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Notes:

# 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, CO<sub>2</sub>, 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 CO<sub>2</sub> 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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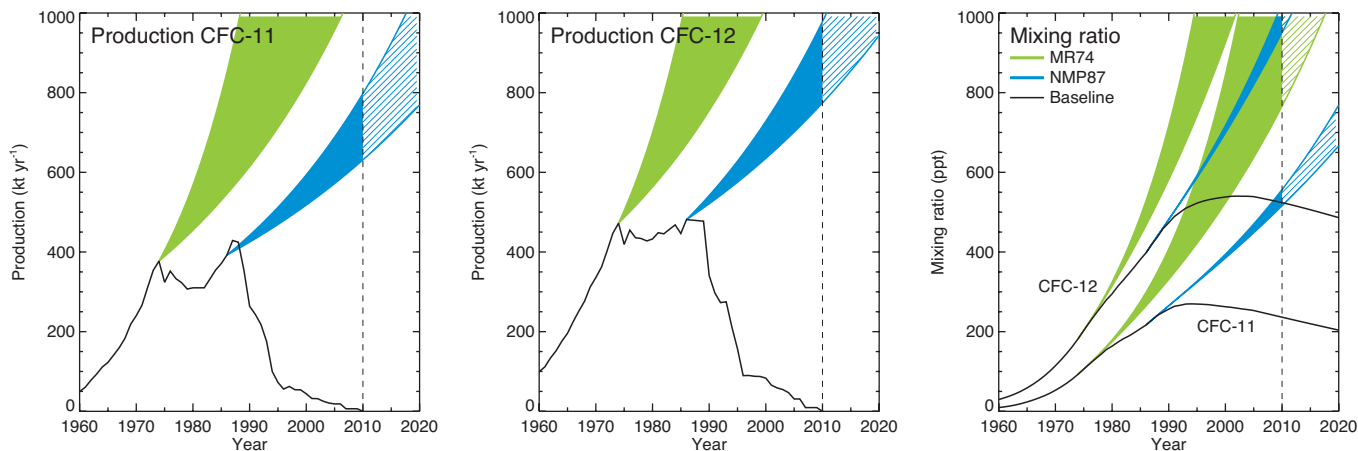
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Abbreviations: CFC, chlorofluorocarbons; GWP, global warming potential; HCFC, hydrochlorofluorocarbons; HFC, hydrofluorocarbons; IPCC, Intergovernmental Panel on Climate Change; MR74, Molina and Rowland; NMP87, no Montreal Protocol; ODS, ozone-depleting substance; RF, radiative forcing.

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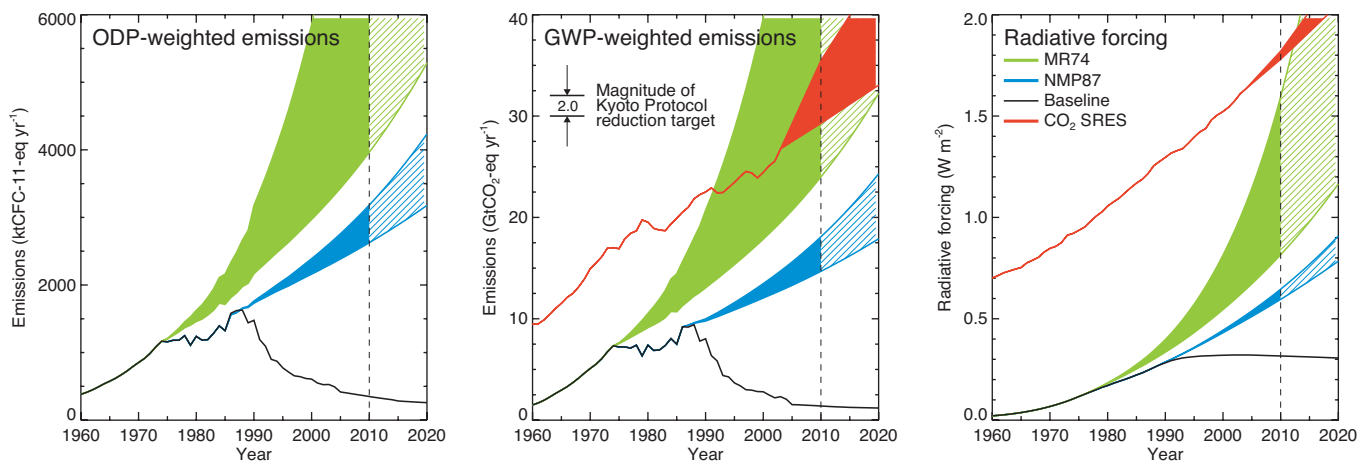
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**Fig. 1.** Scenarios for the global production of CFC-11 (*Left*) and CFC-12 (*Center*) and mixing ratios [*Right*; in ppt (part per trillion)] for the period 1960–2020. Scenarios include the baseline scenario and those of the worlds avoided with 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,  $\text{CCl}_4$ ,  $\text{CH}_2\text{Cl}_2$ , HCFCs,  $\text{CH}_2\text{Cl}$ , Halons, and  $\text{CH}_3\text{Br}$  (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  $\text{CO}_2$  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  $\text{CO}_2$ . 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  $\text{CO}_2$  emissions for 1960–2003 are from global fossil fuel and cement production (45). Beyond 2003, the shaded regions for  $\text{CO}_2$  reflect the maximum (A1B) and minimum (B2) SRES scenarios (25). The  $\text{CO}_2$  RF data are based on  $\text{CO}_2$  observations and SRES scenarios (25). All RF values represent net changes from the start of the industrial era ( $\approx 1750$ ) 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 CO<sub>2</sub>**

Scenario	GWP-weighted emissions, GtCO <sub>2</sub> -eq·yr <sup>-1</sup>			Radiative forcing (W·m <sup>-2</sup> )		
	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 <sub>2</sub>	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 CO<sub>2</sub> 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 CO<sub>2</sub> (CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>. 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 CO<sub>2</sub> emissions. After 1988, the contribution of ODSs falls sharply in contrast to increasing CO<sub>2</sub> emissions. By 2010, ODS emissions will have declined to 4–5% of Special Report on Emissions Scenarios (SRES) CO<sub>2</sub> emissions, which are projected to increase to 29–35 GtCO<sub>2</sub>-eq·yr<sup>-1</sup>. In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 GtCO<sub>2</sub>-eq·yr<sup>-1</sup> 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 CO<sub>2</sub>. In the NMP87 scenario in which ODS increases occur later than in the MR74 scenario, the ODS emissions reach 15–18 GtCO<sub>2</sub>-eq·yr<sup>-1</sup> in 2010, about half of the CO<sub>2</sub> annual emissions. Furthermore, the contribution of ODS emissions (in GtCO<sub>2</sub>-eq·yr<sup>-1</sup>) 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<sup>-2</sup> and decreases slowly by a total of 0.005 W·m<sup>-2</sup> by 2010. Over the same period, RF values for CO<sub>2</sub> are expected to increase by 0.2 W·m<sup>-2</sup> to ≈1.8 W·m<sup>-2</sup>. In the world avoided of MR74, the ODS RF ranges from 45% to 90% of the CO<sub>2</sub> value in 2010 (Table 1). In the NMP87 scenario, the ODS RF is in a lower, narrower range near 35% of the CO<sub>2</sub> 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 <sub>2</sub> -eq-yr <sup>-1</sup>	Radiative forcing, W·m <sup>-2</sup>
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 <sup>†</sup>	9.7–12.5	0.20–0.25

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

<sup>†</sup>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 CO<sub>2</sub> increases in 2010.

The MR74 projection that ODS RF could almost have matched that of anthropogenic CO<sub>2</sub> 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 CO<sub>2</sub> RF to increase by the same amount as the ODS RF would have by 2010 in MR74 or NMP87. When using an averaged CO<sub>2</sub> 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.

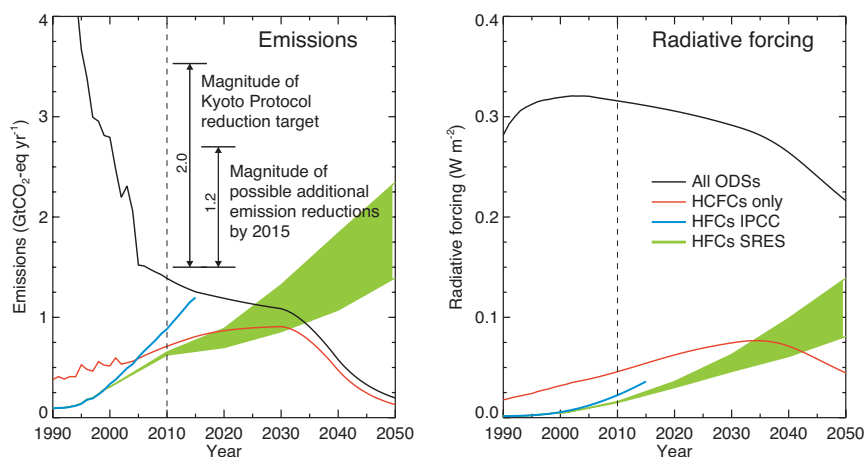
### Ozone Response

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 CO<sub>2</sub>-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 GtCO<sub>2</sub>-yr<sup>-1</sup>. 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 ( $\approx 1750$ ) 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  $\text{CO}_2$ -equivalent emissions in 40 countries (Annex-1 parties) by 2008–2012. The agreed upon reductions will occur in emissions of six key greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , HFCs, PFCs, and  $\text{SF}_6$ ) 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  $\text{CO}_2$ -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*).

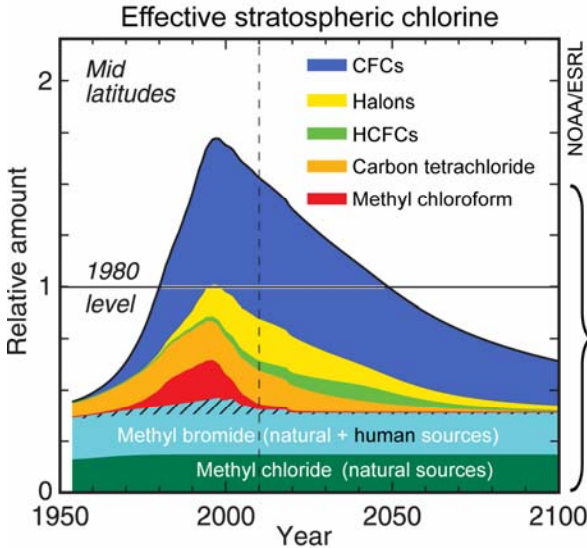
An acceleration of the phase-out of HCFCs might increase the use of HFCs as substitutes, which, at least partly, would offset the benefits from such an acceleration. In order for an acceleration of an HCFC phase-out to increase climate protection, lower-GWP refrigerant systems would need to be developed 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  $\text{CO}_2$  and HFC-152a as a refrigerant for mobile air conditioning (5). More recently, chemical companies (see [www.ineosfluor.com/ArticleText.asp?ID=269](http://www.ineosfluor.com/ArticleText.asp?ID=269), [www.honeywell.com/sites/sm/chemicals/genetron](http://www.honeywell.com/sites/sm/chemicals/genetron), and [www.refrigerants.dupont.com/Suva/en\\_US/index.html](http://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  $\approx 0.12$  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  $\text{CO}_2$ -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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1. World Meteorological Organization Global Ozone Research and Monitoring Project (1995) *Scientific Assessment of Ozone Depletion: 1994* (World Meteorological Organization, Geneva), Report 37.
2. World Meteorological Organization Global Ozone Research and Monitoring Project (1999) *Scientific Assessment of Ozone Depletion: 1998* (World Meteorological Organization, Geneva), Report 44.
3. World Meteorological Organization Global Ozone Research and Monitoring Project (2003) *Scientific Assessment of Ozone Depletion: 2002* (World Meteorological Organization, Geneva), Report 47.
4. World Meteorological Organization Global Ozone Research and Monitoring Project (2007) *Scientific Assessment of Ozone Depletion: 2006* (World Meteorological Organization, Geneva), Report 50.
5. Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons* (Cambridge Univ Press, New York).
6. Molina MJ, Rowland FS (1974) *Nature* 249:810–812.
7. Andersen SO, Sarma KM (2002) *Protecting the Ozone layer: The United Nations History* (Earthscan, London).
8. United Nations Environment Program (2003) *Handbook for the International Treaties for the Protection of the Ozone Layer* (Ozone Secretariat, United Nations Environment Program, Nairobi, Kenya).
9. Farman JC, Gardiner BG, Shanklin JD (1985) *Nature* 315:207–210.
10. Solomon S, Garcia RR, Rowland FS, Wuebbles DJ (1986) *Nature* 321:755–758.
11. World Meteorological Organization Global Ozone Research and Monitoring Project (1988) *Report of the International Ozone Trends Panel* (World Meteorological Organization, Geneva), Report 18.
12. Rowland FS (2006) *Philos Trans R Soc London B* 361:769–790.
13. United Nations Environment Programme (2005) *Production and Consumption of Ozone Depleting Substances under the Montreal Protocol 1986–2004* (Ozone Secretariat, United Nations Environment Programme, Nairobi, Kenya).
14. Solomon S (2004) *Nature* 427:289–291.
15. Newchurch MJ, Yang E-S, Cunnold DM, Reinsel GC, Zawodny JM, Russell JM, III (2003) *J Geophys Res* 108:4507.
16. Wigley TML (1988) *Nature* 335:333–335.
17. Fisher DA, Hales CH, Wang W-C, Ko MKW, Dak Sze N (1990) *Nature* 344:513–516.
18. Ko MKW, Dak Sze N, Molnar G (1993) *Atmos Environ* 27A:581–587.
19. Solomon S, Daniel JS (1996) *Climatic Change* 32:7–17.
20. Intergovernmental Panel on Climate Change (1990) *Scientific Assessment of Climate Change—Report of Working Group I* (Cambridge Univ Press, Cambridge, UK).
21. Hansen J, Laci A, Prather M (1989) *J Geophys Res* 94:16417–16421.
22. den Elzen MGJ, Swart RJ, Rotmans J (1992) *Sci Total Environ* 113:229–250.
23. Kroeze C, Reijnders L (1991) *Sci Total Environ* 111:1–24.
24. Ramanathan V (1975) *Science* 190:50–51.
25. Intergovernmental Panel on Climate Change (2001) *Climate Change 2001: The Scientific Bases: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
26. United Nations Framework Convention on Climate Change (1997) *Kyoto Protocol to the United Nations Framework Convention on Climate Change*.
27. McFarland M (1999) *Applications and Emissions of Fluorocarbon Gases: Past, Present and Prospects for the Future* (Kluwer Academic, Dordrecht, The Netherlands).
28. Montzka SA, Butler JH, Elkins JW, Thompson TM, Clarke AD, Lock LT (1999) *Nature* 398:690–694.
29. Wuebbles DJ (1983) *J Geophys Res* 88:1433–1443.
30. Prather M, Midgley P, Rowland FS (1996) *Nature* 381:551–554.
31. National Academy of Sciences (1979) *Causes and Effects of Stratospheric Ozone Reduction* (Natl Acad Sci, Washington, DC).
32. National Academy of Sciences (1982) *Causes and Effects of Stratospheric Ozone Reduction: An Update* (Natl Acad Sci, Washington, DC).
33. Hammit J, Camm F, Connell PS, Mooz WE, Wolf KA, Wuebbles DJ, Bamezai A (1987) *Nature* 330:711–716.
34. Clodic D, Palandre L (2004) *Determination of comparative HCFC and HFC emission profiles for the foam and refrigeration sectors until 2015. Part 1: Refrigeration emission profiles* (ARMINES, Paris).
35. Nakićenović N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, et al. (2000) *IPCC Special Report on Emissions Scenarios* (Cambridge Univ Press, Cambridge, UK).
36. United Nations Framework Convention on Climate Change (2005) *Greenhouse gas emissions data for 1990–2003 submitted to the United Nations Framework Convention on Climate Change* (Climate Change Secretariat, Bonn, Germany), [http://unfccc.int/resource/docs/publications/key\\_ghg.pdf](http://unfccc.int/resource/docs/publications/key_ghg.pdf).
37. Hansen J, Sato M, Ruedy R, Nazarenko L, Laci A, Schmidt GA, Russell R, Aleinov I, Bauer M, Bauer S, et al. (2005) *J Geophys Res* 110:D18104.
38. Laci AA, Wuebbles DJ, Logan JA (1990) *J Geophys Res* 95:9971–9981.
39. Ramaswamy V, Schwarzkopf MD, Shine KP (1992) *Nature* 355:810–812.
40. United Nations Environment Programme (1999) *Technology and Economic Assessment Panel Report of the HFC, PFC Task Force: The Implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol* (Ozone Secretariat, United Nations Environment Programme, Nairobi, Kenya).
41. United Nations Environment Programme (2003) *Technology and Economic Assessment Panel Report of the HCFC Task Force* (Ozone Secretariat, United Nations Environment Programme, Nairobi, Kenya).
42. United Nations Environment Programme (2002) *Technology and Economic Assessment Panel Report of the Task Force on Destruction Technologies* (Ozone Secretariat, United Nations Environment Programme, Nairobi, Kenya).
43. United Nations Environment Programme (2002) *Technology and Economic Assessment Panel Report of the Task Force on Collection, Recovery and Storage* (Ozone Secretariat, United Nations Environment Programme, Nairobi, Kenya).
44. European Commission (2006) *Directive 2006/40/EC of the European parliament and of the council of 17 May 2006 relating to emissions from air-conditioning systems in motor vehicles and amending council directive 70/156/EEC*.
45. Marland G, Boden TA, Andres RJ (2006) *Global, Regional, and National CO<sub>2</sub> Emissions* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN), <http://cdiac.esd.ornl.gov/trends/emis/em.cont.htm>.

# The dual benefit of the Montreal Protocol: Ozone and climate protection:

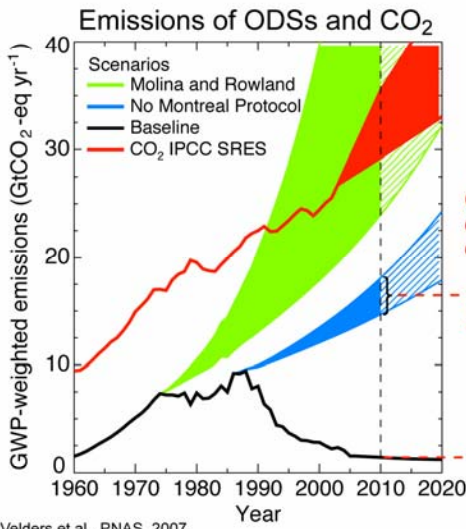


1

The Montreal Protocol has **slowed and reversed** the accumulation of ozone depleting substances (ODSs) in the stratosphere as measured by **effective stratospheric chlorine** amounts.

Scenarios

- Baseline ODS conditions as measured in the past and projected for the future.
- ODS projections for a world with no regulations from the Montreal Protocol.
- ODS projections for a world with no early warning by Molina and Rowland in 1974.
- IPCC SRES results for CO<sub>2</sub> in the past and projected for the future.



3

The Montreal Protocol will have **reduced net GWP-weighted emissions** from ODSs in 2010 by 5-6 times the reduction target of the first commitment period (2008-2012) of the Kyoto Protocol.

2

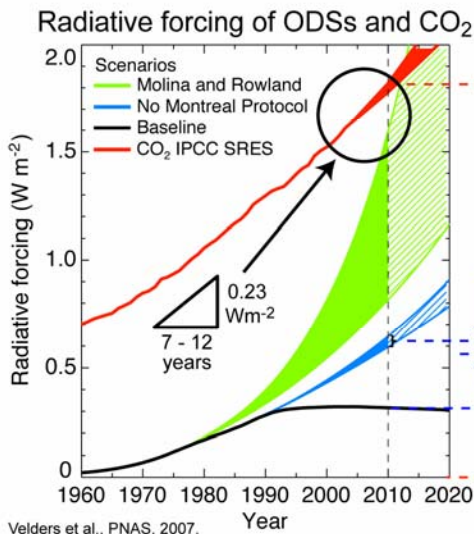
The Montreal Protocol will have **reduced net GWP-weighted emissions** from ODSs in 2010 by about 11 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>.

Ozone depletion offset: 3.0

HFC offset: 0.9

Magnitude of Kyoto Protocol reduction target: 2.0

Velders et al., PNAS, 2007.



5

The Montreal Protocol **net reduction in ODS radiative forcing** in 2010 will be equivalent to about 7-12 years of growth in radiative forcing of CO<sub>2</sub> from human activities.

4

The Montreal Protocol will have **reduced net radiative forcing** from ODSs in 2010 by about 0.23 Wm<sup>-2</sup>, which is about 13% of that due to the accumulated emissions of CO<sub>2</sub> from human activities.

Ozone depletion offset: 10.06

HFC offset: 0.02

Velders et al., PNAS, 2007.