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 near the middle of the 21st century, assuming global compliance with the Montreal Protocol. Recovery will occur as ODSs and reactive halogen gases in the stratosphere decrease in the coming decades. In addition to responding to ODSs, future ozone amounts will increasingly be influenced by expected changes in climate. 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 ODSs is expected in the later decades of this century. The recovery follows from the success of the Montreal Protocol in reducing the global production and consumption of ODSs. Now, the atmospheric abundances of most major ODSs and the associated values of equivalent effective stratospheric chlorine (EESC) are in decline (see Q16). In contrast to the diminishing role of ODSs, changes in climate are expected to have an increasing influence on future ozone. Climate change is driven by the projected growth in greenhouse gas abundances, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which will lead to changes in temperatures, 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 different geographical regions during the recovery period. Global events, such as major volcanic eruptions and geoengineering actions, 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 take into account the influences of changes in ODSs and climate. These models show how changes in ozone are expected to vary across global regions by evaluating the complex interactions of the processes that control ozone and climate involving radiation, chemistry, and transport. Required model inputs include, for example, historical and projected concentrations of ODSs, CO_2, CH_4, and N_2O, and changes in sea surface temperatures. The results from chemistry-climate model simulations are used to identify aspects of the models that are particularly important for future ozone abundances. For example, model projections for the coming decades show a strengthening in the atmospheric circulation that brings air to the stratosphere in the tropics, moves air poleward into both hemispheres, and then returns it 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 from greenhouse gases, the stratosphere is expected to continue to cool. A colder upper stratosphere leads to increases in ozone because lower temperatures decrease the effectiveness of gas-phase ozone-loss reactions. Finally, CH_4 and N_2O are both involved in the chemistry that determines stratospheric ozone levels.

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 of ozone, global total ozone and minimum total ozone values in the Antarctic (available since 1980), are

compared to a group of chemistry-climate model simulations in Figure Q20-1. Both ozone measures show substantial depletion since 1980. The average model value follows the observed decline in both ozone measures, indicating that the main processes involved in ozone depletion are reasonably well represented by the models. Some differences between the simulations and observations can be explained by unusual meteorological conditions, volcanic eruptions, changes in solar activity, or other natural influences, which are not all fully accounted for in the various models used here. In Figure Q20-1, global total ozone has increased in the last 20 years, while Antarctic minimum ozone values have been relatively constant. The global total ozone increases cannot be attributed solely to reductions in ODSs that began in the 1990s, because total ozone has also recovered from additional depletion caused by the 1991 Mt. Pinatubo eruption (see Q14).

Equivalent stratospheric chlorine (ESC) projections. Equivalent stratospheric chlorine (ESC) values are also projected in chemistry-climate models to represent how the potential for reactive halogen gases (see Q8) to destroy ozone varies over time. ESC is similar to equivalent effective stratospheric chlorine (EESC) (see Q16) in that both represent a weighted sum of reactive chlorine and bromine gases in the stratosphere. The weighting in each accounts for the greater effectiveness of bromine atoms in destroying ozone. ESC can be calculated more precisely and comprehensively than EESC because the chemistry-climate models can derive ESC as a function of altitude, latitude, longitude, and time. The ESC 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.

Figure Q20-1. Simulations of ozone depletion. Chemistry-climate models of the atmosphere that account for changes in ozone-depleting substances (ODSs) and climate parameters are widely used to assess past ozone changes and project future 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 global total ozone (top panel) and minimum total ozone values over Antarctica (bottom panel) decreased beginning in the early 1980s (red points). Ozone is no longer decreasing in either region. The observations lie mostly within the range of projections derived from a group of chemistry-climate models (blue shading). Differences between models and observations can occur due to unusual meteorological conditions, volcanic eruptions, changes in solar activity, or other influences, which are not fully accounted for in the different models. As ODS abundances decrease in the 21st century, chemistry-climate models project global total ozone to increase steadily and exceed 1980 values, and Antarctic minimum ozone to return to 1980 values.
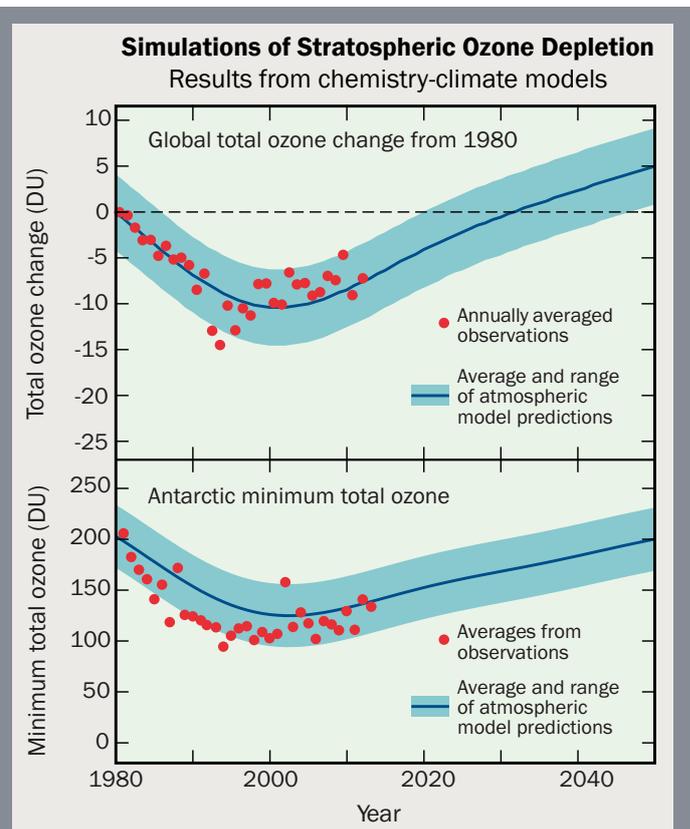
The long-term changes in ESC in the global and regional analyses shown in Figure Q20-2 are highly similar. In all regions, changes in ESC from 1960 values increase smoothly with time, reach a peak near the end of the 20th century, and decrease gradually until the end of the 21st century. Values at the end of the 21st century are approaching those in 1960, indicating that ODSs are largely removed from the stratosphere by that time. ESC returns to 1980 values several decades sooner than to 1960 values because of the slow rate of decline.

Peak ESC values around the year 2000 are highest in 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 Q8). In polar regions, the fraction is much larger because stratospheric air requires several years on average to journey from its entry point in the tropics to the polar lower stratosphere. During this time, a much larger fraction of ODSs undergoes conversion to reactive halogen gases.

Long-term total ozone projections. Total ozone changes derived from chemistry-climate models, as referenced to 1960 values, are shown in Figure Q20-2. The range of values from the group of models is included in the figure as one measure of the uncertainty in the model projections. Total ozone changes in the different 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, total ozone changes mostly *mirror* changes in ESC: as ESC increases, ozone proportionately decreases; as ESC decreases, ozone proportionately increases. Antarctic total ozone is projected to return to 1980 levels after midcentury and later than in any other region. Meteorological variability in the Antarctic in late winter/early spring when ozone depletion occurs causes a large range in the model projections.

• **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 ESC. After midcentury, Arctic total ozone increases to values above those that would be expected from ESC reductions alone because of the strengthening of the atmospheric circulation and the enhanced stratospheric cooling associated with increases in CO_2. By 2100 Arctic total ozone is projected to be well above both 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 1980 levels between 2020 and 2035, which is two to three decades before ESC returns to 1980 levels, and to continue to increase until the end of the century.

• **Northern and southern midlatitudes.** The annual averages of total ozone changes in midlatitudes are much smaller than the springtime losses in polar regions. Both midlatitude regions resemble the Arctic, with total ozone returning to 1960 and 1980 values much sooner than ESC. In the northern midlatitudes, the models predict a return of total ozone to 1960 values in 2030, whereas ESC requires the full century to return close to 1960 values. Total ozone in southern midlatitudes changes in a manner similar to that in the northern midlatitudes. Differences are that in southern midlatitudes, the 1960 return date for total ozone is somewhat later (2055) and the maximum ozone depletion observed near 2000 is greater. Both aspects reflect the influence of Antarctic polar ozone depletion, with stratospheric air low in ozone being transported to southern midlatitudes in spring after the breakup of the polar vortex (see Q11). The more rapid return of

Total Ozone and Equivalent Stratospheric Chlorine
Results from atmospheric chemistry-climate models for 1960 to 2100
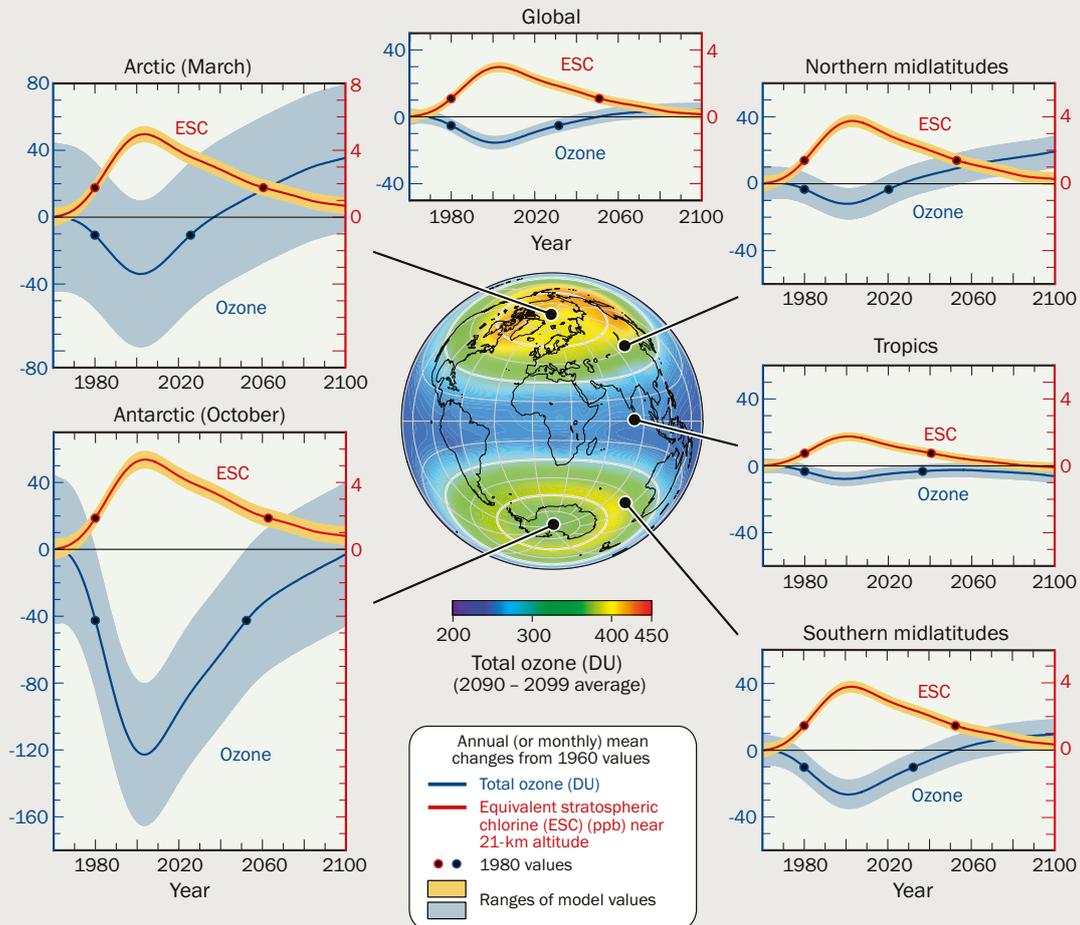
**Figure Q20-2. Long-term changes in ozone and equivalent stratospheric chlorine (ESC).** Chemistry-climate models are used to make projections of total ozone amounts that account for the effects of ozone-depleting substances (ODSs) and climate change. Regional and global projections are shown for total ozone and ESC for the period 1960–2100, referenced to 1960 values. The globe in the center shows average total ozone projections for the last decade of the 21st century. Total ozone depletion increased after 1960 as ESC values steadily increased throughout the stratosphere. ESC values have peaked and are now in a slow decline. All the projections show maximum total ozone depletion around 2000, coincident with the highest abundances of ESC. Thereafter, total ozone increases, except in the tropics, as ESC 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 ESC alone. The earlier returns are attributable to climate change, which influences total ozone through changes in stratospheric transport and temperatures. In the tropics, in contrast, climate change causes total ozone to remain below 1960 values throughout the century. 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 ESC, with both closely approaching 1960 values at century's end. The dots on each curve mark the occurrences of 1980 values of total ozone and ESC. Note that the equal vertical scales in each panel allow direct comparisons of ozone and ESC changes between regions.

total ozone in both regions compared with ESC again is the result of the influence of climate-induced changes in transport and upper stratospheric temperatures in the model projections. The model range is significantly less in midlatitude annual averages than in the polar springtime averages. After returning to either 1960 or 1980 values, total ozone continues to increase in both hemispheres and significantly exceeds those values by 2100.

- **Tropics.** Total ozone changes in the tropics are smaller than in any other region. Ozone is less sensitive to ESC in the tropical stratosphere because of the dominant roles of production and transport in controlling ozone and the low amounts of ESC available in this region. In contrast to other regions, chemistry-climate models project total ozone to remain below 1960 values throughout the 21st century. Total ozone gradually returns to 1980 values in 2040, peaks around 2060, and decreases again until the end of the century. The different total ozone behavior in the tropics is due to the changing balance between ozone increases in the upper stratosphere and decreases in the lower stratosphere. The ozone increases in the upper stratosphere occur from declining ODS abundances and decreases in temperatures caused by increasing greenhouse gases, primarily CO_2. In the lower stratosphere, ozone is reduced because the strengthening of the stratospheric circulation reduces the time for ozone production before air leaves the tropics. These circulation changes also influence the Arctic and midlatitude regions as noted above.

- **The globe.** The annual averages of global total ozone are projected to return to 1960 levels around the middle of the century (2040–2080) while ESC returns to 1960 values near the century's end. The return dates for 1980 values are substantially earlier. Chemistry-climate model analysis suggests that this early return of total ozone is primarily a result of upper stratospheric cooling. The larger total ozone changes shown for polar regions in springtime do not significantly influence global total ozone values because these values are annual averages and polar regions are a small geographical fraction of the globe.

Future ultraviolet radiation. Projections of long-term changes in total ozone can be used to estimate long-term changes in solar ultraviolet radiation reaching Earth's surface (see Q17). The UV-B component of ultraviolet radiation increases as total ozone decreases. Based on the global total ozone projections, clear-sky UV-B radiation is expected to *decrease* below 1960 values by the end of the century because ozone is above 1960 values in the later decades. The latitude regions expected to experience *increased* ultraviolet radiation levels are the Antarctic and the tropics, where total ozone remains lower than 1960 values until the end of the century. Large increases or decreases in surface erythemal radiation away from 1960 values are expected to lead to adverse effects on human and ecosystem health.

Greenhouse gas emission scenarios and impact on future ozone. The climate impacts on future ozone discussed above have been derived using a particular greenhouse gas emission scenario. Emission scenarios specify the amounts of greenhouse gases emitted into the atmosphere in the future and are constructed based on socio-economic assumptions on future population growth, economical developments, technology innovation, and political decisions. Future emissions are highly uncertain and therefore various emission scenarios are designed to cover a wide range of possible future outcomes. Chemistry-climate model simulations are run using the different emission scenarios to determine the range of impacts climate change may have on the ozone layer. Such simulations show that the evolution of ozone and the resulting surface UV levels in different regions of the world are strongly dependent on the mixture and relative abundances of greenhouse gases that will be used.

Global Total Ozone Changes in Response to Increasing Greenhouse Gases
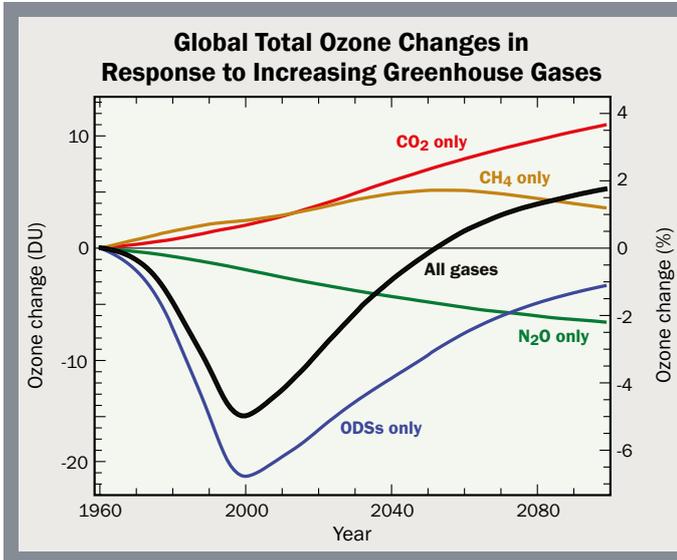
Figure Q20-3. Global total ozone changes in response to increasing greenhouse gases.
Model simulations that include changes in each of the greenhouse gases CO_2, N_2O, and CH_4 separately illustrate how a particular gas affects global total ozone. Increasing CO_2 leads to increases in ozone, because CO_2 lowers stratospheric temperatures and slows down ozone destruction reactions. Increasing CH_4 leads also to increases in ozone, while N_2O leads to decreases in ozone similarly to the ODSs. The results are contrasted with a model simulation that includes changes in all greenhouse gases together. The combined impact of these gases on total global ozone is not simply the sum of the effects of each gas, but depends strongly on the relative abundances of the gases.

Simulations with a simplified model using increases in CO_2, N_2O, and CH_4 separately illustrate the reasons for these dependencies (see Figure Q20-3). The simulation using increases in CO_2 only shows that the main effect of CO_2 is to increase global ozone in the future. The ozone increases are explained mainly by decreases in stratospheric temperatures. As detailed above, lower temperatures in the upper stratosphere slow down the chemical gas-phase reactions that lead to ozone depletion. Note that circulation changes only play a minor role for global mean ozone since decreases in total ozone in the tropics and increases at higher latitudes largely cancel. Simulations using increases in CH_4 and N_2O separately show that the main effect of CH_4 is to increase ozone, while that of N_2O is to decrease ozone in the future. The reason for this behavior is that N_2O and CH_4 are source gases of reactive gases (NO_x and HO_x) that strongly affect stratospheric ozone chemistry. The reactive gases produced from N_2O lead to stratospheric ozone depletion, while those from CH_4 lead to the production of stratospheric ozone.

Volcanoes and geoengineering. Other factors not included in chemistry-climate models can potentially affect future total ozone amounts. Explosive volcanic eruptions have temporarily reduced global total ozone in the past (see Q14). Similar eruptions, especially in the early decades of this century when ESC values are highest, are also expected to reduce total ozone for a few years. Volcanic eruptions are an additional source of uncertainty not included in the ozone projections in Figures Q20-2 and Q20-3.

Several *geoengineering* methods have been proposed to reduce climate forcing from human activities. A widely discussed proposal is the enhancement of sulfate aerosols in the stratosphere from direct injections of sulfur or sulfuric acid. The expected response is a cooling of the climate system from increased aerosol scattering of sunlight, similar to that observed after some explosive volcanic eruptions. The required injections, if sustained over many years, are likely to have unintended consequences such as reductions in total ozone amounts and changes in stratospheric temperatures and circulation.