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The Earth Science Enterprise Series

These articles discuss Earth's many dynamic processes and their interactions

NASA's Earth Science Enterprise: *http://earth.nasa.gov*
NASA's Earth Observing System Project Science Office: *http://eos.nasa.gov*

Ozone

Ozone (O_3) is a relatively unstable molecule made up of three atoms of oxygen (O). Although it represents only a tiny fraction of the atmosphere, ozone is crucial for life on Earth.

Depending on where ozone resides, it can protect or harm life on Earth. Most ozone resides in the stratosphere (a layer of the atmosphere between 10 and 40 km above us), where it acts as a shield to protect Earth's surface from the sun's harmful ultraviolet radiation. With a

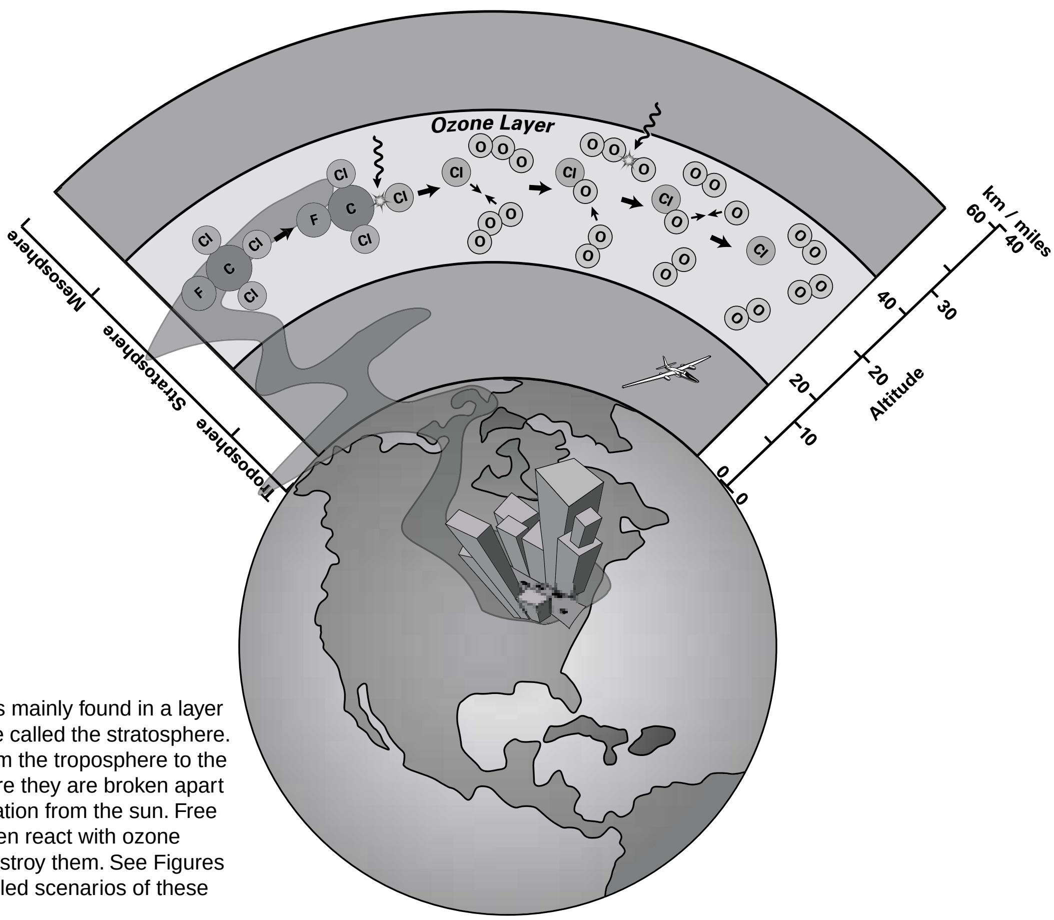

Figure 1. Ozone is mainly found in a layer of the atmosphere called the stratosphere. CFCs migrate from the troposphere to the stratosphere where they are broken apart by ultraviolet radiation from the sun. Free chlorine atoms then react with ozone molecules and destroy them. See Figures 2-4 for more detailed scenarios of these processes.

Ozone Production

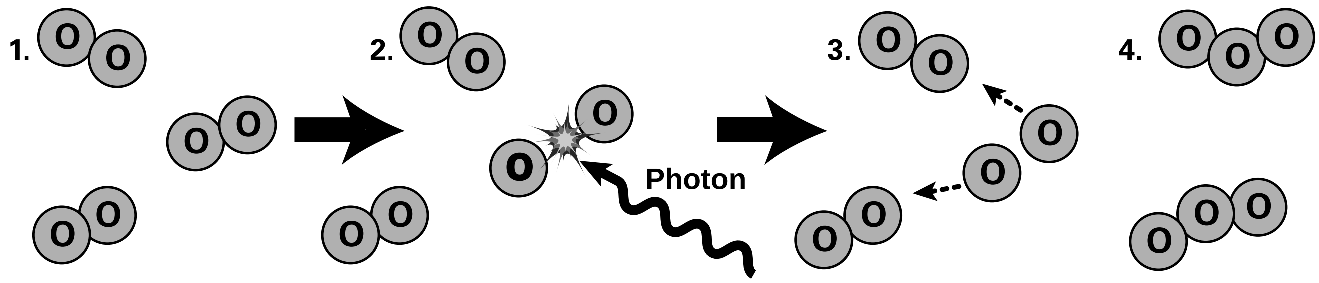

Figure 2. The four steps of ozone production. Step 1: Ordinary oxygen molecules (denoted by OO). Step 2: A photon of energy from the sun splits an oxygen molecule into two single oxygen atoms. Step 3: Free oxygen atoms combine with oxygen molecules. Step 4: Ozone is formed (denoted by OOO). A net change of three oxygen molecules into two ozone molecules.

weakening of this shield, we would be more susceptible to skin cancer, cataracts, and impaired immune systems. Closer to Earth in the troposphere (the atmospheric layer from the surface up to about 10 km), ozone is a harmful pollutant that causes damage to lung tissue and plants.

The amounts of "good" stratospheric and "bad" tropospheric ozone in the atmosphere depend on a balance between processes that create ozone and those that destroy it. An upset in the ozone balance can have serious consequences for life on Earth. Scientists are finding evidence that changes are occurring in ozone levels–the "bad" tropospheric ozone is increasing in the air we breathe, and the "good" stratospheric ozone is decreasing in our protective ozone layer. This article describes processes that regulate "good" ozone levels.

Ozone Balance in the Stratosphere

In the stratosphere, ozone is created primarily by ultraviolet radiation. When high-energy ultraviolet rays strike ordinary oxygen molecules (O_2), they split the molecule into two single oxygen atoms, known as atomic oxygen. A freed oxygen atom then combines with another oxygen molecule to form a molecule of ozone (Figure 2). There is so much oxygen in our atmosphere, that these high-energy ultraviolet rays are completely absorbed in the stratosphere.

Ozone is extremely valuable since it absorbs a range of ultraviolet energy. When an ozone molecule absorbs even low-energy ultraviolet radiation, it splits into an ordinary oxygen molecule and a free oxygen atom. Usually this free oxygen atom quickly re-joins with an oxygen molecule to form another ozone molecule. Because of this "ozone-oxygen cycle," harmful ultraviolet radiation is continuously converted into heat.

Natural reactions other than the "ozone-oxygen cycle" described above also affect the concentration of ozone in the stratosphere. Because ozone and free oxygen atoms are highly unstable, they react very easily with nitrogen (N), hydrogen (H), chlorine (Cl), and bromine (B) compounds that are found naturally in Earth's atmosphere (released from both land and ocean sources). For example, single chlorine atoms can convert ozone into oxygen molecules and this ozone loss balances the production of ozone by high-energy ultraviolet rays striking oxygen molecules.

In addition to the natural ozone balance, scientists have found that ozone levels change periodically as part of regular natural cycles such as the changing seasons, winds, and long time scale sun variations. Moreover, volcanic eruptions may inject materials into the stratosphere that can lead to increased destruction of ozone.

Over the Earth's lifetime, natural processes have regulated the balance of ozone in the stratosphere. A simple way to understand the ozone balance is to think of a leaky bucket. As long as water is poured into the bucket at the same rate that water is leaking out, the amount or level of water in the bucket will remain the same. Likewise, as long as ozone is being created at the same rate that it is being destroyed, the total amount of ozone will remain the same.

Starting in the early 1970's, however, scientists found evidence that human activities are disrupting the ozone balance. Human production of chlorine-containing chemicals such as chlorofluorocarbons (CFCs) has added an additional factor that destroys ozone. CFCs are compounds made up of chlorine, fluorine and carbon bound together. Because they are extremely stable molecules, CFCs do not react easily with other chemicals in the lower atmosphere. One of the few forces that can break up CFC molecules is ultraviolet radiation. In the lower atmosphere, CFCs are protected from ultraviolet radiation by the ozone layer itself. CFC molecules thus are able to migrate intact up into the stratosphere. Although the CFC molecules are heavier than air, the air currents and mixing processes of the atmosphere carry them into the stratosphere.

Once in the stratosphere, the CFC molecules are no longer shielded from ultraviolet radiation by the ozone layer. Bombarded by the sun's ultraviolet energy, CFC molecules break up and release chlorine atoms. Free chlorine atoms then react with ozone molecules, taking one oxygen atom to form chlorine monoxide and leaving an ordinary oxygen molecule (Figure 3).

If each chlorine atom released from a CFC molecule destroyed only one ozone molecule, CFCs would pose very little threat to the ozone layer. However, when a chlorine monoxide molecule encounters a free atom of oxygen, the oxygen atom breaks up the chlorine monoxide, stealing the oxygen atom and releasing the chlorine atom back into the stratosphere to destroy more ozone. This reaction happens over and over again, allowing a single atom of chlorine to act as a catalyst, destroying many molecules of ozone (Figure 4).

Where Does Chlorine Come From?

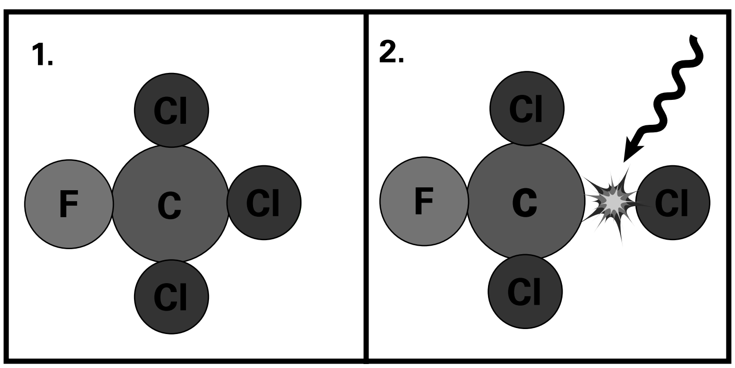

Figure 3. CFC molecules (Step 1) are broken up by the sun's energy (Step 2), releasing a free chlorine atom to react with, and destroy ozone molecules. (C - Carbon, F - Fluorine, Cl - Chlorine)

Fortunately, chlorine atoms do not remain in the stratosphere forever. When a free chlorine atom reacts with gases such as methane (CH_4), it is bound up into a molecule of hydrogen chloride (HCl), which can be carried downward from the stratosphere into the troposphere, where it can be washed away by rain. Therefore, if humans stop putting CFCs and other ozone-destroying chemicals into the stratosphere, the ozone layer eventually may repair itself.

Ozone Depletion

The term "ozone depletion" means more than just the natural destruction of ozone, it means that ozone loss is exceeding ozone creation. Think again of the "leaky bucket." Putting additional ozone-destroying compounds such as CFCs into the atmosphere is like increasing the size of the holes in our "bucket" of ozone. The larger holes cause ozone to leak out at a faster rate than ozone is being created. Consequently, the level of ozone protecting us from ultraviolet radiation decreases.

During the last 15 years, an additional mechanism was found in the areas over the Antarctic and Arctic that rapidly destroys ozone. Over the Earth's poles during their respective winters, the stratosphere cools to very cold temperatures and polar stratospheric clouds (PSCs) form. In the polar stratosphere, nearly all of the chlorine is in the form of inactive or "reservoir" gases such as hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$) that do not react with ozone or each other. However, chemical reactions of these "reservoir" chlorine gases can occur on the polar stratospheric cloud particle surfaces, converting the chlorine gases into very reactive forms that rapidly destroy ozone. This "polar chemistry" on the stratospheric cloud particles has caused very large decreases in ozone concentrations over Antarctica and the Arctic. In fact, ozone levels drop so low in spring over Antarctica that scientists describe this loss as the "Antarctic Ozone Hole."

Monitoring Ozone from Space

Since the 1920's, ozone has been measured by ground-based instruments. Scientists place instruments at locations around the globe to measure the amount of ultraviolet radiation getting through the atmosphere at each site. From these measurements, they calculate the concentration of ozone in the atmosphere above that location. These data, although useful in learning about ozone, are not able to provide an adequate picture of global ozone concentrations.

The amount and distribution of ozone molecules in the stratosphere varies greatly over the globe. Ozone molecules are transported around the stratosphere much as water clouds are transported in the troposphere. Therefore, scientists observing ozone fluctuations over just one spot could not know whether a change in local ozone levels meant an alteration in global ozone levels, or simply a fluctuation in the concentration over that particular spot. Satellites have given scientists the ability to overcome this problem because they provide a picture of what is happening daily over the entire Earth. The United States satellite measurement program for ozone, run jointly by NASA and the National Oceanic and Atmospheric Administration (NOAA), has measured ozone distribution by season, latitude, and longitude, and has observed long-term changes over more than 20 years using a variety of satellite instruments. The instruments in use today will be replaced over the next five to ten years by a new generation of improved, more sophisticated instruments.

Ozone Loss

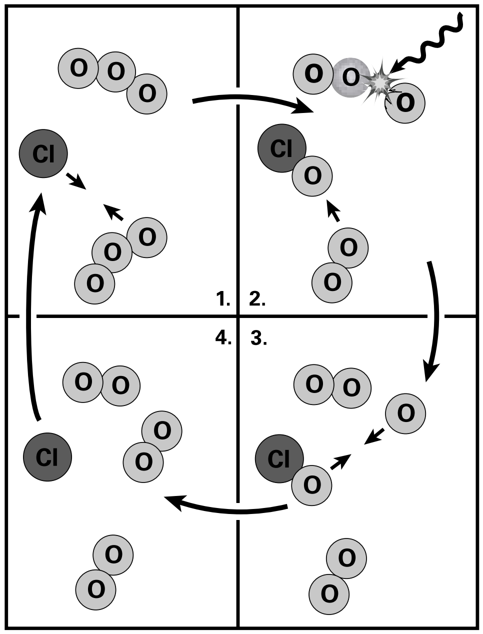

Figure 4: Panel 1: Ozone reacts with a chlorine (Cl) atom to form chlorine oxide (ClO). Panel 2: An ozone molecule is split into an oxygen molecule and an oxygen atom. Panel 3: The ClO molecule from Panel 1 reacts with the oxygen atom from Panel 2 to form a clorine atom and an oxygen molecule. The net reaction is to convert two ozone molecules (see panel 1) into three oxygen molecules. (see panel 4), leaving the Cl atom to repeat this series.

Predicting Ozone Levels

Stratospheric ozone is being depleted worldwide–partly due to human activities. Scientists now know that the large polar ozone losses are a direct result of the effects from human-produced chemicals. However, scientists still do not know how much of the mid-latitude loss is the result of human activity, and how much is the result of fluctuations in natural cycles.

Measurements and research are being used to improve models for predicting ozone levels. In fact, early model predictions have already aided policy makers in determining solutions to the ozone depletion problem. Faced with the strong possibility that CFCs could cause serious ozone depletion, policy makers from around the world signed the Montreal Protocol treaty in 1987, limiting CFC production and usage. By 1992, the growing scientific evidence of ozone loss prompted diplomats to strengthen the Montreal Protocol. The revised treaty called for a complete phase out of CFC production in developed countries by 1996. As a result, most CFC concentrations are slowly decreasing around the globe.

Much remains to be learned about the processes that affect ozone. To create accurate models, scientists must study simultaneously all of the factors affecting ozone creation and destruction. Moreover, they must study these factors from space continuously, over many years, and over the entire globe. NASA's Earth Observing System (EOS) will allow scientists to study ozone in just this way. The EOS series of satellites will carry a sophisticated group of instruments that will measure the interactions within the atmosphere that affect ozone. Building on the many years of data gathered by previous NASA and NOAA missions, these measurements will increase dramatically our knowledge of the chemistry and dynamics of the upper atmosphere and our understanding of how human activities are affecting Earth's protective ozone layer.

Related NASA Web sites

Internet TOMS (Total Ozone Mapping Spectrometer)
http://toms.gsfc.nasa.gov

EOS Aura Project Homepage
http://aura.gsfc.nasa.gov

Ozone Dance
http://asd-www.larc.nasa.gov/edu_act/ozone_dance.html

NASA's Earth Observatory - Ozone
http://earthobservatory.nasa.gov/Library/Ozone/

Atmospheric Chemistry Data & Resources
http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/ATM_CHEM/ac_outline.html

Studying Earth's Environment from Space
Stratospheric Ozone
http://see.gsfc.nasa.gov/edu/SEES/strat/strat.htm