Q15 Has the Montreal Protocol been successful in reducing ozone-depleting substances in the atmosphere?

Yes, as a result of the Montreal Protocol, the overall abundance of ozone-depleting substances (ODSs) in the atmosphere has been decreasing for the past two decades. If the nations of the world continue to comply with the provisions of the Montreal Protocol, the decrease will continue throughout the 21st century. Those gases that are still increasing in the atmosphere, HCFC-22 (CHF_2Cl) and HCFC-141b (CH_3CCl_2F), will begin to decrease this decade if compliance with the Protocol continues. However, it is only after midcentury that the abundance of ODSs is expected to fall to values that were present before the Antarctic ozone hole was first observed in the early 1980s, due to the long atmospheric lifetime of these gases.

The Montreal Protocol and its amendments and adjustments have been very successful in reducing the atmospheric abundances of ozone-depleting substances (ODSs). ODSs are halogen source gases released by human activities whose production and consumption are now controlled by the Montreal Protocol (see Q14). The success of the Montreal Protocol controls is documented by (1) observed changes and future projections of the atmospheric abundances of the principal ODSs and (2) the long-term decrease in ***equivalent effective stratospheric chlorine*** (EESC).

Individual ODS reductions. The reduction in the atmospheric abundance of an ODS in response to controls on production and consumption depends principally on how rapidly this ODS is used and released to the atmosphere after being produced, as well as the atmospheric lifetime of the ODS (see Table Q6-1). For example, the abundances of ODSs with short lifetimes, such as methyl chloroform, respond quickly to emission reductions. In contrast, the abundances of ODSs with long lifetimes such as CFC-11 and CFC-12 respond slowly to emission reductions. Estimates of long-term changes in the atmospheric abundances of ODSs are based upon: (1) their measured abundances in air trapped for years within accumulated snow in polar regions, (2) observed atmospheric abundances using ground-based measurements, (3) projections of future abundances based on estimated future demand and compliance with Montreal Protocol provisions for the production and consumption of ODSs, and (4) emissions from ODS banks. The term ***bank*** refers to the total amounts of ODSs contained in existing equipment, chemical stockpiles, foams, and other products that have not yet been released to the atmosphere. The destruction of ODSs in banks prevents the eventual release of these compounds into the atmosphere. The long-term changes of the atmospheric abundances of individual ODSs and the natural chlorine and bromine source gases, methyl chloride (CH_3Cl) and methyl bromide (CH_3Br), assuming compliance with the Montreal Protocol, are shown in **Figure Q15-1**. Key aspects of families of ODSs shown in this figure are:

- **CFCs.** Chlorofluorocarbons (CFCs) include some of the most destructive chlorine-containing ODSs. CFC-11 and CFC-12, with large Ozone Depletion Potentials (ODPs) of 1 and 0.75, are the most abundant CFCs in the atmosphere owing to large historical emissions and long atmospheric lifetimes of about 50 and 100 years, respectively (see Table Q6-1). Under the Montreal Protocol, allowed production and consumption of CFCs ended in January 1996 for developed countries and in January 2010 for developing countries. As a consequence, the atmospheric abundances of CFC-11 and CFC-113 peaked in 1994 and 1996, respectively, and have been declining for more than two decades. In contrast, the abundance of CFC-12 peaked in 2002 and has been slowly decreasing, owing to its longer lifetime (about 100 years) and continuing emissions from CFC-12 banks, namely, refrigeration and air conditioning equipment and thermal insulating foams. With no further global production of the principal CFCs, except for the use of certain CFCs (mainly CFC-113 and CFC-114) as feedstocks and some limited exempted uses, along with some continuing emissions from banks, CFC abundances are projected to decline steadily throughout this century. From 2012 to 2018, the annual decline in CFC-11 slowed measurably compared to the expected decline, due to unreported production outside the provisions of the Montreal Protocol. In 2019 and 2020, global emissions of CFC-11 declined in a manner indicative of the elimination of most of these unreported emissions.
- **Halons.** Halons are currently the most important bromine-containing ODSs. Halon-1211 and halon-1301 account for a significant fraction of bromine from all ODSs (see Figure Q6-1). Under the Montreal Protocol, production and consumption of halons for controlled uses ended in January 1994 for developed countries and in January 2010 for developing countries, with some essential use exemptions for both developed and developing countries. Atmospheric abundances of halon-1211 show significant decreases since peak concentrations were measured in the mid-2000s. Halon-2402 abundances have been decreasing slowly for the past two decades while those of halon-1301 have nearly peaked and are expected to decline in coming decades. The slow decline in the emission of halon-1301 is likely due to substantial banks in fire-extinguishing

Past and Projected Atmospheric Abundances of Halogen Source Gases

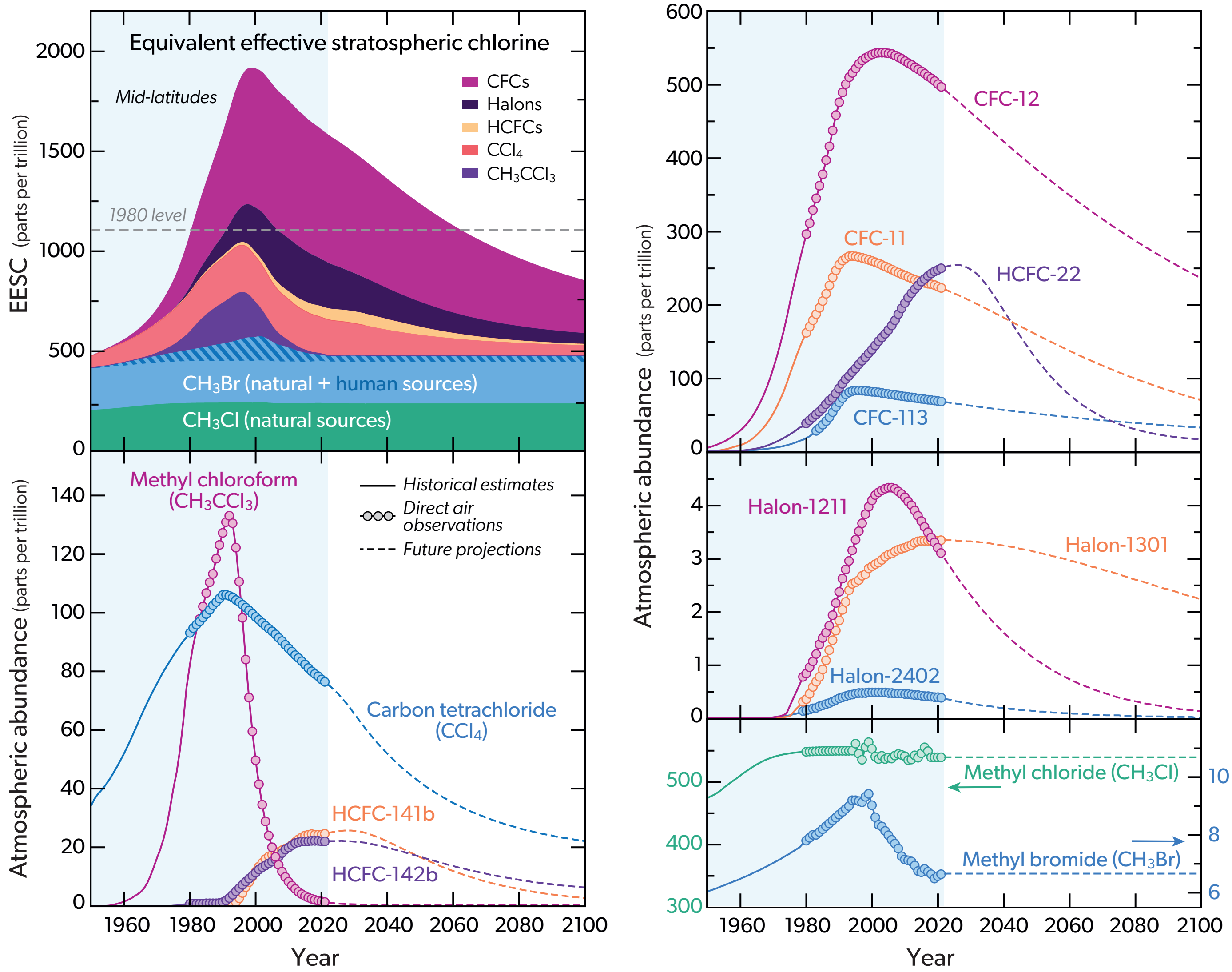

Figure Q15-1. Halogen source gas changes and contributions to EESC. The surface abundances of individual gases shown here were obtained using a combination of direct atmospheric measurements, estimates of historical abundances, and future projections of abundances assuming compliance with the Montreal Protocol. The gases are all ODSs except for methyl chloride, which is primarily emitted from natural processes. Therefore methyl chloride is not controlled by the Montreal Protocol and its abundance is projected to be constant in the future. The past increases of the principal CFCs shown in the figure, along with those of carbon tetrachloride, methyl chloroform, halon-1211, and halon-2402, have slowed and reversed in the last three decades. The abundances of most HCFCs, which are used as transitional substances to replace CFCs, will likely peak during this decade before production and consumption are completely phased out. The abundance of halon-1301 has nearly peaked and is expected to slowly decline in coming decades because of continued small releases and a long atmospheric lifetime. Future decreases in methyl bromide are expected to be modest, since most of the current source is from natural processes and the industrial production of methyl bromide is now much smaller than occurred in the 1990s. Values of EESC shown in the upper left panel are for the midlatitude lower stratosphere (about 19 km altitude), based on observations and projections (see Q14-1). The colored shaded regions depict contributions to EESC from CH_3Cl, CH_3Br, CH_3CCl_3, CCl_4, HCFCs, halons, and CFCs and the top of the magenta shaded region is the sum of all contributions, or EESC. The value of EESC rose rapidly during the latter half of the prior century, peaking in the late 1990s. Since the late 1990s, the trend in EESC has reversed due to the effectiveness of the Montreal Protocol in reducing the production and consumption of ODSs. In the midlatitude stratosphere EESC is projected to return to its 1980 value around 2066. In polar regions EESC is projected to return to 1980 values about two decades later. International compliance with the provisions of the Montreal Protocol is required to ensure that EESC will continue to decrease as projected (see Q14). Over 2012 to 2018, the decline in CFC-11 slowed measurably compared to the expected decline, due to unreported production. In 2019 and 2020, CFC-11 declined in a manner indicative of the elimination of most of this unreported production. The contributions from very short-lived gases (see Figure Q6-1) are not included in this EESC time series.

(The unit "parts per trillion" is defined in the caption of Figure Q6-1.)

and other equipment that gradually release this compound to the atmosphere years after production. The abundance of halon-1301 is expected to remain high well into the 21st century because of its long lifetime (72 years) and continued release. Atmospheric emissions of halons continue to occur due to the use of halon-containing equipment in various fire-fighting applications.

- **Carbon tetrachloride.** Production and consumption of carbon tetrachloride (CCl_4) for controlled uses in developed countries was phased out in 1996 and that in developing countries in 2010, with some essential use exemptions. As a result, atmospheric abundances of carbon tetrachloride have been decreasing for two decades. The decline is considerably less rapid than expected, suggesting that actual emissions are larger than the emissions derived from the reported consumption. Carbon tetrachloride that is used as raw material (feedstock) to make other chemicals is exempted when calculating the controlled levels of production and consumption under the Montreal Protocol, and some residual emissions do occur. Current understanding of global sources suggests emissions of carbon tetrachloride are presently dominated by inadvertent production and subsequent release during the chemical manufacturing processes of other compounds, as well as release from landfills and contaminated soils.
- **Methyl chloroform.** The largest reduction to date in the abundance of an ODS (99% from its peak value) has been observed for methyl chloroform (CH_3CCl_3). Production and consumption of methyl chloroform in developed countries ended in January 1996 and that in developing countries ended in January 2015, with limited essential use exemptions. Atmospheric abundances responded rapidly to the reduced emissions starting in the mid-1990s because methyl chloroform has a short atmospheric lifetime of about 5 years. Methyl chloroform was used mainly as a solvent and had typically been emitted soon after production. This compound is now approaching complete removal from the atmosphere due to the success of the Montreal Protocol.
- **HCFC substitute gases.** The Montreal Protocol allows for the use of hydrochlorofluorocarbons (HCFCs) as short-term, transitional substitutes for CFCs and in other specific applications. As a result, the atmospheric abundances of HCFC-22, HCFC-141b, and HCFC-142b continue to grow in response to continued production, mainly in the developing world. HCFCs pose a lesser threat to the ozone layer than CFCs, because HCFCs have lower ODP values (less than about 0.1; see Table Q6-1). The 2007 Montreal Adjustment to the Protocol accelerated the phaseout of HCFCs by a decade for both developed countries (2020) and developing countries (2030) (see Q14). Future projections indicate that the principal HCFCs will all reach peak values between 2023 and 2030, and steadily decrease thereafter. The response of atmospheric abundances to decreasing emissions (due to gradual releases from existing banks such as insulating foams) will be relatively rapid because of the short atmospheric lifetimes of HCFCs (less than 17 years).
- **Methyl chloride and methyl bromide.** Both methyl chloride (CH_3Cl) and methyl bromide (CH_3Br) are distinct among halogen source gases because substantial fractions of their emissions are associated with natural processes (see Q6). Methyl chloride is not controlled under the Montreal Protocol. The abundance of CH_3Cl in the atmosphere has remained fairly constant throughout the last 40 years (see Figure Q15-1). Current sources of methyl chloride from human activities are thought to be small relative to its natural source, and to be dominated by the combustion of coal and chemical manufacturing.

  In contrast, methyl bromide is controlled under the Montreal Protocol. Methyl bromide was primarily used as a fumigant. Nearly all developed country production and consumption of methyl bromide ended in January 2005 and that in developing countries ended in January 2015. The Protocol currently provides limited exemptions for methyl bromide production and use as a fumigant in agriculture as well as for quarantine and pre-shipment applications. Atmospheric abundances of methyl bromide declined rapidly in response to the reduced emissions starting in 1999, because its atmospheric lifetime is less than 1 year (see Figure Q15-1). Future projections show only small changes in methyl bromide abundances based on the assumptions of unchanged contributions from natural sources and small continued critical use exemptions. An important uncertainty in these projections is the future amount that will be produced and emitted under Montreal Protocol critical use, quarantine, and pre-shipment exemptions.

Equivalent effective stratospheric chlorine (EESC). Important measures of the success of the Montreal Protocol are the past and projected changes in the values of equivalent effective stratospheric chlorine, which was introduced in Figures Q13-1 and Q14-1. EESC is one measure of the potential for ozone depletion in the stratosphere that can be calculated from atmospheric surface abundances of ODSs and natural chlorine and bromine gases. The calculation considers CFCs, HCFCs, methyl chloroform, carbon tetrachloride, halons, as well as methyl chloride and methyl bromide. For both past and future EESC values, the required atmospheric abundances are derived from measurements, historical estimates, or future projections based on compliance with the provisions of the Montreal Protocol.

EESC is derived from the amount of chlorine and bromine available in the stratosphere to deplete ozone. The term equivalent indicates that bromine gases, scaled by their greater per-atom effectiveness in depleting ozone, are included in EESC. Although chlorine is much more abundant in the stratosphere than bromine (about 150-fold) (see Figure Q6-1), bromine atoms are about 60 times more efficient than chlorine atoms in chemically destroying ozone in the lower stratosphere. The term effective indicates that only the estimated fractions of ODSs that have been converted to reactive and reservoir halogen gases, for a particular region of the stratosphere at a specified time, are included in the computed value of EESC value (see Q5 and Q7). Long-term changes of EESC generally depend on the altitude and latitude region in the stratosphere under consideration. The EESC curve shown in Figure Q15-1 is for the midlatitude, lower stratosphere (about 19 km altitude).

Long-term changes in EESC. In the latter half of the 20th century up until the 1990s, EESC values steadily increased (see Figure Q15-1), causing global ozone depletion. As a result of the Montreal Protocol regulations, the long-term increase in EESC slowed, values reached a peak in 1999, and EESC then began to decrease. By 2022, EESC at midlatitudes had declined by about 18% from the peak value. The initial decrease came primarily from the substantial, rapid reductions in the atmospheric abundance of methyl chloroform, which has a lifetime of only 5 years. The decrease is continuing with declining abundances of CFCs, carbon tetrachloride, and halon-1211. Decreases depend on natural processes that gradually decompose and remove halogen-containing gases from the global atmosphere (see Q5). Reduction of EESC to 1980 values or lower will require four more decades because the most abundant ODS gases now in the atmosphere have lifetimes ranging from 10 to 100 years (see Table Q6-1).