Q1 What is ozone, how is it formed, and where is it in the atmosphere?

Ozone is a gas that is naturally present in our atmosphere. Each ozone molecule contains three atoms of oxygen and is denoted chemically as O_3. Ozone is found primarily in two regions of the atmosphere. About 10% of Earth's ozone is in the troposphere, which extends from the surface to about 10–15 kilometers (6–9 miles) altitude. About 90% of Earth's ozone resides in the stratosphere, the region of the atmosphere between the top of the troposphere and about 50 kilometers (31 miles) altitude. The part of the stratosphere with the highest amount of ozone is commonly referred to as the "ozone layer". Throughout the atmosphere, ozone is formed in multistep chemical processes that are initiated by sunlight. In the stratosphere, the process begins with an oxygen molecule (O_2) being broken apart by ultraviolet radiation from the Sun. In the troposphere, ozone is formed by a different set of chemical reactions that involve naturally occurring gases as well as those from sources of air pollution.

Ozone is a gas that is naturally present in our atmosphere. Ozone has the chemical formula O_3 because an ozone molecule contains three oxygen atoms (see **Figure Q1-1**). Ozone was discovered in laboratory experiments in the mid-1800s. Ozone's presence in the atmosphere was later discovered using chemical and optical measurement methods. The word ozone is derived from the Greek word *όζειν (ozein)*, meaning "to smell." Ozone has a pungent odor that allows it to be detected even at very low amounts. Ozone reacts rapidly with many chemical compounds and is explosive in concentrated amounts. Electrical discharges are generally used to produce ozone for industrial processes such as air and water purification and bleaching of textiles and food products.

Ozone location. Most ozone (about 90%) is found in the stratosphere, which begins about 10–15 kilometers (km) above Earth's surface and extends up to about 50 km altitude. The stratospheric region with the highest concentration of ozone, between about 15 and 35 km altitude, is commonly known as the "ozone layer" (see **Figure Q1-2**). The ozone layer extends over the entire globe with some variation in altitude and thickness. Most of the remaining ozone (about 10%) is found in the troposphere, which is the lowest region of the atmosphere, between Earth's surface and the stratosphere. Tropospheric air is the "air we breathe" and, as such, excess ozone in the troposphere has harmful consequences (see Q2).

Ozone abundance. Ozone molecules have a low relative abundance in the atmosphere. Most air molecules are either oxygen (O_2) or nitrogen (N_2). In the stratosphere near the peak concentration of the ozone layer, there are typically a few thousand ozone molecules for every *billion* air molecules (1 billion = 1,000 million). In the troposphere near Earth's surface, ozone is even less abundant, with a typical range of 20 to 100 ozone molecules for each billion air molecules. The highest ozone values near the surface occur in air that is polluted by human activities.

As an illustration of the low relative abundance of ozone in our atmosphere, one can imagine bringing all the ozone molecules in the troposphere and stratosphere down to Earth's surface

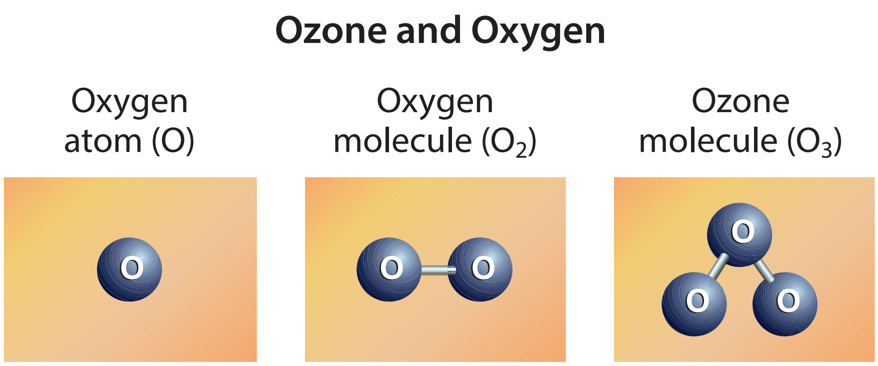

Figure Q1-1. Ozone and oxygen. A molecule of ozone (O_3) contains three oxygen atoms (O) bound together. Oxygen molecules (O_2), which constitute about 21% of the gases in Earth's atmosphere, contain two oxygen atoms bound together.

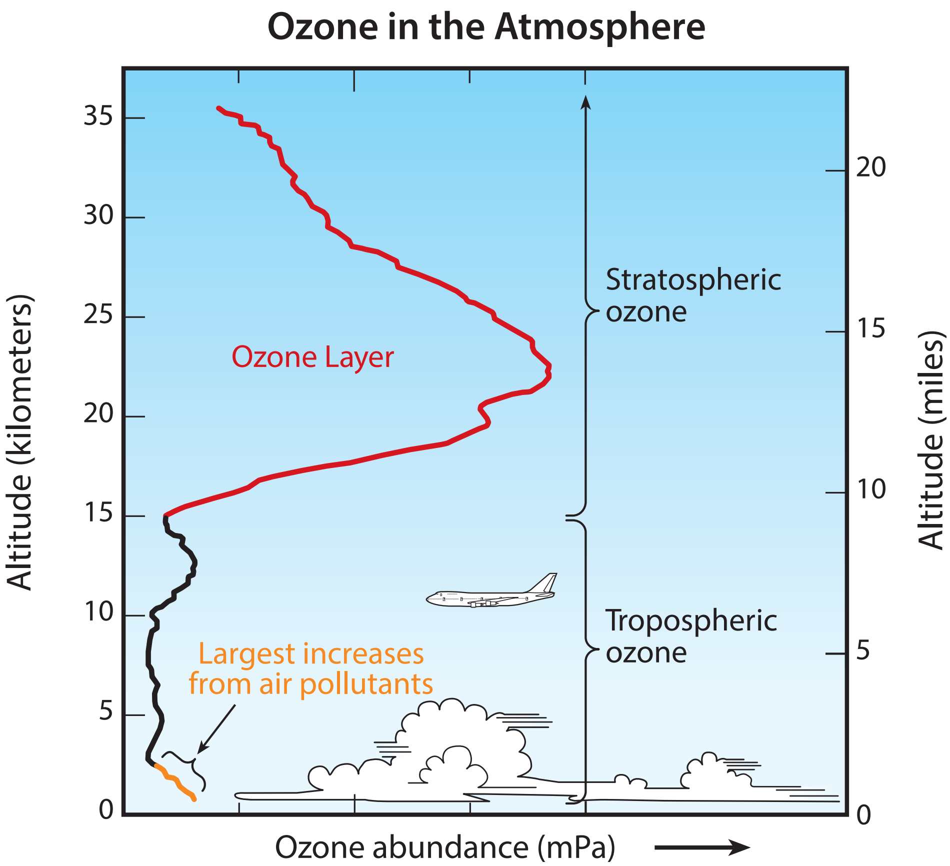

Figure Q1-2. Ozone in the atmosphere. Ozone is present throughout the troposphere and stratosphere. This profile shows schematically how ozone changes with altitude in the tropics. Most ozone resides in the stratospheric "ozone layer." The vertical extent or thickness of this layer varies from region to region and with season over the globe (see Q3). Increases in ozone near the surface are a result of air pollutants released by human activities. The direct exposure to ozone is harmful to humans and other forms of life.

and forming a layer of pure ozone that extends over the entire globe. The resulting layer would have an average thickness of about three millimeters (0.12 inches) (see Q3). Nonetheless, this extremely small fraction of the atmosphere plays a vital role in protecting life on Earth (see Q2).

Stratospheric ozone. Stratospheric ozone is formed naturally by chemical reactions involving solar ultraviolet radiation (sunlight) and oxygen molecules, which make up about 21% of the atmosphere. In the first step, solar ultraviolet radiation breaks apart one oxygen molecule (O_2) to produce two oxygen atoms (2 O) (see **Figure Q1-3**). In the second step, each of these highly reactive oxygen atoms combines with an oxygen molecule to produce an ozone molecule (O_3). These reactions occur continually whenever solar ultraviolet radiation is present in the stratosphere. As a result, the largest ozone production occurs in the tropical stratosphere.

The production of stratospheric ozone is balanced by its destruction in chemical reactions. Ozone reacts continually with sunlight and a wide variety of natural and human-produced chemicals in the stratosphere. In each reaction, an ozone molecule is lost and other chemical compounds are produced. Important reactive gases that destroy ozone are hydrogen and nitrogen oxides and those containing chlorine and bromine (see Q7). Some stratospheric ozone is regularly transported down into the troposphere and can occasionally influence ozone amounts at Earth's surface.

Tropospheric ozone. Near Earth's surface, ozone is produced by chemical reactions involving gases emitted to the atmosphere from both natural sources and human activities. Ozone production reactions primarily involve hydrocarbon and nitrogen oxide gases, as well as ozone itself, and all require sunlight for completion. Fossil fuel combustion is a primary source of pollutant gases that lead to tropospheric ozone production. As in the stratosphere, ozone in the troposphere is destroyed by naturally occurring chemical reactions and by reactions involving human-produced chemicals. Tropospheric ozone can also be destroyed when ozone reacts with a variety of surfaces, such as those of soils and plants.

Balance of chemical processes. Ozone abundances in the stratosphere and troposphere are determined by the balance between chemical processes that produce and destroy ozone. The balance is determined by the amounts of reactive gases and how the rate or effectiveness of the various reactions varies with sunlight intensity, location in the atmosphere, temperature, and other factors. As atmospheric conditions change to favor ozone-producing reactions in a certain location, ozone abundances increase. Similarly, if conditions change to favor other reactions that destroy ozone, abundances decrease. The balance of production and loss reactions, combined with atmospheric air motions that transport and mix air with different ozone abundances, determines the global distribution of ozone on timescales of days to many months (see also Q3). Global stratospheric ozone has decreased during the past several decades (see Q12) because the amounts of reactive gases containing chlorine and bromine have increased in the stratosphere due to human activities (see Q6 and Q15).

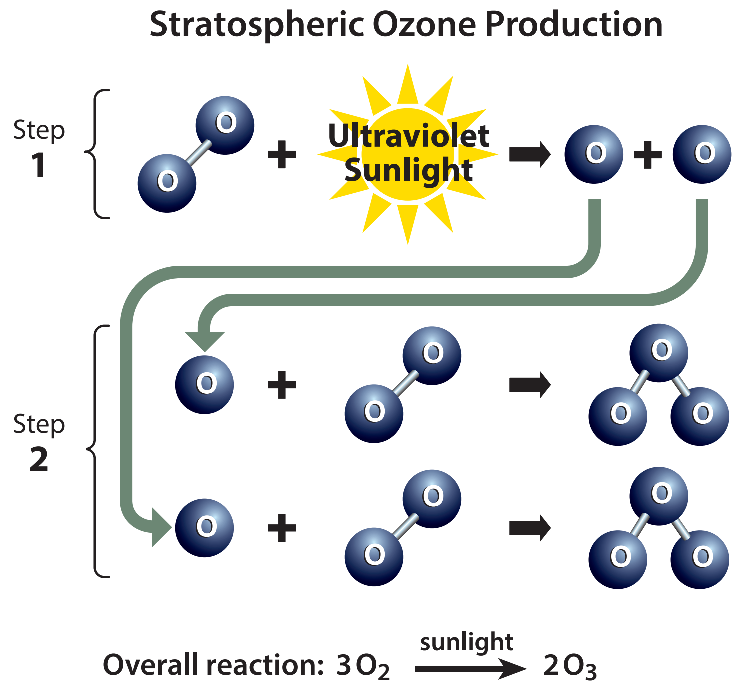

Figure Q1-3. Stratospheric ozone production. Ozone is produced naturally in the stratosphere by a two-step reaction process. In the first step, solar ultraviolet radiation (sunlight) breaks apart an oxygen molecule to form two separate oxygen atoms. In the second step, each oxygen atom collides with another oxygen molecule and forms an ozone molecule in a binding reaction. In the overall process, three oxygen molecules plus sunlight react to form two ozone molecules.