Q13 Do changes in the Sun and volcanic eruptions affect the ozone layer?

Yes, factors such as changes in solar radiation and the formation of stratospheric aerosol particles after explosive volcanic eruptions do influence the ozone layer. Global ozone abundances vary by 1–2% between the maximum and minimum of the 11-year solar cycle. The abundance of global ozone decreased by about 2% for a few years after the June 1991 eruption of Mount Pinatubo, due to volcanic enhancement of stratospheric sulfate aerosols. However, neither factor can explain the observed decrease in global total ozone or the severe ozone depletion observed in polar regions over the past half century. The primary influence on long-term changes in total global ozone is the abundance of stratospheric halogens.

Changes in solar radiation and increases in stratospheric aerosols (small particles) from volcanic eruptions both affect the abundance of stratospheric ozone. Global total ozone in the early 1990s decreased by about 5% when compared to the 1964–1980 average, and is now about 2 to 3% below this value (see Q12). The long-term depletion of ozone is primarily attributed to increases in halogen source gases, with additional depletion in the early 1990s associated with the volcanic eruption of Mount Pinatubo. Equivalent effective stratospheric chlorine (EESC) (see definition in Q15) is often used as a measure of the potential of reactive and reservoir halogen gases to deplete ozone. Comparisons of the long-term changes in solar radiation, stratospheric volcanic aerosol, and EESC are useful in evaluating the contribution of these factors to long-term changes in total ozone.

Total ozone and solar changes. The formation of stratospheric ozone is initiated by ultraviolet (UV) radiation emitted by the Sun (see Q1). As a result, an increase in the Sun's UV radiation output increases the amount of ozone in Earth's atmosphere. Since the 1960s, ground-based and satellite instruments have recorded variations in the total energy emitted by the Sun, which is well correlated with changes in solar UV radiation. The Sun's radiation output varies over the well-documented 11-year solar cycle, as shown in **Figure Q13-1** in the quantity labeled incoming solar radiation. The long-term solar record exhibits alternating maximum and minimum values of total output, with maximum values separated by about 11 years. Global total ozone is relatively high compared to surrounding years during times of solar maxima and is relatively low during solar minima due to the sensitivity of ozone production to UV radiation, which increases during solar maxima. Analysis of measurements of ozone and incoming solar radiation shown in Figure Q13-1 shows that ozone levels vary by 1 to 2% between the maximum and minimum of a typical solar cycle. In addition to this 11-year variation, the total ozone record exhibits a long-term downward trend from the early 1980s to the early 2000s. If a decline in incoming solar radiation were the primary cause of the long-term decline in global total ozone, then the solar radiation would exhibit a similar long-term decrease. Instead, incoming solar radiation varies about a stable baseline over the modern instrument record. This comparison demonstrates that the observed long-term decline in global total ozone does not result from changes in the Sun's UV radiation output.

Total ozone and past volcanoes. Explosive volcanic eruptions inject sulfur gases directly into the stratosphere, causing new sulfate aerosol particles to be produced. These particles initially form downwind of the volcano and then disperse over large regions, as air is transported by stratospheric winds. The largest impact on global ozone usually takes place after explosive volcanic eruptions in the tropics, because the stratospheric circulation efficiently spreads tropical volcanic plumes to both hemispheres. A principal method of detecting the presence of volcanic particles in the stratosphere is to measure the transmission of solar radiation through the stratosphere to the ground, which is termed stratospheric aerosol optical depth (SAOD). When large amounts of new particles form over an extensive region of the stratosphere, SAOD increases and solar transmission is measurably reduced. Figure Q13-1 shows the long-term record of SAOD averaged over the entire stratosphere, based on measurements from ground-based and satellite instruments. Large increases in SAOD (reductions in solar transmission) are apparent after the explosive eruptions of Mount Agung (1963), Volcán de Fuego (1974), El Chichón (1982), and Mount Pinatubo (1991), all of which occurred in the tropics. Reduced transmission of solar radiation persists for a few years after each of these eruptions, until the stratospheric circulation and gravitational settling bring the volcanic sulfate aerosol particles back to the troposphere, where they are removed by precipitation.

Volcanic aerosol is primarily composed of sulfur compounds (sulfate). Chemical reactions on the surface of sulfate aerosol particles destroy stratospheric ozone by increasing the abundance of chlorine monoxide (ClO), a highly reactive chlorine gas (see Q7). The extent of ozone depletion depends on both the amount of sulfate aerosol produced following the eruption and the value of EESC (see Q15). Global ozone decreased for a few years following the eruptions of Mount Agung, Volcán de Fuego, El Chichón, and Mount Pinatubo. The ozone reduction from the eruption of Mount Pinatubo stands out in the global ozone record because it occurred at a time when EESC was near its peak and the perturbation to stratospheric sulfate aerosol was especially large (see Figures Q12-1 and Q13-1). Analysis of ozone observations shows that global total

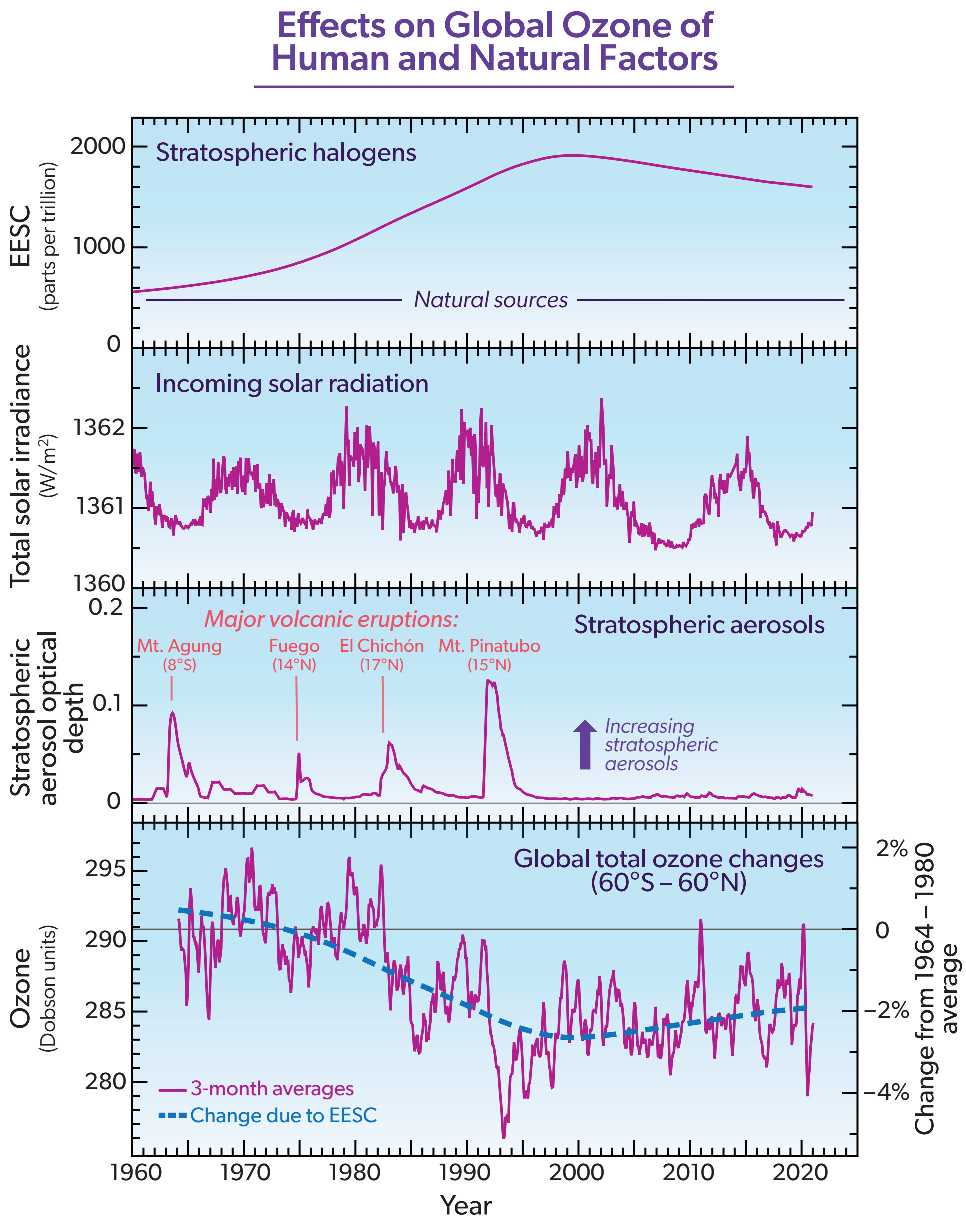

Figure Q13-1. The effects on ozone of EESC, solar changes, and volcanic eruptions. A comparison of the long-term variation in EESC, total solar radiation, and a measure of the abundance of stratospheric sulfate particles with global total ozone provides a basis to evaluate the primary influences on ozone over the past half century. The top panel shows the record of equivalent effective stratospheric chlorine (EESC) for the midlatitude, lower stratosphere (about 19 km altitude). EESC represents the potential for stratospheric ozone depletion by halogens, which result primarily from human activities (see Q15). The second panel shows the total energy of incoming solar radiation, with peaks and valleys defining the maxima and minima of the 11-year solar cycle. Following the explosive volcanic eruptions marked on the third panel, the number of sulfur-containing particles in the stratosphere exhibits a dramatic rise. These particles decrease the transmission of solar radiation through the stratosphere, which is recorded by an increase in the quantity termed stratospheric aerosol optical depth. The bottom panel shows differences in global total ozone, averaged over 60°S to 60°N latitude, from the 1964–1980 average value. Global total ozone is 1 to 2% higher at solar maxima than solar minima due to enhanced formation of ozone by solar ultraviolet radiation (see Q1). Reactions on sulfate particles enhance the abundance of highly reactive chlorine compounds, increasing the depletion of stratospheric ozone after major volcanic eruptions. The maximum depletion of ozone occurs in mid-1993, after the eruption of Mount Pinatubo. The bottom panel also shows the change in global total ozone attributed to EESC, found using an analysis that considers the effects on ozone of numerous natural and human-related factors. The long-term changes in ozone are consistent with the variation of EESC: prior to the mid-1990s EESC steadily rose while global ozone declined, and since the late 1990s EESC has declined and global ozone has risen. This figure illustrates that the primary influence on changes in global total ozone over the past half century is the abundance of stratospheric halogens.

ozone declined by about 2% following the eruption of Mount Pinatubo in June 1991, and that this effect persisted for 2 to 3 years after the eruption. At times of relatively low EESC, such as the early 1960s, total ozone is not as sensitive to a volcanically induced increase in stratospheric aerosol as during current times, when values of EESC are much higher than background levels.

If changes in the abundance of volcanic aerosol in the stratosphere were the primary cause of the long-term decline in global total ozone, then the record of stratospheric aerosol optical depth (marker of volcanic sulfate particles) would exhibit a slow, gradual rise. Instead, stratospheric volcanic aerosol has been quite low since 1995, a period of time over which global total ozone has been about 2 to 3% below the 1964–1980 value. The data record shown in Figure Q13-1 provides evidence that the long-term decrease in global total ozone relative to the 1964–1980 average does not result from changes in volcanic aerosol.

Total ozone and EESC. Values of EESC are derived from surface observations of ozone-depleting substances (ODSs) and represent the potential for ozone depletion from halogens at particular times and locations of the stratosphere (see Q15). The EESC record for the midlatitude, lower stratosphere rose well above the natural background level in the 1980s, peaked in 1998, and in 2022 was 18% below the peak value. The bottom panel of Figure Q13-1 compares the observed long-term record of global total ozone (magenta line) to the variation in ozone attributed to the changes in EESC (blue dashed line). This attribution curve is computed by a statistical model that considers the effects on ozone of EESC, stratospheric sulfur containing particles, variations in the total energy of incoming solar radiation, as well as a few factors related to changes in stratospheric circulation. The observed record of global total ozone follows the same general tendencies of the EESC attribution curve over the past half century, providing strong evidence that changes in stratospheric halogens in response to human activities are the primary factor responsible for the long-term variation of ozone depletion. Further evidence linking ODSs and long-term variations in total column ozone is provided by the climate-chemistry model simulations highlighted in Q20.

Halogen gases from volcanic eruptions. Explosive volcanic eruptions have the potential to inject halogens directly into the stratosphere, in the form of gases such as hydrogen chloride (HCl), bromine monoxide (BrO), and iodine monoxide (IO). Although HCl does not react directly with ozone, stratospheric injections of HCl and other chlorine-containing gases following explosive volcanic eruptions can lead, through chemical reactions, to elevated amounts of reactive chlorine monoxide (ClO) that destroys ozone (see Figure Q7-3). Eruption plumes also contain a considerable amount of water vapor, which forms rainwater and ice in the rising fresh plume. Rainwater and ice efficiently scavenge and remove HCl while the plume is still in the lower atmosphere (troposphere). Most of the HCl in the explosive plume of Mount Pinatubo did not enter the stratosphere because of this scavenging by precipitation. The amount of injected halogens depends on the chemical composition of the magma, conditions of the eruption such as its explosivity and the local meteorology. Recent analyses of several historic, extremely large volcanic eruptions show the potential for quite large ozone loss from the stratospheric injection of halogens. A volcanic eruption of this nature has not occurred during the time period of the modern observational record.

Antarctic volcanoes. Volcanoes on the Antarctic continent are of special interest due to their close proximity to the Antarctic ozone hole. An explosive eruption could in principle inject volcanic aerosol or halogens directly into the stratosphere over Antarctica and contribute to ozone depletion. To be a possible cause of the annually recurring ozone hole beginning in the early 1980s, explosive eruptions of Antarctic volcanoes large enough to inject material into the stratosphere would need to have occurred at least every few years. This is not the case. Mount Erebus and Deception Island are the only two currently active volcanoes in Antarctica. No explosive eruptions of these volcanoes, or any other Antarctic volcano, have occurred since 1980. Explosive volcanic eruptions in the last three decades have not caused the Antarctic ozone hole and, as noted above, have not been sufficient to cause the long-term depletion of global total ozone.

Total ozone and future volcanoes. The abundance of EESC will remain high for much of the 21st century due to the long atmospheric lifetime of ODSs (see Figure Q15-1). With its slow decline, EESC will remain above the 1960 value throughout this century. Consequently, throughout the rest of this century, increases in the abundance of stratospheric sulfate aerosol particles caused by large volcanic eruptions similar to Mount Pinatubo have the potential to reduce global total ozone values for a few years. The ozone layer will be most vulnerable to such an eruption until midcentury, since EESC is projected to return to the 1980 value around 2066. Following an explosive eruption much larger than Mount Pinatubo, or an eruption that injects halogens into the stratosphere, peak ozone losses could both be greater than previously observed and persist for longer periods of time.