Q19 How has the protection of climate by the Montreal Protocol expanded beyond the regulation of ozone-depleting substances?

At the 28th Meeting of the Parties to the Montreal Protocol held in Kigali, Rwanda, in October 2016, the Montreal Protocol was amended to control the production and consumption of hydrofluorocarbons (HFCs). The Montreal Protocol phaseout of chlorofluorocarbons (CFCs) led to the temporary use of hydrochlorofluorocarbons (HCFCs). The subsequent phaseout of HCFCs led to expanded long-term use of HFCs, because HFCs pose no direct threat to the ozone layer. However, HFCs are greenhouse gases and therefore contribute to climate change. Limiting the production and consumption of those HFCs with high global warming potentials is projected to avoid 0.3 to 0.5°C of global warming over this century. The Kigali Amendment marks the first time the Montreal Protocol has adopted regulations solely for the protection of climate.

The control of ozone-depleting substances (ODSs) by the Montreal Protocol provides the dual benefit of protecting Earth's ozone layer and global climate (see Q18). The widespread global use of hydrofluorocarbons (HFCs) and their projected future growth in the coming decades has been recognized by the Montreal Protocol as a potentially significant contribution to climate change from human activities. In response, the Kigali Amendment was adopted to control production and consumption of HFCs with high Global Warming Potentials (GWPs) (see Q17). Full compliance with the provisions of the Kigali Amendment will significantly enhance the climate-protection benefit of the Montreal Protocol.

Hydrofluorocarbons (HFCs). HFCs are replacement compounds for ODSs that were chosen because they contain no chlorine or bromine that cause ozone depletion. HFCs are widely used in the residential air-conditioning and refrigeration sectors and as foam-blowing agents, spray-can propellants, and feedstocks for the production of other chemicals. These uses are growing as the global phaseout of hydrochlorofluorocarbons (HCFCs), the early replacement compounds, nears completion. The GWPs of HFCs vary over a wide range due to differences in their physical and radiative properties (see Table Q6-1 and Figure Q17-3). For example, the GWP of HFC-134a (primarily used in air conditioning and refrigeration) is 1470, which means that after release to the atmosphere, each kilogram of HFC-134a is 1470 times more effective than a kilogram of CO_2 in increasing climate forcing over a century-long time period. In contrast, the GWP of HFO-1234yf, a substitute for HFC-134a, is less than 1.

HFC-23. HFC-23 is considered separately in the Kigali Amendment because this gas is primarily produced as an unwanted by-product in the manufacture of HCFC-22 and HFCs. The global warming potential of HFC-23 is quite large (14,700), in part due to its long atmospheric lifetime of 228 years. Although many methods exist to chemically destroy HFC-23 at production facilities, this compound continues to be released to the atmosphere. For example, the atmospheric abundance of HFC-23 increased by 44% between 2009 and 2019. In 2019, the radiative forcing of HFC-23 was 0.006 W/m^2, which is approximately 15% of the total forcing from all HFCs. The Kigali Amendment phases down, in conjunction with the other HFCs, unwanted by-production of HFC-23, but provides no specific control measures for emissions of HFC-23. Instead, the amendment directs nations to destroy HFC-23 to the extent practicable in order to avoid future emissions and the associated increased climate forcing.

Climate implications of HFC use. The total global emission of HFCs expressed in terms of CO_2-equivalent emissions has grown steadily since 2000, equaling about 1 gigatonne CO_2-equivalent per year in 2020 (see **Figure Q19-1**). The primary emissions of HFCs are of HFC-134a as well as HFC-143a, HFC-125 and HFC-32, which are widely used in blended refrigerants such as R404A (52% HFC-143a, 44% HFC-125, and 4% HFC-134a) and R410A (50% HFC-32, 50% HFC-125). Recent growth in the consumption (and emissions) of HFCs is due in part to replacing HCFCs that are being phased out under the Montreal Protocol with HFCs. In 2019, the atmospheric abundances of HFCs contributed about 10% of climate forcing from all halocarbon compounds (see Figure Q17-2) and less than 1% of the total climate forcing from all other long-lived greenhouse gases (see Figure Q17-1). Projections based on current production and consumption patterns and future economic growth indicate that, without the Kigali Amendment, HFC emissions could have reached around 5 gigatonnes CO_2-equivalent per year by 2050 and nearly double that value by 2100 (see Figure Q19-1). This projected emission value for 2050 is about one half of the peak in CO_2-equivalent emissions of ODSs in 1987 (see Figure Q18-1). Thus, in the absence of the Kigali Amendment, the projected growth in HFC emissions in the coming decades offsets a significant amount of the climate protection gained from reductions in ODS emissions under the Montreal Protocol.

Kigali Amendment. The future of HFC emissions was changed by the Montreal Protocol with the adoption of the Kigali Amendment in 2016. The amendment requires a phasedown of the global pro-

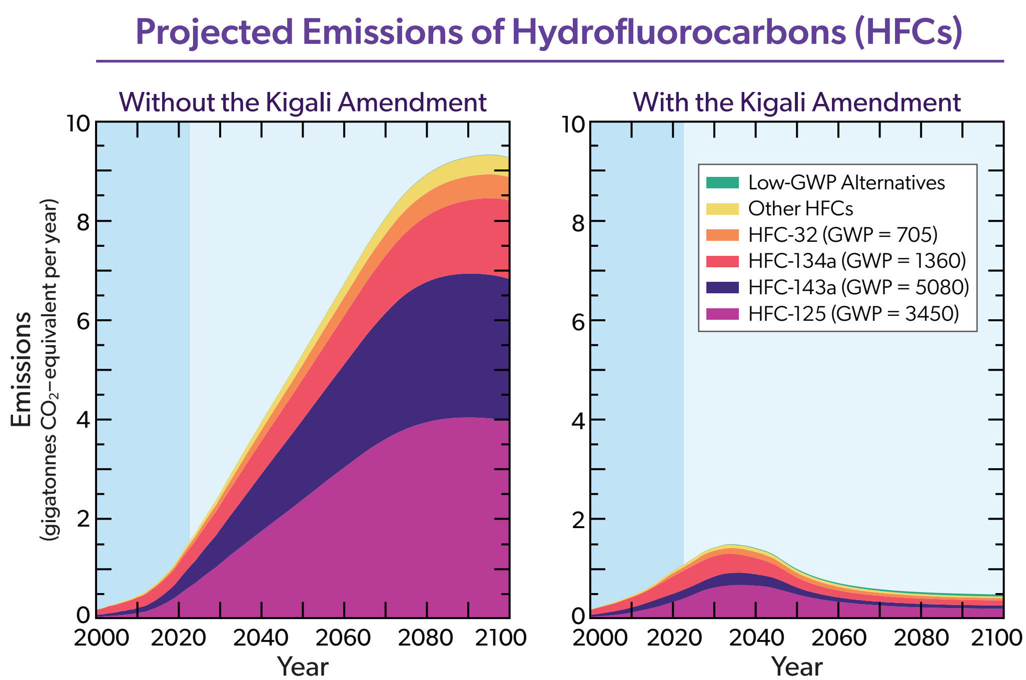

Figure Q19-1. HFC emissions and the Kigali Amendment. The Kigali Amendment to the Montreal Protocol limits the production and consumption of a group of hydrofluorocarbons (HFCs) with high global warming potentials (GWPs). HFCs are considered replacement compounds for ozone-depleting substances (ODSs) because HFCs lack chlorine and bromine, and therefore pose no direct threat to the ozone layer. Avoiding substantial emissions of high-GWP HFCs through the implementation of the Kigali Amendment will increase future climate protection. HFCs have a wide range of GWPs given their different physical and chemical properties (see Table Q6-1 and Figure Q17-3). The panels show emissions of widely used high-GWP HFCs. The emissions are weighted by the 100-yr GWP of each compound; with this weighting, emissions are expressed as CO_2-equivalent mass per year. In the left panel, emissions are based upon an analysis of atmospheric observations up to 2013 and projections to 2100 that represent an upper range to future global emissions in the absence of the Kigali Amendment and national regulations. The right panel shows GWP-weighted emissions based on atmospheric observations up to 2020 as well as projections to 2100, again assuming international compliance with the provisions of the Kigali Amendment. The projections in the right panel include a category termed low-GWP alternatives that is comprised of refrigerant compounds that have GWPs much lower than the refrigerants they replace. Low-GWP alternatives include a subset of HFCs known as hydrofluoroolefins (HFOs), which are also composed only of hydrogen, fluorine and carbon atoms. The chemical structure of HFOs results in these compounds being more reactive in the lower atmosphere (troposphere) than other HFCs and, consequently, HFOs have shorter lifetimes after atmospheric release (see Table Q6-1). As a result, emissions of HFOs cause substantially lower radiative forcing than emissions of the same mass of high-GWP HFCs.

(A gigatonne = 1 billion (10^9) metric tons = 1 trillion (10^{12}) kilograms. 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 a release of the same mass of CO_2.)

duction and consumption of high-GWP HFCs by more than 80% (in CO_2-equivalent) from the baseline level over the next 30 years. The phasedown schedule accommodates the concerns and interests of developed and developing countries, including those with high ambient temperatures that are likely going to have future increased demand for the use of air-conditioners. The Kigali Amendment entered into force on 1 January 2019. Figure Q19-1 shows how the amendment provisions dramatically reduce projected emissions of HFCs in the coming decades. The emissions of HFCs that are avoided by 2100 total about 420 gigatonnes CO_2-equivalent, which is more than 10 years of present-day annual emissions of CO_2 due to human activities.

Expanding climate protection. The Kigali Amendment substantially expands the protection of climate afforded by the Montreal Protocol (see Q18). With full implementation of the amendment, annual global emissions of HFCs reach their peak value before 2040 (see Figure Q19-1). Without the amendment, yearly emissions are projected to increase until market saturation is reached in the second half of the century, at a value of about 10 gigatonnes CO_2-equivalent per year, nearly five times more than the emission peak under the amendment. Furthermore, as shown in **Figure Q19-2**, the long-term radiative forcing of climate, which is proportional to atmospheric abundances, is substantially reduced. Without the amendment, projected radiative forcing from HFCs increases throughout this century, reaching a value of about 0.6 W/m^2 in 2100. In this scenario, radiative forcing due to HFCs by the end of the century exceeds that of nitrous oxide and rivals that of methane. With the amendment, the radiative forcing of climate by HFCs reaches a peak value before 2050 and gradually decreases to about 0.07 W/m^2 in 2100. The ranges of radiative forcing values for meth-

Climate Benefit of the Kigali Amendment

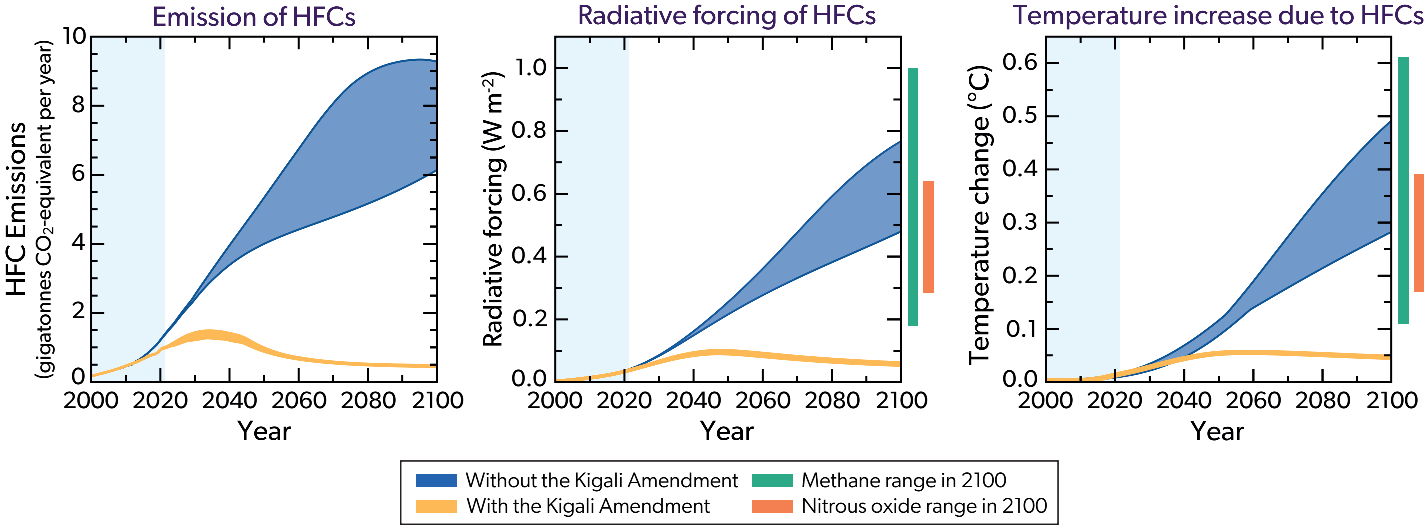

Figure Q19-2. Kigali Amendment Climate Protection. The successful implementation of the Kigali Amendment will enhance the protection to Earth's climate afforded by the Montreal Protocol. The panels display the CO_2-equivalent emissions (left), radiative forcing (middle) and surface temperatures (right) for HFC emission scenarios without (blue shaded regions) and with (gold lines) the implementation of the Kigali Amendment and national regulations. Historical emissions of HFCs are derived from atmospheric observations. Emissions for latter years are based upon projections of production and consumption patterns as well as future economic growth. All emissions are weighted by the 100-yr GWP of each compound (CO_2-equivalent emissions). Emissions of HFC-23 are excluded. The emission projections without the Kigali Amendment and national regulations are based on lower and upper ranges of projected HFC consumption. The increases in global mean surface temperature from HFC emissions are shown beginning in year 2000. For comparison, the radiative forcing and surface temperature increases are shown for methane (CH_4) and nitrous oxide (N_2O) in the middle and right panel margins, respectively, for year 2100 based on accumulated emissions since 1750. Compliance with the Kigali Amendment has the potential to avoid a 0.3 to 0.5°C rise in global surface temperature over this century due to restrictions on the future emission of high-GWP HFCs.

(A gigatonne = 1 billion (10^9) metric tons = 1 trillion (10^{12}) kilograms. The end of century values for CH_4 and N_2O are based upon the Shared Socioeconomic Pathway (SSP) SSP1-2.6 (lower limit) and SSP3-7.0 (upper limit) scenarios.)

ane and nitrous oxide in 2100 as shown in Figure Q19-2 far exceed the 0.07 W/m^2 forcing due to HFCs under the Kigali Amendment.

The benefit of avoiding HFC radiative forcing over many decades as a result of the Kigali Amendment provisions can be expressed as an avoided increase in globally averaged surface temperature. The increase in temperature by the year 2100 due to future atmospheric growth of HFCs without the Kigali Amendment and national regulations is projected to be between 0.3 and 0.5°C (see Figure Q19-2). In contrast, the temperature increase is projected to be about 0.06°C with full implementation of the amendment, which is significantly less, for example, than the warming expected from projected abundances of methane and nitrous oxide in 2100. Currently, global warming due to all emissions from human activities is about 1.2°C since 1750, the start of the Industrial Era. The goal of the United Nations Framework Convention on Climate Change Paris Agreement is to limit global warming to well below 2.0°C since the start of the Industrial Era and to pursue efforts to limit global warming to 1.5°C. The temperature increase of 0.3 to 0.5°C avoided by the Kigali Amendment contributes substantially to the achievability of this goal.

Low-GWP substances. The Kigali Amendment encourages the use of low-GWP substances or other alternatives to replace high-GWP HFCs in the coming decades (see Table Q6-1 and Figure Q17-3). Other alternatives include propane, ammonia, and other climate-friendly technologies. The low-GWP substances include a subset of HFCs known as hydrofluoroolefins (HFOs), which are also composed only of hydrogen, fluorine and carbon atoms. The chemical structure of HFOs includes a double carbon bond, causing these compounds to be more reactive in the lower atmosphere (troposphere) than other HFCs. Consequently, HFOs have very short atmospheric lifetimes. One such compound, HFO-1234yf, has a lifetime of only 12 days, in contrast to HFC-23, HFC-143a, and HFC-134a with lifetimes of 228, 52, and 14 years, respectively (see Table Q6-1). The short atmospheric lifetimes of HFOs lead to very low GWPs. As a result, the emission of an HFO results in substantially lower climate forcing than the forcing caused by emission of the same mass of high-GWP HFCs (see Figure Q19-1).

The projections of emissions under the Kigali Amendment include a group of compounds labeled Low-GWP Alternatives in Figure Q19-1. These compounds are expected to cover the application demand from sectors in which the use of high-GWP HFCs is phased down. Even with the emissions of a large mass of these low-GWP alternatives, the future projected contribution to climate change is much less than contributions from projected emissions of high-GWP HFCs in the absence of the Kigali Amendment.

Other environmental consequences of HFC use. The atmospheric abundance of trifluoroacetic acid (TFA, chemical formula $C_2HF_3O_2$) is expected to increase in the coming decades due to future emissions of HFCs (including HFOs), HCFCs, and related compounds. When these compounds breakdown in the atmosphere, they produce TFA, a persistent, long-lived chemical with potentially harmful effects on animals, plants, and humans. The current concentration of TFA in rainwater and ocean water is generally very far below toxicity limits. Potential future environmental impacts of TFA are a subject of active research.

The Future. The phasedown of HFCs under the Kigali Amendment sets a path in which HFCs play a very limited role in future climate forcing. Achieving the maximum climate protection from the implementation of the amendment requires that compounds replacing high-GWP HFCs have much smaller or negligible GWPs. Technological developments related to low-GWP replacement substances or other alternatives along with improved refrigeration and air conditioning equipment will help achieve this maximum protection. The release of greenhouse gases in generating electricity for powering refrigeration and air conditioning equipment contributes to the indirect climate forcing from this sector. Improvements in the energy efficiency of equipment in this sector during the transition to low-GWP alternative refrigerants could potentially double the direct climate benefits of the Kigali Amendment. The combination of low-GWP replacement compounds, energy efficiency improvements, and the growth in renewable energy sources has great potential to minimize the direct and indirect contributions to climate forcing from global refrigeration and air conditioning applications.