Twenty Questions and Answers About the Ozone Layer: 2018 Update

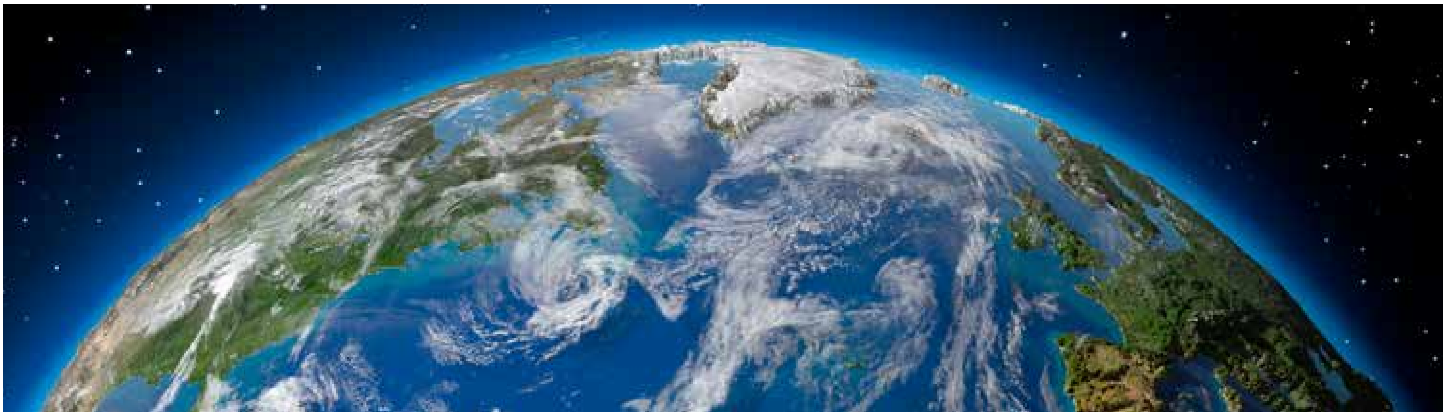
Scientific Assessment of Ozone Depletion: 2018

Lead Author

Ross J. Salawitch

Coauthors

David W. Fahey
Michaela I. Hegglin
Laura A. McBride
Walter R. Tribett
Sarah J. Doherty



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

Q20 How is ozone expected to change in the coming decades?

Substantial recovery of the ozone layer from the effects of ozone-depleting substances (ODSs) is expected around the middle of the 21st century, assuming global compliance with the Montreal Protocol. Recovery will occur as ODSs and reactive halogen gas abundances in the stratosphere decrease in the coming decades. In addition to responding to ODSs, ozone abundances are increasingly being influenced by climate change. The impacts of future climate change on the ozone layer will vary between the tropics, midlatitudes, and polar regions, and strongly depend on future emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). During the long recovery period, large volcanic eruptions could temporarily reduce global ozone amounts for several years.

Substantial recovery from the depletion of global and polar ozone caused by ozone-depleting substances (ODSs) is expected in the middle of this century. The recovery follows from the success of the Montreal Protocol in reducing the global production and consumption of ODSs. Currently, the atmospheric abundances of most major ODSs and the associated annual values of equivalent effective stratospheric chlorine (EESC) are in decline (see Q15). In contrast to the diminishing role of ODSs, changes in climate are expected to have an increasing influence on future levels of total ozone. Climate change is driven by the projected growth in the abundance of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Rising abundances of GHGs will lead to changes in temperature, chemistry, and the circulation of the stratosphere, all of which affect ozone. Chemistry-climate models can be used to project how ozone is expected to respond to changes in ODSs and climate in particular geographical regions during the recovery period. Global events, such as major volcanic eruptions or actions to mitigate global warming by geoengineering, may also influence future ozone levels.

Using chemistry-climate models. Projections of total ozone presented here are based on the results from a group of chemistry-climate models that account for the influences of changes in ODSs and GHGs. These models show how changes in ozone are expected to vary across geographic regions by evaluating the complex interactions of the processes that control ozone and climate involving radiation, chemistry, and transport. Model inputs include historical and projected concentrations of ODSs, CO_2, CH_4, N_2O, air pollutant gases, as well as solar output. The results from chemistry-climate model simulations are used to identify particular processes that are important for future abundances of ozone. For example, model projections for the coming decades show a strengthening in the atmospheric circulation that brings air from the troposphere into the stratosphere in the tropics, moves air poleward into both hemispheres, and then returns air to the troposphere at middle to high latitudes. These circulation changes will significantly alter the global distribution of ozone and the atmospheric lifetimes of ODSs and other long-lived gases. Also, while Earth's surface is expected to continue to warm in response to positive radiative forcing (RF) of climate from GHGs (see Q17), the stratosphere is expected to continue to cool. A colder upper stratosphere leads to increases in ozone because lower temperatures slow down the gas-phase reactions responsible for ozone loss (see box in Q12). Finally, methane and nitrous oxide are both involved in the chemistry that determines future levels of stratospheric ozone.

Simulating recent ozone changes. Comparisons of model results with observations help confirm the causes of ozone depletion and increase confidence in model projections of future ozone amounts. Two important measures are the globally averaged total column ozone (see Q3) as well as total ozone in the Antarctic during October (the month of peak ozone depletion). These are compared to a group of chemistry-climate model simulations in **Figure Q20-1**. Both measures of ozone show substantial depletion since 1980. The average model values of ozone follow the observed general decline in both of these measures, suggesting that the main processes involved in ozone depletion are reasonably well represented by these models. There are significant year-to-year variations in global and Antarctic ozone that are not captured by these simulations. The differences between the observed and modeled values of ozone are due to factors such as interannual meteorological variability and volcanic eruptions that are not well represented in these simulations. Over the past few years, observed global ozone has been about 2.2% lower than the 1964–1980 average and has exhibited no statistically significant trend (see Figure Q12-1). Antarctic ozone during October has exhibited considerable variability with no strong trend over the past 20 years (see Figure Q20-1). However, there are emerging indications that the ozone hole has diminished in size and depth (maximum

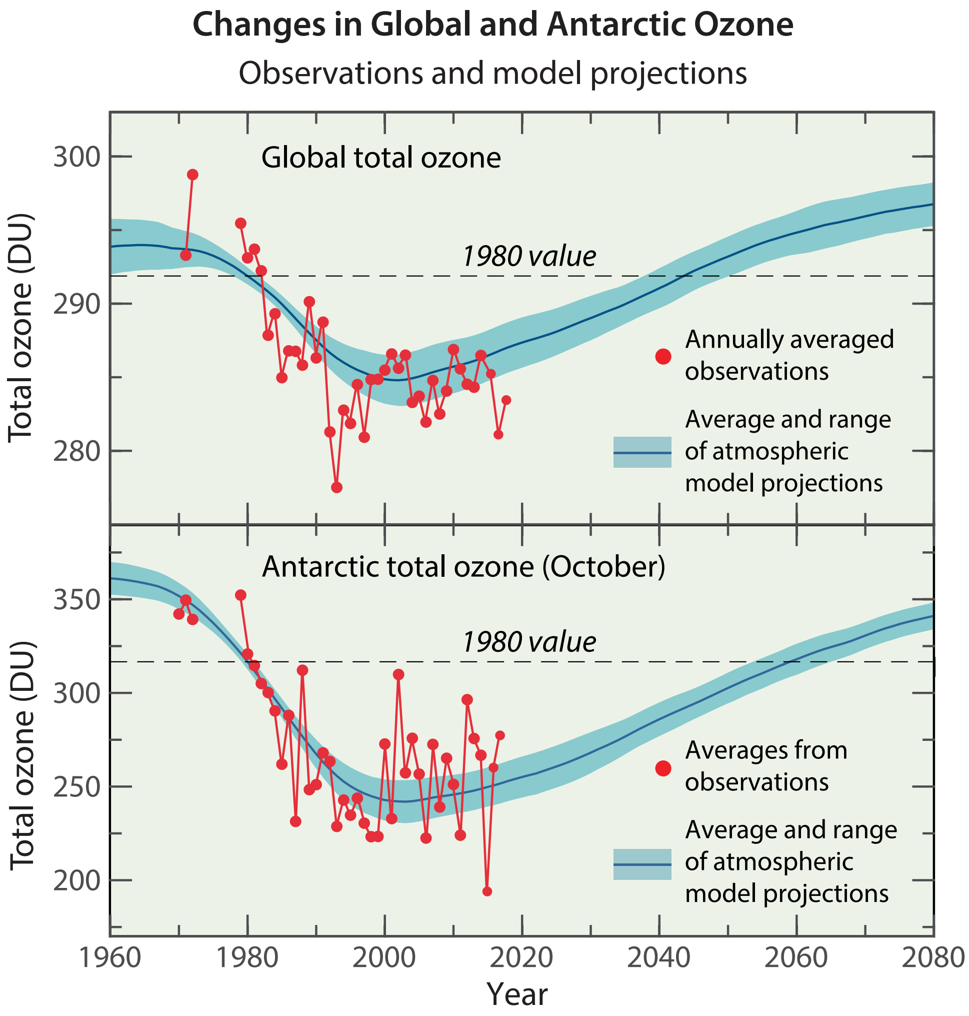


Figure Q20-1. Simulations of ozone depletion. Chemistry-climate models that account for changes in ozone-depleting substances (ODSs) and greenhouse gases are widely used to assess past ozone changes and project future values of ozone. Agreement in comparisons of model results with observations increases confidence in the model projections and our understanding of the processes leading to ozone depletion. Observed values of total ozone averaged over 60°S to 60°N latitude (top panel) and total ozone values over Antarctica during October (bottom panel) decreased during the latter decades of the prior century (red points). Ozone is no longer decreasing in either region. The projections derived from a group of chemistry-climate models (blue shading) generally follow the trend seen in the observations. Differences between models and observations can occur due to natural variations in meteorological conditions, volcanic eruptions, changes in solar activity, or other influences, which are not fully accounted for in the various models. As ODS abundances decrease in this century, chemistry-climate models project global total ozone to increase steadily and exceed 1960 values, and Antarctic ozone during October to approach the 1960 values by the end of the 21st century. The dashed horizontal lines denote the 1980 values of ozone. The bottom panel shows measurements and model output for October, since this is the month of peak ozone depletion in the Antarctic region (see Figure Q10-3).

amount of ozone depletion) since 2000, particularly during early spring (see Figure Q10-2 and box in Q12).

Equivalent effective stratospheric chlorine (EESC) projections. Equivalent effective stratospheric chlorine (EESC) represents how the potential for reactive chlorine and bromine gases to destroy ozone varies over time (see Q15). Output from chemistry-climate models is used to compute EESC as a function of altitude, latitude, longitude, and time. These calculations are based on the history and projections of ODS surface abundances and the chemical and transport processes that control (1) the conversion of ODSs to reactive halogen gases, (2) the distribution of reactive halogen gases in the global stratosphere, and (3) their ultimate removal from the stratosphere. Long-term changes in EESC for five geographic regions as well as the global average are shown in **Figure Q20-2** as the differences relative to the amount present in 1960. For all regions, values of EESC increase smoothly with time starting in 1960, reach a peak near the end of the past century, and decrease gradually until the end of this century. Global and regional values of EESC at the end of this century are very near their 1960 values, indicating that ODSs are largely removed from the stratosphere by that time.

Peak values of EESC, which occur around the year 2000, are highest in the polar regions and lowest in the tropics. In the tropics, stratospheric air has only recently been transported from the troposphere, with the result that only a small fraction of ODSs has undergone conversion to reactive halogen gases (see Q7 and Q12). In polar regions, this fraction is much larger because more conversion can occur over the several years it takes stratospheric air to journey from entry points in the tropics to the stratosphere in both polar regions.

Long-term total ozone projections. Total ozone changes derived from chemistry-climate models, referenced to 1960 values, are shown for 1960 to 2100 in Figure Q20-2. The range of values from the group of models is included in the figure as one measure

Change in Total Ozone and Equivalent Effective Stratospheric Chlorine Since 1960

Results from atmospheric chemistry-climate models for 1960 to 2100

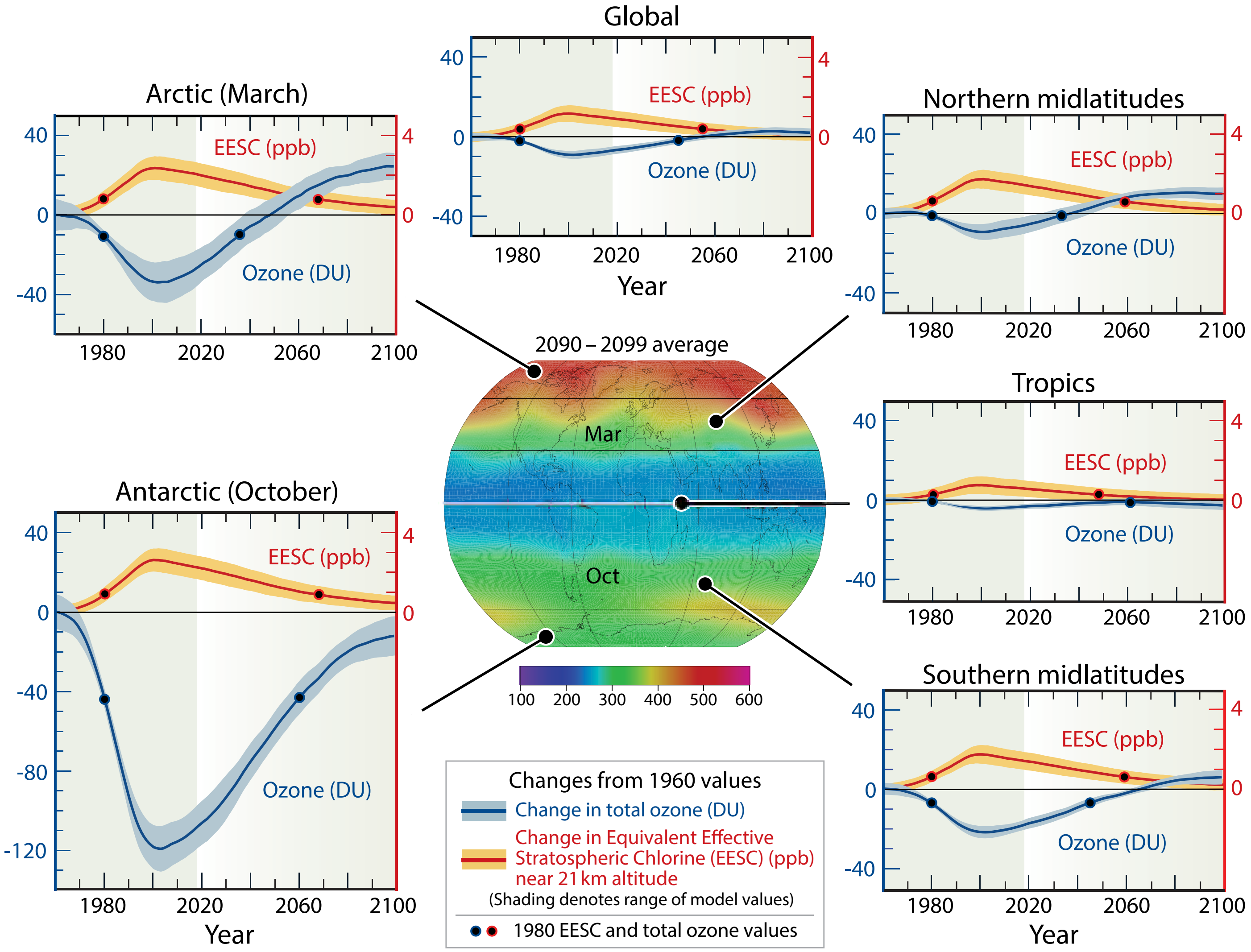


Figure Q20-2. Long-term changes in ozone and stratospheric chlorine. Chemistry-climate models (CCMs) are used to make projections of total ozone amounts that account for the effects of ozone-depleting substances (ODSs) and climate change. Projections of total ozone and equivalent effective stratospheric chlorine (EESC) are shown for various geographic regions as well as 60°S to 60°N latitude (global panel) for the time period 1960–2100. All quantities are displayed relative to values in 1960. The globe in the center shows the projected average total ozone for the last decade of this century, as provided by one of these models, for March in the Northern Hemisphere and October in the Southern Hemisphere. Total ozone depletion increased after 1960 as EESC values steadily increased throughout the stratosphere. Values of EESC have peaked and are now in a slow decline. All of the projections show maximum total ozone depletion around the year 2000, coincident with the highest abundances of EESC. Thereafter, total ozone increases, except in the tropics, as EESC slowly declines. In all the projections except the Antarctic and the tropics, total ozone returns to 1960 values by midcentury, which is earlier than expected from the decrease in EESC alone. The earlier returns are attributable to climate change driven by rising levels of greenhouse gases (GHGs), which influences total ozone through changes in stratospheric transport and temperatures, as well as chemical effects of CH_4 and N_2O (see Figure Q20-3). In the tropics, climate change causes total ozone to remain below 1960 values throughout the century, due to enhanced transport of ozone out of the tropics by a strengthened stratospheric circulation. In the Antarctic, the effect of climate change is smaller than in other regions. As a result, Antarctic total ozone in springtime mirrors the changes in EESC, with both closely approaching 1960 values at the end of the century. The dots on each curve mark the occurrences of 1980 values of total ozone and EESC. The equal vertical scales in each panel allow direct comparisons of ozone and EESC changes between regions. (The CCM projections utilize abundances of GHGs from the RCP 6.0 scenario and ODSs from the baseline (A1) scenario of the 2010 *Scientific Assessment of Ozone Depletion* report. The quantity termed EESC in this figure is sometimes referred to as Equivalent Stratospheric Chlorine (ESC) when derived from the output of chemistry-climate models.)

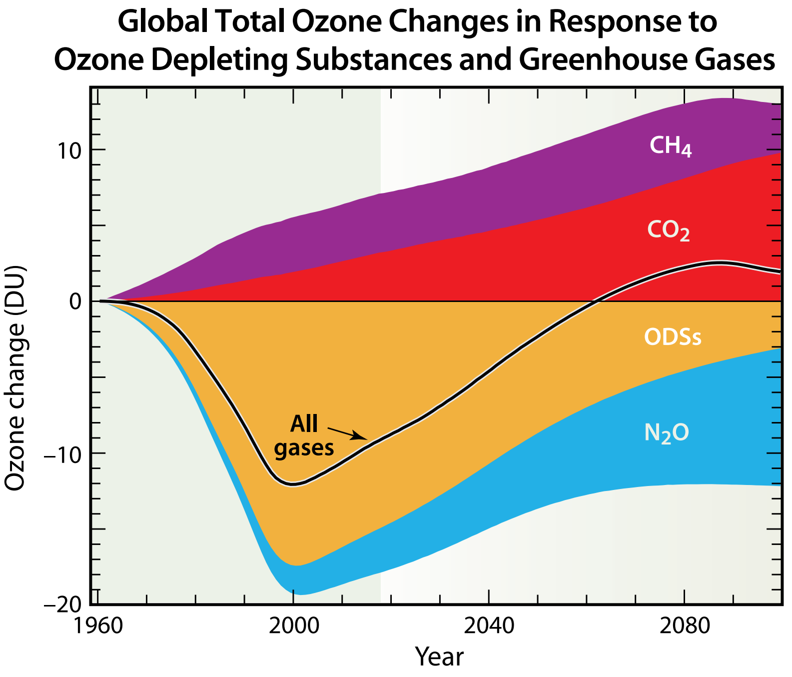


Figure Q20-3. Global total ozone changes in response to increasing greenhouse gases. Model simulations that represent individual changes in the greenhouse gases CO_2, CH_4, and N_2O, as well as ODSs, illustrate how each particular gas (or family of gases for ODSs) affects total ozone averaged over 60°S to 60°N latitude. Increasing CO_2 results in lower temperatures throughout the stratosphere. Lower temperatures slow down the rate of most ozone destruction reactions, particularly those that regulate the abundance of ozone outside of polar regions, leading to an increase in global ozone. Rising CH_4 leads to changes in stratospheric chemistry that augment the increase in ozone driven by stratospheric cooling. Conversely, the expected future increase in N_2O results in significant decreases in global ozone due to chemical effects. As the atmospheric abundance of ODSs declines towards the end of this century, ozone reductions due to increasing N_2O may become more prominent. The "All gases" scenario represents the combined effect of CO_2, CH_4, N_2O, and ODSs in a model simulation. In this scenario, global total ozone is projected to exceed the 1960 value towards the end of this century. When global total ozone exceeds the 1960 value, which can only occur once the abundance of ODSs have steeply declined, the condition is termed super-recovery of the ozone layer. The response of ozone varies according to geographic region, with some regions projected to experience super-recovery sooner than others (see Figure Q20-2).

(These projections utilize abundances for CO_2, CH_4, N_2O from the RCP 6.0 scenario and ODSs from the baseline (A1) scenario of the 2010 *Scientific Assessment of Ozone Depletion* report.)

of the uncertainty in the model projections. These simulations utilize abundances of CO_2, CH_4, and N_2O from a particular projection developed for climate models termed Representative Concentration Pathway 6.0 (RCP6.0), coupled with the projected abundances of ODSs given in the 2010 *Scientific Assessment of Ozone Depletion* report (see caption). Total ozone changes in the various regions are described as follows:

- **Antarctic.** Total ozone changes are largest in the Antarctic region in springtime (October). Chemistry-climate models show that ODSs are the predominant factor in Antarctic ozone depletion in the past and in the coming decades. Changes in climate parameters have a smaller role. As a result, changes in total ozone mostly mirror changes in EESC: as EESC increases, ozone proportionately decreases; as EESC decreases, ozone proportionately increases. Meteorological variability in the Antarctic in late winter/early spring when ozone depletion occurs causes a large range in the model projections. Antarctic total ozone is projected to return to 1980 levels after midcentury, which is later than found for most other regions.
- **Arctic**. Total ozone changes in the Arctic region in springtime (March) are considerably smaller than in the Antarctic. In contrast to the Antarctic, ozone changes do not closely mirror changes in EESC. After midcentury, Arctic total ozone increases to values above those that would be expected from EESC reductions alone because of the strengthening of atmospheric circulation and enhanced stratospheric cooling associated with increases in GHGs such as CO_2. By 2100 Arctic total ozone is projected to be well above both the 1960 and 1980 values. The large range in projections compared to other nonpolar regions is due to greater meteorological variability, as noted for the Antarctic. Arctic total ozone is projected to return to the 1980 level in the mid-2030s, about three decades before EESC returns to its 1980 level.
- **Northern and southern midlatitudes.** The annual averages of total ozone changes in midlatitudes are much smaller than the springtime losses in polar regions. In the northern midlatitudes, the models predict a return of total ozone to the 1960 value in the early 2030s, whereas EESC requires the full century to return close to the 1960 value. In the southern midlatitudes, total ozone returns to the 1960 level by mid-century, somewhat later than found for the Northern Hemisphere. The maximum ozone depletion near the year 2000 is much larger for the Southern Hemisphere, and total ozone more closely follows EESC. This behavior reflects the influence of the Antarctic ozone hole on the southern midlatitudes from the transport of ozone-depleted air following

the breakup of the polar vortex in late spring (see Q10). The more rapid return of total ozone to 1960 values for both regions, compared to the return of EESC, reflects the influence of climate-induced changes in stratospheric circulation and upper stratospheric temperatures. After returning to the 1960 value, total ozone continues to increase in both hemispheres and significantly exceeds that value by 2100.

- **Tropics.** Total ozone changes in the tropics are smaller than in any other region. Ozone is less sensitive to ODSs in the tropical stratosphere because of the dominant roles of production and transport in controlling ozone and the low amounts of EESC available in this region. In contrast to other regions, chemistry-climate models project total ozone to remain below the 1960 value throughout this century. Total ozone gradually returns to the 1980 level around 2060, and then decreases gradually until the end of the century. The decline of tropical ozone during the latter part of the century is primarily due to a strengthening of the stratospheric circulation, which leads to enhanced transport of ozone out of the tropics and into midlatitudes. This circulation change also influences the Arctic and midlatitude regions, as noted above.
- **The globe.** The annual average of global (60°S to 60°N) total ozone is projected to return to the 1960 level around 2060, while EESC returns to its 1960 value near the end of the century. Ozone returns to the 1980 value near 2047, about a decade prior to the return of EESC to its 1980 level. By the end of the century the abundance of global total ozone is projected to be 3 DU larger than the 1960 level, a 1% increase. Chemistry-climate model analysis suggests the early return of total ozone relative to EESC, as well as the end of century rise, are primarily a result of upper stratospheric cooling.

Future ultraviolet radiation. Projections of long-term changes in total ozone can be used to estimate long-term changes in solar ultraviolet (UV) radiation reaching Earth's surface (see Q16). The UV-B component of ultraviolet radiation (see Q2) decreases as total ozone increases. Based on the ozone increases in the chemistry-climate model projections, clear-sky UV-B radiation is expected to be substantially below the 1960 value by the end of the century across much of the globe. The latitude regions expected to continue experiencing elevated UV-B radiation values are the Antarctic and the tropics, where total ozone remains below the respective 1960 values until the end of the century.

Future compliance with the Montreal Protocol. Recovery of the stratospheric ozone layer requires full compliance with the Montreal Protocol. In recent years, the decline in CFC-11 has slowed measurably relative to the expected decline, due to emissions from unreported production (see Q15). The simulations shown here assume full compliance with the Montreal Protocol in the future.

Greenhouse gas emission scenarios and the influence on future ozone. The influence of climate change on future ozone in Figure Q20-2 as discussed above was derived using a particular GHG emission scenario, termed RCP 6.0. Emission scenarios specify the amounts of GHGs emitted into the atmosphere in the future and are constructed based on socio-economic assumptions of future population growth, economic developments, technology innovation, and political decisions. The RCP 6.0 projection is a mid-range scenario with the abundance of CO_2 and N_2O increasing until the end of this century and the abundance of CH_4 peaking in 2070. Chemistry-climate model simulations show that the evolution of ozone and the resulting surface UV-B levels in different regions of the world are strongly dependent on the future atmospheric abundances of CO_2, CH_4, and N_2O, the three most important human-driven GHGs.

Simulations with a model using the projected, individual increases of CO_2, CH_4, N_2O, and ODSs in RCP 6.0 illustrate the impacts of these different GHGs on ozone (see **Figure Q20-3**). The simulation using only an increase of atmospheric CO_2 shows rising future levels of ozone, which is caused by the projected decrease in stratosphere temperatures. As detailed above, lower temperatures in the upper stratosphere slow down the gas-phase chemical reactions that destroy ozone. Simulations using individual increases in CH_4 and N_2O show that the main effect of rising CH_4 is to increase ozone, while that of rising N_2O is to decrease ozone. The stratospheric decomposition of CH_4 leads to more reactive hydrogen gases that produce ozone in the lowest parts of the stratosphere and increase the conversion of reactive chlorine into its reservoir gas HCl (see Q7). CH_4 decomposition also leads to larger abundances of H_2O that cool the upper stratosphere, slowing down ozone loss reactions. Conversely, the decomposition of N_2O produces reactive nitrogen gases that destroy ozone (see Q8). By the end of the century, increased abundances of N_2O deplete more ozone than ODSs for the scenario used here (RCP 6.0).

The combined effect of changes in ODSs, CO_2, CH_4, and N_2O on globally averaged total column ozone (line marked "All gases") is a balance of the separate contributions of the different gases that act to increase and decrease ozone. In the last decades of this century, this balance results in ozone levels that are just above 1960 values. The wide range of possible future levels of CO_2, CH_4, and N_2O is an important limitation to providing accurate future projections of total column ozone.

Volcanoes and geoengineering. Other factors not included in chemistry-climate model projections shown above have the potential to affect future amounts of total ozone. For example, explosive volcanic eruptions have temporarily reduced global total ozone in the past (see Q13) by enhancing the stratospheric sulfate aerosol layer. Similar volcanic eruptions, especially until the middle of this century while EESC values are high, are also expected to reduce total ozone for a few years. Volcanic eruptions are an additional source of uncertainty that cannot be included in the ozone projections in Figures Q20-2 and Q20-3.

Several *geoengineering* (or climate intervention) methods have been proposed to reduce climate forcing from human activities.

A widely discussed method is the intentional enhancement of sulfate aerosols in the stratosphere from direct injections of sulfur-containing substances. With sufficient enhancement, the added aerosols will cool the climate system through increased reflection of sunlight back to space, similar to the effect observed after some explosive volcanic eruptions. Reducing global radiative forcing for an extended period of time requires sustained enhancements of stratospheric sulfate, due to the short lifetime of these stratospheric aerosols (see Q13). Sustained enhancements of stratospheric sulfate large enough to offset climate forcing due to GHGs are likely to have unintended consequences, such as reductions in global total ozone, a delay in the recovery of the ozone hole, and changes in stratospheric temperatures and circulation. Alterations in precipitation amounts and patterns may also occur. These responses are sensitive to variables such as the amount, altitude, geographic location, and type of sulfur injection as well as the value of EESC at the time of climate intervention. Much less is known about the effects on ozone that might occur from enhancing the stratospheric aerosol layer with substances that do not contain sulfur.

Terminology

CCM	chemistry-climate model
CFC	chlorofluorocarbon, a group of industrial compounds that contains at least one chlorine, fluorine, and carbon atom
CFC-11-equivalent	a unit for the measure of the mass of emission of an ODS, equal to the product of the actual mass emission of the ODS times its ODP
CO_2-equivalent	a unit for the measure of the mass of emission of a GHG, equal to the product of the actual mass emission of the GHG times its GWP
DU	Dobson unit, a measure of total column ozone; 1 DU = 2.687×10^{16} molecules/cm^2
EESC	equivalent effective stratospheric chlorine, a measure of the total amount of reactive chlorine and bromine gases in the stratosphere that is available to deplete stratospheric ozone
GHG	greenhouse gas
gigatonne	1 billion (10^9) metric tons = 1 trillion (10^{12}) kilograms
GWP	global warming potential, a measure of the effectiveness of the emission of a gas to cause an increase in the radiative forcing of climate, relative to the radiative forcing caused by the emission of the same mass of CO_2; all GWPs used here are for a 100-year time interval
halon	a group of industrial compounds that contain at least one bromine and carbon atom; may or may not contain a chlorine atom
HCFC	hydrochlorofluorocarbon, a group of industrial compounds that contain at least one hydrogen, chlorine, fluorine, and carbon atom
HFC	hydrofluorocarbon, a group of industrial compounds that contain at least one hydrogen, fluorine, and carbon atom and no chlorine or bromine atoms
HFO	hydrofluoroolefin, a group of industrial compounds that contain at least one hydrogen, fluorine, and carbon atom and no chlorine or bromine atoms, and also include a double carbon bond that causes these gases to be more reactive in the troposphere than other HFCs
IPCC	Intergovernmental Panel on Climate Change
kilotonne	1000 metric tons = 1 million (10^6) kilograms
megatonne	1 million (10^6) metric tons = 1 billion (10^9) kilograms
mPa	millipascal; 100 million mPa = atmospheric sea-level pressure
nm	nanometer, one billionth of a meter (10^{-9} m)
ODP	ozone-depletion potential, a measure of the effectiveness of the emission of a gas to deplete the ozone layer, relative to the ozone depletion caused by the emission of the same mass of CFC-11
ODS	ozone-depleting substance
ozone layer	the region in the stratosphere with the highest concentration of ozone, between about 15 and 35 km altitude
ppb	parts per billion; 1 part per billion equals the presence of one molecule of a gas per billion (10^9) total air molecules
ppm	parts per million; 1 part per million equals the presence of one molecule of a gas per million (10^6) total air molecules
ppt	parts per trillion; 1 part per trillion equals the presence of one molecule of a gas per trillion (10^{12}) total air molecules
PFC	perfluorocarbon, a group of industrial compounds that contain only carbon and fluorine atoms
PSC	polar stratospheric cloud
RCP	Representative Concentration Pathway
RF	radiative forcing of climate
SAOD	stratospheric aerosol optical depth
stratosphere	layer of the atmosphere above the troposphere that extends up to around 50 km altitude, and that includes the ozone layer
TEAP	Technology and Economic Assessment Panel of the Montreal Protocol
troposphere	lower layer of the atmosphere that extends from the surface to about 10-15 km (6-9 miles) altitude
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

UV	ultraviolet radiation
UV-A	ultraviolet radiation between wavelengths of 315 and 400 nm
UV-B	ultraviolet radiation between wavelengths of 280 and 315 nm
UV-C	ultraviolet radiation between wavelengths of 100 and 280 nm
WMO	World Meteorological Organization

Chemical Formulae

Bromine Compounds:

$CBrClF_2$	halon-1211
$CBrF_3$	halon-1301
$CBrF_2CBrF_2$	halon-2402
CH_2Br_2	dibromomethane
$CHBr_3$	bromoform
CH_3Br	methyl bromide
Br	atomic bromine
BrO	bromine monoxide
BrCl	bromine monochloride

Chlorine Compounds:

CCl_3F	CFC-11
CCl_2F_2	CFC-12
CCl_2FCClF_2	CFC-113
CCl_4	carbon tetrachloride
CH_2Cl_2	dichloromethane
CH_3CCl_3	methyl chloroform
CH_3Cl	methyl chloride
CHF_2Cl	HCFC-22
CH_3CCl_2F	HCFC-141b
CH_3CClF_2	HCFC-142b
Cl	atomic chlorine
ClO	chlorine monoxide
$(ClO)_2$	chlorine monoxide dimer, chemical structure ClOOCl
$ClONO_2$	chlorine nitrate
HCl	hydrogen chloride

Other Halogens:

CHF_3	HFC-23
CH_2F_2	HFC-32
CHF_2CF_3	HFC-125
CH_2FCF_3	HFC-134a
CH_3CF_3	HFC-143a
CH_3CHF_2	HFC-152a
$CF_3CF{=}CH_2$	HFO-1234yf
CF_4	carbon tetrafluoride
C_2F_6	perfluoroethane
IO	iodine monoxide
SF_6	sulfur hexafluoride

Other gases:

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H	atomic hydrogen
H_2O	water vapor
HNO_3	nitric acid
H_2SO_4	sulfuric acid
N_2	molecular nitrogen
N_2O	nitrous oxide
NO_x	nitrogen oxides
O	atomic oxygen
O_2	molecular oxygen
O_3	ozone