Q18 Are Montreal Protocol controls of ozone-depleting substances also helping protect Earth's climate?

Yes. Many ozone-depleting substances (ODSs) 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 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 climate forcing due to ODSs could now be nearly two and a half times the present value.

The success of the Montreal Protocol in controlling the production and consumption of ozone-depleting substances (ODSs) has protected the ozone layer (see Q14). The resulting reductions in atmospheric abundances of ODSs also decreased the human influence on climate because all ODSs are greenhouse gases (see Q17). By protecting both ozone and climate, the Montreal Protocol has provided a *dual benefit* to society and Earth's ecosystems. As shown in **Figure Q18-1** and described below, the dual benefit of the Montreal Protocol is highlighted by considering a long-term baseline and a world-avoided scenario of ODS emissions that use Ozone Depletion Potentials (ODPs), Global Warming Potentials (GWPs), equivalent effective stratospheric chlorine (EESC), and the radiative forcing of climate.

Baseline ODS scenario. The baseline scenario refers to actual past ODS emissions of the principal halogen source gases and projected emissions for the years 2017 to 2020. The baseline scenario is labeled "From observed ODS abundances" in Figure Q18-1 since, for 1960–2016, the emissions are based upon analysis of observed abundances of the principal ODS gases at Earth's surface (see Figure Q15-1). This scenario also includes emissions of the naturally occurring halogen source gases methyl chloride (CH_3Cl) and methyl bromide (CH_3Br). For this scenario the peak emission of ODSs occurs in the late 1980s (see Figure Q0-1).

For all of the emission scenarios shown in Figure Q18-1, the annual emissions of each gas are added together after being *weighted* (multiplied) by their corresponding Ozone Depletion Potential (ODP) (upper left) or Global Warming Potential (GWP) (upper right) (see Q17 and Table Q6-1). 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 2110 kg of CO_2-equivalent emissions because the GWP of carbon tetrachloride is 2110.

World-avoided ODS scenario. The baseline scenario of ODS emissions can be contrasted with a scenario of ODS emissions that the world has avoided by successfully implementing the Montreal Protocol (see Figure Q18-1). The world-avoided scenario is derived by assuming that emissions of ODSs in the baseline scenario increase beyond 1987 values at a 3% annual growth rate. This growth rate is consistent with the strong market for ODSs in the late 1980s that included a wide variety of current and potential applications and had the potential for substantial growth in developing countries.

CO_2 emission scenario. Long-term emissions of CO_2 are also shown in the upper right panel of Figure 18-1. Atmospheric CO_2 is the principal greenhouse gas emitted by human activities. The CO_2 emission curve represents global emissions from the sum of each nation's reported emissions from the combustion of coal, oil, natural gas, the fuels used by the world's ships and airplanes, cement manufacturing, and the release of CO_2 due to global deforestation.

ODP-weighted emissions. The ODP-weighted emission scenario based upon observed ODS abundances is one measure of how the overall threat to stratospheric ozone from ODSs has changed over time (see Figure Q18-1, upper left panel). When ODP-weighted emissions increase in a given year, more ozone will be destroyed in future years relative to the amount of ozone depletion caused by the emissions in the prior year. Conversely, when emissions decline, less ozone will be destroyed in future years. Annual ODP-weighted emissions increased substantially between 1960 and 1987, the year the Montreal Protocol was signed (see Q0-1). After 1987, annual 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 all individual ODSs to eventually decrease (see Figure Q15-1). The reductions in ODP-weighted emissions following the peak value in 1987 represent lower limits of the annual emissions avoided by the Montreal Protocol, which are a measure of its increasing success over time in protecting the ozone layer.

The upper limits of annual reductions in ODP-weighted emissions are derived from the world-avoided scenario. The difference between the world-avoided emission scenario and the

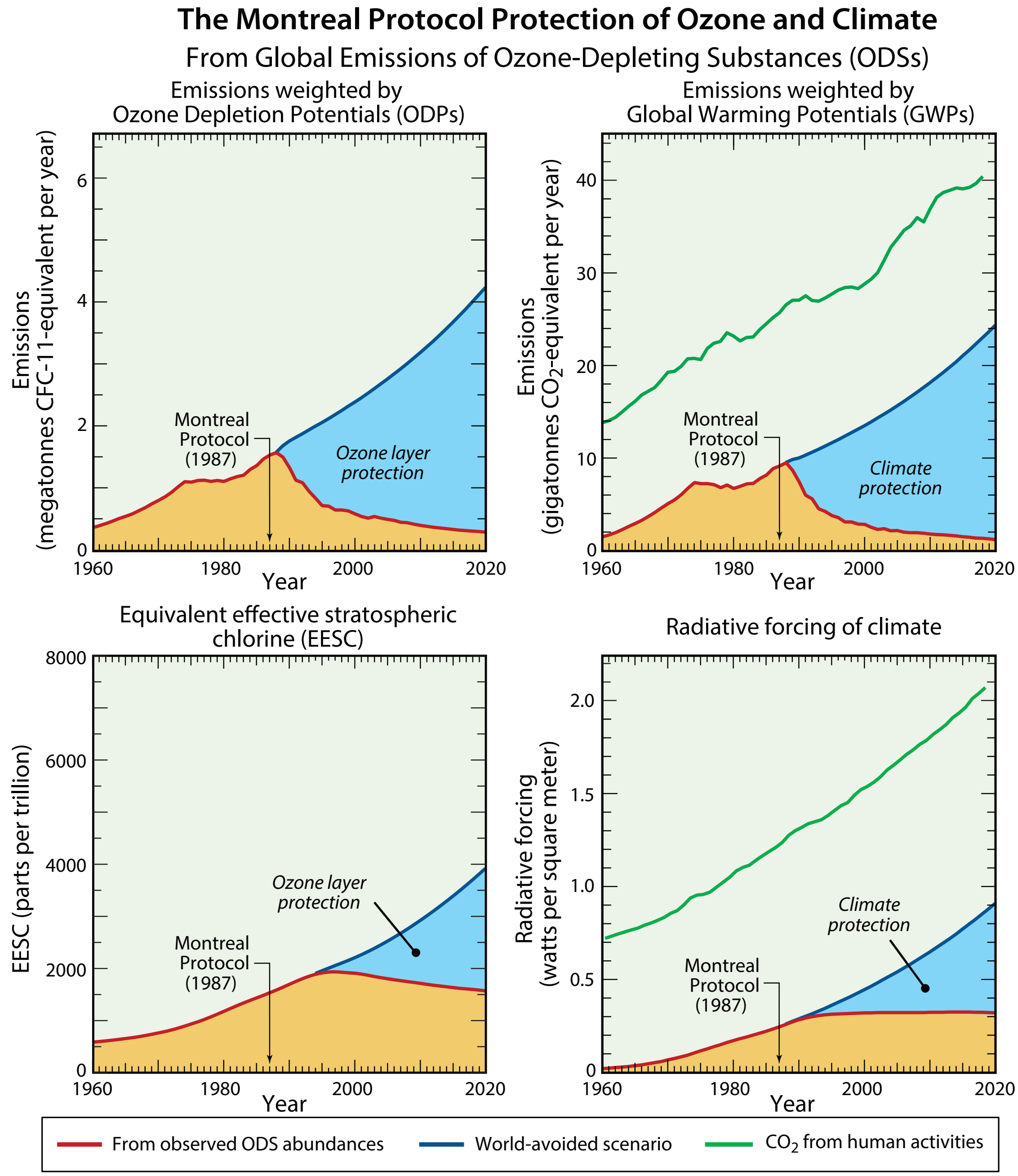

Figure Q18-1. Montreal Protocol protection of ozone and climate. The Montreal Protocol has protected the ozone layer and also reduced the potential for climate change, because ozone-depleting substances (ODSs) are greenhouse gases (GHGs). The baseline ODS scenario (red) includes actual emissions of all principal gases weighted either by their Ozone Depletion Potentials (ODPs) (upper left) or Global Warming Potentials (GWPs) (upper right) coupled with projected emissions for years 2017 to 2020. With these weightings, emissions are expressed as CFC-11-equivalent or CO_2-equivalent mass per year. The lower panels show equivalent effective stratospheric chlorine (EESC) (see Figure Q15-1) and total radiative forcing (RF) of climate (see Figure Q17-2), as derived from the observed abundances of ODSs as well as projected abundances for 2017 to 2020. The world-avoided emission scenario (blue) assumes a 3% per year growth in the emission of ODSs beyond 1987 values, consistent with the assumption for the No Protocol scenario shown in Figure Q14-1. The emission and RF of atmospheric CO_2 (green) are shown for reference on the right panels. The magnitude of the dual benefit has steadily increased since 1987, as shown by the differences between the world-avoided scenario and the observed ODS abundance scenario (blue shaded region) in each panel.

(A megatonne = 1 million (10^6) metric tons = 1 billion (10^9) kilograms. A gigatonne = 1 billion (10^9) metric tons = 1 trillion (10^{12}) kilograms. The CFC-11-equivalent emission unit means release of an ODS would result in the same amount of ozone depletion as release of the same mass of CFC-11; the CO_2-equivalent emission unit means release of a GHG would result in the same amount of RF of climate as release of the same mass of CO_2, over a 100-year time interval. Emissions of CO_2 used in this figure are from the Global Carbon Project.)

baseline scenario (blue shaded region in Figure Q18-1, upper left panel) provides a reasonable upper limit to the ODP-weighted emissions that have been avoided by the Montreal Protocol since 1987. The avoided emissions are a measure of the *ozone layer protection* afforded by the Protocol. If the emissions of ODSs had followed the world avoided scenario, annual ODP-weighted emissions in 2018 would be more than 10 times the current value.

GWP-weighted emissions. The GWP-weighted emission scenario based upon observed ODS abundances is a measure of how the overall threat to Earth's climate from ODSs has changed over time (see Figure Q18-1, upper right panel). As GWP-weighted emissions rise, the radiative forcing of climate in the future due to the accumulation of ODSs in the atmosphere also 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 a 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 reductions in GWP-weighted emissions since the 1987 peak represent lower limits of the annual emissions avoided by the Montreal Protocol, which are a measure of its *climate protection* from human activities. The difference between the world-avoided emission scenario and the baseline scenario (blue shaded region in Figure Q18-1, upper right panel) provide an estimated upper limits to the GWP-weighted emissions avoided by the Montreal Protocol since 1987. If the emissions of ODSs had followed the world avoided scenario, annual GWP-weighted emissions in 2018 would be more than 10 times the current value.

Annual GWP-weighted emissions of ODSs were a large percentage (about 20–40%) of global emissions of CO_2 between 1960 and 1987. Thereafter, this percentage has steadily decreased and was 2–3% of global CO_2 emissions in 2018. This past trend stands in sharp contrast to the world-avoided scenario, in which emissions of ODSs are more than 50% of CO_2 emissions in 2018. Another way to understand the climate benefit of the Montreal Protocol is to compare the height of the blue shaded region in 2018 to the rise in the emissions of CO_2 since 1987, as shown in Figure Q18-1 (upper right panel). These two quantities are nearly equal in magnitude, demonstrating that since 1987 the Montreal Protocol has avoided an increase in GWP-weighted emissions of ODSs that nearly equals the increase in global emissions of CO_2 over this same period of time.

EESC scenarios. The EESC scenarios in Figure Q18-1 (lower left panel) provide a measure of the year-to-year potential of the atmospheric abundances of ODSs to destroy stratospheric ozone. Two scenarios are shown: the baseline that is based on observed abundances of ODSs (with a projection to 2020) and the world-avoided scenario described above. The derivation of EESC from ODS atmospheric abundances is discussed in Q15 and the same EESC baseline scenario is shown in Figures Q13-1, Q14-1 (red curve), and Q15-1 for different time intervals. When ODS-weighted emissions declined after 1987, EESC did not decrease in a proportional manner because of the long atmospheric lifetimes of the principal ODSs (see Table Q6-1). As shown in Figure Q18-1, EESC reached its peak value nearly a decade after the peak in ODP-weighted emissions, and by 2018 the decrease in EESC from its peak value was only about 18%, compared to the 80% decrease in ODP-weighted emissions achieved by 2018. Conversely, had the emissions of ODSs followed the world-avoided scenario, EESC would be more than twice the value in today's stratosphere. In this case, computer simulations indicate that in the year 2020, global total ozone would have been about 17% lower than the 1964–1980 average. Even larger depletions would have occurred in subsequent years. The Montreal Protocol and its Amendments and Adjustments have provided vitally important protection to the global ozone layer and climate.

Radiative forcing scenarios. The scenarios for radiative forcing in Figure 18-1 (lower right panel) provide a measure of the year-to-year contribution to climate change from the atmospheric abundances of ODSs. The radiative forcing of an ODS is equal to the net increase in its atmospheric abundance since 1750 multiplied by its radiative efficiency. Increases in abundance up to the present are derived from atmospheric observations. The radiative forcing due to ODSs increases smoothly from 1960 onward, peaks in 2010, and decreases very gradually in subsequent years. The response of radiative forcing to ODS emission reductions is a slow decline attributable to the high abundances of the two principal contributing gases, CFC-11 and CFC-12, and their long atmospheric lifetimes (50–100 years).

Increasing the benefits of the Montreal Protocol. The benefits of the Montreal Protocol for protection of the ozone layer and climate could be further increased by the expanded capture and destruction of halons, chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs) in banks, by avoiding emissions in continued use of ODSs, and by eliminating future emissions of halogen source gases not controlled by the Montreal Protocol, such as dichloromethane (CH_2Cl_2). Banks are largely associated with ODSs contained in refrigeration, air conditioning, and fire protection equipment, and stockpiles for servicing long-term applications. Atmospheric release of ODSs from existing banks is projected to contribute more to ozone depletion in the coming decades than the limited production and consumption of ODSs (HCFCs and CH_3Br) allowed by the Montreal Protocol after 2020. If all available options were implemented to avoid future atmospheric release of ODSs starting in 2020, the return of EESC to 1980 values would be advanced by about a decade for both the midlatitude (see Fig Q14-1) and polar stratosphere.

Notably, the annual decline in the atmospheric abundance of CFC-11 has slowed measurably during recent years compared to the expected decline, due to emissions from unreported production (see Q15). If these emissions of CFC-11 are assumed to continue in the coming decades at the value derived for the 2002-2016 period, the return of EESC to the 1980 value is delayed by about seven years for the midlatitude stratosphere relative to the projections for EESC shown in Figures Q14-1 and Q15-1. Similarly, the delay is about 20 years for the polar stratosphere.