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 global warming 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 global warming due to ODSs could now be nearly three times the present value. With the 2016 Kigali Amendment to the Montreal Protocol, climate protection was extended to include controls on HFCs, which do not deplete ozone but contribute to global warming (see Q19).

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 emissions and 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 long-term ***baseline*** and ***world-avoided*** scenarios of ODS emissions, Ozone Depletion Potentials (ODPs), Global Warming Potentials (GWPs), equivalent effective stratospheric chlorine (EESC), and the radiative forcing (RF) 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 2021 to 2025. The baseline scenario is labeled "from observed ODS abundances" in Figure Q18-1 since, for 1960–2020, 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). The ODP and GWP of a given gas quantify how effective the gas is at destroying ozone (ODP) or warming climate (GWP) for the emission of a certain mass of the gas, relative to the effect on ozone or warming of the emission of the same mass of CFC-11 (for ODP) or CO_2 (for GWP). In both cases, the reference gases (CFC-11 and CO_2) are assigned a value of 1, and the ODP and GWP for all other gases are scaled accordingly (see Table Q6-1 and Q17). For example, 1 kg of halon-1211 emissions is expressed as 7.1 kg of CFC-11-equivalent emissions because the ODP of halon-1211 is 7.1. 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. Likewise, 1 kg of carbon tetrachloride emissions is considered to be 2150 kg of CO_2-equivalent emissions because the GWP of carbon tetrachloride is 2150. GWP-100 values are shown here and throughout reflecting a choice of a time horizon of 100 years.

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, from 1987 onwards, emissions of ODSs increase at a rate of 3% per year. This growth rate is consistent with the strong market for ODSs in the late 1980s, which 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 Q18-1. 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, as well as 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). Since most ODSs remain in the atmosphere for years (see "Atmospheric lifetime" column in Table Q6-1), when ODP-weighted emissions rise this means there will be an increase in ozone destruction for many future years. Conversely, when emissions decline, less ozone will be destroyed in future years than if emissions had remained high. Annual ODP-weighted emissions increased substantially between 1960 and 1987, the year the Montreal Protocol was signed (see Figure 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

The Montreal Protocol Protection of Ozone and Climate from Global Emissions of Ozone-Depleting Substances (ODSs)

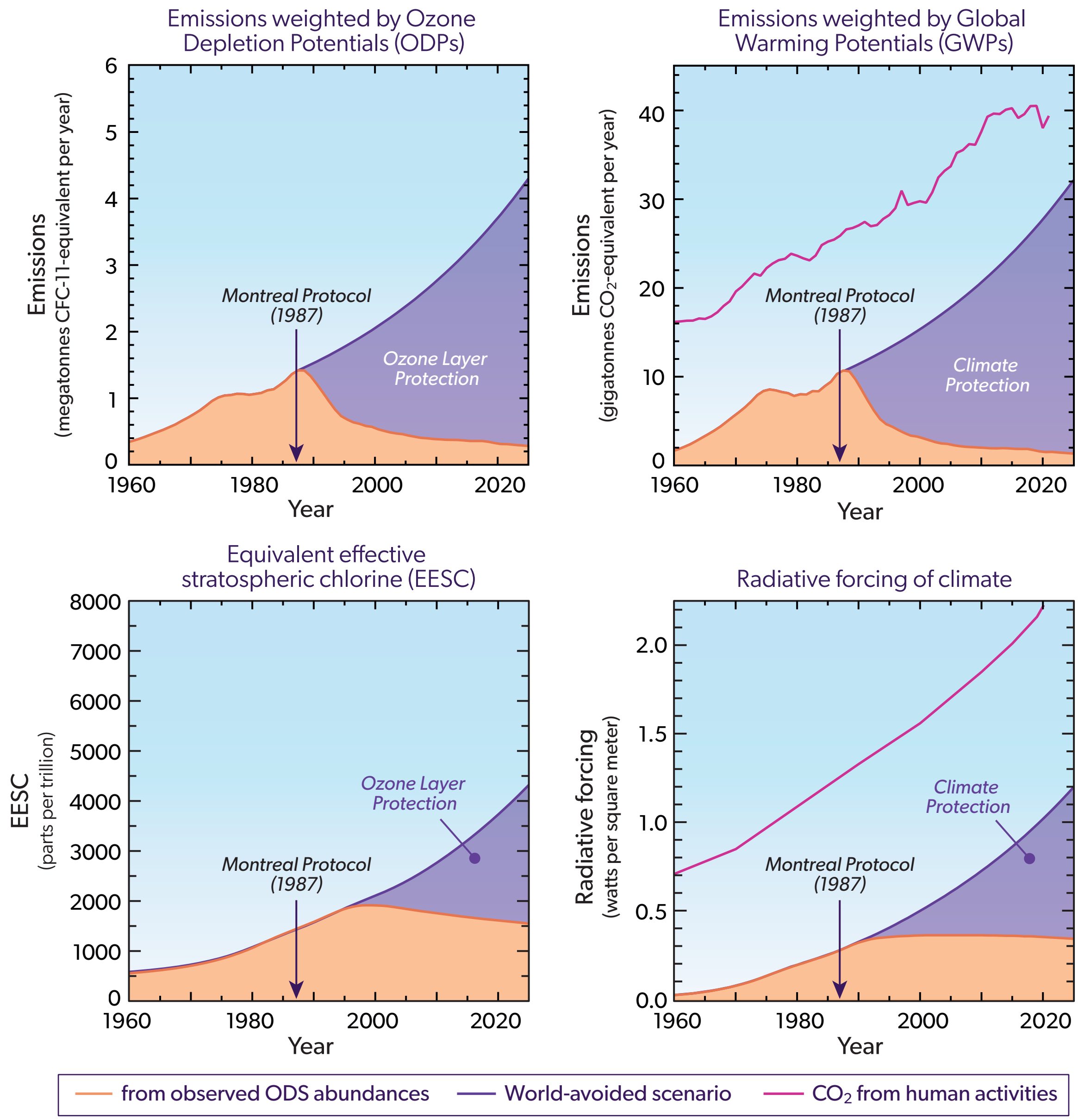

Figure Q18-1. Montreal Protocol protection of ozone and climate. The Montreal Protocol has protected the ozone layer and also reduced the potential for climate change, because ozone-depleting substances (ODSs) are greenhouse gases (GHGs). The baseline ODS scenario (orange line) includes actual emissions of all principal gases weighted either by their Ozone Depletion Potentials (ODPs) (upper left) or Global Warming Potentials (GWPs) (100-yr timeline) (upper right) coupled with projected emissions for years 2021 to 2025. 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 2021 to 2025. The world-avoided emission scenario (purple line) 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 (magenta line) are shown for reference on the right panels. The magnitude of the dual benefit of the Montreal Protocol has steadily increased since 1987, as shown by the differences between the world-avoided scenario and the observed ODS abundance scenario (purple 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. A CFC-11-equivalent emission of an ODS is an emission amount that results in the same ozone depletion as the release of the same mass of CFC-11; a CO_2-equivalent emission of a non-CO_2 GHG is an emission amount that results in the same RF of climate over a 100-year time interval as the release of the same mass of CO_2. Emissions of CO_2 used in this figure are from the Global Carbon Project.

reductions in ODP-weighted emissions relative to 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 baseline scenario (purple shaded region in Figure Q18-1, upper left panel) represents an estimate of the ozone layer protection provided by the Montreal Protocol.

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 RF 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. This similarity follows from the dominant role that both CFC-11 and CFC-12 play in ozone depletion and climate forcing from ODSs. The difference between the world-avoided emission scenario and the baseline scenario (purple shaded region in Figure Q18-1, upper right panel) represents an estimate of the climate protection provided by the Montreal Protocol.

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 2022. This past trend stands in sharp contrast to the world-avoided scenario, in which emissions of ODSs rise to more than 50% of CO_2 emissions in 2022. Another way to understand the climate benefit of the Montreal Protocol is to compare the height of the purple shaded region in 2022 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 time period.

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 uses observed abundances of ODSs (with a projection to 2025) 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 2022 the decrease in EESC from its peak value was only about 18%, compared to the 80% decrease in ODP-weighted emissions achieved by 2022. 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 show global total ozone values in 2020 are about 17% lower than the 1964–1980 average. Even larger depletions occur 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 (RF) scenarios. The RF of climate scenarios in Figure Q18-1 (lower right panel) provide a measure of the year- to-year contribution to climate change from the atmospheric abundances of ODSs. The RF of an ODS is equal to the net increase in its atmospheric abundance since 1750 multiplied by its radiative efficiency, which quantifies how effective a given ODS molecule is at retaining infrared radiation. The RF of ODSs up to the present is calculated using observed atmospheric abundances. The RF due to ODSs increases smoothly from 1960 onward, peaks in 2010, and decreases very gradually in subsequent years. The decline of RF of climate in response to ODS emission reductions is slow because of the high abundances of the two principal contributing gases, CFC-11 and CFC-12, and their long atmospheric lifetimes of about 50 and 100 years, respectively.

Increasing the benefits of the Montreal Protocol. The benefit of the Montreal Protocol for protection of climate was expanded in 2016 through the Kigali Amendment, which placed controls on the production and consumption of some hydrofluorocarbons (HFCs) (see Q19). HFC compounds do not contain chlorine or bromine, and therefore do not deplete ozone. Many HFC gases have a high radiative efficiency and a long atmosphere lifetime, which leads to significant global warming (see Figure Q19-2). The ozone layer and climate benefits of the Montreal Protocol could be further increased by expanded capture and destruction of halons, chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs) in banks, by avoiding emissions in continued use of ODSs as feedstock for the production of other chemicals, 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, fire protection equipment, insulating foams, 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 2023. If all available options were implemented to avoid future atmospheric release of ODSs starting in 2023, 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.