Correct use of radiative efficiencies in calculating global warming potentials and other emission metrics

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Abstract

The calculations of Global Warming Potentials (GWPs) and other related climate emission metrics should use radiative efficiencies that are representative of the mean atmospheric mole fraction, rather than the surface mole fraction as is commonly used. This correction leads to an upward revision of GWP values. ~~Radiative forcing from projected changes in mean atmospheric mole fraction (such as for climate scenarios) also need to be corrected.~~ For species with lifetimes greater than a few years, the revision is an increase of a few percent e.g., ~~8~~7% for trichlorofluoromethane (CFC-11). For species with lifetimes ~~less than~~of the order of a year or less this correction can lead to increases in the GWPs ~~(and in some cases~~ estimates ~~of their radiative forcing)~~ of over ten~~s of~~ percent, which could impact on policymaker decisions on the desirability of using such gases

Short summary

The global warming potential (GWP) is a commonly used metric for relating the climate impact of emissions of a gas relative to that for carbon dioxide. We show that previous calculations have systematically underestimated these values by applying calculations of radiative forcing efficiency appropriate to changes in surface mole fractions rather than changes in the mass-weighted mean mole fraction in the atmosphere.

1. Introduction

The Global Warming Potential (GWP) of a species is given by the ratio of the absolute global warming potential (AGWP) to that of CO_2. The AGWPs are the radiative forcing following a 1 kg emission integrated over a specified time horizon H with units of W m^{-2} yr kg^{-1} (Shine et al., 1990).

$$\mathrm{AGWP}_x = \int_0^H A_x R_x(t)\,dt \qquad (1)$$

~~where~~ Here A_x is the radiative forcing from 1 kg of species x (i.e. units of W m^{-2} kg^{-1}), and $R_x(t)$ is the time evolution of the atmospheric mass of the species following the pulse emission. Hence, the AGWPs are proportional to the radiative efficiency defined per unit mass of the emitted species.

Values of radiative efficiency for many species have been calculated (Etminan et al., 2016; Hodnebrog et al., 2020) but are usually reported defined per change in surface mole fraction. This letter sets out to clarify the

34 importance of using the appropriate conversion from mole fraction to mass when calculating GWPs and other
35 climate emission metrics.

36 **2. Radiative efficiencies**

37 The radiative efficiencies for atmospheric species are typically calculated using sophisticated radiative transfer
38 models in which the mole fractions of the species of interest are varied. The radiative efficiencies are then
39 calculated as the ratio of the radiative forcing change to the mole fraction change, for small changes in mole
40 fraction. Originally calculations used constant profiles of mole fraction with height (Pinnock et al., 1995) but
41 vertical profile information from models or observations was later adopted for many species (Etminan et al., 2016;
42 Freckleton et al., 1998; Jain et al., 2000; Myhre et al., 1998; Myhre & Stordal, 1997; Naik et al., 2000). This is
43 now done routinely in international assessments for halogenated gases using parameterisations based on species
44 lifetime (Hodnebrog et al., 2013, 2020). These radiative efficiencies are typically reported per change in surface
45 mole fraction (Etminan et al., 2016; Freckleton et al., 1998; Hodnebrog et al., 2013, 2020; Jain et al., 2000; Myhre
46 et al., 1998; Myhre & Stordal, 1997; Naik et al., 2000) where "surface" refers to the lowest layer in the radiative
47 transfer model.
48 Species that are destroyed in the stratosphere (N_2O, chlorofluorocarbons (CFCs)) will have lower mole fractions
49 in the stratosphere than at the surface. Species that have very short tropospheric lifetimes (comparable to the
50 vertical mixing timescales in the troposphere) such as some hydrocarbons and halocarbons will have significantly
51 lower mole fractions in the upper troposphere than at the surface. In both cases the radiative forcing will be less
52 (for the same surface mole fraction change) than if a constant profile were used, and so the radiative efficiency
53 will be lower too. Figure 1a shows the adjustments to the radiative efficiency for species destroyed in the
54 stratosphere (dashed red line) and troposphere (dashed blue line) based on parameterisations[1] derived in
55 (Hodnebrog et al., 2013). The adjustments can be considered to comprise two components, a correction due to the
56 spatial distribution of the species (radiative efficiency per mass is greatest in the upper troposphere and lower
57 stratosphere (Maycock et al., 2021) and over relatively cloud-free regions of higher surface temperature) and a
58 correction because of the lower atmospheric mass of a species for a given surface mole fraction (solid lines in
59 Figure 1a).
60 A key use of radiative efficiencies is to determine the radiative forcing from observed changes in surface mole
61 fractions of different species which are determined from measurements representative of the well-mixed lower
62 troposphere (Forster et al., 2021; Gulev et al., 2021). ~~so a~~Accounting for the declining mole fractions with height
63 has allowed a more complete determination of their climate effects (Hodnebrog et al., 2013). These adjustments
64 however make them less useful for directly determining GWPs which are based on radiative efficiency per mass.
65 To calculate GWPs it is important to understand what vertical profile has been used for the species in the radiation
66 calculations so that the radiative efficiencies can be correctly converted to a mass basis.
67

[1] $f(\tau) = 1 - 0.1826\tau^{-0.3339}$ for stratospheric destruction, $f(\tau) = \frac{2.962\tau^{0.9312}}{1+2.994\tau^{0.9302}}$ for tropospheric destruction, where τ is the total lifetime.

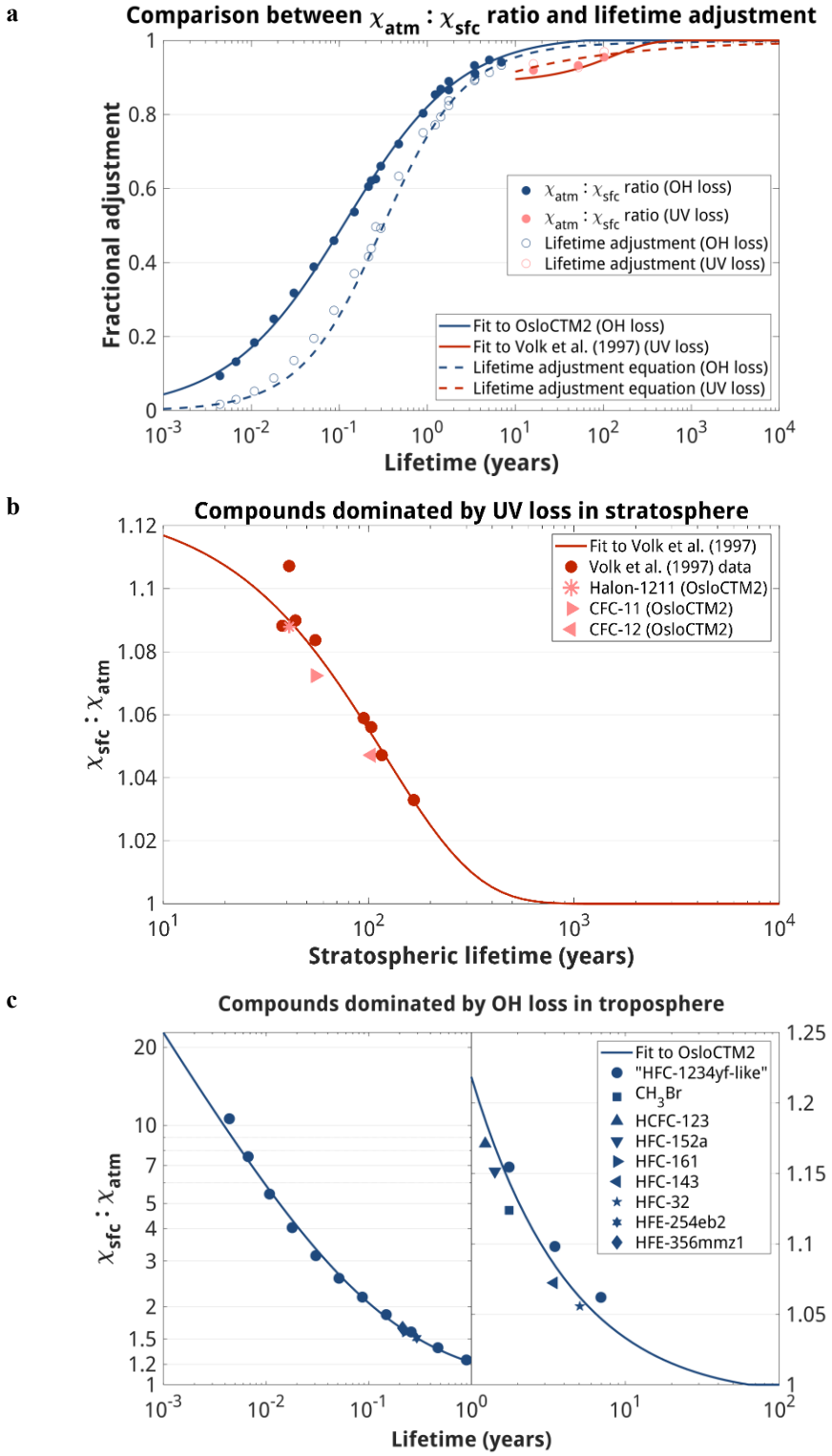


Figure 1. (a) Comparison between the ratio of mean atmospheric-to-surface mole fraction (χ_{atm}:χ_{sfc}; filled circles) and the lifetime adjustment that corrects RE to account for non-homogeneous atmospheric distribution (open circles) based on OsloCTM2 simulations (see Figure 9 and associated discussion in Hodnebrog et al., 2013). (b) Ratio χ_{sfc}:χ_{atm} from the OsloCTM2 simulations, and from observations in Volk et al. (1997) and associated fit from Collins et al. (2026) (see Equation ~~34~~ 45), against stratospheric lifetimes from WMO (2022). (c) Ratio χ_{sfc}:χ_{atm} against total lifetimes from OsloCTM2 simulations in Hodnebrog et al. (2013) and associated fit (see Equation 45). Note that in (a), red circles and solid red line are plotted against stratospheric lifetimes and not total lifetimes.

3 Radiative forcing per mass.

In the climate assessments from the Intergovernmental Panel on Climate Change (IPCC) and the ozone assessments from the World Meteorological Organization (WMO) (Forster et al., 2021; WMO, 2022), the conversion from mole fraction to mass has been done using the following formula (Aamaas et al., 2013; Shine et al., 2005)

$$A_x = \mathrm{RE} \times \frac{M_{\mathrm{air}}}{M_x} \times \frac{10^9}{T_M} \quad (1\text{~~1~~}2)$$

where A_x and RE are the radiative efficiencies given in W m^{-2} kg^{-1} and W m^{-2} ppb^{-1}, respectively, M_{air} is the mean molecular weight of dry air (28.97 kg kmol^{-1}), M_x is the molecular weight of species x, and T_M is the total dry air mass of the atmosphere (5.1352×10^{18} kg; (Trenberth & Smith, 2005)). This conversion is appropriate if the RE is defined per mean atmospheric mole fraction change, but not if it is defined per surface mole fraction change since the assumed mass burden will be incorrect. In the latter case a correction factor $\frac{\Delta\chi_{\mathrm{sfc}}}{\Delta\chi_{\mathrm{atm}}}$ is needed (Collins et al., 2026) that is the ratio of the change in surface mole fraction $\Delta\chi_{\mathrm{sfc}}$ to the change in mass-weighted mean atmospheric mole fraction $\Delta\chi_{\mathrm{atm}}$, i.e. Equation (1~~1~~2) should be modified to

$$A_x = \left(\mathrm{RE} \times \frac{\Delta\chi_{\mathrm{sfc}}}{\Delta\chi_{\mathrm{atm}}}\right) \times \frac{M_{air}}{M_x} \times \frac{10^9}{T_M} \quad (2\text{~~3~~})$$

Physically, the radiative efficiency per mean atmospheric mole fraction (i.e. the whole term in parenthesis in Eq. (3)) is higher because a lower $\Delta\chi_{\mathrm{atm}}$ (or equivalently a lower change in atmospheric burden) is required to generate the same forcing as a 1 ppb change in χ_{sfc}.

Ideally the ratio $\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}}$ should be that used in the original radiative efficiency calculations, but that is not available in all cases, so we fit empirical functions to allow values to be derived for any species. Values of $\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}}$ for a range of species were calculated in Volk et al. (1997). These were species where the main effect on the vertical profile came from destruction in the stratosphere. Collins et al. (2026) derived the following empirical fit to the data in Volk et al. (1997):

$$\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}} = \frac{1}{1 - 0.113e^{-\frac{\tau_{\mathrm{strat}}}{130}}} \quad (3\text{~~4~~})$$

τ_{strat} is the stratospheric lifetime of a species in years (WMO, 2022). Note the reciprocal of this term $\left(\frac{\chi_{\mathrm{atm}}}{\chi_{\mathrm{sfc}}}\right)$ is ~~referred~~ similar to the~~as a~~ "fill factor c" in Prather et al. (2012) although they use the tropospheric mole fraction in the denominator. Figure 1b shows that OsloCTM2 results from Hodnebrog et al. (2013) align relatively well with the empirical fit that is based on Volk et al. (1997).

To calculate the $\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}}$ ratio for species with short tropospheric lifetimes we fit to OsloCTM2 results for a range of molecules that react with OH in the troposphere in (Hodnebrog et al., 2013) using a similar form of equation to their lifetime adjustment (τ is the total atmospheric lifetime in years).

$$\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}} = \max\left(\frac{1 + 3.908\tau^{0.6512}}{4.028\tau^{0.648}}, \quad 1\right) \quad (4\text{~~5~~})$$

Figure 1c shows this fit on top of the $\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}}$ ratio against lifetime for all the OsloCTM2 simulations. For these species the mole fraction also varies horizontally in the radiative efficiency~~forcing~~ calculations ~~radiation model~~ so χ_{sfc} is the global mean mole fraction in the lowest model layer, both in the determination of radiative efficiency and in the fit in figure 1c. ~~For species with both tropospheric and stratospheric loss, the larger value of $\frac{\chi_{\mathrm{sfc}}}{\chi_{\mathrm{atm}}}$ from equations (3) and (4) should be used.~~Equation 4 should be used for species where stratospheric loss through photolysis is more important (shorter stratospheric partial lifetime). Equation 5 should be used for species where loss through OH in the troposphere has the shorter partial lifetime.

Table 1 shows, for a few selected molecules, how correcting for the $\frac{\chi_{sfc}}{\chi_{atm}}$ impacts GWP100 values (i.e. for H = 100 years). For CFC-11 the increase is approximately 7~~8~~% ~~and less for other CFCs~~. For some HFCs the effect can be very large, suggesting the previous determinations of GWP100 were underestimated by over 10~~s of~~ %.

The methane and nitrous oxide radiative efficiencies used in the IPCC 6th Assessment (Forster et al., 2021) come from Etminan et al. (2016). The profiles of methane and nitrous oxide used in that study were from Myhre & Stordal (1997) with values of $\frac{\chi_{sfc}}{\chi_{atm}}$ of 1.0~~2~~ 019 and 1.031. ~~This means that IPCC AR6 GWP100s should be increased from 28.1 to 28.7 and from 267 to 275 for fossil methane and nitrous oxide respectively[2].~~ Note these ratios are less than ~~those in or~~ expected from Equation ~~3~~4. If the ratios used in the original ~~radiation~~radiative efficiency~~forcing~~ calculations are known, it is more appropriate to use these than Equations 4 or 5. In Hodnebrog et al. (2020) the explicit ratios for CFC-11, CFC-12 and Halon-1211 are 1.072, 1.047 and 1.088 respectively (Figure 1b).

Table 1. The effect on GWP100 of correcting the approach for converting RE values from per ppb to per kg compared to the previous approach for a selection of molecules. For CH_4, N_2O, CFC-11, CFC-12 and Halon-1211 explicit correction factors are used as described in the text, for CFC-113 Equation ~~3~~ 4 is used ~~for CFC-11 and CFC-12~~, and E~~e~~quation ~~4~~ 5 is used for the other halogenated compounds. Lifetimes, REs and $AGWP_{CO2}$ are as in WMO (2022) for the halogenated species, and in Forster et al. (2021)[3]. for CH_4 and N_2O.

Acronym/name	Lifetime (yr)	Stratospheric lifetime (yr)	GWP100 (IPCC/WMO)	GWP100 corrected	Difference
CH_4	11.8		28.1	28.6	1.9%
N_2O	109		267	275	3.1%
CFC-11	52	55	6,410	6,879~~20~~	~~+~~7.2~~8~~%
CFC-12	102	103	12,500	13,~~200~~100	~~+~~4.7~~5~~%
CFC-113	93	65.4	4,600	4,940	7.3%
Halon-1211	16	41	1,990	2,170	8.8%
HCFC-22	11.6	120	1,910	1,96~~7~~0	~~+~~32.9%
HFC-32	5.27	146	749	794	~~+~~6.0%
HFC-134a	13.5	313	1,470	1,510	~~+~~2.4%
HFC-152a	1.50	44.3	153	178	~~+~~16.2%
HFC-161	0.217	20	5	8	~~+~~63.4%
~~Fluorobenzene~~	~~0.059~~	~~20~~	~~<1~~	~~1~~	~~+152%~~

4. Discussion

The factor $\frac{\Delta\chi_{sfc}}{\Delta\chi_{atm}}$ discussed above is necessary to correct radiative efficiencies that have been reported per change in surface mole fraction when RE per change in mean atmospheric mole fraction is required, such as in the calculation of GWPs. This ratio should strictly be the ratio of the changes as used in the radiative ~~forcing~~efficiency~~on~~ calculations which is not necessarily that observed in the atmosphere or derived from models.

~~[2] We use here the GWP100 values from the Errata to the IPCC AR6 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Errata.pdf rather than from the tables initially published in~~ Click or tap here to enter text.~~.~~

[3] We use here the GWP100 values from the Errata to the IPCC AR6 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Errata.pdf rather than from the tables initially published in Forster et al. (2021).

Hence, we correct the methane and nitrous oxide radiative efficiencies using the profiles used in Etminan et al. (2016) rather than from Equation ~~3~~4. For CO_2 the radiative ~~forcing~~efficiency ~~on~~ calculations from Etminan et al. (2016) and parameterised in Meinshausen et al. (2020) used a constant profile with height so do not need a correction. For halogenated species the ratios shown in figure 1c are taken from the profiles used to calculate the radiative efficiencies in (Hodnebrog et al., 2013, 2020) so are appropriate to correct the reported values.

Although the GWP100 values for species with lifetimes less than a year are very uncertain and depend, for example, on where the species are emitted, they are widely reported and used; hence even for these it is important to correct systematic underestimates of over 10%.

We have shown here the application to the GWP, but as most climate emission metrics (for example, GWP* and global temperature-change potential – GTP) scale with the radiative efficiency per mass (e.g., Forster et al. 2021) these will be similarly affected, as will calculations of GWP for different time horizons.

~~Simple climate models often project atmospheric mean mole fractions of greenhouse gases to generate climate scenarios . Radiative forcing calculations based on these projections should also correct the radiative efficiencies using the $\frac{\Delta\chi_{sfc}}{\Delta\chi_{atm}}$ factor.~~ However, calculations of radiative forcing from observed changes in *surface* mole fractions using radiative efficiencies should not use this correction. We recommend that, in future, calculations or assessments of radiative efficiencies report both the radiative forcing per surface mole fraction change and per mean-atmospheric mole fraction change.

5. Conclusions

We have shown that it is inconsistent to use radiative efficiency (per surface mole fraction) calculations in the standard GWP formulation if the radiative efficiency calculations~~y~~ account for decreases in atmospheric mole fraction above the surface. Since these calculations account for a decreased atmospheric mass of the species, this must also be accounted for in the conversion to radiative efficiency per mass; otherwise, the inconsistency will cause errors in the GWP calculation. ~~Similarly, calculations of radiative forcing from projected greenhouse gas molar fractions for climate scenarios should also be corrected to use radiative forcing per mean-atmospheric mole fraction rather than per surface mole fraction.~~

For species where the main decrease in mole fraction occurs in the stratosphere, the effect is only around 5% to ~~8~~7% but, nevertheless, neglect of the correction leads to a systematic underestimate of the GWP ~~or radiative forcing~~. For species with short tropospheric lifetimes (of the order of a year or less) the underestimates can be 10~~-60~~%, or even larger ~~for species with lifetimes less than a month~~.

Correcting these underestimates can bring the GWP100 for some species over critical legislative thresholds (see, for example, Section 4 of Hodnebrog et al., 2020) and thus impact on their perceived desirability for use for certain applications. For instance, the GWP100 for HFC-32 increases from 749 to 794. It is recommended that the corrections provided in this letter are applied to GWP values and other climate emission metrics from the IPCC Assessment Reports and WMO Ozone Assessments.

Data Availability

The data for the figure are available from Zenodo with the DOI 10.5281/zenodo.18485657 (Hodnebrog, 2026)

Acknowledgements

WJC and KPS were supported by the UK Natural Environment Research Council (NERC) Grant "Investigating Halocarbon Impacts on the global environment" (Grant Reference NE/X004198/1). ØH was supported by the Research Council of Norway (project no. 336227).

Author contributions

WJC and ØH conceived the study. ØH analysed the data. All authors contributed to drafting and reviewing the text.

Competing interests

The authors declare that they have no conflict of interest

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