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UV and infrared absorption spectra, atmospheric lifetimes, and ozone depletion and global warming potentials for CCl$_2$FCCl$_2$F (CFC-112), CCl$_3$CCIF$_2$ (CFC-112a), CCl$_3$CF$_3$ (CFC-113a), and CCl$_2$FCF$_3$ (CFC-114a)

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Abstract. The potential impact of CCl$_2$FCF$_3$ (CFC-114a) and the recently observed CCl$_2$FCCl$_2$F (CFC-112), CCl$_3$CCIF$_2$ (CFC-112a), and CCl$_3$CF$_3$ (CFC-113a) chlorofluorocarbons (CFCs) on stratospheric ozone and climate is presently not well characterized. In this study, the UV absorption spectra of these CFCs were measured between 192.5 and 235 nm over the temperature range 207–323 K. Precise parameterizations of the UV absorption spectra are presented. A 2-D atmospheric model was used to evaluate the CFC atmospheric loss processes, lifetimes, ozone depletion potentials (ODPs), and the associated uncertainty ranges in these metrics due to the kinetic and photochemical uncertainty. The CFCs are primarily removed in the stratosphere by short-wavelength UV photolysis with calculated global annually averaged steady-state lifetimes (years) of 63.6 (61.9–64.7), 51.5 (50.0–52.6), 55.4 (54.3–56.3), and 105.3 (102.9–107.4) for CFC-112, CFC-112a, CFC-113a, and CFC-114a, respectively. The range of lifetimes given in parentheses is due to the 2σ uncertainty in the UV absorption spectra and O(1D) rate coefficients included in the model calculations. The 2-D model was also used to calculate the CFC ozone depletion potentials (ODPs) with values of 0.98, 0.86, 0.73, and 0.72 obtained for CFC-112, CFC-112a, CFC-113a, and CFC-114a, respectively. Using the infrared absorption spectra and lifetimes determined in this work, the CFC global warming potentials (GWPs) were estimated to be 4260 (CFC-112), 3330 (CFC-112a), 3650 (CFC-113a), and 6510 (CFC-114a) for the 100-year time horizon.

1 Introduction

Chlorofluorocarbons (CFCs) are potent ozone-depleting and greenhouse gases that were phased out of production under the Montreal Protocol agreement (1987) and its subsequent amendments and adjustments. Laube et al. (2014) recently reported the first observation of tetrachloro-1,2-difluoroethane (CCl$_2$FCCl$_2$F, CFC-112), tetrachloro-1,1-difluoroethane (CCl$_3$CCIF$_2$, CFC-112a), and 1,1,1-trichloro-2,2,2-trifluoroethane (CCl$_3$CF$_3$, CFC-113a) in the atmosphere with emission sources dating back to the 1960s. The atmospheric mixing ratios in the year 2000 were found to be ~0.5 ppt (parts per trillion) (CFC-112), ~0.08 ppt (CFC-112a), and ~0.3 ppt (CFC-113a), which are minor compared to a total chlorine mixing ratio of 3.3 ppb (parts per billion) (year 2012), where CCl$_3$F (CFC-11), CCl$_2$F$_2$ (CFC-12), and CCl$_2$FCCIF$_2$ (CFC-113) account for ~60% of the total (WMO, 2014). The atmospheric mixing ratio of CFC-112 and CFC-112a was found to have leveled off in the late
1990s, while the mixing ratio of CFC-113a was found to be increasing through to the present day, which is contrary to the objectives of the Montreal Protocol. Laube et al. (2014) estimated the stratospheric lifetimes for these substances, using a tracer–tracer analysis, to be 51 (37–82), 44 (28–98), and 51 (27–264) years for CFC-112, CFC-112a, and CFC-113a, respectively, where the values in parentheses are the range of the lifetimes determined in their analysis. The inferred ozone depletion potentials (ODPs) were 0.88 (0.62–1.44), 0.88 (0.5–2.19), and 0.68 (0.34–3.79) for CFC-112, CFC-112a, and CFC-113a, respectively, where the range in parentheses was derived from the range in the CFC lifetime given above. Atmospheric measurements of CFC-114 are estimated to include a ∼10 % fraction due to CFC-114a (WMO, 2014). The atmospheric lifetime of CFC-114a is estimated to be similar to that of CFC-12, i.e., ∼100 years (WMO, 2014). It is clear that the CFCs are long-lived compounds and potent ozone-depleting substances and greenhouse gases. It is expected that these compounds would be predominantly removed from the atmosphere via short-wavelength UV photolysis, primarily in the stratosphere. However, to date, there are no UV absorption spectra for these compounds available, which are needed to better evaluate their atmospheric impact.

In this study, UV absorption spectra were measured for CFC-112, CFC-112a, CFC-113a, and 1,1-dichlorotetrafluoroethane (CCl2FCF3, CFC-114a) between 192.5 and 235 nm over the temperature range 207–323 K. The Goddard Space Flight Center (GSFC) 2-D atmospheric model was used to evaluate the reactive and photolytic loss processes and calculate globally averaged lifetimes and ozone depletion potentials. In addition, infrared absorption spectra were measured at 296 K for these compounds and used to estimate their global warming potentials (GWP).

The concentration ranges used were (in 10⁻³): CFC-112, CFC-112a, CFC-113a, and 1,1-dichlorotetrafluoroethane (CCl2FCF3, CFC-114a) between 192.5 and 235 nm over the temperature range 207–323 K. The Goddard Space Flight Center (GSFC) 2-D atmospheric model was used to evaluate the reactive and photolytic loss processes and calculate globally averaged lifetimes and ozone depletion potentials. In addition, infrared absorption spectra were measured at 296 K for these compounds and used to estimate their global warming potentials (GWP).

2 Experimental details

2.1 UV measurements

The experimental apparatus has been described in detail previously (McGillen et al., 2013; Papadimitriou et al., 2013a, b) and is only briefly discussed here. The output of a stable 30 W deuterium (D2) lamp light source was collimated and directed through a jacketed 90.4 ± 0.3 cm single-pass absorption cell. The beam exiting the cell was focused onto the entrance slit (150 µm) of a 0.25 m monochromator (∼1 nm resolution) and detected using a photomultiplier tube (PMT). The temperature of the absorption cell was controlled to within ±1 K. Absorption measurements were made at 10 discrete wavelengths at temperatures between 207 and 323 K to enable spectrum parameterizations appropriate for stratospheric conditions.

Beer’s law was applied to determine the absorption cross section, σ(λ, T), at each wavelength and temperature:

\[ A(\lambda, T) = \ln \left( \frac{I(\lambda)}{I(\lambda) - I_d} \right) = \sigma(\lambda, T) \times L \times [\text{CFC}], \]  

where \( A(\lambda, T) \) is the absorbance at wavelength \( \lambda \) and temperature \( T \), \( I_d \) is the signal recorded in the absence of light, \( I(\lambda) \) and \( I(\lambda) \) are the measured signal in the absence and presence of the CFC sample, \( L \) is the cell pathlength, and \([\text{CFC}]\) is the gas-phase CFC concentration. The PMT signal was recorded with a 1 kHz sampling rate and a ∼20 s average was used in the data analysis. \( I(\lambda) \) was recorded at the beginning and end of each measurement, which typically agreed to 0.1 % or better. Absorbance measurements were made at each wavelength over a range of CFC concentration under static conditions. The CFCs were added to the absorption cell from dilute mixtures; the CFC concentration was determined using the sample mixing ratio, the absorption cell pressure and temperature, and the ideal gas law. A linear least-squares fit of \( A(\lambda, T) \) vs. \([\text{CFC}]\) was used to obtain \( \sigma(\lambda, T) \).

For the CFC-112 and CFC-112a measurements, an optical neutral density filter was inserted between the D2 lamp and the absorption cell to attenuate the probe beam and minimize CFC loss due to photolysis (sample photolysis was not observed for CFC-113a and CFC-114a). In addition, a mechanical shutter blocked the D2 lamp beam while the absorption cell was being filled. Under most conditions, photolytic loss of the CFC-112 and CFC-112a was undetectable. However, at the higher concentrations used in this study minor photolytic loss (∼2 %) was observed. In these cases, a least-squares fit of the first ∼20 s of the PMT signal was used in the data analysis to obtain the initial \( I(\lambda) \) signal.

2.2 Infrared absorption measurements

Infrared absorption spectra at 296 K for CFC-112, CFC-112a, CFC-113a, and CFC-114a were measured over the 500 to 4000 cm⁻¹ wavenumber range using Fourier transform infrared (FTIR) spectroscopy. Measurements were made using a 15 cm single-pass Pyrex absorption cell and an MCT detector at a resolution of 1 cm⁻¹ with 100 co-adds. The CFC sample was introduced into the absorption cell from a dilute mixture prepared offline, and the CFC concentration was determined using the ideal gas law. Absorption cross sections were determined using Beer’s law, Eq. (1), with the spectrum measurements consisting of ∼10 different concentrations. The concentration ranges used were (in 10¹⁶ molecule cm⁻³) (0.348–10.2), (0.453–3.84), (0.376–1.90), and (0.279–4.02) for CFC-112, CFC-112a, CFC-113a, and CFC-114a, respectively. The infrared absorption spectra recorded for CFC-112 and CFC-112a were corrected for the presence of a minor (∼4 %) isomer impurity as determined from a ¹⁹F NMR sample analysis.

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3 Results and discussion

The absorption spectrum, $\sigma(\lambda, T)$, measurements obeyed Beer’s law with fit precisions of $\sim 1\%$ or less for all wavelengths and temperatures included in this study. Replicate measurements using different sample mixing ratios, bath gas, range of absorption, and optical filtering agreed to within the measurement precision and were combined in a global linear least-squares fit in the final data analysis.

The UV absorption spectra of the CFC-112 and CFC-112a samples were measured at 10 discrete wavelengths between 192.5 and 235 nm at 5 discrete temperatures between 230 and 323 K. The results, not corrected for the isomeric impurity present in the samples, are summarized in Tables S1 and S2 and shown in Figs. S1 and S2 of the Supplement. To account for the isomeric impurity, $\sigma(\lambda, T)$ for CFC-112 and CFC-112a were parameterized using the following empirical formula:

$$\ln (\sigma(\lambda, T)) = \sum_i A_i \lambda_i^{-1} + (T - 296) \sum_i B_i \lambda_i^{-1}.$$  \hspace{1cm} (2)

The parameterizations reproduced the experimental data to better than $\sim 2\%$ over the wavelength range most critical to atmospheric photolysis, i.e., between 195 and 215 nm. The results from the $^{19}$F NMR sample analysis were then used to obtain the final spectrum parameterizations.

The UV absorption spectra for CFC-113a and CFC-114a were measured at 10 discrete wavelengths between 192.5 and 235 nm at 6 discrete temperatures between 207 and 323 K. The cross section results are given in Tables 1 and 2 and shown in Figs. 1 and 2. The CFC UV absorption spectra were parameterized using Eq. (2). The parameterizations reproduced the experimental data to within $\sim 4\%$ or better, as shown in Figs. 1 and 2.

The fit parameters are given in Table 3, and a comparison of the parameterized 296 K spectra is shown in Fig. 3. The UV absorption spectra of the CFCs are continuous over the wavelength range included in this study with a precipitous decrease in cross section with increasing wavelength. A decrease in $\sigma(\lambda, T)$ with decreasing temperature was observed at nearly all wavelengths included in this study with the temperature dependence being greatest at the longer wavelengths (see Figs. 1, 2, and S1 and S2). The $\sigma(\lambda, 323 K)$ measurements, although not entirely atmospherically relevant, were included in the study to better define the absorption spectrum temperature dependence and its parameterization. As shown in Fig. 3, the UV absorption spectra for the CFCs show distinct differences in their absolute cross sections and wavelength dependence over the region most critical for determining their atmospheric photolysis rates, i.e., lifetimes. The spectra demonstrate that CFCs with increased chlorine content are stronger absorbers in this wavelength region, although the molecular structure of the molecule also plays an important role. For example, the C$_2$ClF$_2$ isomer with more
Table 1. CCl₃CF₃ (CFC-113a) UV absorption cross section data (10⁻²⁰ cm² molecule⁻¹, base e) obtained in this work.

| λ (nm) | 323 K | 296 K | 271 K | 250 K | 232 K | 207 K |
|--------|-------|-------|-------|-------|-------|-------|
| 192.5  | 131.6 ± 1.5 | 132.5 ± 1.1 | 136.9 ± 1.0 | 137.2 ± 0.9 | 141.4 ± 1.6 | 139.7 ± 0.9 |
| 195    | 103.9 ± 0.2  | 106.6 ± 0.6  | 106.8 ± 0.9  | 107.5 ± 1.2  | 110.2 ± 1.0  | 111.0 ± 0.3  |
| 200    | 64.3 ± 0.2   | 63.9 ± 0.6   | 63.9 ± 1.2   | 63.6 ± 0.6   | 64.5 ± 0.6   | 63.5 ± 0.4   |
| 205    | 35.3 ± 0.14  | 34.1 ± 0.2   | 33.5 ± 0.13  | 33.2 ± 0.2   | 31.9 ± 0.3   | 31.3 ± 0.3   |
| 210    | 17.3 ± 0.10  | 16.2 ± 0.1   | 15.3 ± 0.11  | 14.4 ± 0.1   | 13.9 ± 0.17  | 12.5 ± 0.2   |
| 215    | 7.99 ± 0.02  | 7.25 ± 0.01  | 6.58 ± 0.02  | 5.94 ± 0.06  | 5.77 ± 0.06  | 5.26 ± 0.07  |
| 220    | 3.57 ± 0.014 | 3.07 ± 0.02  | 2.65 ± 0.007 | 2.36 ± 0.02  | 2.23 ± 0.008 | 2.09 ± 0.02  |
| 225    | 1.55 ± 0.014 | 1.29 ± 0.01  | 1.04 ± 0.004 | 0.912 ± 0.006 | 0.813 ± 0.01  | 0.778 ± 0.04  |
| 230    | 0.673 ± 0.009 | 0.521 ± 0.004 | 0.418 ± 0.003 | 0.357 ± 0.008 | 0.322 ± 0.003 |
| 235    | 0.297 ± 0.018 | 0.208 ± 0.001 | 0.157 ± 0.006 | 0.139 ± 0.006 |

* Quoted uncertainties are 2σ fit precision values (rounded off).

Table 2. CCl₂CF₃ (CFC-114a) UV absorption cross section data (10⁻²⁰ cm² molecule⁻¹, base e) obtained in this work.

| λ (nm) | 323 K | 296 K | 271 K | 250 K | 232 K | 207 K |
|--------|-------|-------|-------|-------|-------|-------|
| 192.5  | 32.8 ± 0.2 | 32.2 ± 0.3 | 31.6 ± 0.2 | 30.7 ± 0.2 | 30.0 ± 0.3 | 28.2 ± 0.2 |
| 195    | 21.8 ± 0.1 | 20.7 ± 0.1 | 19.9 ± 0.1 | 19.0 ± 0.1 | 18.4 ± 0.1 | 17.3 ± 0.1 |
| 200    | 8.72 ± 0.01 | 7.86 ± 0.045 | 7.26 ± 0.02 | 6.70 ± 0.03 | 6.26 ± 0.04 | 5.88 ± 0.05 |
| 205    | 3.31 ± 0.01 | 2.86 ± 0.01 | 2.50 ± 0.03 | 2.29 ± 0.02 | 2.12 ± 0.02 | 1.91 ± 0.02 |
| 210    | 1.21 ± 0.003 | 0.991 ± 0.003 | 0.835 ± 0.006 | 0.757 ± 0.006 | 0.655 ± 0.083 | 0.555 ± 0.002 |
| 215    | 0.440 ± 0.002 | 0.345 ± 0.001 | 0.276 ± 0.001 | 0.246 ± 0.006 | 0.197 ± 0.001 | 0.168 ± 0.001 |
| 220    | 0.162 ± 0.002 | 0.118 ± 0.0004 | 0.0926 ± 0.0003 | 0.0786 ± 0.0013 | 0.0626 ± 0.0003 | 0.0534 ± 0.0014 |
| 225    | 0.0600 ± 0.0001 | 0.0409 ± 0.0006 | 0.0307 ± 0.0002 | 0.0253 ± 0.0002 | 0.0204 ± 0.0004 | 0.0176 ± 0.0046 |
| 230    | 0.0147 ± 0.0004 | 0.0110 ± 0.0002 |
| 235    | 0.00553 ± 0.00025 |

* Quoted uncertainties are 2σ fit precision values (rounded off).

chlorine atoms on a carbon atom, CFC-112a (CCl₃CCIF₂), absorbs more strongly than CFC-112 (CCl₂FCCl₂F).

The spectrum parameterizations given in Table 3 reproduce the experimental data very well. The overall 2σ uncertainty in σ(λ, T) for CFC-112, CFC-112a, CFC-113, and CFC-114a, including estimated systematic errors, is estimated to be ~4% over the range of wavelengths and temperatures included in this study.

The measured infrared spectra for each of the CFCs obeyed Beer’s law with a fit precision of ~0.3% and were independent of total pressure over the pressure range 20–250 Torr (He bath gas). The infrared spectra are shown in Fig. 4, and digitized spectra are available in the Supplement. Table S3 in the Supplement provides a detailed comparison of our results with those of Olliff and Fischer (1992, 1994) for all the CFCs and Etminan et al. (2014) for CFC-113a. Overall the agreement between the studies is better than 10%.

4 Atmospheric implications

The atmospheric loss processes, lifetimes, ODPs, and associated uncertainties for the CFCs included in this study were quantified using the Goddard Space Flight Center (GSFC) 2-D atmospheric model (Fleming et al., 2011). The calculations used the UV spectrum parameterizations obtained in this work with an assumed unit photolysis quantum yield at all wavelengths. As discussed in Sect. 3, an overall 2σ uncertainty of 4% was used at all wavelengths and temperatures for the UV cross sections of the four CFCs. For Lyman-α (121.567 nm), absorption cross sections are not available for these CFCs; values (in units of 10⁻¹⁷ cm² molecule⁻¹) of 13, 15, 9.8, and 2 were estimated for CFC-112, CFC-112a, CFC-113a, and CFC-114a, respectively, based on values available for similar molecules (see Ko et al., 2013, chap. 3). An estimated Lyman-α cross section uncertainty factor of 2 (2σ) was used. Rate coefficients for the O(¹D) reaction with CFC-113a and CFC-114a were taken from Baasandorj et al. (2011) with 2σ uncertainty factors of 1.25 and 1.2, respectively (Burkholder et al., 2015b). Rate coefficients for the O(¹D) reaction with CFC-112 and CFC-112a were estimated to be 3 x 10⁻¹⁰ cm³ molecule⁻¹ s⁻¹ with a 0.9 reac-
Table 3. Parameterization of the UV absorption spectra for CCl$_2$FCCl$_2$F (CFC-112), CCl$_3$CCIF$_2$ (CFC-112a), CCl$_3$CF$_3$ (CFC-113a), and CCl$_2$FCF$_3$ (CFC-114a) obtained in this work. The parameterization is for wavelengths 192.5–235 nm and temperatures 230–323 K for CFC-112 and CFC-112a and 207–323 K for CFC-113a and CFC-114a. Units: $\sigma(\lambda, T)$ (cm$^2$ molecule$^{-1}$, base e), $\lambda$ (nm), and $T$ (K) $\ln(\sigma(\lambda, T)) = \sum_i A_i \lambda_i^i + (T - 296) \sum_i B_i \lambda_i^i$.

| Molecule | $i$ | $A_i$ | $B_i$ |
|----------|-----|-------|-------|
| CCl$_2$FCCl$_2$F (CFC-112) | 0 | -1488.6207 | 6.04688 |
| | 1 | 18.43604 | -0.0801501 |
| | 2 | -0.02897393 | 0.0001201698 |
| | 3 | -0.00051504703 | 2.610366 $\times 10^{-6}$ |
| | 4 | 2.644261 $\times 10^{-6}$ | -1.3959106 $\times 10^{-8}$ |
| | 5 | -3.7258313 $\times 10^{-9}$ | 2.0719264 $\times 10^{-11}$ |
| CCl$_3$CCIF$_2$ (CFC-112a) | 0 | -560.3404 | 10.37492 |
| | 1 | 9.534427 | -0.182485408 |
| | 2 | -0.06987945 | 0.0011614979 |
| | 3 | 0.0002657157 | 2.9864183 $\times 10^{-6}$ |
| | 4 | -5.491224 $\times 10^{-7}$ | 1.5478787 $\times 10^{-9}$ |
| | 5 | 4.993769 $\times 10^{-10}$ | 3.36518 $\times 10^{-12}$ |
| CCl$_3$CF$_3$ (CFC-113a) | 0 | -319.173 | 2.89174 |
| | 1 | 2.70954 | -0.0348043 |
| | 2 | 0.00457404 | 3.6233 $\times 10^{-5}$ |
| | 3 | -0.0001288147 | 1.08853 $\times 10^{-6}$ |
| | 4 | 4.71409 $\times 10^{-7}$ | -5.25744 $\times 10^{-9}$ |
| | 5 | -5.35388 $\times 10^{-10}$ | 7.26095 $\times 10^{-12}$ |
| CCl$_2$FCF$_3$ (CFC-114a) | 0 | -253.6338 | 0.52031 |
| | 1 | 2.899454 | -0.005044 |
| | 2 | -0.0081158 | 1.6142 $\times 10^{-6}$ |
| | 3 | -3.68328 $\times 10^{-5}$ | 7.2259 $\times 10^{-8}$ |
| | 4 | 2.071842 $\times 10^{-7}$ | 2.4996 $\times 10^{-11}$ |
| | 5 | -2.5764 $\times 10^{-10}$ | -5.9642 $\times 10^{-13}$ |

tive branching ratio and an uncertainty factor of 1.5 (2$\sigma$). All other kinetic and photochemical parameters were taken from Sander et al. (2011). All model results presented in this study are for year 2010 steady-state conditions. Surface mixing ratio boundary conditions for 2010 are based on the Laube et al. (2014) results for CFC-112, CFC-112a, and CFC-113a; for CFC-114a, a 2010 value of 1.6 ppt is used, based on measurements of CFC-114, which are a combination of CFC-114 and CFC-114a, with an assumed relative contribution of 10% for CFC-114a (WMO, 2014).

Model calculations of the CFC fractional atmospheric loss processes are given in Table 4, and the altitude profiles for CFC-112 are shown in Fig. 5. The calculated atmospheric profiles for CFC-112a, CFC-113a, and CFC-114a are provided in the Supplement. UV photolysis is the predominant atmospheric loss process for each of the CFCs. Lyman-α photolysis is important only in the mesosphere above 65 km; it has a negligible contribution to the overall global loss (< 0.001). The O(1D) reaction is a minor stratospheric loss process, ~2%, for CFC-112, CFC-112a, and CFC-113a, but more significant for CFC-114a, ~7%. The UV photolysis and O(1D) reactive loss of the CFCs leads to the direct release of reactive chlorine and the formation of chlorine containing radicals (Burkholder et al., 2015a).

The CFC lifetimes were computed as the ratio of the annually averaged global atmospheric burden to the vertically integrated annually averaged total global loss rate (Ko et al., 2013). The total global lifetime ($\tau_{Tot}$) was also separated by the troposphere ($\tau_{trop}$, surface to the tropopause, seasonally and latitude-dependent), stratosphere ($\tau_{Strat}$), and meso-
Table 4. Fractional losses and ranges (in parentheses) for CCl$_2$FCCl$_2$F (CFC-112), CCl$_3$CClF$_2$ (CFC-112a), CCl$_3$CF$_3$ (CFC-113a), and CCl$_2$FCF$_3$ (CFC-114a) calculated using the GSFC 2-D model and the UV absorption spectra and estimated Lyman-α cross sections reported in this work.

| Molecule          | Lyman-α | 190–230 nm (in parentheses) | O(^1D) |
|-------------------|---------|-----------------------------|--------|
| CCl$_2$FCCl$_2$F  | < 0.001 | 0.978 (0.953–0.99)          | 0.022  |
| (CFC-112)         |         | (0.047–0.01)                |        |
| CCl$_3$CClF$_2$   | < 0.001 | 0.979 (0.955–0.99)          | 0.021  |
| (CFC-112a)        |         | (0.045–0.01)                |        |
| CCl$_3$CF$_3$     | < 0.001 | 0.979 (0.968–0.986)         | 0.021  |
| (CFC-113a)        |         | (0.032–0.014)               |        |
| CCl$_2$FCF$_3$    | < 0.001 | 0.929 (0.903–0.948)         | 0.071  |
| (CFC-114a)        |         | (0.097–0.052)               |        |

Figure 2. CCl$_2$FCF$_3$ (CFC-114a) UV absorption spectrum (base e) and parameterization obtained in this work. Cross section data (symbols, Table 2) and the parameterization of the data using the empirical formula and parameters given in Table 3 (see text). The lower frame shows the overall quality of the parameterization.

The 2-D model total global annually averaged lifetimes and the range in lifetimes are given in Table 5. The 2σ range in the lifetime was calculated using the absolute 2σ maximum and minimum in the UV absorption spectra and estimated Lyman-α cross sections reported in the present work, along with the 2σ uncertainties in the O(^1D) rate coefficients taken from Sander et al. (2011). The CFCs are long-lived and primarily removed in the stratosphere by UV photolysis. The uncertainty in the calculated lifetime due to the uncertainty in the UV absorption spectra measured in this work is small, < 3%. The absolute lifetime uncertainty due to the kinetic and photochemical input parameters is expected to be small compared to that calculated using different atmospheric models due to the individual model treatment of dynamics, chemistry, radiation, numerics, and other processes (Chipperfield et al., 2014; Ko et al., 2013). In general, the lifetime uncertainty due to the kinetic and photochemical input parameters is also expected to be small compared to the uncertainty due to transport processes and actinic fluxes (due to, for example, uncertainty in the J[O$_2$] cross sections; e.g., see Ko et al., 2013). However, evaluation of all processes that contribute to uncertainty in the total CFC lifetime is beyond the scope of the present paper.

The model-calculated stratospheric lifetimes for CFC-112, CFC-112a, CFC-113a, and CFC-114a are in reasonable agreement with
the values of 51 (37–82), 44 (28–98), and 51 (27–264) years reported by Laube et al. (2014) (uncertainty ranges in parentheses). The lifetimes reported by Laube et al. were based on a tracer-tracer analysis (see Plumb and Ko, 1992; Volk et al., 1997, for method details) using a reference CFC-11 lifetime of 45 years. Scaling to the 52-year CFC-11 lifetime given in WMO (2014) brings the results into better agreement with the present work. The range of lifetimes obtained in the model results, which was determined solely based on the uncertainty in the kinetic and photochemical input parameters, is, however, significantly less than that obtained in the tracer-tracer analysis. It is worth noting that while the total global lifetimes of the isomers CFC-112 and CFC-112a are similar, the lifetimes of CFC-113a (55.4 years) and CFC-114a (105.3 years) are substantially shorter (by ∼60%) than those of the isomers CFC-113 (93 years) and CFC-114 (189 years) (WMO, 2014).

### 4.1 Ozone depletion potentials (ODPs)

The semi-empirical and model-calculated ODPs for the CFCs are given in Table 6. The ODP was calculated following the methodology used previously (Fisher et al., 1990; Wuebbles, 1983). Steady-state simulations for year 2010 were run with the surface boundary conditions for the four CFCs, and CFC-11 (used as the reference compound) in-
Figure 5. Global annually averaged vertical profiles of the atmospheric loss processes, molecular loss rates, and mixing ratio for CCl₂FCCl₂F (CFC-112) calculated using the GSFC 2-D atmospheric model for year 2010. The model calculations were performed using the CFC-112 UV absorption spectrum from this work and other model input parameters taken from the literature as described in the text. The global annually averaged lifetime for CFC-112 was calculated to be 63.6 (61.9–64.7) years.

Table 6. Lifetimes, ozone depletion potentials (ODPs), radiative efficiencies (REs), and global warming potentials (GWPs) obtained in this work and literature values for comparison.

| Molecule         | Lifetime (years) | Ozone depletion potential (ODP) | Radiative efficiency (W m⁻² ppb⁻¹) | Global warming potential time horizons (years) |
|------------------|------------------|---------------------------------|-------------------------------------|-----------------------------------------------|
|                  | Semi-empirical   | 2-D model²                      | 20                   | 100    | 500    |
| CCl₂FCCl₂F (CFC-112) | 63.6             | 0.88 (0.62–1.44)               | 0.28                              | 5330   | 4260   | 1530   |
| CCl₃CCl₂F (CFC-112a) | 51.5             | 0.88 (0.50–2.19)               | 0.25                              | 4600   | 3330   | 1110   |
| CCl₃CF₃ (CFC-113a) | 55.4             | 0.68 (0.34–3.79)               | 0.24                              | 4860   | 3650   | 1240   |
| CCl₂FCF₃ (CFC-114a) | 105.3            | 0.72 (±0.01)                   | 0.28                              | 6750   | 6510   | 3000   |
| CCl₂FCCIF₂ (CFC-113) | 93²              | 0.81–0.82²                     | 0.95                              | 6490²  | 5820²  |
| CClIF₂CCIF₂ (CFC-114) | 189²             | 0.50²                          | 0.31²                             | 7710²  | 8590²  |
| CClIF₂CF₃ (CFC-115) | 540²             | 0.26²                          | 0.20²                             | 5860²  | 7670²  |
| CCl₂F₂ (CFC-12) | 102²             | 0.73–0.81²                     | 1.01                              | 10 800² | 10 200² |
| CCl₄ | 26², c         | 0.72²                          | 1.06                              | 0.17²  | 3480²  | 1730²  |

² Semi-empirical ODPs and uncertainty ranges taken from Laube et al. (2014). b Taken from WMO (2014). c CCl₄ stratospheric lifetime of 44 years given in WMO (2014). d The uncertainty range in the model-calculated ODPs reported here is due to the uncertainty in the UV and Lyman-α (estimated) spectra obtained in this work and uncertainty in the O(1D) rate coefficients taken from Sander et al. (2011).

mean age of air, i.e., the fractional amount of a CFC that has been dissociated at a given point in the stratosphere (and the subsequent release of inorganic chlorine), relative to the amount of a CFC that entered at the tropopause (e.g., Daniel et al., 2007; Douglass et al., 2008; Laube et al., 2013; Newman et al., 2007; Schauffler et al., 2003). Differences in the semi-empirical vs. model ODPs in Table 6 are due, at least in part, to differences in the observationally based fractional release factors taken for mid-latitude conditions compared to the global model calculations. Differences in the ODPs may...
also arise from differences in the Ko et al. (2013) lifetimes used for the semi-empirical ODPs vs. the model lifetimes, although these lifetime differences are small.

4.2 Calculated radiative efficiencies (REs) and global warming potentials (GWPs)

Table 6 summarizes the radiative efficiencies (REs) for the CFCs calculated using the methods described in Hodnebrog et al. (2013) and the global warming potentials (GWPs) for the 20-, 100-, and 500-year time horizons using the lifetimes and infrared spectra from this work. The CFCs are potent greenhouse gases and radiative forcing agents due to their high REs and long atmospheric lifetimes. The GWPs for these long-lived compounds are comparable or less than those of the atmospherically most abundant CFCs. For example, the 100-year time-horizon GWPs for CFC-11 (CClF), CFC-12 (CClF2), and CFC-113 (CClFCClF2) are 4660, 10 200, and 5820, respectively (WMO, 2014). Emnian et al. (2014) reported a RE of 0.23 W m⁻² ppb⁻¹ for CFC-113a and a GWP₁₀₀ of 3310 using a lifetime of 51 years. These values are in reasonable agreement with the present results.

5 Conclusions

Short-wavelength UV absorption spectra for CClFCClF₂ (CFC-112), CClF₂CCl₂F (CFC-112a), CCl₂F₃ (CFC-113a), and CCl₂FCClF₃ (CFC-114a) measured in this work between 192.5 and 235 nm and at temperatures in the range 207 to 323 K were combined with 2-D model-calculated ODPs of 0.98, 0.86, 0.73, and 0.72 for CFC-112, CFC-112a, CFC-113a, and CFC-114a, respectively. The uncertainty in the model-calculated lifetimes due to the 2σ uncertainty in the UV absorption spectra reported in this work was found to be small, < 3%. These CFCs are potent ozone-depleting substances with 2-D model-calculated ODPs of 0.98, 0.86, 0.73, and 0.72 for CFC-112, CFC-112a, CFC-113a, and CFC-114a, respectively. The uncertainty in the model calculated ODPs due to the uncertainty in the UV spectra and O(¹D) reactive loss was small, ± 0.015. These CFCs are also potent greenhouse gases with GWPs comparable to those of the most abundant CFCs present in the atmosphere.

6 Data availability

Additional data and figures can be found in the Supplement.

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