

# Q20

## How is stratospheric ozone expected to change in the coming decades?

*Recovery of the global 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 will increasingly be 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<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). During the long recovery period, large volcanic eruptions could temporarily reduce global ozone amounts for several years.*

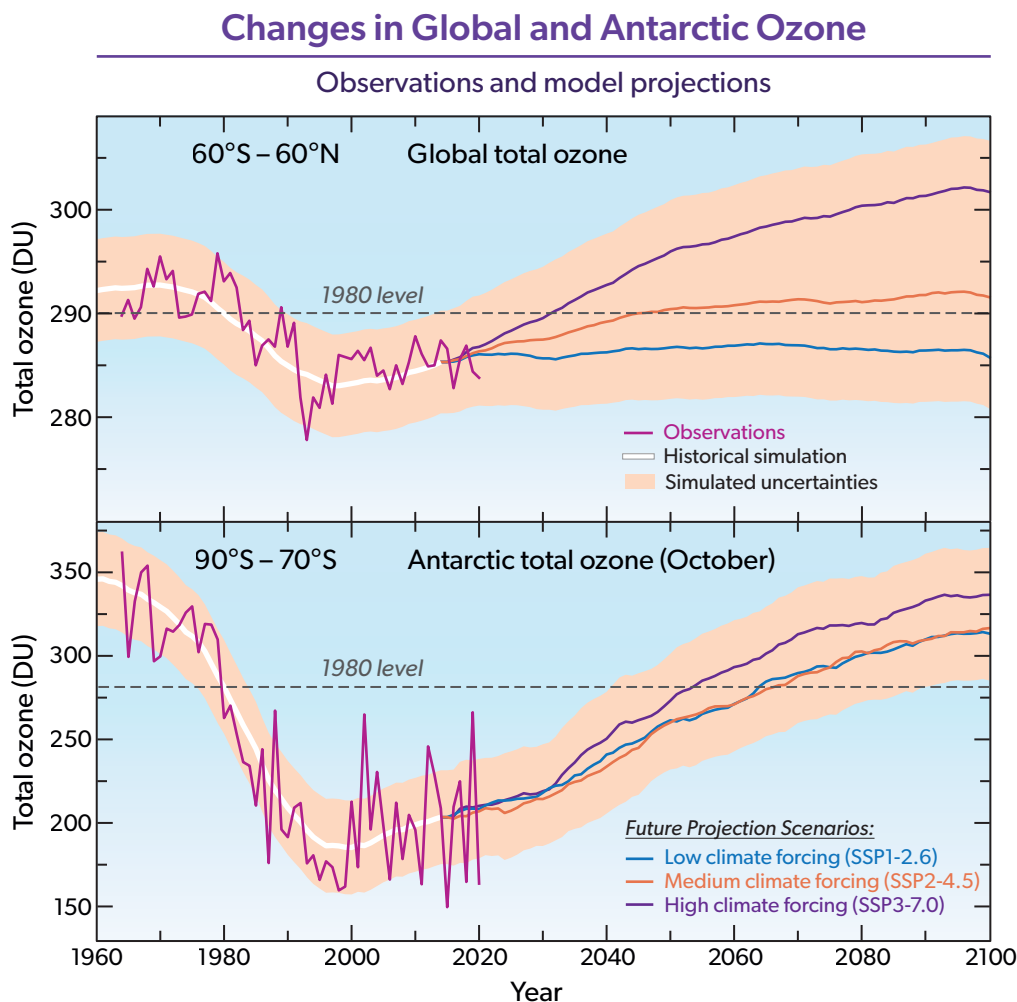
The expected recovery of the global and polar ozone layer is a direct consequence of the success of the Montreal Protocol in reducing the global production and consumption of ODSs. Currently, the atmospheric abundances of most major ODSs and the associated annual values of equivalent effective stratospheric 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<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). Increasing amounts 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 geographic regions during the recovery period. Sporadic events such as major volcanic eruptions and wildfires, or deliberate actions such as the injection of aerosols into the stratosphere to mitigate global warming may also influence future ozone levels.

**Using chemistry-climate models.** Chemistry-climate models (CCMs) are complex computer programs that simulate temperature, winds, radiation, and the chemical composition of the atmosphere, including stratospheric ozone. The simulations of ozone are conducted as a function of time, altitude, and geographic location. 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 of chemicals by stratospheric winds. Model inputs include historical and projected concentrations of ODSs, GHGs (including CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), air pollutant gases, as well as incoming solar radiation. 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 driven by increases in the atmospheric abundance of GHGs over the coming decades show a strengthening in the global-scale atmospheric circulation that brings air from the troposphere into

the stratosphere in the tropics, moves stratospheric 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 (see Q6). Also, while Earth's surface is expected to continue to warm in response to positive radiative forcing 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. Conversely, colder conditions at lower altitudes in the polar stratosphere have the potential to exacerbate ozone loss, especially if the presence of polar stratospheric clouds (PSCs) increases.

Methane and nitrous oxide are both involved in the chemistry that determines levels of stratospheric ozone. The main effect of higher amounts of CH<sub>4</sub> is to increase ozone, while that of rising N<sub>2</sub>O is to decrease ozone. The stratospheric decomposition of CH<sub>4</sub> leads to more reactive hydrogen gases that produce ozone in the lowest parts of the stratosphere and increases the conversion of reactive chlorine into its reservoir gas HCl (see Q7). The decomposition of CH<sub>4</sub> also leads to larger abundances of H<sub>2</sub>O, which cool the upper stratosphere, slowing down ozone loss reactions. Conversely, the decomposition of N<sub>2</sub>O produces reactive nitrogen gases that destroy ozone (see Q8). The effect of higher amounts of N<sub>2</sub>O on the depletion of the ozone layer becomes increasingly important as halogen levels decline.

**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 outside of polar regions (see Q3) and total ozone in the Antarctic during October (the month of peak ozone depletion). These observations are compared to simulations from a group of chemistry-climate models in **Figure Q20-1**. Both time series of ozone show substantial depletion since 1980. The average model values of ozone follow the observed general decline in both regions, suggesting that the main processes involved in ozone depletion are well represented by these models.



**Figure Q20-1. Simulations of ozone depletion.** Chemistry-climate model (CCM) simulations that account for changes in ozone-depleting substances (ODSs) and greenhouse gases (GHGs) are widely used to assess past ozone changes and project future values of ozone. Agreement between model results and observations increases confidence in the model projections and our understanding of the processes leading to ozone depletion. Observed values of total ozone (in Dobson units, DU) annually averaged over 60°S–60°N latitude (top panel) and total ozone values over 70°S–90°S during October (bottom panel) decreased during the latter decades of the prior century (magenta lines). Future ODS projections assume compliance with the Montreal Protocol, and future abundances of GHGs follow either the SSP1-2.6 (low climate forcing), SSP2-4.5 (medium climate forcing), or SSP3-7.0 (high climate forcing) scenario for 2015–2100. The simulation uncertainties for modeled ozone represent the standard deviation about the multi-model mean (MMM), either added to the SSP3-7.0 MMM (upper limit) or subtracted from the SSP1-2.6 MMM (lower limit). As ODS abundances decrease in this century, CCMs project global total ozone to increase steadily and exceed the 1980 value by mid-century for the medium climate forcing scenario. Antarctic ozone during October is projected to exceed the 1980 values around mid-century for all three scenarios.

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 that are not well represented in these simulations. Over the time period 1996–2020, observed global ozone has exhibited considerable variability and risen slightly, by less than 1% (see Q12). Antarctic ozone during October has exhibited even more year-to-year variability, but there are emerging indications that the ozone hole has diminished in size and depth (maximum amount of ozone deple-

tion) since 2000, particularly during September when the effects of meteorological variability are smaller (see Q10).

**Long-term total ozone projections.** Total ozone changes derived from chemistry-climate models are shown for 1960 to 2100 in Figure Q20-1. These simulations use the projected abundances of ODSs given in the 2018 Scientific Assessment of Ozone Depletion report. A computation of EESC (see Q15) based on this 2018 projection of ODSs shows a return to the 1980 level in years 2061 and 2077 for the midlatitude and polar stratospheres, respectively.

The model simulations shown in Figure Q20-1 use projections of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O termed the Shared Socioeconomic Pathways (SSPs). Each SSP provides an estimate of future abundances of GHGs based on projected emissions, which are constructed using various assumptions of population growth and economic development, as well as technological innovation and political decisions related to the environment. Figure Q20-1 shows the evolution of annually averaged ozone outside the polar regions (60°S–60°N) (top) and ozone during October at 70°S–90°S (bottom), for a high climate forcing scenario (SSP3-7.0; purple line), a medium scenario (SSP2-4.5; dark orange line), and a low scenario (SSP1-2.6; blue line). These three lines represent the multi-model mean (MMM) projection from numerous CCMs.

These simulations show that the future recovery of the ozone layer outside of the polar regions will be governed mostly by GHGs, assuming continued adherence to the Montreal Protocol. The wide range of possible future levels of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O is an important limitation to providing accurate future projections of ozone globally and for the ozone hole (Figure Q20-1), as well as in other geographic regions. For 60°S–60°N, total ozone recovers to the 1980 level more rapidly under the high climate forcing scenario because large future increases in both CO<sub>2</sub> and CH<sub>4</sub> tend to increase ozone. Under the low climate forcing scenario, the MMM of the CCMs projects that ozone over 60°S–60°N may not reach the 1980 level by the end of this century. In this low climate forcing simulation, future declines in total ozone driven by rising N<sub>2</sub>O outweigh the small future ozone increases caused by CO<sub>2</sub> and CH<sub>4</sub>. For the MMM of the medium climate forcing scenario (dark orange line in Figure Q20-1), total ozone over 60°S–60°N is projected to return to the 1980 level around year 2040.

The one-standard deviation range of computed values of ozone from these CCMs for all three scenarios is shown by the orange shaded region in Figure Q20-1 (see caption), which depicts the uncertainty in the model projections of ozone for both regions. There is a considerable range of model projections for total ozone at the end of the century for 60°S–60°N, because of sensitivity to the actual future abundance of GHGs for the three scenarios considered here, as well as variations among CCMs regarding how the stratospheric circulation will actually respond to a specific GHG scenario. The CCM simulations in Figure Q20-1 show that for the Antarctic ozone hole (October, 70°S–90°S) the future evolution of total ozone is largely governed by ODSs, with modest sensitivity to GHGs. Here, total ozone is projected to return to the 1980 level in 2066 for both the low and medium climate forcing scenarios (blue and dark orange lines, Figure Q20-1). Under the high climate forcing scenario, a more rapid recovery of October total ozone for 70°S–90°S is projected, with a return to the 1980 level at mid-century. Because of the impact of GHGs, these recovery years for the return of Antarctic total ozone to the 1980 level precede 2078, which is the year EESC is projected to return to its 1980 level for the polar stratosphere.

The multi-model mean of CCM simulations conducted for Northern Hemisphere (NH) midlatitudes (35°N–60°N) and Southern Hemisphere (SH) midlatitudes (35°S–60°S) (results not shown) project a return of total ozone to the 1980 level around years 2035 and 2045, respectively, for the medium climate forcing scenario. The faster return of total ozone to the 1980 level forecast for NH

midlatitudes under this scenario is caused by a greater sensitivity of ozone to future abundances of GHGs in the NH compared to the SH, as explained below. The return to the 1980 level of total ozone for both NH and SH midlatitudes occurs considerably sooner than year 2061, when EESC is projected to return to the 1980 level. Finally, the MMM of CCM simulations for the tropics (20°S–20°N) (results not shown) under the medium climate forcing scenario indicates that total ozone will remain below the 1980 level until the end of this century.

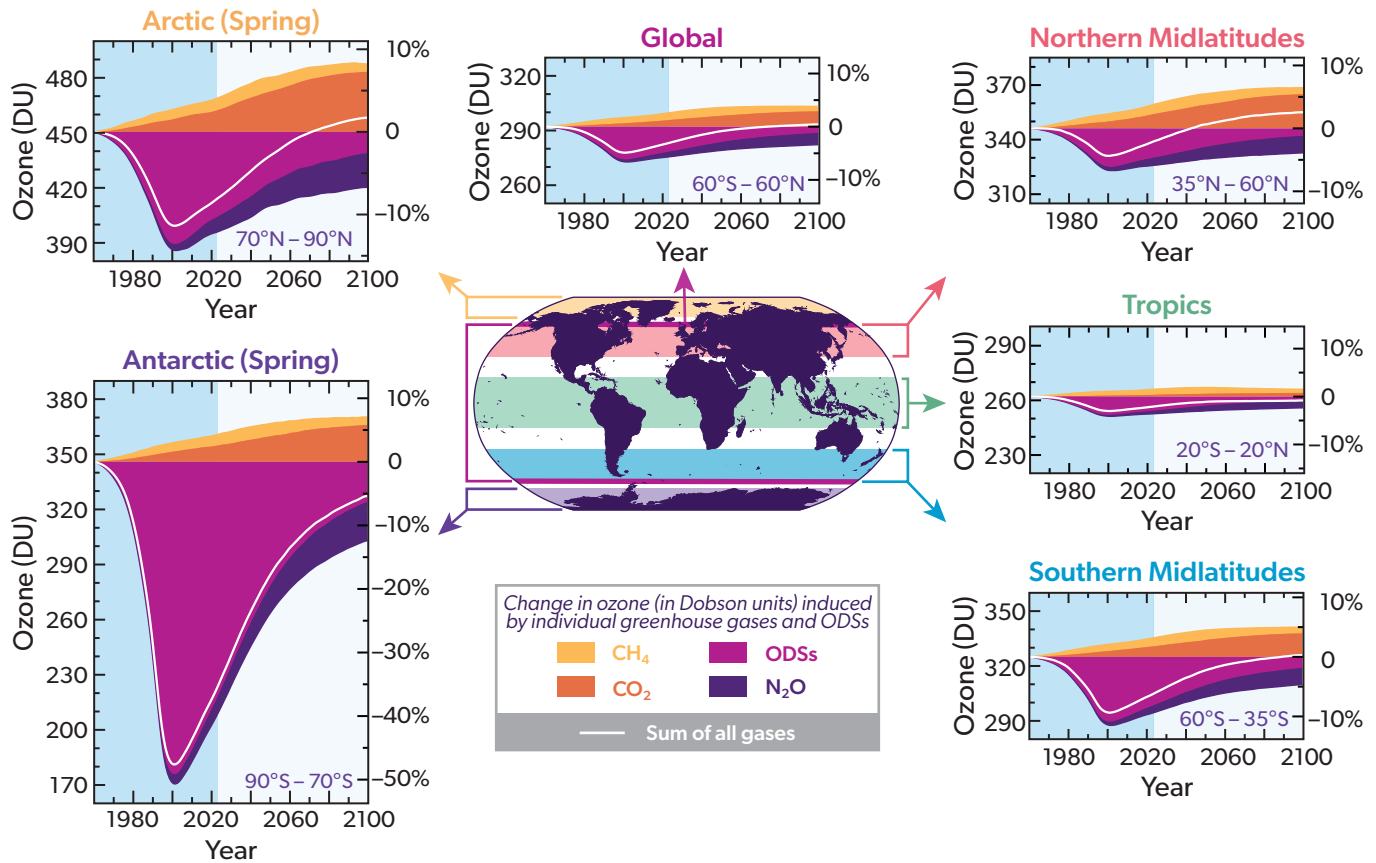
**Figure Q20-2** illustrates, for six geographic regions, the combined effect on ozone of future changes in ODSs, the GHGs CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O (white line marked “Sum of all gases”) as well as the individual effect on ozone of each GHG and all ODSs. These effects on ozone are determined by varying the abundance of each quantity individually, while holding the abundances of the others constant at their level in 1960. All of the results shown in Figure Q20-2 are for the medium climate forcing SSP2-4.5 scenario and rely on simulations from a single CCM. As such, the timing of the recovery of ozone to the 1980 level differs slightly from the values stated above, which are based on the MMM of simulations from numerous CCMs. In Figure Q20-2 the change of ozone is shown relative to the 1960 level to more clearly display the results prior to 1980.

The breakdown of individual drivers of future ozone for these six selected regions shown in Figure Q20-2 is an illustrative example of the complexity of projecting the future recovery of stratospheric ozone, as the sensitivity to various factors differs markedly between regions.

Future changes in total ozone for the various regions are described with respect to a return to the level in year 1960 (see figure caption):

- **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. The future increase of CO<sub>2</sub> and CH<sub>4</sub> in this scenario acts to increase ozone, while the future increase in N<sub>2</sub>O decreases ozone. All of these impacts on ozone are smaller than the present impact of ODSs, and the effects of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O nearly cancel one another later in the century. As a result, changes in total ozone when all forcings are considered (white line) mostly follow the change driven by ODSs (dark pink shaded region). Although meteorological variability in the Antarctic in late winter/early spring when ozone depletion occurs causes a substantial range in the observations and model projections (see Figure Q20-1), Antarctic total ozone is projected to remain below the 1960 level throughout the rest of this century.
- **Arctic.** Total ozone changes in the Arctic during spring (March) are considerably smaller than in the Antarctic (see Q11). After midcentury, Arctic total ozone increases to values above those expected from future reductions in ODSs alone because of the strengthening of atmospheric circulation and enhanced stratospheric cooling associated with increases in GHGs such as CO<sub>2</sub>. For this medium climate forcing scenario, Arctic spring total ozone is projected to exceed the 1960 level after around 2065.

## Total Ozone Changes in Response to Ozone-Depleting Substances and Greenhouse Gases



**Figure Q20-2. Total ozone changes in response to greenhouse gases and ODSs.** Results from model simulations of a single CCM show the sensitivity of total ozone to individual changes in the abundances of the greenhouse gases CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O as well as to ODSs starting in 1960. These total ozone changes (in Dobson units, DU) are shown for spring in the polar regions (March for the Arctic and October for the Antarctic) and for the annual average for the Tropics, for both the northern and southern midlatitudes, and for the global average outside of the polar regions (“Global”). The solid shaded regions illustrate how each particular gas (or family of gases for ODSs) affects total ozone, with negative contributions shown below the 1960 level of ozone and positive contributions shown above. These simulations use CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O from the medium climate forcing (SSP2-4.5) scenario of Figure Q20-1. The abundances of the greenhouse gases and ODSs are varied individually while the others are kept constant at their level in 1960 to compute the individual constituent’s contribution to prior and projected total ozone. Increasing CO<sub>2</sub> results in lower temperatures throughout the stratosphere. Lower temperatures slow down the rate of most ozone destruction chemical reactions, particularly those that regulate the abundance of ozone outside of polar regions, leading to an increase in ozone. Increasing CO<sub>2</sub> also enhances the transport of ozone from the tropics to middle and high latitudes by stratospheric winds. Increasing CH<sub>4</sub> leads to changes in stratospheric chemistry that augment the increase in ozone driven by stratospheric cooling. Conversely, the expected future increase in N<sub>2</sub>O results in significant decreases in ozone due to chemical effects. As the atmospheric abundance of ODSs declines towards the end of this century, ozone reductions due to increasing N<sub>2</sub>O may become more prominent. The white “Sum of all gases” line on each panel represents the combined effect on ozone of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and ODSs.

(These projections use abundances for CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O from the SSP2-4.5 scenario and ODSs from the baseline (A1) projection of the 2018 Scientific Assessment of Ozone Depletion report.)

- **Northern and Southern Midlatitudes.** Changes in the annual averages of total ozone in midlatitudes are much smaller than the springtime losses in polar regions. In the northern midlatitudes, the all-forcings simulation (white line) indicates a return of total ozone to the 1960 value around 2045, even though EESC remains above its 1960 value until the end of the century.

In the southern midlatitudes, total ozone returns to the 1960 level around 2085, about four decades later than projected for the Northern Hemisphere. The maximum ozone depletion near year 2000 is much larger for the Southern Hemisphere, and total ozone more closely follows the depletion driven by ODSs. This behavior reflects the influence of the Antarctic



ozone hole on the southern midlatitudes, driven by the transport of ozone-depleted air following the breakup of the polar vortex in late spring (see Q10). The larger value of midlatitude total ozone from mid-century to the end of this century when all forcings are considered (white lines) compared to ozone depletion due only to ODSs (dark pink shaded region) reflects the influence of changes in stratospheric circulation and upper stratospheric temperatures by CO<sub>2</sub> and CH<sub>4</sub> for this medium climate forcing scenario, especially in the NH.

- **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 reactive halogens available in this region (see Q12). Total ozone gradually increases until around 2060, and then remains fairly constant and slightly below the 1960 level until the end of the century. The near-constant value of tropical ozone during the latter part of the century is primarily due to climate-change-induced 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 2075, even though EESC remains above its 1960 value until the end of the century. Chemistry-climate model analysis suggests that 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 and strengthening of the stratospheric circulation caused by increasing GHGs. Towards the latter part of this century, increased abundances of N<sub>2</sub>O may lead to more ozone depletion (dark blue shaded region) than ODSs (dark pink shaded region).

**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 (cloud-free) UV-B radiation is expected to be below the 1960 value by the end of the century across much of the globe in regions that are not currently affected by high levels of tropospheric air pollution. Clear-sky UV-B radiation values are expected to remain high in Antarctica, where total ozone is expected to remain below its 1960 value even at the end of this century.

**Volcanoes, wildfires, and climate intervention.** There are several factors not included in chemistry-climate model projections

shown above that 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. Large volcanic eruptions that occur while EESC values remain high are expected to reduce total ozone for a few years. Such volcanic eruptions are an additional source of uncertainty that is not included in the ozone projections in Figures Q20-1 and Q20-2. Extreme wildfires can generate deep thunderstorms, termed pyrocumulonimbus (pyroCb) clouds, that inject particles from biomass burning into the stratosphere. The biomass burning particles consist of organic carbon, inorganic components and a significant fraction of black carbon that enhance the absorption of solar radiation. These pyroCb particles likely impact the ozone layer and climate in a manner that differs substantially from the impact of sulfate aerosols.

Numerous climate intervention (also called geoengineering) 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, known as Stratospheric Aerosol Injection (SAI). With sufficient enhancement, the added aerosols would cool the Earth's surface through increased reflection of sunlight back to space, similar to the effect observed after volcanic eruptions that inject sulfate into the stratosphere (see Figure Q13-1). While SAI could reduce some of the impacts of global warming, it cannot restore past climatic conditions and may cause unintended side effects, including changes in the concentration of stratospheric ozone, a delay in the recovery of the ozone hole, and changes to the atmospheric circulation. Aerosol heating of the lowermost stratosphere by SAI using sulfates could result in further residual impacts, including changes in regional surface temperature and precipitation patterns. How much aerosol injection would be needed and the duration of that injection would depend on the desired climate outcomes and the trajectory of greenhouse gas emissions and decarbonization efforts. The sign of stratospheric ozone changes will depend on the details of the SAI implementation as well as the concentrations of EESC and N<sub>2</sub>O at the time of injection. Changes in stratospheric water vapor due to variations in temperature and circulation resulting from SAI may also play a role in governing how stratospheric ozone would be affected by SAI.

Studies are currently being conducted to determine materials for SAI other than sulfate that have chemical and radiative properties that would reduce the effect of SAI on ozone and stratospheric heating. These studies are just beginning; significant laboratory and modeling work on materials other than sulfate is needed before their effects on ozone and stratospheric transport can be reliably estimated.