Q17 Is depletion of the ozone layer the principal cause of global climate change?

No, ozone depletion is not the principal cause of global climate change. Ozone depletion and global climate change are linked because both ozone-depleting substances and their substitutes are greenhouse gases. Ozone is also a greenhouse gas, so stratospheric ozone depletion leads to surface cooling. Conversely, increases in tropospheric ozone and other greenhouse gases lead to surface warming. The cooling from ozone depletion is small compared to the warming from the greenhouse gases responsible for observed global climate change. The Antarctic ozone hole has contributed to changes in Southern Hemisphere surface climate through effects on the atmospheric circulation.

While stratospheric ozone depletion is not the principal cause of climate change, aspects of ozone depletion and climate change are closely linked. Both processes involve gases released to the atmosphere by human activities. The links are best understood by examining the contribution to climate change of the gases involved: ozone; ozone-depleting substances (or halogen source gases) and their substitutes; and other leading greenhouse gases.

Greenhouse gases and the radiative forcing of climate. The warming of Earth by the Sun is enhanced by the presence of greenhouse gases (GHGs). The natural abundances of GHGs in Earth's atmosphere absorb outgoing infrared radiation, trapping heat in the atmosphere and warming the surface. The most important natural GHG is water vapor. Without this natural greenhouse effect, Earth's surface would be much colder than current conditions. Human activities have led to significant increases in the atmospheric abundances of a number of long-lived and short-lived GHGs since 1750, the start of the Industrial Era, leading to warming of Earth's surface and associated climate changes. This group includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone, and halocarbons. Ozone-depleting substances (ODSs) and their substitutes make up a large fraction of the halocarbons in today's atmosphere. Increases in the abundances of these gases from human activities cause more outgoing infrared radiation to be absorbed and reemitted back to the surface, further warming the atmosphere and surface. This change in Earth's energy balance caused by human activities is called a *radiative forcing of climate* or, more simply, a climate forcing. The magnitude of this energy imbalance is usually evaluated at the top of the troposphere (tropopause) and is expressed using units of watts per square meter (W/m^2). The potential for climate change rises as this radiative forcing increases.

A summary of radiative forcings of climate in 2011 resulting from the increases in the principal long-lived and short-lived GHGs from human activities since 1750 is shown in **Figure Q17-1**. Positive forcings generally lead to *warming* and negative forcings lead to *cooling* of Earth's surface. Climate forcings also lead to other changes, for example reductions in glacier and sea-ice extent, variations in precipitation patterns, and more extreme weather events. International climate assessments conclude that much of the observed surface warming and changes in other climate parameters over the last several decades are due to increases in the atmospheric abundances of CO_2 and other GHGs, which result from a variety of human activities.

Carbon dioxide, methane, and nitrous oxide. All three of these GHGs have both human and natural sources. The accumulation of CO_2 since 1750 represents the largest climate forcing caused by human activities. Carbon dioxide concentrations continue to increase in the atmosphere primarily as the result of burning fossil fuels (coal, oil, and natural gas) for energy and transportation, as well as from cement manufacturing. The global mean atmospheric abundance of CO_2 now exceeds 400 parts per million (ppm), which is more than 40% larger than the abundance of CO_2 present in 1750. Carbon dioxide is considered a *long-lived* gas, since a significant fraction remains in the atmosphere 100–1000 years after emission.

Methane is a *short-lived* climate gas (atmospheric lifetime of about 12 years). Sources related to human activities include livestock, fossil fuel extraction and use, rice agriculture, and landfills. Natural sources include wetlands, termites, and oceans. The global mean atmospheric abundance of CH_4 has more than doubled since 1750.

Nitrous oxide is a *long-lived* climate gas (atmospheric lifetime of about 120 years). The largest source related to human activities is agriculture, especially the use of fertilizer. Microbial processes in soils that are part of natural biogeochemical cycles represent the largest natural source. In the stratosphere, nitrous oxide is the principal source of reactive nitrogen species that participate in ozone destruction cycles (see Q8). The global mean

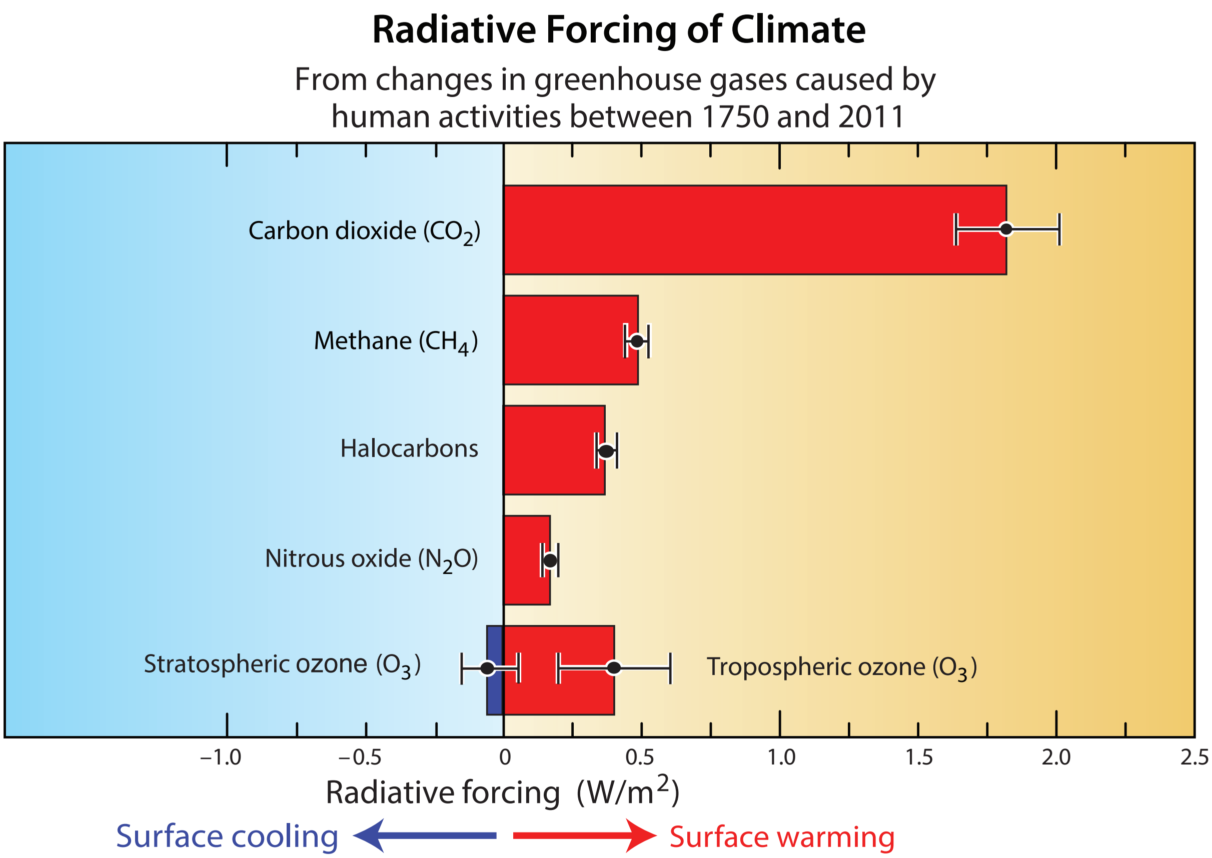

Figure Q17-1. Radiative forcing of greenhouse gases and ozone depletion. Human activities since the start of the Industrial Era (around 1750) have caused increases in the atmospheric abundance of greenhouse gases (GHGs). Rising levels of GHGs lead to an increase in the radiative forcing of climate (RF) by trapping infrared radiation released by Earth's surface. Here, values of RF are for the time period from 1750 to 2011 and are expressed in units of watts per square meter (W/m^2); black whiskers on each bar show uncertainties. Positive values of RF (shown in red) contribute to climate warming and negative values (shown in blue) contribute to climate cooling. The largest positive RFs are due to carbon dioxide (CO_2), methane (CH_4), tropospheric ozone (O_3), halocarbons, and nitrous oxide (N_2O). Halocarbons include all ozone-depleting substances, hydrofluorocarbons, and a few other gases (see Figure Q17-2). The RF due to ozone is shown as the separate response to changes in ozone within two layers of the atmosphere: the troposphere and stratosphere. Tropospheric ozone increases result from the emission of air pollutants and lead to surface warming whereas stratospheric ozone depletion results in a small forcing that most likely cools the surface.

atmospheric abundance of nitrous oxide has increased by about 20% since 1750.

Halocarbons. Halocarbons in the atmosphere contribute to both ozone depletion and climate change. The halocarbons considered in Figures Q17-1 and Q17-2 are gases containing chlorine, bromine, or fluorine atoms that are either controlled under the Montreal Protocol or are GHGs that fall under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC). Historically, ODSs were the only halocarbons controlled under the Montreal Protocol. In 2016, the Kigali Amendment to the Montreal Protocol established controls on the future production and consumption of certain hydrofluorocarbon (HFC) substitute gases. Perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) are in the UNFCCC group of GHGs that now fall under the Paris Agreement. Perfluorocarbons are compounds that contain only carbon and fluorine atoms, such as carbon tetrafluoride (CF_4) and perfluoroethane (C_2F_6). Technically, SF_6 is not a halocarbon since it lacks carbon. However, the environmental effects of SF_6 are commonly examined with those of halocarbon gases since all of these compounds contain at least one halogen atom.

In 2011, the halocarbon contribution to the radiative forcing of climate was 0.36 W/m^2, which is the fourth largest GHG forcing following carbon dioxide, methane, and tropospheric ozone (see Figure Q17-1). The contributions of individual halocarbon gases are highlighted in **Figure Q17-2**. Within the halocarbons, CFCs contribute the largest percentage (71%) to 2011 climate forcing. The intermediate-term ODS substitutes,

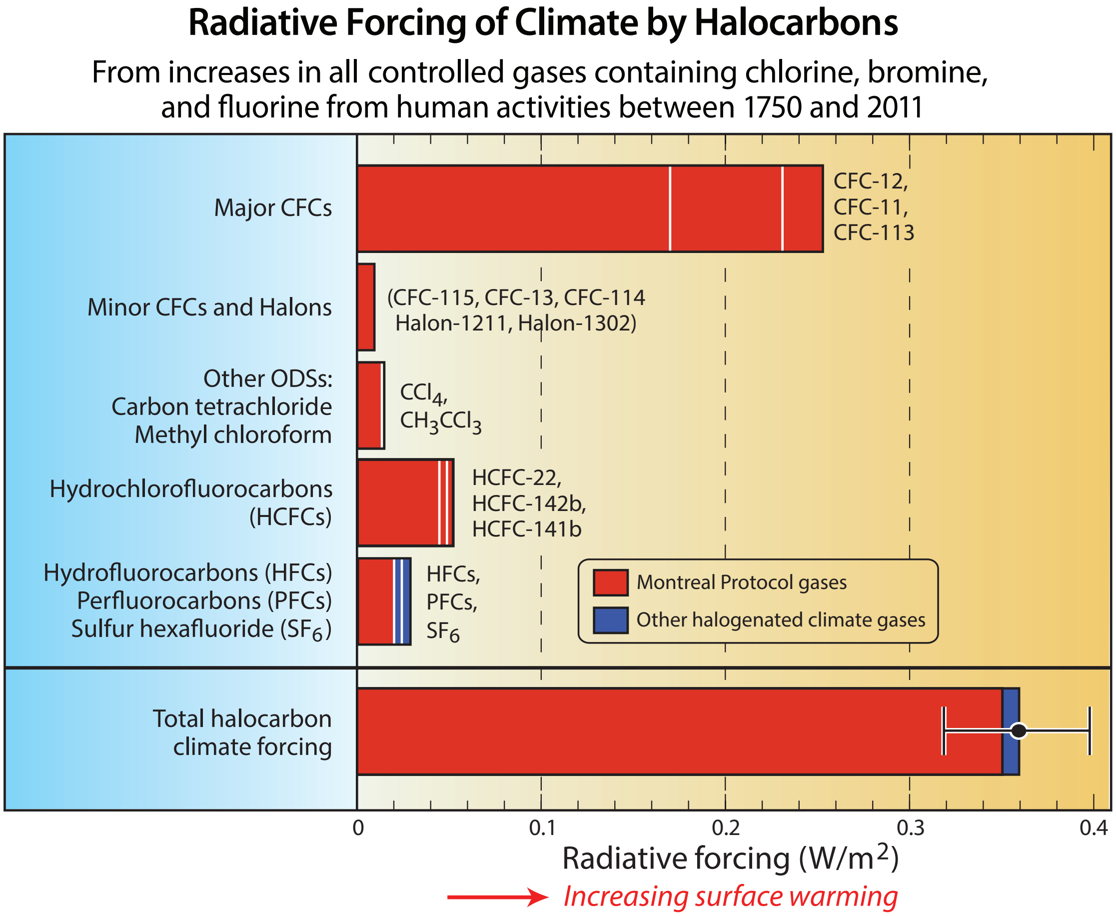

Figure Q17-2. Halocarbons and radiative forcing of climate. Halocarbon gases in the atmosphere represent an important contribution to the radiative forcing (RF) of climate since the start of the Industrial Era (see Figure Q17-1). Halocarbons are gases containing chlorine, bromine, or fluorine atoms, with at least one carbon atom, that contribute to RF by trapping infrared radiation released by Earth's surface. The rise in RF between 1750 and 2011 is shown for all halocarbons controlled either under the Montreal Protocol (red) or included in the Paris Agreement (blue) along with the RF due to the rise in SF_6. Note that while SF_6 is technically not a halocarbon because it lacks any carbon atoms, it is an important halogen-containing gas in the atmosphere. Separate contributions to RF of each gas or group of gases are indicated as estimated using atmospheric abundance histories and the radiative efficiency specific to each compound. The gases listed in the right-hand labels begin with the largest contribution in each group and proceed in descending order, except for the entry for minor CFCs and halons, which are shown as one total value. The individual RF terms add together to form the bottom bar, representing the total RF due to halocarbons and SF_6. The RFs of CFC-11 and CFC-12, the largest halocarbon contributors, are decreasing and will continue to decline as CFCs are gradually removed from the atmosphere (see Figure Q15-1). In contrast, the total RF of HCFCs, the intermediate-term ODS substitute gases, is projected to grow for about another one to two decades before decreasing. HFCs are the long-term ODS substitute gases. With the October 2016 Kigali Amendment, the Montreal Protocol now controls future production and consumption of important HFCs. As a result, nearly all of the RF due to halogen-containing GHGs is now controlled by the Montreal Protocol (bottom bar). The future RF of climate due to HFCs is expected to peak in about two decades under the provisions of the Kigali Amendment (see Q19).

hydrochlorofluorocarbons (HCFCs), make the next largest contribution (14%). The long-term ODS substitutes, HFCs, contribute 5% and, finally, PFCs and SF_6 contribute another 3%.

The large contribution of the CFCs has been gradually decreasing following the decline in their atmospheric abundance and is expected to further decrease (see Figure Q15-1). Based on their long lifetimes, CFCs will still make a significant contribution, and most likely the largest contribution from ODSs, to halocarbon climate forcing at the end of this century. Even with adherence to the provisions of the Kigali Amendment to the Montreal Protocol, the radiative forcing from HFCs is projected to increase for another two to three decades before starting to slowly decline (see Figure Q19-2).

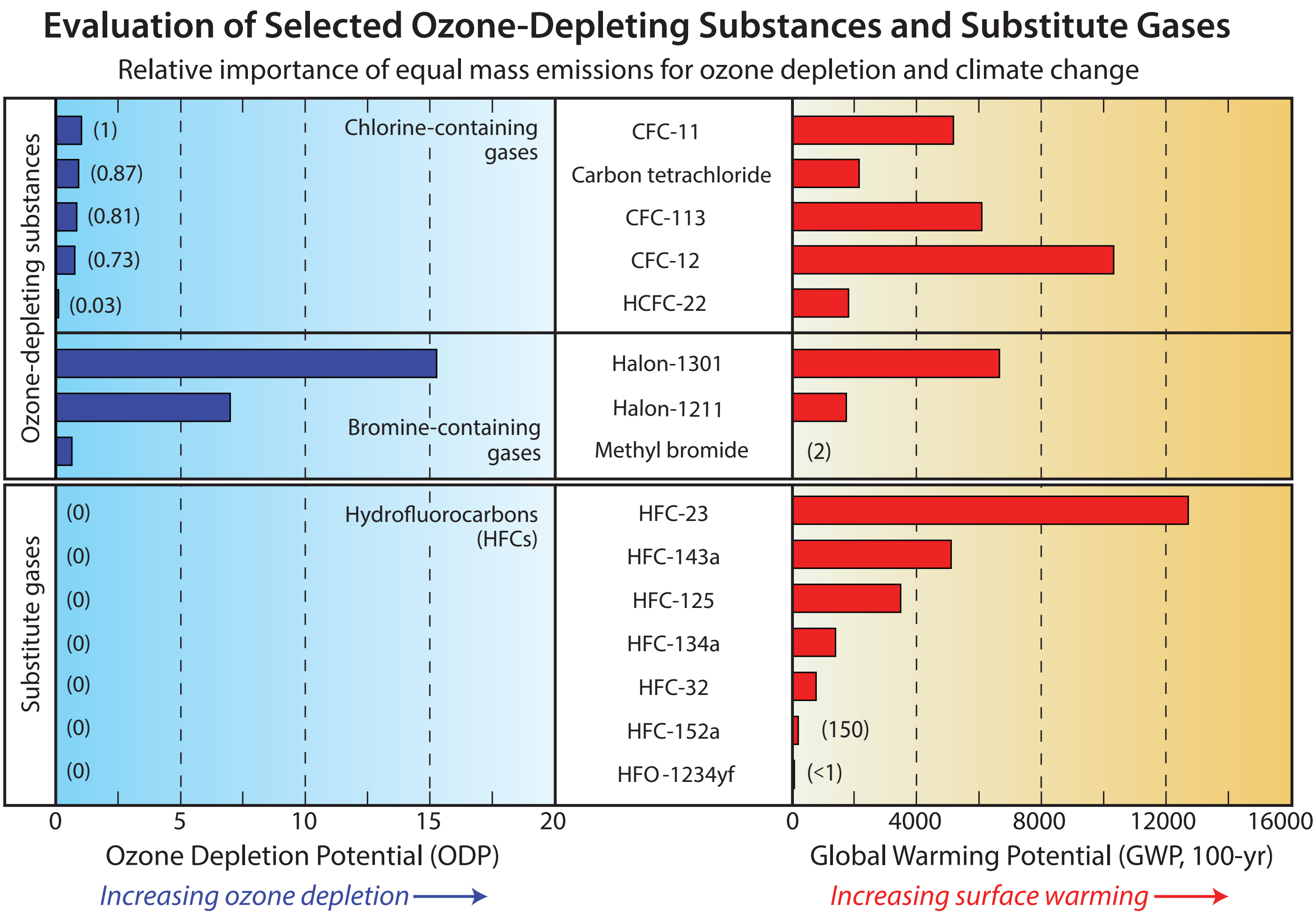

Figure Q17-3. ODPs and GWPs. The environmental impacts of ozone-depleting substances and their substitutes are commonly compared based upon their Ozone Depletion Potentials (ODPs) and Global Warming Potentials (GWPs) (see Table Q6-1). The ODPs and GWPs represent the magnitude of ozone depletion and climate forcing, respectively, of a given mass of gas emitted to the atmosphere, relative to that of CFC-11 (for ODP) or CO_2 (for GWP). Therefore, the ODP of CFC-11 and the GWP of CO_2 are assigned reference values of 1. The GWPs shown here are evaluated for a 100-year time interval after emission. The CFCs, halons, and HCFCs are ozone-depleting substances (ODSs) since they contain either chlorine or bromine (see Q6). HFCs, used as ODS substitutes, do not destroy ozone (ODPs equal zero) since they are mixtures of only hydrogen, fluorine, and carbon atoms. The ODPs of halons far exceed those of the CFCs, since all halons contain bromine. The GWPs of these gases span a wide range of values, from less than 1 (HFO-1234yf) to 12,690 (HFC-23).

Stratospheric and tropospheric ozone. Ozone in both the stratosphere and the troposphere absorbs infrared radiation emitted from Earth's surface, trapping heat in the atmosphere. Ozone also significantly absorbs solar ultraviolet (UV) radiation. As a result, increases or decreases in stratospheric or tropospheric ozone induce a climate forcing and, therefore, represent direct links between ozone and climate. Air pollution from a variety of human activities has led to increases in global tropospheric ozone (see Q2), causing a *positive* radiative forcing (warming) estimated to be +0.4 W/m^2 over the 1750–2011 time period, with a range of uncertainty spanning +0.2 to +0.6 W/m^2 (see Figure Q17-1). The large uncertainty in the climate forcing due to release of air pollutants reflects our limited knowledge of changes in the abundance of tropospheric ozone between 1750 and the mid-1950s as well as the difficulty in modeling the complex chemical processes that control the production of tropospheric ozone.

On the other hand, rising abundances of ODSs in the atmosphere since the middle of the 20th century have led to decreases in stratospheric ozone, most likely causing a *negative* radiative forcing of –0.05 W/m^2 (cooling) over the 1750–2011 time period, with a range of uncertainty spanning –0.15 to +0.05 W/m^2 (see Figure Q17-1). The sign of the radiative forcing due to stratospheric ozone depletion is uncertain because this quantity is the difference between two terms of comparable magnitude, each of which has an associated uncertainty. The first term represents the trapping by ozone of outgoing infrared radiation released by the surface and lower atmosphere: this is a cooling term because less ozone results in less trapping of heat. The second term represents the absorption of solar UV radiation by ozone: this is a warming term because less ozone results in greater penetration of solar UV radiation into the lower atmosphere (troposphere). The 2013 Intergovernmental Panel on Climate Change (IPCC) climate assessment concluded that stratospheric ozone depletion most likely caused a *slight cooling* of Earth's surface, as shown in Figure Q17-1. This radiative forcing due to stratospheric ozone depletion will diminish in the coming decades, as ODSs are gradually removed from the atmosphere.

The 2013 IPCC climate assessment also evaluated the radiative effects due to changes in ozone induced solely by the release of ODSs and as well as changes in ozone caused only by air pollutants. They concluded that changes in atmospheric ozone over the 1750–2011 time period caused solely by the release of ODSs led to a cooling of –0.18 W/m^2 with a range of uncertainty spanning –0.03 to –0.33 W/m^2 and that changes in atmospheric ozone over the same time period caused only by release of air pollutants led to a warming of +0.50 W/m^2 with a range of uncertainty spanning +0.30 to +0.70 W/m^2. The radiative forcings for ozone shown in Figure Q17-1 are based on estimates of the actual changes in the abundance of stratospheric ozone and tropospheric ozone, respectively. The values given in Figure Q17-1 differ from those stated in this paragraph because some stratospheric air masses that experience loss of ozone due to human release of ODSs are transported to the troposphere, somewhat mitigating the radiative forcing of climate due to elevated amounts of tropospheric ozone caused by air pollutants. Similarly, polluted tropospheric air entering the stratosphere has led to changes in stratospheric composition that have slightly offset the decline in ozone caused solely by ozone-depleting substances.

It is clear that stratospheric ozone depletion is not a principal cause of present-day global warming. First, the climate forcing from ozone depletion is small and very likely acts to cool Earth's surface. Second, the total radiative forcing of climate from other GHGs such as carbon dioxide, methane, halocarbons, and nitrous oxide is large and positive, leading to warming (see Figure Q17-1). The total forcing from these other GHGs is the principal cause of the observed warming of Earth's surface.

Ozone Depletion Potentials and Global Warming Potentials. A useful way of comparing the influence of individual emissions of halocarbons on ozone depletion and climate change is to compare Ozone Depletion Potentials (ODPs) and Global Warming Potentials (GWPs). The ODP and GWP are the effectiveness of an emission of a gas in causing ozone depletion and climate forcing, respectively, relative to a reference gas (see Table Q6-1). The principal halocarbon gases are contrasted with each other in **Figure Q17-3**. The ODP of CFC-11 and the GWP of carbon dioxide are assigned reference values of 1. The CFCs and carbon tetrachloride all have ODPs near 1, indicating comparable effectiveness in causing ozone depletion per mass emitted. The principal halons have ODPs greater than 7, making them the most effective ozone-depleting substances per mass emitted. All HFCs have ODPs of zero since they contain no chlorine and bromine, and therefore do not directly cause ozone depletion (see Q6).

All halocarbons have non-zero GWPs and, therefore, contribute to the radiative forcing of climate. The GWP does not correspond strongly with the ODP of a gas because these quantities depend on different chemical and physical properties of the molecule. For example, while HFC-143a does not destroy ozone (ODP equals zero), each gram emitted is about 5000 times more effective than a gram of carbon dioxide in causing climate forcing. When HFCs are released to the atmosphere, their contribution to climate forcing depends on their GWPs, which vary over a wide range (less than 1 to 13,000).

Montreal Protocol regulations have led to reductions in CFC emissions and increases in HCFC emissions (see Q15). As a result of these actions, the total radiative forcing from ODSs stopped increasing and is now slowly decreasing (see Q18). Overall halocarbon radiative forcing, however, is slowly increasing because of growing contributions from non-ODS gases (HFCs, PFCs, and SF_6). The growth in the HFC contribution will be limited by the provisions of the 2016 Kigali Amendment (see Q19). It is important to note that despite having a GWP that is small in comparison to many other halocarbons and other greenhouse gases, carbon dioxide is the most important greenhouse gas produced by human activities because its emissions are large, its atmospheric lifetime is long, and its atmospheric abundance is far greater than those of all other greenhouse gases associated with human activities.

The Antarctic ozone hole and Southern Hemisphere climate. While stratospheric ozone depletion is not the principal cause of global climate change, the reoccurring Antarctic ozone hole has contributed to observed changes in climate parameters in the atmosphere and oceans of the Southern Hemisphere. These research findings are explained in more detail in the box below.

The Antarctic Ozone Hole and Southern Hemisphere Surface Climate

Links between stratospheric ozone depletion and changes in surface climate were first found in research studies in the early 2000s, based on both observations and models. While increasing greenhouse gases (such as carbon dioxide, methane, and nitrous oxide) are the primary drivers of global climate change, the Antarctic ozone hole, which has occurred every spring since the early 1980s, was shown to contribute to observed changes in Southern Hemisphere surface climate during summer due to its effects on atmospheric circulation.

The severe springtime depletion of ozone over the Antarctic leads to a strong cooling of the polar lower stratosphere persisting into early summer in the Southern Hemisphere. This cooling increases the temperature contrast between the tropics and the polar region and strengthens stratospheric winds. As a result, in the Southern Hemisphere there has been a poleward shift of tropospheric circulation features including the tropical Hadley cell (which determines the location of the subtropical dry zones) and the midlatitude jet stream (which is associated with weather systems). There is evidence from both models and observations that subtropical and midlatitude summer precipitation patterns in the Southern Hemisphere have been affected by these changes. The observed wind changes over the Southern Ocean have also likely driven significant changes in ocean currents. Model studies indicate that even though long-lived greenhouse gases that cause climate change exacerbate this shift in the summertime tropospheric circulation in the Southern Hemisphere, ozone depletion has been the dominant contributor to the observed changes over the last few decades. Paleoclimate reconstructions suggest the current state of these climate features is unprecedented over the past 600 years.

During the 21st century, as the ozone hole recovers due to the decline of stratospheric halogens, the ozone-depletion related climate impacts discussed above will lessen (see Q20). Thus, ozone recovery will offset some of the future Southern Hemisphere circulation changes driven by rising abundances of greenhouse gases. The extent of this offset depends on the greenhouse gas emissions assumed in future climate projections. The Southern Hemisphere surface climate response to ozone depletion in other seasons is weaker than the summer response. No such links between ozone depletion and regional climate change have been observed for the Northern Hemisphere.