Twenty Questions and Answers About the Ozone Layer: 2018 Update

Scientific Assessment of Ozone Depletion: 2018

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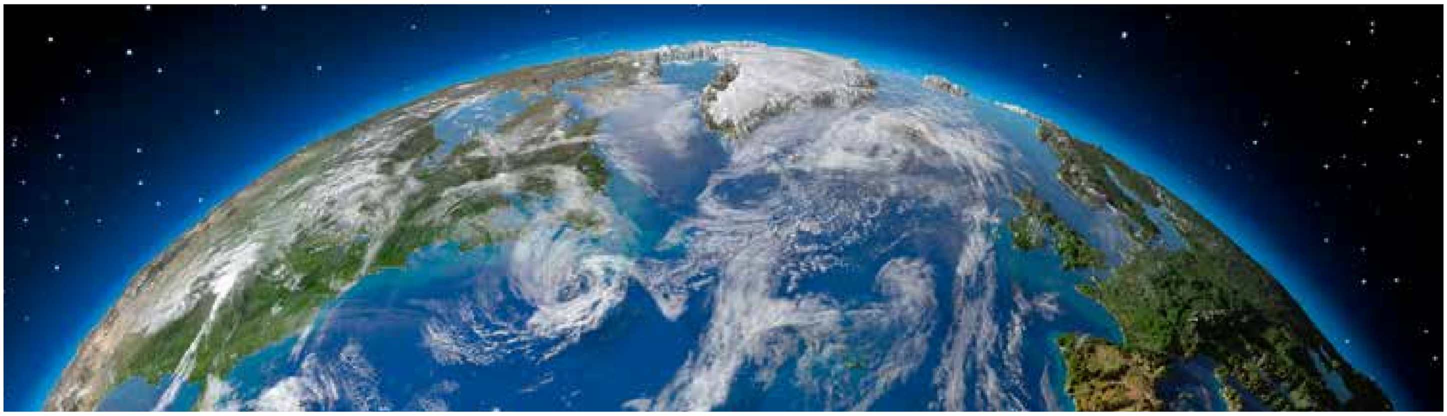

World Meteorological Organization
United Nations Environment Programme
National Oceanic and Atmospheric Administration
National Aeronautics and Space Administration
European Commission

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Q1

What is ozone, how is it formed, and where is it in the atmosphere?

Ozone is a gas that is naturally present in our atmosphere. Each ozone molecule contains three atoms of oxygen and is denoted chemically as O_3. Ozone is found primarily in two regions of the atmosphere. About 10% of Earth's ozone is in the troposphere, which extends from the surface to about 10–15 kilometers (6–9 miles) altitude. About 90% of Earth's ozone resides in the stratosphere, the region of the atmosphere between the top of the troposphere and about 50 kilometers (31 miles) altitude. The part of the stratosphere with the highest amount of ozone is commonly referred to as the "ozone layer". Throughout the atmosphere, ozone is formed in multistep chemical processes that are initiated by sunlight. In the stratosphere, the process begins with an oxygen molecule (O_2) being broken apart by ultraviolet radiation from the Sun. In the troposphere, ozone is formed by a different set of chemical reactions that involve naturally occurring gases as well as those from sources of air pollution.

Ozone is a gas that is naturally present in our atmosphere. Ozone has the chemical formula O_3 because an ozone molecule contains three oxygen atoms (see **Figure Q1-1**). Ozone was discovered in laboratory experiments in the mid-1800s. Ozone's presence in the atmosphere was later discovered using chemical and optical measurement methods. The word ozone is derived from the Greek word *όζειν (ozein)*, meaning "to smell." Ozone has a pungent odor that allows it to be detected even at very low amounts. Ozone reacts rapidly with many chemical compounds and is explosive in concentrated amounts. Electrical discharges are generally used to produce ozone for industrial processes such as air and water purification and bleaching of textiles and food products.

Ozone location. Most ozone (about 90%) is found in the stratosphere, which begins about 10–15 kilometers (km) above Earth's surface and extends up to about 50 km altitude. The stratospheric region with the highest concentration of ozone, between about 15 and 35 km altitude, is commonly known as the "ozone layer" (see **Figure Q1-2**). The ozone layer extends over the entire globe with some variation in altitude and thickness. Most of the remaining ozone (about 10%) is found in the troposphere, which is the lowest region of the atmosphere, between Earth's surface and the stratosphere. Tropospheric air is the "air we breathe" and, as such, excess ozone in the troposphere has harmful consequences (see Q2).

Ozone abundance. Ozone molecules have a low relative abundance in the atmosphere. Most air molecules are either oxygen (O_2) or nitrogen (N_2). In the stratosphere near the peak concentration of the ozone layer, there are typically a few thousand ozone molecules for every *billion* air molecules (1 billion = 1,000 million). In the troposphere near Earth's surface, ozone is even less abundant, with a typical range of 20 to 100 ozone molecules for each billion air molecules. The highest ozone values near the surface occur in air that is polluted by human activities.

As an illustration of the low relative abundance of ozone in our atmosphere, one can imagine bringing all the ozone molecules in the troposphere and stratosphere down to Earth's surface

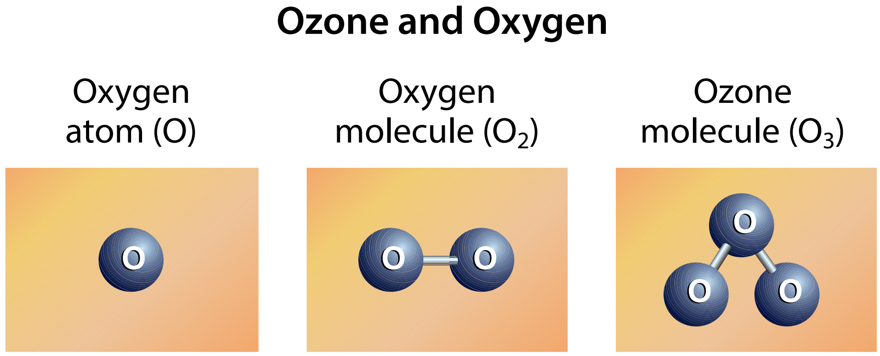


Figure Q1-1. Ozone and oxygen. A molecule of ozone (O_3) contains three oxygen atoms (O) bound together. Oxygen molecules (O_2), which constitute about 21% of the gases in Earth's atmosphere, contain two oxygen atoms bound together.

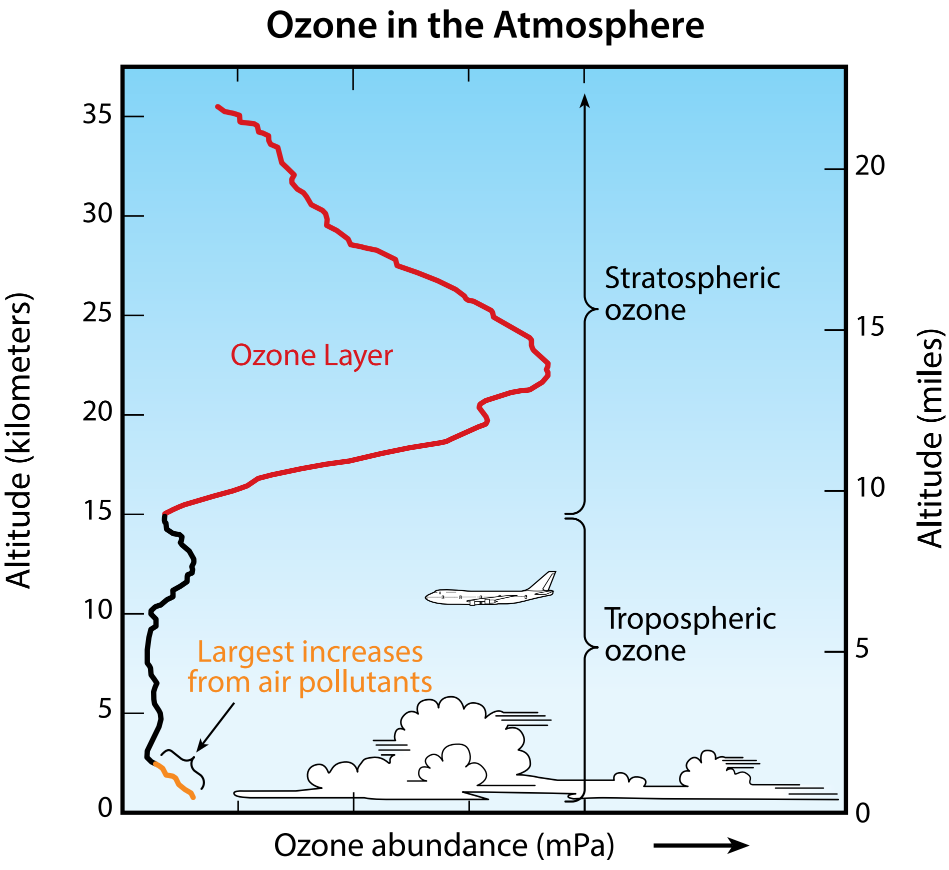


Figure Q1-2. Ozone in the atmosphere. Ozone is present throughout the troposphere and stratosphere. This profile shows schematically how ozone changes with altitude in the tropics. Most ozone resides in the stratospheric "ozone layer." The vertical extent or thickness of this layer varies from region to region and with season over the globe (see Q3). Increases in ozone near the surface are a result of air pollutants released by human activities. The direct exposure to ozone is harmful to humans and other forms of life.

and forming a layer of pure ozone that extends over the entire globe. The resulting layer would have an average thickness of about three millimeters (0.12 inches) (see Q3). Nonetheless, this extremely small fraction of the atmosphere plays a vital role in protecting life on Earth (see Q2).

Stratospheric ozone. Stratospheric ozone is formed naturally by chemical reactions involving solar ultraviolet radiation (sunlight) and oxygen molecules, which make up about 21% of the atmosphere. In the first step, solar ultraviolet radiation breaks apart one oxygen molecule (O_2) to produce two oxygen atoms (2 O) (see **Figure Q1-3**). In the second step, each of these highly reactive oxygen atoms combines with an oxygen molecule to produce an ozone molecule (O_3). These reactions occur continually whenever solar ultraviolet radiation is present in the stratosphere. As a result, the largest ozone production occurs in the tropical stratosphere.

The production of stratospheric ozone is balanced by its destruction in chemical reactions. Ozone reacts continually with sunlight and a wide variety of natural and human-produced chemicals in the stratosphere. In each reaction, an ozone molecule is lost and other chemical compounds are produced. Important reactive gases that destroy ozone are hydrogen and nitrogen oxides and those containing chlorine and bromine (see Q7). Some stratospheric ozone is regularly transported down into the troposphere and can occasionally influence ozone amounts at Earth's surface.

Tropospheric ozone. Near Earth's surface, ozone is produced by chemical reactions involving gases emitted to the atmosphere from both natural sources and human activities. Ozone production reactions primarily involve hydrocarbon and nitrogen oxide gases, as well as ozone itself, and all require sunlight for completion. Fossil fuel combustion is a primary source of pollutant gases that lead to tropospheric ozone production. As in the stratosphere, ozone in the troposphere is destroyed by naturally occurring chemical reactions and by reactions involving human-produced chemicals. Tropospheric ozone can also be destroyed when ozone reacts with a variety of surfaces, such as those of soils and plants.

Balance of chemical processes. Ozone abundances in the stratosphere and troposphere are determined by the balance between chemical processes that produce and destroy ozone. The balance is determined by the amounts of reactive gases and how the rate or effectiveness of the various reactions varies with sunlight intensity, location in the atmosphere, temperature, and other factors. As atmospheric conditions change to favor ozone-producing reactions in a certain location, ozone abundances increase. Similarly, if conditions change to favor other reactions that destroy ozone, abundances decrease. The balance of production and loss reactions, combined with atmospheric air motions that transport and mix air with different ozone abundances, determines the global distribution of ozone on timescales of days to many months (see also Q3). Global stratospheric ozone has decreased during the past several decades (see Q12) because the amounts of reactive gases containing chlorine and bromine have increased in the stratosphere due to human activities (see Q6 and Q15).

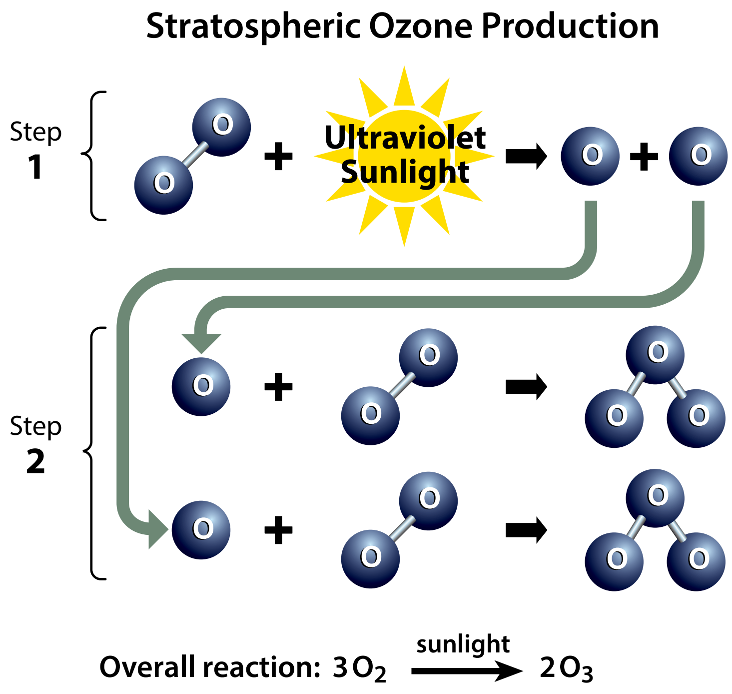


Figure Q1-3. Stratospheric ozone production. Ozone is produced naturally in the stratosphere by a two-step reaction process. In the first step, solar ultraviolet radiation (sunlight) breaks apart an oxygen molecule to form two separate oxygen atoms. In the second step, each oxygen atom collides with another oxygen molecule and forms an ozone molecule in a binding reaction. In the overall process, three oxygen molecules plus sunlight react to form two ozone molecules.

Q2 Why do we care about atmospheric ozone?

Ozone in the stratosphere absorbs a large part of the Sun's biologically harmful ultraviolet radiation. Stratospheric ozone is considered "good" ozone because of this beneficial role. In contrast, ozone formed at Earth's surface in excess of natural amounts is considered "bad" ozone because it is harmful to humans, plants, and animals.

Ozone in the stratosphere (*Good ozone*). Stratospheric ozone is considered good for humans and other life forms because it absorbs ultraviolet (UV) radiation from the Sun (see **Figure Q2-1**). If not absorbed, high energy UV radiation would reach Earth's surface in amounts that are harmful to a variety of life forms. The Sun emits three types of UV radiation: UV-C (100 to 280 nanometer (nm) wavelengths); UV-B (280 to 315 nm), and UV-A (315 to 400 nm). Exposure to UV-C radiation is particularly dangerous to all life forms. Fortunately, UV-C radiation is entirely absorbed within the ozone layer. Most UV-B radiation emitted by the Sun is absorbed by the ozone layer; the rest reaches Earth's surface. In humans, increased exposure to UV-B radiation raises the risks of skin cancer and cataracts, and suppresses the immune system. Exposure to UV-B radiation before adulthood and cumulative exposure are both important health risk factors. Excessive UV-B exposure also can damage terrestrial plant life, including agricultural crops, single-celled organisms, and aquatic ecosystems. Low energy UV radiation, UV-A, which is not absorbed significantly by the ozone layer, causes premature aging of the skin.

Protecting stratospheric ozone. In the mid-1970s, it was discovered that gases containing chlorine and bromine atoms released by human activities could cause stratospheric ozone depletion (see Q5 and Q6). These gases, referred to as halogen source gases, and also as ozone-depleting substances (ODSs), chemically release their chlorine and bromine atoms after they reach the stratosphere. Ozone depletion increases surface UV-B radiation above naturally occurring amounts. International efforts have been successful in protecting the ozone layer through controls on the production and consumption of ODSs (see Q14 and Q15).

Ozone in the troposphere (*Bad ozone*). Ozone near Earth's surface in excess of natural amounts is considered bad ozone (see Figure Q1-2). Surface ozone in excess of natural levels is formed

UV Protection by the Stratospheric Ozone Layer

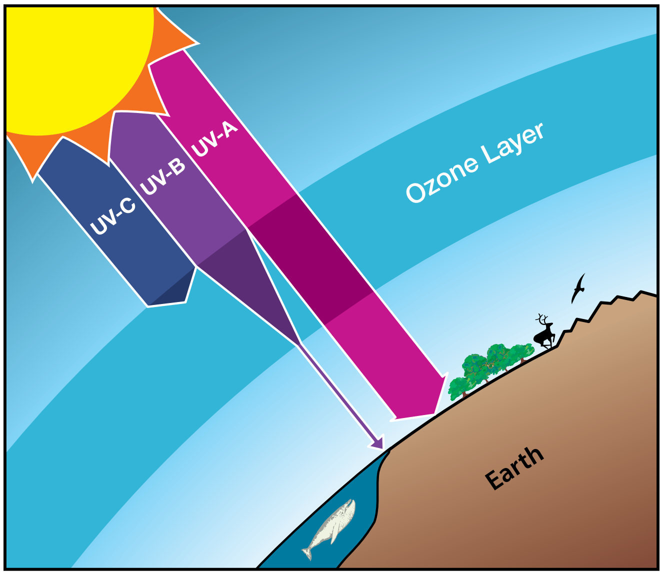


Figure Q2-1. UV protection by the ozone layer. The ozone layer is located in the stratosphere and surrounds the entire Earth. The Sun emits three types of ultraviolet (UV) radiation that reach the top of the ozone layer. Solar UV-C radiation (wavelength range 100 to 280 nanometer (nm)) is extremely damaging to humans and other life forms; UV-C radiation is entirely absorbed within the ozone layer. Solar UV-B radiation (280 to 315 nm) is only partially absorbed and, as a result, humans and other life forms are exposed to some UV-B radiation. Excessive exposure to UV-B radiation increases the risks of skin cancer, cataracts, and a suppressed immune system for humans and also damages terrestrial plant life, single-cell organisms, as well as aquatic ecosystems. UV-A (315 to 400 nm), visible light, and other solar radiation are only weakly absorbed by the ozone layer. Exposure to UV-A is associated with premature aging of the skin and some skin cancers. Depletion of the ozone layer increases primarily the amount of UV-B radiation that reaches the surface (Q16). Avoiding ozone depletion that would increase human exposure to UV-B radiation is a principal objective of the Montreal Protocol.

(The unit "nanometer" (nm) is a common measure of the wavelength of light; 1 nm equals one billionth of a meter (=10^{-9} m).)

by reactions involving air pollutants emitted from human activities, such as nitrogen oxides (NO_x), carbon monoxide (CO), and various hydrocarbons (gases containing hydrogen, carbon, and often oxygen). Exposure to surface ozone above natural levels is harmful to humans, plants, and other living systems because ozone reacts strongly to destroy or alter many biological molecules. Enhanced surface ozone caused by air pollution reduces crop yields and forest growth. In humans, exposure to high levels of ozone can reduce lung capacity; cause chest pains, throat irritation, and coughing; and worsen pre-existing health conditions related to the heart and lungs. In addition, increases in tropospheric ozone lead to a warming of Earth's surface because ozone is a greenhouse gas (GHG) (see Q17). The negative effects of excess tropospheric ozone contrast sharply with the protection from harmful UV radiation afforded by preserving the natural abundance of stratospheric ozone.

Reducing tropospheric ozone. Limiting the emission of certain common pollutants reduces the production of excess ozone near Earth's surface where it can affect humans, plants, and animals. Major sources of pollutants include large cities where fossil fuel consumption and industrial activities are greatest. Many programs around the globe have been successful in reducing or limiting the emission of pollutants that cause production of excess ozone near Earth's surface.

Natural ozone. In the absence of human activities, ozone would still be present near Earth's surface and throughout the troposphere and stratosphere because ozone is a natural component of the clean atmosphere. Natural emissions from the biosphere, mainly from trees, participate in chemical reactions that produce ozone. Atmospheric ozone plays important ecological roles beyond absorbing UV radiation. For example, ozone initiates the chemical removal of many pollutants as well as some GHGs, such as methane (CH_4). In addition, the absorption of UV radiation by ozone is a natural source of heat in the stratosphere, causing temperatures to increase with altitude. Stratospheric temperatures affect the balance of ozone production and destruction processes (see Q1) and air motions that redistribute ozone throughout the stratosphere (see Q3).

Q7

What are the reactive halogen gases that destroy stratospheric ozone?

The chlorine- and bromine-containing gases that enter the stratosphere arise from both human activities and natural processes. When exposed to ultraviolet radiation from the Sun, these halogen source gases are converted to more reactive gases that also contain chlorine and bromine. Some reactive gases act as chemical reservoirs which can then be converted into the most reactive gases, namely ClO and BrO. These most reactive gases participate in catalytic reactions that efficiently destroy ozone.

Halogen-containing gases present in the stratosphere can be divided into two groups: *halogen source gases and reactive halogen gases* (see **Figure Q7-1**). The source gases, which include ozone-depleting substances (ODSs), are emitted at Earth's surface by natural processes and by human activities (see Q6). Once in the stratosphere, the halogen source gases chemically convert at different rates to form the reactive halogen gases. The conversion occurs in the stratosphere instead of the troposphere for most gases because solar ultraviolet radiation (a component of sunlight) is more intense in the stratosphere (see Q2). Reactive gases containing the halogens chlorine and bromine lead to the chemical destruction of stratospheric ozone.

Reactive halogen gases. The chemical conversion of halogen source gases, which involves solar ultraviolet radiation and other chemical reactions, produces a number of reactive halogen gases. These reactive gases contain all of the chlorine and bromine atoms originally present in the source gases. The most important reactive chlorine- and bromine-containing gases that form in the stratosphere are shown in Figure Q7-1. Throughout the stratosphere, the most abundant are typically hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$). These two gases are considered important *reservoir* gases because, while they do not react directly with ozone, they can be converted to the *most reactive* forms that do chemically destroy ozone. The most

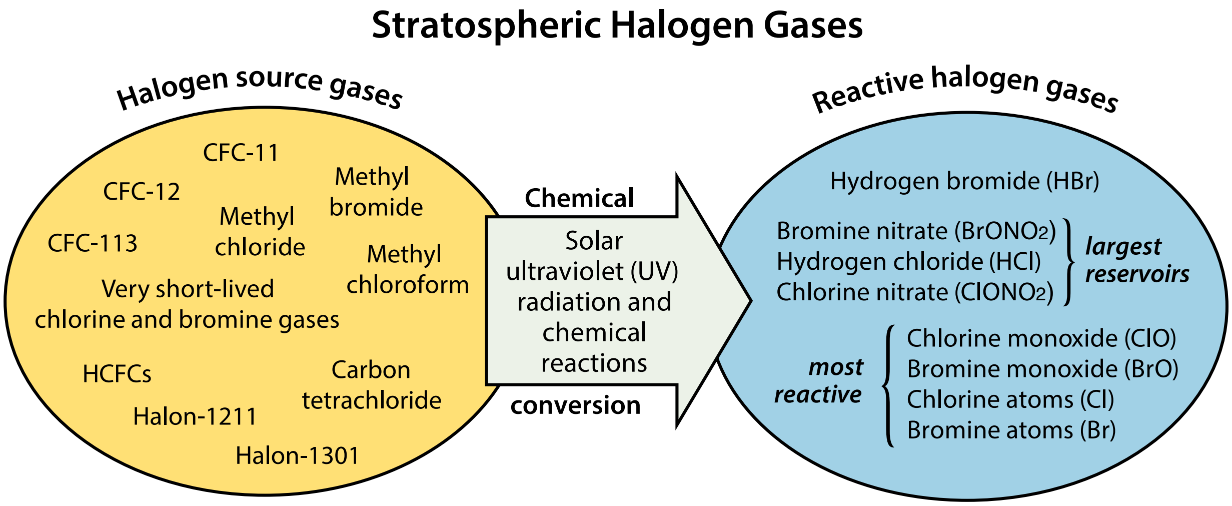


Figure Q7-1. Conversion of halogen source gases. Halogen source gases containing chlorine and bromine are chemically converted to reactive halogen gases, primarily in the stratosphere. Most of the halogen source gases are ozone-depleting substances. The conversion requires solar ultraviolet radiation and a few chemical reactions. The shorter-lived gases undergo partial conversion in the troposphere. The reactive halogen gases contain all the chlorine and bromine originally present in the source gases before conversion. The reactive gases can be grouped into the reservoir gases, which do not directly destroy ozone, and the most reactive gases, which participate in ozone destruction cycles (see Q8). A principal reactive gas, ClO, is formed by reactions of the reservoir gases HCl and $ClONO_2$ that occur on the surfaces of liquid and solid polar stratospheric clouds (PSCs) (see Q9).

reactive forms are chlorine monoxide (ClO) and bromine monoxide (BrO), and chlorine and bromine atoms (Cl and Br). A large fraction of total reactive bromine is generally in the form of BrO, whereas usually only a small fraction of total reactive chlorine is in the form of ClO. The special conditions that occur in the polar regions during winter cause the reservoir gases HCl and $ClONO_2$ to undergo nearly complete conversion to ClO in reactions on polar stratospheric clouds (PSCs) (see Q9).

Reactive chlorine at midlatitudes. Reactive chlorine gases have been observed extensively in the stratosphere using both local and remote measurement techniques. The measurements from space displayed in **Figure Q7-2** are representative of how the amounts of chlorine-containing gases change between the surface and the upper stratosphere at middle to high latitudes. Total available chlorine (see red line in Figure Q7-2) is the sum of chlorine contained in halogen source gases (e.g., CFC-11, CFC-12) and in the reactive gases (e.g., HCl, $ClONO_2$, and ClO). Available chlorine is constant to within about 10% from the surface to above 50 km (31 miles) altitude. In the troposphere, total chlorine is contained almost entirely in the source gases described in Figure Q6-1. At higher altitudes, the source gases become a smaller fraction of total available chlorine as they are converted to the reactive chlorine gases. At the highest altitudes, available chlorine is all in the form of reactive chlorine gases.

In the altitude range of the ozone layer at midlatitudes, as shown in Figure Q7-2, the reservoir gases HCl and $ClONO_2$ account for most of the available chlorine. The abundance of ClO, the most reactive gas in ozone depletion, is a small fraction of available chlorine. The low abundance of ClO limits the amount of ozone destruction that occurs outside of polar regions.

Reactive chlorine in polar regions. Reactive chlorine gases in polar regions undergo large changes between autumn and late winter. Meteorological and chemical conditions in both polar regions are now routinely observed from space in all seasons. Autumn and winter conditions over the Antarctic are contrasted in **Figure Q7-3** using seasonal observations made near the center of the ozone layer (about 18 km (11.2 miles) altitude; see Figure Q11-3).

Ozone values are high over the entire Antarctic continent during autumn in the Southern Hemisphere. Temperatures are mid-range, HCl and nitric acid (HNO_3) are high, and ClO is very low. High HCl indicates that substantial conversion of halogen source gases has occurred in the stratosphere. In the 1980s and early 1990s, the abundance of reservoir gases HCl and $ClONO_2$ increased substantially in the stratosphere following increased emissions of halogen source gases. HNO_3 is an abundant, primarily naturally-occurring stratospheric compound that plays a major role in stratospheric ozone chemistry by both moderating ozone destruction and condensing to form PSCs, thereby enabling conversion of chlorine reservoirs gases to ozone-destroying forms. The low abundance of ClO indicates that little conversion of the reservoir gases occurs in the autumn, thereby limiting catalytic ozone destruction.

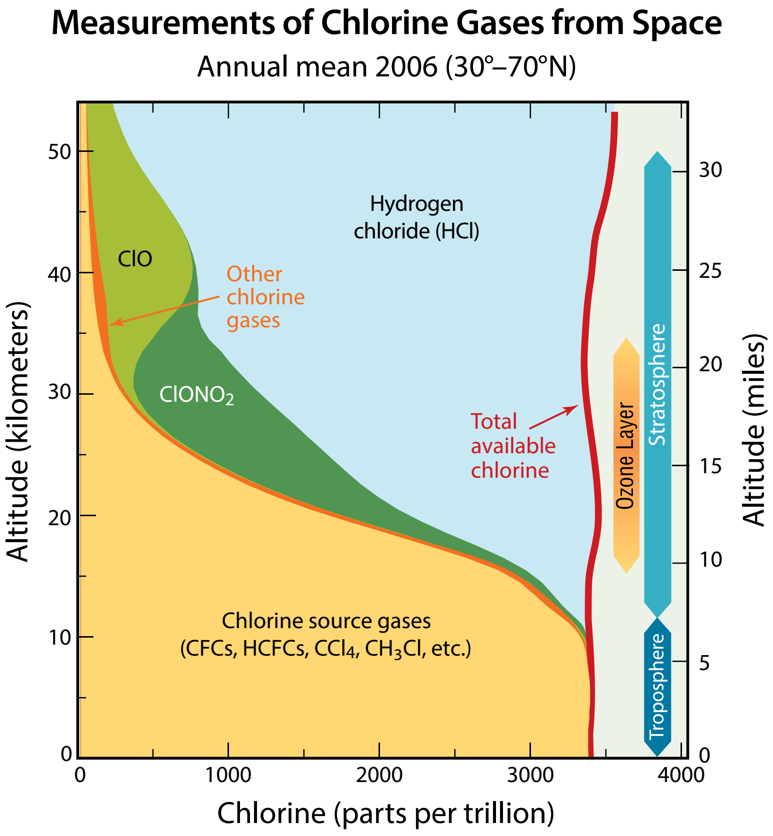


Figure Q7-2. Reactive chlorine gas observations. The abundances of chlorine source gases and reactive chlorine gases as measured from space in 2006 are displayed as a function of altitude for a range of latitudes. In the troposphere (below about 12 km), all of the measured chlorine is contained in the source gases. In the stratosphere, the total chlorine content of reactive gases increases with altitude as the amount of chlorine source gases declines. This is a consequence of chemical reactions initiated by solar ultraviolet radiation that convert source gases to reactive gases (see Figure Q7-1). The principal reactive chlorine gases formed are HCl, $ClONO_2$, and ClO. Adding up the source gases with the reactive gases gives "Total available chlorine", which is nearly constant with altitude throughout the stratosphere. In the ozone layer (15–35 km), chlorine source gases are still present and HCl and $ClONO_2$ are the most abundant reactive chlorine gases at midlatitudes.

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

By late winter (September), a remarkable change in the composition of the Antarctic stratosphere has taken place. Low amounts of ozone reflect substantial depletion at 18 km altitude over an area larger than the Antarctic continent. Antarctic ozone holes arise from similar chemical destruction throughout much of the altitude range of the ozone layer (see altitude profile in Figure Q11-3). The meteorological and chemical conditions in late winter, characterized by very low temperatures, very low HCl and HNO_3, and very high ClO, are distinctly different from those found in autumn. Low stratospheric temperatures occur during winter, when solar heating is reduced. Low HCl and high ClO reflect the conversion of the reactive halogen reservoir compounds, HCl and $ClONO_2$, to the most reactive form of chlorine, ClO. This conversion occurs selectively in winter on PSCs, which form at very low temperatures (see Q9). Low HNO_3 is indicative of its condensation to form PSCs, some of which subsequently descend to lower altitudes through gravitational settling. High ClO abundances generally cause ozone depletion to continue in the Antarctic region until mid-October (spring), when the lowest ozone values usually are observed (see Q10).

As temperatures rise at the end of the winter, PSC formation is halted, ClO is converted back into the reservoir species HCl and $ClONO_2$ (see Q9), and ozone destruction is curtailed.

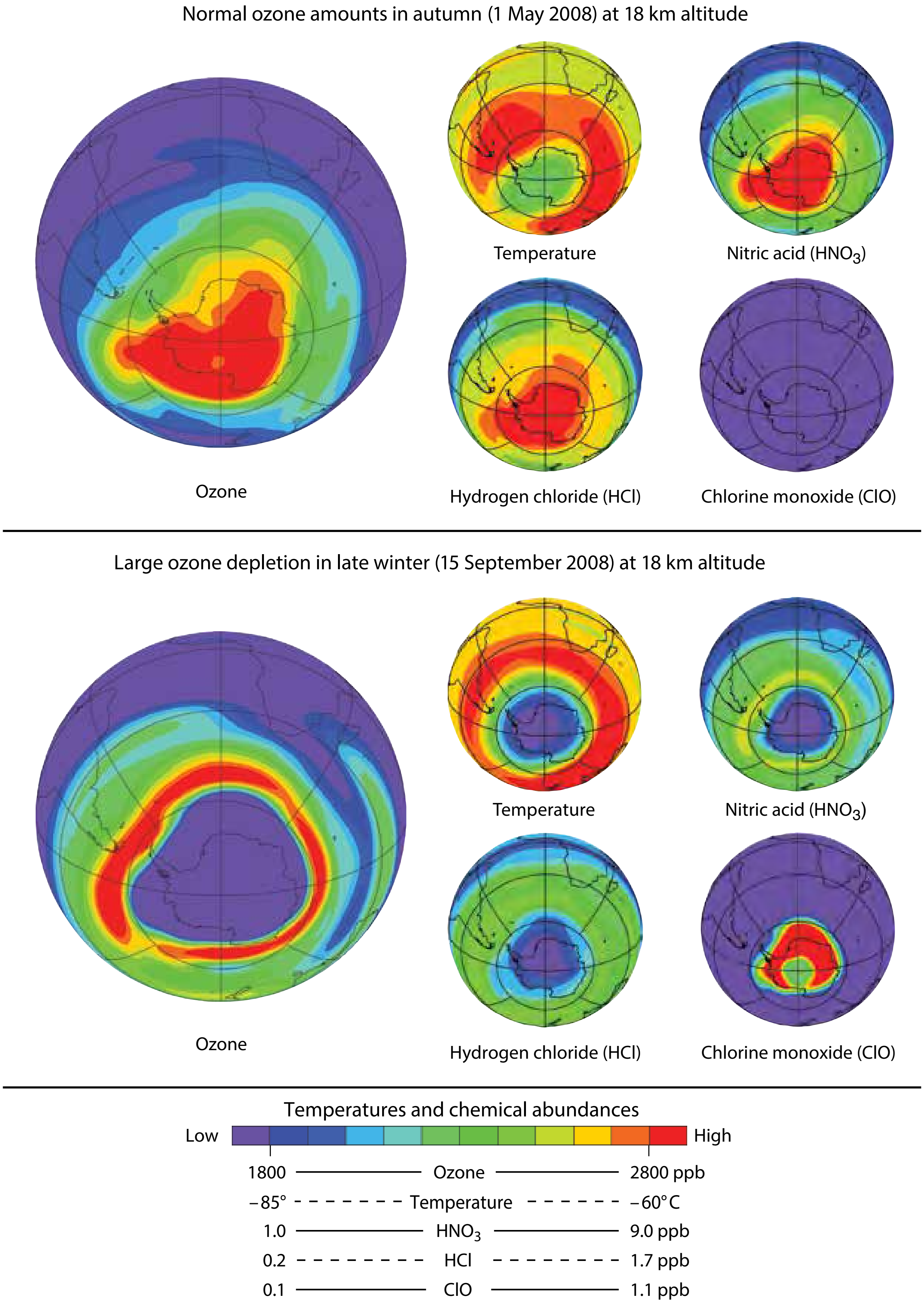
Similar though less dramatic changes in meteorological and chemical conditions are also observed between autumn and late winter in the Arctic, where ozone depletion is less severe than in the Antarctic.

Reactive bromine observations. Fewer measurements are available for reactive bromine gases in the lower stratosphere than for reactive chlorine. This difference arises is in part because of the lower abundance of bromine, which makes quantification of its atmospheric abundance more challenging. The most widely observed bromine gas is BrO, which can be observed from space. Estimates of reactive bromine abundances in the stratosphere are larger than expected from the conversion of the halons and methyl bromide source gases, suggesting that the contribution of the very short-lived bromine-containing gases to reactive bromine must also be significant (see Q6).

Figure Q7-3. Chemical conditions in the ozone layer over Antarctica. Observations of the chemical conditions in the Antarctic region highlight the changes associated with the formation of the ozone hole. Satellite instruments have been routinely monitoring ozone, reactive chlorine gases, and temperatures in the global stratosphere. Results are shown here for autumn (May) and late winter (September) seasons in the Antarctic region, for a narrow altitude region near 18 km (11.2 miles) within the ozone layer (see Figure Q11-3). Ozone has naturally high values in autumn, before the onset of ozone destruction reactions that cause widespread depletion. The high ozone is accompanied by moderate temperatures, high values of HCl and HNO_3, and very low amounts of ClO. When the abundance of ClO is low, significant ozone destruction from halogens does not occur. Chemical conditions are quite different in late winter when ozone undergoes severe depletion. Temperatures are much lower, HCl has been converted to ClO (the most reactive chlorine gas), and HNO_3 has been removed by the gravitational settling of polar stratospheric cloud particles. The abundance of ClO closely surrounding the South Pole is low in September because formation of ClO requires sunlight, which is still gradually returning to the most southerly latitudes. The high values of ClO in late winter cover an extensive area that at times exceeds that of the Antarctic continent and can last for several months, leading to efficient destruction of ozone in sunlit regions in late winter/early spring. Ozone typically reaches its minimum values in early to mid-October (see Q11). Note that the first and last colors in the color bar represent values outside the indicated range of values.

(The unit "parts per billion," abbreviated "ppb," is used here as a measure of the relative abundance of a substance in dry air: 1 part per billion equals the presence of one molecule of a gas per billion ($=10^9$) total air molecules (compare to ppt in Figure Q6-1).)

Chemical Conditions Observed in the Ozone Layer Over Antarctica



Q14

Are there controls on the production of ozone-depleting substances?

Yes, the production and consumption of ozone-depleting substances (ODSs) are controlled under a 1987 international agreement known as the "Montreal Protocol on Substances that Deplete the Ozone Layer" and its subsequent Amendments and Adjustments. The Protocol, now ratified by 198 parties, establishes legally binding controls on national production and consumption of ODSs. Production and consumption of all principal ODSs by developed and developing nations will be almost completely phased out by 2030.

The Vienna Convention and the Montreal Protocol. In 1985, a treaty called the *Vienna Convention for the Protection of the Ozone Layer* was signed by 28 nations in Vienna. The signing nations agreed to take appropriate measures to protect the ozone layer from human activities. The Vienna Convention was a framework agreement that supported research, exchange of information, and future protocols. In response to growing concern, the *Montreal Protocol on Substances that Deplete the Ozone Layer* was signed in 1987 and, following ratification, entered into force in 1989. The Protocol has been successful in establishing legally binding controls for developed and developing nations on the production and consumption of halogen source gases known to cause ozone depletion. Halogen source gases containing chlorine and bromine controlled under the Montreal Protocol are referred to as ozone-depleting substances (ODSs). National consumption of an ODS is defined as production plus imports of the controlled substance, minus exports of the substance. The Protocol provisions are structured for developed countries to act first and for developing countries to follow with some financial assistance. In 2009, the Montreal Protocol became the first multilateral environmental agreement to achieve universal ratification.

Amendments and Adjustments. As the scientific basis of ozone depletion became more certain after 1987 and substitutes and alternatives became available to replace ODSs, the Montreal Protocol was strengthened with Amendments and Adjustments. Each Amendment is named after the city in which the Meeting of the Parties to the Montreal Protocol took place and by the year of the meeting. The timeline in Figure Q0-1 shows some of the major decisions that have been adopted in the last three decades. These decisions listed additional ODSs under control, accelerated the timing of existing control measures, and prescribed phaseout dates for the production and consumption of certain gases. The initial Protocol measures were a 50% reduction in chlorofluorocarbon (CFC) production and a freeze on halon production. The 1990 London Amendment called for a phaseout of the production and consumption of the most damaging ODSs in developed nations by 2000 and in developing nations by 2010. The 1992 Copenhagen Amendment accelerated the phaseout date for CFCs, halons, carbon tetrachloride, and methyl chloroform to 1996 in developed nations and also initiated controls on future production of hydrochlorofluorocarbons (HCFCs) in developed nations. Further controls on ODSs were agreed upon in later meetings in Vienna (1995), Montreal (1997, 2007), and Beijing (1999). The latest development is the 2016 Kigali Amendment (see Q19), which expanded the Montreal Protocol to control production and consumption of certain hydrofluorocarbons (HFCs). As explained below, HFCs are greenhouses gases (GHGs) which warm climate and do not cause ozone depletion.

Influence of the Montreal Protocol. Montreal Protocol controls are based on several factors that are considered separately for each ODS. The factors include (1) the effectiveness in depleting ozone in comparison with other substances (see Ozone Depletion Potential, ODP, in Q17), (2) the availability of suitable substitutes for domestic and industrial use, and (3) the potential impact of controls on developing nations. The influence of Montreal Protocol provisions on stratospheric ODS abundances can be demonstrated with long-term changes in equivalent effective stratospheric chlorine (EESC).

Calculations of EESC combine the amounts of chlorine and bromine present in surface air to form a measure of the potential for ozone destruction in a particular stratospheric region on an annual basis (see definition in Q15). EESC values in the coming decades will be influenced by (1) the slow natural removal of ODSs still present in the atmosphere, (2) emissions from continued production and use of ODSs, and (3) emissions from existing ODS banks containing a variety of compounds. The phrase ODS banks refers to long-term containment of ODSs in various applications. Examples are CFCs in refrigeration equipment and insulating foams, and halons in fire-extinguishing equipment. Annual emissions are projected based on release from existing banks and any new production and consumption of ODSs allowed under the Montreal Protocol. The long-term changes in EESC at midlatitudes are shown in **Figure Q14-1** for several cases:

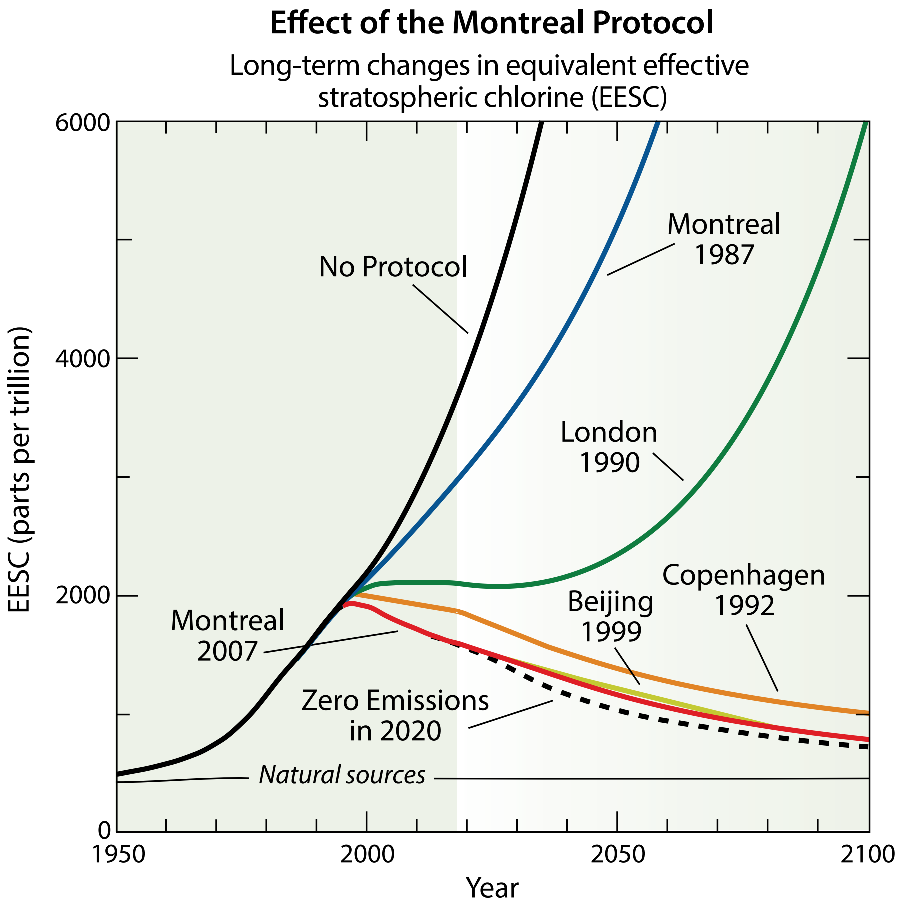


Figure Q14-1. Effect of the Montreal Protocol. The Montreal Protocol protects the ozone layer through control of the global production and consumption of ozone-depleting substances (ODSs). Equivalent effective stratospheric chlorine (EESC) is a quantity that represents the abundance of halogens available for ozone depletion in the stratosphere. Values of EESC are based upon either analysis of surface observations of ODSs (see Q15) or projections of future abundances of ODSs. Projections of EESC for the midlatitude lower stratosphere (about 19 km altitude) are shown separately for: no Protocol provisions; the provisions of the original 1987 Montreal Protocol and some of its subsequent Amendments and Adjustments; and zero emissions of ODSs starting in 2020. The city names and years indicate where and when changes to the original 1987 Protocol provisions were agreed upon (see Figure Q0-1). Without the Protocol, EESC values would have increased significantly in the 21st century, leading to large amounts of ozone depletion throughout the world, including over highly populated regions. Only with the Copenhagen (1992) and subsequent Amendments and Adjustments did projected EESC values show a long-term decrease. The EESC values from observations shown in Figure Q15-1 agree well with the Montreal 2007 curve shown in this figure. The contributions from very short-lived gases (see Figure Q6-1), which have been minor to this point, are not included in any of these EESC time series.

- **No Protocol.** In a scenario without the Montreal Protocol, the production, use and emissions of CFCs and other ODSs continue to increase after 1987 at a rate faster than what actually occurred. This No Protocol scenario is illustrated using an annual growth rate of 3% for the emissions of all ODSs. As a result, EESC increases nearly 10-fold by the mid-2050s compared with the 1980 value. Computer models of the atmosphere show that EESC under the No Protocol scenario doubles global total ozone depletion between 1990 and 2010 relative to what actually occurred, and increases ozone depletion much more by midcentury. As a result, harmful UV-B radiation increases substantially at Earth's surface by the middle of the 21st century, causing damage to ecosystem health, and a global rise in skin cancer and cataract cases (see Q16). Since ODSs are powerful GHGs, the climate forcing from ODSs would have increased substantially without the Montreal Protocol (see Q18).
- **Montreal Protocol provisions.** International compliance with only the 1987 provisions of the Montreal Protocol and the later 1990 London Amendment would have substantially slowed the projected growth of EESC. The projections showed a decrease in future EESC values for the first time with the 1992 Copenhagen Amendments and Adjustments. The provisions became more stringent with

the Amendments and Adjustments adopted in Beijing in 1999 and Montreal in 1997 and 2007. Now, with full compliance to the Protocol, ODSs will ultimately be phased out, with some exemptions for critical uses (see Q15). Global EESC is slowly decaying from its peak value in the late 1990s and is expected to reach 1980 values in the mid-21st century. The success of the Montreal Protocol to date is demonstrated by the decline in ODP-weighted emissions of ODSs shown in Figure Q0-1. Total emissions peaked in 1987 at values about 10-fold higher than natural emissions. Between 1987 and 2018, ODS emissions from human activities have decreased by almost 80%.

- **Zero emissions.** The zero emissions scenario demonstrates the reduction in EESC that occurs if emissions of all ODSs are set to zero beginning in 2020. This assumption eliminates the emissions from new production as well as banks. Significant differences from the Montreal 2007 projections are evident in the first decades following 2020 because the phaseout of all ODS production under the Protocol will not be complete in 2020 and continued bank emissions are substantial. In the zero-emissions scenario, EESC returns to the 1980 value about a decade earlier than currently projected (solid red and dashed black lines, Figure Q14-1).

HCFC substitute gases. The Montreal Protocol provides for the use of hydrochlorofluorocarbons (HCFCs) as transitional, short-term substitute compounds for ODSs with higher ODPs, such as CFC-12. HCFCs are used for refrigeration, in making insulating foams, and as solvents, all of which were primary uses of CFCs. HCFCs are generally more reactive in the troposphere than other ODSs because they contain hydrogen (H) in addition to chlorine, fluorine, and carbon. HCFCs are 88 to 98% less effective than CFC-11 in depleting stratospheric ozone because their chemical removal occurs primarily in the troposphere (see ODPs in Table Q6-1). This removal protects stratospheric ozone from most of the halogen content of HCFC emissions. In contrast, CFCs and some other ODSs release all of their halogen content in the stratosphere because they are chemically inert in the troposphere (see Q5).

Under the provisions of the Montreal Protocol, developed and developing countries may continue to use HCFCs as ODS substitutes in the coming decades before they are ultimately phased out. In the 2007 Adjustment to the Protocol, the phaseout of HCFCs was accelerated so that production ceases by 2020 for developed countries and by 2030 for developing countries, about a decade earlier than in previous provisions. In adopting this decision, the parties reduced the contribution of HCFC emissions to both long-term ozone depletion and future climate forcing (see Q17 and Q18).

HFC substitute gases. Hydrofluorocarbons (HFCs) are used as transitional, short-term substitute compounds for CFCs, HCFCs, and other ODSs. HFCs contain hydrogen, fluorine, and carbon. HFCs do not contribute to ozone depletion because they contain no chlorine or bromine. However, HFCs and all ODSs are also GHGs with long atmosphere lifetimes, so they contribute to human-induced climate change (see Q18 and Q19). Under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), HFCs are included in the basket of controlled GHGs. The Paris Agreement of the UNFCCC is an international accord designed to reduce the emissions of GHGs in order to limit global warming to well below 2.0°C relative to the start of the Industrial Era and pursue efforts to limit global warming to 1.5°C warming. Future growth in the emissions of HFCs with high Global Warming Potentials (GWPs) is limited by the 2016 Kigali Amendment to the Montreal Protocol (see Q19).

Very short-lived chlorine source gases. Very short-lived halogenated source gases, defined as compounds with atmospheric lifetimes shorter than 0.5 years, are primarily converted to reactive halogen gases in the lower atmosphere (troposphere). Atmospheric release of most very short-lived chlorine source gases, such as dichloromethane (CH_2Cl_2), result primarily from human activities. This class of compounds is not regulated by the Montreal Protocol. The atmospheric abundance of very-short lived chlorine source gases has increased substantially since the early 1990s and these gases presently contribute about 3.5% (115 ppt) to the total chlorine entering the stratosphere (see Figure Q6-1). Nonetheless, the estimates of EESC shown in Figure Q14-1 do not include contributions from very short-lived chlorine source gases because prior abundances of key gases such as CH_2Cl_2 exhibit large variability with respect to time and place of observation. Furthermore, projection of future abundances of very short-lived chlorine source gases are highly uncertain due to the lack of information on industrial sources. Should this class of compounds ever pose a threat to the ozone layer, future controls would be effective almost immediately because these compounds are removed from the stratosphere within a few years.