

An Updated Inventory of Fluorspar (CaF_2) Production, Industrial Use, and Emissions of Trifluoroacetic Acid (TFA) from 1930, Including the Period from 2000 to 2020

Andrew A. Lindley 

Isle of North Uist, Scotland

Email: andy.a.lindley@outlook.com

How to cite this paper: Lindley, A. A. (2025). An Updated Inventory of Fluorspar (CaF_2) Production, Industrial Use, and Emissions of Trifluoroacetic Acid (TFA) from 1930, Including the Period from 2000 to 2020. *Journal of Geoscience and Environment Protection*, 13, 132-167. <https://doi.org/10.4236/gep.2025.1311008>

Received: October 11, 2025

Accepted: November 18, 2025

Published: November 21, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0). <http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

The publication of trifluoroacetic acid (TFA) concentrations in the Atlantic Ocean in 2022-2023 prompted an inventory update to include the period 2000 to 2020 for fluorspar (CaF_2) production, use, TFA emissions, and their contribution to TFA in the Atlantic Ocean. The update accounts for 90% of the acid spar used to produce hydrogen fluoride in the period 2000 to 2020. Emissions of TFA due to fluorocarbons (HFCs, HFOs, HCFOs, HCFCs, and anaesthetics) are estimated at 503,700 tonnes in this period. Generation of TFA from the use of pesticides is estimated at 239,000 to 796,000 tonnes globally, assuming a 30% to 100% yield of TFA. In total, estimated emissions of TFA, from 1930 to 2020, are 1,019,000 tonnes, with a theoretical upper limit of 2,283,000 tonnes, which includes the quantity of TFA manufactured, where production is assumed to equal emissions. The estimated emissions of TFA to the Atlantic Ocean from 1930 to 2020 are 467,000 tonnes, with a theoretical upper limit of 1,215,000 tonnes. This is not consistent with the measured TFA concentrations, which suggest the Atlantic Ocean contains at least 40 million tonnes of TFA, possibly over 80 million tonnes, and must therefore include a large natural burden.

Keywords

Fluorspar, Trifluoroacetic Acid (TFA), HFCs, Pesticides, Anesthetics

1. Introduction

There continue to be different positions on whether trifluoroacetic acid (TFA) occurs naturally in the oceans, although it is generally accepted that there are only very minor quantities of TFA transferred from the oceans to land, estimated at

less than 1 tonne/year, if the behaviour of TFA is analogous to that of HCl transport from sea salt aerosol, but scaled according to the concentrations of TFA and Cl^- in surface seawater (Clegg, 2023). This is consistent with the conclusion that the ocean is essentially a sink for TFA, in contrast to enrichment of longer-chain perfluoro alkyl acids (PFAAs) in nascent sea spray aerosols (SSA), suggesting that SSA are an important source of PFAAs to the atmosphere (Sha et al., 2021a, 2021b). Therefore, anthropogenic TFA is the source of TFA found in rivers, ground waters, surface waters, and precipitation. Recent publications have reported TFA concentrations in a wide range of water types, foodstuffs, and beverages (Garavagno et al., 2024; Moscato et al., 2025). The publication of trifluoroacetic acid (TFA) concentrations in the Atlantic Ocean in 2022-2023 (UBA, 2024) prompted an update to the inventory of fluorospar production and use, and TFA emissions to include the period 2000 to 2020. The previous inventory covered the period 1930 to 1999 (Lindley, 2023), as TFA oceanic concentrations were previously measured in 1998-2002 and, assuming uniform distribution of 200 ng/L, was of the order of 500 - 1000 times greater than the estimated total anthropogenic TFA input to the environment (including Montreal Protocol gases, pesticides, pharmaceuticals, and industrial uses) in the period 1930-1999, hence demonstrating the contribution of one or more natural source(s) of TFA (Neale et al., 2025). The earlier TFA concentration measurements were not as extensive as the 2022-2023 measurements, and their extrapolation to estimate oceanic burdens of TFA was disputed in review paper "Insufficient evidence for the existence of natural trifluoroacetic acid" (Joudan, De Silva, & Young, 2021) "*Such estimates are speculative as the calculated TFA burdens are based on extrapolation of uncertain concentrations using unrealistic assumptions of spatial homogeneity throughout the ocean, and that their limited measurements are the most representative. The propagation of error in this workflow results in a highly uncertain burden.*" In addition, the paper also stated that for measurements (Scott et al., 2005) "*For example, in the Atlantic Ocean, TFA ranged from 20 to 200 ng L⁻¹ from 23°N, 20°W to 38°N, 73°W. This variability is consistent with more recent analysis of PFAS profiles in ocean sampling across extensive latitudinal gradients.*" The review paper concludes that "*the presence of TFA in the deep ocean and lack of closed TFA budget is not sufficient evidence that TFA occurs naturally, especially without a reasonable mechanism of formation.*"

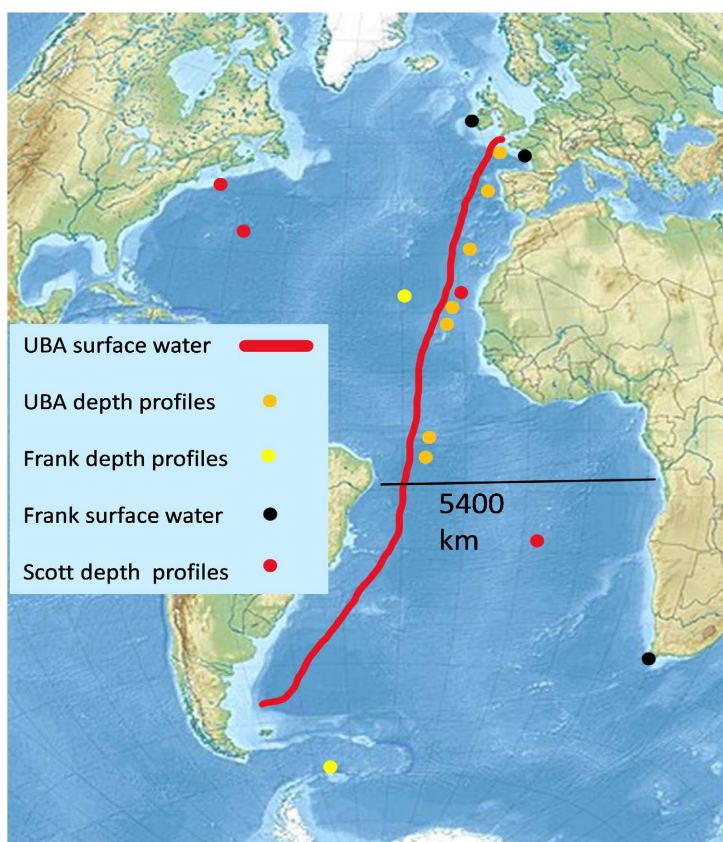
The UBA report "Analysis of current seawater samples for trifluoroacetic acid" (UBA, 2024) is an important new study on current concentrations of TFA in the Atlantic Ocean and can be used to address some of the points raised by Joudan et al. A validated analytical method was applied by UBA to surface water and deep-sea water samples of the Atlantic Ocean collected in 2022 and 2023 during two independent sampling campaigns. During the expeditions, a total of 33 surface water samples were taken in the Atlantic Ocean at 31 measuring points between latitudes 47° south to 50° north. The surface water samples had TFA concentrations between 260 ng/L and 306 ng/L. A total of seven depth profiles of the Atlan-

tic Ocean were obtained, at maximum extraction depths of 3800 m and 4590 m. The TFA concentrations of samples from seven depth profiles ranged from 237 ng/L to 294 ng/L. All depth profiles, with one exception, showed a slight decrease in TFA concentration with increasing ocean depth. The UBA report comments that, compared with sampling campaigns in the Atlantic from 1998 (Frank et al., 2002) and 1998/2002 (Scott et al., 2005), the TFA contents of depth profiles determined in the UBA report work are at a greater level. Frank et al. found a median TFA content of 202 ng/L (range: 190 - 210 ng/L) for a depth profile in the mid-Atlantic, while the median content of all seawater samples obtained in the UBA study was 273 ng/L (range: 237 - 294 ng/L; n = 41). Including the near-surface seawater samples collected, the median TFA content of the depth profile samples in the UBA study is 278.5 ng/L (range: 237 - 306 ng/L; n = 48). The Frank results for the Southern Ocean were similar to those of the depth profile in the mid-Atlantic (Frank et al., 2002). The small fluctuation range of the TFA contents within and between UBA depth profiles is similar to that observed by Frank et al., who also found no pronounced spatial heterogeneity in TFA content. The UBA reported TFA was found at high concentrations over a wide area of the Atlantic Ocean and at depths to 4590 m. The lowest TFA concentration reported by UBA is 237 ng/L, surface seawater samples were taken over a distance of about 12,000 km, and depth profiles were taken over a distance of about 5500 km. **Table 1** and **Figure 1** summarises TFA concentration measurements and sampling locations for the Atlantic Ocean from several sources. The UBA report (UBA, 2024) notes that other PFAS tend to have greater levels in seawater samples from the northern hemisphere (Ahrens et al., 2009; Ahrens et al., 2010; Savvidou et al., 2023). This is attributed to greater production and emission levels of PFAS in the northern compared to the southern hemisphere (Savvidou et al., 2023). In the UBA measurement campaign, no significant difference (two-sample permutation tests; $\alpha = 0.05$) could be determined in the mean TFA contents of samples from the northern and southern hemisphere.

The UBA (UBA, 2024) and Frank (Frank et al., 2002) South Atlantic depth profiles span about 13,300 km. Assuming a narrow corridor of 200 km (about the width of the red line on **Figure 1**) over this distance, a depth of 2000 m, and 200 ng/L TFA results in about 1 million tonnes of TFA, just in this body of water. However, it is highly unlikely that TFA concentrations of ≥ 200 ng/L only occur in this narrow corridor, particularly as similar TFA concentrations have been measured in other areas of the Atlantic Ocean and Arctic Ocean as shown in **Table 1**. While an extrapolation of these concentration measurements to the whole of the Atlantic Ocean (National Centers for Environmental Information, 2025) may have a high degree of uncertainty, the concentration data suggest that there could be over 80 million tonnes of TFA in the Atlantic Ocean, assuming 278.5 ng/L (UBA, 2024) for the whole volume of the Atlantic Ocean. Excluding the depth below 4000 m where there are limited TFA concentration measurements, there would be about 40 million tonnes of TFA. Measurements for the Pacific Ocean in

Table 1. TFA concentration measurements for the Atlantic Ocean.

UBA Surface Water (UBA 2024)	31 measuring points	260 to 306 ng/L	2022, 2023
UBA Depth Profiles (UBA 2024)	7 depth profiles Maximum depths 3800 m and 4590 m	237 to 294 ng/L	2022, 2023
Frank Depth Profiles (Frank et al., 2002)	Mid-Atlantic 0 to 4150 m	190 to 210 ng/L	1998
	South Atlantic (Elephant Island) 10 m to 2000 m	185 to 220 ng/L	1998
Frank Surface Water (Jordan & Frank, 1999)	Ile d'Yeu; France	250 ng/L	1995
	Mace Head; Ireland	70 ng/L	1995
	Cape Point; RSA	160 ng/L	1996
Scott Depth Profiles (Scott et al., 2005) <i>(Note UBA indicates some of the profile locations; concentrations are unclear—these have been omitted from this table and location map)</i>	North Atlantic ~38°N, 73°W 0 - 1000 m	28 to 190 ng/L	1998
	North Atlantic ~31°N, 64°W 0 - 947 m	17 to 150 ng/L	1998
	North Atlantic ~23°N, 20°W 0 - 3800 m	120 to 150 ng/L	2002
	South Atlantic ~18°S, 4°E ~100 to 5300 m	64 to 155 ng/L	2002
	Eastern Arctic Nares Strait to ~500 m <i>Not included in Figure 1</i>	~150 ng/L	1998

**Figure 1.** Locations of TFA concentration measurements.

1999 showed elevated concentrations of TFA but, compared to the recent data for the Atlantic Ocean, are relatively limited in scope. However, high concentrations (160 ng/L) were measured in 1998 for the Canadian Basin Deep Waters at 3000 m depth for waters with a high average age (Scott et al., 2005).

Even though the UBA report can be used to address some of the points raised by Joudan et al. about TFA occurring naturally, an updated inventory of fluorospar use and estimated TFA emissions to 2020 globally and to the Atlantic Ocean can provide complementary evidence that the quantity of TFA in the oceans, at least in the Atlantic Ocean, includes a large natural burden.

2. Development of the Updated Inventory

The general methodology employed in the 1930 to 1999 inventory was used (Lindley, 2023) to extend the inventory up to the end of 2020. This was selected as the end date because emissions data, which are required for TFA generation, are available for significant fluorocarbon sources of TFA up to 2020 in the Scientific Assessment Panel Report (Scientific Assessment of Ozone Depletion, 2022). Additional emissions of TFA in the period 2021 to 2022 could increase the estimated emissions by about 10% in the period 2000 to 2020. Emissions of the major CFCs, HCFCs, and HFCs are relatively well characterized, either by atmospheric measurements (top-down) or from production, use, and bottom-up emission factors (e.g., AFEAS, 2000). The quantity of TFA generated depends on the estimated emissions, which typically are reported as annual means with an uncertainty range. Slightly different annual emissions are reported depending on the source, which will determine the derived generation of TFA. Therefore, estimates of TFA generated in this inventory for fluorocarbon emissions to the atmosphere have an uncertainty range which could be $\pm 10\%$ from emissions uncertainty. The yields of TFA from fluorocarbons released to the atmosphere are not completely characterised. A sensitivity analysis uses upper limits of TFA yields to estimate the likely maximum TFA formation from fluorocarbons (EEAP, 2023). Production data for HCFCs and CFCs are published by the Ozone Secretariat (Ozone Secretariat, 2025), but there are no similar data for HFCs, requiring a different approach to estimate production. HFOs and HCFOs were introduced commercially in the period after 2010; their production data are not available and emissions are not characterised due to their rapid degradation in the atmosphere, although estimated emissions are reported for global emissions of HFO-1234yf (Scientific Assessment of Ozone Depletion, 2022) and for European emissions (UBA, 2021). The formation of TFA from pesticides containing the CF_3 group is uncertain, as there are a relatively large number of pesticides having the CF_3 group, and global pesticide production and use data are not available. However, three recent publications (EEAP, 2023; Joerss et al., 2024; UBA, 2023) provide sufficient data to develop an estimate of possible maximum TFA formation globally. In reviewing the previous inventory (1930-1999), the TFA formation from pesticides has been revised, due to availability of new data and revision of a previous assumption, and, for

anaesthetics, the data for the period until the end of 1999 have been revised to correct for the emissions data previously used, which was in error. Emissions from the use of HFCs (HFC-134a and HFC-227ea) as propellants for pressurized metered dose inhalers (pMDIs) are included in total atmospheric emissions, and HFOs were not used for pMDIs in the period to 2020. Other sources considered include pharmaceuticals and fluoropolymers. In addition, TFA discharges and deposition to the Atlantic Ocean drainage basin are estimated for these sources of TFA, as the recent UBA TFA measurements are only for the Atlantic Ocean.

Uncertainties in the TFA emissions estimates are considered. Sensitivity analyses increase fluorocarbon emissions by 10% and separately use the upper limits or upper theoretical limits for TFA yields (EEAP, 2023). A theoretical upper limit for TFA emissions combines 100% molar yields from pesticides and assumes 100% of the quantity of TFA manufactured is emitted. Emissions to the Atlantic Ocean use the maximum ocean and drainage basin areas for TFA in precipitation and for pesticide use. The surface-area approach is a reasonable first-order approximation for long-lived, globally dispersed precursors, such as HFCs. The location of pesticide use determines the eventual discharge of TFA generated. Potential TFA emissions in 2021 and 2022 are also considered.

3. Inventory for Fluorspar Production and Emissions of TFA until 2020

Emissions of TFA are estimated at 799,000 tonnes, with a theoretical upper limit of 1,685,000 tonnes in the period 2000 to 2020 (Table 2). The theoretical upper limit includes 350,000 tonnes of TFA manufactured, which are assumed to be emitted, although this is highly unlikely, and 796,000 tonnes from pesticides assuming 100% molar yields of TFA. The fluorocarbons (HFCs, HFOs, HCFOs, HCFCs, and anaesthetics) account for 503,700 tonnes of the estimated TFA emissions. The total estimated TFA emissions for the period from 1930 until the end of 2000 are 1,019,000 tonnes. The theoretical upper limit of 2,283,000 tonnes includes the quantity of TFA manufactured, assuming production equals emissions, and for pesticides, assumes 100% yield of TFA. Table 3 shows two sensitivity calculations: increasing emissions of these fluorocarbons by 10% and separately using the upper limits or upper theoretical limits for TFA yields (EEAP, 2023). These would increase TFA emissions by 55,000 tonnes (10% emissions increase) or 202,000 tonnes (upper theoretical limits). Significant other industrial uses of fluorspar have not been identified that could account for large additional emissions of TFA.

In the period 2000 to 2020, reported global production of fluorspar is 132.3 million tonnes, of which 71.7 million tonnes is acid spar, and the inventory accounts for 90% of acid spar production by use in this period, and in total for 79% in the period 1930 to 2020 (Table 4). There is a wide range of minor uses of HF that are not accounted for, but do not result in TFA formation. Some of these were

discussed in the previous inventory, but also include perfluorocarbons such as C_2F_6 (used, for example, in electronics manufacture).

An estimate of the contribution of anthropogenic TFA to the Atlantic Ocean is 467,000 tonnes, with a theoretical upper limit of 1,215,000 tonnes until 2020, using the Atlantic Ocean, Caribbean Sea, and Mediterranean Sea and their drainage basins as the catchment area for discharges of TFA to water and for precipitation of TFA from the degradation of fluorocarbons in the atmosphere. The mean ages of the water masses in the Atlantic Ocean are sufficiently long (Liu & Tanhua, 2024) for the TFA contribution estimated since 1930. The estimated contributions from different sources of TFA to the Atlantic Ocean are shown in Table 5. This can be compared with an estimated 1 million tonnes of TFA in the narrow body of water in the Atlantic Ocean, where depth profiles for TFA concentration have been reported (as discussed in the introduction). Clearly, the estimated contribution of anthropogenic TFA to the Atlantic Ocean would be widely dispersed and would be about 0.6% - 1.2% of the TFA burden in the Atlantic Ocean, if it contains 40 to 80 million tonnes estimated from TFA concentration measurements. For the theoretical upper limit of anthropogenic TFA, it would be about 1.5% - 3%. This suggests a large natural burden, and increased emissions of TFA for the sensitivity analysis, additional emissions in 2021 to 2022, or the theoretical upper limit of TFA emissions to the Atlantic Ocean do not change this conclusion.

Table 2. Inventory: Summary of TFA emissions 1930-2020.

Tonnes	2000 to 2020	Up to 1999	Total until the end of 2020
HFCs	284,700	6700	291,400
HFOs, HCFOs	30,600	0	30,600
HCFCs	140,000	16,100	156,100
Anaesthetics (TFA corrected for the period up to 1999)	48,400	33,000	81,400
Pesticides 30% to upper limit 100% TFA yield and revised for the period to 1999.	239,000 to 796,000	150,000 to 500,000	389,000 to 1,296,000
Hexafluoropropene	25,000	7300	32,300
Thermolysis of fluoropolymers	130	60	190
The theoretical upper limit for TFA manufacture assumes all TFA manufactured is emitted—highly unlikely.	21,000 to 350,000	2000 to 30,000	23,000 to 380,000
Pharmaceuticals	10,000	5000	15,000
Total TFA emissions (rounded)	799,000	220,000	1,019,000
Total TFA emissions theoretical upper limit (rounded)	1,685,000	598,000	2,283,000

Table 3. Inventory: Summary of TFA emissions 1930-2020. Sensitivity analysis.

Tonnes	2000 to 2020	Up to 1999	Total until the end of 2020 (rounded)
HFCs, HFOs, HCFOs, HCFCs, anaesthetics (from Table 2)	503,700	55,800	560,000
HFCs, HFOs, HCFOs, HCFCs, anaesthetics (from Table 2), plus 10% uncertainty due to emissions estimates	554,000	61,400	615,000
HFCs, HFOs, HCFOs, HCFCs, anaesthetics (from Table 2) apply upper limits or upper theoretical limits for TFA yields.	696,500	65,800	762,000

Table 4. Inventory: Summary of production and consumption of fluorspar 1930-2020.

Million tonnes	2000 to 2020	Up to 1999	Total until the end of 2020
Global Fluorspar production	132.3	191.9	324.2
Metspar and ceramic grade production and use (inorganic)	60.6	96.9	157.5
Acidspar grade production (with a minimum purity of 97%) for HF	71.7	95.0	166.7
Losses due to acidspar purity (97.5%) and HF yield (97.5%).	3.6	8.9	12.5
Overall availability HF as CaF₂ equivalent	68.1	86.1	154.2
Identified uses of HF as CaF₂ equivalent			
HFCs	13.8	1.1	14.9
HFOs, HCFOs	0.3	0	0.3
HCFCs (including feedstock use)	18.6	8.1	26.7
CFCs	0.5	14.6	15.1
Anaesthetics	0.3	0.1	0.4
Pesticides	0.9	0.3	1.2
TFA manufacture	0.5	0.03	0.5
Primary aluminium production	17.7	25.3	43
Rare earth metals, other inorganic, and catalytic uses of hydrogen fluoride	8.1	9.6	17.7
Halons	0	0.1	0.1
Total acid spar accounted for (including losses)	64.3	68.1	132.4
Acid spar was accounted for as a share of the total	90%	72%	79%

Table 5. Estimate of maximum contribution of anthropogenic TFA to the Atlantic Ocean.

Tonnes	1930-2020
HFCs, HCFCs, Anaesthetics	180,000
HFOs, HCFOs	30,600
Pesticides 30% to upper limit 100% TFA yield and revised for the period to 1999	214,000 to 712,000
Hexafluoropropene	16,000
TFA manufacture theoretical upper limit assumes all TFA manufactured is emitted – highly unlikely	16,000 to 266,000
Pharmaceuticals	10,500
Total TFA emissions (rounded)	467,000
Total TFA emissions theoretical upper limit (rounded)	1,215,000

4. Sources of Anthropogenic TFA Emissions

4.1. HFCs

There are no reported global production data for HFCs for the period 2000 to 2020. The production in this period for HFC-134a, HFC-125, and HFC-143a is estimated using this method:

- Production for 2000 to 2020 = Estimated bank in 2020 + emissions until 1999 + emissions 2000 to 2020 – production until 1999.

Production and emissions until 1999 are reported in the previous inventory for HFC-134a, HFC-125, and HFC-143a, and estimates of the refrigerant bank are available for 2020 (MCTOC, 2022). HFC-32 production was estimated from emissions in the period 2000-2020 and the bank in 2020 (no HFC-32 production was included in the previous inventory). HFC-152a emissions are assumed to equal production, and emissions prior to 2000 are not included as they are relatively minor and HFC-152a does not degrade to TFA. Estimated HFC-227ea production in the period 2000 to 2020 equals emissions plus the bank in fire protection equipment (FSTOC, 2022). Production of HFC-245fa and HFC-365mfc is assumed to be twice cumulative emissions in the period 2000 to 2020. Production of minor HFCs (HFC-43-10mee & HFC-236fa) is not considered for CaF₂ consumption, although emissions are used to estimate TFA generation. Emissions of all these HFCs are available to 2020 (Scientific Assessment of Ozone Depletion, 2022). Other emissions data sources used are for HFC-365mfc, HFC-245fa, HFC-227ea, and HFC-236fa up to 2010 (Vollmer et al., 2011), HFC-134a up to 2010 (Fortems-Cheiney et al., 2015) and 2018 (Harrison et al., 2021), HFC-152a until 2014 (Simmonds et al., 2016), HFCs and HCFCs (Simmonds et al., 2017), and HFC-43-10mee (Arnold et al., 2014).

Generation of TFA from HFCs in the period 2000 to 2020 is calculated using global emissions, atmospheric lifetimes (IPCC AR6 values), and TFA yields (EEAP, 2023), noting that any emissions prior to 2000 are included in calculations as they contribute to TFA generation in the period 2000 to 2020. For HFC-134a, 14% TFA generation is assumed as a range is given and, as expected, the calculated TFA generated from HFC-134a in 2020 is about the mid-point of the range reported (Scientific Assessment of Ozone Depletion, 2022). Table 6 has cumulative HFC production, required calcium fluoride use, TFA emissions for the period 2000 to 2020, and the overall totals until the end of 2020.

Table 6. HFCs production, CaF₂ equivalent, and TFA generation.

	Cumulative production (kilotonnes)	Calcium Fluoride equivalent (million tonnes)	TFA generation (tonnes)
HFC-134a	4640	7.3	267,000
HFC-125	1260	2.1	1800
HFC-143a	540	0.8	2100
HFC-152a	910	1.1	0

Continued

HFC-32	890	1.4	0
HFC-227ea	220	0.4	8500
HFC-245fa	300	0.5	700
HFC-365mfc	110	0.2	500
HFC-43-10mee		minor	4100
HFC-236fa		minor	40
Total (2000-2020)	8900	13.8	284,700
Total until the end of 1999	708	1.1	6700
Overall total to the end of 2020	9600	14.9	291,400

Potential TFA generation from HFCs into the Atlantic Ocean. Due to their atmospheric lifetimes, HFCs are dispersed globally, and the generated TFA is deposited globally. The Atlantic Ocean, Caribbean Sea, and Mediterranean Sea and their drainage basins (World Atlas, 2025), an area of about 34% of the global surface, can be used to provide an indication of the quantity of TFA generated from HFCs that can contribute to the anthropogenic TFA in the Atlantic Ocean. This is about 99,000 tonnes of TFA generated from HFCs for the period to the end of 2020. The mean ages of the water masses in the Atlantic Ocean are sufficiently long (Liu & Tanhua, 2024) for TFA generation and deposition from HFCs and other sources.

4.2. HFOs and HCFOs

Significant production and consumption of HFOs and HCFOs commenced around 2013, with the transition to HFO-1234yf for new vehicle types under Directive 2006/40/EC and for all new cars from 2017. According to a market trends assessment (Booten et al. 2020), HFO-1234yf is the dominant HFO refrigerant, with significant production of other HFOs and HCFOs occurring from 2015. There are no published data on HFO and HCFO global production, but the use of HFO-1234yf in mobile air-conditioning allows an estimate of production in the period to 2020. It was estimated that 140 million vehicles would use HFO-1234yf by the end of 2020, and assuming 750 g refrigerant per vehicle (Booten et al., 2020), although this is probably an overestimate of the charge size, it equates to 105,000 tonnes of production. HFO-1234yf is also used, to a lesser extent, in other refrigeration and air-conditioning applications, so total production until the end of 2020 may be greater than 105,000 tonnes. Including production of HFO-1234ze(E), HFO-1336mzz isomers, and HCFO-1233zd, CaF₂ equivalent use for their total production until the end of 2020 is estimated as 0.3 million tonnes, based on data from a chemical industry consultant, of estimated total production of HFOs-1234yf, HFO-1234ze, HFO-1336mzz isomers, and HCFO-1233zd until 2020.

Global emissions of HFOs and HCFOs are not well characterised, but emissions of 30,000 tonnes of HFO-1234yf in 2020 have been estimated ([Scientific Assessment of Ozone Depletion, 2022](#)). This appears to be overstated, based on the estimated production volumes, its uses, and reported leakage rates from new vehicles ([MPCA, 2022](#)). In addition, emissions for the EU in 2020 are estimated at about 7,000 tonnes ([UBA, 2021](#)), and the EU probably accounts for about half the HFO-1234yf vehicles by 2020. Therefore, it is assumed that 30,000 tonnes are the total emissions of HFO-1234yf by 2020, equating to 30,000 tonnes of TFA at 100% yield. Emissions of HFO-1234ze(E), HFO-1336mzz isomers, and HCFO-1233zd(E) for the EU in 2020 are reported as 4,500 tonnes ([UBA, 2021](#)). For these three substances together, even assuming global similar emissions to HFO-1234yf up to 2020, estimated TFA generation would be about 600 tonnes depending on the ratio of their emissions, with an upper theoretical limit of around 10,000 tonnes ([EEAP, 2023](#)). Much greater global emissions of HFO-1234ze(E), HFO-1336mzz(Z), and HCFO-1233zd(E) are estimated using atmospheric abundances measured at one monitoring station in Europe in 2020 or 2022. It is acknowledged that these are overestimates ([Scientific Assessment Panel, 2024](#)). The derived emissions probably exceed cumulative production of these substances up to 2020 by at least a factor of two.

Potential TFA generation from HFOs and HCFOs into the Atlantic Ocean.

It is assumed that all TFA generated from HFOs and HCFOs in the period until 2020 contributes to anthropogenic TFA in the Atlantic Ocean, due to their short atmospheric lifetime and the dominant use in the EU and U.S. in the period until 2020, although this may be an overestimate. For HFO-1234yf, about 30-40% of the emissions are deposited within Europe in the form of TFA; the rest is transported in the atmosphere toward the Atlantic, Central Asia, and Africa ([Henne, et al. 2012](#)), with some TFA from use of HFO-1234yf in the U.S. deposited in Europe ([Wang et al., 2018](#)).

4.3. HCFCs

Reported production of HCFC-22, HCFC-124, HCFC-141b, and HCFC-142b for feedstock and non-feedstock uses for the period 2000 to 2020 is available ([Ozone Secretariat, 2025](#)). Minor HCFCs are not considered for CaF₂ consumption, and HCFC-133a is accounted for in HFC-134a production. Three HCFCs (HCFC-133a, 123, and 124) generate some TFA upon degradation in the atmosphere. Generation of TFA from HCFCs in the period 2000 to 2020 is calculated using the global emissions, atmospheric lifetimes (IPCC AR6 values), and TFA yields ([EEAP, 2023](#)), noting that emissions prior to 2000 are included in calculations as they contribute to TFA generation in the period 2000 to 2020. Emissions are reported for HCFC-133a ([Vollmer et al., 2021](#)), and there is considerable uncertainty in the reported emissions for HCFC-123 and HCFC-124 ([Western et al., 2025](#)). **Table 7** has cumulative HCFC production, required calcium fluoride use, TFA emissions for the period 2000 to 2020, and the overall totals until the end of 2020.

Table 7. HCFCs production, CaF₂ equivalent, and TFA generation.

	Cumulative production (kilotonnes)	Calcium Fluoride equivalent (million tonnes)	TFA generation (tonnes)
HCFC-22	16,500	15.9	0
HCFC-124			92,000
HCFC-141b	4450	2.7	0
HCFC-142b			0
HCFC-123	minor		40,000
HCFC-133a	minor		8000
Total (2000-2020)	20,950	18.6	140,000
Total until the end of 1999	6400 (excluding feedstock HCFC-22)	5.6 + 2.5 (from fluoropolymers)	16,100
Overall total to the end of 2020	27,350	26.7	156,100

Potential TFA generation from HCFCs into the Atlantic Ocean. Due to their atmospheric lifetimes, HCFCs that generate TFA are dispersed globally. Over the period until the end of 2020, 53,000 tonnes is an indication of the quantity of TFA generated from HCFCs that can contribute to the anthropogenic TFA in the Atlantic Ocean.

4.4. Anaesthetics

There are no updated emission estimates for desflurane, isoflurane, and sevoflurane (*Scientific Assessment of Ozone Depletion, 2022*), and emissions data are available up to 2014 for these and (*Vollmer et al., 2015*). Collected sales data for desflurane are similar to estimated emissions in 2014. Differences between sales and emissions for isoflurane might be partially explained by veterinary use, which may not be captured by the sales data (*Talbot et al., 2025*). The reported sales data from 2014 to 2020 show a 13% increase for sevoflurane, broadly level until 2019 for desflurane and halothane, and broadly level for isoflurane. In the absence of more recent emissions data, it is assumed that emissions remain constant from 2014 until 2020 and that production equals emissions. The data for the period until end 1999 have been revised to correct for the emissions data previously used. **Table 8** has cumulative anaesthetics production, required calcium fluoride use, TFA emissions for the period 2000 to 2020, and the overall totals until end 2020.

Table 8. Production of anaesthetics, CaF₂ equivalent, and TFA generation.

	Cumulative production (kilotonnes)	Calcium Fluoride equivalent (million tonnes)	TFA generation (tonnes)
Halothane	17.9		6200
Isoflurane	69.7		41,000
Sevoflurane	52.5		600
Desflurane	54.0		600

Continued

Total (2000-2020)	194.1	0.3	48,400
Total until the end of 1999 Corrected	87.4	0.1	33,000
<i>Total until the end of 1999 (previous inventory)</i>	<i>71.5</i>	<i>0.06</i>	<i>23,600</i>
Overall total to the end of 2020	281.5	0.4	81,400

Potential TFA generation from anaesthetics into the Atlantic Ocean. Due to their atmospheric lifetimes, anaesthetics that generate TFA are dispersed globally. Over the period until the end of 2020, 28,000 tonnes is an indication of the quantity of TFA generated that can contribute to the anthropogenic TFA in the Atlantic Ocean.

4.5. TFA from Hexafluoropropene and Fluoropolymers

Fluoropolymers containing tetrafluoroethylene (TFE) and hexafluoropropene (HFP) monomers account for the majority of global fluoropolymer production (Henry et al., 2018 and European Environment Agency, 2021). It is estimated that 97% of HCFC-22 used as feedstock is for the manufacture of fluoropolymers based on TFE and/or HFP, and the reported use of HCFC-22 as feedstock is available (Mühle et al., 2022). The CaF₂ equivalence for feedstock use of HCFCs is included with all HCFC production, as data are available for the period 2000 to 2020.

HFP has an atmospheric lifetime of 5.5 days (AR6 value) and degrades in the atmosphere, yielding a near-quantitative yield of CF₃CFO, which then hydrolyses to TFA (Acerboni et al., 2001). Some HFP is co-produced with TFE, but the main manufacturing process is by pyrolysis of TFE (JACC, 2005). Estimated production or demand data are available for HFP for 1999 (JACC, 2005) and 2014 to 2020 from publicly available summary data from a market report (Prismane Consulting, 2025). Emissions from the production and use of HFP as feedstock are assumed to be 3.6 weight %, the MCTOC most likely emission factor for modern-day, regulated manufacturing from production, supply chain, and use of feedstock (TEAP, 2024). In the period 2000 to 2020, this results in about 25,000 tonnes TFA that could have been generated from HFP emitted to the atmosphere. In the period until the end of 1999, about 7300 tonnes of TFA could have been generated, according to the previous inventory. TFA generated from HFP would be regional, but the production and feedstock use of HFP occurs in the USA, Europe, and Asia, as all these regions have major fluoropolymer industries. Perhaps up to 50% of the TFA generated from HFP emissions, about 16,000 tonnes, could contribute to TFA in the Atlantic Ocean.

Fluoropolymer degradation due to thermolysis can result in the formation of some quantities of TFA. The same methodology as the previous inventory is used to estimate TFA generation, although experimental results may not translate to the 'real world'. Some PTFE production data are available (Teng, 2012; European Environment Agency, 2021) and from publicly available summary data from a market report (Markets Report World, 2025), allowing an estimate of PTFE pro-

duction in the period 2000 to 2020. Applying the Cui methodology (Cui et al., 2019) TFA generation rate for PTFE (1.2%) and medium thermolysis scenario (0.1%) for the 5 previous years of global PTFE production annually results in, theoretically, about 130 tonnes of emissions of TFA over the period 2000 to 2020 from the estimated global PTFE production. It must be emphasised that this is theoretical and highly uncertain, but provides an indication of potential emissions of TFA from PTFE if thermolysis were to occur at a 0.1% rate (unlikely). Smaller TFA yields were reported for two fluoro-copolymers (Cui et al., 2019). In 2018, PTFE was 53% of global consumption (European Environment Agency, 2021), so it seems unlikely that other fluoropolymers generated more TFA than PTFE in the period 2000 to 2020. In the period until the end of 1999, TFA generation from PTFE was estimated as 60 tonnes.

4.6. Pesticides (Plant Protection Products)

A comprehensive paper (Joerss et al., 2024) on the generation of TFA from pesticide use (plant protection products) estimates TFA formation for the EU (including the UK), Switzerland, and the USA from available data for pesticide quantities applied to crops. For Europe, uncertainties are related to the fact that the pesticide emission dataset used is based on the heterogeneous sales data reported by eight Member States and extrapolated to all European regions using regression models, taking land use and climate variables into consideration. According to the paper, the German agrochemical industry association, Industrieverband Agrar (IVA), reported an average TFA formation rate in metabolism studies of approximately 0.3 per CF₃ moiety (range: <0.05 - 0.73) for 13 CF₃-containing pesticides (IVA, 2022). For the USA, the estimated amounts applied in 3,037 counties in 2017 reported from the Pesticide National Synthesis Project were taken as a basis. The paper reported that no national data could be obtained for China, and TFA formation was estimated for a single pesticide for the crop cotton. The authors state that the TFA formation potential from PPP in China may be of a similar order of magnitude as in the US. The cropland areas of China: 1.62 million km² and US: 1.54 million km² are similar (Tubiello et al., 2023b). The paper (Joerss et al., 2024) also provides an update to a detailed report (UBA, 2023) that estimated the maximum TFA formation for pesticides used in Germany, assuming 100% yield of TFA. The Environmental Effects Assessment Panel, in its 2022 Assessment Report (EEAP, 2023), estimated TFA formation from pesticides used in the USA for each year from 1992 to 2018. In the absence of global production and consumption data for CF₃-C pesticides, the available data from these publications can be used to provide an order-of-magnitude estimate for the formation of TFA from pesticide use globally and for eventual discharge into the Atlantic Ocean.

Pesticides are typically used on cropland, and a simple definition of cropland is land used for cultivation of crops, which is the total of areas under arable land and permanent crops, such as cocoa and coffee (Tubiello et al., 2023a). Several cropland area databases are available that provide country, regional, and global

Table 9. Available published data for TFA formation from pesticides and cropland area rates.

Country, Region, Global	TFA formation rate tonnes/year		Cropland area million km ² (Tubiello et al., 2023b)	kg TFA/km ² cropland/year	
	Upper limit 100%	30%		Upper limit 100%	30%
EU + UK + Switzerland (2011-2017) annual reference (Joerss et al., 2024)	3200	970	1.44	2.22	0.7
Germany (mean 2016-2019) (Joerss et al., 2024)	525	156	0.16	3.32	1.0
USA excl. Alaska & Hawaii 2017 (Joerss et al., 2024) <i>see note</i>	5000	1500	1.54	3.25	1.0
USA 2011-2017 annual mean (EEAP, 2023) <i>see note</i>	4150	1250	1.54	2.70	0.8
Globally assuming the same formation rate as the USA (2011-2017)	41,500	12,500	15.40	2.70	0.8

Table notes: Alaska has limited cropland area, reported as 72,708 acres or 294 km² (USDA's National Agricultural Statistics Service Alaska Field Office, 2022), and Hawaii's total cropland was reported as 158,053 acres or 640 km², (Department of Agriculture, State of Hawaii, 2024), which will not significantly affect the TFA formation rate/km² cropland for the USA. The 2011-2017 data extracted from SI **Table 2** (EEAP, 2023) may have small errors due to data rounding in SI **Table 2** (EEAP, 2023).

cropland areas. One that is easily accessible is "A new cropland area database by country circa 2020" (Tubiello et al., 2023b). The reported TFA formation from pesticides and the calculated rate of TFA formation/km² cropland are shown in **Table 9**. The rates of TFA formation/km² cropland are similar for EU + UK + Switzerland, Germany, and the USA. Applying the USA 2011-2017 annual mean TFA formation/km² cropland rate globally provides a possible upper limit on annual TFA formation from pesticides in this period, given that the formation rate/km² is smaller for the EU + UK + Switzerland.

The USA TFA formation data from pesticides (EEAP, 2023) provide annual use data for 1992-2018 for pesticides containing CF₃ groups. Over this period, for the USA, 8 pesticides account for about 85% of TFA formation assuming 100% yield. In 1992, trifluralin accounted for about 64% of TFA formation, assuming 100% yield of TFA from each pesticide.

TFA formation potential for 2000-2020 from Pesticides. The available published data on pesticide use and TFA formation potential can be used to estimate a global maximum TFA formation quantity. The mean annual TFA formation, assuming 100% yield over the period 2000-2018 for the USA, is about 3800 tonnes, equivalent to 2.5 kg TFA formation/km² cropland, similar to the values calculated in **Table 9**. Applying this formation rate to the global cropland area results in 38,000 tonnes TFA formation annually, assuming 100% yield. Over the period 2000-2020, and assuming this annual formation rate for each year, results in 796,000 tonnes TFA, a possible upper limit on TFA formation in this period. A 30% formation rate is equivalent to 239,000 tonnes in this period. This is summarised in **Table 10**. This quantity of pesticides containing CF₃C groupings could

account for 0.9 million tonnes of CaF₂ equivalent, and other fluorine-containing pesticides would also result in the consumption of CaF₂.

Table 10. Estimated global TFA formation from pesticides in the period 2000-2020.

	TFA tonnes at formation rates		Cropland area million km ²	kg TFA/km ² cropland/year	
	100%	30%		100%	30%
USA 2000-2018 annual mean	3800	1100	1.54	2.5	0.74
Global applying USA rate/km ² annually	38,000	11,000	15.40	2.5	0.74
Global TFA formation 2000–2020	796,000	239,000			

TFA formation 1930-1999. The maximum TFA formation quantity in the 1930-1999 inventory was estimated as 380,000 tonnes, assuming a 100% TFA yield from trifluralin, and is based on limited data (Lindley, 2023). In 1992, for the USA, trifluralin accounted for 64% of TFA formation, assuming a 100% yield (EEAP, 2023). Other pesticides containing the CF₃-group were introduced after trifluralin, so it is possible that the upper limit of TFA formation in the period is greater than 380,000 but smaller than 600,000 tonnes, which assumes trifluralin accounts for 64% of TFA in the period to 1999. It is assumed that 500,000 tonnes of TFA is the possible upper limit. Applying a 30% TFA formation rate results in 150,000 tonnes in the period up to 1999.

Potential TFA discharge from pesticides into the Atlantic Ocean. TFA formation from pesticides will be mainly transported by surface waters and eventually discharged to terminal water bodies, including the oceans. This is similar to the river transport of sea salt deposited over land (Grini et al., 2002). The Atlantic Ocean, Caribbean Sea, and Mediterranean Sea drainage basins can be used to estimate the maximum quantity of TFA formation from pesticides that could potentially contribute to anthropogenic TFA in the Atlantic Ocean. These drainage basins include the EU, UK, Switzerland, part of the USA and Canada, most of South and Central America, and a part of Africa (Craig, 2019). For simplicity, it is assumed that the Americas, Africa, EU, UK, and Switzerland could contribute to TFA from pesticides in the Atlantic Ocean, although some of the Americas and Africa contribute to other drainage basins. The TFA formation rate/km² cropland for Africa and the Americas is assumed to be the same as the USA in this period. The potential contribution of TFA from pesticides in the Atlantic Ocean for the period 2000 to 2020 is shown in Table 11. The estimated TFA in this period is 115,000 to 382,000 tonnes, assuming 30% to an upper limit of 100% TFA yield. In the period up to 1999, it is assumed that North America and EU + UK + Switzerland used 50% of the global quantity (500,000 tonnes TFA assuming 100% yield). This is perhaps not unreasonable as the USA accounted for about 25% of trifluralin global use in 1987 (Lindley, 2023). On a pro rata cropland area basis, Central and South America and Africa would account for about one third of the remaining 250,000 tonnes of TFA assuming 100% yield. The potential upper limit contribution of TFA from pesticides in the Atlantic Ocean for the period until 1999 is

330,000 tonnes (250,000 + 80,000 tonnes). At 30% TFA yield, the contribution is 99,000 tonnes. The potential contribution of TFA from pesticides in the Atlantic Ocean for the period until 1999 is shown in **Table 12**. In total, the estimated upper limit of TFA formation from pesticides that may contribute to TFA in the Atlantic Ocean is estimated at 712,000 tonnes. At a 30% TFA formation rate, the TFA quantity is estimated at 214,000 tonnes in the period until 2020.

Table 11. Estimated TFA potentially contributing to TFA in the Atlantic Ocean, 2000-2020.

	Cropland area million km ²	kg TFA/km ² cropland	TFA formation at 100% yield (tonnes)
America's annual TFA formation	4.1	2.5	10,000
EU + UK + Switzerland annual TFA formation	1.4	2.2	3200
Africa annual TFA formation	2.0	2.5	5000
Share of global cropland % (Americas, Africa, Europe)	49		
Atlantic Ocean 2000-2020 assuming upper limit 100% TFA yield			382,000
Atlantic Ocean 2000-2020 assuming 30% TFA yield			115,000

Table 12. Estimated TFA potentially contributing to TFA in the Atlantic Ocean until the end of 1999.

	Cropland area million km ²	Share of TFA from pesticides	TFA formation at 100% yield (tonnes)
North America, EU + UK + Switzerland	3.4	50%	250,000
Remaining global cropland area, including Africa and South A	12.0	Pro rata based on cropland area	
Africa, South America	4.1		80,000
Share of global cropland % (Americas, Africa, Europe)	49		
Atlantic Ocean until 1999, assuming an upper limit of 100% TFA yield			330,000
Atlantic Ocean until 1999, assuming a 30% TFA yield			99,000

4.7. Pharmaceuticals

In 2021, 408 active pharmaceutical ingredients, including gaseous anaesthetics, contained a C-CF₃ grouping. Assuming 100% molar yield of TFA, a theoretical release of 22 tonnes/year TFA from the degradation of human medicinal products has been derived for Germany for the year 2020 (UBA, 2023; UBA, 2022). There is little information on the amounts of pharmaceuticals containing C-CF₃ groups produced and used globally (EEAP, 2023). In a study on the use of gaseous anaesthetics, high-income countries accounted for over 71% of the greenhouse gas impact of halogenated anaesthetic agents (Talbot et al., 2025). Scaling the theoretical release of TFA from pharmaceuticals for Germany to high-income countries by population, and assuming these contribute 71% of relevant pharmaceutical use, may give an indication of possible global TFA generation. This would result in globally 400 to 500

tonnes of TFA annually, or roughly 8000 to 10,000 tonnes globally over the period 2000 to 2020, assuming 100% yield of TFA. However, due to the persistence of many pharmaceuticals, a complete transformation to TFA during wastewater treatment or during river transport is unlikely (UBA, 2023). In the period until the end of 1999, about 5000 tonnes of TFA could have been generated, according to the previous inventory. It is assumed that 70% of this quantity, about 10,500 tonnes, is discharged to the Atlantic Ocean. Fluoxetine and one of its degradation products have been shown to form TFA in varying yields of < 100%, depending on the experimental conditions, using bacteria (Khan & Murphy, 2021), photolysis (Guo et al., 2025), or treatment of wastewater with ozone (Scheurer et al., 2017).

4.8. Production and Use of TFA

According to a market research report (publicly available summary), TFA is produced in China, North America, Europe, and India, with global production about 21,000 tonnes in 2012, estimated at 26,000 tonnes in 2017, and 34,000 tonnes in 2023 (Pmarketresearch, 2021). The estimated TFA quantity manufactured for the period 2000 to 2020 is about 350,000 tonnes. TFA is widely used in industrial organic synthesis, including in the early stages of the synthesis of many fluorinated organic compounds. TFA may be directly released into the environment due to fugitive emissions or in wastewater discharge. Such point sources have been shown to significantly elevate TFA concentrations in surface water, river water, outdoor dust, and soils in close proximity to the source and, in one case, at a considerable distance from it (Garavagno et al., 2024). Given its wide use, including in relatively small-scale processes, an estimate of TFA emissions from its production and use is uncertain. The MCTOC most likely emission factor range (1.5% to 6.1%) for modern-day, regulated manufacturing from production, supply chain, and use of feedstock was primarily based on data from large-scale continuous processes where the feedstock was not fed to excess and where the feedstock did not leave the reaction section or loop. These are for processes with high overall conversion rates and yields, requiring little or no recovery and recycling of unreacted feedstock from downstream in the process (TEAP, 2024). However, the 6.1% upper limit of the MCTOC (Medical and Chemical Technical Options Committee to the Montreal Protocol) most likely emission factor range may provide an indication of the emissions from the production and use of TFA. River TFA concentration data in 2016/17 have been reported downstream of a point source producing and using TFA (Scheurer et al., 2017). The reported concentration data and river flows allow an estimate of TFA discharges. The ECHA REACH registration band is for 100 to 1000 tonnes of TFA (ECHA CHEM, 2025). From these data, the 6.1% emission factor may not be unreasonable. The quantity of TFA manufactured sets a theoretical upper limit on TFA emissions, but some TFA manufactured would also be accounted for in, for example, pesticides (Scheurer et al., 2017). Emissions of TFA would be virtually all to water. Emissions of TFA in the period 2000 to 2020 are estimated at 21,000 tonnes, with a theoretical upper limit

of 350,000 tonnes. In the period until 1999, applying the same emission factor, TFA emissions are estimated at 2,000 tonnes, with a theoretical upper limit of 30,000 tonnes. Emissions would be expected to be regional, including the USA, Europe, and Asia. It is assumed that 70% of emissions are discharged to the Atlantic Ocean. In the period until the end of 2020, the potential discharge to the Atlantic Ocean is 16,000 tonnes, with a theoretical upper limit, set by TFA production, of 266,000 tonnes. TFA manufacture in the period 2000 to 2020 is estimated to have required the equivalent to 0.5 million tonnes CaF_2 .

4.9. Minor Sources of TFA

The lampricide, 4-nitro-2-(trifluoromethyl) phenol (TFM), has been used in the Great Lakes basin since 1958. In the period from 2000 to 2019, 1,158 tonnes of TFM were used (Sullivan et al., 2021), resulting in the formation of 206 tonnes of TFA over the period, assuming the maximum reported TFA yield of 17.8% (Ellis & Mabury, 2000). In the period until 1999, TFM use resulted in 156 tonnes of TFA, using the same maximum yield.

For Germany, it has been assumed that the contribution of biocides to the TFA balance plays a minor role due to the small number of potential precursor substances, and no spatial analysis of the TFA input and contamination could be carried out for veterinary pharmaceuticals due to limited data (UBA, 2023).

Fluorotelomer alcohols are reported to degrade in the environment and potentially produce low yields of TFA, either by atmospheric or biological degradation. Atmospheric chemistry experiments resulted in very low yields of TFA (Ellis et al., 2004). TFA is formed in low yields from 6:2 FTOH and 4:2 FTOH by a landfill soil microbial culture. The authors estimate global emissions of 3.9 to 47.3 tonnes of TFA in the period from 1961 to 2019 (Sun et al., 2020). Fluorotelomer alcohols are not considered to be significant sources of TFA.

Trifluoroethanol ($\text{CF}_3\text{CH}_2\text{OH}$) reacts with oxidising species in the atmosphere to form CF_3CHO (Sellevåg et al., 2004). Further degradation in the atmosphere forms 2% TFA with an upper theoretical limit of 30% (EEAP, 2023). Trifluoroethanol is used as a solvent and as an intermediate for pharmaceuticals and agrochemicals. It is the feedstock for production of isoflurane and desflurane (Halocarbon, 2025), reported to be a main application. The main industrial process for production of trifluoroethanol is reported to be from TFA or its derivatives by reduction (PrimaryInfo, 2025), but it is also reported to be produced from HCFC-133a by hydrolysis (TOSOH, 2003). Reported production of trifluoroethanol in the United States was in the range 227 - 454 tonnes (2016), 454 - 4536 tonnes (2017 & 2018), 454 - 9072 tonnes (2019) (PubChem, 2025). Global production and emissions data are not available. However, the reported use of HCFC-133a as feedstock is available for some years in the period 2012 to 2020 in annual TEAP Progress Reports and MCTOC Assessment Reports (Ozone Secretariat, 2025). Reported feedstock production is about 1000 tonnes in these years. Some HCFC-133a is used to produce halothane, but even assuming it is all used to produce

trifluoroethanol, it is equivalent to about 850 tonnes of trifluoroethanol. Assuming none of this is used as feedstock, a 2% yield of TFA would result in about 20 tonnes annually. Trifluoroethanol produced from TFA, will also result in minor emissions of TFA unless it is used as feedstock, but these are already considered in the theoretical upper limit of TFA emissions from TFA. This suggests that trifluoroethanol can be considered as a minor source of TFA.

5. Production of Fluorspar, Other Fluoride Minerals, and Hydrogen Fluoride

The U.S. Geological Survey publishes annual reports of fluorspar production globally (U.S. Geological Survey, 2025a), although for more recent years, it does not provide a detailed breakdown of acid spar production, but some reports have estimated acid spar's share of total production. Production data for acid spar and total fluorspar production for more recent years are available from other sources (Clarke & Huxtable, 2017; Rhode, 2020; Rockstone Research, 2019). There are some differences in total fluorspar production quoted by the U.S. Geological Survey and the other sources. For consistency, the U.S. Geological Survey data are used for total fluorspar, and for recent years the acid spar data are from the other sources. These combined data sources are used to estimate acid spar and total fluorspar production in the period 2000 to 2020. Production of fluorspar by grade in the period 1930 to 2020 is shown in **Figure 2** and summarised in **Table 13**. The 1930 to 1999 data are from the earlier inventory (Lindley, 2023). In recent years (U.S. Geological Survey, 2018), numerous fluorspar producers have begun to develop and market products specifically for the cement industry. The CaF_2 content of these products was generally 40% to 50%, much lower than the CaF_2 content of metspar typically used as a steelmaking flux. An overview of fluorspar production and use from an EU perspective is available (CRM, 2020), quoting essentially the same global fluorspar production for the period 2012 to 2016 as the U.S. Geological Survey.

Fluorosilicic acid (FSA) is a byproduct of phosphoric acid production and is used for the manufacture of aluminium trifluoride (AlF_3), which is used in the production of primary aluminium. Starting in 2008, anhydrous hydrogen fluoride (AHF) has been produced from FSA at a commercial scale. By 2016, three production plants of 12,000 tonnes/year and 20,000 tonnes/year (two plants) were in operation in China (Dahlke et al., 2016). In 2017, 3% of the global AHF production capacity was based on using FSA as a feedstock (Dahlke et al., 2017). By 2020, five plants may have been in operation in China (Dahlke & Sen, 2021), which suggests a possible AHF capacity of the order of 100,000 tonnes/year from FSA. Over the period 2000 to 2020, it is estimated that 1% to 2% of AHF global production might have been from FSA.

Some synthetic fluorspar can be produced as a byproduct of petroleum alkylation, stainless-steel pickling, and uranium processing; however, there is no available survey data for synthetic fluorspar produced in the United States (U.S.

Geological Survey, 2017). These are expected to be relatively minor and as aqueous HF. Aqueous HF is generally not used for organic fluorochemical production.

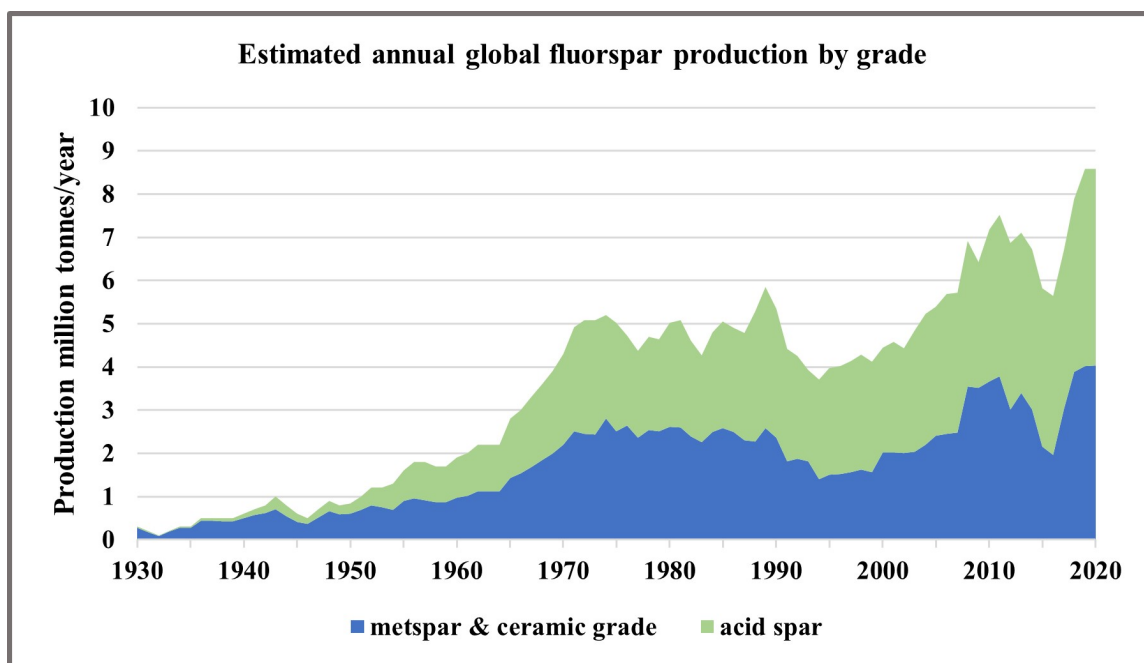


Figure 2. Estimated annual global fluorspar production by grade.

Table 13. Fluorspar production by grade.

Production million tonnes	1930 to 1999	2000 to 2020	1930 to 2020
Acid spar	95.0	71.7	166.7
Metspar & ceramic grade	96.9	60.6	157.5
Total fluorspar	191.9	132.3	324.2

The yield of hydrogen fluoride from acid spar has increased since the 1930s as the manufacturing process has improved. Some fluoride is lost as H_2SiF_6 , although this can be used for a range of applications if recovered. In the 1990s and 2000s, fluoride recovery systems were introduced for HF production. Anhydrous hydrogen fluoride (AHF) is normally produced with a concentration of 99 - 99.9%, and aqueous HF (hydrofluoric acid) is primarily produced as a 70% solution, although a range of other strengths is then prepared for a wide range of applications. For the period 2000 to 2020, an independent industry expert indicated that the overall yield of AHF from acid spar is estimated at 95%, based on 97.5% acid spar purity and 97.5% yield of AHF from CaF_2 . **Table 14** shows the estimated availability of AHF as CaF_2 equivalent. In the period 2000 to 2020, production of AHF from FSA could have resulted in additional AHF availability equivalent to about 1 million tonnes CaF_2 (assumes 1.5% AHF from this source).

Table 14. Estimated availability of AHF as CaF₂ equivalent.

Million tonnes	1930 to 1999	2000 to 2020	1930 to 2020
Acid spar production	95.0	71.7	166.7
AHF yield from acidspar (97.5% purity)	91% (weighted average)	95%	
Accounting for losses due to HF yield from acid spar purity (97.5%)		8.9	3.6 12.5
Overall availability of HF as CaF ₂ equivalent		86.1	68.1 154.2

6. Applications of Hydrogen Fluoride Not Generating TFA

6.1. CFCs

The non-feedstock global production of CFCs (CFC-11,12,113,114,115) in the period 2000-2010 (phase-out) is from data reported to the Ozone Secretariat (Ozone Secretariat, 2025). In addition, the estimated cumulative total of unreported CFC-11 production is 320 - 700 kilotonnes (central estimate 510 kilotonnes) in the period 2007-2019 (TEAP, 2019). Total CFC non-feedstock production is estimated as 1090 kilotonnes equivalent to 0.5 million tonnes CaF₂. The total CaF₂ equivalent use from 1930 to 2020 is 15.1 million tonnes.

6.2. Production of Primary Aluminium

Aluminium fluoride (AlF₃) and cryolite (Na₃AlF₆) form the electrolyte for the aluminium smelting process from alumina, allowing the process to operate at about 960°C. One of the uses of aluminium fluoride or cryolite is to replace lost fluoride. Fluoride use per tonne of primary aluminium production reduced considerably in the period until 2000, remaining relatively constant until 2020. The consumption of fluoride is available for some years in the period 2000 to 2020. The fluoride consumption is reported as 16 kg AlF₃/tonne primary aluminium produced globally in 2005, 16 kg in 2010, 17 kg in 2015, and 18 kg in 2019. The data is for companies representing over 60% of global bauxite, alumina, and aluminium production (International Aluminium Institute, 2025). The dominant source of fluoride for synthetic cryolite or aluminium fluoride is fluorspar (CaF₂). Since 2000, there has been an increase in the use of byproduct fluorosilicic acid (FSA), from phosphoric acid production, for the manufacture of aluminium trifluoride (AlF₃), which is used in primary aluminium production. According to four sources, FSA was used for about 10% of AlF₃ production (Saxby, 2013), 11% (U.S. Geological Survey, 2018), 15% to 20% (Clarke & Huxtable, 2017), and 13% (U.S. Geological Survey, 2020). It is assumed that FSA accounts for 10% of AlF₃ production up to 2014 (the same as in the previous inventory), increasing to 15% by 2017. Global annual primary aluminium production is available (U.S. Geological Survey, 2025b). Figure 3 shows the consumption of fluoride minerals and primary aluminium production by year for the period 1930-2020. This also shows the recent increase in the use of FSA as the fluoride source. Table 15 summarises the use of fluorspar and other fluoride sources for primary aluminium with the 1930 to 1999 data from the earlier inventory.

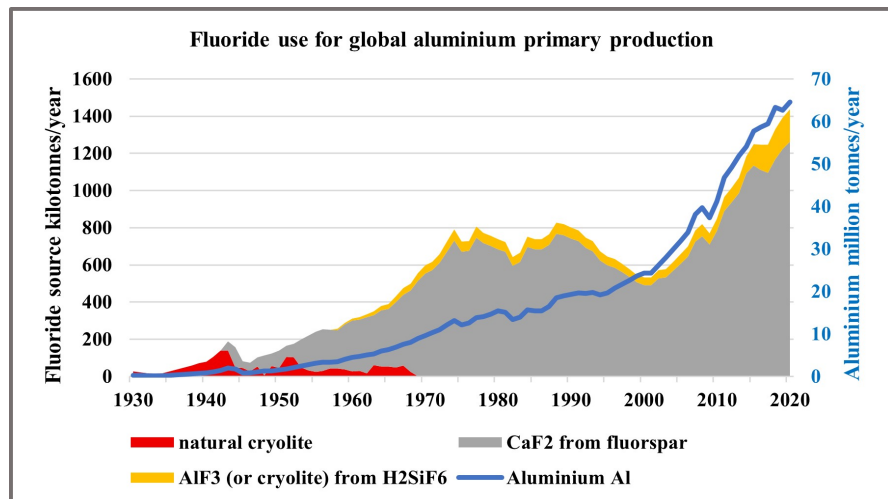


Figure 3. Fluoride mineral use for global aluminium primary production.

Table 15. Fluoride use for primary aluminium production.

Time period	Millions of tonnes		
	1930 to 1999	2000 to 2020	1930 to 2020
Primary aluminium production	594.5	922.9	1517.4
CaF ₂ use	25.3	17.7	43.0
Natural cryolite use (to 1968)	1.9	0.0	1.9
AlF ₃ from H ₂ SiF ₆ (FSA)	1.8	1.8	3.7

6.3. Production of Rare Earth Metals

Molten salt electrolysis, similar to primary aluminium production, is the preferred method for production of four light rare earth metals and alloys from their oxides (REOs). These are Lanthanum (La), Cerium (Ce), Praseodymium (Pr), and Neodymium (Nd) (Liao et al., 2024). Around 2010, molten salt electrolysis accounted for 80% to 90% of rare earth metal production in China. In the process, REOs are electrolyzed in a fluoride salt medium to produce rare earth metals (99.8% purity) (Lee & Wen, 2016). In 2024, more than 95% of rare earth metals and their alloys in China are produced by electrolytic preparation using the fluoride molten salt system (Liao et al., 2024). The final production of rare earth metals by electrolysis takes place almost exclusively in China (Schreiber et al., 2020). A paper on life cycle assessment of neodymium oxide electrolysis in molten salt reviews available data, including fluoride consumption (Schreiber et al., 2020). For the four light rare earths (RE), the electrolysis process typically uses an electrolyte containing the RE fluoride and lithium fluoride (LiF), both prepared using HF, and the RE oxide is added to the melt (Liao et al., 2024). Fluoride consumption occurs during the electrolysis process, which, according to the published data, is only about 40% fluoride efficient as a central estimate, requiring make-up with the RE fluoride and LiF (Lee & Wen, 2016). It is reported that production of LiF is 97% fluoride efficient (Han et al., 2023). From the reported data (Lee & Wen, 2016), the fluoride

consumption during electrolysis is about 50 kg fluoride/tonne RE production. This is considerably greater than for primary aluminium production. Global production data for 2000 to 2020 is available for the four rare earth metals as the REOs (*Raw Materials Information System—RMIS, 2025*). In total, 2.28 million tonnes of the REOs were produced, requiring 0.4 million tonnes CaF₂ equivalent, to manufacture 1.90 million tonnes of the RE metals, assuming only fluoride molten salt electrolysis is used.

6.4. Other Inorganic and Catalytic Uses of Hydrogen Fluoride

Sulphur hexafluoride (SF₆) is produced commercially by direct fluorination of sulphur using elemental fluorine (obtained by electrolysis from AHF), and an overall fluoride efficiency of 90% is assumed. A comprehensive paper on SF₆ emissions, sources, installed power generation capacity until 2018 (*Simmonds et al., 2020*) and global emissions for 2019 and 2020 (*Scientific Assessment of Ozone Depletion, 2022*) is used to estimate SF₆ production in the period 2000 to 2020 and the required CaF₂ equivalent. Estimated global production of SF₆ in the period 2000 to 2020 is 312,000 tonnes, requiring 0.56 million tonnes CaF₂ equivalent.

Sulphuryl fluoride (SOF₂) is a chemical pesticide used for the control of insects in stored agricultural products or for structural (building) fumigation, and its use is widespread in most developed and some developing countries. After fumigation, SOF₂ is typically vented to the atmosphere. Emissions are estimated for the period until 2020 (*Gressent et al., 2021*) and are assumed to equal production. Emissions in the period 2000 to 2020 are reported to be 46,154 tonnes. A 95% fluoride efficiency from CaF₂ for production from, e.g., direct fluorination of SO₂, would require 0.04 million tonnes of CaF₂.

Nitrogen trifluoride (NF₃) is used in semiconductor and other electronics manufacturing in plasma etching and chamber cleaning. Some NF₃ is emitted to the atmosphere during production, and although the etching processes break down NF₃ to produce plasma-generated fluorine radicals, some NF₃ is emitted to the atmosphere (*IPCC, 2019*). Production was estimated at 12,000 tonnes in 2011 (*Arnold et al., 2013*), and production estimates for 2017 to 2020 are available (*Liu et al., 2024*). For some years, emission/production ratios have been estimated (*Arnold et al., 2013*). Emissions for 2011 to 2014 (*Scientific Assessment of Ozone Depletion, 2022*) and 2015 and 2016 (*Liu et al., 2024*) are available. From this data, production in the period 2000 to 2020 is estimated at about 300,000 tonnes, requiring 0.52 million tonnes CaF₂, assuming 95% fluoride efficiency.

Stainless steel pickling. The most common pickling solution is 10 to 15% nitric acid plus 1% to 3% hydrofluoric acid. In the early 2000s, it was reported that 3.44 kg HF is consumed per tonne of stainless steel production assuming no HF recovery (*Brown, 2002*). Several different processes to reuse acid and recover valuable waste metals became available from the 1990s onwards, but the use of these techniques globally in the period 2000 to 2020 is not readily available (*Rögener et al., 2019; Regel-Rosocka, 2010; Dahlgren, 2010*). It is assumed that 80% HF recovery

occurs for all stainless steel production with a net use of 0.69 kg HF/tonne. Global production of stainless steel in the period 2000 to 2020 was 707.88 million tonnes (Statista, 2022), requiring 0.5 million tonnes HF, equivalent to 0.95 million tonnes CaF_2 .

Petroleum alkylation fluids are used in lubricants, industrial fluids, and specialty cleaning agents, as well as fuel components. In 2014, HF alkylation had about 40% of the total installed alkylation capacity (Norton Engineering, 2016). In 2004, it was reported that 2% (22,000 tonnes) of global HF consumption was used for alkylation (Will, 2007). Consumption of HF catalyst was reported in 2016 as 0.001 to 0.002 lb/gal alkylate (Norton Engineering, 2016). Consumption of 0.0015 lb/gal alkylate results in about 18,000 tonnes HF consumption annually. There has been a slight increase in US alkylation capacity over the period 2000 to 2021 (U.S Energy Information Administration, 2025), and global alkylate capacity is increasing, with one market research report public summary indicating over 50% HF process market share in 2025 (Hengce, 2025). Assuming no change in the HF alkylation output over the period 2000 to 2021, results in HF use equivalent to 0.7 million tonnes of CaF_2 . Some synthetic fluorspar may be recovered as a by-product of petroleum alkylation, but the actual amount recovered is unknown.

Niobium and tantalum are chemically similar and are associated with each other in nature, which makes them very difficult to separate. The extraction of these metals from their primary and secondary resources is carried out through well-known metallurgical techniques, based on the use of hydrofluoric acid in the various production chains (Machaca et al., 2025). Depending on applications, they need to be separated, and all commercial solvent extraction processes are performed in the presence of fluorides after digestion with HF ($+\text{H}_2\text{SO}_4$) forming NbOF_5^{2-} and TaF_7^{2-} as potassium salts. Other purification processes that can be used for niobium are not via NbOF_5^{2-} (Bourgeois et al., 2017). Global production in the period 2000 to 2020 is 1,222,100 tonnes of niobium and 28,577 tonnes of tantalum (U.S. Geological Survey, 2025c). Assuming only 50% of the niobium is processed via NbOF_5^{2-} with 95% fluoride efficiency, requires HF equivalent to 1.4 million tonnes CaF_2 . A minor use of HF is for the electropolishing of niobium used for superconducting radio frequency (SRF) accelerators (Lozano-Morales et al., 2024).

Ammonium bifluoride (NH_4HF_2) is produced from the reaction of anhydrous hydrogen fluoride (AHF) with ammonia. It has a wide range of applications, including glass etching, metal surface treatment, and oil well acidizing. According to the public summary of one market research report (24ChemicalResearch, 2024), the production was 150,000 tonnes in 2023, with a trend of increasing production. Over the period 2000 to 2020, production may have required of the order of 2.5 million tonnes of CaF_2 equivalent, assuming 60,000 tonnes of NH_4HF_2 production in 2000, increasing to 150,000 tonnes in 2023.

Boron trifluoride (BF_3) is produced by reaction of boron oxides with AHF. It is used as a catalyst in a range of chemical processes and the semiconductor in-

dustry. Production of BF_3 was less than 5000 tonnes/year in the period before 2000 (Brotherton et al., 2000), increasing to 22,000 tonnes in 2023, according to a market research report publicly available summary (DataVagyanik, 2025). From this, it is estimated that AHF equivalent to 0.4 million tonnes CaF_2 may have been required over the period 2000 to 2020.

Lithium hexafluorophosphate (LiPF_6) is manufactured by reacting phosphorus pentachloride with AHF and lithium fluoride. It is used as an electrolyte in Li-ion batteries for electric vehicles. Production reached 12,000 tonnes in 2016 (CCM, 2016), with forecast demand of 20,000 tonnes in 2017 (Green Car Congress, 2016). Global production of 50,000 tonnes in 2021 was reported in a publicly available summary (Research and Markets, 2023). Over the period 2000 to 2020, about 0.3 million tonnes CaF_2 equivalent may have been required to produce LiPF_6 .

Lithium fluoride. According to the public summary of one market research report (Chemanalyst, 2025), global production of lithium fluoride was 83,000 tonnes in 2024 (requiring about 0.13 million tonnes CaF_2 equivalent). Lithium fluoride has a wide range of uses, including ceramics, glass, optics, electronics, nuclear power generation, and advanced battery technologies (Sharopov et al., 2025). Excluding LiF used to produce LiPF_6 and its use in light rare earth electrolysis, over the period 2000 to 2020, LiF production could account for 0.3 million tonnes CaF_2 equivalent.

Uranium processing is assumed to have zero net HF use, as conversion to UF_6 uses HF and deconversion of depleted uranium DUF_6 generates HF. For 2022, the estimated global conversion capacity to UF_6 is broadly similar to the deconversion capacity. Although estimates of UF_6 production are provided, an estimate of deconversion production is not provided (World Nuclear Association, 2024).

7. Conclusion

The first fluorspar (CaF_2) and trifluoroacetic acid (TFA) inventory (1930-1999) discussed the use of acidspar, which is used to produce hydrogen fluoride (HF) and is the raw material for the production of organic fluorine-containing compounds (Lindley, 2023). It discussed the uses of metspar, mainly for steel production, and explained that TFA is not generated from inorganic processes or from primary aluminium production. The updated inventory presented here includes the period 2000 to 2020, when a further 132.3 million tonnes of fluorspar were mined, including 71.7 million tonnes of acidspar. The updated inventory accounts for 90% of acidspar production. There are many other uses of HF that are not easily estimated but do not result in the formation of TFA, as these uses are aqueous HF, inorganic, catalysis, solvent, or uses that do not result in substances that could degrade to TFA. The maximum TFA formation from pesticides and data for anaesthetics through 1999 in the previous inventory have been revised.

The publication of concentrations of TFA in the Atlantic Ocean, measured in 2022-2023, is significant as the concentration measurements are extensive, includ-

ing depth profiles in the North and South Atlantic Oceans, and allow an estimate of the burden of TFA in the Atlantic Ocean. The concentration data suggest that there could be approximately 80 million tonnes, or, excluding depths below 4000 m where there are limited measurements, there could be approximately 40 million tonnes of TFA in the Atlantic Ocean. The updated inventory provides estimates for global TFA emissions and the share of emissions that contribute to TFA in the Atlantic Ocean for the period from 1930 to 2020. The Atlantic Ocean, Caribbean Sea, and Mediterranean Sea and their drainage basins account for 34% of the global surface area. This can be used as the catchment area for discharges of TFA to water, and TFA in precipitation from atmospheric degradation of fluorocarbons, to estimate the quantity of anthropogenic TFA in the Atlantic Ocean. Due to their atmospheric lifetimes, HFCs, HCFCs, and anaesthetics are dispersed globally, and generated TFA is deposited globally, allowing an estimate of the quantity deposited in the relevant oceans and seas, and their drainage basins. Recent assessments of the use of pesticides and their formation of TFA on degradation have reported a TFA yield of 30% on average. These assessments allow an estimate of relevant pesticide use globally and generation of TFA, using a cropland area database to estimate global and regional pesticide use, and TFA discharge to the relevant drainage basins. An upper limit of TFA generation from pesticides is derived by assuming 100% TFA yield.

In the period from 1930 to 2020, the production of TFA from the atmospheric degradation of fluorocarbons (HFCs, HFOs, HCFOs, HCFCs, and anaesthetics) is estimated at 560,000 tonnes. Generation of TFA from the global use of pesticides is estimated at 389,000 - 1,296,000 tonnes, assuming 30% - 100% yield of TFA. The emissions from the manufacture and use of TFA are uncertain, but applying the MCTOC most likely emission factor gives 23,000 tonnes of emissions, with a theoretical upper limit of 380,000 tonnes. Emissions of hexafluoropropene occur during production and use as a feedstock, and rapidly degrade in the atmosphere to TFA, with estimated emissions of 32,300 tonnes. Other TFA emissions are estimated for thermolysis of fluoropolymers and from pharmaceuticals. Minor emissions occur from the lampricide 4-nitro-2-(trifluoromethyl)phenol (TFM), biocides, from fluorotelomer alcohols and trifluoroethanol. Significant other industrial uses of fluorspar that could account for large additional emissions of TFA have not been identified. In total, emissions of TFA are estimated at 1,019,000 tonnes, with a theoretical upper limit of 2,283,000 tonnes (assuming 100% yield of TFA from pesticides and 100% of TFA manufactured is emitted).

From 1930 to 2020, the anthropogenic contribution to TFA in the Atlantic Ocean is estimated to be 467,000 tonnes, with a theoretical upper limit of 1,215,000 tonnes. This is about 0.6% - 1.2% of the estimated 40 - 80 million tonnes burden of TFA in the Atlantic Ocean, and for the theoretical upper limit, 1.5% - 3%. Anthropogenic TFA is widely dispersed, but the narrow body of water where relevant depth-profiles for TFA concentrations have been reported, covering a distance of about 13,300 km, a narrow corridor of 200 km, to a depth of 2000 m and 200 ng/L

TFA, contains about 1 million tonnes of TFA. This is greater than the estimated anthropogenic TFA in the whole of the Atlantic Ocean, and similar to the theoretical upper limit. Therefore, anthropogenic emissions are responsible for only a small fraction of the TFA observed in the Atlantic Ocean. Increased emissions of TFA for the sensitivity analyses or additional emissions in 2021 to 2022 do not change this conclusion. The Atlantic Ocean must therefore contain a large natural burden of TFA. However, the mechanism of formation for naturally occurring TFA is yet to be determined.

Author Note

The author is solely responsible for conceptualization, writing, content, and data compilation.

Funding

This work was supported financially by the EFCTC trade association.

Conflicts of Interest

The author is a science consultant to EFCTC (European Fluorocarbons Technical Committee). EFCTC trade association members produce HFCs, HCFCs, HFOs, and HCFOs (discussed in this inventory), and some of the substances EFCTC members produce degrade to TFA, which is the subject of this review paper.

References

- 24ChemicalResearch (2024). *Ammonium Bifluoride Market-Global Outlook and Forecast 2024-2030*.
<https://www.24chemicalresearch.com/reports/158316/global-ammonium-bifluoride-market-2022-2028-623>
- Acerboni, G., Beukes, J. A., Jensen, N. R., Hjorth, J., Myhre, G., Nielsen, C. J. et al. (2001). Atmospheric Degradation and Global Warming Potentials of Three Perfluoroalkenes. *Atmospheric Environment*, 35, 4113-4123.
[https://doi.org/10.1016/s1352-2310\(01\)00209-6](https://doi.org/10.1016/s1352-2310(01)00209-6)
- AFEAS (2000). *Alternative Fluorocarbons Environmental Acceptability Study*. Introduction to AFEAS, Production, Sales and Atmospheric Release of Fluorocarbons through 2000.
https://unfccc.int/files/methods/other_methodological_issues/interactions_with_ozone_layer/application/pdf/introafeas.pdf
- Ahrens, L., Barber, J. L., Xie, Z., & Ebinghaus, R. (2009). Longitudinal and Latitudinal Distribution of Perfluoroalkyl Compounds in the Surface Water of the Atlantic Ocean. *Environmental Science & Technology*, 43, 3122-3127. <https://doi.org/10.1021/es803507p>
- Ahrens, L., Xie, Z., & Ebinghaus, R. (2010). Distribution of Perfluoroalkyl Compounds in Seawater from Northern Europe, Atlantic Ocean, and Southern Ocean. *Chemosphere*, 78, 1011-1016. <https://doi.org/10.1016/j.chemosphere.2009.11.038>
- Arnold, T., Harth, C. M., Mühle, J., Manning, A. J., Salameh, P. K., Kim, J. et al. (2013). Nitrogen Trifluoride Global Emissions Estimated from Updated Atmospheric Measurements. *Proceedings of the National Academy of Sciences*, 110, 2029-2034.
<https://doi.org/10.1073/pnas.1212346110>

- Arnold, T., Ivy, D. J., Harth, C. M., Vollmer, M. K., Mühle, J., Salameh, P. K. et al. (2014). HFC-43-10mee Atmospheric Abundances and Global Emission Estimates. *Geophysical Research Letters*, 41, 2228-2235. <https://doi.org/10.1002/2013gl059143>
- Booten, C. W., Nicholson, S. R., Mann, M. K., & Abdelaziz, O. (2020). *Refrigerants: Market Trends and Supply Chain Assessment. No. NREL/TP-5500-70207*. National Renewable Energy Lab. (NREL). <https://docs.nrel.gov/docs/fy20osti/70207.pdf>
- Bourgeois, F., Andreiadis, E., & Lambert, J.-M. (2017). *Tantalum and Niobium Production, State of the Art*. REFRAM—Final Conference, Brussels. <https://www.scribd.com/document/463491022/9-MSP-REFRAM-Tantalum-Niobium-production-SotA-F-Bourgeois>
- Brotherton, R. J., Weber, C. J., Guibert, C. R., & Little, J. L. (2000). *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH. https://en.wikipedia.org/wiki/Ullmann%27s_Encyclopedia_of_Industrial_Chemistry
- Brown, C. J. (2002). Recovery of Stainless Steel Pickle Liquors: Purification vs. Regeneration. In *CISA International Steel Congress*. <https://www.semanticscholar.org/paper/RECOVERY-OF-STAINLESS-STEEL-PICKLE-LIQUORS:-VS.-Brown-Eng./01f5fdb92b1fcd7fe2063ab18392838e3808f316>
- CCM (2016). *CCM: China's LiPF6 Market Ushering Favorable Export Tax Refund in 2015*. China Market News. <https://www.cnchemicals.com/Press/87489-CCM:%20China%E2%80%99s%20LiPF6%20market%20ushering%20favorable%20export%20tax%20refund%20in%202015.html>
- Chemanalyst (2025). *Lithium Fluoride Market Analysis*. <https://www.chemanalyst.com/industry-report/lithium-fluoride-market-2865>
- Clarke, G., & Huxtable, P. (2017). Fluorspar to 2018 and Beyond. In *Fluorine Forum Conference*. <https://imformed.com/wp-content/uploads/2017/11/CLARKE-Fluorine-Forum-2017-IMFORMED.pdf>
- Clegg, S. L. (2023). *Assessment of Possible Transport of Trifluoroacetic Acid from the Oceans to the Atmosphere*. Report Prepared for EFCTC. <https://www.fluorocarbons.org/publication/assessment-of-possible-transport-of-trifluoroacetic-acid-from-the-oceans-to-the-atmosphere/>
- Craig, P. (2019). *Catchment Boundaries of Ocean Drainage Basins*. Research Data Reading University. <https://researchdata.reading.ac.uk/195/7/documentation.pdf>
- CRM (2020). *Fluorspar Critical Raw Materials Fact Sheet*. https://screen.eu/wp-content/uploads/2023/01/FLUORSPAR_CRM_2020_Fact-sheets_critical_Final.pdf
- Cui, J., Guo, J., Zhai, Z., & Zhang, J. (2019). The Contribution of Fluoropolymer Thermolysis to Trifluoroacetic Acid (TFA) in Environmental Media. *Chemosphere*, 222, 637-644. <https://doi.org/10.1016/j.chemosphere.2019.01.174>
- Dahlgren, L. (2010). *Treatment of Spent Pickling Acid from Stainless Steel Production. A Review of Regeneration Technologies with Focus on the Neutralisation Process for Implementation in Chinese Industry*. KTH Industrial Engineering and Management. Master of Science Thesis. <https://www.diva-portal.org/smash/get/diva2:473369/fulltext01>
- Dahlke, T., & Sen, E. (2021). *Converting Fluorosilicic Acid into Value-Added Hydrogen Fluoride*. Fertilizer International 504. <https://www.fertilizerinternational.com>
- Dahlke, T., Ruffiner, O., & Cant, R. (2016). Production of HF from H₂SiF₆. *Procedia Engineering*, 138, 231-239. <https://doi.org/10.1016/j.proeng.2016.02.080>

- Dahlke, T., Ruffiner, O., & Dincer, B. (2017). *Economical Comparison of Hydrofluoric Acid Production from Fluorosilicic Acid and Fluorspar*. <https://www.scribd.com/document/662954873/acide-fluorhydrique>
- DataVagyanik (2025). *Boron Trifluoride (BF₃) Market Size, Production, Price, Market Share, Import vs Export*. <https://datavagyanik.com/reports/boron-trifluoride-bf3-market-size-production-sales-average-product-price-market-share-import-vs-export/>
- Department of Agriculture, State of Hawaii (2024). *Distribution of Farmland for Horticultural Crops State of Hawaii, 2022*. https://dab.hawaii.gov/add/files/2025/01/Distribution-of-Farmland-for-Horticulture-2022_SOH_12.30.2024.pdf
- ECHA CHEM (2025). *Trifluoroacetic Acid 100.000.846*. Active REACH Registrations—ECHA CHEM.
- EEAP (2023). *Montreal Protocol on Substances That Deplete the Ozone Layer*. UNEP 2022 Assessment Report of the Environmental Effects Assessment Panel. <https://ozone.unep.org/system/files/documents/EEAP-2022-Assessment-Report-May2023.pdf>
- Ellis, D. A., & Mabury, S. A. (2000). The Aqueous Photolysis of TFM and Related Trifluoromethylphenols. An Alternate Source of Trifluoroacetic Acid in the Environment. *Environmental Science & Technology*, *34*, 632-637. <https://doi.org/10.1021/es990422c>
- Ellis, D. A., Martin, J. W., De Silva, A. O., Mabury, S. A., Hurley, M. D., Sulbaek Andersen, M. P. et al. (2004). Degradation of Fluorotelomer Alcohols: A Likely Atmospheric Source of Perfluorinated Carboxylic Acids. *Environmental Science & Technology*, *38*, 3316-3321. <https://doi.org/10.1021/es049860w>
- European Environment Agency (2021). *Fluorinated Polymers in a Low Carbon, Circular and Toxic-Free Economy*. Technical Report, Eionet Report-ETC/WMGE 2021/9. https://www.researchgate.net/publication/357866831_Fluorinated_polymers_in_a_low_carbon_circular_and_toxic-free_economy
- Fortems-Cheiney, A., Saunois, M., Pison, I., Chevallier, F., Bousquet, P., Cressot, C. et al. (2015). Increase in HFC-134a Emissions in Response to the Success of the Montreal Protocol. *Journal of Geophysical Research: Atmospheres*, *120*, 11,728-11,742. <https://doi.org/10.1002/2015jd023741>
- Frank, H., Christoph, E. H., Holm-Hansen, O., & Bullister, J. L. (2002). Trifluoroacetate in Ocean Waters. *Environmental Science & Technology*, *36*, 12-15. <https://doi.org/10.1021/es0101532>
- FSTOC (2022). *Fire Suppression Technical Options Committee 2022 Assessment Report* (p. 145). Technology and Economic Assessment Panel (TEAP)|Ozone Secretariat.
- Garavagno, M. D. L. A., Holland, R., Khan, M. A. H., Orr-Ewing, A. J., & Shallcross, D. E. (2024). Trifluoroacetic Acid: Toxicity, Sources, Sinks and Future Prospects. *Sustainability*, *16*, Article No. 2382. <https://doi.org/10.3390/su16062382>
- Green Car Congress (2016). *CCM: LiPF₆ Industry in China May Face Overcapacity in 2017*.
- Gressent, A., Rigby, M., Ganesan, A. L., Prinn, R. G., Manning, A. J., Mühle, J. et al. (2021). Growing Atmospheric Emissions of Sulfuryl Fluoride. *Journal of Geophysical Research: Atmospheres*, *126*, e2020JD034327. <https://doi.org/10.1029/2020jd034327>
- Griini, A., Myhre, G., Sundet, J. K., & Isaksen, I. S. A. (2002). Modeling the Annual Cycle of Sea Salt in the Global 3D Model Oslo CTM2: Concentrations, Fluxes, and Radiative Impact. *Journal of Climate*, *15*, 1717-1730. [https://doi.org/10.1175/1520-0442\(2002\)015<1717:mtacos>2.0.co;2](https://doi.org/10.1175/1520-0442(2002)015<1717:mtacos>2.0.co;2)

- Guo, Z., Attar, A. A., Qiqige, Q., Lundgren, R. J., & Joudan, S. (2025). Photochemical Formation of Trifluoroacetic Acid: Mechanistic Insights into a Fluoxetine-Related Aryl-CF₃ Compound. *Environmental Science & Technology*, *59*, 1367-1377. <https://doi.org/10.1021/acs.est.4c10777>
- Halocarbon (2025). *2,2,2-Trifluoroethanol*. Halocarbon Life Sciences. <https://halocarbonlifesciences.com/fluorinated-building-blocks/2-2-2-trifluoroethanol-tfe/>
- Han, Z., Wu, S., Wu, X., Guan, W., Cao, Z., Li, Q. et al. (2023). Recycling of Lithium and Fluoride from Lf Wastewater from Lf Synthesis Industry by Solvent Extraction. *Journal of Environmental Chemical Engineering*, *11*, Article ID: 110557. <https://doi.org/10.1016/j.jece.2023.110557>
- Harrison, J. J., Chipperfield, M. P., Boone, C. D., Dhomse, S. S., & Bernath, P. F. (2021). Fifteen Years of HFC-134a Satellite Observations: Comparisons with SLIMCAT Calculations. *Journal of Geophysical Research: Atmospheres*, *126*, e2020JD033208. <https://doi.org/10.1029/2020jd033208>
- Hengce (2025). *Global Alkylate Market Research Report 2025*. Hengce Research. <https://hengceresearch.com/products/alkylate/211074>
- Henne, S., Shallcross, D. E., Reimann, S., Xiao, P., Brunner, D., O'Doherty, S. et al. (2012). Future Emissions and Atmospheric Fate of HFC-1234yf from Mobile Air Conditioners in Europe. *Environmental Science & Technology*, *46*, 1650-1658. <https://doi.org/10.1021/es2034608>
- Henry, B. J., Carlin, J. P., Hammerschmidt, J. A., Buck, R. C., Buxton, L. W., Fiedler, H. et al. (2018). A Critical Review of the Application of Polymer of Low Concern and Regulatory Criteria to Fluoropolymers. *Integrated Environmental Assessment and Management*, *14*, 316-334. <https://doi.org/10.1002/ieam.4035>
- International Aluminium Institute (2025). *International-Aluminium.org IAI Life Cycle Inventory Survey, Which Takes Place Every 5 Years Starting from 2005*.
- IPCC (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.
- IVA (2022). Molar TFA Formation Rates of Thirteen Fluorinated Pesticides. In *Mark Winter (Industrieverband Agrar e. V. (IVA)) at the TFA Stakeholder Workshop in Karlsruhe, Germany on Minimization Strategies of the German Federal Environment Agency*.
- JACC (2005). *Hexafluoropropylene JACC No. 48, ISSN-0773-6339-48 JACC Report 48-Hexafluoropropylene-ECETOC*.
- Joerss, H., Freeling, F., van Leeuwen, S., Hollender, J., Liu, X., Nödler, K. et al. (2024). Pesticides Can Be a Substantial Source of Trifluoroacetate (TFA) to Water Resources. *Environment International*, *193*, Article ID: 109061. <https://doi.org/10.1016/j.envint.2024.109061>
- Jordan, A., & Frank, H. (1999). Trifluoroacetate in the Environment. Evidence for Sources Other than HFC/HCFs. *Environmental Science & Technology*, *33*, 522-527. <https://doi.org/10.1021/es980674y>
- Joudan, S., De Silva, A. O., & Young, C. J. (2021). Insufficient Evidence for the Existence of Natural Trifluoroacetic Acid. *Environmental Science: Processes & Impacts*, *23*, 1641-1649. <https://doi.org/10.1039/d1em00306b>
- Khan, M. F., & Murphy, C. D. (2021). Bacterial Degradation of the Anti-Depressant Drug Fluoxetine Produces Trifluoroacetic Acid and Fluoride Ion. *Applied Microbiology and Biotechnology*, *105*, 9359-9369. <https://doi.org/10.1007/s00253-021-11675-3>
- Lee, J. C. K., & Wen, Z. (2016). Rare Earths from Mines to Metals: Comparing Environ-

- mental Impacts from China's Main Production Pathways. *Journal of Industrial Ecology*, 21, 1277-1290. <https://doi.org/10.1111/jiec.12491>
- Liao, C., Que, L., Fu, Z., Deng, P., Li, A., Wang, X. et al. (2024). Research Status of Electrolytic Preparation of Rare Earth Metals and Alloys in Fluoride Molten Salt System: A Mini Review of China. *Metals*, 14, Article No. 407. <https://doi.org/10.3390/met14040407>
- Lindley, A. A. (2023). An Inventory of Fluorspar Production, Industrial Use, and Emissions of Trifluoroacetic Acid (TFA) in the Period 1930 to 1999. *Journal of Geoscience and Environment Protection*, 11, 1-16. <https://doi.org/10.4236/gep.2023.113001>
- Liu, M., & Tanhua, T. (2024). *Water Masses in the Atlantic Ocean: Water Mass Ages and Ventilation*. Preprint Egusphere 1362. <https://doi.org/10.5194/egusphere-2024-1362>
- Liu, Y., Sheng, J., Rigby, M., Ganesan, A., Kim, J., Western, L. M. (2024). Increases in Global and East Asian Nitrogen Trifluoride (NF₃) Emissions Inferred from Atmospheric Observations. *Environmental Science & Technology*, 58, 13318-13326.
- Lozano-Morales, A., Inman, M., & Taylor, E. J. (2024). *Niobium Electropolishing Using an HF-Free Electrolyte*. Finishing and Coating.
- Machaca, D. M. C., de Carvalho, T. C., Tenório, J. A. S., Espinosa, D. C. R. (2025). Advancements in the Extraction of Niobium and Tantalum: Innovative Strategies in Hydrometallurgical Processes. *Minerals Engineering*, 222, Article ID: 109125. <https://doi.org/10.1016/j.mineng.2024.109125>
- Markets Report World (2025). *Polytetrafluoroethylene (PTFE) Market Size, Share, Growth, and Industry Analysis, by Type (Particles PTFE, Fine Powder PTFE), by Application (Construction, Automotive, Medical, Other), Regional Insights and Forecast to 2033*.
- MCTOC (2022). *Medical and Chemical Technical Options Committee 2022 Assessment Report Chapter 8*. Technology and Economic Assessment Panel (TEAP)|Ozone Secretariat.
- Moscato, A., Longo, M. V., Ferrante, M., & Fiore, M. (2025). Trifluoroacetic Acid: A Narrative Review on Physico-Chemical Properties, Exposure Pathways, and Toxicological Concerns. *Environments*, 12, Article No. 277. <https://doi.org/10.3390/environments12080277>
- MPCA (2022). *Minnesota Pollution Control Agency, Mobile Conditioner Leakage Rates for Model Year 2021*. Mobile Air Conditioner Leakage Rates—Model Year 2021 (Alphabetical List) (state.mn.us).
- Mühle, J., Kuijpers, L. J. M., Stanley, K. M., Rigby, M., Western, L. M., Kim, J. et al. (2022). Global Emissions of Perfluorocyclobutane (PFC-318, *c*-C₄f₈) Resulting from the Use of Hydrochlorofluorocarbon-22 (HCFC-22) Feedstock to Produce Polytetrafluoroethylene (PTFE) and Related Fluorochemicals. *Atmospheric Chemistry and Physics*, 22, 3371-3378. <https://doi.org/10.5194/acp-22-3371-2022>
- National Centers for Environmental Information (2025). *World Ocean Volumes*.
- Neale, P. J., Hylander, S., Banaszak, A. T., Häder, D., Rose, K. C., Vione, D. et al. (2025). Environmental Consequences of Interacting Effects of Changes in Stratospheric Ozone, Ultraviolet Radiation, and Climate: UNEP Environmental Effects Assessment Panel, Update 2024. *Photochemical & Photobiological Sciences*, 24, 357-392. <https://doi.org/10.1007/s43630-025-00687-x>
- Norton Engineering (2016). *Alkylation Technology Study Final Report, 2016*. <https://www.aqmd.gov/docs/default-source/permitting/alkylation-technology-study-final-report.pdf>
- Ozone Secretariat (2025). <https://ozone.unep.org/>

- Pmarketresearch (2021). *Global Trifluoroacetic Acid Production Will Increase to 33,958 Tons by 2023*. Pmarketresearch Predicts-PW Consulting.
- PrimaryInfo (2025). *Trifluoroethanol-Msds, Process, Patents, Suppliers, Company Profiles, Consultants, Technology, Uses, Study*.
- Prismane Consulting (2025). *Global Hexafluoropropylene Market Demand & Forecast Analysis 2018-2030. Hexafluoropropylene Market Size & Share/Global Forecast from 2018 to 2034*.
- PubChem (2025). *2,2,2-Trifluoroethanol/C2H3F3O/CID 6409-PubChem*.
- Regel-Rosocka, M. (2010). A Review on Methods of Regeneration of Spent Pickling Solutions from Steel Processing. *Journal of Hazardous Materials*, 177, 57-69.
<https://doi.org/10.1016/j.jhazmat.2009.12.043>
- Research and Markets (2023). *Global Lithium Hexafluorophosphate Market Analysis. Global Lithium Hexafluorophosphate Market Analysis: Plant Capacity, Production, Operating Efficiency, Demand & Supply, End-User Industries, Sales Channel, Regional Demand, Company Share, 2015-2035*.
- Rhode, O. (2020). *Fluorspar Supply & Demand Overview, Fluorine Forum Conference*. PowerPoint-Präsentation.
- RMIS-Raw Materials Information System (2025). European Commission Raw Materials Profiles for Lanthanum (La). <https://rmis.jrc.ec.europa.eu/rmp/Lanthanum>
Cerium (Ce) <https://rmis.jrc.ec.europa.eu/rmp/Cerium>
Praseodymium (Pr) <https://rmis.jrc.ec.europa.eu/rmp/Praseodymium>
Neodymium (Nd) <https://rmis.jrc.ec.europa.eu/rmp/Neodymium>
- Rockstone Research (2019). *Fluorspar: The Sweet Spot for Quebec's Steel and Aluminium Industries*. Rockstone Research.
- Rögener, F., Lednova, Y. A., Andrianova, M. Y., & Lednov, A. V. (2019). Sustainable Stainless Steel—A Review on Acid Regeneration Systems for Application in Continuous Pickling Lines. *Vestnik of Nosov Magnitogorsk State Technical University*, 17, 38-48.
<https://doi.org/10.18503/1995-2732-2019-17-2-38-48>
- Savvidou, E. K., Sha, B., Salter, M. E., Cousins, I. T., & Johansson, J. H. (2023). Horizontal and Vertical Distribution of Perfluoroalkyl Acids (PFAAs) in the Water Column of the Atlantic Ocean. *Environmental Science & Technology Letters*, 10, 418-424.
<https://doi.org/10.1021/acs.estlett.3c00119>
- Saxby, A. M. B. (2013). Chinese Fluorspar—What Next? Roskill Information Services. In *Industrial Minerals Events Fluorspar 2013 Conference*.
- Scheurer, M., Nödler, K., Freeling, F., Janda, J., Happel, O., Riegel, M. et al. (2017). Small, Mobile, Persistent: Trifluoroacetate in the Water Cycle—Overlooked Sources, Pathways, and Consequences for Drinking Water Supply. *Water Research*, 126, 460-471.
<https://doi.org/10.1016/j.watres.2017.09.045>
- Schreiber, A., Marx, J., Zapp, P., & Kuckshinrichs, W. (2020). Comparative Life Cycle Assessment of Neodymium Oxide Electrolysis in Molten Salt. *Advanced Engineering Materials*, 22, Article ID: 1901206. <https://doi.org/10.1002/adem.201901206>
- Scientific Assessment of Ozone Depletion (2022). *GAW Report No. 278* (509 p.). World Meteorological Organization (WMO), Scientific Assessment Panel (SAP)|Ozone Secretariat.
- Scientific Assessment Panel (2024). *Report of the Scientific Assessment Panel in Response to Decision XXXV/7: Emissions of HFC-23*. NOAA Global Monitoring Laboratory, Scientific Assessment Panel (SAP).
- Scott, B. F., Macdonald, R. W., Kannan, K., Fisk, A., Witter, A., Yamashita, N. et al. (2005).

Trifluoroacetate Profiles in the Arctic, Atlantic, and Pacific Oceans. *Environmental Science & Technology*, 39, 6555-6560. <https://doi.org/10.1021/es047975u>

Sellevåg, S. R., Nielsen, C. J., Søvde, O. A., Myhre, G., Sundet, J. K., Stordal, F. et al. (2004). Atmospheric Gas-Phase Degradation and Global Warming Potentials of 2-Fluoroethanol, 2,2-Difluoroethanol, and 2,2,2-Trifluoroethanol. *Atmospheric Environment*, 38, 6725-6735. <https://doi.org/10.1016/j.atmosenv.2004.09.023>

Sha, B., Johansson, J. H., Benskin, J. P., Cousins, I. T., & Salter, M. E. (2021a). Influence of Water Concentrations of Perfluoroalkyl Acids (PFAAs) on Their Size-Resolved Enrichment in Nascent Sea Spray Aerosols. *Environmental Science & Technology*, 55, 9489-9497. <https://doi.org/10.1021/acs.est.0c03804>

Sha, B., Johansson, J. H., Tunved, P., Bohlin-Nizzetto, P., Cousins, I. T., & Salter, M. E. (2021b). Sea Spray Aerosol (SSA) as a Source of Perfluoroalkyl Acids (PFAAs) to the Atmosphere: Field Evidence from Long-Term Air Monitoring. *Environmental Science & Technology*, 56, 228-238. <https://doi.org/10.1021/acs.est.1c04277>

Sharopov, U., Juraev, T., Kakhkhorov, S., Juraev, K., Kurbanov, M., Karimov, M. et al. (2025). New Challenges for Lithium Fluoride: From Dosimeter to Solid-State Batteries (Review). *Next Materials*, 8, Article ID: 100548. <https://doi.org/10.1016/j.nxmte.2025.100548>

Simmonds, P. G., Rigby, M., Manning, A. J., Lunt, M. F., O'Doherty, S., McCulloch, A. et al. (2016). Global and Regional Emissions Estimates of 1,1-Difluoroethane (HFC-152a, CH₃CHF₂) from in Situ and Air Archive Observations. *Atmospheric Chemistry and Physics*, 16, 365-382. <https://doi.org/10.5194/acp-16-365-2016>

Simmonds, P. G., Rigby, M., Manning, A. J., Park, S., Stanley, K. M., McCulloch, A. et al. (2020). The Increasing Atmospheric Burden of the Greenhouse Gas Sulfur Hexafluoride (SF₆). *Atmospheric Chemistry and Physics*, 20, 7271-7290. <https://doi.org/10.5194/acp-20-7271-2020>

Simmonds, P. G., Rigby, M., McCulloch, A., O'Doherty, S., Young, D., Mühle, J. et al. (2017). Changing Trends and Emissions of Hydrochlorofluorocarbons (HCFCs) and Their Hydrofluorocarbon (HFCs) Replacements. *Atmospheric Chemistry and Physics*, 17, 4641-4655. <https://doi.org/10.5194/acp-17-4641-2017>

Statista (2022). *Global Stainless Steel Melt Shop Production*. Statista.

Sullivan, W. P., Burkett, D. P., Boogaard, M. A., Criger, L. A., Freiburger, C. E., Hubert, T. D. et al. (2021). Advances in the Use of Lampricides to Control Sea Lampreys in the Laurentian Great Lakes, 2000-2019. *Journal of Great Lakes Research*, 47, S216-S237. <https://doi.org/10.1016/j.jglr.2021.08.009>

Sun, M., Cui, J., Guo, J., Zhai, Z., Zuo, P., & Zhang, J. (2020). Fluorochemicals Biodegradation as a Potential Source of Trifluoroacetic Acid (TFA) to the Environment. *Chemosphere*, 254, Article ID: 126894. <https://doi.org/10.1016/j.chemosphere.2020.126894>

Talbot, A., Holländer, H. C., & Bentzer, P. (2025). Greenhouse Gas Impact from Medical Emissions of Halogenated Anaesthetic Agents: A Sales-Based Estimate. *The Lancet Planetary Health*, 9, e227-e235. [https://doi.org/10.1016/s2542-5196\(25\)00027-0](https://doi.org/10.1016/s2542-5196(25)00027-0)

TEAP (2019). *Technology and Economic Assessment Panel Report, Volume 1, Decision XXX/3 TEAP Task Force Report on Unexpected Emissions of CFC-11*. Technology and Economic Assessment Panel (TEAP)|Ozone Secretariat.

TEAP (2024). *Technology and Economic Assessment Panel Progress Report, Volume 1, Table 5-9*. Technology and Economic Assessment Panel (TEAP)|Ozone Secretariat.

Teng, H. (2012). Overview of the Development of the Fluoropolymer Industry. *Applied Sciences*, 2, 496-512. <https://doi.org/10.3390/app2020496>

- TOSOH (2003). *2,2,2-Trifluoroethanol (TFEA). Its Production Process and Various Applications*. TFEAComplete.
- Tubiello, F. N., Conchedda, G., Casse, L. et al. (2023b). *Cropland Area Database by Country Circa 2020*. Zenodo [Dataset]. <https://doi.org/10.5281/zenodo.7987515>
- Tubiello, F. N., Conchedda, G., Casse, L., Hao, P., De Santis, G., & Chen, Z. (2023a). A New Cropland Area Database by Country Circa 2020. *Earth System Science Data*, 15, 4997-5015. <https://doi.org/10.5194/essd-15-4997-2023>
- U.S Energy Information Administration (2025). *U.S. Refinery Alkylates Production Capacity as of January 1 (Barrels per Stream Day)*.
- U.S. Geological Survey (2017). *2017 Minerals Yearbook, Fluorspar*. Fluorspar Statistics and Information|U.S. Geological Survey (usgs.gov).
- U.S. Geological Survey (2018). *2018 Minerals Yearbook, Fluorspar* (14th ed.). Quoting Roskill Information Services Ltd., 2020, Fluorspar-Outlook to 2029.
- U.S. Geological Survey (2020). *2020 Minerals Yearbook, Fluorspar*.
- U.S. Geological Survey (2025a). *Fluorspar Statistics and Information*. U.S. Geological Survey (usgs.gov).
- U.S. Geological Survey (2025b). *Aluminum Statistics and Information*. U.S. Geological Survey
- U.S. Geological Survey (2025c). *Niobium and Tantalum Statistics and Information*. U.S. Geological Survey (usgs.gov).
- UBA (2021). *Persistent Degradation Products of Halogenated Refrigerants and Blowing Agents in the Environment: Type, Environmental Concentrations, and Fate with Particular Regard to New Halogenated Substitutes with Low Global Warming Potential*. Umweltbundesamt.
- UBA (2022). *UBA Background Paper: Reducing Chemical Inputs into Waters—Trifluoroacetate (TFA) as a Persistent and Mobile Substance from Many Sources. Sources, Input Pathways, Environmental Concentrations of TFA, and Regulatory Approaches. Reducing the Input of Chemicals into Waters: Trifluoroacetate (TFA) as a Persistent and Mobile Substance with Many Sources*. Umweltbundesamt.
- UBA (2023). *Trifluoroacetate (TFA): Laying the Foundations for Effective Mitigation—Spatial Analysis of the Input Pathways into the Water Cycle*. <https://www.umweltbundesamt.de/en/publikationen/trifluoroacetate-tfa-laying-the-foundations-for>
- UBA (2024). *Untersuchung von aktuellen Meerwasserproben auf Trifluoressigsäure (Investigation of Current Seawater Samples for Trifluoroacetic Acid)*. <https://www.umweltbundesamt.de/publikationen/untersuchung-von-aktuellen-meerwasserproben-auf#:~:text=Der%20Bericht%20beschreibt%20die%20Entwicklung%20und%20Validierung%20einer,aus%20den%20Jahren%202022%20und%202023%20zu%20bestimmen>
- USDA's National Agricultural Statistics Service Alaska Field Office (2022). *2022 Census of Agriculture State Profile Alaska*. https://www.nass.usda.gov/Publications/AgCensus/2022/Online_Resources/County_Profiles/Alaska/cp99002.pdf
- Vollmer, M. K., Miller, B. R., Rigby, M., Reimann, S., Mühle, J., Krummel, P. B. et al. (2011). Atmospheric Histories and Global Emissions of the Anthropogenic Hydrofluorocarbons HFC-365mfc, HFC-245fa, HFC-227ea, and HFC-236fa. *Journal of Geophysical Research*, 116, D08304. <https://doi.org/10.1029/2010jd015309>
- Vollmer, M. K., Mühle, J., Henne, S., Young, D., Rigby, M., Mitrevski, B. et al. (2021). Un-

- expected Nascent Atmospheric Emissions of Three Ozone-Depleting Hydrochlorofluorocarbons. *Earth, Atmospheric, and Planetary Sciences*, 118, e2010914118. <https://doi.org/10.1073/pnas.2010914118>
- Vollmer, M. K., Rhee, T. S., Rigby, M., Hofstetter, D., Hill, M., Schoenenberger, F. et al. (2015). Modern Inhalation Anesthetics: Potent Greenhouse Gases in the Global Atmosphere. *Geophysical Research Letters*, 42, 1606-1611. <https://doi.org/10.1002/2014gl062785>
- Wang, Z., Wang, Y., Li, J., Henne, S., Zhang, B., Hu, J. et al. (2018). Impacts of the Degradation of 2,3,3,3-Tetrafluoropropene into Trifluoroacetic Acid from Its Application in Automobile Air Conditioners in China, the United States, and Europe. *Environmental Science & Technology*, 52, 2819-2826. <https://doi.org/10.1021/acs.est.7b05960>
- Western, L. M., Bourguet, S., Crotwell, M., Hu, L., Krummel, P. B., De Longueville, H. et al. (2025). *Increasing Emissions of HCFC-123 and HCFC-124 May Be Due to Leakage during HFC-125 Production*. EGUSphere Preprint. <https://doi.org/10.5194/egusphere-2025-3000>
- Will, R. (2007). Global Fluorspar Supply and Demand Trends. In *Industrial Minerals Events Fluorspar 2007 Conference*.
- World Atlas (2025). *Largest Drainage Basins in the World*. WorldAtlas.
- World Nuclear Association (2024). *Conversion and Deconversion*. World Nuclear Association.