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The importance of the Montreal Protocol in protecting climate

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The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer is a landmark agreement that has successfully reduced the global production, consumption, and emissions of ozone-depleting substances (ODSs). ODSs are also greenhouse gases that contribute to the radiative forcing of climate change. Using historical ODS emissions and scenarios of potential emissions, we show that the ODS contribution to radiative forcing most likely would have been much larger if the ODS link to stratospheric ozone depletion had not been recognized in 1974 and followed by a series of regulations. The climate protection already achieved by the Montreal Protocol alone is far larger than the reduction target of the first commitment period of the Kyoto Protocol. Additional climate benefits that are significant compared with the Kyoto Protocol reduction target could be achieved by actions under the Montreal Protocol, by managing the emissions of substitute fluorocarbon gases and/or implementing alternative gases with lower global warming potentials.

Kyoto Protocol | ozone layer | radiative forcing

Chlorofluorocarbons (CFCs) and other ozone-depleting substances (ODSs) are now globally recognized as the main cause of the observed depletion of the ozone layer (1–5). Molina and Rowland (6) first recognized the potential for CFCs to deplete stratospheric ozone in 1974, thereby providing an “early warning.” This scientific warning led to ODS emission reductions by citizen action and national regulations (7, 8). A decade later, the discovery of the ozone hole over Antarctica (9) and the subsequent attribution to ODSs (10, 11) further heightened concern. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer formally recognized the significant threat of the ODSs to the ozone layer and provided a mechanism to reduce and phase-out the global production and consumption of ODSs. Under the Montreal Protocol and national regulations, significant decreases have occurred in the production, use, emissions, and observed atmospheric concentrations of CFC-11, CFC-113, methyl chloroform, and several other ODSs (4, 12–14) and there is emerging evidence for recovery of stratospheric ozone (4, 15). In a “world avoided” that lacks the early warning in 1974 and the Montreal Protocol of 1987, depletion of the ozone layer likely would be much greater than observed in our world today.

ODSs and their substitute fluorocarbon gases are also greenhouse gases (16–21), which contribute to the radiative forcing (RF) of climate (5). Thus, actions under the Montreal Protocol to phase out ODSs and/or increase the use of substitute gases have consequences for climate forcing. Earlier studies have recognized that continued growth in ODS emissions would lead to significant increases in direct RF or climate warming (16–19, 21–24), although ozone depletion from ODS would counteract some of the forcing (25). More specifically, reductions in atmospheric ODS concentrations, achieved to protect ozone, also serve to protect climate. This dual protection of ozone and climate by Montreal Protocol provisions warrants a comprehensive assessment, especially since the 1997 Kyoto Protocol (26) of the United Nations Framework Convention on Climate Change

entered into force in February 2005. The Kyoto Protocol is a global treaty to reduce the emissions of carbon dioxide, CO₂, the leading greenhouse gas, and five other gases, none of which are ODSs. The absence of ODSs in the Kyoto Protocol and the absence of formal climate considerations in the Montreal Protocol serve as motivation to consider past and future scenarios of ODS emissions and their substitutes, and their relevance to anthropogenic RF.

We report here how national regulations, voluntary actions, and compliance with the Montreal Protocol have protected climate in the past and can add to climate protection in the future. Our comprehensive evaluation of the “worlds avoided” with ODS regulation considers three aspects: (i) time-dependent scenarios of annual ODS production, emissions, concentrations, and associated RF; (ii) the time dependence of CO₂ emissions and associated RF; and (iii) the offsets of climate protection by ODSs caused by stratospheric ozone depletion and the use of ODS substitute gases. We show what has already been achieved for climate by the Montreal Protocol and compare it with the Kyoto Protocol target, what is likely to happen in the near future based on current ODS regulations, and finally what potentially can be achieved for climate in the future with additional ODS regulations.

ODS Scenarios

Three scenarios are considered in this analysis. Each scenario uses observations, calculations, and certain assumptions to formulate annual emissions between 1960 and 2020 for ODSs. These emissions are expressed in terms of mass with and without weighting by 100-yr Global Warming Potentials (GWP) (4) [see Figs. 1 and 2, Table 1, and [supporting information \(SI\) Text](#)].

The first is the baseline scenario representing ODS emissions as they have occurred up to 2004 and as projected into the future assuming compliance with Montreal Protocol provisions. CFC-11 and CFC-12 were the most abundant CFCs in the atmosphere before 1974 and remain so today. Before 1974, the production of ODSs grew rapidly primarily as a result of use as aerosol propellants and refrigerants, and the introduction of new uses including solvents and foams (7). In response to the early warning (6) in 1974 by scientists, and encouraged by advertisements for alternative products, many consumers in North Amer-

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Abbreviations: CFC, chlorofluorocarbons; GWP, global warming potential; HCFC, hydrochlorofluorocarbons; HFC, hydrofluorocarbons; IPCC, Intergovernmental Panel on Climate Change; MR74, Molina and Rowland; NMP87, no Montreal Protocol; ODS, ozone-depleting substance; RF, radiative forcing.

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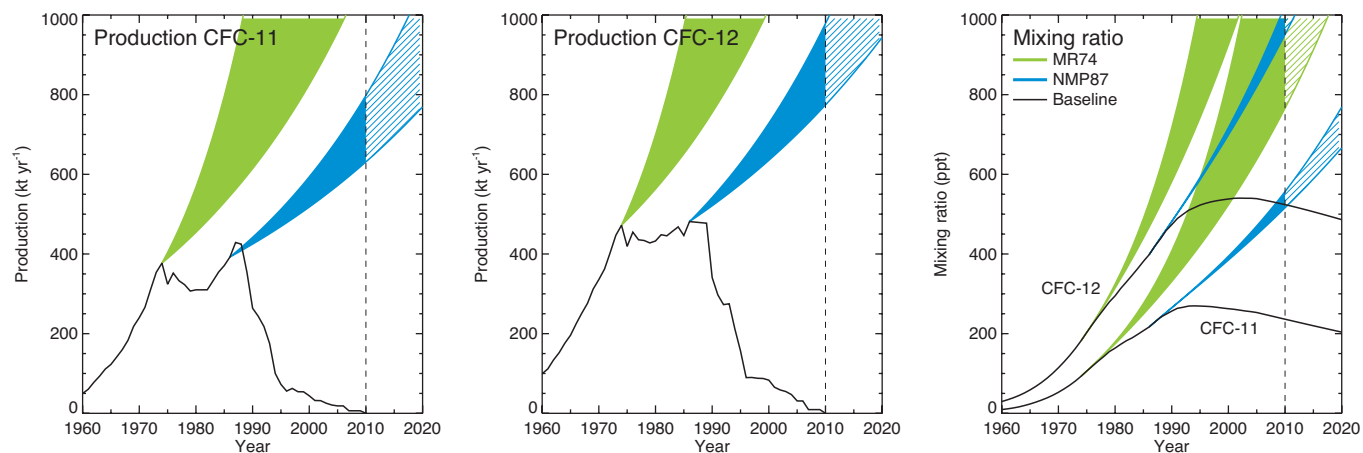


Fig. 1. Scenarios for the global production of CFC-11 (*Left*) and CFC-12 (*Center*) and mixing ratios [*Right*; in ppt (part per trillion)] for the period 1960–2020. Scenarios include the baseline scenario and those of the worlds avoided with the early warning of Molina and Rowland (MR74) and with the adoption of the Montreal Protocol (NMP87). The shaded regions for MR74 and NMP87 reflect a range of 3–7% and 2–3%, respectively, for the assumed annual production increases in ODSs. The stripes in the shaded regions indicate the larger uncertainties past 2010. The average annual growth rate in global production between 1960 and 1974 was $\approx 17\%$ for CFC-11 and 12% for CFC-12. Current total annual emissions of CFCs are $< 10\%$ of late 1980 values. The baseline scenario represents ODS emissions observed up to 2004 and as projected past 2004 assuming global compliance to the latest provisions of the Montreal Protocol. The emissions up to 2004 are derived primarily from atmospheric observations of ODS concentrations (4) and production records (13). The primary ODS compounds included in the scenarios presented here are CFCs, CCl_4 , CH_2Cl_2 , HCFCs, CH_2Cl , Halons, and CH_3Br (see *SI Text*).

ica stopped using CFC aerosol products (e.g., deodorants and hairsprays), and governments in the United States, Canada, the Netherlands, and Sweden either banned or discouraged use of ODSs in most personal care aerosol products (7). These actions reduced annual global CFC production from $\approx 910 \text{ kt}\cdot\text{yr}^{-1}$ in 1974 to $\approx 850 \text{ kt}\cdot\text{yr}^{-1}$ by 1979. Continued growth in refrigerant uses, rapid growth in the more recently introduced applications of solvents, foam-blowing agents, and fire protection agents and continued use in aerosol products in Europe and Asia returned production to $\approx 1,170 \text{ kt}\cdot\text{yr}^{-1}$ by 1987. Both the early warning and the Montreal Protocol initiated a change in fluorocarbon quantities and their use patterns toward more environmentally ac-

ceptable alternative compounds and technologies (27). Starting in the late 1980s, when the Montreal Protocol began to take effect, net ODS emissions (Fig. 2) decreased, largely driven by reductions in CFC-11 and CFC-12 production (4, 14, 28). With the force of an international treaty and substantial scientific evidence connecting ODSs to ozone depletion, there was a rapid development and deployment of suitable ODS substitutes and not-in-kind alternatives, which steadily achieved reductions over the last two decades in ODS production, consumption, and emissions. Due to the long atmospheric lifetimes of CFC-11 and CFC-12, their mixing ratios are decreasing slowly after the sharp decreases that have occurred in their emissions (Fig. 1).

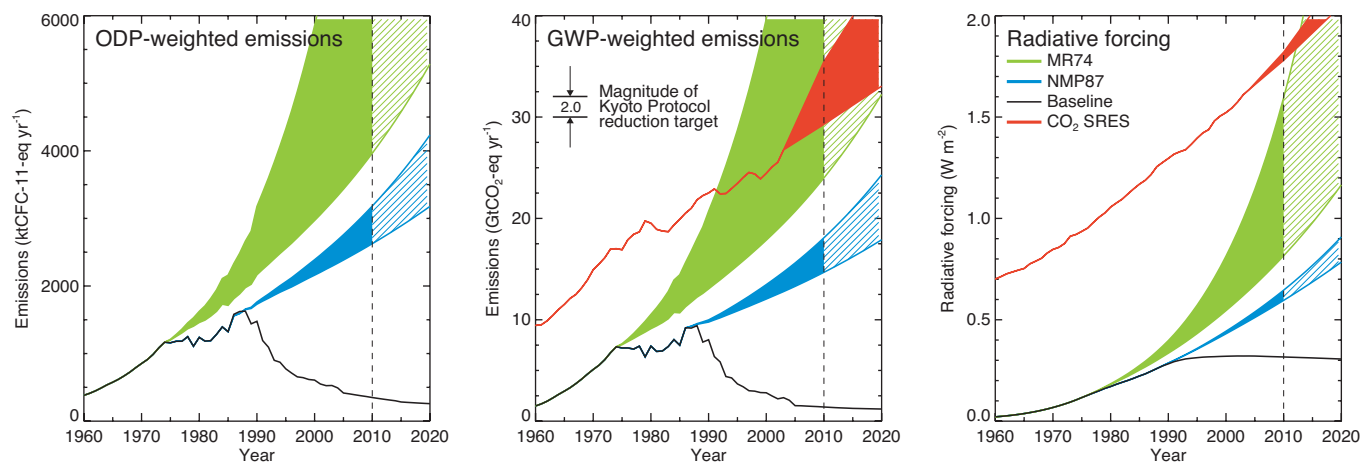


Fig. 2. ODP-weighted emissions (*Left*), GWP-weighted emissions (*Center*), and RF (*Right*) for ODS and CO_2 scenarios for the period 1960–2020. Calculated GWP-weighted emissions (100-yr time horizon) and associated RF values are shown for four scenarios: baseline, MR74, NMP87, and SRES CO_2 . All emissions are normalized by their direct GWPs to equivalent $\text{Gt}\text{CO}_2\cdot\text{yr}^{-1}$ (see also Fig. 1 legend). The indirect contribution to the GWP due to ozone depletion, which is thought to be $\approx 20\%$ (see text), is not included in these figures. The shaded regions for MR74 reflect a range of 3–7% for assumed annual production increases in CFC-11 and CFC-12 starting in 1975 and a 3% annual increase for other ODSs starting in 1987. The shaded regions for NMP87 reflect a range of 2–3% for assumed annual production increases in all ODSs. The stripes in the shaded regions indicate the larger uncertainties past 2010. The CO_2 emissions for 1960–2003 are from global fossil fuel and cement production (45). Beyond 2003, the shaded regions for CO_2 reflect the maximum (A1B) and minimum (B2) SRES scenarios (25). The CO_2 RF data are based on CO_2 observations and SRES scenarios (25). All RF values represent net changes from the start of the industrial era (≈ 1750) to present. Shown for reference is the magnitude of the reduction target of the first commitment period of the Kyoto Protocol, which is based on a 1990–2010 projection of global greenhouse gas emission increases and the average reduction target for participating countries (see text) (36).

Table 1. Direct GWP-weighted emissions and radiative forcing of ODSs and CO₂

Scenario	GWP-weighted emissions, GtCO ₂ -eq·yr ⁻¹			Radiative forcing (W·m ⁻²)		
	1975	1988	2010	1975	1988	2010
Baseline	7.2	9.4	1.4	0.12	0.26	0.32
MR74	7.6	12–18	24–76	0.12	0.30–0.34	0.8–1.6
NMP87	7.2	9.6	15–18	0.12	0.26	0.60–0.65
CO ₂	17	22	29–35	0.94	1.25	1.8

The second scenario is the Molina and Rowland scenario (hereafter referred to as the MR74 scenario) representing an approximation to the world of ODS growth and atmospheric concentrations that was avoided as a result of their early warning and the subsequent consumer and government actions before the Montreal Protocol. The scenario starts in 1975 (Figs. 1 and 2) by increasing CFC-11 and CFC-12 in the baseline scenario with a 3–7% range of annual growth rates. The difference above the baseline scenario becomes substantial quickly with a 7% annual growth rate causing a doubling in a decade. The 7% rate is significantly smaller than the reported growth rates for the period 1960–1974 (Fig. 1) and so could underestimate initial growth. The higher rate is in agreement with earlier scenarios (29) that used a 7% annual growth in emissions from 1980 to 2030 and also closely resembles the growth rate in a previously formulated analysis using a “free market” scenario of ODSs (30).

The third scenario is the No Montreal Protocol scenario (hereafter referred to as NMP87 scenario) representing an approximation to the world of ODS emissions and atmospheric concentrations that was avoided by the adoption of the Montreal Protocol provisions. The scenario starting in 1987 has ODS emissions increasing above the baseline values with a 2–3% range in annual growth rates. Historical studies (1, 2, 31, 32) have typically assumed that annual growth rates of up to 3% would have occurred in the absence of the Montreal Protocol (see *SI Text*). This value is further justified by noting that a 3% annual growth occurred in ODS use as it increased after the aerosol emission bans (1, 2) and that 3% is comparable to the historical and expected growth rates of mature markets such as refrigeration, air conditioning, foam production, and solvents (5, 33, 34); such markets typically grow at about the rate of growth in gross domestic product. Furthermore, the annual growth in 2002–2015 in the demand for CFCs, HCFCs (hydrochlorofluorocarbons), and HFCs (hydrofluorocarbons) for refrigeration, air conditioning and foams is estimated to be 2.8% in the Intergovernmental Panel on Climate Change (IPCC) business-as-usual scenario (5). In addition, rapid growth in ODS use in developing countries and new markets (e.g., self-cooled beverage containers) could have increased growth above this range.

The MR74 and NMP87 scenarios are presented as simple estimations of the worlds avoided by events and regulation to examine the basic consequences for climate protection. To help indicate that the uncertainty in these scenarios increases with time after the initial year due to unknowable factors, the scenario shadings in Figs. 1 and 2 are changed after 2010. In using these scenarios, we acknowledge that others could be proposed. For example, we do not take into account the possibility that production of ODSs could have been reduced without the early warning and without the Montreal Protocol, due to precautionary climate protection. Our scenarios show what could have happened without any further national regulations, international agreements, or public actions.

Radiative Forcing in ODS Scenarios

The effects of ODS regulations on climate are evaluated by comparing GWP-weighted ODS emissions and RF values re-

sulting from these emissions (Fig. 2 and Table 1) with the corresponding values for anthropogenic CO₂ emissions as derived from observations and the IPCC Special Report on Emissions Scenarios (25, 35). GWP weighting is used routinely to evaluate the relative climate impact of emissions of various gases (by mass) and is the basis for emission targets under the Kyoto Protocol (36). The GWPs of the principal ODSs range between 5 (methyl bromide) and 11,000 (CFC-12), much larger than that of CO₂ (CO₂ weighting is unity). The relative importance of the accumulation of greenhouse gases for climate change is evaluated by using the metric of RF, defined as the difference from the start of the industrial era (1750) (25).

Additional factors to be considered in scenario comparisons of emissions or RF are the offsets related to stratospheric ozone depletion from ODSs and the use and emissions of fluorocarbon substitute gases as discussed below. An important assumption in these comparisons is that, except for use of non-ODS fluorocarbon substitute gases, the ODS reductions did not lead to increases in other greenhouse gas emissions. For example, because energy efficiency regulations have not been related to regulatory or voluntary actions to reduce use of ODSs, it is assumed that impacts on CO₂ emissions due to changes in the efficiency of energy intensive products using ODSs would have been minimal.

The GWP-weighted emissions comparisons in Fig. 2 and Table 1 allow a direct comparison of the climate influences of ODSs and CO₂. In the baseline scenario, the annual contribution of ODSs to GWP-weighted emissions peaked in 1988 at a value slightly less than half that of global CO₂ emissions. After 1988, the contribution of ODSs falls sharply in contrast to increasing CO₂ emissions. By 2010, ODS emissions will have declined to 4–5% of Special Report on Emissions Scenarios (SRES) CO₂ emissions, which are projected to increase to 29–35 GtCO₂-eq·yr⁻¹. In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 GtCO₂-eq·yr⁻¹ in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO₂. In the NMP87 scenario in which ODS increases occur later than in the MR74 scenario, the ODS emissions reach 15–18 GtCO₂-eq·yr⁻¹ in 2010, about half of the CO₂ annual emissions. Furthermore, the contribution of ODS emissions (in GtCO₂-eq·yr⁻¹) in NMP87 is 11–13 times larger in 2010 than in the baseline scenario.

A RF time series depends on atmospheric concentrations and, hence, is not a simple scaling of the associated GWP-weighted emissions time series. As shown in Fig. 2, the RF from ODSs peaks in the baseline scenario around 2003 at a value of 0.32 W·m⁻² and decreases slowly by a total of 0.005 W·m⁻² by 2010. Over the same period, RF values for CO₂ are expected to increase by 0.2 W·m⁻² to ≈1.8 W·m⁻². In the world avoided of MR74, the ODS RF ranges from 45% to 90% of the CO₂ value in 2010 (Table 1). In the NMP87 scenario, the ODS RF is in a lower, narrower range near 35% of the CO₂ value in 2010. The emissions avoided under the protocol (NMP87) will have re-

Table 2. Scenario differences and offsets for 2010

Parameter	GWP-weighted emissions, GtCO ₂ -eq-yr ⁻¹	Radiative forcing, W·m ⁻²
NMP87 minus baseline	13.3–16.7	0.28–0.33
Ozone depletion offset	2.7–3.3*	0.06
HFC offset	0.9	0.02
Net value [†]	9.7–12.5	0.20–0.25

*Estimated as 20% of ODS GWP-weighted emissions, based on RF value (see text).

[†]Reductions attributable to the Montreal Protocol provisions after accounting for offsets due to ozone depletion and HFC increases.

duced the RF of climate by $\approx 0.3 \text{ W}\cdot\text{m}^{-2}$ in 2010, which is $\approx 17\%$ of the contribution of anthropogenic CO₂ increases in 2010.

The MR74 projection that ODS RF could almost have matched that of anthropogenic CO₂ in 2010 is a striking result considering that the RF of anthropogenic ODSs was essentially zero in 1960. However, because the length of time associated with this projection (1974–2010) increases the level of uncertainty, the results must be interpreted with care. A more certain result is that, using the NMP87 scenario, the Montreal Protocol will have reduced RF from ODSs by $\approx 50\%$ in 2010 (Table 2).

The RF scenarios in Fig. 2 illustrate the extent to which ODSs reductions, in effect, have delayed the growth of overall anthropogenic RF. A delay is a form of climate protection, because more time is required to reach any given anthropogenic RF increase and its associated climate change risk (37). The delay is expressed here as the years required for the CO₂ RF to increase by the same amount as the ODS RF would have by 2010 in MR74 or NMP87. When using an averaged CO₂ RF growth rate, the MR74 delay is calculated to be 13–18 or 31–45 yr, corresponding to the 3% and 7% annual growth rates, respectively. Similarly, the delay attributable to the Montreal Protocol (NMP87) is calculated to be 7–12 yr.

Ozone Response

Increasing ODSs in the atmosphere creates, in addition to the direct positive RF response, an indirect negative (cooling) RF response

due to the associated depletion of stratospheric ozone (38, 39). In the IPCC evaluation (25) the ozone offset of $0.15 \pm 0.1 \text{ W}\cdot\text{m}^{-2}$ represents a large fraction of the ODS RF. However, it is currently estimated (37) that the observed changes in stratospheric ozone in 2000 contributed a globally averaged RF of $-0.06 \text{ W}\cdot\text{m}^{-2}$, which is $\approx 20\%$ of the direct positive RF. Although the true magnitude might be larger, the updated value is likely more accurate than larger previous values (25). In the worlds avoided based on the MR74 and NMP87 scenarios, stratospheric ozone depletion and its associated negative RF now would be substantially larger than current levels. However, the response of ozone depletion to increasing ODS concentrations would plausibly be less than currently observed (see *SI Text*). As a result, a 20% offset is a reasonable first approximation to the ODS RF and GWP-weighted emissions presented here (see Table 2).

The emissions of ODS substitute gases that occur in response to Montreal Protocol provisions generally have the potential to reduce or offset the climate protection of those provisions. It is important to note that $\approx 80\%$ of ODSs that would be used today without the Montreal Protocol have been successfully phased out without the use of other fluorocarbons. Instead, this ODS use was eliminated with a combination of “not-in-kind” chemical substitutes, product alternatives, manufacturing-process changes, conservation, and doing without (7, 27). HCFCs and HFCs are among the fluorocarbons used as substitutes (17, 23, 27) (Fig. 3), because HCFCs have lower ozone depletion potentials than the CFCs and HFCs do not destroy ozone. Because HCFC emissions and their RF values are included in the baseline scenarios, increases in HCFC use associated with Montreal Protocol provisions do not represent offsets to the reductions in CO₂-eq emissions and RFs derived here for the MR74 and NMP87 scenarios.

HFCs are not controlled by the Montreal Protocol because they do not destroy ozone but are included in the Kyoto Protocol because they are greenhouse gases. The Montreal Protocol has resulted in increased uses and emissions of HFC-134a, as the primary alternative to CFC-12 refrigerant, and emissions of HFC-23, which is an unwanted byproduct of HCFC-22 production. Because HFC-134a has a lower GWP than CFC-12, the direct substitution on a mass basis increases climate protection relative to the NMP87 scenario. Use and emissions of other

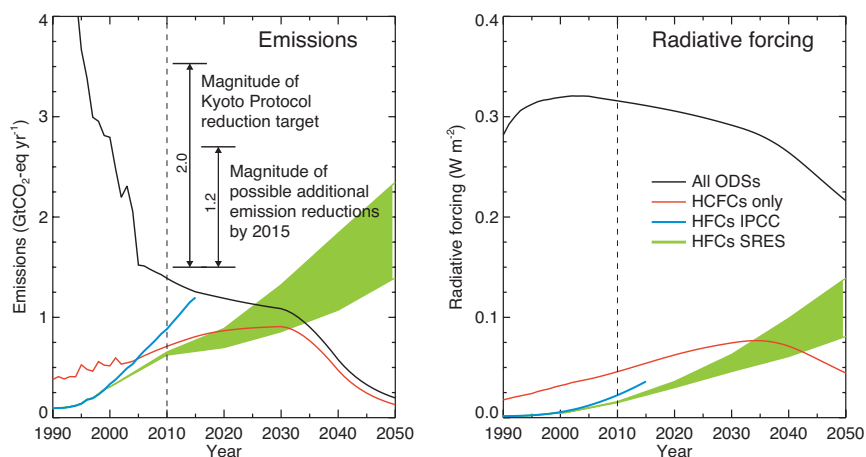


Fig. 3. GWP-weighted emissions (Left) and RF (Right) scenarios for all ODSs, HCFCs, and HFCs for the period 1990–2050. Calculated GWP-weighted emissions (100-yr time horizon) and associated RF values for all ODSs from Fig. 2 are shown on an expanded scale. Additional curves show the contribution of the HCFCs and the growth of HFCs according to an IPCC business-as-usual scenario (5) and as in the older and more uncertain SRES A1B and B1 scenarios (25). All emissions are normalized by their GWPs to equivalent GtCO₂-yr⁻¹. Under the controls of the current Montreal Protocol, developed countries will step-down HCFC use by 99.5% by 2020, with phase-out in 2030, while developing countries are allowed to increase HCFC use until 2016 and then continue at that level until phase-out in 2040 (8). Shown for reference are the magnitude of the reduction target of the first commitment period of the Kyoto Protocol (see Fig. 2 legend) and the magnitude of possible additional emission reductions in ODSs and HFCs achievable by 2015. All RF values represent net changes from the start of the industrial era (≈ 1750) to present. The HFC RF contribution is $\approx 0.02 \text{ W}\cdot\text{m}^{-2}$ in 2010, which is small compared with the other scenario differences discussed here. The HFC data before 2000 are based on observed concentrations (5).

HFCs as substitutes for HCFCs have been increasing since 1990. The IPCC business-as-usual (5) estimate of HFC emissions in 2010 is $\approx 0.9 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$ (Fig. 3). Comprehensive estimates of ODS emissions or RF reductions from worlds avoided must take HFC emissions into account as an offsetting factor (Table 2). For the NMP87 scenario, the emissions and RF offsets are both $<10\%$. When combined with the offsets from ozone depletion, these offsets amount to $\approx 30\%$ of the direct positive forcing of ODSs in 2010.

The Kyoto Protocol

The Kyoto Protocol (26) aims, in its first commitment period, to reduce CO_2 -equivalent emissions in 40 countries (Annex-1 parties) by 2008–2012. The agreed upon reductions will occur in emissions of six key greenhouse gases (CO_2 , CH_4 , N_2O , HFCs, PFCs, and SF_6) referenced to a 1990 baseline. It is widely acknowledged that the first commitment period of the Kyoto Protocol is only a first step to obtain the objective of the United Nations Framework Convention on Climate Change; namely, “stabilization of greenhouse gases concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” The adopted CO_2 -equivalent emission reduction target is -5.8% (range of $+10\%$ to -8% for the individual countries), corresponding to $-0.97 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$ by 2008–2012 (36). Because most countries would normally have had increasing greenhouse gas emissions after 1990, it can be argued that the emission reduction necessary to achieve the agreed Kyoto target must be calculated from a business-as-usual scenario between the 1990 baseline and 2008–2012. Projections (36) have total greenhouse gas emissions of Annex-1 parties increasing by 6% ($1.06 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$) above the 1990 value by 2010. The 6% value reflects large increases in developed countries (e.g., United States of America, 32% ; Spain, 47%) offsetting large decreases for countries with economies in transition (e.g., Russia, -19% ; Estonia, -57%). Therefore, an arguably more realistic estimate of the greenhouse gas emission reduction that will have occurred by meeting the first Kyoto Protocol target is found by combining the 5.8% decrease and 6% increase for a total of $\approx 2 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$. And finally, we note that those countries without emission targets in the Kyoto Protocol (non-Annex-1) accounted for $\approx 41\%$ of reported (36) global greenhouse gas emissions in 1994.

Over the Kyoto Protocol period (1990–2010), the reduction in GWP-weighted ODS emissions expected with compliance to the provisions of the Montreal Protocol is $\approx 8 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$ (baseline scenario for 1990 minus 2010). This reduction, most of which has already occurred, is substantially greater than the first Kyoto reduction target even after accounting for an offset of $\approx 30\%$ due to ozone depletion and HFC emissions (Table 2). The ODS emissions remaining in 2010 are expected to be equivalent to $\approx 1.4 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$ and to decrease steadily in the following decades under existing Montreal Protocol provisions (Fig. 3).

In assessing the avoided worlds of the MR74 and NMP87 scenarios in the 1990s and beyond, it must be realized that without the Montreal Protocol most ODSs would have almost certainly been included in the Kyoto Protocol because of their large GWPs, affecting the provisions and timing of the Kyoto Protocol. Waiting to regulate ODSs with the Kyoto Protocol would likely have resulted in a delay in achieving what the Montreal Protocol is expected to achieve by 2010. A delay could be expected because Kyoto Protocol regulations likely would have entered into force when ODS uses and emissions were larger than in the early 1990s, making reductions economically and practically more difficult.

The Future

New scenarios for future ODS regulation in addition to the baseline scenario have been formulated because parties to the

Montreal Protocol have acknowledged interest in increasing its dual benefit to ozone and climate protection. The parties first considered this in 1999 when the Kyoto Protocol had been signed but had not yet entered into force (40). During diplomatic meetings and in decisions, parties to the Montreal Protocol have considered options to further mitigate ozone depletion while incidentally reducing climate forcing. Some important examples are the following: (i) further acceleration of the HCFC phase-out (8, 41) and use of low-GWP substitutes; (ii) collection and destruction of ODSs contained in “banks” of old refrigeration, air conditioning equipment, and thermal insulating foam products (8, 42, 43); and (iii) formulation of the technical and economical feasibility of further reducing overall ODS emissions (5). Reductions in the emissions of compounds with already declining emissions or expected phase-outs in the coming decades, e.g., CFCs and HCFCs, will generally be less effective than those for compounds with increasing concentrations or growing emissions (see *SI Text*).

An acceleration of the phase-out of HCFCs might increase the use of HFCs as substitutes, which, at least partly, would offset the benefits from such an acceleration. In order for an acceleration of an HCFC phase-out to increase climate protection, lower-GWP refrigerant systems would need to be developed and widely used and/or refrigerant containment and service practices would need to be improved to reduce emissions in these systems, and the energy efficiency of the systems would need to be maintained or improved. The alternatives currently being used to replace HCFC-22 are HFC blends with higher GWPs. However, driven by regulation (44) in Europe that will phase out refrigerants with a GWP of >150 in mobile air conditioning over the period 2011–2017, companies have explored the use of CO_2 and HFC-152a as a refrigerant for mobile air conditioning (5). More recently, chemical companies (see www.ineosfluor.com/ArticleText.asp?ID=269, www.honeywell.com/sites/sm/chemicals/genetron, and www.refrigerants.dupont.com/Suva/en_US/index.html) have announced new low-GWP fluorocarbon alternatives to replace HFC-134a in mobile air conditioning. If this new technology can be leveraged to other refrigerant and foam expansion applications, then an accelerated HCFC phase-out and its associated climate benefits would be more easily achieved.

Based on considering overall emissions in refrigeration and foams developed for an IPCC mitigation scenario (5), CFC and HCFC emissions could be reduced by ≈ 0.12 and $0.34 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$, respectively, in 2015 compared with 2002, with associated additional reductions of $0.30 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$ in HFC-23 emissions released as a byproduct of HCFC-22 production. These possible emissions reductions would derive mainly from better containment in refrigeration and destruction of ODS banks. Detailed scientific and technical assessments could provide policymakers with information necessary to fine-tune an accelerated HCFC phase out to allow desirable uses of HCFCs, such as a feedstock for fluoropolymers and in other applications where emissions are near zero or there are overriding energy efficiency benefits. Additional HFC emission reductions (5) of $0.44 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$ in 2015 compared with 2002 could be achieved by a transition to alternative chemicals that are safer to both the ozone and climate. Thus, plausible scenarios exist and have been considered that could achieve reductions in CO_2 -eq emissions of ODSs and alternative gases by 2015 (see Fig. 3) that are significant compared with the reduction target of the first commitment period of the Kyoto Protocol of $\approx 2 \text{ GtCO}_2\text{-eq}\cdot\text{yr}^{-1}$.

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Supporting Information (SI)

Additional information is presented here on (i) the assumptions used to formulate the baseline, MR74, and NMP87 scenarios; (ii) the offset due to stratospheric ozone depletion; (iii) HCFCs as ODS substitute gases; (iv) the exclusion of ODSs from the Kyoto Protocol; and (v) comparing emission reductions.

Scenario Specifications. For constructing scenarios of ODSs information on the annual production, use and emissions of ODSs is needed. Mixing ratios and RF values of ODSs are calculated from annual emissions using reported lifetimes (1). The following additional information applies to the scenarios used in the analysis.

- The baseline scenario of the Scientific Assessment of Ozone Depletion 2006 (1) forms the basis for all species and all scenarios discussed here. The mixing ratios of this scenario are consistent with the surface observations of AGAGE [Advanced Global Atmospheric Gases Experiment (2)] and GMD [Global Monitoring Division, formerly the Climate Monitoring and Diagnostics Laboratory, CMDL (3)] and the UNEP production data (4) through 2004. The emissions are derived directly using a 1-box model (5) from the observed mixing ratios when available. In the baseline scenario the fraction of the bank emitted annually (Ef) is calculated from the derived emissions and production data and held constant from 2004 onward.

- The MR74 scenario uses a 3-7% annual growth for CFC-11 and CFC-12 starting in 1975 and a 3% annual growth for the other ODSs starting in 1987 (the same as in the NMP87 scenario). A 3% growth rate is appropriate for mature markets where sales are primarily for replacement products, product service, and minor sales to new customers. A 7% or greater growth rate is appropriate when new markets are opening up as a result of population and income growth, when applications in new products are booming, and when regulations encourage sales (6-8).

- The 2-3% annual growth in ODSs production in the NMP87 scenario is in agreement with emission scenarios for 1985-2040 based on market analysis (6) and constructed before the Montreal Protocol.

- The 2-3% annual growth in the NMP87 scenario is applied to CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl₄, CH₃CCl₃, HCFC-22, HCFC-142b, Halon-1211, Halon-1301 and CH₃Br. The production of HCFC-141b started only in about 1990 and is therefore not increased and assumed equal to the baseline value for all scenarios.

- Further justification for the MR74 and NMP87 scenarios follows from the fact that in 2002 refrigerants formed the dominant market for fluorocarbons with smaller uses as foam blowing agents [79% and 17%, respectively (9)]. Even with the Montreal Protocol in place, with industry actions worldwide to reduce and better contain refrigerants system charge, and with recovery and recycle at service and at end of product life, the annual growth of the global refrigerant market was still nearly 6% in 1990-2000 (10). The annual growth in blowing agent use for foams was 1.8% in 1986-2000 (9), partly because markets shifted to not-in-kind mineral wool and fibreglass products.

- Without the early warning in 1974 and the Montreal Protocol the development of new applications of ODSs would likely have continued and precluded the search for replacement substitute gases and less emissive uses, which could have increased the production and emission of ODSs. For example, self-cooled

beverage containers were originally designed to expel 55 grams of CFC-12 to cool 340 grams of beverage, but were redesigned to use HFC-134a after the Montreal Protocol was adopted. The U.S. Environmental Protection Agency estimated that a 5% United States market penetration of the containers would release 270 kt yr⁻¹ of HFC-134a, equivalent to 0.39 GtCO₂-eq yr⁻¹. Without CFC restrictions, 270 kt yr⁻¹ of CFC-12 emissions, equal to 2.9 GtCO₂-eq yr⁻¹, could have been emitted increasing the total ODS emissions significantly. In 1999, the U.S. Environmental Protection Agency banned the use of HFCs in self-chilling cans and in 2006 the European Commission included a similar ban (as part of its F-Gas Directive).

- The CCl₄ emission is, for all scenarios except the baseline (1), taken as a fraction (12.5%) of the production of CFC-11 and CFC-12 [similar to earlier analysis (11)]. This fraction is the average over the period 1980-1990.

- The emissions of CH₃Cl are for all scenarios the same as in the baseline scenario, consistent with the expectation that its emission is predominately natural.

- About 50% of the CFC-11 and CFC-12 produced in the middle of the 1970s was for use as aerosol propellant with high Ef values (12). Different Ef values have therefore been used for the MR74 and NMP87 scenarios than for the baseline scenario since Ef values have decreased since the middle of the 1970s due to changes in uses (less emissive), reduced leakage in refrigeration, etc.

- For CFC-11 an Ef of 25% was used in the MR74 scenario from 1974 onwards and of 18% in the NMP87 scenario from 1987 onwards in agreement with the Ef used in the baseline scenario for that year. This compared to an Ef of 3.3% as used in the baseline scenario after 2004.

- For CFC-12 an Ef of 42% was used in the MR74 scenario from 1974 onwards and of 31% in the NMP87 scenario from 1987 onwards in agreement with the Ef used in the baseline scenario for that year. This compared to an Ef of 8.5% as used in the baseline scenario after 2004.

- The precise value of Ef has a small effect on the annual emissions in the MR74 and NMP87 scenarios. A lower emission function results in a larger size of the bank which compensates the reduced emission per banked ton. For example, decreasing the emission function by 50% in the MR74 and NMP87 scenarios decreases the emissions by only 6-14% in 2010.

Offset Due to Stratospheric Ozone Depletion. It is plausible that the response of ozone depletion to increasing ODSs will decrease as ODSs reach concentrations substantially larger than today's values. As justification we note that under scenarios with increasing ODSs, ozone depletion in the polar regions would saturate across large altitude ranges, perhaps resulting in less export of ozone-depleted air to mid-latitudes, which now represents a significant contribution to mid-latitude ozone depletion (1). This saturation effect could cause the ozone negative RF offset to become a smaller fraction of the direct positive RF as ODSs increased. If the in situ mid-latitude depletion became so large that the region of additional ozone depletion caused by more ODSs moved to higher altitudes, away from the tropopause, the RF due to that ozone loss would become smaller still in comparison to the direct ODS forcing due to the strong altitude dependence of ozone RF (13, 14). It is also important to note that the direct and indirect RF from ODSs do not simply offset one another because of different spatial and

seasonal distributions of the RF and associated climate responses (9).

HCFCs as ODS Substitute Gases. With the phase-out of CFCs, HCFC-22 has also been used as an interim substitute, primarily as a refrigerant in commercial refrigeration replacing R-502 (a 50%/50% azeotrope of CFC-115 and HCFC-22). Assuming that half of the use of HCFC-22 in 2010 is as a substitute, we estimate that Montreal Protocol driven use of HCFC-22 represents an emission of about 0.3 GtCO₂-eq yr⁻¹ in 2010. The production of HCFC-141b and HCFC-142b, mostly used in insulating foams with some HCFC-141b use in solvents, started in the 1980s and exhibited high annual growth rates in the 1990s. Most of the uses of these two compounds are as substitutes for phased-out ODSs with projected emissions of about 0.08 GtCO₂-eq yr⁻¹ in 2010.

Exclusion of ODSs from the Kyoto Protocol. In adopting the Kyoto Protocol in 1997, the parties specifically excluded ODSs for several reasons: (i) the Montreal Protocol was already controlling ODS production and use and future production was expected to end soon, (ii) it was recognized that the negative RF of ozone depletion was a potentially large and uncertain offset, (iii) regulating ODSs in the United Nations Kyoto protocol and the UNEP Montreal protocol would be confusing and could give potentially conflicting result.

Comparing Emission Reductions. Care must be exercised in comparing emission reductions for a particular year for compounds due to be phased out in the coming decades (e.g., CFCs and HCFCs) with emission reductions of compounds that are expected to continue to be emitted in substantial quantities in the future. Although both can be quantified in terms of GtCO₂ using the annual emission and the 100-year GWP, the implications for the future can be dramatically different. For a compound that will continue to be emitted in the future, an intentional reduction that occurs in a given year can be thought of as having a continuing effect indefinitely because this reduction effectively sets a new baseline to which future growth will add. Conversely, if compounds are to be phased out in the coming decades regardless of near-term controls, the elimination of any emission in the near term will have more limited long-term implications. So while an emission reduction of, for example, 0.1 GtCO₂-eq for HCFC-22 and for CO₂ are considered equivalent, the long-term implications of the two reductions are not the same.

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