Contents lists available at ScienceDirect



Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

The first remote-sensing measurements of HFC-32 in the Earth's atmosphere by the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS)



魙

ournal of Ouantitative Spectroscopy &

adiative

R. Dodangodage^a, P.F. Bernath^{a,b,c,*}, C.D. Boone^c, J. Crouse^c, J.J. Harrison^{d,e}

^a Department of Physics, Old Dominion University, Norfolk, VA, United States 23529

^b Department of Chemistry and Biochemistry, Old Dominion University, Norfolk, VA, United States 23529

^c Department of Chemistry, University of Waterloo, Waterloo, ON Canada N2L 3G1

^d Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, United Kingdom

^e National Centre for Earth Observation, University of Leicester, Leicester LE1 7RH, United Kingdom

ARTICLE INFO

Article history: Received 14 January 2021 Revised 11 June 2021 Accepted 13 June 2021 Available online 18 June 2021

Keywords: Difluoromethane (HFC-32) Atmospheric Chemistry Experiment Infrared solar absorption spectroscopy Montreal Protocol

ABSTRACT

Atmospheric hydrofluorocarbon (HFC) abundances are increasing rapidly because of the Montreal Protocol phase-out of the production and consumption of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). HFC-32 (CH_2F_2 , difluoromethane) mole fractions (volume mixing ratios, VMRs) have been retrieved from infrared absorption spectra recorded from orbit with the Atmospheric Chemistry Experiment Fourier transform spectrometer (ACE-FTS) between 2004 and 2020. Global altitude-latitude distributions have been determined from the ACE-FTS VMR altitude profiles. The HFC-32 VMR time series have been computed and compared with values obtained from in situ flask measurements made by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory. HFC-32 abundances are increasing exponentially.

© 2021 Elsevier Ltd. All rights reserved.

1. Introduction

Molina and Rowland [1] showed that chlorine atoms released by the photolysis of chlorofluorocarbons (CFCs) destroy stratospheric ozone, which blocks UV radiation in the 200 to 300 nm range from reaching the Earth's surface. In order to protect the stratospheric ozone layer, the Montreal Protocol [2] was adopted in 1987 to phase out the production and consumption of ozonedepleting substances (ODSs) such as CFCs. The parties to the Montreal Protocol meet annually, and there have been many amendments and adjustments.

The developing countries ("Article 5 countries") and developed countries ("non-Article 5 countries") have different schedules for phaseout of ODSs. CFCs are now phased out in all countries and their temporary replacements, hydrochlorofluorocarbons (HCFCs), are phased out for dispersive uses in developed countries and by 2031 will be phased out in all countries. HCFCs have shorter atmospheric lifetimes than CFCs because they react with OH radicals, but they still reach the stratosphere and deplete ozone. Hydrofluorocarbons (HFCs) have replaced HCFCs because they have very

* Corresponding author. E-mail address: pbernath@odu.edu (P.F. Bernath). small ozone depletion potentials [3]. HFCs in use, however, typically have large Global Warming Potentials (GWPs) [4] and contribute to an increase in surface temperature. For example, the widely used HFC-134a (CF_3CH_2F) has a GWP of 1360 (100 yr). HFCs have a small effect on stratospheric ozone because they alter the temperature of the stratosphere which indirectly leads to the destruction of stratospheric ozone [3].

The most recent amendment to the Montreal Protocol is the Kigali amendment which will phase-down production of HFCs with large GWPs [5]. CH_2F_2 (HFC-32, difluoromethane) is a controlled substance under the Kigali amendment. Phase-down of HFC production started in 2019 for developed countries. Under the Kigali amendment, the allowable GWP-weighted HFC production and consumption will have to be reduced to 15–20% of the current values by 2045–2047 for developing countries and to 15% by 2036 for developed countries.

CFCs, HCFCs, and HFCs are used as refrigerants, in air conditioning systems, as fire suppressants and as foam blowing agents. HFC-32 is used in air conditioners. It is also used in various blends in refrigeration systems; for example, R-407F which has a GWP of 1790 (100-year) consists of 30% HFC-32, 30% HFC-125 (CF₃CHF₂) and 40% HFC-134a, and R-410A with a GWP of 2080 (100-year) consists of 50% HFC-32 and 50% HFC-125 [3]. Reaction with hydroxyl radicals (OH) in the troposphere and stratosphere, and reaction with $O(^{1}D)$ in the stratosphere are the main HFC sinks. HFC-32 has an atmospheric lifetime of 5.2 years [4] (5.4 years [3]), stratospheric lifetime of 124 years [3], a GWP of 809 (100-year) [4] (705 (100-year) [3]) and a radiative efficiency of 0.11 W m⁻² ppb⁻¹ [3,4].

Atmospheric abundances of HFCs, including HFC-32, have been increasing rapidly in recent years and there have been extensive in situ ground-based measurements. The Advanced Global Atmospheric gases Experiment (AGAGE) stations [6] have provided a set of CFC, HCFC and HFC observations; for example, HFC-32 had a global abundance of 12.6 ppt in 2016 with a precision of 3% [6]. In 2004, HFC-32 had an abundance of only 0.7 ppt at Mace Head in Ireland [7] and was growing rapidly. In December 2020, the NOAA flask value for Mace Head had increased to 28.7 ppt (see below). Simmonds et al. [8] used data for HCFC-22, HCFC-141b, HCFC-142b, HCFC-124, HCFC-134a, HFC-125, HFC-143a, and HFC-32 from five AGAGE sites with a two-dimensional chemical transport model to estimate global emissions. HFC-32 global emissions were estimated to be 31.2 \pm 14.4 Gg/yr in 2015, third largest after HFC-134a and HFC-125. The rapid growth of HFC-143a and HFC-32 was reported by O'Doherty et al. [9] using AGAGE measurements for the period 2003 to 2012 combined with archived flask measurements dating back to 1977. In addition to the continuous AGAGE monitoring of HFC-32, the NOAA (National Oceanic and Atmospheric Administration) Global Monitoring Laboratory is making extensive flask measurements of HFC-32 at many sites starting in 2009 [10].

In addition to global measurements, regional atmospheric emissions have also been determined in several studies. Kim et al. [11] estimated Chinese emissions of many anthropogenic halogenated compounds including HFC-32 based on in situ measurements from the Gosan station in Korea. US emissions of HFC-32 were estimated using AGAGE data from MACE Head in Ireland [12] as well as NOAA flask samples from around the globe [13]. Say et al. [14] report the first top-down estimates for India's halocarbons including HFC-32 from a low-altitude aircraft campaign in June and July 2016.

According to the 2018 Ozone Assessment [3], HFC-32 was the fifth most abundant HFC in 2016 with a global mean surface mole fraction of 11.9 ppt, increasing by 1.6 ppt/year during 2012 - 2016. There are, however, no published remote sensing observations of HFC-32; we report the first measurements of HFC-32 by solar infrared absorption spectroscopy from orbit.

2. Methods

SCISAT also known as the Atmospheric Chemistry Experiment (ACE) was launched by NASA on August 12, 2003. The original goal was to improve the understanding of chemical and dynamical processes that control the distribution of ozone, simultaneously measuring a wide range of molecules in the stratosphere and the upper troposphere [15]. With 17 years of data, measuring changes in atmospheric composition is now an important goal [16,17]. The satellite orbits the Earth at an altitude of 650 km with an inclination of 73.9° to the equator. The primary instrument onboard ACE is the high resolution Fourier Transform Spectrometer (ACE-FTS) operating in the 750 - 4400 cm⁻¹ region with a spectral resolution of 0.02 cm⁻¹. ACE-FTS uses the solar occultation technique to measure atmospheric absorption spectra during sunset and sunrise with respect to the orbiting satellite, typically 30 measurement opportunities per day.

The HFC-32 results employed in this study represent a "research product" using the software, viewing geometry, and the pressure and temperature altitude profiles from ACE-FTS version 4.1 processing [18]. Well-calibrated, reliable infrared absorption cross sections are essential for HFC retrievals. Our retrievals employed new

cross sections generated from measurements at the High Resolution Spectroscopy Facility (HRSF), Rutherford Appleton Laboratory (RAL) using an experimental setup and procedures described previously for similar measurements [19,20]. These HFC-32 measurements are described in greater detail in a separate paper [21], but a few brief observations will be made here. The set of suitable high resolution HFC-32 cross sections currently available in the HI-TRAN compilation [22] are from a 1996 study by Smith et al. [23]. As noted by Harrison [21], the new cross sections are up to ~15% larger than the Smith et al. [23] cross sections. The Smith et al. [23] cross sections are also under-resolved and suffer from a significant wavenumber shift (~0.04 cm⁻¹). The new cross sections [21] are wavenumber calibrated with N₂O lines and intensity calibrated using the PNNL cross sections [24]. As discussed and based on experience [19-21], the integrated areas of the PNNL cross sections are assumed to be "standard" values. The estimated absolute error (1σ) of the cross sections is 3% [21], which propagates directly into the VMR retrievals.

The calculated HFC-32 spectrum at tangent height 5 km for volume mixing ratios (VMRs) circa 2020 is shown in Fig. 1. Peak absorption is ~5% in 2020 but was significantly smaller early in the ACE mission when HFC-32 levels were relatively low. There is a relatively sharp feature near 1090 cm⁻¹ that helps discriminate the HFC-32 contribution to the spectrum. Microwindows employed in the HFC-32 retrieval, listed in Table 1, are indicated in Fig. 1 by the bars below the spectrum. In the least-squares fitting, a common set of baseline parameters (baseline scaling and baseline slope) are used for the first 14 microwindows listed in Table 1 (corresponding to the bars in Fig. 1). Regions between the microwindows typically have elevated residuals for lines from molecules such as H₂O [25], which could introduce a bias in the retrieval if included in the analysis (and are therefore avoided).

The given spectral region contains contributions from a large number of interfering species. In the retrieval, weak contributions to the microwindow regions are calculated for acetone, CFC-113 (CClF₂CCl₂F), HCFC-142b (CH₃CClF₂), and HFC-134a (CF₃CH₂F) based on previously generated retrieval results for these molecules. Contributions from PFC-116 (C₂F₆), H-1211 (CBrClF₂), H-1301 (CBrF₃), and CFC-13 (CClF₃) are calculated from expected VMRs based on AGAGE observations [6]. VMR profiles for molecules with more significant contributions to the microwindow regions are determined simultaneously with the HFC-32 retrieval, using separate VMR profiles for different isotopologues of the same molecule in order to account for atmospheric fractionation. The interferers in the HFC-32 retrieval are CFC-11 (CCl₃F), CFC-12 (CCl₂F₂), HCFC-141b (CH₃CCl₂F), HCFC-22 (CHClF₂), H₂O, H₂¹⁸O, HDO, CO₂, ¹⁸OCO, O₃, ¹⁸000, O¹⁸00, CH₄, CH₃D, HCOOH, and COClF. Other molecules that have reasonable abundances (about 10 ppt at the surface) and for which cross sections are available such as HFC-143a (CH₃CF₃), HFC-152a (CH₃CHF₂) and HFC-125 (CF₃CHF₂) were also considered as interferers but were not found to be significant. CH₃Cl was also included as an interferer due to its presence in the window used to improve results for CH₃D indicated in Table 1. Line parameters and cross sections were taken from HITRAN 2016 [22], except for improved cross sections employed for CFC-11 [26] and HCFC-141b [27].

3. Results and discussion

ACE-FTS HFC-32 VMRs were sorted into 5° latitude bins at each altitude (1 km vertical grid) for the entire mission (Feb. 2004-July 2020). Based on the expected VMR values and retrieval errors, VMR values less than -24 ppt and greater than 50 ppt were removed. Negative VMRs are allowed in the retrieval and are retained in our averages in order to prevent a positive bias. Median average deviation (MAD) values at each altitude were calculated



Fig. 1. The calculated HFC-32 spectrum at tangent height 5 km for a VMR profile corresponding to occultation sr90644, measured June 9th, 2020 near latitude 35 °N and longitude 125 °W. Bars under the spectrum indicate microwindow regions employed in the retrieval (see Table 1).

Table 1

Microwindow center (cm ⁻¹)	Microwindow width (cm^{-1})	Lower altitude limit (km)	Upper altitude limit (km)
1076.55	0.46	7 - 2sin ² (latitude)	23
1078.00	0.44	7 - 2sin ² (latitude)	23
1079.33	0.58	7 - 2sin ² (latitude)	23
1080.47	0.74	7 - 2sin ² (latitude)	23
1082.95	0.66	7 - 2sin ² (latitude)	23
1084.06	0.76	7 - 2sin ² (latitude)	23
1086.35	0.70	7 - 2sin ² (latitude)	23
1087.43	0.78	7 - 2sin ² (latitude)	23
1089.33	2.46	7 - 2sin ² (latitude)	23
1093.85	3.30	7 - 2sin ² (latitude)	23
1097.60	3.00	7 - 2sin ² (latitude)	23
1099.10	0.80	14 - 5sin ² (latitude)	23
1101.65	0.70	15 - 6sin ² (latitude)	23
1103.48	1.00	7 - 2sin ² (latitude)	23
1085.56 ^a	1.40	7 - 2sin ² (latitude)	11 - 4sin ² (latitude)
1091.00 ^a	0.80	11 - 4sin ² (latitude)	21
1977.60 ^b	0.50	7 - 2sin ² (latitude)	21
2623.87 ^c	0.90	7 - 2sin ² (latitude)	21
2950.86 ^d	0.26	9 - 3sin ² (latitude)	23

^a Microwindow to improve result for H₂O.

^b Microwindow to improve result for H₂¹⁸O.

^c Microwindow to improve result for HDO (includes ¹⁸OCO and CH₄).

^d Microwindow to improve result for CH₃D (includes H₂O, H₂¹⁸O, and CH₃Cl).

and then VMRs outside the range of the median ± 4 MADs were filtered out to remove unphysical data. Each HFC-32 VMR for an individual profile has an associated statistical error of ~8 ppt. The fractional error for an individual profile at altitudes 7.5–16.5 km is between 45%–65%, increasing to 120%–200% at altitudes 17.5–20.5 km. As altitude increases, the VMR decreases but the uncertainty remains relatively constant thus increasing the percentage error.

The global altitude-latitude distribution of HFC-32 VMRs averaged over the entire period February 2004 to July 2020 is given Fig. 2. The VMRs are larger in the Northern Hemisphere which has a larger land mass and where the major emitters are located, consistent with the relatively short lifetime of 5.2 years [3]. The average altitude VMR profiles for 30–60°N (red) and 30–60°S (blue) for June, July and August 2019 in Fig. 3 clearly show a hemispheric asymmetry of about 3–4 ppt above 8 km, in comparison to a hemispheric difference of about 6 ppt from NOAA surface data. One standard deviation on the mean values are plotted in Fig. 3. There is also a small seasonal cycle of about 1 ppt in the Northern Hemisphere (45°N-80°N, 7.5–10.5 km) with the highest values in June, July and August. This cycle is likely caused by increased emissions from air conditioners and refrigeration in the summer. The VMRs decrease almost linearly with altitude in both the troposphere and the stratosphere. The VMR values at low altitudes are high relative to surface values due to retrieval problems in the troposphere.

There is spectroscopic interference, possibly H_2O , in the retrieval at low altitude in the troposphere because HFC-32 VMRs should be relatively constant in the troposphere as a consequence of vertical mixing. Interference from H_2O is often a problem because of non-Voigt line shapes that are not correctly represented



Fig. 2. HFC-32 mission average altitude-latitude distribution. VMR is given in ppt and latitude in degrees. Contour lines are labeled in ppt.

Table 2

in the forward model and it is difficult to avoid water lines at low altitudes. Retrievals below 6.5 km in altitude were not satisfactory, even in the polar regions. There is also a potential problem with the retrieval at 20.5 km in altitude (the retrieved VMR profile unexpectedly stops decreasing with increasing altitude) where the HFC-32 signal is very low.

VMR values from February 2004 to July 2020 were separated into four seasons: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA) and September, October, November (SON), and then averaged. The four distributions (not shown) were all very similar to Fig. 2, except for a noticeable localized stratospheric deficit of HFC-32 in the SON plot due to descent in the Antarctic polar vortex.

As HFC-32 is a replacement for HCFCs, its atmospheric abundance is rapidly increasing. To determine the VMR time series, the VMR values in the 30°N to 60°N latitude region for the 7.5 km to 9.5 km altitude range were averaged for each quarter in each year from 2004 to 2020. For comparison, NOAA flask data from seven Northern Hemisphere stations (Table 2) were averaged. The VMR data were not mass-weighted in the averages. Flask data and ACE data show an exponential growth of HFC-32 as illustrated in Fig. 4.

ACE data has a small annual cycle, which peaks in the summer, was removed in Fig. 4 and the exponential equation, $VMR(t) = VMR(2004)e^{at}$, with t = year-2004 and VMRs in ppt was used to fit the time series. The equation for ACE-FTS VMR time series is

$$VMR(t) = 3.65 \pm 0.23e^{0.114 \pm 0.0024t}$$
(1)

Table	~		
NOAA	flask	stations	used

Station Name	Latitude	Height above Sea Level	Data Period Start
Mauna Loa, USA	19.5°N	3397 m	2009
Cape Kumukahi, USA	19.5°N	3 m	2009
Niwot Ridge, USA	40.1°N	3475 m	2014
Trinidad Head, USA	41.0°N	120 m	2009
Wisconsin, USA	45.6°N	868 m	2014
Harvard Forest, USA	42.5°N	340 m	2014
Mace Head, Ireland	53.3°N	42 m	2014

and the equation for the NOAA flask data is

$$VMR(t) = 3.15 \pm 0.52e^{0.1903 \pm 0.0056t}.$$
 (2)

For the NOAA time series, t = year-2009. The derivatives of equations (1) and (2) give the instantaneous annual trend values in ppt/year. HFC-32 observations from in situ Medusa GC–MS measurements at AGAGE stations, as reported by O'Doherty et al. [9], also indicate rapid and accelerating growth.

In the early part of the time series, the ACE-FTS values are biased high (Fig. 4) relative to NOAA, likely related to an interferer missing in the calculated spectrum, which would also explain the slope in the tropospheric VMR in Fig. 3. The spectral window used for the HFC-32 retrieval is very busy with numerous interferers already included. The retrieval gives a constant value of about 5 ppt for early times rather than trending towards 0 (Fig. 4). At later times, the agreement with NOAA is better, but a bias in the retrieval may still be present.



Fig. 3. HFC-32 average VMR profiles for 30-60°N (red) and 30-60°S (blue) for June, July and August 2019. For this time period, the average surface value at Mace Head in Ireland is 22.5 ppt and at Cape Grim in Australia is 15.6 ppt.



Fig. 4. ACE-FTS and NOAA HFC-32 VMR time series. The ACE-FTS quarterly average VMR values are for 30°N to 60°N and for 7.5 km to 9.5 km in altitude.

4. Conclusion

The first remote sensing retrievals of HFC-32 have been carried out using infrared solar occultation spectra recorded from orbit with the ACE-FTS. The VMR profiles show a nearly linear decrease in VMR with altitude in the upper troposphere and lower stratosphere. The altitude-latitude VMR distribution is as expected, except in the troposphere, for a molecule with an atmospheric lifetime of 5.2 years. The VMRs are enhanced in the Northern Hemisphere where most of the emitters are located. HFC-32 abundances are increasing exponentially; the exponents are 0.1140 \pm 0.0024t for ACE-FTS and 0.1903 \pm 0.0056t for NOAA. The ACE-FTS retrieval has a time-dependent bias relative to NOAA surface measurements. This molecule will be included in the next ACE-FTS processing version (version 5.0). ACE-FTS research retrievals of HFC-32 are available upon request from the ACE Science Operations center at the University of Waterloo (jcrouse@scisat.ca).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

R. Dodangodage: Writing - original draft, Formal analysis, Visualization. **P.F. Bernath:** Writing - review & editing, Supervision. **C.D. Boone:** Data curation, Writing - review & editing, Software. **J. Crouse:** Data curation, Writing - review & editing. **J.J. Harrison:** Data curation, Writing - review & editing.

Acknowledgements

The ACE satellite mission is funded by the Canadian Space Agency. The new spectroscopic measurements of HFC-32 were funded as part of the UK Research and Innovation Natural Environment Research Council's support of the National center for Earth Observation, contract number PR140015. The HFC-32 flask data are provided by the Global Monitoring Division of the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL/GMD) (ftp://ftp.cmdl.noaa.gov/hats/hfcs/). HFC-32 data from the Global Monitoring Laboratory are provided courtesy of I. Vimont and S. Montzka.

References

- Molina MJ, Rowland FS. Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone. Nature 1974;249:810–12. doi:10.1038/ 249810a0.
- [2] Montreal Protocol on Substances that Deplete the Ozone. Layer 1987. https: //ozone.unep.org/treaties/montreal-protocol.
- [3] (World WMO. Meteorological Organization), Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project-report no 2018;58:588.
- [4] Hodnebrog Ø, Aamaas B, Fuglestvedt JS, Marston G, Myhre G, Nielsen CJ, et al. Updated global warming potentials and radiative efficiencies of halocarbons and other weak atmospheric absorbers. Rev Geophys 2020;58 e2019RG000691. doi:10.1029/2019RG000691.
- [5] Kigali Amendment to the Montreal Protocol 2016; https://ozone.unep.org/ treaties/montreal-protocol/amendments/kigali-amendment-2016-amendmentmontreal-protocol-agreed

- [6] Prinn RG, Weiss RF, Arduini J, Arnold T, DeWitt HL, Fraser PJ, et al. History of chemically and radiatively important atmospheric gases from the Advanced Global Atmospheric Gases Experiment (AGAGE). Earth Syst Sci Data 2018;10:985–1018. doi:10.5194/essd-10-985-2018.
- [7] Greally B, Simmonds P, O'Doherty S, McCulloch A, Miller B, Salameh P, et al. Improved continuous in situ measurements of C1-C3 PFCs, HFCs, HFCs, CFCs and SF₆ in Europe and Australia. Environ Sci 2005;2:253–61. doi:10.1080/ 15693430500402614.
- [8] Simmonds PG, Rigby M, McCulloch A, O'Doherty S, Young D, Mühle J, et al. Changing trends and emissions of hydrochlorofluorocarbons (HCFCs) and their hydrofluorocarbon (HFCs) replacements. Atmos Chem Phys 2017;17:4641–55. doi:10.5194/acp-17-4641-2017.
- [9] O'Doherty S, Rigby M, Mühle J, Ivy D, Miller B, Young D, et al. Global emissions of HFC-143a (CH₃CF₃) and HFC-32 (CH₂F₂) from in situ and air archive atmospheric observations. Atmos Chem Phys 2014;14:9249–58. doi:10.5194/ acp-14-9249-2014.
- [10] Montzka SA, McFarland M, Andersen SO, Miller BR, Fahey DW, Hall BD, et al. Recent trends in global emissions of hydrochlorofluorocarbons and hydrofluorocarbons: reflecting on the 2007 adjustments to the Montreal Protocol. J Phys Chem A 2015;119:4439–49. doi:10.1021/jp5097376.
- [11] Kim J, Li S, Kim K-R, Stohl A, Mühle J, Kim S-K, et al. Regional atmospheric emissions determined from measurements at Jeju Island, Korea: halogenated compounds from China. Geophys Res Lett 2010;37:L12801. doi:10. 1029/2010GL043263.
- [12] Simmonds P, Derwent R, Manning A, McCulloch A, O'Doherty S. USA emissions estimates of CH₃CHF₂, CH₂FCF₃, CH₃CF₃ and CH₂F₂ based on in situ observations at Mace Head. Atmos Environ 2015;104:27–38. doi:10.1016/j.atmosenv. 2015.01.010.
- [13] Hu L, Montzka SA, Lehman SJ, Godwin DS, Miller BR, Andrews AE, et al. Considerable contribution of the Montreal Protocol to declining greenhouse gas emissions from the United States. Geophys Res Lett 2017;44:8075–83. doi:10.1002/2017GL074388.
- [14] Say D, Ganesan AL, Lunt MF, Rigby M, O'Doherty S, Harth C, et al. Emissions of halocarbons from India inferred through atmospheric measurements. Atmos Chem Phys 2019;19:9865–85. doi:10.5194/acp-19-9865-2019.
- [15] Bernath P. The Atmospheric Chemistry Experiment (ACE). J Quant Spectrosc Rad Transfer 2017;186:3–16. doi:10.1016/j.jqsrt.2016.04.006.
- [16] Bernath PF, Steffen J, Crouse J, Boone CD. Sixteen-year Trends in Atmospheric Trace Gases from Orbit. J Quant Spectrosc Rad Transfer 2020;253:107178. doi:10.1016/j.jqsrt.2020.107178.
- [17] Bernath PF, Crouse J, Hughes RC, Boone CD. The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) version 4.1 retrievals: trends and seasonal distributions. J Quant Spectrosc Rad Transfer 2021;259:107409. doi:10.1016/j.jqsrt.2020.107409.
- [18] Boone CD, Bernath PF, Cok D, Steffen J, Jones SC. Version 4 retrievals for the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) and Imagers. J Quant Spectrosc Rad Transfer 2020;247:106939. doi:10.1016/j. jqsrt.2020.106939.
- [19] Harrison JJ, Allen NDC, Bernath PF. Infrared absorption cross sections for ethane (C₂H₆) in the 3 μm region. J Quant Spectrosc Rad Transfer 2010;111:357–63. doi:10.1016/j.jqsrt.2009.09.010.
- [20] Harrison JJ. New and improved infrared absorption cross sections for dichlorodifluoromethane (CFC-12). Atmos Meas Tech 2015;8:3197-207. doi:10. 5194/amt-8-3197-2015.
- [21] Harrison JJ. New infrared absorption cross sections of difluoromethane (HFC-32) for remote sensing. J Quant Spectrosc Rad Transfer 2021;270:107639. doi:10.1016/j.jqsrt.2021.107639.
- [22] Gordon IE, Rothman LS, Hill C, Kochanov RV, Tan Y, Bernath PF, et al. The HI-TRAN 2016 molecular spectroscopic database. J Quant Spectrosc Rad Transfer 2017;203:3–69. doi:10.1016/j.jqsrt.2017.06.038.
- [23] Smith K, Newnham D, Page M, Ballard J, Duxbury G. Infrared band strengths and absorption cross-sections of HFC-32 vapour. J Quant Spectrosc Rad Transfer 1996;56:73–82. doi:10.1016/0022-4073(96)00019-2.
- [24] Sharpe SW, Johnson TJ, Sams RL, Chu PM, Rhoderick GC, Johnson PA. Gas-phase databases for quantitative infrared spectroscopy. Appl Spectrosc 2004;58:1452–61. doi:10.1366/0003702042641281.
- [25] Boone CD, Walker KA, Bernath PF. Speed-dependent Voigt profile for water vapor in infrared remote sensing applications. J Quant Spectrosc Rad Transfer 2007;105:525–32. doi:10.1016/j.jqsrt.2006.11.015.
- [26] Harrison JJ. New and improved infrared absorption cross sections for trichlorofluoromethane (CFC-11). Atmos Meas Tech 2018;11:5827–36. doi:10.5194/ amt-11-5827-2018.
- [27] Harrison JJ. Infrared absorption cross sections for air-broadened 1,1-dichloro-1-fluoroethane (HCFC-141b). J Quant Spectrosc Rad Transfer 2019;238:106489. doi:10.1016/j.jqsrt.2019.04.041.