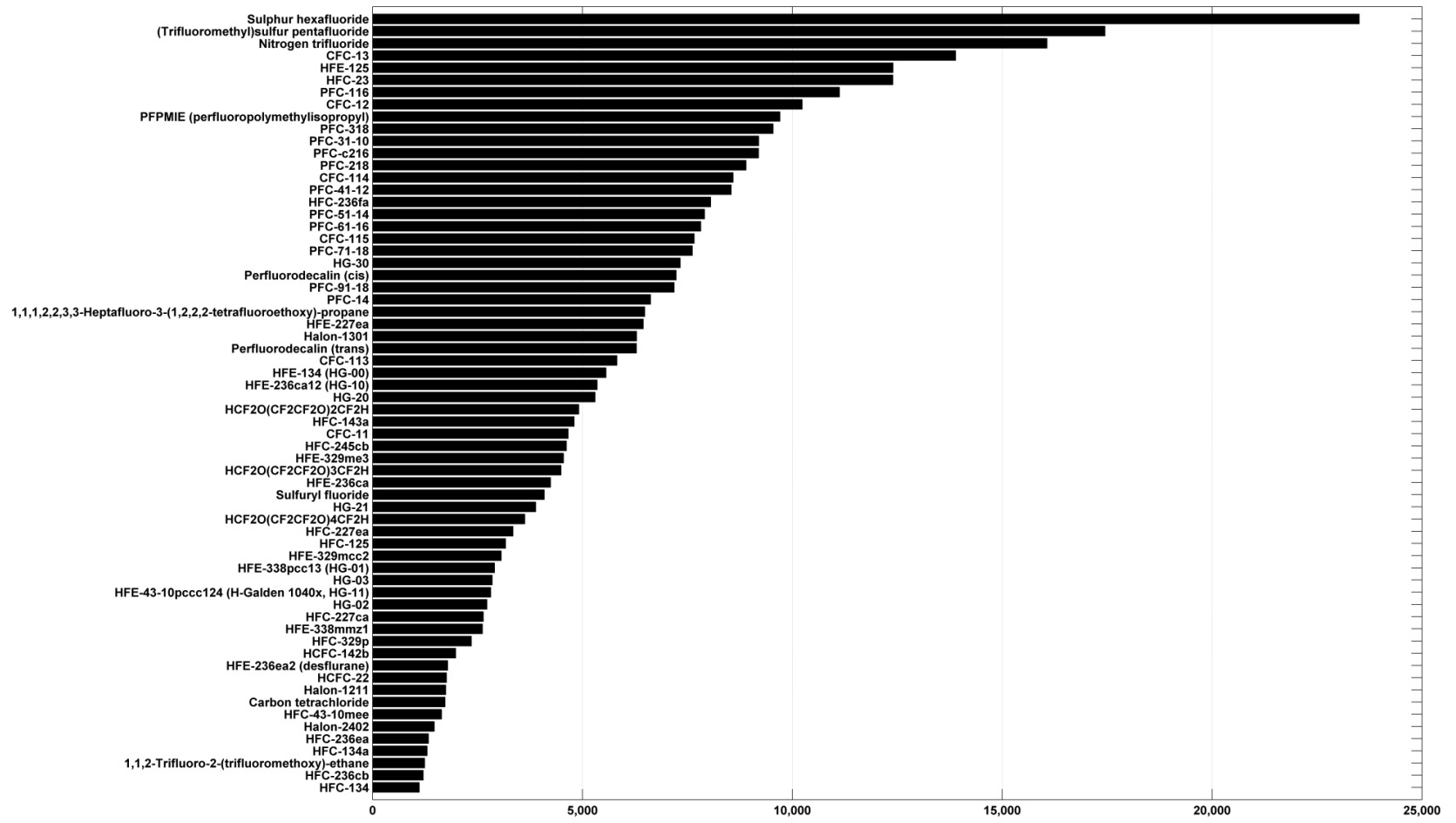




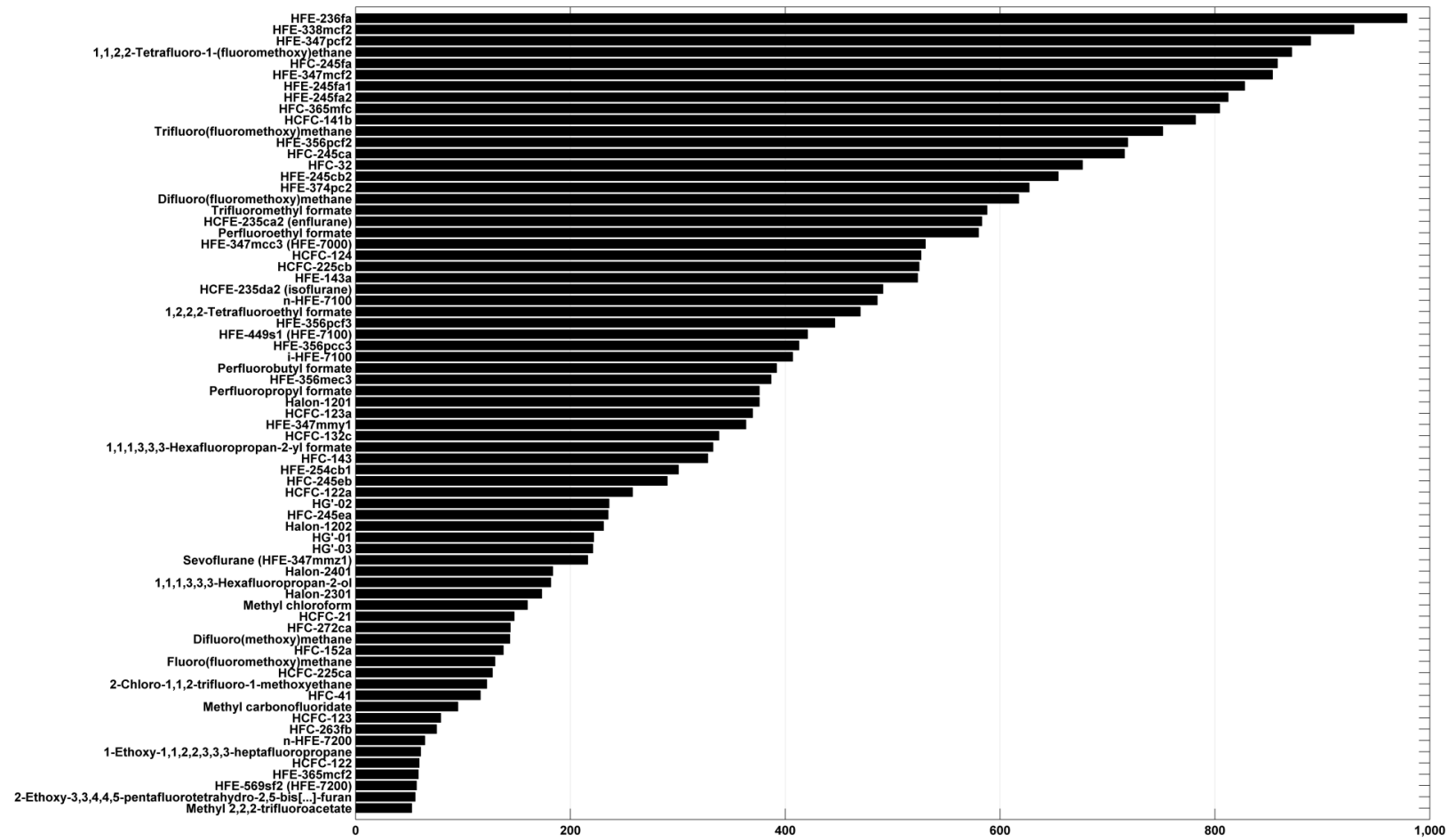
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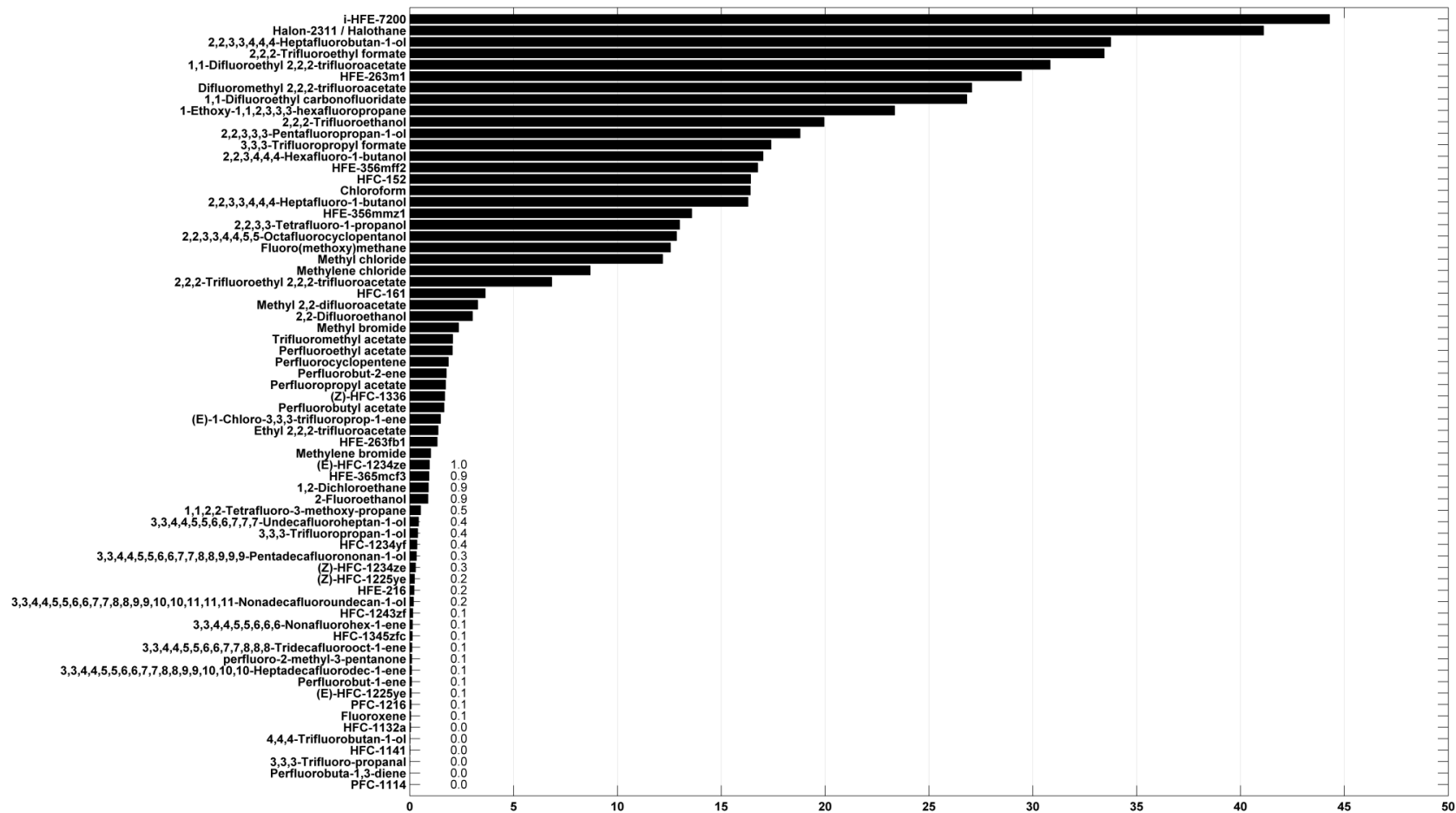
4619 **Figure 18.** Comparison of radiative efficiencies calculated in this study (lifetime-corrected adjusted cloudy-sky)  
 4620 and from AR4 [Forster *et al.*, 2007]. Green dots represent compounds where the RE in this study is less than 5%  
 4621 different from AR4, while red and black dots represent compounds where the REs are significantly different  
 4622 (>5% and >10%, respectively). Black dots have been labeled and represent compounds where the RE calculated  
 4623 here is more than 10% different from AR4. Two compounds are off scale and therefore not shown in the plot:  
 4624 HFE-43-10pccc124 (H-Galden 1040x, HG-11) with a RE of  $1.02 \text{ W m}^{-2} \text{ ppb}^{-1}$  calculated in the present study  
 4625 (compared to  $1.37 \text{ W m}^{-2} \text{ ppb}^{-1}$  in AR4), and HFE-338pcc13 (HG-01) with a RE of  $0.86 \text{ W m}^{-2} \text{ ppb}^{-1}$  calculated  
 4626 in the present study (compared to  $0.87 \text{ W m}^{-2} \text{ ppb}^{-1}$  in AR4).

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4631 **Figure 19.** GWP 100-yr of all compounds calculated in this study.