Q18 Is depletion of the ozone layer the principal cause of global climate change?

No, ozone depletion itself is not the principal cause of global climate change. Changes in ozone and climate are directly linked because ozone absorbs solar radiation and is also a greenhouse gas. Stratospheric ozone depletion leads to surface cooling, while the observed 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. Ozone depletion and global climate change are indirectly linked because both ozone-depleting substances and their substitutes are greenhouse gases. The Antarctic ozone hole has contributed to changes in Southern Hemisphere surface climate through indirect 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 (ODSs) (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 natural *greenhouse gases*, of which water vapor is an important example. The natural abundances of these gases in Earth's atmosphere change the balance between incoming solar radiation and outgoing infrared radiation, warming the atmosphere and surface. Without this natural greenhouse effect, Earth's surface would be much colder. Human activities in the Industrial Era have led to long-term increases in the atmospheric abundances of a number of long-lived and short-lived greenhouse gases. This group includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone, and halocarbons. 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 radiation to be absorbed, which further warms the atmosphere and surface. This change in the Earth's radiative 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 increases as this radiative forcing increases.

A summary of radiative forcings in 2011 resulting from the increases in the principal long-lived and short-lived greenhouse gases during the Industrial Era is shown in Figure Q18-1. All forcings shown relate to human activities. Positive forcings generally lead to *warming* and negative forcings lead to *cooling* of Earth's surface. Climate forcings also lead to other changes, such as in precipitation patterns and extreme weather events. International climate assessments conclude that much of the observed surface warming and changes in other climate parameters over the last decades is due to increases in the abundances of carbon dioxide and other greenhouse gases caused by human activities.

Carbon dioxide, methane, and nitrous oxide. All three of these greenhouse gases have both human and natural sources. The accumulation of carbon dioxide during the Industrial Era represents the largest climate forcing related to human

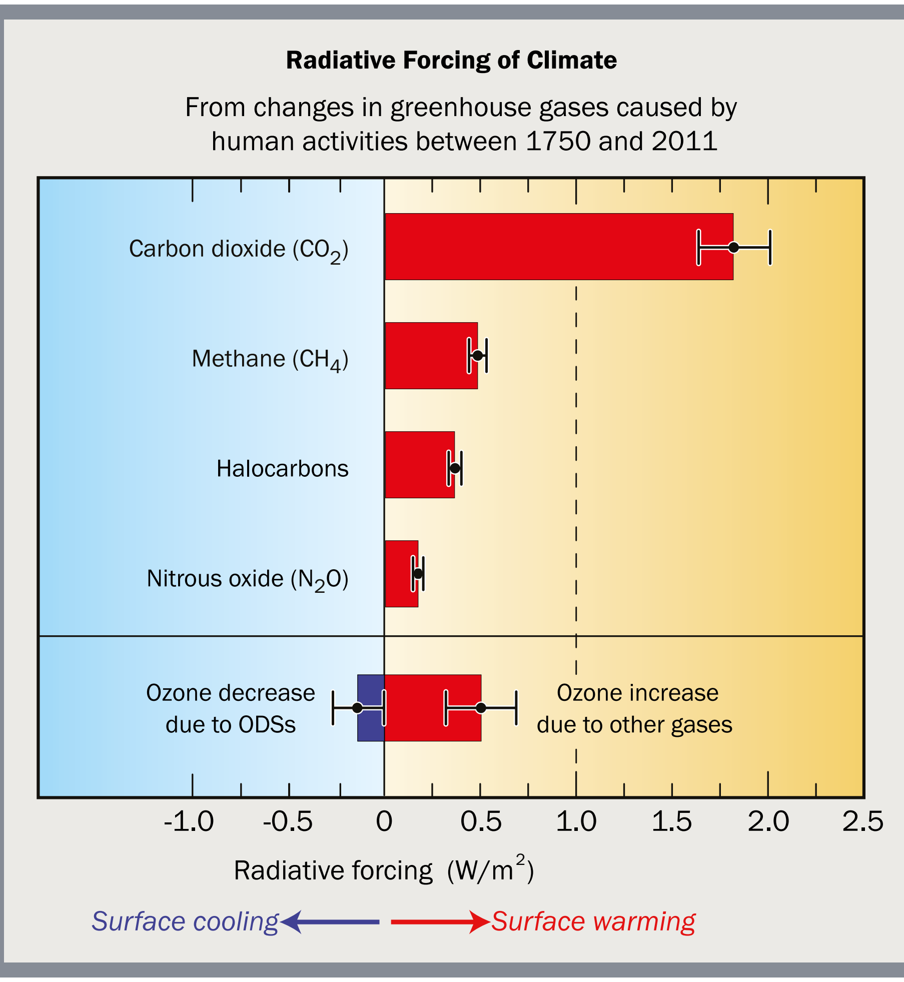

Figure Q18-1. Radiative forcing of greenhouse gases. Human activities since the start of the Industrial Era (around 1750) have caused increases in the abundances of several short-lived and long-lived gases, known as greenhouse gases, that all contribute to the radiative forcing of climate, also known as climate forcing. Radiative forcing is expressed in units of watts per square meter (W/m^2). As shown in the figure, the largest forcings are those of carbon dioxide (CO_2), followed by methane (CH_4), ozone increases due to air pollution gases, halocarbon gases, and nitrous oxide (N_2O). These positive forcings lead to a warming of Earth's surface. Halocarbons include all ODSs, their substitutes, and a few other gases (see Figure Q18-2). In contrast, ozone decreases due to ODSs represents a negative forcing, which leads to cooling of Earth's surface and tends to partially offset the positive forcing from the halocarbons. The black whiskers on each bar show uncertainties in the values.

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 carbon dioxide is now more than 40% above what it was in preindustrial times (before 1750), approaching values of 400 parts per million by volume (ppmv). 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 10 years). Human sources include livestock, fossil fuel extraction and use, rice agriculture, and landfills. Natural sources include wetlands, termites, and oceans. Methane has increased by about 150% since preindustrial times.

Nitrous oxide is a *long-lived* climate gas (atmospheric lifetime of about 110 years). The largest human source is agricultural activities, especially related to fertilization. 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, which participate in ozone destruction cycles (see Q2 and Q7). Nitrous oxide has increased by about 20% since preindustrial times.

Halocarbons. Halocarbons in the atmosphere contribute to both ozone depletion and climate change. As used here, halocarbons represent those gases containing chlorine, bromine, or fluorine atoms that are now controlled substances under the Montreal Protocol or the Kyoto Protocol. ODSs are the halocarbons controlled under

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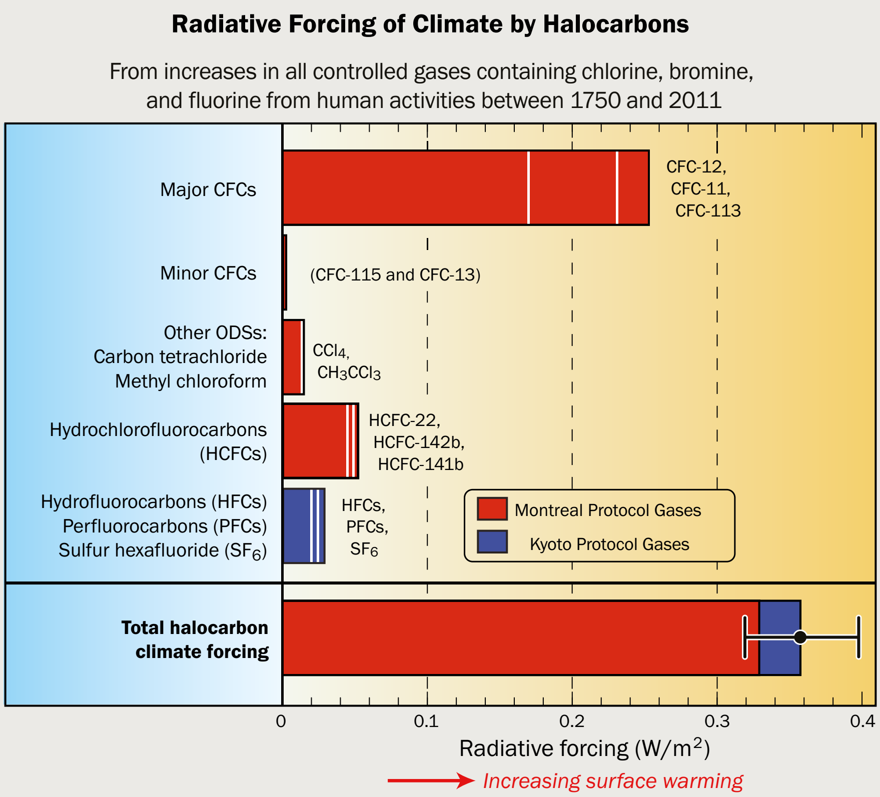
Figure Q18-2. Halocarbons and radiative forcing of climate.
Halocarbon gases in the atmosphere represent an important contribution to the radiative forcing of climate between 2011 and the start of the Industrial Era (see Figure Q18-1). Halocarbons are all gases containing chlorine, bromine, or fluorine atoms that are now controlled as ozone-depleting substances (ODSs) by the Montreal Protocol or as climate change gases by the Kyoto Protocol (see color shading). Shown in the figure are the separate contributions of each gas or group of gases, as estimated using atmospheric abundance histories and Global Warming Potentials (GWPs) (see Figure Q18-3). The gases listed in the right hand labels begin with the largest contribution in each group, except for CFC-13 and CFC-115, which are shown as one total value. The individual forcing terms add together to form the bottom bar representing the total halocarbon forcing. The forcings of CFC-11 and CFC-12, the largest halocarbon contributions, are already decreasing and will continue to decrease as CFCs are gradually removed from the atmosphere (see Figure Q16-1). In contrast, the contributions of the intermediate-term ODS substitute gases, HCFCs, are projected to grow for another two decades before decreasing. The future contributions of the long-term ODS substitute gases, HFCs, are also expected to increase. In this case, the total contribution will depend strongly on which HFCs are used because the GWPs of individual HFCs vary widely (see Figures Q18-3 and Q19-2).



the Montreal Protocol. HFC substitute gases, perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are controlled under the Kyoto Protocol. In 2011, the halocarbon contribution to climate forcing was 0.36 W/m^2, which is the fourth largest forcing following carbon dioxide, methane, and tropospheric ozone (see Figure Q18-1). The contributions of individual halocarbon gases are highlighted in Figure Q18-2. Within the halocarbons, CFCs contribute the largest percentage (73%) to the 2011 climate forcing. HCFCs, the intermediate-term ODS substitutes, make the next largest contribution (14%). The atmospheric abundance of HFCs, the longer-term ODS substitutes, contributes 5% to the 2011 halocarbon climate forcing.

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 Q16-1). Based on their long lifetimes, CFCs will still make a significant contribution, and most likely the largest ODS contribution, to halocarbon climate forcing at the end of the 21st century. Halocarbons controlled under the Kyoto Protocol

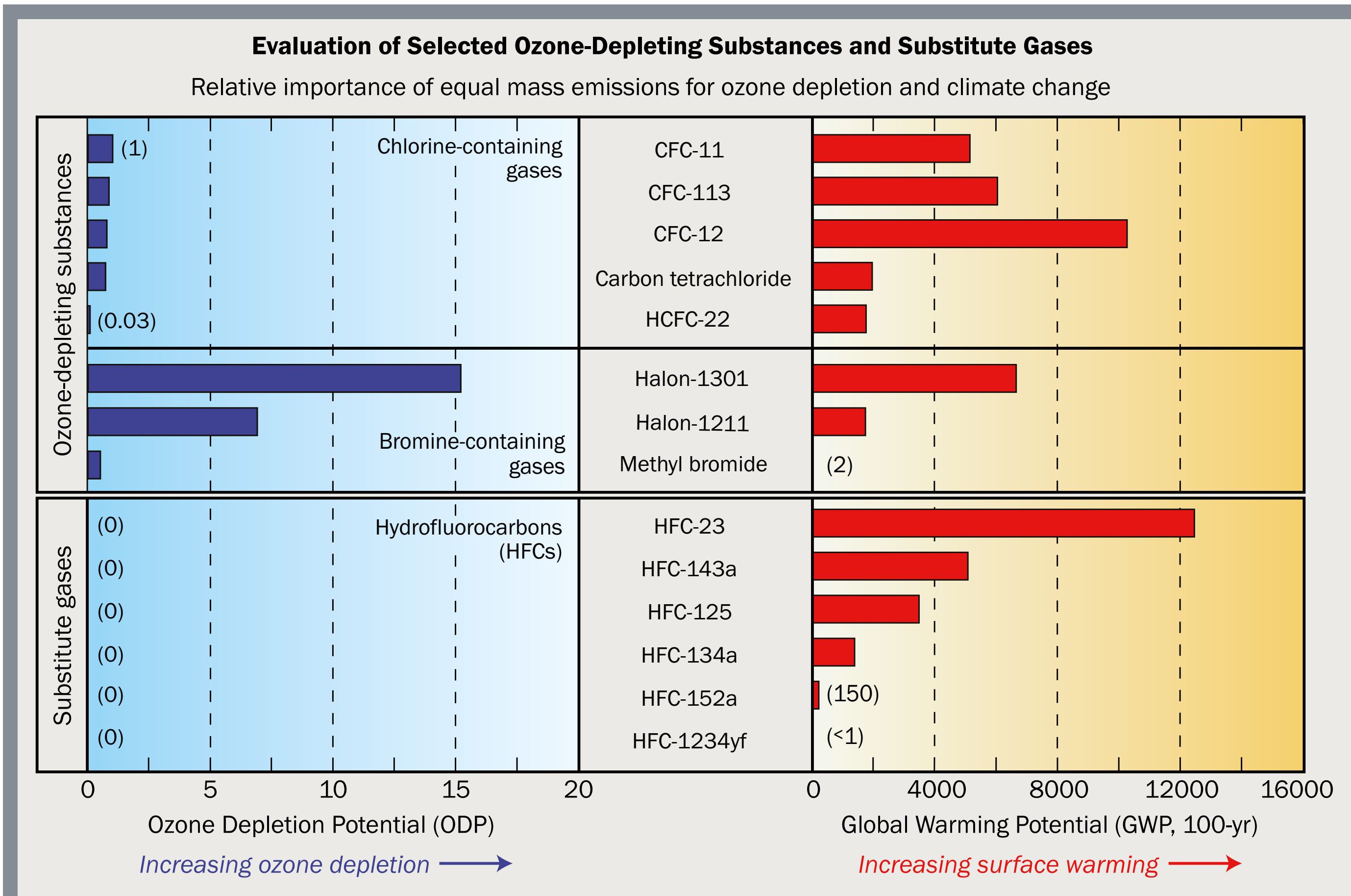


Figure Q18-3. ODPs and GWPs.
ODSs and their substitutes can be compared via their Ozone Depletion Potentials (ODPs) and Global Warming Potentials (GWPs) (see Table Q7-1). Larger ODPs or GWPs indicate greater potential for ozone depletion or climate warming, respectively, when a gas is emitted to the atmosphere. The ODP and GWP values are derived assuming an equal mass of each gas is emitted. The GWPs shown here are evaluated for a 100-year time interval after emission. The ODP of CFC-11 and the GWP of CO_2 are assigned reference values of 1. The CFCs, halons, and HCFCs are ozone-depleting substances (see Q7) while HFCs, used as ODS substitutes, do not destroy ozone (ODPs equal 0). The ODPs of the halons far exceed those of the CFCs. All ODSs and their substitutes shown here have a non-zero GWP, with values spanning the wide range of 2 to 13,000.

(HFCs, PFCs, and SF_6) represent about 8% of halocarbon climate forcing in 2011. With the projected growth of HFC production and consumption in developing nations, this percentage contribution is expected to continue to increase in the coming decades (see Figure Q19-2).

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. Stratospheric ozone also significantly absorbs solar 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 human activities has led to increases in global tropospheric ozone, causing a *positive* radiative forcing (warming) since preindustrial times (see Figure Q18-1). The large uncertainty in tropospheric ozone forcing reflects the difficulty in

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quantifying tropospheric ozone trends and in modeling the complex production and loss processes that control its abundance. On the other hand, rising ODS abundances in the atmosphere since the middle of the 20^{th} century have led to decreases in stratospheric ozone and in the amounts of stratospheric ozone transported into the troposphere, causing a negative radiative forcing (cooling) since preindustrial times. The negative radiative forcing resulting from stratospheric ozone depletion will diminish in the coming decades as ODSs are gradually removed from the atmosphere.

Stratospheric ozone depletion cannot be a principal cause of present-day global climate change for two reasons: first, the climate forcing from ODS-induced ozone depletion acts to cool Earth's surface. Second, the total forcing from other long-lived and short-lived gases in Figure Q18-1 is positive (leading to warming). The total forcing from these other greenhouse gases (carbon dioxide, methane, halocarbons, and nitrous oxide) is the principal cause of observed climate change.

Ozone Depletion Potentials and Global Warming Potentials. An important way of comparing the influence of individual emissions of halocarbons on ozone depletion and climate change is to use 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 Q7-1). The principal halocarbon gases are contrasted with each other in Figure Q18-3. 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. HFCs have ODPs of zero since they cause no ozone depletion (see Q7).

All halocarbons have non-zero GWPs and, therefore, contribute to climate forcing. The GWP does not correspond strongly with the ODP of a gas because these quantities depend on different chemical and physical properties. For example, while HFC-134a does not destroy ozone (ODP equal 0), each gram emitted is 1,360 times more effective than a gram of carbon dioxide in causing climate forcing. The future selection of specific HFCs as ODS substitutes or for use in new global applications will have important consequences for climate forcing. When these HFCs are eventually released to the atmosphere, their contribution to climate forcing will depend on their GWPs, which could vary over a wide range (2 to 13,000).

Montreal Protocol regulations have led to reductions in CFC emissions and increases in HCFC emissions (see Q16). As a result of these actions, the total radiative forcing from ODSs stopped increasing and is now slowly decreasing (see Q19). Overall halocarbon radiative forcing, however, is slowly increasing because of growing contributions from HFCs, PFCs, and SF_6. 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 related to human activities because its emissions are large and its atmospheric abundance is far greater than the abundances of other emitted gases.

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 indirectly contributed to observed changes in Southern Hemisphere summertime surface climate through circulation changes. These new 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 reoccurs every spring since the early 1980s, was shown to contribute indirectly to observed changes in Southern Hemisphere surface climate during summer due to its effects on atmospheric circulation.

The severe springtime ozone depletion over the Antarctic leads to a strong cooling of the polar lower stratosphere persisting into early summer. This increases the temperature contrast between the tropics and the polar region, which strengthens stratospheric winds. For reasons that are not well understood but are consistently reproduced in models, this leads to 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 (which is associated with weather systems). There is some evidence from both models and observations that subtropical and midlatitude summer precipitation patterns 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 suggest that long-lived greenhouse gases that cause climate change exacerbate this shift in summertime Southern Hemisphere tropospheric circulation, but that ozone depletion has been the dominant contributor to the changes over the last few decades.

During the 21st century, ozone recovery is expected to lead to the reversal of the above climate impacts driven by the ozone hole. This reversal will result in some cancellation of future Southern Hemisphere circulation changes driven by greenhouse gas increases. The extent of such a cancellation 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. No such links between ozone depletion and regional climate change have been observed for the Northern Hemisphere.