

The Precautionary Principle and the Environment: A Case Study of an Immediate Global Response to the Molina and Rowland Warning

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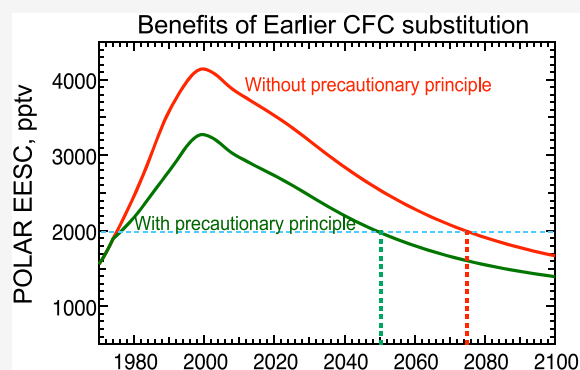
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ABSTRACT: In 1974, Mario J. Molina and F. Sherwood Rowland warned that chlorofluorocarbons (CFCs) could destroy the stratospheric ozone layer, which protects Earth against the harmful effects of ultraviolet radiation [Molina and Rowland *Nature* 1974, 249, 810]. In 1975, Ramanathan warned that CFCs are powerful greenhouse gases (GHGs) and would rival carbon dioxide (CO₂) in causing climate change if left unabated [Ramanathan *Science* 1975, 190, 50]. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (Protocol), arguably the most successful global environmental treaty in history, was enacted in response to these warnings. This Protocol has phased out almost 99% of the production and consumption of ozone depleting substances (ODSs). Other papers have explored the “world avoided” by actions under the Protocol [Prather et al. *Nature* 1996, 381, 551; Newman et al. *Atmos. Chem. Phys.* 2009, 9, 2113; Morgenstern et al. *Geophys. Res. Lett.* 2008, 35, 1]. They concluded that the ozone layer would have been highly depleted across the globe by the mid-21st century without the Protocol and that the Protocol contributed significantly to reduce climate change. This paper explores what could have been achieved if the world had acted against the continued use of ODSs, which were both ozone-depleting and greenhouse gases, immediately after Molina and Rowland warned of stratospheric ozone depletion and Ramanathan warned of climate forcing using chemicals and technology that were already globally available in the mid-1970s. We show that such “precautionary principle” actions would have reduced global ozone layer depletion, reduced the extent of the ozone hole, brought forward the dates for ozone layer recovery, and helped minimize climate change.

KEYWORDS: ozone layer, chlorofluorocarbons, climate change, Montreal Protocol, ozone-depleting substances, hydrofluorochlorocarbons



INTRODUCTION

The first chlorofluorocarbons (CFCs) were developed in the 1920s and were rapidly commercialized as replacements for toxic and flammable refrigerants such as ammonia (NH₃), methyl chloride (CH₃Cl), and sulfur dioxide (SO₂). CFCs are thermally stable and nonflammable, have low toxicity, and exhibit an array of desirable properties that make them energy-efficient refrigerants. Their many other physical and chemical properties led to the invention of a half dozen more CFCs used as cleaning solvents, blowing agents in thermal insulating and flexible foam, and medical, cosmetic, and convenience aerosol product propellants. Consequently, CFC production and usage climbed quickly. By the 1960s, the CFC industry was worth \$8 billion in the United States alone (estimated in 1996 by the World Resources Institute^{6,7}) and growing rapidly. All the while, other chlorinated and brominated ozone depleting substances (ODSs), including carbon tetrachloride, fluorobromocarbons (halons), hydrochlorofluorocarbons (HCFCs), methyl chloroform (CH₃CCl₃), and methyl bromide (CH₃Br),

were marketed for rapidly increasing and widespread uses such as solvents, fire extinguishing agents, pesticides, and feedstocks.

In June 1974, Molina and Rowland¹ warned that CFCs, which were stable in the troposphere, could migrate to the stratosphere, where they could destroy the ozone layer through chlorine-catalyzed reactions. They concluded that the depleted ozone layer would increase harmful surface UV-B radiation and cause ecological and environmental problems. There was little immediate public or policy reaction to their warning. However, when they presented their findings at a side event of the American Chemical Society annual meeting in 1974, Rowland and Molina called for a ban on the use of CFCs in cosmetic and convenience products such as deodorant and hair spray.

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Table 1. Lifetime, ODP, and GWP of Chemicals Considered Here^a

chemical	formula	atmospheric lifetime, years	Ozone Depleting Potential	radiative efficiency, W m ⁻² ppb ⁻¹	Global Warming Potential
CFC-11	CFCl ₃	52	1.0	0.25	5160
CFC-12	CF ₂ Cl ₂	102	0.86 ^b	0.32	10 300
CFC-113	CCl ₂ FCClF ₂	93	0.8	0.30	6080
CFC-114	CClF ₂ CClF ₂	189	0.5	0.31	8580
CFC-115	CClF ₂ CF ₃	540	0.26	0.18	7310
HCFC-22	CHF ₂ Cl	11.9	0.03	0.20	1780
HCFC-141b	CH ₃ CCl ₂ F	9.4	0.085	0.14	800

^aThey are taken from the WMO/UNEP 2018 assessment.²² The radiative forcing efficiency was taken from the WMO/UNEP 2010 assessment.¹⁵

^bCalculations were carried out with an ODP of 0.86, while the most recent assessment lists it as varying from 0.73 to 0.81.

They based their call on the argument that early action should be taken as a precaution against potentially catastrophic harm: the precautionary principle. Their call was met with consumer boycotts and regulatory actions by a few countries that phased out CFCs as aerosol propellants in Canada, USA, and a few Nordic countries but not in the rest of the world. A year later, Ramanathan² showed that continued emissions of CFCs would lead to large climate forcings since these ODSs are also potent greenhouse gases, GHGs. Thus, by 1975, it was known that CFCs could pose two harms to Earth's environment: ozone layer depletion and climate change.

Research into ozone depletion continued during the next decade while ODS emissions from new uses and growth in existing applications offset the initial aerosol propellant bans. In the meantime, in 1972, the landmark United Nations Conference on the Human Environment (Stockholm Conference) established the United Nations Environment Programme, which as early as 1975 began organizing for atmospheric protection and in March 1985 agreed to the Vienna Convention on Protection of the Ozone Layer, which established the framework for a protocol. Supported by increased scientific confidence about the global ozone layer depletion, 27 countries plus the European Community (EC) signed the Vienna Convention for the Protection of the Ozone Layer. With the increased scientific consensus of the potential threat to the ozone layer represented in the 1985 three-volume World Meteorological Organization (WMO) report⁸ and the May 1985 warning by Farman, Gardiner, and Shanklin⁹ of the unexpected appearance of the ozone hole over Antarctica during the Austral springtime, 26 countries and the EC signed the Montreal Protocol¹⁰ in 1987. The Montreal Protocol became the first UN treaty to achieve universal ratification and is now considered one of the most successful international agreements.¹¹

The Montreal Protocol is widely credited for being the first to apply the precautionary principle of restricting the use of chemicals known to provide high social value on the suspicion that they might cause harm far greater than benefits. When the Montreal Protocol was signed, the understanding was that fluorocarbons containing chlorine and bromine could deplete stratospheric ozone, which protects Earth against the harmful effects of ultraviolet radiation (DeSombre;¹² Jacobs¹³).

Upon signing the Montreal Protocol, the industry began replacing CFCs with similar but less harmful substances such as hydrochlorofluorocarbons (HCFCs) while simultaneously pursuing nonfluorocarbon replacements (called not-in-kind replacements) and reducing their overall use through better chemical containment, recycling, and in some cases, simply doing without. In response to scientific advancements, learned environmental effects, and technical and economic assess-

ments, the Montreal Protocol was continuously strengthened by amendments to add new controlled substances and adjustments to accelerate the phaseout of ODSs. Birmpili,¹⁴ successive quadrennial ozone layer assessments,^{15–19} Andersen and Sarma,²⁰ and Andersen et al.²¹ have detailed the path to the complete phaseout of the ODSs. More recently, the hydrofluorocarbons (HFCs) are scheduled for phase down via the 2016 Kigali Amendment.

HCFCs, like CFCs, contain chlorine but lead to lesser ozone layer depletion because they are destroyed in the lower atmosphere, resulting in lesser amounts reaching the ozone layer. Whereas CFCs have atmospheric lifetimes ranging from roughly 50 years (CFC-11; CFCl₃) to 640 years (CFC-13; CF₃Cl), the common HCFCs have lifetimes shorter than 20 years (e.g., HCFC-142b, with a lifetime of 18 years, is one of the longer-lived HCFCs).²² The shorter lifetimes (sometimes coupled with a smaller number of chlorine atoms) lead to smaller ozone depletion potentials (ODPs); they are usually a tenth or less than that of CFC-11 and CFC-12. Furthermore, the shorter lifetimes of HCFCs also lead to smaller global warming potentials (GWPs). Table 1 lists the atmospheric lifetimes, ODPs, radiative efficiency, and 100-year GWPs of the chemical considered here. Clearly, HCFCs have a lesser impact on ozone layer depletion and climate change when used in place of CFCs, assuming that their quantities used per application are similar and the energy efficiencies are comparable.

There have been explorations of “the world avoided” by actions put in motion by the Montreal Protocol, i.e., continued increases in emissions of ODSs at rates consistent with growth before the Protocol's adoption in 1987.^{3–5} Such examinations conclude that the ozone layer would have been highly depleted across the globe by the mid-21st century if actions were not taken even in the face of the continually depleting ozone layer and would have greatly increased surface UV radiation. They also concluded that the Montreal Protocol avoided high levels of climate forcing by avoiding the unabated buildup of CFCs and other ODSs that are potent GHGs. It is noted by Velders et al.²³ that the Montreal Protocol reduced the CO₂-equivalent emissions five times more than the first commitment period of the Kyoto Protocol had it been fully implemented. If Molina and Rowland had not sounded the scientific warning, the ozone layer depletion and the climate impacts likely would have been severe. By comparing what the world could have faced with what we have experienced, the Montreal Protocol is indeed a resounding success for protecting the ozone layer and mitigating climate change.

Without knowing the replacement chemicals and technologies, one cannot estimate the cost. Therefore, to the best of our knowledge, there were no credible cost-benefit analyses for

phasing out the CFCs in the 1970s. In retrospect, it is clear that the impacts on ozone and climate would have been catastrophic. The economic cost of avoiding that catastrophe was so small that few consumers even noticed the market transformation to ozone-safe technology.

Later modeling by the US Environmental Protection Agency (US EPA) estimated that full implementation of the Montreal Protocol would avoid more than 280 million cases of skin cancer, approximately 1.6 million skin cancer deaths, and more than 45 million cases of cataracts in the United States, resulting in societal health benefits in the United States over the period of 1990 to 2165 valued at about USD 4.2 trillion.²⁴

We wish to note that we are not criticizing the international controls as they occurred in history. At the time of the Molina and Rowland paper,¹ in addition to a lack of economic analysis, the science of ozone layer depletion was not universally accepted. There were significant uncertainties in the projected ozone layer depletion and, indeed, noticeable depletions were expected only in the middle of the 21st century with continued emissions. In addition, it is known that science is only one input for policymaking (see, e.g., Molina et al.²⁵ and Birmipili¹⁴). Therefore, we are not arguing that the path taken was unreasonable. Instead, we are pointing out that, while there are often many legitimate reasons to delay responding to new science concerns, there are also risks associated with long-lasting environmental consequences.

We believe that it is valuable and appropriate to ask what more could have been accomplished if the world had taken faster action after Molina and Rowland warned of stratospheric ozone depletion and Ramanathan warned of climate forcing. Therefore, this paper explores what could have been achieved before the Montreal Protocol if governments had mandated reductions to ODS uses that were already feasible in the mid-1970s. This paper does not detract from the resounding success of the Montreal Protocol. It demonstrates one of the lessons for application to other environmental issues from the global environmental experiment of phasing out ODSs. It is a question that one of the authors of this paper (Ravishankara) discussed with Mario Molina at some length.

■ WHAT MORE COULD HAVE BEEN DONE?

In this paper, we develop a methodology and present a case study on the benefits that would have occurred from the rapid replacement of the CFCs if undertaken beginning in 1975, i.e., immediately after the warnings of Molina, Rowland, and Ramanathan. In our analysis, we take a relatively conservative approach; these replacements occur at the pace accomplished later by the Montreal Protocol. Since less than 5% of use was in developing countries and the chemicals were used in the same applications as in the developed countries, it is presumed that those developing countries could have transitioned simultaneously with developed countries. It is worth noting that the developing countries had little CFC production in those years. Further, this assumption is contrary to the presumption of the Montreal Protocol that developing countries needed a 10-year grace period for phaseout. We do not consider that the ODS phaseouts that actually occurred could have taken place even faster if the Montreal Protocol had considered the climate cobenefits. (Note: We do not include here calculations where CFC-12 use could have been replaced by HFC-134a, which was developed and tested in the 1970s but not produced commercially until after the Montreal Protocol was enacted.)

Lastly, we acknowledge that there are many other possible scenarios that one could envision.

History shows that making these substitutions was possible as outlined in detail in the timeline included in Andersen and Sarma²⁰ and elaborated further in Andersen et al.²⁴ In 1976, cosmetic and convenience aerosol products represented about 58% of CFC sales (CFC-12 as a propellant and CFC-11 as a solvent). They were eliminated in North America by 1978 except for what was considered to be essential uses, such as medical applications. We could assume the same transition could have been accomplished worldwide for aerosol products.

In May 1988, the US Environmental Protection Agency and environmental nongovernmental organizations (NGOs) agreed with the American food packing industry to phase out CFC-12 within one year using HCFC-22 and hydrocarbons (HCs), share that technology worldwide, and then phase out HCFC-22 as soon as technically feasible. In January 1989, US EPA, mobile air climate system manufacturers, Underwriters Laboratories (UL), and automakers announced the successful development of unpatented recovery and recycling equipment that cut emissions from the service of motor vehicle air conditioning by about 50%. In 1990, \$2 billion in recycling equipment was marketed. In December 1989, German manufacturers announced technology that could reduce CFC-12 use in thermal insulating foam by 50% without compromising energy performance. Closed-cell foam uses for CFC-12 could have, and are assumed to have, decreased to 50% of what they were starting in 1975. After one year of research in anticipation of the Montreal Protocol, Bell Laboratories and AT&T announced in January 1988 an aqueous cleaning solution based on terpene from natural orchard and forest sources capable of replacing 50% of CFC-113 use within one year. Minor uses for CFC-11 could have been replaced by HCFC-141b starting in 1980, when it was found to have a reasonably low ODP and was available for use. In April 1990, Digital Equipment Corporation donated patented aqueous technology for free global use. We list these changes that we are aware of through various announcements to point to feasible substitutions accomplished rapidly once motivated by the Montreal Protocol.

Many other scenarios are possible. However, as noted earlier, we are examining only that plausible scenario where HCFC-22, which was already in production, replaces refrigerants. Here, we suggest a set of scenarios that would have been technologically viable and economically feasible in the mid-1970s to allow the phaseout of ODSs and that could occur with a slight delay if society, governments, and industry were willing.

CFC-11.

- The replacement of CFC-11 with nonfluorocarbon technologies in aerosol products could have decreased the use of this chemical by 97% starting in 1975.
- Open-cell foam uses could have been almost entirely replaced by nonfluorocarbon technologies that already existed in 1975 or were invented and implemented soon after.
- Production for closed-cell foam uses could have decreased to 50% of what they were starting in 1975.

Overall, CFC-11 production could have been reduced to 75% of what it was by better service practices starting in 1975, on top of the changes mentioned above.

CFC-12.

- Aerosol use of CFC-12 could have decreased to 3% of what it had been by replacing most CFC-12 with nonfluorocarbon technologies starting in 1975. In our scenario, we reduced CFC-12 propellant emission by 97% in 1975.
- In 1988, about 22% of CFCs was used for air conditioning and refrigeration. We assume better-servicing practices and recycle technology could have been developed by 1976 and implemented worldwide by 1978.
- 20% of refrigerant use could have been replaced by HCFC-22 starting in 1980.
- Overall production could have been cut to 75% of what it was due to better service practices in 1975, on top of the changes mentioned above.

In addition to these major changes, for completeness, we included changes to the minor uses of CFC-113, -114, and -115; these CFCs were used to a minimal extent in the early 1970s.

CFC-113.

- All uses could have stopped beginning in 1975.

CFC-114.

- All expansions of existing uses could have stopped beginning in 1975 (i.e., production rates do not increase after 1975).

CFC-115.

- We assume that the production rates do not increase after 1975 and that HCFC-22 could have replaced all CFC-115 use.
- All uses are decreased to 75% due to better service practices starting in 1975.

HCFC-22.

- All uses of HCFC-22, including its use as a substitution in the scenarios above, could have been decreased by 25% due to better service practices starting in 1975.

We have calculated the consequences of the above possible substitution on the ozone layer and climate forcing. Note that all these assumptions are consistent with the technologies in use and available at that time. Also, the primary replacements available were for CFC-11 and CFC-12. The other ODSs in our scenario were less important contributors to ozone depletion and climate change. Other scholars and sector experts can fine-tune these conservative assumptions and come to even stronger conclusions on the benefits if action had been taken at the time of the original warnings.

■ ASSESSING THE CONSEQUENCES OF THE ABOVE ACTIONS

We evaluate the consequences of these hypothetical actions on ozone depletion and climate change and compare them to what actually occurred from enacting the Montreal Protocol. To assess the impact on the ozone layer, we calculate the equivalent effective stratospheric chlorine (EESC) for the midlatitudes and polar regions. These are good proxies for the extent of ozone layer depletion that would occur in our scenarios, as EESC is frequently used to assess ozone depletion and projected EESC values are often used as a metric to gauge the recovery of the ozone layer.²² The date for the ozone layer's return to 1980 values is commonly called "recovery" in

the scientific and policy literature. It is frequently estimated by when the projected EESC returns to the 1980 value.

Similarly, we use the estimated RF changes to evaluate the impacts on climate. RF is a standard scientific and policy metric for the extent of climate forcing by a GHG and places the contributions of all GHGs on a common scale.²⁶ The RF of a GHG can be used to roughly calculate the expected surface temperature change via a relationship with its climate sensitivity factor. Our calculated RF for the ODSs does not include the offset due to the ozone depletion caused by the ODSs.^{22,27}

■ CALCULATING EESC AND RF CHANGES

Before we can calculate either EESC or RF, we need to calculate the atmospheric concentrations of the chemicals for the different scenarios considered. To ensure accurate accounting for the atmospheric concentrations of long-lived CFCs, we start our calculations in 1950, when ODS emissions remained very small relative to subsequent decades. Because there were no official reports of CFC and HCFC production numbers back to 1950, measured atmospheric mixing ratios were first calculated using both UNEP production numbers and the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS) sales data (WMO/UNEP 2014) (AFEAS 2013) for the available years. AFEAS sales data were partitioned into various end-use categories, while production data from the United Nations Environment Programme (UNEP) was not categorized by use. Therefore, we determined the production of each end-use category after 2003 by determining the proportions of each end-use based on the total sales reported by AFEAS in the final year in which it is available (2003) and applying those proportions to the UNEP total production numbers. AFEAS sales data was only available from 1980 to 2003; therefore, we followed the procedure described by Velders.²³ (There was some gray literature on CFC-11 and -12 sales from one or more manufacturers before 1980. However, they are not sufficiently comprehensive or citable for use here.) Furthermore, by the end of the time period that AFEAS compiled this data, substantial production of the CFCs and HCFCs occurred in companies that did not report to AFEAS. Because of this, from 1989 through 2003, when production was reported to UNEP and AFEAS, all AFEAS figures are scaled up so that global production is equal to global production reported to UNEP.

In some applications, such as solvents, cleaning agents, and propellants, the manufactured chemicals are released soon after they are produced and sold. In other applications, such as closed-cell foam, the chemicals are sequestered for a long time and slowly released over many decades. The time for which a produced chemical is sequestered before it is released into the atmosphere is known as its banking time. Attention is paid to the banking times for each use sector to calculate emissions from production numbers.

We estimate annual emissions and changes in banked amounts of CFC-11 and CFC-12 using a vintaging model. Each year's production is tracked separately with the fractional emission of that year's production in subsequent years depending on the release functions for a given use. We consider three categories of use and, thus, three release functions into which all production is divided. This division follows the estimates from AFEAS (2005) as stated above. The application category in which the CFCs reside the longest before being emitted is closed-cell foams (Category 1).

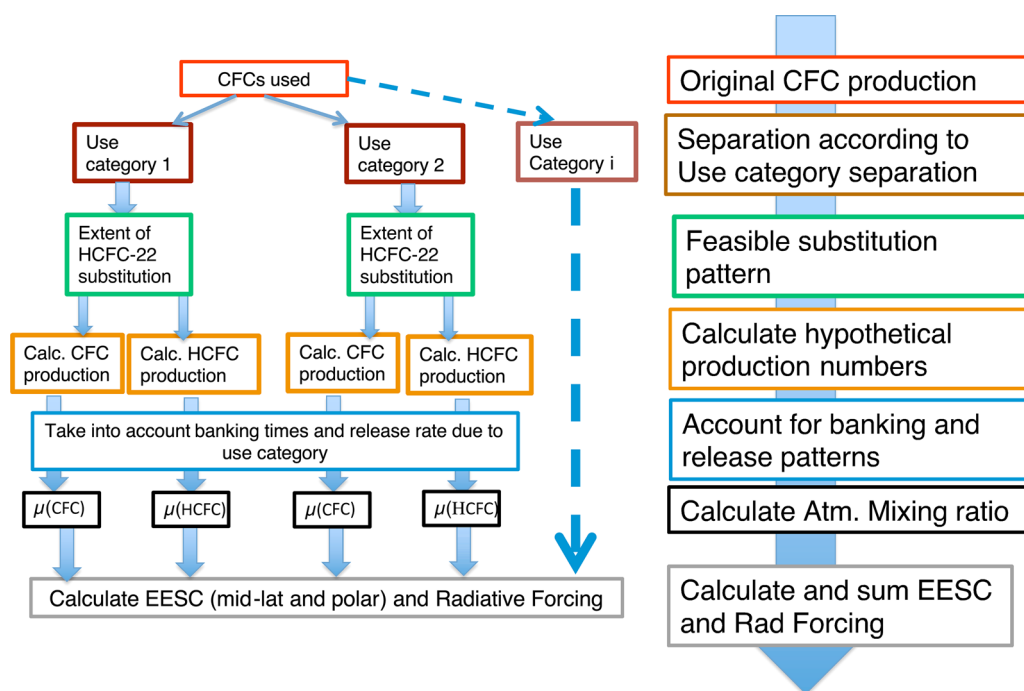


Figure 1. Left: A flow diagram for the steps used to substitute the use of HCFCs and other technologies/chemicals in place of CFCs to calculate the EESC and RF. The use of substitutes other than HCFCs is not shown because the ones considered here do not significantly influence the calculated EESC and RF. Right: A general diagram showing the flow of information in the calculation. In this paper, we have grouped production into three use categories, as discussed in the text.

Refrigeration and air conditioning represent the second category (Category 2). The final group (Category 3) includes open-cell foams, aerosol uses, and other more minor applications; CFCs in this last category are assumed to be emitted in the same year as production. The release formulas for the first two categories are assumed to be time invariant and identical for CFC-11 and CFC-12; they are estimated using a least-squares approach in which differences between the modeled atmospheric concentrations and surface concentration observations are minimized. The functional after the first year (Category 3) for each of the two banked categories is assumed to be a Gaussian of the form:

$$E_i = A \left\{ \exp \left(- \frac{(t_i - a_1)^2}{a_2^2} \right) \right\}$$

where E_i is the fraction of production emitted in time steps after production, t_i is the time since production calculated out to 60 years after production, a_1 and a_2 are two of the retrieved parameters, and A is the normalization constant to ensure all that is produced eventually is emitted. A third parameter, not shown in the equation above, is simultaneously retrieved. It represents an additional amount of emission that occurs in the first year after production, which accounts for leakage in transport, filling equipment, etc. Finally, two additional terms are included in the fitting process that allows for reported production to be increased by a scale factor; the scale factors for CFC-11 and CFC-12 production are distinct. The retrieved bank release functions are then also applied to CFC-113, CFC-114, and CFC-115; there is no scaling up of these three production numbers.

The release functions calculated from this vintaging model and used for the subsequent analysis are shown in Figure S1. Our vintage model, by its nature, yields slightly different values

for atmospheric concentrations than those previously reported by Velders and Daniel.²⁸ Since the release functions here do not lead to releases beyond a few decades, the emissions must occur and cease somewhat sooner than those from previous WMO/UNEP ozone assessment calculations. For instance, the recent assessment, in which it is assumed that a constant fraction of the bank is released each year, therefore reported calculated emissions for CFC-11 extend beyond 2100 while our calculated emissions of CFC-11 end by 2070. However, the aggregated annual emissions calculated here are within 5% for all CFCs except CFC-114; in this case, our aggregated emissions always agree within 20% of that reported by UNEP. As seen later, CFC-114 plays a minor role in the EESC and RF presented here.

The conclusions here are essentially unaffected by using a vintaging approach compared with an approach in which a constant fraction of the bank is released each year, nor are the conclusions fundamentally affected by the uncertainties in the release functions.

Figure 1 shows a flow diagram of the calculation of the atmospheric mixing ratios for the substitution, i.e., the steps used to calculate the atmospheric abundances. First, we calculate the atmospheric concentrations for the current realization, i.e., without the substitutions noted in this paper. These values are projected into the future using the estimated future production, leakage from banks, and atmospheric lifetimes of the species. The steps for this calculation are shown on the left-hand side. The amount of historical CFC productions is divided into different usage sectors to calculate the use in each sector. Then, we apply the banking times for the CFCs used in each sector to calculate the emissions to the atmosphere. From the emissions rates, coupled with the known atmospheric lifetimes of the CFCs, we calculate the abundance of the CFCs in the past. It is important to note that the

atmospheric lifetime includes what happens in the stratosphere to the chemical. Further, for CFCs, we are assuming that any degassing from the oceans is minimal.

SUBSTITUTION CALCULATIONS

The atmospheric abundances of ODSs were calculated for the scenario that would be obtained if the substitution strategies noted above were used. The algorithm used to calculate such substitutions is shown in Figure 1. Here, CFC usage during the past decades dating back to those noted in the substitution strategy was replaced by either an HCFC or a nonozone depleting substance. The extent of HCFC substitution use was incorporated for each use. We do not explicitly calculate the amounts of HCs and releases from alternate technologies in this scenario since they do not add significantly to the calculated EESC or to the RF. The needs not met by the HCFCs or other substitutes were assumed to be met by the continued use of CFCs until the Montreal Protocol phaseouts and phasedowns were implemented. These calculated CFC and HCFC production amounts are used with the retrieved banking release function to calculate the emissions to the atmosphere. From the emissions and known atmospheric lifetimes, the atmospheric abundances are computed as a function of time.

EQUIVALENT EFFECTIVE STRATOSPHERIC CHLORINE (EESC)

EESC is calculated by multiplying the number of halogens a compound contains by its mixing ratio, the relative ability of bromine to destroy ozone compared to Cl (for Br-containing chemicals), and the compound's fractional release factor (FRF) as given by Newman et al.²⁹ FRF represents the fraction of a chemical that is broken down in the relevant region of the stratosphere, thus allowing for ozone depletion to occur. FRF can be parametrized according to the transport time to a specific location in the stratosphere; we use the FRF values for both the midlatitude stratosphere (~3 years) and the polar regions (~5 years) of the stratospheres. The former is a good metric for the global ozone depletion, while the latter is a metric for the extent of the ozone hole. There are more sophisticated ways to calculate the release function (e.g., Newman's Green's Function²⁹). However, as long as we use the same function for the original and suggested scenarios, the calculated relative EESC differences are similar. We sum the contributions of the compounds in our baseline and substitution scenarios. The contributions are from CH₃CCl₃, CCl₄, HCFC-142b, halon-1211, halon-1301, halon-2402, halon-1202, CH₃Br, and CH₃Cl, which were unchanged between the scenarios. Thus, our calculated EESC values in the substitution scenarios represent the levels that could have been achieved if the feasible substitution for only the CFCs had been implemented.

RADIATIVE FORCING (RF)

RF is a metric for the relative effectiveness of a chemical in restricting long-wave radiation from escaping back to space, i.e., acting as a GHG. Therefore, we calculate RF to quantify the extent to which our alternative scenarios would have also helped mitigate climate change.

Like EESC, RF is calculated using the atmospheric mixing ratios of each of the chemicals that are either present or present upon implementing the above substitution strategies.

The mixing ratio is multiplied by the chemical's known radiative efficiency ($W m^{-2} ppb^{-1}$).²² As in the case of the EESC, we also add the contributions of CH₃CCl₃, CCl₄, HCFC-142b, halon-1211, halon-1301, halon-2402, halon-1202, CH₃Br, and CH₃Cl to obtain the total RF. (Note: the contributions of halons, CCl₄, CH₃Br, and CH₃Cl are not significant.)

In these RF calculations, we only consider the direct RF caused by the ODSs. The ODS emissions lead to ozone depletion, of course, which reduces the net RF to some degree.^{15,26} The degree to which this term offsets the direct RF remains quite uncertain; recent work suggests that the offset may be greater than previously thought.²⁷

EESC RESULTS

The calculated EESC for midlatitudes and the polar regions is shown in Figures 2 and 3, respectively. The top line shows the

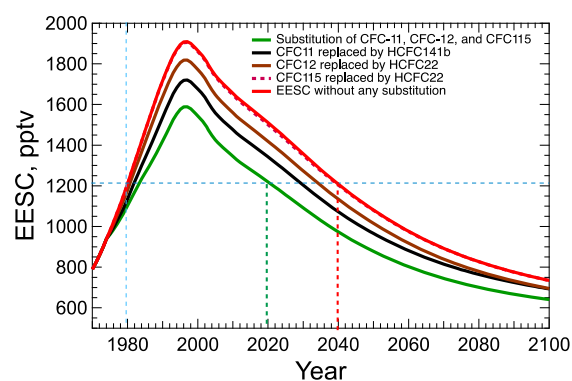


Figure 2. Calculated midlatitude EESC for substituting the original scenario (red line) with suggested replacements for CFC-115 (dashed purple line), CFC-12 (brown line), and CFC-11 (black line). The green line shows the EESC when all three of these chemicals are replaced, as noted in the text. The lines for substituting CFC-113 and CFC-114 are not shown because they would be indistinguishable from the red line.

EESC for the unaltered scenario and its projection going forward. The incremental changes in the EESC for each of the substitution strategies are also shown. Lastly, we show the

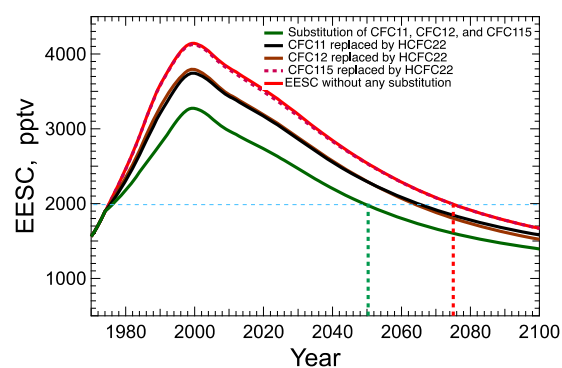


Figure 3. Calculated polar EESC for substituting the original scenario (red line) with suggested replacements for CFC-115 (dashed purple line), CFC-12 (brown line), and CFC-11 (black line). The green line shows the EESC when all three of these chemicals are replaced, as noted in the text. The lines for substituting CFC-113 and CFC-114 are not shown because they would be indistinguishable from the red line.

temporal change in EESC that would have been obtained if all the above strategies were implemented simultaneously.

Figure 2 shows the midlatitude EESC as a function of year. It is clear from the figure that the two major contributors to the decrease in EESC are the substitutions for CFC-11 and CFC-12. Of course, if more of these chemicals were reduced further, the EESC values would have been smaller. The contributions of substitution or elimination of CFC-113, -114, and -115 would have had minimal impact on the potential gains since their uses were much smaller than CFC-11 and CFC-12. Our suggested possible substitution of the CFCs would have reduced the maximum EESC by about 20%. The timing of the maximum does not change significantly. This is primarily because of the chemicals' atmospheric lifetimes and how long they reside in equipment before release into the atmosphere. In other words, an earlier phaseout would not have significantly altered the time at which EESC peaked but would have led to a lower value.

Interestingly, the maximum value of EESC in this scenario is roughly equal to what we experienced in 1987 when the Montreal Protocol was enacted. In other words, those 10+ years in which only minimal action was taken (only aerosol propellant uses were curbed) led to a substantially larger value by the time the Montreal Protocol was enacted, and the phasedown of CFCs then began what could have been achieved if our early substitution patterns were employed. Clearly, the global ozone layer depletion would have been smaller than what we have seen to date. Indeed, global ozone layer depletion would have remained well below 5%, the highest recorded depletion observed from the 1990s to the early 2000s. Lastly, the return of ODS levels to their 1980 values seen in the atmosphere, a quantity often used as a metric for the recovery of the global ozone layer, would have been about 20 years sooner (see Figure 2). Along with the influence of climate change, the ozone layer, in a total column sense, would have returned to its pre-1980 values even sooner.

Figure 3 shows the EESC for polar regions. On the basis of the observations going back to the 1960s, it is clear that a discernible ozone hole was formed when EESC was around 2000 ppt. Therefore, we can view when the ozone hole disappears to be when EESC returns to this value. With our substitutions, we find that the maximum polar EESC (Figure 3) encountered is roughly 30% lower than the actual recorded maximum. Specifically, our replacement scenario's maximum polar EESC value is approximately equal to the level we experienced around 1985, when the ozone hole was discovered. In other words, the fast response noted in this paper would not have avoided the ozone hole. Still, its area (below a certain level of depletion) would have been smaller. The magnitude (as measured by the lowest value of column ozone) of ozone depletion would have been substantially smaller. Compared to our alternative scenario, we have experienced three decades with polar EESC values greater than our hypothetical maximum. Furthermore, we can speculate that the ozone hole would have "recovered" a full 25 years earlier than the current expectation when all factors aside from ODSs are assumed to be unchanged.

Our findings highlight that the formation and continuation of the ozone hole is a legacy of the CFCs used well before Molina and Rowland warned of the deleterious effects of CFCs. Our (relatively) ephemeral use of ODSs provides an important lesson; human-caused emissions for a few decades can lead to consequences that the world must bear long after

those emissions cease, even when no adverse effects are detected during the emission period. Furthermore, this finding reinforces the importance of vigilance of atmospheric conditions necessitating monitoring and data interpretation and calls for action when warranted.

■ RADIATIVE FORCING RESULTS OF FAST ODS REDUCTIONS

Figure 4 shows the calculated RF with and without the substitution strategy. In addition, it shows the RF reported in

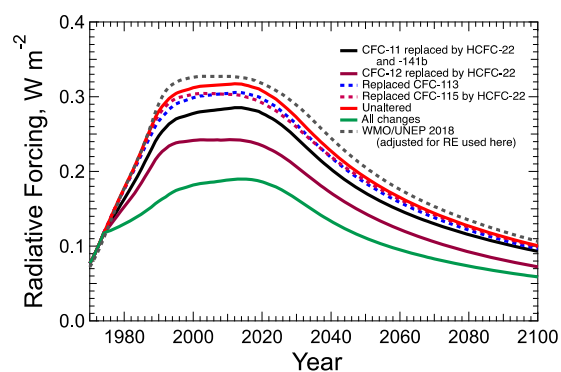


Figure 4. Calculated RF for substituting the original scenario (red line) with suggested replacements for CFC-115 (dashed purple line), CFC-113 (dashed blue line), CFC-12 (brown line), and CFC-11 (black line). The green line shows the EESC when all four of these chemicals are replaced, as noted in the text. The line for substituting CFC-114 is not shown because it would be indistinguishable from the red line. The gray dashed line is that reported by the WMO/UNEP 2018 report after correcting it for the radiative efficiencies used in this paper, which are slightly different from those in the report.

the latest WMO/UNEP ozone layer assessment. This line is slightly larger than our calculated line for no changes since our converted concentrations from consumptions are slightly different, but it shows a generally good agreement.

First, if all the potential substitutions were carried out, the peak RF would have been roughly 0.12 W m^{-2} lower with the most significant contribution from the substitution of CFC-12 with HCFC-22. The CFC-11 substitution contributes about 30% with the others contributing very small amounts. The radiative forcing at a given time does not tell the whole story. It can be illuminating to cast the gains in terms of the CO_2 -equivalent emissions. If the above-noted actions were taken, we would have avoided 85 gigatons of CO_2 emission between 1975 and 2000 (26 years). This is about 16% of the total global CO_2 emissions during the same period of 547 gigatons.

Interestingly, RF shows a much more significant relative change than EESC (comparing Figure 4 with Figures 2 or 3). This is because only CFCs play a more dominant role in the calculated RF among the Montreal Protocol gases. At the same time, many other highly potent ozone-depleting chemicals, e.g., CCl_4 , halons, CH_3Br , and methyl chloroform, whose emissions are unchanged in this scenario, also contribute significantly to the EESC.

As in the case of EESC, the timing of the peak contribution of ODSs to RF does not change significantly with our substitutions. Again, this is primarily due to the atmospheric lifetimes of the chemicals involved and their banking times in the various applications.

CONCLUSIONS

The Montreal Protocol is arguably the most successful global environmental treaty in history, and we can continue to learn from its successes and implementation. Other studies have calculated the consequences of the hypothetical “world that was avoided” by the phaseout of the CFCs. This paper complements those analyses by calculating how much healthier the world would be today if actions were taken immediately after science pointed to the negative impacts of ODSs on stratospheric ozone. Ozone layer depletion would have been significantly less, but the Molina and Rowland warning in 1974 was already too late to avoid the Antarctic ozone hole. Similarly, the climate forcing by ODSs would have been smaller, yet climate change from the direct forcing of the ODSs would not have been substantially mitigated by a more rapid ODS phaseout. There would likely be additional impacts on climate change due to lessening the ozone layer depletion; such impacts have not been evaluated here.

While science only plays a partial role in discussions and decisions about environmental policies,^{14,25} this study demonstrates that delaying policy actions can impose a long-term environmental penalty, particularly when the time scales of chemicals and their detrimental actions are long-lived, as is the case with CFC emissions. The climate change issue is very analogous to the ozone depletion issue in that science has already pointed out a myriad of risks associated with climate change, uncertainties related to GHGs, and the long time scales associated with their emissions (e.g., Solomon et al.³⁰). As was the case with ozone layer depletion, every delay in controlling long-lived GHG emissions is expected to lead to consequences lasting generations. Society has to work harder to undo the consequences of inaction that persisted even after knowing about these environmental issues, highlighting the importance of the precautionary principle. The precautionary principle is particularly important when the lifetimes of chemicals are long. In September 1976, Russell Peterson, chair of US President Gerald Ford’s Council on Environmental Quality, who had spent twenty-six years as a chemist for DuPont, called for immediate regulation of CFC and is quoted³¹ as saying, “we cannot afford to give chemicals the same constitutional rights that we enjoy under the law.” Then, he is quoted as adding, “Chemicals are not innocent until proven guilty.” This highlights the need to consider atmospheric lifetimes (including any return from reservoirs) as an essential consideration in approving a chemical’s widespread use. It is interesting to note that the European Union appears to be taking such a stance with their REACH program on chemicals (https://ec.europa.eu/environment/chemicals/reach/reach_en.htm).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsearthspacechem.1c00244>.

Calculated release fraction as a function of the year subsequent to its consumption; acronyms (PDF)

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Notes

The authors declare no competing financial interest.

M.M.: Retired from DuPont Company. Fluorochemicals business was split off as part of The Chemours Co. before retirement.

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