Q19 Have Montreal Protocol controls of ozone-depleting substances also protected Earth's climate?

Yes. Many ozone-depleting substances are also potent greenhouse gases that contribute to climate forcing when they accumulate in the atmosphere. Montreal Protocol controls have led to a substantial reduction in the emissions of ozone-depleting substances (ODSs) over the last two decades. These reductions, while protecting the ozone layer, have the additional benefit of reducing the human contribution to climate change. Without Montreal Protocol controls, the contribution to climate forcing from annual ODS emissions could now be 10-fold larger than its present value, which would be a significant fraction of the climate forcing from current carbon dioxide (CO_2) emissions. Increases in ODS substitute gases, which are also greenhouse gases, could offset much of this climate benefit by substantially contributing to human-induced climate forcing in the coming decades.

The success of the Montreal Protocol in controlling the production and consumption of ozone-depleting substances (ODSs) has protected the ozone layer (see Q15). The resulting reductions in atmospheric abundances of ODSs also reduced the human influence on climate because all ODSs are greenhouse gases (see Q18). By protecting both ozone and climate, the Montreal Protocol has provided a *dual benefit* to society and Earth's ecosystems. In the following, the dual benefit of the Montreal Protocol is highlighted by considering long-term baseline and world-avoided scenarios of ODS emissions that use Ozone Depletion Potentials (ODPs), Global Warming Potentials (GWPs), equivalent effective stratospheric chlorine (EESC), and the radiative forcing of climate. However, the climate benefit of the Montreal Protocol may be significantly offset by increasing future use of ODS substitute gases such as HFCs.

Baseline ODS scenarios. The baseline scenarios of past and future ODS emissions presented here include the emissions of principal halogen source gases assuming compliance with the Montreal Protocol provisions. They are constructed from (1) historical annual production and consumption of individual ODSs reported to the Montreal Protocol, (2) projected annual production and consumption of ODSs for future years based on provisions of the Protocol, (3) estimates of ODS banks, (4) atmospheric observations of ODSs and some naturally occurring halogen source gases, such as methyl chloride (CH_3Cl), and (5) weighting factors related to ozone depletion and climate change.

In forming two of the baseline scenarios shown in Figure Q19-1 (upper panels), the emissions of each gas are added together after being *weighted* (multiplied) by the Ozone Depletion Potential (ODP) or the Global Warming Potential (GWP) of the respective gas (see Q18 and Table Q7-1). In the ODP-weighted scenario, the sum of emissions is expressed as *CFC-11-equivalent* emissions because CFC-11 is the reference gas, with an assigned ODP value of 1. For example, in the sum, 1 kg of halon-1211 emissions is added as 6.9 kg of CFC-11-equivalent emissions because the ODP of halon-1211 is 6.9. Similarly, the GWP-weighted sum is expressed as *CO_2-equivalent* emissions because CO_2 is the reference gas, with an assigned GWP of 1. For example, in the sum, 1 kg of carbon tetrachloride emissions is added as 1730 kg of CO_2-equivalent emissions because the GWP of carbon tetrachloride is 1730.

World-avoided ODS scenarios. The baseline scenario of ODS emissions can be contrasted with a scenario of ODS emissions that the world has avoided by agreeing to the Montreal Protocol (see Figure Q19-1). These world-avoided emissions are

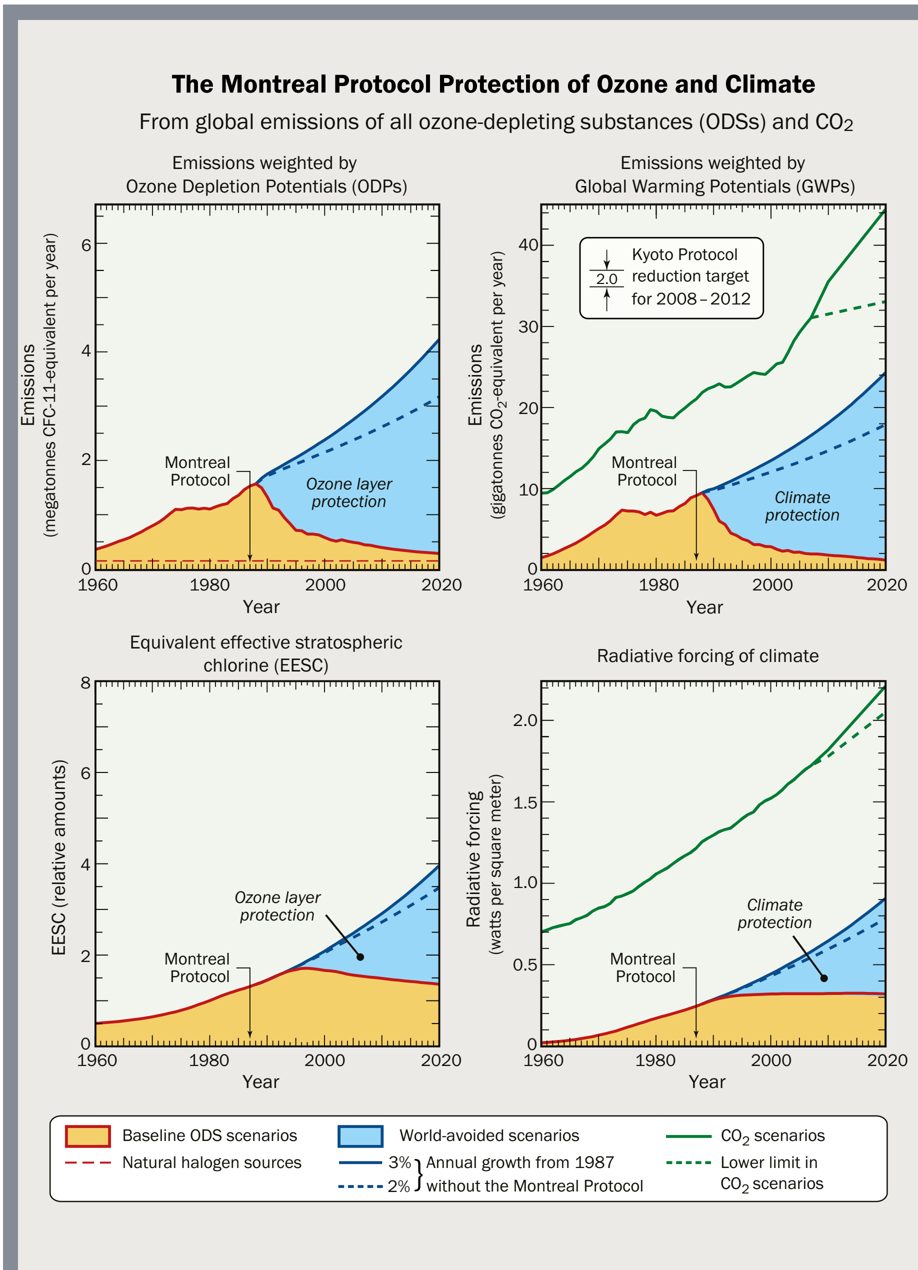

Figure Q19-1. Montreal Protocol protection of ozone and climate. The provisions of the Montreal Protocol have substantially reduced ozone-depleting substances (ODSs) in the atmosphere. This has protected the ozone layer and also reduced the potential for climate change because ODSs are greenhouse gases. The scenarios and comparisons shown here demonstrate this dual benefit of the Montreal Protocol. Baseline scenarios for ODS emissions include all principal gases weighted by their Ozone Depletion Potentials (ODPs) or Global Warming Potentials (GWPs) (top panels). With these weightings, emissions are expressed as CFC-11-equivalent or CO_2-equivalent mass per year. The lower panels show EESC and radiative forcing of climate as derived from the respective ODP- and GWP-weighted scenarios. The world-avoided emission scenarios assume ODS emission growth of 2 or 3% per year beyond 1987 abundances. Shown for reference are the emissions and radiative forcing of CO_2, and the emissions reduction target of the first commitment period of the Kyoto Protocol. The contributions of natural halogen source gases are shown in the ODP-weighted and EESC scenarios (red dashed lines) and are negligible in the GWP-weighted and radiative forcing scenarios. The magnitude of the dual benefit has increased since about 1987 as shown by differences between the world-avoided and baseline scenarios (blue shaded regions in each panel). For completeness, these differences can be adjusted by offsets due to additional ozone depletion and HFC emissions (see text). (A megatonne = 1 billion (10^9) kilograms. A gigatonne = 1 trillion (10^{12}) kilograms.)

estimated by assuming that emissions of ODSs in the baseline scenario increase beyond 1987 values with a 2 or 3% annual growth rate. These growth rates are consistent with the strong market for ODSs in the late 1980s that included a wide variety of current and potential applications and that had potential for substantial new growth in developing countries.

CO_2 emission scenarios. Long-term CO_2 emission scenarios are also shown for comparison, as derived from past and projected CO_2 emissions, because CO_2 is the principal greenhouse gas related to human activities. The projected CO_2 emissions have high and low scenarios that are derived using different basic assumptions about future economies, technical progress, and societal decisions.

ODP-weighted emissions scenarios. The ODP-weighted emissions in the ODS baseline scenario are a measure of the overall threat to stratospheric ozone from ODSs (see Figure Q19-1, upper left panel). When ODP-weighted emissions increase (decrease) in a given year, more (less) ozone will be destroyed in future years. ODP-weighted emissions increased substantially in the baseline scenario between 1960 and 1987, the year the Montreal Protocol was signed (see Figure Q19-1 and Q0-1). After 1987, ODP-weighted emissions began a long and steady decline to present-day values. The decline in emissions is expected to continue, causing the atmospheric abundances of individual ODSs to decrease (see Figure Q16-1). The reduction in ODP-weighted emissions from the 1987 value is a conservative measure of the annual emissions avoided by the Montreal Protocol since 1987 and, hence, of the success of the Montreal Protocol in protecting the ozone layer.

Annual ODP-weighted emissions in the world-avoided scenario are about double the 1987 values by 2020. The annual differences between the world-avoided emissions and the baseline scenario (blue shaded region in Figure Q19-1) provide reasonable upper limits to the ODP-weighted emissions avoided by the Montreal Protocol each year since 1987.

GWP-weighted emissions scenarios. The GWP-weighted emissions in the ODS baseline scenario are a measure of the overall threat to climate from ODSs (see Figure Q19-1, upper right panel). As ODS emissions accumulate in the atmosphere, their climate forcing contribution increases. The long-term changes in the GWP-weighted scenario are very similar to those in the ODP-weighted scenario. Both show an increase before 1987 and decrease afterwards. The similarity follows from the predominant role that CFC-11 and CFC-12 emissions play in ozone depletion and climate forcing from ODSs. The reduction in GWP-weighted emissions since 1987 is a conservative measure of the substantial success of the Montreal Protocol in reducing the potential for climate change from human activities. The annual differences since 1987 between the world-avoided emissions and the baseline scenario (blue shaded region in Figure Q19-1) provide reasonable upper limits to the GWP-weighted emissions avoided by the Montreal Protocol each year since 1987.

The climate protection calculated using differences between world-avoided emissions and the baseline scenario has two offsetting effects. The first is the additional ozone depletion that would be caused by world-avoided ODS emissions. Ozone depletion offsets ODS climate forcing because a greenhouse gas (ozone) is being removed from the atmosphere in response to ODS emissions (see Q18). The second effect is the increase in emissions of HFC substitute gases that occurred in response to ODS reductions from Montreal Protocol controls. More HFCs in the atmosphere have the potential to offset much of the gain in climate protection from ODS reductions (see Figure 19-2) because HFCs are also greenhouse gases (see Q18).

The combined magnitude of these offsets in 2010, for example, is about 30% of the difference between the baseline and world-avoided scenarios. The resulting net GWP-weighted emission reduction in 2010 is about 9.7–12.5 gigatonnes CO_2-equivalent per year. In contrast, the annual emissions reduction target adopted by the Kyoto Protocol during its first commitment period (2008–2012) is estimated as 2 gigatonnes CO_2-equivalent per year (see Figure Q19-1). The reductions are expected to result from controlling the Kyoto Protocol basket of gases that includes HFCs and does not include ODSs (see Q18). As a result, the upper limit for the net reduction in annual GWP-weighted emissions achieved by the Montreal Protocol in 2010 is *5- to 6-fold larger* than the Kyoto Protocol target.

Annual GWP-weighted emissions of ODSs were a large percentage (about 20–40%) of CO_2-baseline emissions between 1960 and 1987 (see Figure Q19-1). Thereafter, this percentage has steadily decreased and is projected to reach 2–3% by 2020.

This projection stands in sharp contrast to the world-avoided scenario, in which the percentage increases to 40–75% of CO_2-baseline emissions by 2020.

EESC scenarios. The EESC scenario in Figure Q19-1 (lower left panel) provides a measure of the year-to-year potential of the atmospheric abundances of ODSs to destroy stratospheric ozone. Changes in historical and projected atmospheric emissions of ODSs cause changes in their atmospheric abundances. The derivation of EESC from ODS atmospheric abundances is discussed in Q16 and similar EESC baseline scenarios are shown in Figures Q14-1, Q15-1, and Q16-1 for different time intervals. An increase in ODP-weighted emissions always leads to some increase in EESC in the years following the emissions. When ODS-weighted emissions decreased after 1987, EESC did not proportionally decrease because of the long atmospheric lifetimes of the principal ODSs. In Figure Q19-1, for example, EESC reached its peak nearly a decade after the peak in ODP-weighted emissions, and by 2010 the decrease in EESC from its peak value was only about 10%, compared to the 70% decrease in ODP-weighted emissions achieved by 2010.

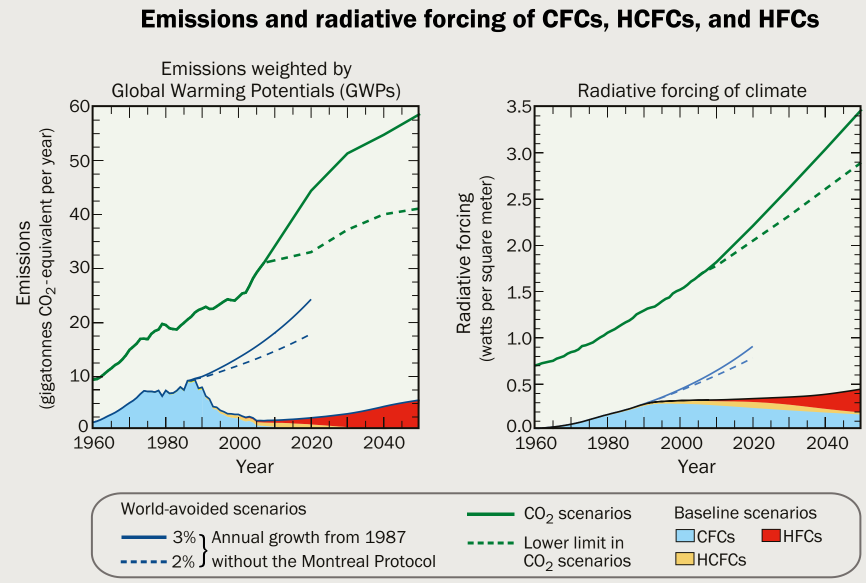

Figure Q19-2. Implications of HFC usage for climate.
The provisions of the Montreal Protocol have reduced ozone-depleting substances (ODSs), but as a result increased the demand for ODS substitute gases. Most of the hitherto available substitute gases such as HCFCs and HFCs have large Global Warming Potentials (GWPs), and hence future emissions of these gases have the potential to offset the climate benefit gained from the Montreal Protocol. A baseline scenario is calculated using current HCFC consumption in leading applications, patterns of replacement of HCFCs by HFCs in developed countries, and economic growth. The baseline scenario for HFC emissions includes four major HFCs weighted by their GWP (expressed as CO_2-equivalent mass per year) (left panel). Note that the used baseline scenario represents average increases in HFC emissions only. Radiative forcing as calculated from the GWP-weighted scenarios for CFCs, HCFCs and HFCs is shown in the right panel. By 2050, the projected increases in HFC abundances are sufficient to significantly offset the climate benefit achieved by the Montreal Protocol and produce a radiative forcing that is approximately 15% of the projected CO_2 value.

Radiative forcing of climate. The radiative forcing derived for the ODS baseline scenario in Figure Q19-1 (lower right panel) provides a measure of the year-to-year contribution to climate forcing from atmospheric ODS abundances. The radiative forcing of an ODS is proportional to its radiative efficiency (that is, the radiative forcing per abundance change) and the net increase in its atmospheric abundance during the Industrial Era. Increases in abundance up to the present are derived from atmospheric observations. Future abundances rely on projected emissions and atmospheric lifetimes of each gas. In Figure Q19-1, radiative forcing due to ODSs increases smoothly from 1960 onward, peaks in 2003, and decreases very gradually in subsequent years. Radiative forcing responds to ODS emission reductions in a manner similar to EESC, with the current slow decline attributable to the two principal contributing gases, CFC-11 and CFC-12, and their long atmospheric lifetimes (50–100 years).

The differences in ODS climate forcing between the world-avoided and baseline scenarios are offset by additional ozone depletion and HFC emissions in a manner similar to that noted above for differences in GWP-weighted emissions. After accounting for these two offsets, the climate forcing due to ODSs in the world-avoided scenario is approximately 70% higher than that in the baseline scenario in 2010 and approximately 30% of that due to CO_2.

The considerable contributions that ODSs could have made to climate forcing, if not controlled by the Montreal Protocol, attests to their potency as greenhouse gases. ODSs had negligible atmospheric abundances 50–60 years ago and, as a group, represent chlorine amounts that currently are about 100,000 times less abundant in the atmosphere than CO_2.

Implications of HFC usage for climate. HFCs are currently principal substitute gases for ODS uses. Many of these HFCs are also potent greenhouse gases. In the coming decades, the projected growth in HFC emissions has the potential to offset much of the climate benefit gained from the Montreal Protocol controls, depending on emissions scenarios. An average future projection scenario based on current production and consumption patterns and projected economic growth suggests that increasing HFC demands could result in GWP-weighted emissions of around 5 gigatonnes CO_2-equivalent per year by 2050 (see Figure Q19-2), primarily in developing nations. The 2050 value is comparable to half of the peak in GWP-weighted ODS emissions in 1987 (see Figure Q19-1). The resulting radiative forcing from these projected emissions would reach levels of the early 2000s and contribute almost 10% of that due to CO_2 to the total anthropogenic climate forcing by 2050.

This projection assumes that HFC application demand in developing countries would be met using the same suite of HFCs currently used in developed countries. If future HFC demand is met instead with lower-GWP substances, the 2050 projection would be substantially reduced.

Increasing the benefits of the Montreal Protocol into the future. Fewer control options are available to increase the dual benefit of the Montreal Protocol beyond 2020 because the most effective and abundant ODSs have already been phased out under Montreal Protocol provisions (see Q16). The most recent Montreal Protocol action increased ozone and climate protection by accelerating the phase-out of HCFCs (Montreal in 2007) (see Q15). This provision is expected to reduce total GWP-weighted emissions of HCFCs by about 50% between 2010 and 2050, corresponding to about 18 gigatonnes of CO_2-equivalent emissions.

Ozone and climate protection could be further enhanced with Montreal Protocol provisions that increase the effectiveness of capturing and destroying ODSs contained in halon, CFC, and HCFC banks, namely, those ODSs currently being used in refrigeration, air conditioning, and fire protection equipment, or stockpiled for servicing long-term applications. Current banks are projected to contribute more to ozone depletion in the coming decades than the limited future production of ODSs allowed by the Montreal Protocol provisions.

The available options, such as cutting the remaining production of HCFCs, halting emissions of CCl_4 and quarantine or pre-shipment CH_3Br, as well as destroying halon, CFC, and HCFC banks, would together advance the return of the ozone layer to 1980 levels by 11 years.