

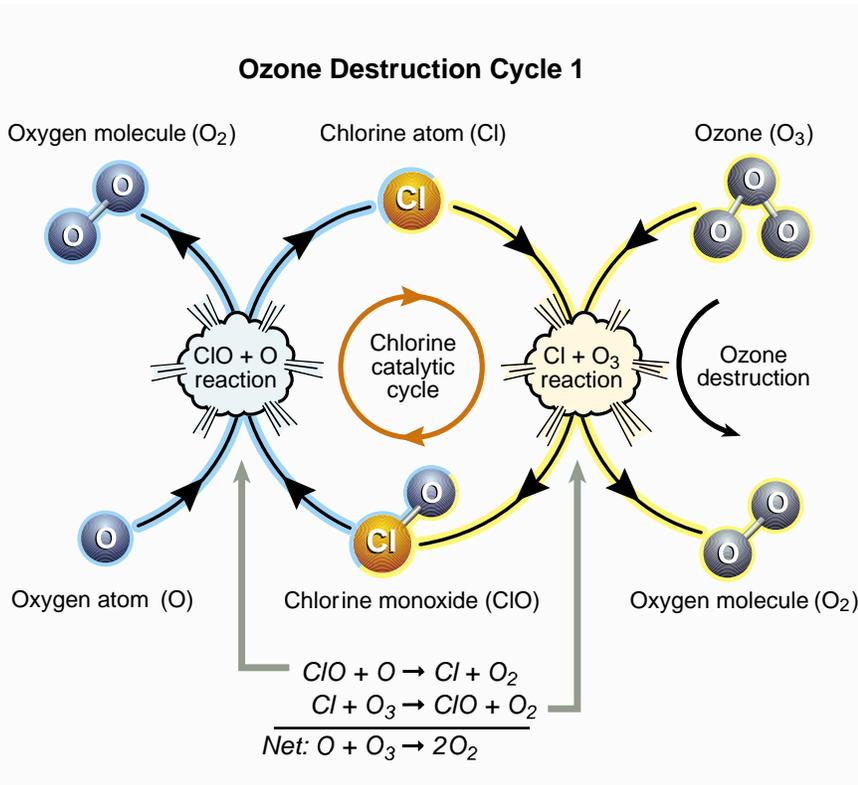
**Q9: What are the chlorine and bromine reactions that destroy stratospheric ozone?**

Reactive gases containing chlorine and bromine destroy stratospheric ozone in “catalytic” cycles made up of two or more separate reactions. As a result, a single chlorine or bromine atom can destroy many hundreds of ozone molecules before it reacts with another gas, breaking the cycle. In this way, a small amount of reactive chlorine or bromine has a large impact on the ozone layer. Special ozone destruction reactions occur in polar regions because the reactive gas chlorine monoxide reaches very high levels there in the winter/spring season.

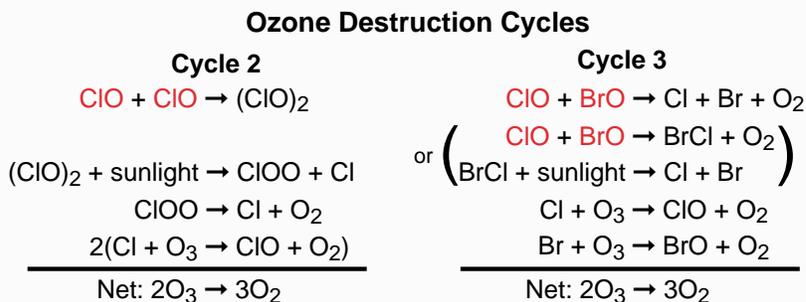
Stratospheric ozone is destroyed by reactions involving *reactive halogen gases*, which are produced in the chemical conversion of *halogen source gases* (see **Figure Q8-1**). The most reactive of these gases are chlorine monoxide (ClO) and bromine monoxide (BrO), and chlorine and bromine atoms (Cl and Br). These gases participate in three principal reaction cycles that destroy ozone.

**Cycle 1.** Ozone destruction Cycle 1 is illustrated in **Figure Q9-1**. The cycle is made up of two basic reactions:  $\text{ClO} + \text{O}$  and  $\text{Cl} + \text{O}_3$ . The net result of Cycle 1 is to convert one ozone molecule and one oxygen atom into two oxygen molecules. In each cycle chlorine acts as a *catalyst* because ClO and Cl react and are reformed. In this way, one Cl atom participates in many cycles, destroying many ozone molecules. For typical stratospheric conditions at middle or low latitudes, a single chlorine atom can destroy hundreds of ozone molecules before it reacts with another gas to break the catalytic cycle.

**Polar Cycles 2 and 3.** The abundance of ClO is greatly increased in polar regions during winter as a result of reactions on the surfaces of polar stratospheric cloud (PSC) particles (see **Q10**). Cycles 2 and 3 (see **Figure Q9-2**) become the dominant reaction mechanisms for polar ozone loss because of the high abundances of ClO and the relatively low abundance of atomic oxygen (which limits the rate of ozone loss by Cycle 1). Cycle 2 begins with the self-reaction of ClO. Cycle 3, which begins with the reaction of ClO with BrO, has two reaction pathways to produce either Cl and Br or BrCl. The net result of both cycles is to destroy two ozone molecules and create three oxygen molecules. Cycles 2 and 3 account for most of the ozone loss observed in the Arctic and Antarctic stratospheres in the late winter/spring season (see **Q11** and **Q12**). At high ClO abundances, the rate of ozone destruction can reach 2 to 3% per day in late winter/spring.



**Figure Q9-1. Ozone destruction Cycle 1.** The destruction of ozone in Cycle 1 involves two separate chemical reactions. The net or overall reaction is that of atomic oxygen with ozone, forming two oxygen molecules. The cycle can be considered to begin with either ClO or Cl. When starting with ClO, the first reaction is ClO with O to form Cl. Cl then reacts with (and thereby destroys) ozone and reforms ClO. The cycle then begins again with another reaction of ClO with O. Because Cl or ClO is reformed each time an ozone molecule is destroyed, chlorine is considered a catalyst for ozone destruction. Atomic oxygen (O) is formed when ultraviolet sunlight reacts with ozone and oxygen molecules. Cycle 1 is most important in the stratosphere at tropical and middle latitudes where ultraviolet sunlight is most intense.



**Figure Q9-2. Polar ozone destruction Cycles 2 and 3.** Significant destruction of ozone occurs in polar regions because ClO abundances reach large values. In that case, the cycles initiated by the reaction of ClO with another ClO (Cycle 2) or the reaction of ClO with BrO (Cycle 3) efficiently destroy ozone. The net reaction in both cases is two ozone molecules forming three oxygen molecules. The reaction of ClO with BrO has two pathways to form the Cl and Br product gases. Ozone destruction Cycles 2 and 3 are catalytic, as illustrated for Cycle 1 in **Figure Q9-1**, because chlorine and bromine react and are reformed in each cycle. Sunlight is required to complete each cycle and to help form and maintain ClO abundances.

**Sunlight requirement.** Sunlight is required to complete and maintain Cycles 1 through 3. Cycle 1 requires sunlight because atomic oxygen is formed only with ultraviolet sunlight. Cycle 1 is most important in the stratosphere at tropical and middle latitudes where sunlight is most intense.

In Cycles 2 and 3, sunlight is required to complete the reaction cycles and to maintain ClO abundances. In the continuous darkness of winter in the polar stratospheres, reaction Cycles 2 and 3 cannot occur. It is only in late winter/spring when sunlight returns to the polar regions that these cycles can occur. Therefore, the greatest destruction of ozone occurs in the partially to fully sunlit periods after midwinters in the polar stratospheres. The sunlight needed in Cycles 2 and 3 is not sufficient to form ozone

because ozone formation requires ultraviolet sunlight. In the stratosphere in the winter/spring period, ultraviolet sunlight is weak because Sun angles are low. As a result, ozone is destroyed in Cycles 2 and 3 in the sunlit winter stratosphere but is not produced in significant amounts.

**Other reactions.** Atmospheric ozone abundances are controlled by a wide variety of reactions that both produce and destroy ozone (see *Q2*). Chlorine and bromine catalytic reactions are but one group of ozone destruction reactions. Reactive hydrogen and reactive nitrogen gases, for example, are involved in other catalytic ozone-destruction cycles that also occur in the stratosphere. These reactions occur naturally in the stratosphere and their importance has not been as strongly influenced by human activities as have reactions involving halogens.