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|   | Global WarmingBy Jeannie Allen, *April 19, 2002*http://earthobservatory.nasa.gov/Features/OzoneWeBreathe/  |

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|  | Ozone forms readily when sunlight strikes oxygen, so it is naturally present in our oxygen-rich atmosphere. In the upper atmosphere, ultraviolet light from the sun strikes the two atoms of molecular oxygen (O2) and splits them into single atoms. Those individual atoms each combine with another molecule of two-atom oxygen to make a three-atom molecule, which is ozone (O3). Most of this ozone converts readily back to oxygen, but a small amount of ozone persists.Another ozone-forming process takes place in the lower atmosphere, where chemicals emitted from industrial processes, vehicle exhaust, and other products of fossil fuel combustion form ozone through a more complex series of chemical reactions. As concentrations of these pollutants involved in ozone formation (precursors of ozone) increase with industrialization and vehicle traffic, ozone concentrations increase at ground level where we breathe.Photo of Cars on the Bay BridgeEmissions from heavy vehicle traffic, coal-fired power plants, and other sources take part in the reactions that produce ozone in the air we breathe. Human health effects of short-term exposure to ozone appear to be reversible, but effects of exposure over the long term appear to cause significant damage to the lungs, particularly those of children. (Photograph courtesy [Philip Greenspun](http://photo.net/philg/))When we breathe air unpolluted by human activities, we usually take in about 10 to 15 parts of ozone per billion parts of air (10-15 ppb). However, pollution from human activities has elevated levels of the ozone we breathe. Surface ozone measurements have increased considerably since the onset of the Industrial Revolution, possibly by as much as 100-200 percent at some locations over the past century. (Fishman et al. 1999) Spring and summer ozone concentrations in many regions reach above 125 ppb during episodes of excessive heat and stagnant air. The U.S. Environmental Protection Agency (EPA) has established 80 ppb of ozone exposure over eight hours as the National Ambient Air Quality Standard, but recognizes the possibility that ozone exposure at lower levels over several years can significantly impair human health, especially the health of children. Scientists liken the effect of overexposure to ozone to premature aging in our lungs. Ground-level ozone can adversely affect everyone. Ironically, people living in many rural areas suffer from ozone overexposure more than many people living in cities. This is because ozone levels are generally higher downwind of ozone precursor sources, at distances of hundreds or even thousands of kilometers, so ozone concentrations in rural areas can be higher than in urban areas. The high levels of ozone that are now common downwind of cities adversely affect the productivity of some crops and even wild plant species. Additionally, overexposure to ozone can compound effects from other conditions that stress plants, such as drought. Reactions involving ozone also cause deterioration of electronic devices and materials such as rubber, plastics, outdoor paints, photographic papers, and fabrics. Ozone plays other roles the Earth’s climate system. It is a minor greenhouse gas and contributes to climate change. It’s also involved in chemical reactions that produce the hydroxyl radical (OH), which plays a critical role in the atmosphere’s ability to cleanse itself of many chemicals we consider pollutants. At the same time, the hydroxyl radical itself is necessary for ozone formation in the lower atmosphere. Ozone chemistry in sunlight (photochemistry) is one of the most complex phenomena in the natural world. Ozone’s effects on the systems of the Earth are no less complex. They challenge our understanding, and at the same time, they are very important for us to understand. Ozone affects human well-being and the health of agriculture and ecosystems.  |
|  | **Ozone’s Effects on Human Health** Shortness of breath, dry cough or pain when taking a deep breath, tightness of the chest, wheezing, and sometimes even nausea are common responses to ozone. Ozone reacts with molecules in the lining of our airways. Chemical bonds break and reform in different ways with the addition of oxygen atoms (the process of oxidation) from ozone, and this causes acute inflammation. The lining of our airways loses some of its ability to serve as a protective barrier to microbes, toxic chemicals, and allergens. Our airways respond by covering the affected areas with fluid and by contracting muscles. Breathing becomes more difficult.Micrographs of Human Lung TissueMicroscopic views of human lung tissue (epithelium, or lining) show damage resulting from exposure to relatively low levels of ozone. In the control image (upper) from the lung of a person exposed only to air, the tiny cilia that clear the lungs of mucus appear along the top of the image in a neat and regular row. In the lung exposed to 20 ppb of ozone added to the air for four hours during moderate exercise, many cilia appear missing and others appear misshapen. Arrows point to tiny bodies called neutrophils in the ozone-exposed subject. The presence of neutrophils indicates inflammation. Magnification: x400. (Micrographs courtesy of the American Thoracic Society, from American Review of Respiratory Diseases, Vol. 148, 1993, Robert Aris et al., pp. 1368-1369.)The National Institute of Environmental Health Sciences (NIEHS) at the National Institutes of Health reports that in controlled tests, a 5 to 10 percent reduction in lung capacity occurred in volunteers engaged in moderate exercise for 6.5 hours at just 80 ppb (National Institutes of Health 2001), a level commonly reached during warm weather in many parts of the world. Ozone also triggers asthma and may aggravate other respiratory illnesses such as pneumonia and bronchitis. Ozone concentrations can make the small bands of muscles that help control breathing more sensitive to dry air, cold or dust, so ozone exposure may increase allergic responses in susceptible people.While the effects of acute, short-term episodes of ozone exposure are reversible, the human body’s response to long-term exposure may not be reversible. Exposure to ozone at levels we commonly encounter in many of our own communities permanently scars the lungs of experimental animals, causing long-term impairment of lung capacity, or the volume of air that can be expelled from fully inflated lungs. Ozone may have similar effects on human lungs. Studies in animals also suggest that ozone may reduce the human immune system’s ability to fight bacterial infections in the respiratory system. Ozone damage to people can occur without any noticeable signs. Even when initial symptoms appear, they can disappear while ozone continues to cause harm. Otherwise healthy people can expect to experience acute but reversible effects if they exercise regularly outdoors when ozone levels are high. The NIEHS considers such people to be especially susceptible as a group.Children’s vulnerability to ozone’s ill effects provokes great concern among health professionals for several reasons. One reason is that children’s respiratory defenses have not reached their full capability. Another is that children breathe more air per pound of body weight than adults so they take in more ozone per pound of body weight than adults do. Children are also in a phase of rapid growth, and their metabolic rates are higher than adult rates tend to be. Furthermore, children generally exercise outdoors more than adults do. According to a recent study conducted by researchers at the University of Southern California Keck School of Medicine with fourth grade school children, each increase of 20 ppb in ozone is associated with a 63 percent school absence rate increase for illness. The same increase in ozone concentration is associated with an 83 percent increase for respiratory illness. (Gilliland 2001) 20 ppb represents a relatively small and common increase in ozone concentration.Responses to ozone pollution vary from one individual to another, sometimes for reasons we don’t yet understand. The U.S. Environmental Protection Agency (EPA) estimates that 5 to 20 percent of the total U.S. population has an unexplained greater susceptibility (American Lung Association 2000) The EPA has designated ozone one of six "criteria air pollutants" and therefore a pollutant that must be kept in check. Yet few state governments have enforced regulations designed to bring ozone air pollution under control. Tropospheric ozone levels in the more polluted regions of the Northern Hemisphere appear to be rising at about 1 percent per year (Turco 1997) The American Lung Association reports that scientists’ estimates of the annual number of deaths in the United States associated with air pollution range from 50,000 to 100,000. (American Lung Association 2001) While another form of air pollution, particulate matter, is the one most prominently linked to premature death, ozone pollution plays an important role as well in this threat to human health and well-being. |

**Ozone’s Effects on Plants**
Because ozone formation requires sunlight, periods of high ozone concentration coincide with the growing season. Just as in damage to people, ozone damage to plants can occur without any visible signs. Many farmers are unaware that ozone is reducing their yields. Ozone enters the plant’s leaves through its gas exchange pores (stomata), just as other atmospheric gases do in normal gas exchange. It dissolves in the water within the plant and reacts with other chemicals, causing a variety of problems. Plant physiologists are still trying to understand the specific pathways and locations of ozone’s effects within plant cells. Physiologists know that some cell membranes become leaky, possibly because of ozone’s ability to interact with lipid (fatty) components and/or membrane proteins. Photosynthesis slows, resulting in slower plant growth. Compounds resulting from oxidation by ozone interfere with the cell’s energy production in the mitochondria. Such ozone-induced compounds also decrease the numbers of flowers and fruits a plant will produce, and they impair water use efficiency and other functions. Plants weakened by ozone may be more susceptible to pests, disease, and drought.


Browning on potato leaves shows evidence of exposure to high concentrations of ozone. (Photograph courtesy UDA-ARS Air Quality Program, North Carolina State University; photo by Gerald Holmes)

Severely affected plants do show symptoms of ozone stress. Leaves may have tiny light-tan irregular spots less than 1mm in diameter (flecking), small darkly pigmented areas approximately 2-4 mm diameter (stippling), bronzing, and reddening. An increasing number of reports have appeared during the past 25 years regarding ozone-induced injury to plant leaves in many countries. (Krupa et al. 2001)

Although research shows that ozone pollution harms forests and that prolonged exposure has serious consequences, the precise extent of ozone damage to mature forests has proven a difficult issue to resolve. Natural ecosystems are highly variable and complex, and laboratory studies can never fully simulate them. Variability extends to individual plant species, subspecies, and varieties; some react to ozone more strongly than others.

Among crop plants, tobacco is a "canary in the mine" (or early warning) for detecting harmful levels of ozone. Plants such as soybean, cotton, peanut, clover, quaking aspen, and yellow poplar (dicotyledons) tend to be more sensitive to ozone than plants such as sorghum, field corn, and winter wheat (monocotyledons). Agricultural researchers study ozone’s effects on major crops that include tobacco, soybeans, cotton, wheat, and corn because they’re important to our agricultural economy.

Studies of ozone’s influence on crop yields differ in their results. Studies of soybean yield at the University of Maryland found a 10 percent loss of soybean crop due to current levels of ozone in that state, which are commonly 40-80 ppb during the growing season, with particular episodes much higher. The same study showed that ozone exposure causes the loss of 6-8 percent of winter wheat and 5 percent of the corn crop yields to Maryland farmers. (Mulchi 2001) The National Crop Loss Assessment Network in Raleigh, North Carolina, found a 2-5 percent loss for winter wheat at current levels of ozone (which usually average between 50 and 55 ppb). (Heagle 2001)

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| http://earthobservatory.nasa.gov/Features/OzoneWeBreathe/Images/crop_loss_lft.gif | Graph Showing Crop Loss Due to Tropospheric OzoneSome species of crop plants react more strongly to high concentrations of ozone than others. This graph from a study by the Environmental Protection Agency shows the reduction in yield of crops exposed to ozone. At an ozone concentration of 60 parts per billion, soybeans yields decrease to about 75 percent of normal, while wheat, corn, and alfalafa yields decrease to about 90 percent of normal. (Graph by Adams et al., 1989, adapted by Chameides et al., 1999, based on data from the National Crop Loss Assessment Network)Chemical changes in the atmosphere spread throughout other parts of the Earth system, including land, water, and living organisms. Effects of crops’ exposure to ozone appear in the soil as well as in the plants themselves. In soybeans, overexposure to ozone results in the plant metabolizing less carbon dioxide. This reduces carbon flow from the atmosphere to the roots. Reduced carbon flow suppresses nitrogen fixation, and the plant then "mines" the soil for some of the nitrogen it needs to grow. Under conditions of high ozone exposure, soybean farmers who want to maximize their soybean crop production must add more nitrogen to the soil than it normally requires. In Maryland and nearby states, an overabundance of nitrogen runoff from the land causes serious and expensive problems for natural ecosystems and fisheries in Chesapeake Bay. While the exact extent of this nitrogen runoff due to ozone exposure remains to be established, adding more nitrogen to the watershed presents an unattractive solution to the ozone pollution problem.Image of Plant Photosynthetic EfficiencyFluorescence imaging technology captures soybean plant responses to elevated levels of ozone. Within each image, the two leaves on the left-hand side grew in control chambers, and the two leaves on the right-hand side grew in chambers with moderately elevated ozone concentrations. Purples and blues in ozone-exposed leaves indicate that the leaves are carrying out photosynthesis less efficiently than leaves in the control chambers, where deeper reds and yellows appear. (From Kim, M.S., McMurtrey, J.E., Mulchi, C.L., Daughtry, C.S.T., Chappelle, E.W., and Chen, Y.R. Steady-state multispectral fluorescence imaging system for plant leaves. *Applied Optics,* 40:157-166. 2001)High ozone concentrations can affect not only plant growth, but soil fertility. Plants exposed to low ozone concentrations normally metabolize a certain amount of carbon dioxide. They send carbon to their roots, and then to the surrounding soil. Microbes in the soil make use of this carbon. Plants that are exposed to high ozone concentrations metabolize less carbon dioxide, so less carbon is available in the soil, and fewer soil microbes grow and thrive. Microbial activities that result in soil enrichment and carbon processing decrease, with the result that soil fertility diminishes. Ozone’s harmfulness at ground level extends to non-living things. In the earliest days of ozone research, cracks in rubber served as the indicators used by scientists to determine atmospheric concentrations of ozone. Ozone accelerates fading in dyes and speeds deterioration of some paints and other coatings. It also damages cotton, acetate, nylon, polyester, and other textiles. Photographic paper companies caution users about ozone exposure. |
|  | Ozone’s Role in Atmospheric Cleansing On the positive side, ozone plays a beneficial and important role in the atmosphere’s wonderful self-cleansing function. Ozone is the primary precursor of the hydroxyl radical. The hydroxyl radical is so called because it has an unpaired electron in its outermost electronic orbit. Unpaired electrons are "lonely" and readily pair up with others, forming chemical bonds. The hydroxyl radical serves as the main scavenger in the atmosphere, reacting with a variety of compounds such as hydrocarbons, hydrogen sulfide, and carbon monoxide that would otherwise accumulate and poison us.Because of its high reactivity and its ability to harm microscopic organisms, ozone has the reputation of being an air and water purifier, only some of which it deserves. A few commercial companies market air cleaners or air "fresheners" that are said to work by generating ozone. According to the National Institutes of Health, this is a potentially harmful idea. (National Institutes of Health, 2000) In order to generate enough ozone to be effective, such equipment has to produce dangerous amounts of ozone.Whatever they are, the future effects of ozone must be predicted in light of changing concentrations of other chemicals and climate conditions in the atmosphere. The atmosphere is extremely complicated. Changes in the concentration of one chemical generally affect the concentrations of several others, often in very short spans of time, and this makes such changes difficult to predict and to track. Predicting tropospheric gas concentrations much beyond several years from now lies beyond the capacity of most computer models and even most computers. Achieving a thorough and complete understanding of surface ozone chemistry presents a multitude of challenges. |
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Ozone in the lower atmosphere (troposphere) is toxic to human beings and to many other living things that breathe it. Before scientists began to track the global travels of ozone in the troposphere with satellite data and measurements made from aircraft, they assumed that much of that part of the atmosphere was relatively free of ozone. But after combining satellite observations with data-rich models that simulate the atmosphere’s chemistry and dynamics, they are finding tropospheric ozone in some unexpected places. Tropospheric ozone turns out to be an intercontinental traveler, crossing geographic and political boundaries. Where ozone forms and where it travels have become key concerns for international health and economic policy-making. On the stage of global change, ozone plays the role of both hero and villain.

Ozone in the stratosphere (upper atmosphere) protects us from harmful ultraviolet radiation from the sun, but ozone plays a different role in the troposphere, where we live, because it is toxic to living things. Ozone in the upper troposphere is also a greenhouse gas, meaning that its presence contributes somewhat to global warming. On the other hand, tropospheric ozone plays a role that is key to enhancing human health and well being, since it is involved in chemical reactions that cleanse the troposphere of some pollutants. Therefore considerable research is now underway to understand the conditions under which ozone forms and how ozone travels from its source.

Understanding the chemical and physical dynamics of ozone and other trace gases is becoming increasingly urgent as world population rises and economic activity increases among developing nations. Increased combustion of fossil fuels, which produces chemicals that contribute to ozone formation ("precursors") accompanies that economic activity. Asian economic development is proceeding particularly rapidly, and most Asian governments do not strictly regulate emissions from fossil fuel combustion. The lifetime of ozone’s precursors in the troposphere is sufficiently long that they can produce ozone hundreds or even thousands of miles away before further chemical reactions transform ozone into oxygen and other chemicals. Of course, Asia is not the only problem area. Air currents move pollution from all developed and developing nations to other parts of the world. Governments need to adopt a global perspective when designing a strategy to meet regional air quality objectives for limiting ozone.

Scientists combine satellite data with data from observations made at the surface, from ozonesondes (meteorological balloons that carry ozone sensors), from aircraft and from models (simulations of the atmosphere on computers), to study ozone on a range of spatial scales and to ensure that satellite measurements are accurate. Atmospheric scientists began to recognize the extent of ozone’s travels relatively recently. Anne Thompson, an atmospheric chemist at NASA ’s Goddard Space Flight Center, explains, “What we’re trying to do is to parse out what ozone comes from natural causes and what ozone comes from human activity.” (Natural causes include lightning, production of methane from decomposition of organic materials, and some emissions from plants—isoprene and terpenes.) “It’s extremely hard to separate natural and manmade sources of gases. The precursors of ozone such as nitrogen oxides are not labeled ‘I came from an aircraft engine,’ ‘I came from the stratosphere,’ ‘I came from the ground,’ or ‘I came from lightning.’ You have to measure other related chemicals that fingerprint the source.”