

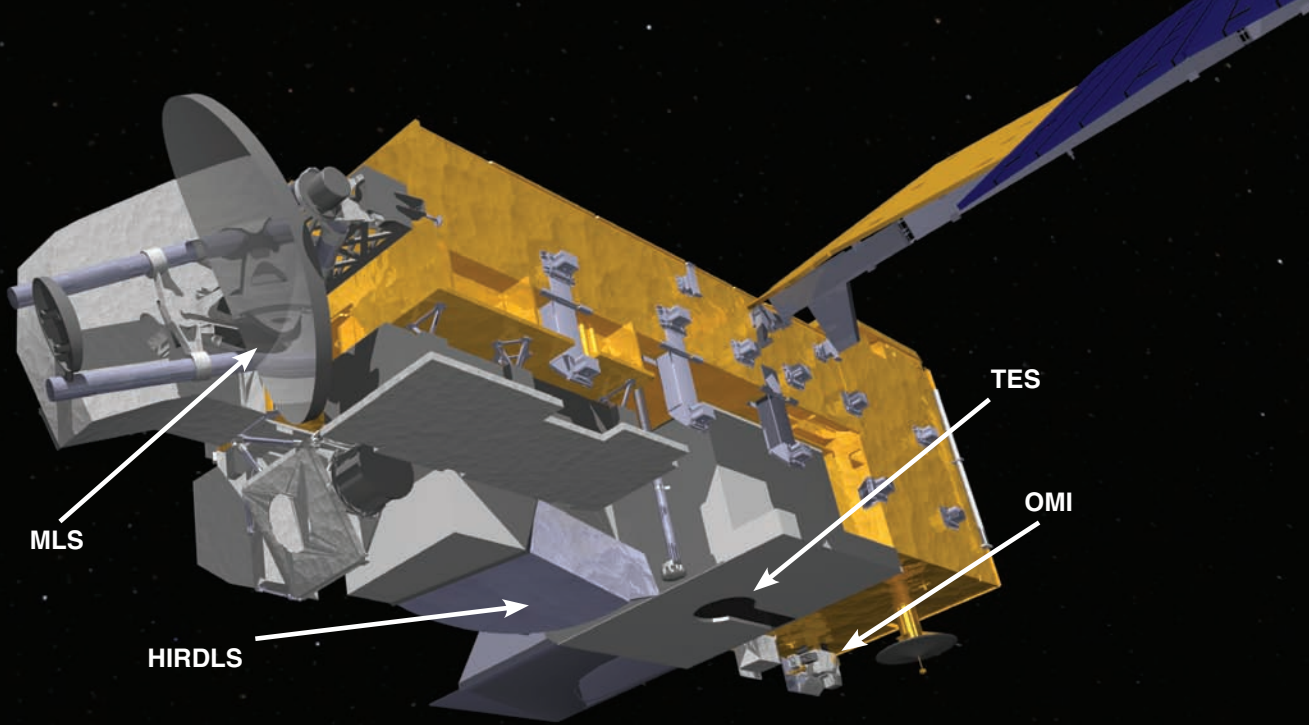
National Aeronautics and Space Administration



OUR CHANGING ATMOSPHERE

# Discoveries from EOS Aura



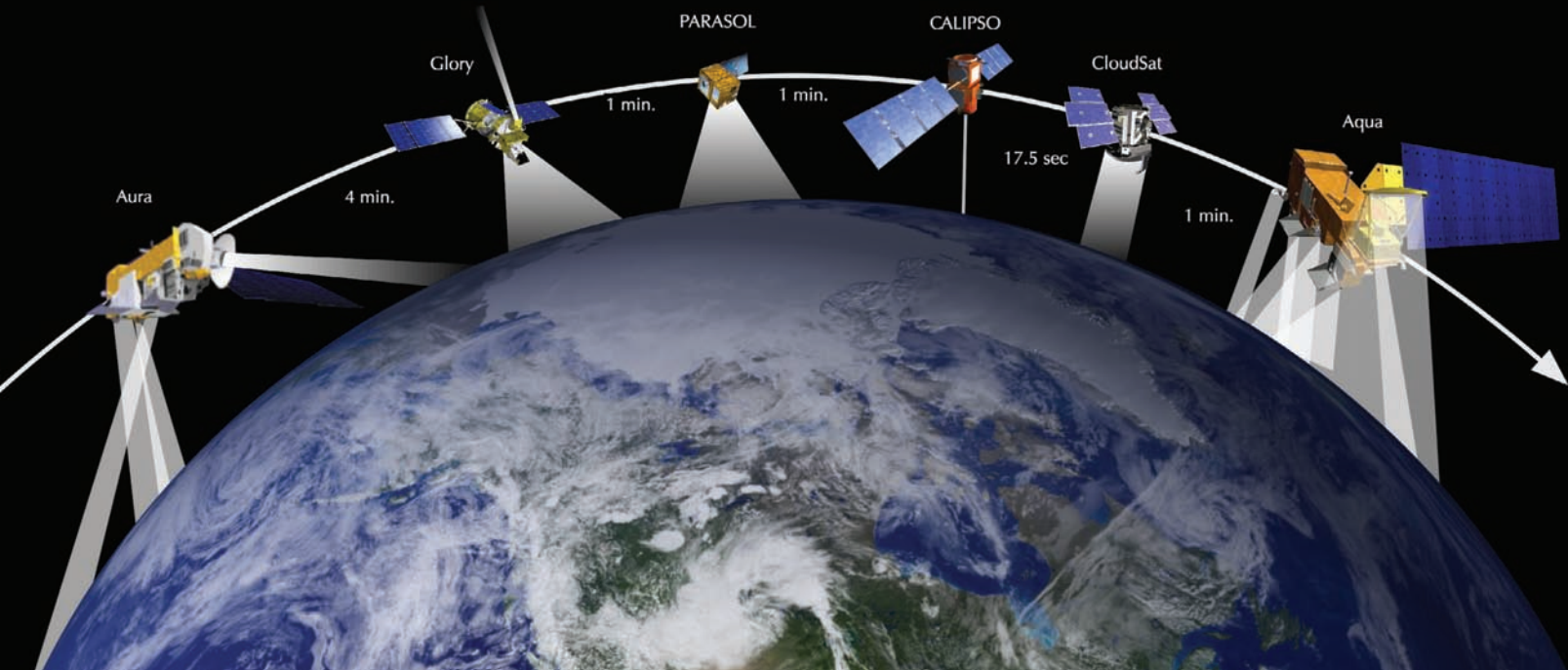


### Aura's Four Instruments

The Aura spacecraft illustration (above) shows where the instruments are mounted. MLS looks out of the front of the spacecraft at the atmosphere, while OMI and TES (in nadir mode) look down. HIRDLS and TES (in limb mode) look backward at the atmosphere.

### The "A" Train

Aura is part of a constellation of satellites called the "A-train." Instruments on these satellites make measurements of the same location as they pass over it, one at a time, within an 8 minute period. (NOT TO SCALE)



## The Aura Mission

Aura is NASA's third large Earth Observing System mission and is dedicated to understanding the changing chemistry of our atmosphere.

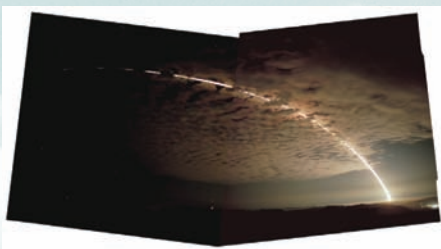
### Aura's Four Instruments

- The High Resolution Dynamics Limb Sounder (HIRDLS)
- The Microwave Limb Sounder (MLS)
- The Ozone Monitoring Instrument (OMI)
- The Tropospheric Emission Spectrometer (TES)

### Aura's Principal Science Questions

- Is the ozone layer changing as expected?
- What are the processes that control tropospheric pollutants?
- What are the roles of upper tropospheric aerosols, water vapor and ozone in climate change?

Aura's strategy is to obtain measurements of ozone, aerosols and key gases throughout the atmosphere using technologically innovative space instrumentation. Scientists use these data to gain revolutionary insights into the chemistry of our atmosphere. Highlights from the first five years of Aura discoveries appear on the following pages and the web site <http://aura.gsfc.nasa.gov/>

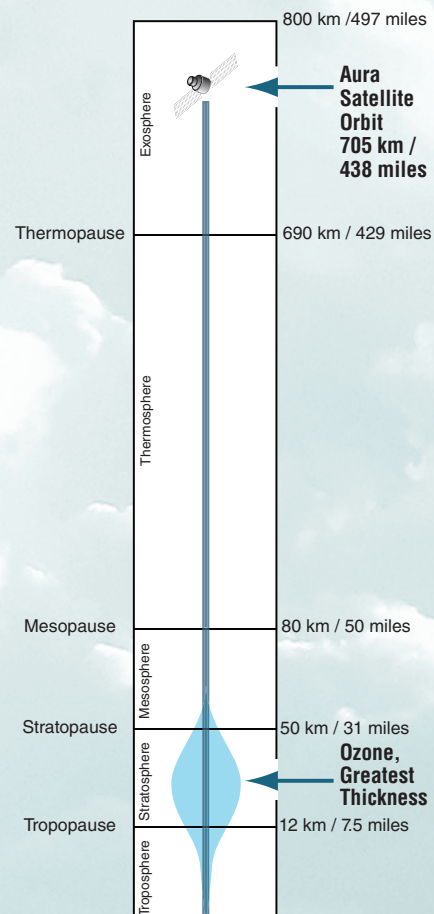


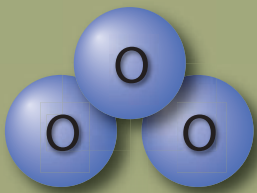
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**ON THE COVER:** A time lapse photo of the Aura launch was taken from the crest of the Santa Ynez Mountains, CA about 56 km (35 miles) east of Space Launch Complex 2 at Vandenberg Air Force Base. © BRIAN LOCKETT

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## OZONE

### Ozone and Life

#### Stratospheric Ozone Facts

- Most ozone is found between the tropopause (~10 - 18 km) and the stratopause (~50 km).
- Stratospheric ozone absorbs almost all the harmful UV radiation from the sun, protecting life on the Earth's surface.
- Stratospheric ozone is created when ultraviolet light splits oxygen molecules. Ozone is destroyed by chemical reactions with chlorine, bromine, nitrogen, and hydrogen radicals.
- The chemical reactions in catalytic cycles take place rapidly. There are 1000 ozone molecules for every ozone-destroying radical, yet these catalytic cycles control the ozone amounts throughout the stratosphere.

Ozone molecules protect the surface from harmful solar ultraviolet (UV) radiation, making them important for life on Earth. It may be surprising to learn that ozone molecules can also be dangerous. An ozone molecule may be either beneficial or harmful to life depending on whether it is near the Earth's surface in the troposphere or more than 12 km above the surface in the stratosphere.

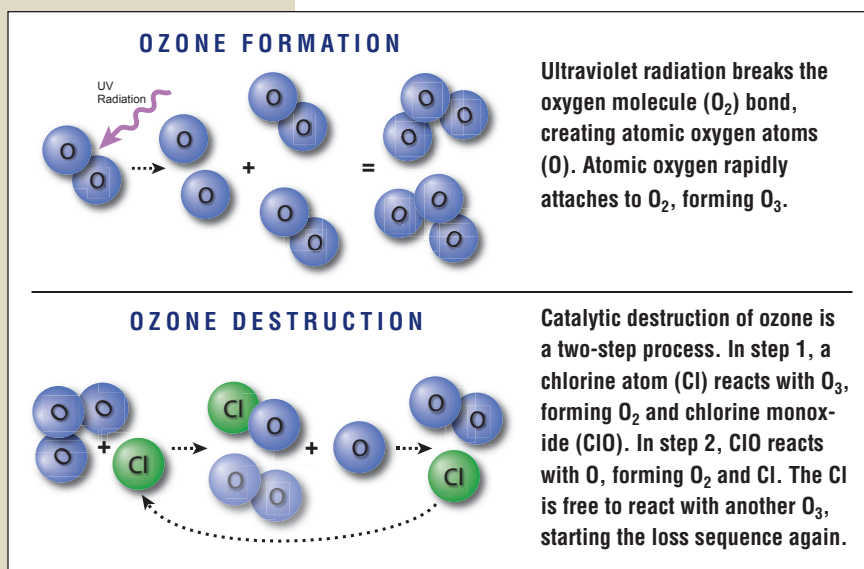
Ozone molecules are rare. Oxygen atoms (O) are building blocks for oxygen molecules (O<sub>2</sub>, 2 oxygen atoms) and for ozone molecules (O<sub>3</sub>, 3 oxygen atoms). About 1 out of every 5 molecules in the Earth atmosphere is an oxygen molecule. Most ozone is found in the stratosphere and, even where the ozone concentration is highest, there is only 1 ozone molecule for every 10,000 oxygen molecules.

The troposphere is the part of the atmosphere nearest the surface. In the troposphere

the temperature almost always decreases with increasing altitude. The temperature begins to increase with increasing altitude at the tropopause, marking the start of the stratosphere. The tropopause is located at about 18 km in the tropics and between ~10 and 12 km elsewhere. The temperature continues to increase throughout the stratosphere up to the stratopause (~50 km).

Stratospheric ozone is formed when high-energy ultraviolet rays strike an oxygen molecule (O<sub>2</sub>), breaking it into 2 oxygen atoms. Each oxygen atom can combine with an oxygen molecule, forming an ozone molecule. Ozone molecules are also destroyed by chemical reactions. For example, an ozone molecule can react with an oxygen atom, forming two oxygen molecules. The oxides of nitrogen, hydrogen, chlorine, and bromine are called radicals because they react quickly with many other gases. Radicals take part in catalytic reaction cycles in which ozone is destroyed but ozone-destroying molecules are unchanged, as illustrated in the box on the lower left.

Human production of chlorofluorocarbons (CFCs) has upset the normal balance between ozone production and loss processes. CFCs are stable molecules made of chlorine, fluorine and carbon. CFCs have many uses, for example refrigeration and air conditioning, and the atmospheric concentration of CFCs grew for many years. CFC molecules eventually made their way into the stratosphere. Once above most of the ozone layer, ultraviolet radiation breaks apart the CFCs, releasing chlorine atoms. Chlorine can initiate a catalytic reaction cycle that destroys



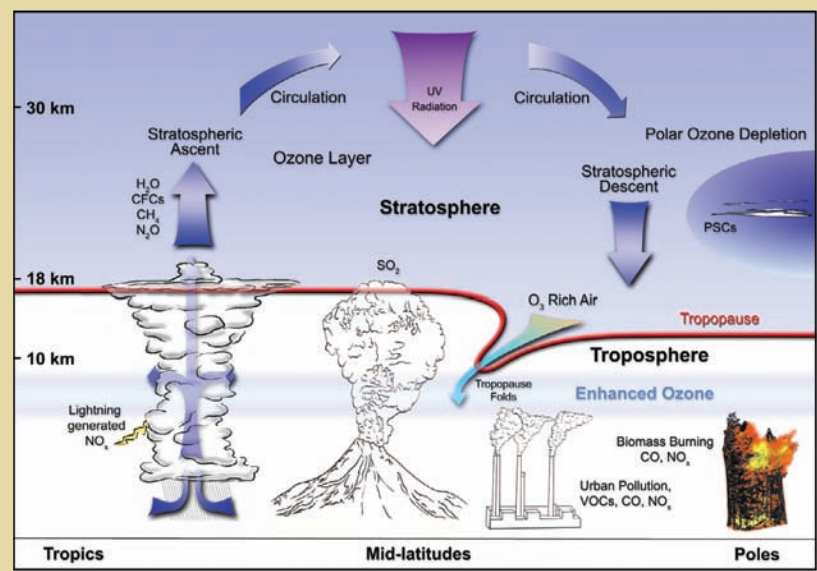


### Tropospheric Ozone Facts

- Ozone near the surface is a pollutant. It is damaging to plants and dangerous to breathe if the levels are high.
- In the most polluted cities surface ozone levels can be greater than 200 ppb, about 60 times smaller than the largest concentration in the stratosphere.
- Photochemical reactions with tropospheric  $O_3$  form OH, the hydroxyl radical. OH reacts with many other pollutants, scrubbing them from the air.
- In the upper troposphere  $O_3$  absorbs infrared radiation and is an important greenhouse gas.

## Ozone in the Atmosphere

This schematic shows the sources and transport processes that affect ozone in the troposphere and stratosphere and illustrates the connections between the two regions. The atmosphere is divided into layers based on the temperature change with altitude. In the troposphere, the layer between the surface and 10 to 18 km (6 to 11 miles) (depending on latitude), the temperature decreases with altitude. In the strato-



sphere, between 18 and 50 km (11 and 31 miles), the temperature increases with altitude.

osphere. In the last 30 years, the amount of chlorine in the stratosphere has risen to about three times its natural level. The ozone hole forms each Antarctic spring when reactions with chlorine compounds rapidly destroy ozone.

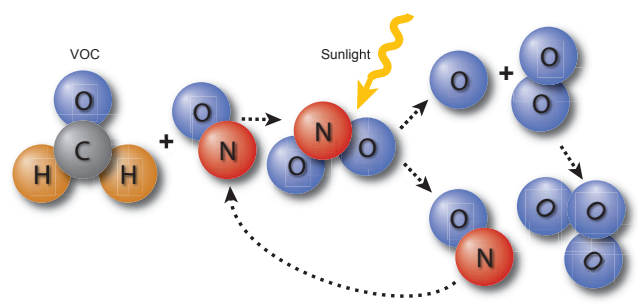
In the troposphere, ozone concentrations are 100 times smaller than in the stratosphere. Near the surface, most ozone comes from the interaction of nitrogen oxides and hydrocarbons—common pollutants. These pollutants that lead to ozone production are called ozone precursors. It takes sunlight and some time for ozone concentrations to build up in a polluted environment. This is why peak surface ozone levels usually occur in the afternoon. Surface air with a high ozone concentration is dangerous to breathe and damages plants; some people call it the ‘bad’ ozone. This helps them to distinguish it from the ‘good’ ozone in the stratosphere that protects us from ultraviolet radiation.

In the upper troposphere ozone descends from the stratosphere along weather fronts

and is also produced by chemical reactions following lightning flashes. Ozone in the upper troposphere is of concern to climate scientists because ozone absorbs and emits infrared radiation and thus is a “greenhouse” gas. Some radiation from the surface is trapped by ozone in the upper troposphere. This warms the surface and makes upper tropospheric ozone an important part of the climate-radiation balance.

In the troposphere,  $O_3$  is formed through a two-step process involving an industrial pollutant nitric oxide (NO) and volatile organic compounds (VOCs). VOCs are molecules like formaldehyde (HCHO) that can come from pollutants or natural sources. VOCs react with NO forming nitrogen dioxide ( $NO_2$ ) and other products (not shown). Sunlight breaks apart  $NO_2$ , releasing atomic oxygen (O) and NO. The NO can react with another VOC, starting the production sequence again.

### TROPOSPHERIC OZONE FORMATION





## STRATOSPHERIC OZONE

### The Rise and Fall of Stratospheric Chlorine

#### Chlorine Facts

■ About 85% of chlorine in the stratosphere comes from anthropogenic (human-produced) compounds, primarily chlorofluorocarbons (CFCs). CFCs were widely used for air conditioning, refrigeration and as aerosol propellants before they were banned by international treaties in the 1980s. Chlorine from CFCs causes the ozone hole to appear each spring in the Southern Hemisphere.

■ CFCs have a very long atmospheric lifetime and are now slowly decreasing in abundance. At the present rate of decrease, the ozone hole is predicted to disappear sometime after 2050.

■ CFCs are also greenhouse gases, and the agreement to stop CFC production to protect the ozone layer also reduces the human impact on the Earth's climate.

**C**hlorofluorocarbons (CFCs) are human-produced (called anthropogenic) compounds that were used for many industrial purposes, including refrigerators and air conditioners. CFCs are harmless and nonreactive in the lower atmosphere. Their chemical bonds, however, can be broken by ultraviolet light. In the lower atmosphere CFCs are protected from ultraviolet radiation by the ozone layer, but as they are mixed throughout the troposphere they eventually enter the stratosphere in the tropics. Once in the stratosphere, CFCs ascend above the ozone layer where their chemical bonds are broken by ultraviolet radiation, releasing chlorine radicals. Chlorine radicals then react with ozone in a catalytic cycle that can rapidly reduce the ozone concentration. Chlorine atoms can also react with methane ( $\text{CH}_4$ )

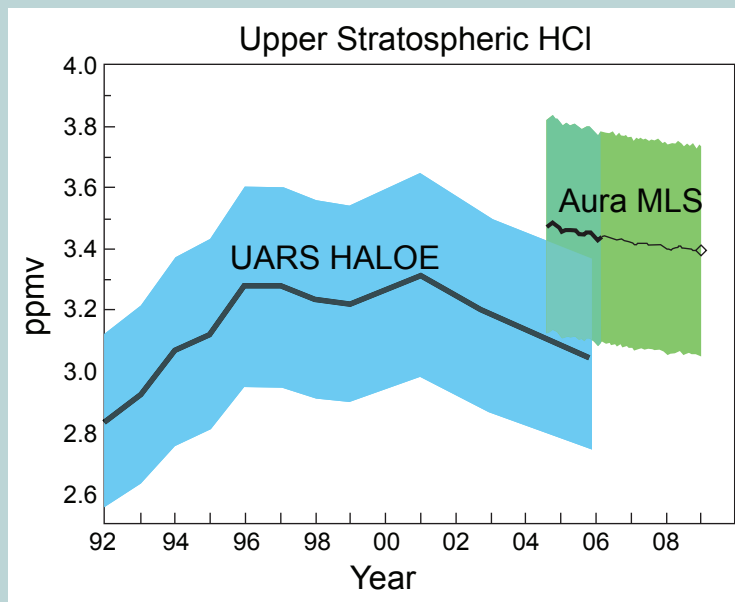
forming hydrochloric acid (HCl). More than 95% of the chlorine in the stratosphere is contained in HCl molecules.

Because of the threat to the ozone layer, in 1987 the governments of the world agreed to the Montreal Protocol, restricting CFC production. The 1990 London amendments and the 1992 Copenhagen amendments set a schedule to eliminate production of CFCs. As a result, CFC amounts at the surface are no longer increasing.

The Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite measured HCl from late in 1991 until the end of 2005. During that time the HCl reached a peak value and began a slow decline. Aura MLS began measuring HCl in August 2004, and the slow decline continues.

#### Decline of Stratospheric Chlorine

Measurements from UARS HALOE show the increase in chlorine during the 1990s and the slow decrease thereafter. The Aura MLS measurements continue the time series. The shaded bands show the measurement accuracy for each instrument. Although the mean values are offset during the overlap period from Aura's launch in July 2004 until HALOE ceased taking data in November 2005, they fall within each other's accuracy band.



## The Ozone Hole

The ozone hole is a region of exceptionally depleted ozone in the stratosphere that forms each spring over the Antarctic. The ozone column is measured in Dobson Units (DU), a convenient measure of the total number of molecules in a column of air. From the historical record, we know that total column ozone values of less than 220 Dobson Units were not observed over Antarctica prior to 1979. The area where the ozone column is less than 220 DU is called the ozone hole.

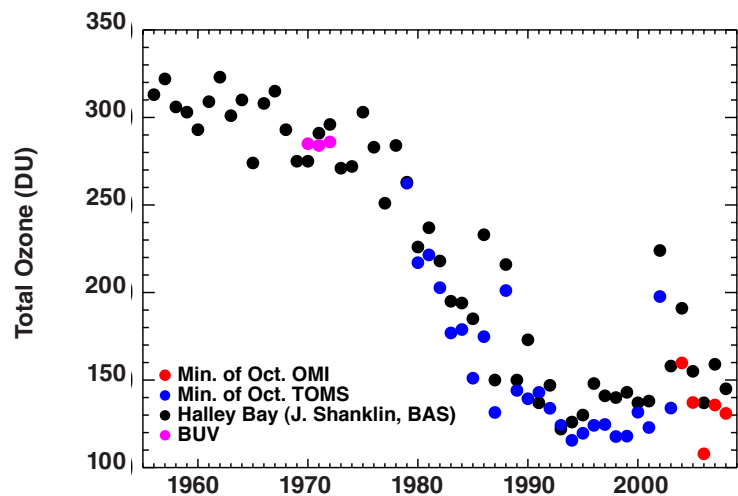
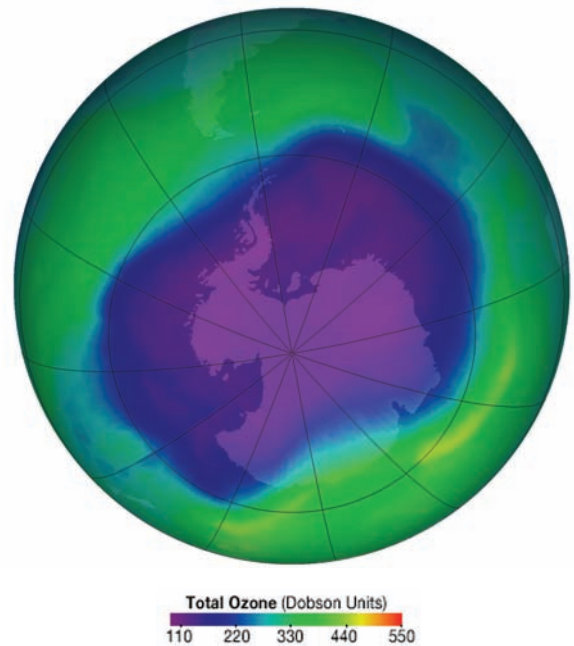
The ozone hole forms at the beginning of Southern Hemisphere spring (August–October). Aura’s OMI instrument provides us with daily images of ozone over the Antarctic region, and this instrument continues the record begun in 1979 by the total ozone mapping spectrometer (TOMS) series. The ozone hole image shown here is the largest ozone hole ever formed. It occurred on September 24, 2006 when the area covered by ozone column amounts less than 220 Dobson Units reached 11.4 million square kilometers.

The graph shows the October monthly mean minimum ozone amount over Antarctica from a variety of data sources, including satellites and ground-based measurements at Halley Bay in Antarctica. The onset of the ozone hole in the late 1970s is now believed to be due to the rapid increase in stratospheric chlorine as the industrial use of chlorofluorocarbons grew in the 1960s and 1970s. With the ban on chlorofluorocarbons in the late 1980s and the tightening of regulations in the 1990s, stratospheric chlorine amounts peaked and are now declining slowly.

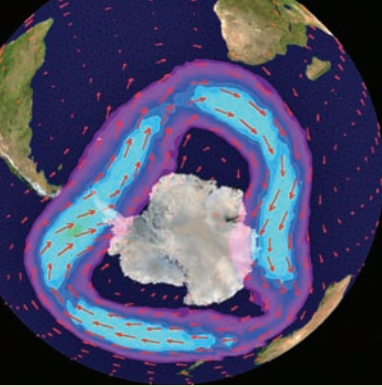


### The Largest Ozone Hole

On September 24, 2006 the ozone hole reached a historical maximum and has not exceeded that size since. The area was 11.4 million square kilometers (4.4 million square miles), larger than the area of North America. The figure below shows the historical change in Antarctic October ozone minimum values seen from ground-based Halley Bay station as well as from satellites.



Minimum October ozone column amounts recorded over Antarctica since 1955 show the development of the ozone hole. Ground-based (Halley Bay) October average measurements are shown in black. Satellite measurements began in the mid-1970s. Data from different instruments are identified by color.



## STRATOSPHERIC OZONE

### The Chemistry of the Ozone Hole Revealed by Aura MLS

#### The Polar Vortex

The polar vortex is a strong stratospheric wind jet that surrounds the polar region during winter. Above, the colored region shows where the winds are strongest as they follow the small arrows around the polar region. This band of winds acts to contain the unusual chemistry of the ozone hole. The polar vortex forms in the fall and reaches maximum intensity during the winter. It breaks up in the spring. The vortex is much stronger in the Southern Hemisphere than in the Northern Hemisphere.

**D**uring austral spring (Sept-Oct-Nov), ozone in the Antarctic lower stratosphere is destroyed by chemical reactions involving chlorine. The ozone column falls to very low levels, a phenomenon called the ozone hole. During the late 1980s and 1990s scientists pieced together the processes that cause ozone destruction using data obtained with instruments on the ground, high-flying aircraft and satellites. The daily maps of ozone ( $O_3$ ), hydrochloric acid (HCl), nitric acid ( $HNO_3$ ), and chlorine monoxide (ClO) from Aura MLS reveal in full detail the events that create the ozone hole.

At the start of winter, the polar stratosphere cools and the polar vortex forms. Strong winds prevent mixing across the vortex boundary. The vortex is dark and contains HCl and chlorine nitrate, chlorine-containing compounds that do not themselves destroy ozone.

By midwinter, MLS measurements show very little gas phase  $HNO_3$  or HCl in the vortex. Temperatures have become so cold

that  $HNO_3$  has condensed, creating polar stratospheric clouds (PSCs). In the darkness, reactions on the surfaces of the PSCs have depleted HCl, producing chlorine compounds that will be broken apart by the smallest amount of sunlight. In spring, the sun returns. Chlorine atoms (Cl) immediately react with  $O_3$ , forming chlorine monoxide (ClO). A catalytic cycle of ozone destruction begins. ClO reacts with itself, forming a dimer  $Cl_2O_2$ . The dimer is broken apart by sunlight, releasing Cl. Cl destroys ozone while reforming ClO; the cycle continues until all  $O_3$  is destroyed. Without  $O_3$ , Cl builds up and HCl is produced by the reaction of Cl with  $CH_4$  (methane). By October almost all of the  $O_3$  in the vortex has been destroyed, nearly all of the chlorine in the polar vortex has been converted to HCl, and the ClO has returned to normal levels.  $O_3$  remains depleted until the polar vortex breaks apart in late November.

Stages of ozone hole chemical changes are shown on the facing page.

#### Fall

The cooling of the stratosphere causes the polar vortex to form, keeping air confined in the polar region and trapping gases HCl,  $HNO_3$ , and  $O_3$ .

#### Winter

Temperatures approach 185K (-126F) and wispy clouds of nitric acid trihydrate and ice form. Nitric acid moves from gas phase to solid. Satellite sensors do not detect solid  $HNO_3$ .

On the surfaces of the ice crystals, chlorine nitrate

and hydrogen chloride react to form chlorine gas. MLS measurements show near zero levels for HCl.

#### Spring

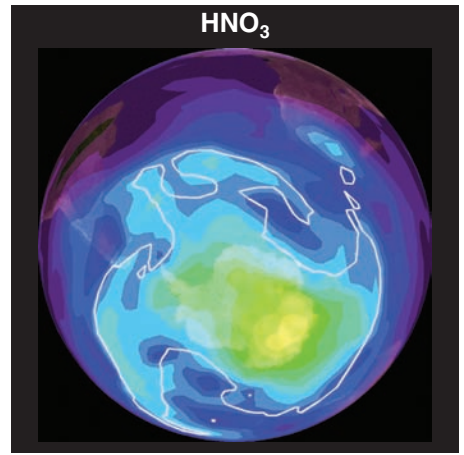
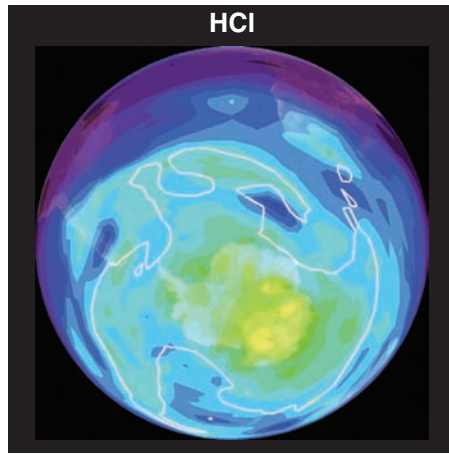
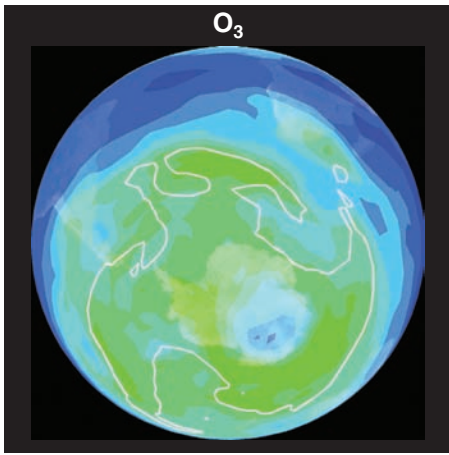
As the sun rises on the pole, more and more chlorine monoxide is produced and ozone is rapidly depleted, causing the ozone hole.

#### Late Spring

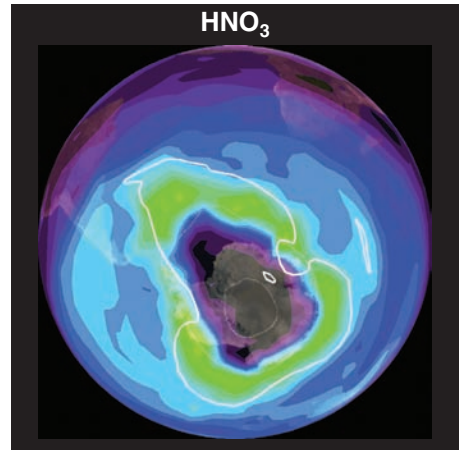
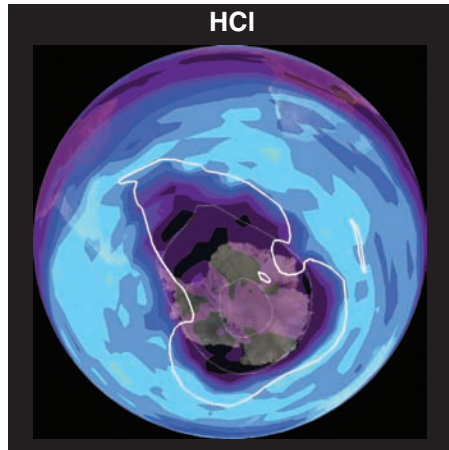
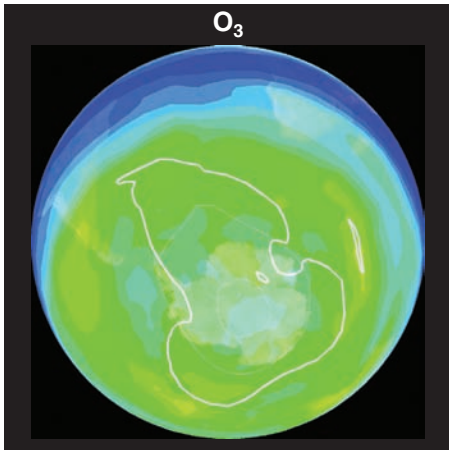
All the ozone is gone. Chlorine reacts with methane reforming HCl and creating an abundance of this gas where the ozone hole exists.



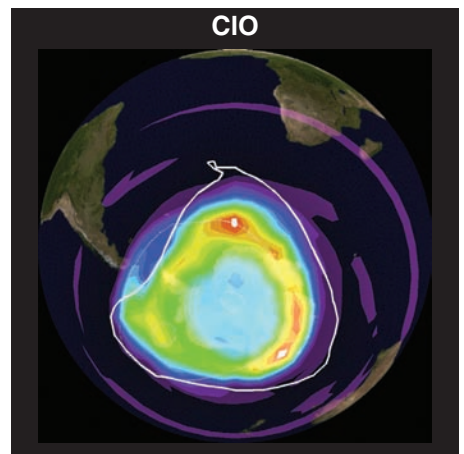
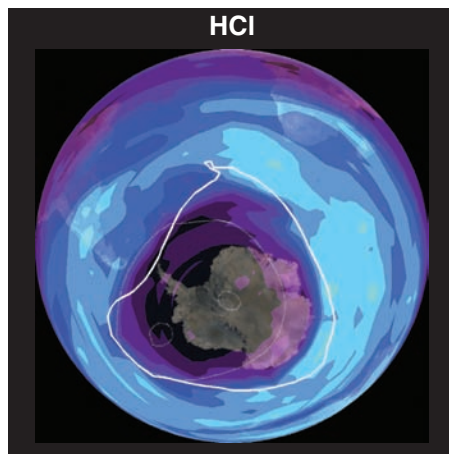
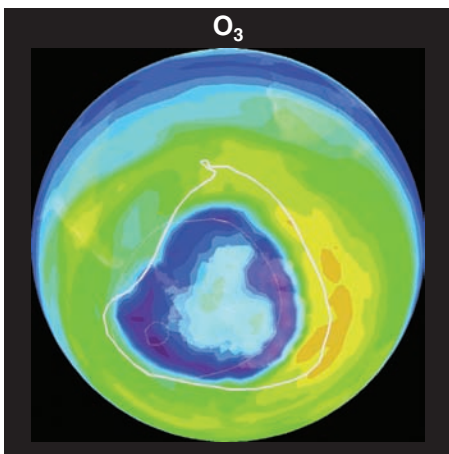




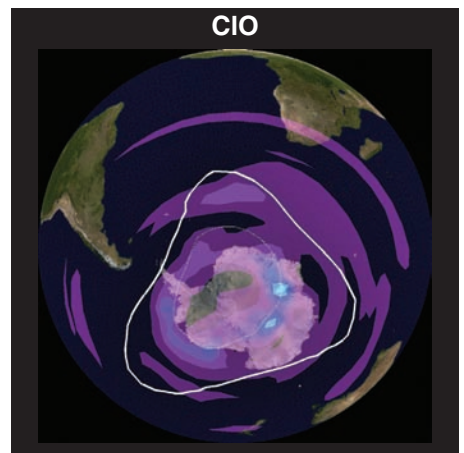
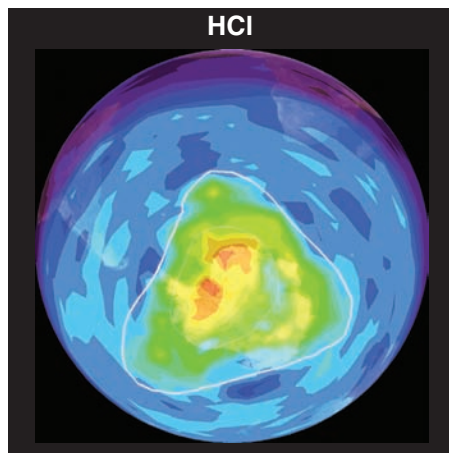
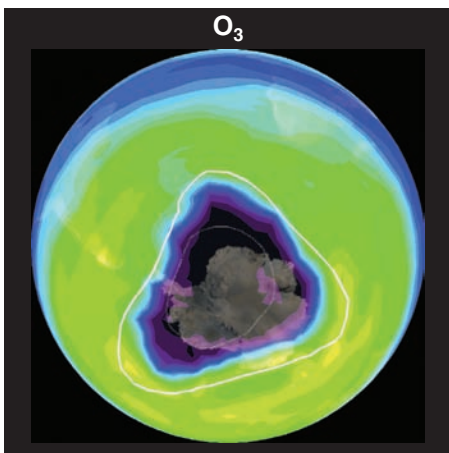
FALL



WINTER



SPRING



LATE SPRING



## STRATOSPHERIC OZONE

### Stratospheric Mixing

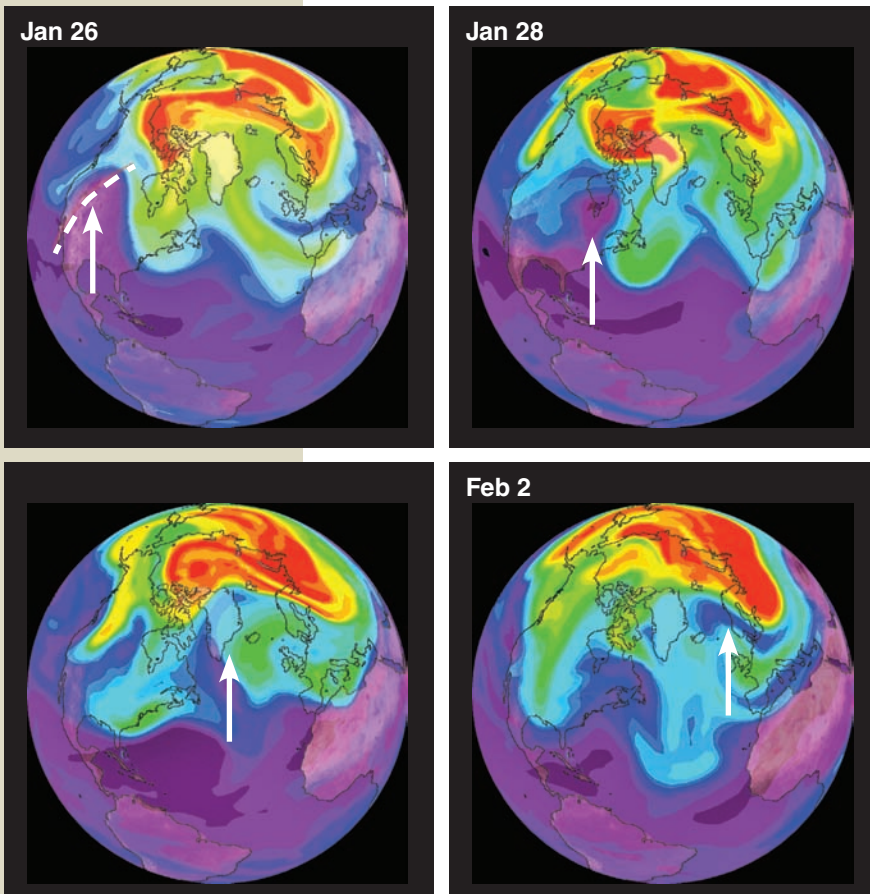
#### Stratosphere Facts

The stratosphere is a region of very strong winds. These winds can move trace gases rapidly north and south, especially during winter. During such events, filaments and streamers form quickly and are mixed with other air.

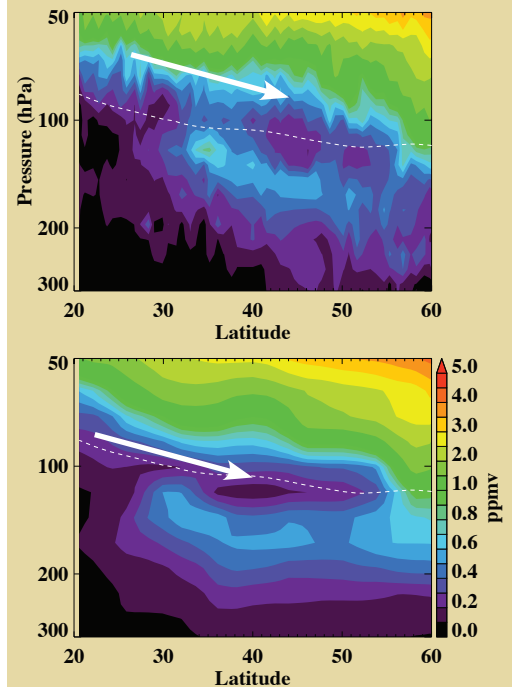
The ozone concentration in the tropical lower stratosphere is small because air is moving upward from the troposphere and contains little ozone. The ozone concentration in the extratropical stratosphere is much higher because air is moving downward from high-ozone upper stratosphere. The upward motion in the tropics and downward motion in the extratropics sets up a strong north-south gradient in ozone.

The four globes below show the evolution of model ozone at the 405K level (~16 km, ~100 hPa or ~10 miles, see dotted line in figures on right). The mixing event is identified by the arrows. The dashed line on the Jan 26 globe shows the location of the HIRDLS measurement path.

Waves propagating upward into the stratosphere from the lower atmosphere pull ozone-poor air out of the tropics and ozone-rich air from the high latitudes and mix them forming streamers and filaments as seen in the model simulation globes below. Ozone-poor air is pulled from the tropical region and is extruded toward the polar region. The model simulation is confirmed by HIRDLS observations (below, also the dashed line on the globe). The transport of ozone and other gases out of the tropics into the middle latitudes by stratospheric waves has never before been observed in such detail.



#### HIRDLS Observations and Model Simulations



These figures show the ozone cross section measured by HIRDLS on Jan 26, 2006 (top) and a model simulation (bottom) of ozone along the same path.

## Gravity Waves

**G**ravity waves breaking in the upper atmosphere act as a drag force on the mean winds. HIRDLS, with its high vertical resolution measurements, can make direct observations of gravity waves. HIRDLS captured this spectacular mountain gravity

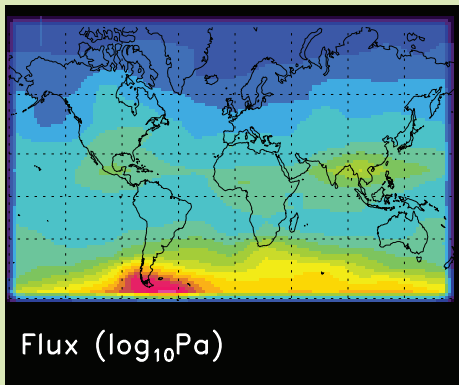
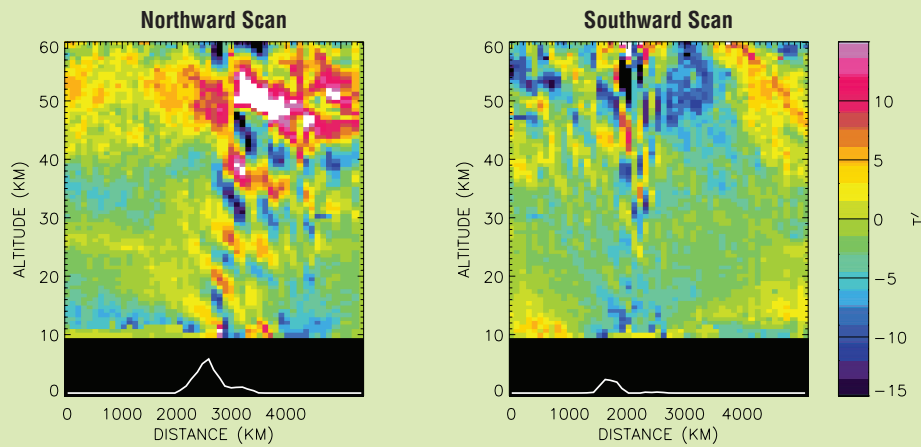
wave event over the tip of South America on June 19, 2005. Stratospheric circulation models crudely represent gravity wave effects. HIRDLS data allows us to develop a better physical basis for gravity wave parameterizations.



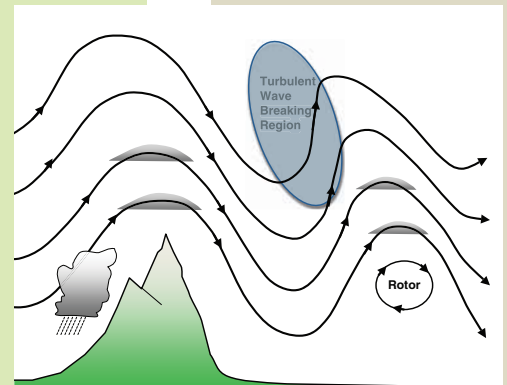
### Gravity Wave Facts

- Gravity waves are natural vertical oscillations of the atmosphere and are similar to water waves.
- Gravity waves are formed by winds blowing over mountains and by storms. As gravity waves propagate vertically into the thin upper atmosphere, their amplitude grows. When the wave amplitude gets quite large, the wave becomes unstable and breaks, decelerating the atmospheric flow.

### Mountain Wave



Mountain waves—a type of gravity wave—form as winds blow over steep topography. HIRDLS observed a huge mountain wave that formed over the southern tip of South America. The wave produces stacked temperature anomalies ( $T'$ ) shown in the figure above. The global upward flux of gravity wave momentum (left) was dominated by this June 2005 event.



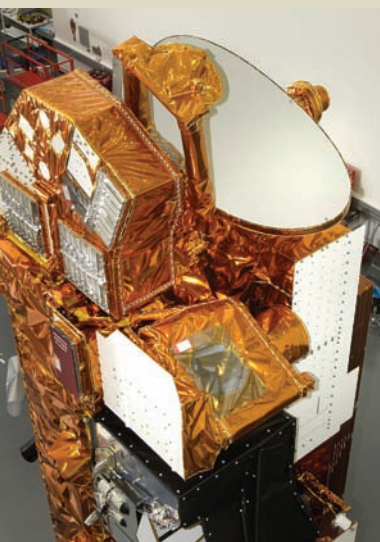
## The Chemistry of the Upper Atmosphere

**A**ura MLS has succeeded in making global measurements of the hydroxyl radical (OH) and the hydroperoxy radical (HO<sub>2</sub>). This impressive technical achievement is important because OH and HO<sub>2</sub> play primary roles in ozone photochemistry. In the upper stratosphere the production of ozone (O<sub>3</sub>) and atomic oxygen (O) from oxygen molecules (O<sub>2</sub>) is balanced by loss. One loss process is recombination of O and O<sub>3</sub> to reform O<sub>2</sub>. Other sequences of chemical reactions involve molecules containing nitrogen, chlorine and hydrogen. The net effect of these catalytic sequences is recombination of O and O<sub>3</sub>. The molecules that take part in a catalytic sequence are unchanged (see box below).

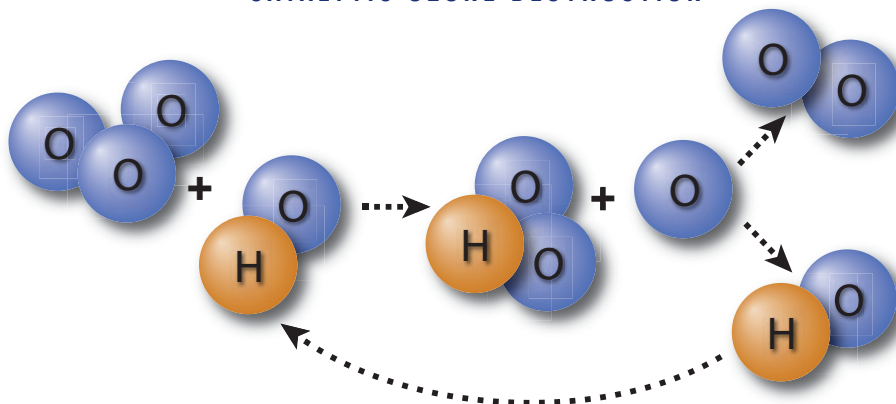
Aura MLS OH and HO<sub>2</sub> measurements are the final missing piece in a long-standing photochemistry puzzle. Before Aura was launched, there were only a few measure-

ments of OH, some from balloon-borne instruments and some from an instrument on the Space Shuttle. The earlier measurements of OH did not agree with values that were calculated from measurements of H<sub>2</sub>O and O<sub>3</sub> using laboratory measured photochemical reaction rates. The Aura measurements of OH and HO<sub>2</sub> agree with new balloon measurements made with a far-infrared Fourier Transform Spectrometer and with calculated values. Photochemical reactions convert OH to HO<sub>2</sub> and back again. By comparing the ratio HO<sub>2</sub>/OH to calculated values at different altitudes, latitudes, seasons, and times of day, scientists are able to test this very fast photochemistry. The calculated values and their ratio vary the same way as observed by MLS, showing that scientists now understand and can model this important part of ozone chemistry.

The MLS instrument (below) made the first global spaceborne measurement of the OH radical using an ultra high frequency radiometer developed specially for this purpose. The receiver is visible below the main dish-shaped antenna and operates at 2.5 THz.

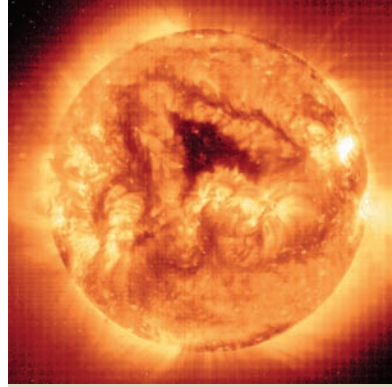


### CATALYTIC OZONE DESTRUCTION



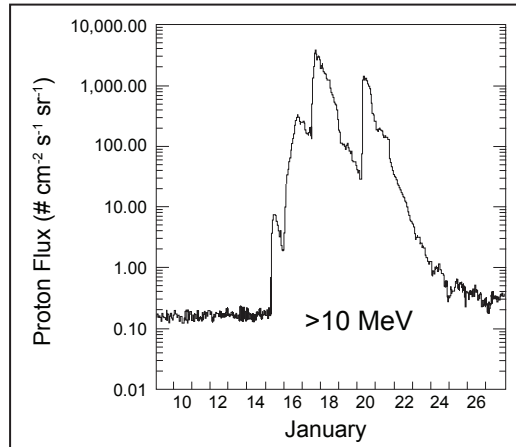
Hydroxyl and hydroperoxy radicals (OH and HO<sub>2</sub>) take part in catalytic ozone destruction. An ozone molecule (O<sub>3</sub>) reacts with OH, forming an oxygen molecule (O<sub>2</sub>) and HO<sub>2</sub>. The HO<sub>2</sub> then reacts with

atomic oxygen (O), forming another O<sub>2</sub> and reforming OH. The OH may start the cycle over again by destroying another O<sub>3</sub> molecule.



## Solar Flares Create Hydroxyl Radical in the Upper Atmosphere

In 1973 scientists proposed that OH and HO<sub>2</sub> would be produced by solar protons that reach the Earth's atmosphere following intense solar flares. Aura observations in January 2005 showed that their hypothesis was true. Protons from a succession of solar flares in middle January reached the Earth's atmosphere and were guided into the polar upper atmosphere near 80 km (50 miles) by the Earth's magnetic field. MLS detected an increase in OH and a decrease in O<sub>3</sub> in the Arctic polar night. The solar flare is a natural experiment—the observed ozone loss due to the increase in OH and HO<sub>2</sub> can be compared with simulations. Scientists confirmed their hypothesis and at the same time learned that their ideas made sense quantitatively.



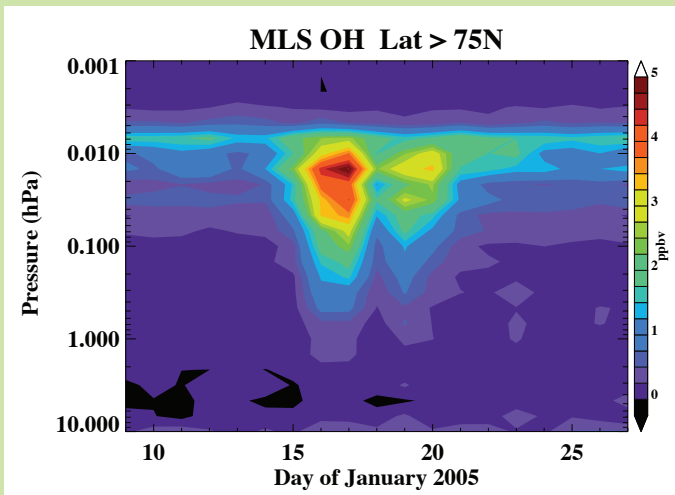
GOES-11 measurements show that the flux of protons with energy greater than 10 MeV increased dramatically in mid-January 2005. A 10 MeV proton deposits its energy between about 0.1 and 0.001 hPa (60 – 110 km); thus, a large portion of the proton energy flux above 10 MeV will be deposited in the upper atmosphere where MLS observed the largest increase in OH.

The January 20, 2005 flare—the most intense in 50 years—is visible along the center right edge of the sun in this image captured by SOHO's Extreme ultraviolet Imaging Telescope.

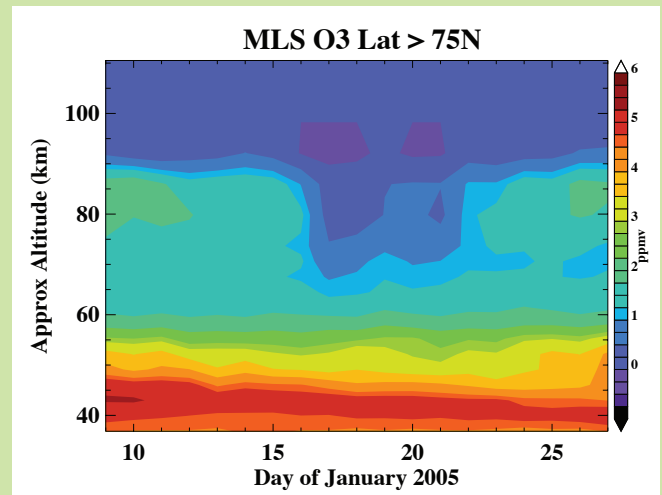
Image of the sun can be found at:

<http://earthobservatory.nasa.gov/IOTD/view.php?id=5536>

### OH Increases Cause Ozone Decreases



MLS measurements of OH (left) and O<sub>3</sub> (right) show that O<sub>3</sub> decreases during mid-January take place at the same time as OH increases, even though the high altitudes are in polar night darkness. Computations show that the O<sub>3</sub> decrease seen by MLS is caused by chemical reac-



tions with OH and HO<sub>2</sub> radicals in the dark polar night. This nighttime chemical destruction of O<sub>3</sub> is unusual because most chemical reactions in the upper atmosphere require sunlight.

# THE AIR WE BREATHE



Pollution episodes can envelop cities like Toronto during summer (above).



Power plants and factories contribute to pollution (right).

## Air Quality

According to the World Health Organization, 2.4 million deaths each year are directly attributable to air pollution. Air pollution includes toxic gases and fine particles or aerosols. Aura provides information about many of the pollutants identified by the U. S. Environmental Protection Agency. These include  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$ ,  $\text{CO}$  and aerosols. Aura also provides information on the gases that contribute to the formation of ozone such as volatile organic compounds (VOCs).

**Nitrogen Oxides**  $\text{NO}_2$  and  $\text{NO}$  are oxides of nitrogen, or  $\text{NO}_x$ , that form in high temperature combustion and lightning. High concentrations of  $\text{NO}_2$  produce a brown haze that often envelops cities. Nitrogen oxides are critical in the formation of ozone pollution, and they also lead to nitrate aerosols.

### Volatile Organic Compounds (VOCs)

VOCs are volatile organic compounds; they are molecules containing carbon, typically with hydrogen and oxygen, that evaporate quickly. They include fumes from turpentine, gasoline, and other solvents. Some types of vegetation also produce VOCs naturally, especially when under stress from hot weather. VOCs are an important ingredient in the formation of ozone pollution.

**Ozone ( $\text{O}_3$ )**  $\text{O}_3$  is one of the most toxic pollutants, causing decreased lung function and damage to vegetation and materials such as rubber.  $\text{O}_3$  near the Earth's surface forms primarily from reactions in sunlight involving VOCs or  $\text{CO}$  and  $\text{NO}_2$ , both abundant in urban areas.

**Sulfur Dioxide**  $\text{SO}_2$  emissions lead to acid rain and sulfate aerosols.  $\text{SO}_2$  sources are both natural (volcanoes) and human-

produced (smelters and power plants). Anthropogenic sources (those produced by humans) contribute 5 times more  $\text{SO}_2$  [to the lower atmosphere/troposphere] than volcanic sources.

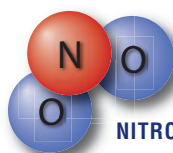
**Aerosols** Natural aerosols include sea salt, dust, and smoke from forest fires. Human-produced aerosols include industrial smoke and agricultural burning. Aerosols are also formed by chemical reactions involving pollutant gases  $\text{NO}_2$ ,  $\text{SO}_2$  and VOCs. Aerosols are harmful to human health and also affect climate by reflecting and absorbing sunlight.

**Carbon Monoxide**  $\text{CO}$  forms during incomplete combustion. It is odorless and toxic in high concentrations.  $\text{CO}$  sources include internal combustion engines and agricultural burning.  $\text{CO}$  has a lifetime of approximately a month, and thus can serve as a good tracer for atmospheric mixing and transport.

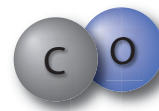
### Pollution Facts

- Unhealthy air leads to many deaths worldwide each year.
- High concentrations of ozone and fine aerosols are the leading causes of air pollution-related illness and death.
- Ozone near the surface forms from chemical reactions involving nitrogen oxides and organic gases in sunlight.
- Fine aerosols come from natural and man-made sources.
- Sulfur dioxide leads to acid rain.

### The Dirty Half Dozen



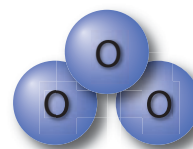
NITROGEN DIOXIDE



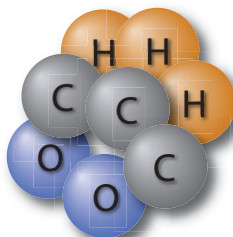
CARBON MONOXIDE



SULFUR DIOXIDE



OZONE

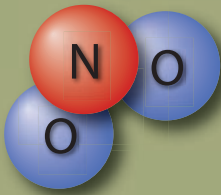


VOLATILE ORGANIC COMPOUNDS



AEROSOL

These gases and particulates are among the biggest contributors to poor air quality. Aura instruments detect aerosols,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{CO}$ ,  $\text{O}_3$ , and the VOCs, HCHO and CHOCHO.



## NITROGEN DIOXIDE

### AIR QUALITY

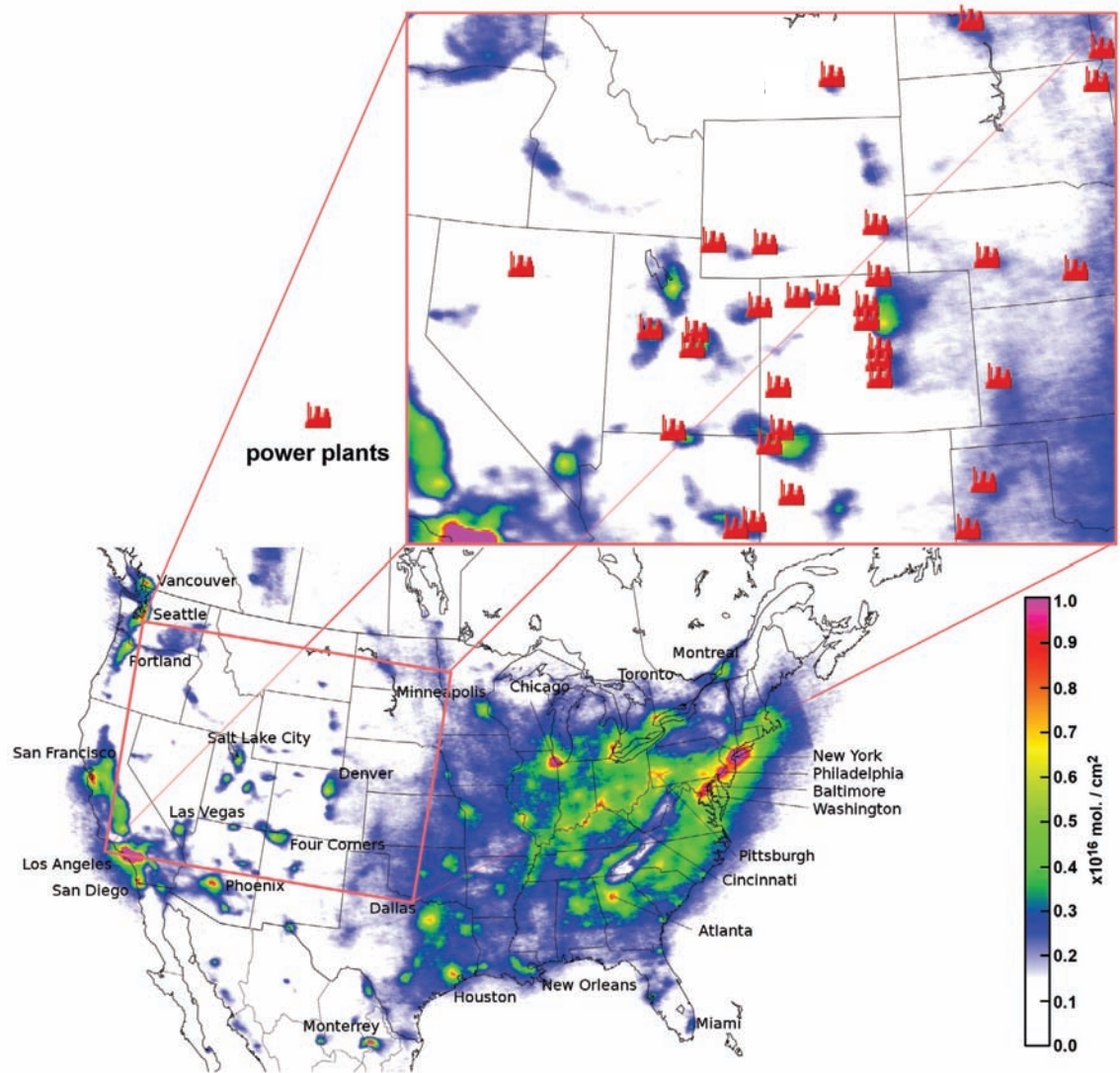
## Nitrogen Dioxide

### NO<sub>2</sub> Facts

- The NO<sub>2</sub> precursor NO is produced during incomplete combustion.
- NO is very quickly converted to NO<sub>2</sub> by reactions with O<sub>3</sub> and other oxidizers in the atmosphere.
- NO<sub>2</sub> absorbs sunlight, primarily at blue and ultraviolet wavelengths. Satellite measurements of this absorption are used to identify NO<sub>2</sub> in the Earth's atmosphere.

Nitrogen oxides (NO<sub>x</sub> = NO + NO<sub>2</sub>) are formed by both natural and anthropogenic processes. Power plants, internal combustion engines, fertilizer application, and agricultural burning are examples of anthropogenic sources of NO<sub>x</sub>. Lightning, wild-

fires, and soil emissions are natural sources of NO<sub>x</sub>. NO<sub>2</sub> has a relatively short lifetime (about a day) and is therefore concentrated near its sources. NO<sub>2</sub> can be measured from a satellite, while NO cannot.

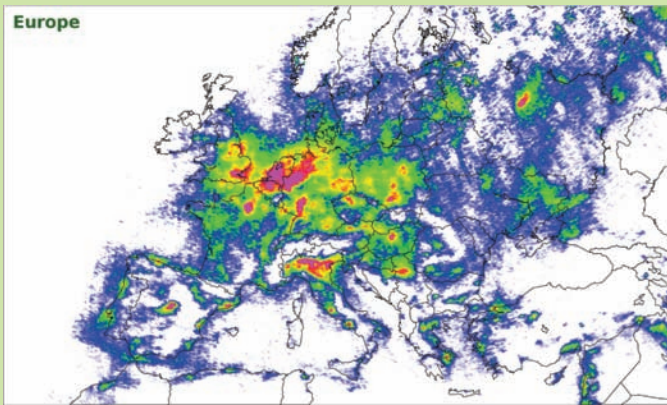


The maps of the tropospheric column of NO<sub>2</sub> produced by the OMI team give us a clear picture of industrial and agricultural activity across the globe. The inset

shows a map with locations of some of the coal-fired power plants in the western US. The units are 10<sup>16</sup> molecules per square centimeter.



## The Fingerprint of Civilization



The maps above show the tropospheric NO<sub>2</sub> column density (10<sup>16</sup> mol./cm<sup>2</sup>). The left image is from SCIAMACHY, an instrument on the European Space Agency Envisat, which passes over Europe at 10 am. The right

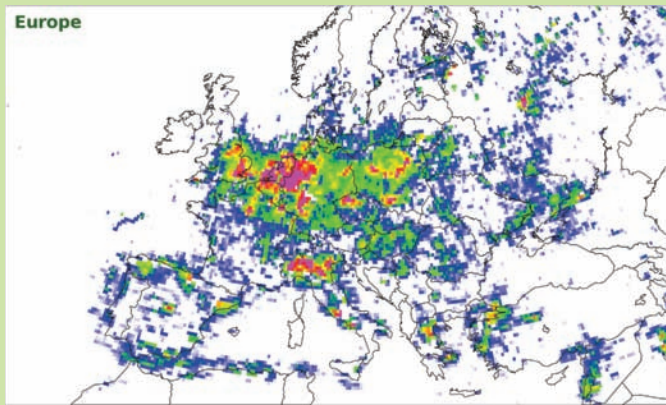
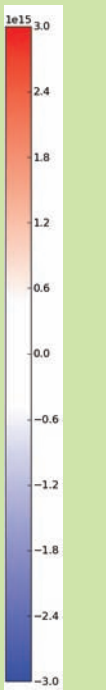
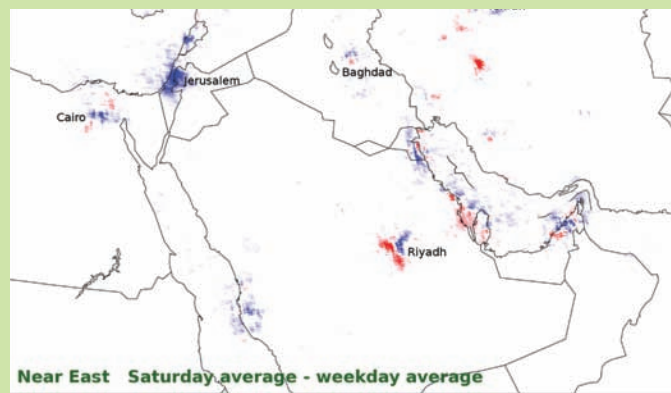
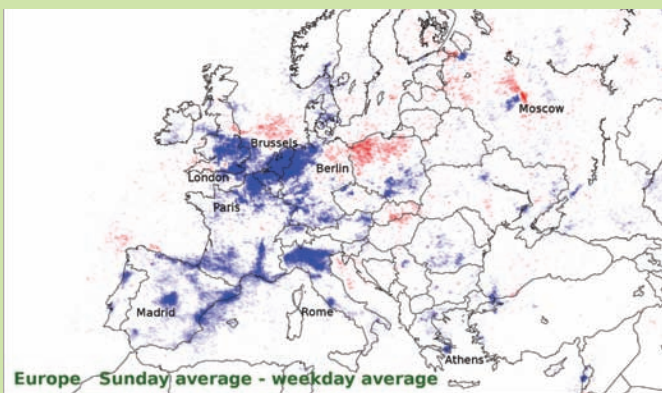
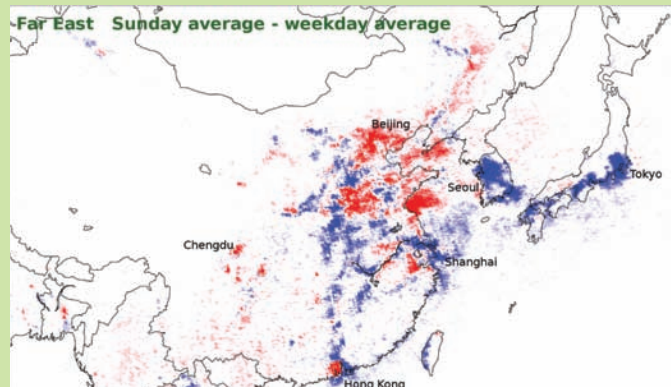
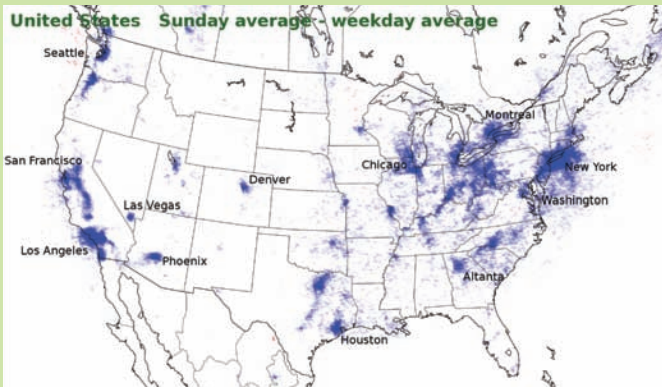
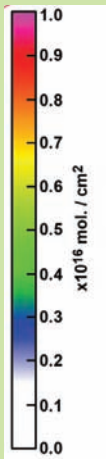
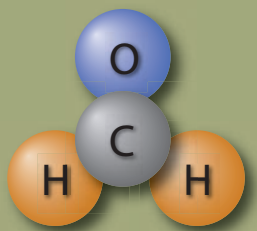


image is from OMI, which passes over Europe at 1:30 pm. The urban pollutant NO<sub>2</sub> levels decrease markedly from their morning values in the 3.5 hours between measurements.



NO<sub>2</sub> varies with levels of human activity during the week. The maps show that on Sunday, NO<sub>2</sub> levels in the United States (top, left) and Europe (bottom, left) are much lower than midweek values (blue areas).

In the Far East (top, right), the Sunday levels are lower than midweek in Japan and Korea, but not in China (red areas). In the Near East (bottom, right), NO<sub>2</sub> levels are lower on Saturday, the Sabbath in Israel.



FORMALDEHYDE

## AIR QUALITY

### Formaldehyde and Volatile Organic Compounds

#### Isoprene

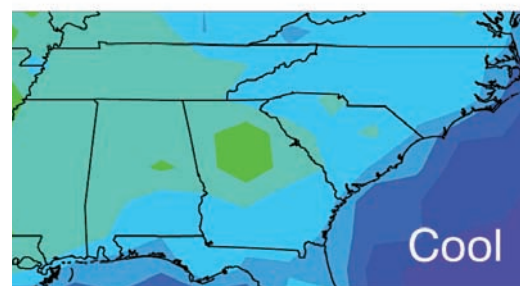
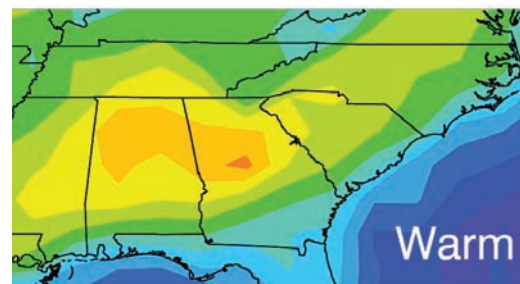
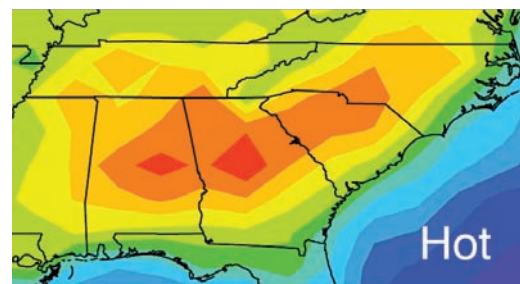
- Isoprene is the common name for the chemical compound 2-methyl-1,3-butadiene.
- Isoprene is the predominant VOC emitted from trees, such as oak and poplar.
- Isoprene molecules have 5 carbon atoms and are the building blocks for terpenes, which can contain several isoprene units.
- Terpenes are responsible for the characteristic scents of many trees such as pine trees.

OMI measures formaldehyde (HCHO), a volatile organic compound (VOC), that is produced during the oxidation of other VOCs. Isoprene, a VOC that is emitted naturally from trees, is an important source of HCHO. The global map of HCHO, measured by OMI, shows that areas with the highest HCHO levels correspond to heavily forested regions, such as the southeastern U.S. and the Amazon River region of South America.

It is not well understood why some plants emit isoprene and others do not. One hypothesis is that isoprene emission may be part of a process that helps protect leaves from stresses, such as heat and drought. Isoprene also appears to provide protection from ozone damage.

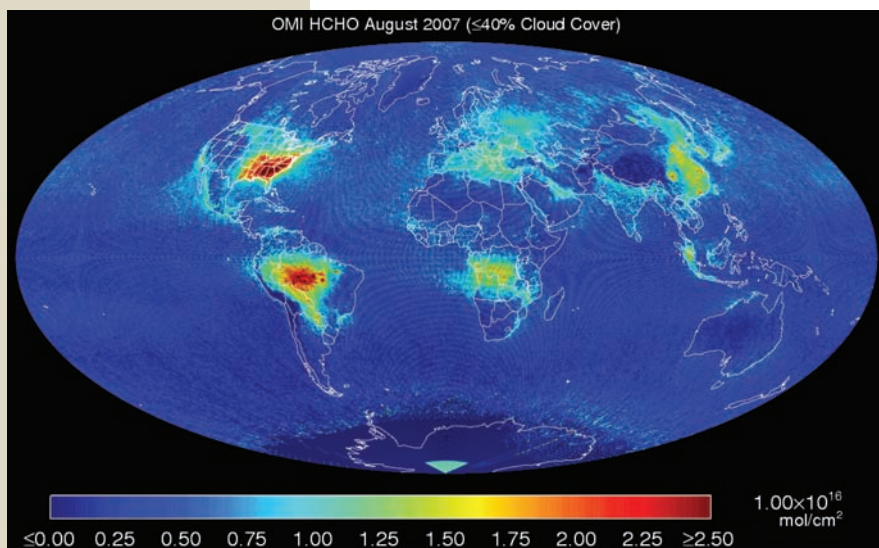
Formaldehyde also has anthropogenic sources. While in forests HCHO is produced naturally by oxidation of isoprene, HCHO

in industrial areas is produced by the oxidation of anthropogenic hydrocarbons and from biofuels.



0.5 1.1 1.7 2.3 2.9 [ $\times 10^{16}$  molec/cm<sup>2</sup>]

A map of global HCHO as measured by the Ozone Monitoring Instrument (OMI).

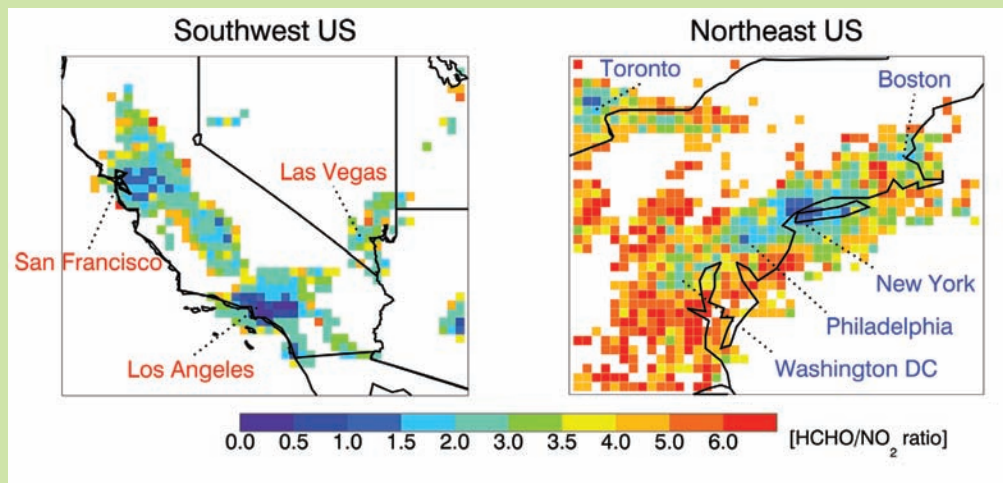


Laboratory experiments show that the amount of isoprene emitted from vegetation depends on the ambient temperature. More isoprene is emitted by plants when the weather is hot because isoprene protects the plants from environmental stresses. Formaldehyde (HCHO) is produced from isoprene by chemical reactions. The maps above show that during the summer over the southeastern U.S., OMI sees the highest HCHO when the weather is hot and the lowest HCHO when the weather is cool.



- A volatile organic compound (VOC) is a hydrocarbon that evaporates quickly.
- In the 1980s, VOCs from cars and industry were reduced in an attempt to control unhealthy levels of ozone in the United States. However, the natural VOC, isoprene, is so high in the eastern part of the country that ozone was relatively unaffected by the reductions.
- Some plants emit isoprene and isoprene can play an important part in the formation of unhealthy levels of surface ozone, some people have said that trees cause pollution. However, without nitrogen oxides from cars, industry, and power plants, surface ozone would be low even when isoprene is high.

## Strategies to Control Pollution



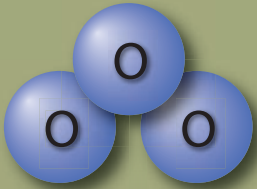
Ratio of OMI HCHO/NO<sub>2</sub>. When the ratio is less than one, the better strategy to reduce surface ozone is to reduce VOCs. When the ratio is greater than two,

nitrogen oxides should be reduced. In areas where the ratio is between one and two, both VOCs and nitrogen oxides should be reduced.

Unhealthy levels of surface ozone are formed by chemical reactions involving VOCs, nitrogen oxides, and sunlight. The ratio of OMI HCHO to NO<sub>2</sub> tells scientists whether chemical reactions involving VOCs or nitrogen oxides are more important to ozone production. This information is needed to develop effective strategies to reduce surface ozone.

The best strategy to decrease surface ozone in some regions is to lower nitrogen oxides. In others regions, it is more effective to reduce VOC emissions, and sometimes it is most effective to reduce both VOC and nitrogen dioxide emissions. For instance, the ratio of HCHO to NO<sub>2</sub> in the northeastern United

States (see figure) shows that the effective way to reduce surface ozone in this region is to limit emissions of nitrogen oxides, except near New York City where reductions in both VOCs and NO<sub>2</sub> would be more beneficial. In the center of New York City reductions in VOCs are most important. Most areas in the southwestern United States would benefit from reductions in both VOCs and NO<sub>2</sub>. In Los Angeles and San Francisco a reduction in VOCs is most important to improve air quality.



## OZONE

## AIR QUALITY

### Tropospheric Ozone

#### Ozone Pollution

- Ground-level ozone concentrations exceeding 60 - 70 ppbv are considered unhealthy.
- In the United States, the EPA regulates air quality by regulating the VOC and NO<sub>x</sub> emissions that create ozone. On days when the weather is stagnant or there is an atmospheric inversion, “ozone alerts” may trigger the shut down of industries to reduce NO<sub>x</sub> and/or VOC production.

**T**ropospheric ozone is formed when nitrogen oxides (NO<sub>x</sub>) and volatile organic compounds (VOCs) or carbon monoxide (CO) react in the presence of sunlight (p. 3). Human sources of VOCs and NO<sub>x</sub> are the most important contributors to tropospheric ozone formation.

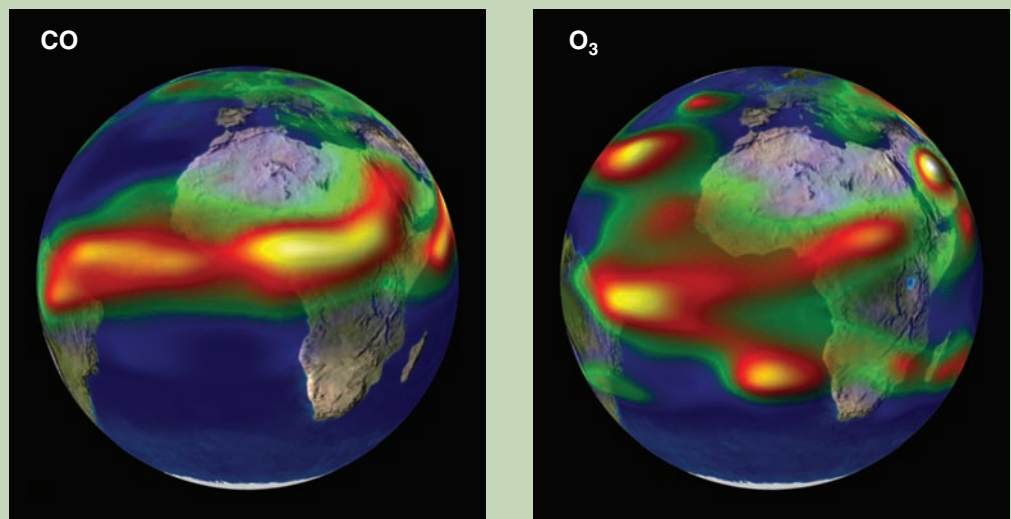
Tropospheric ozone is difficult to measure from space because instruments must look through the stratospheric ozone layer to “see” the tropospheric ozone. The ozone concentration in the stratosphere is more than 100 times higher than typical tropospheric values.

With its fine spectral resolution, TES directly measures tropospheric ozone simultaneously with carbon monoxide as shown below.

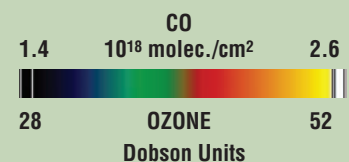
Tropospheric ozone can also be estimated by subtracting the MLS limb measurement of the stratospheric column from the OMI nadir measurement of the total column ozone. The difference between the total column and the stratospheric column is called the Tropospheric Ozone Residual or TOR (see right-hand page). The average tropospheric ozone concentration can be computed from the TOR using the measured depth of the troposphere.

Both techniques measure ozone primarily in the middle to upper troposphere. This region is known as the “free troposphere.” Unlike the region near the Earth’s surface where pollution is often trapped, weather systems mix the air in the free troposphere.

#### TES Column Measurements



TES, the Tropospheric Emission Spectrometer, simultaneous measurements of CO (left) and tropospheric ozone column (right) show the maximum CO produced by biomass burning over Africa and a downwind ozone maximum over the Atlantic Ocean.



The images below show the average ozone mixing ratio derived from the TOR. Tropospheric ozone concentrations vary with season as shown below. Global chemistry and transport models and other satellite data are needed to help determine the relative

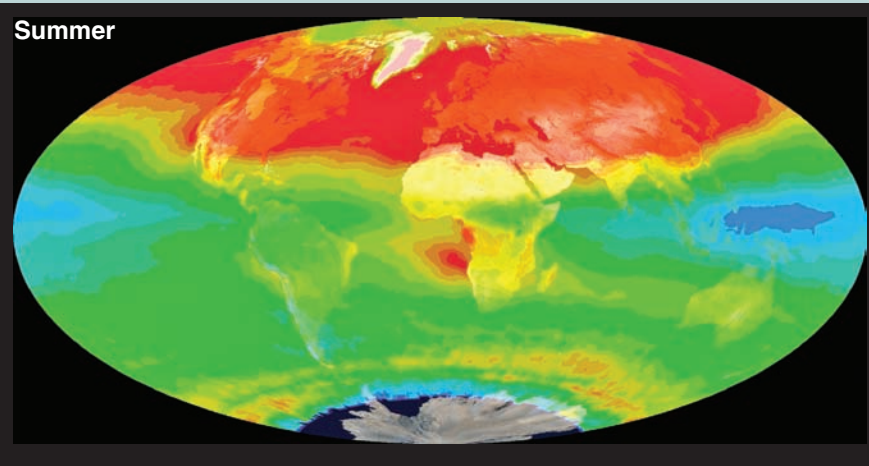
importance of the natural and anthropogenic processes that contribute to these seasonal differences. The tropospheric ozone is persistently low in the tropical western Pacific because convection lifts clean marine surface air into the middle and upper troposphere.

© MARK SCHOEBERL

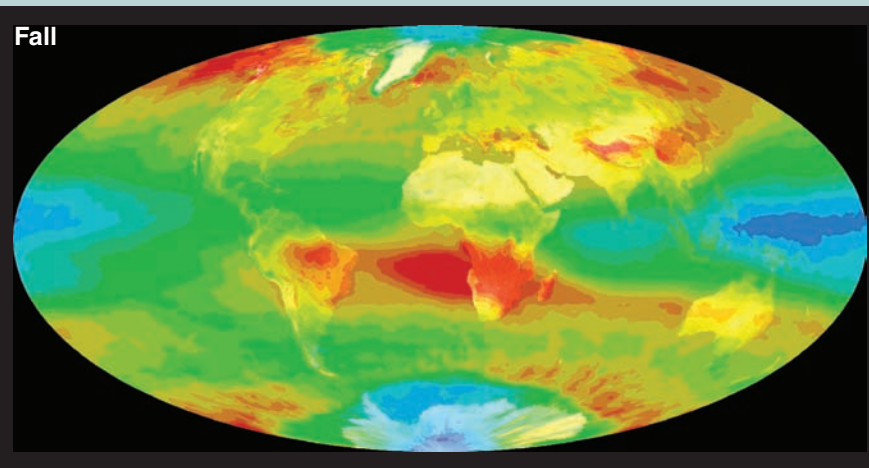


**Average Tropospheric Ozone Mixing Ratio**

Summer

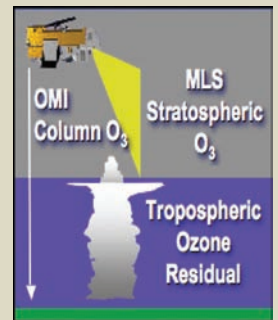


Fall

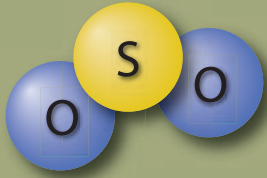


Tropospheric ozone mixing ratios vary from July (top) to September (bottom) owing to changes in ozone precursors that have both natural and human

sources. There are also seasonal variations in transport from the ozone-rich stratosphere to the troposphere.



The Tropospheric Ozone Residual (TOR) is calculated by subtracting the MLS stratospheric ozone column from the OMI total column ozone. The average mixing ratio is computed using the TOR and measured thickness of the troposphere.



SULFUR DIOXIDE

AIR QUALITY

Industrial Sulfur

EPA

- In 1971, the US Clean Air Act mandated a limit on the amount of atmospheric SO<sub>2</sub>. All power plants built after 1977 are required to install scrubbers to remove SO<sub>2</sub>.
- Most scrubbers in the US remove at least 90% of SO<sub>2</sub> emissions. The recovered sulfur in the form of sulfuric acid or gypsum sludge can be sold or recycled.
- SO<sub>2</sub> emissions from US power plants were 33 percent lower in 2001 as compared with 1990.
- In 2005, approximately 25.5 million tons of SO<sub>2</sub> were emitted by Chinese factories, up 27% from 2000.

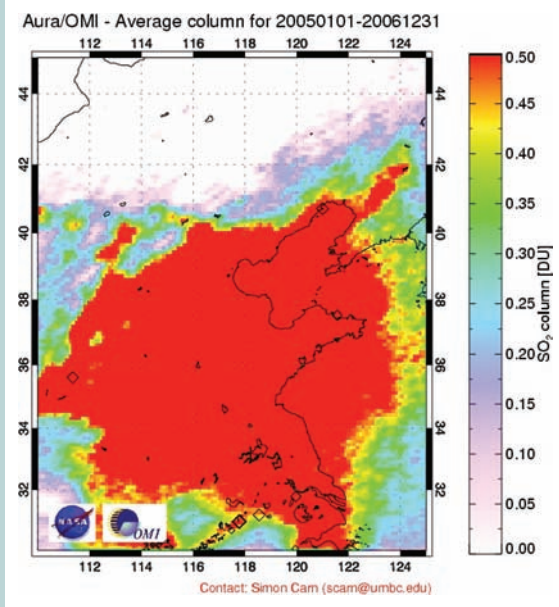
Sulfur dioxide (SO<sub>2</sub>) has both natural and anthropogenic sources. Industrial processes using sulfur-rich fossil fuels like coal fired power plants, oil refineries, and metal smelters discharge significant amounts of SO<sub>2</sub> into the atmosphere. SO<sub>2</sub> is also produced naturally from oceanic emissions of dimethyl sulfide (DMS) and volcanoes. SO<sub>2</sub> is converted to sulfuric acid by reactions with OH to produce sulfate aerosols. These aerosols can be deposited as acid rain or transported long distances when lofted into the upper atmosphere.

Both SO<sub>2</sub> and sulfate aerosols are pollutants that are hazardous to human health. Sulfate aerosols in the stratosphere create haze that directly impacts our climate by reflecting solar radiation back to space.

Sulfate aerosols alter cloud properties and precipitation (see p. 36 for details). The lifetime of SO<sub>2</sub> and sulfate aerosol increases with altitude. Climatic impacts of aerosols are most significant when explosive volcanic eruptions inject SO<sub>2</sub> directly into the stratosphere where the aerosols have a lifetime of months to years.

Measurements by OMI provide an unprecedented global view of SO<sub>2</sub>, allowing us to detect individual anthropogenic sulfur sources such as smelters and oil refineries from space. Aura's SO<sub>2</sub> measurements are being used to update inventories of SO<sub>2</sub> emissions, to examine long-range transport of SO<sub>2</sub>, and to study the impact of SO<sub>2</sub> emissions on climate.

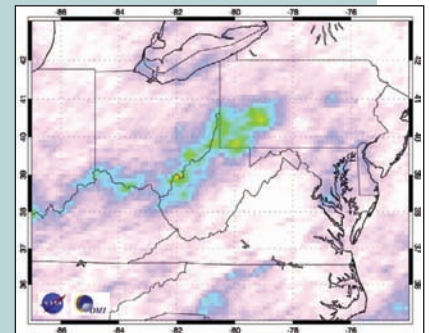
Sulfur Dioxide



	Northern Hemisphere	Southern Hemisphere	Global
<b>Natural Sources</b>			
Marine and Terrestrial DMS of Dimethyl Sulfide (DMS)	7.5	11.0	18.5
<b>Volcanic SO<sub>2</sub></b>	10.0	4.0	14.0
Explosive degassing		0.5-4	
Passive degassing		5-10	
<b>Biomass Burning</b>	1.0	1.5	2.5
<b>Fossil Fuel Use and Industry</b>	60.5	6.3	66.8
<b>TOTAL (S, Tg)</b>	79.0	22.8	101.8

The table is an inventory of emitted sulfur (in terra-grams or Tg) from natural and anthropogenic sources made in the 1990s.

These figures show the total column of SO<sub>2</sub> (in Dobson units) averaged over 2005 and 2006 over eastern China (left) and the U.S. Ohio Valley (right). The same color scale is used for both images. Ohio Valley power plants have SO<sub>2</sub> scrubbers that greatly reduce emissions.



## Smelters and Volcanoes

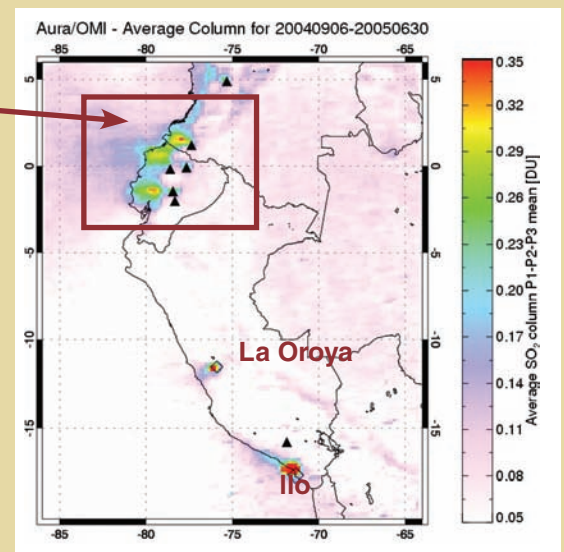
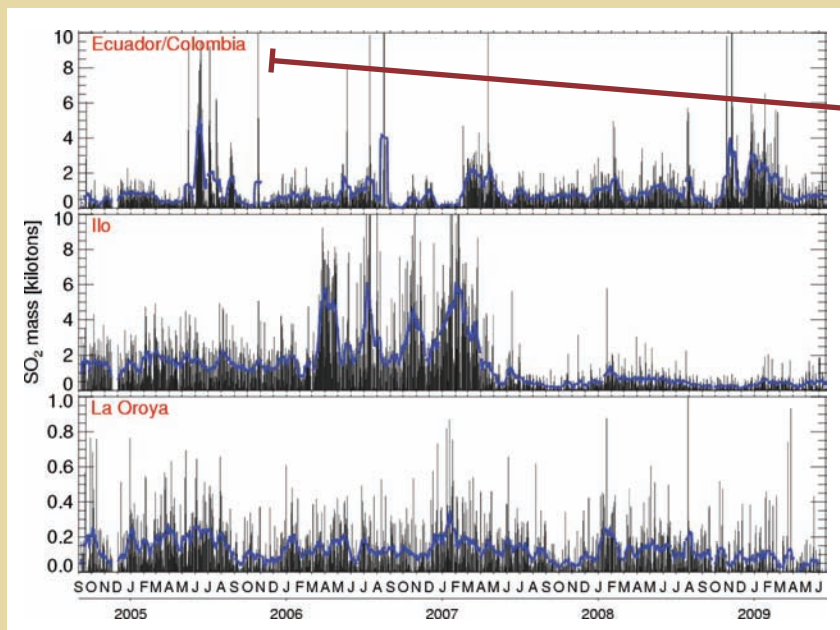
Aura measurements of SO<sub>2</sub> from volcanic and anthropogenic sources allow us to compare these different sources. The effects of the SO<sub>2</sub> emissions on air quality and climate may then be assessed.

OMI has the highest spatial resolution of any satellite instrument of its type and views the Earth at many different wavelengths. This makes OMI about 100 times more sensitive to SO<sub>2</sub> than previously flown instruments such as the Total Ozone Mapping Spectrometers (TOMS) that flew between 1979 and 2005. For the first time, passive degassing of SO<sub>2</sub> from volcanoes and industrial sources can be reliably measured from space.



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The inhabitants of La Oroya, Peru experience the pollution from the copper smelter. La Oroya is one of the 10 most polluted cities in the world.



The total mass of emitted SO<sub>2</sub> from various sources in South America as estimated from daily OMI observations. Top panel: Volcanoes; middle and lower panels: Peruvian copper smelters Ilo and La Oroya. Blue line is the 14-day running mean of the data. The image on the right shows the locations of the smelters and volcanoes along with the average SO<sub>2</sub> columns measured by OMI. Initially the SO<sub>2</sub> measurements at Ilo and La Oroya are dominated by smelter emissions. Then fumes from the Ubinas volcano (Peru) elevate the Ilo mass estimates in early 2006. After the Ubinas subsides in early 2007, emissions drop because the Ilo smelter was upgraded with scrubbers to capture most of its SO<sub>2</sub>. Ubinas remained intermittently active in 2008 - 2009. La Oroya smelter was shut down in mid-2009.

Copper-rich ores produced by volcanoes in the distant past are being mined and smelted in Peru. These smelters are among the world's largest industrial point sources of SO<sub>2</sub>. They produce tons of SO<sub>2</sub> per day and rival the SO<sub>2</sub> production by volcanoes just to the north in Ecuador and Colombia.

# VOLCANIC ERUPTIONS



© MARCO LILLINI

Mount Stromboli in the Aeolian islands, Italy.



The Tungurahua volcano in central Ecuador.

© PATRICK TASCHLER



The Alaskan volcano Mount Cleveland erupting on May 23, 2006 photographed from the International Space Station.



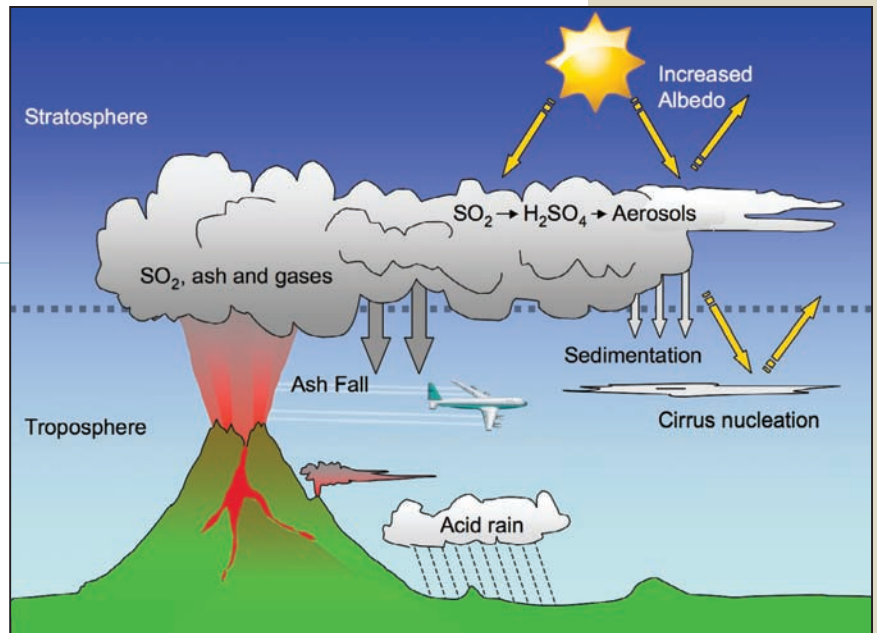
## Volcanoes

**H**uge amounts of gas, aerosols and ash can be injected into the upper troposphere and lower stratosphere during explosive volcanic eruptions. Volcanoes also fume intermittently between and after eruptions. This is known as passive degassing.

Volcanic ash can be extremely hazardous to aircraft. Some volcanic gases, such as  $\text{CO}_2$ , contribute to global warming. Others, like  $\text{SO}_2$ , lead to cooling because they are transformed into aerosols which reflect sunlight back to space. The increase in sulfate aerosols can also cause stratospheric ozone destruction.

OMI can detect atmospheric  $\text{SO}_2$  because this gas is a strong absorber of ultraviolet radiation. The OMI measurements can be combined with TES infrared measurements of  $\text{SO}_2$  to provide information about the height of volcanic  $\text{SO}_2$  plumes.

Between August 7 and August 8, 2008, explosive eruptions rocked the Kasatochi

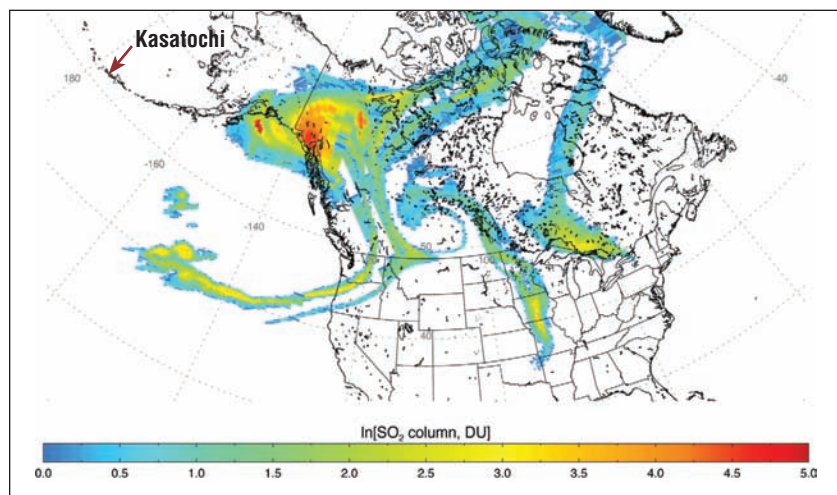


Volcano in the Alaskan Aleutian Islands. In addition to sending a thick plume of ash to at least 35,000 feet (10.6 km), the volcano released 1 to 1.5 million tons of  $\text{SO}_2$  into the upper troposphere and lower stratosphere. In the days that followed the eruption, OMI tracked the Kasatochi  $\text{SO}_2$  cloud around the globe. Airlines canceled flights or diverted planes around the cloud because of the potential ash hazard. Because the Kasatochi Volcano is located in a remote, uninhabited region, the eruption caused no property damage.

- The most common gases emitted by volcanoes are water, carbon dioxide and sulfur dioxide. Volcanoes also release small amounts of hydrogen sulfide ( $\text{H}_2\text{S}$ , which has the odor of rotten eggs), hydrochloric acid ( $\text{HCl}$ ), hydrogen ( $\text{H}_2$ ), carbon monoxide ( $\text{CO}$ ), and hydrofluoric acid ( $\text{HF}$ ), as well as volatile minerals.

- Fine volcanic ash can clog jet engines, causing them to stall. Ash also damages windshields and metal on aircraft.

- Exposure to acidic volcanic gases such as  $\text{SO}_2$  can damage eyes, mucous membranes, and the respiratory system. Under extreme conditions, this can lead to death.



OMI captured this  $\text{SO}_2$  image on August 12, 2008. Jet stream winds had already spread the plume of  $\text{SO}_2$  across the Arctic, well away from the eruption.

The logarithmic color scale shows  $\text{SO}_2$  column amounts in Dobson Units.

# AEROSOLS



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Montana forest fires, August 24, 2007.



Dust storm in Texas 1935.



© MARCO LILLINI

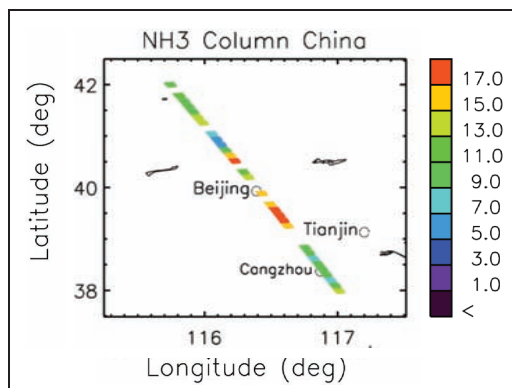
Agricultural fire in central Italy.

## Aerosols: Smoke, Dust and Precursors

**A**erosols are tiny particles and droplets suspended in the air. They are formed in nature by volcanoes, dust storms, sea spray, and emissions from vegetation. Humans create aerosols and alter their natural sources by burning fossil fuels and exposing soils by clearing land. Agricultural fires, commonly used to prepare fields for planting and to remove brush, are an important source of aerosols.

Aerosols have complex effects on Earth's climate. In general, they tend to cool the surface by reflecting (scattering) radiation from the sun back into space. Some aerosols, such as dust and smoke, absorb solar radiation and heat the atmosphere where they are concentrated. Additionally, aerosols change the properties of clouds. In aerosol polluted environments, clouds tend to have smaller droplets than clouds formed in cleaner environments; these polluted clouds actually appear brighter from space because they reflect more sunlight, and they may persist longer and not rain as intensely. We can see aerosols clearly from space as a haze layer over the ocean. Because aerosols of different composition and sizes scatter light differently, we can use OMI's spectral coverage to measure the absorptive properties of aerosols. These observations complement measurements of other aerosol properties, such as size distribution, from instruments on the EOS Terra and Aqua satellites.

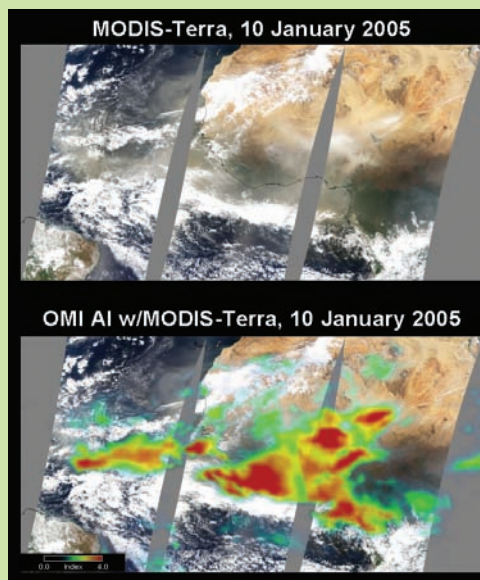
Aura instruments also measure constituents from which aerosols are formed. OMI measures sulfur dioxide (p. 20), a precursor of sulfate aerosols. TES measures ammonia, which plays an important role in air quality because it reacts with other gases to make nitrate aerosols. Ammonia comes from many sources (animal waste, fertilizers, soil, industrial emis-



**Ammonia concentrations (in parts per billion by volume) along an orbit over China.**

sions). Ammonia reacts quickly with other gases, remaining in the atmosphere for only a few hours. TES sees elevated concentrations of ammonia over industrial areas as shown in the above figure.

### Observations of Aerosols



The top picture shows a false color image from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's Terra satellite. Clouds and aerosols (most likely a mixture of Saharan dust and smoke) are visible over the dark Atlantic ocean off the west coast of Africa. It is more difficult to discern aerosols over the brighter African deserts.

The bottom picture shows the Absorbing Aerosol Index derived from OMI overlaying the MODIS image, where warmer colors (yellows to red) indicate

the presence of significant amounts of absorbing aerosols such as dust and smoke. These absorbing aerosols are clearly seen over bright land surfaces and clouds.





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## AEROSOLS

### Aerosols and Air Quality

#### Aerosol Facts

- Aerosol is the generic term for very small atmospheric particles. To be called an aerosol, the particle size should be less than ~10 microns (one tenth the thickness of a human hair). Aerosols are a component of air pollution and the Environmental Protection Agency monitors the surface concentration of 10 micron and 2.5 micron aerosols.

- Aerosols interact with Earth's climate by reflecting and absorbing incoming shortwave sunlight and outgoing infrared radiation emitted by the Earth (see p. 29 for a diagram of the Earth's radiation budget).

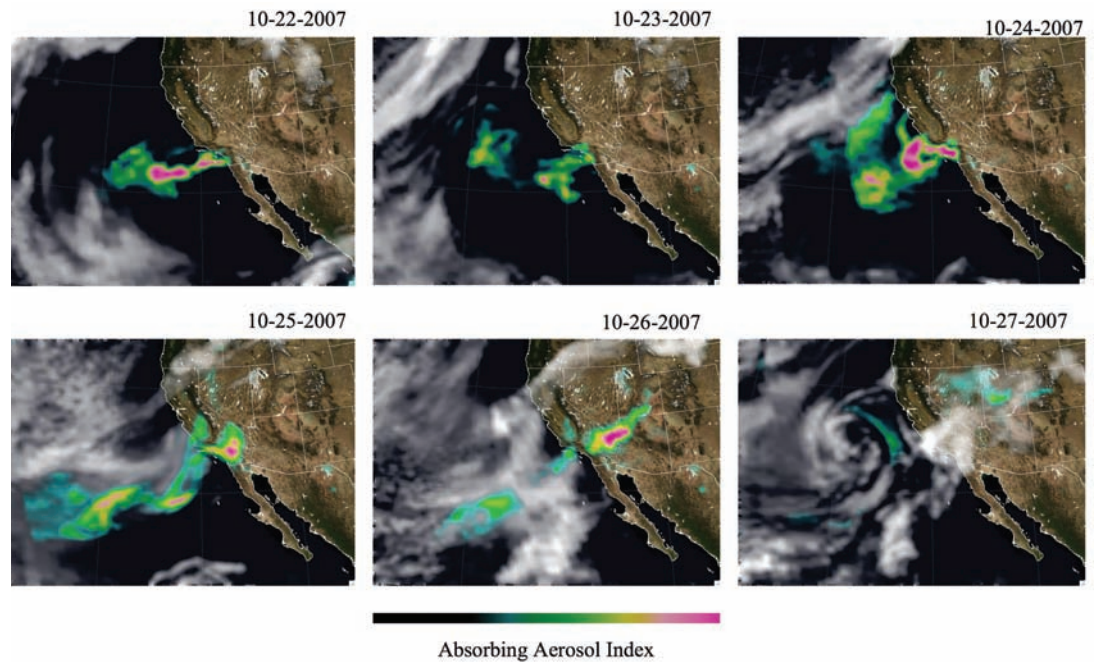
- Aerosols also affect the properties of clouds by changing the size of water droplets. This can affect cloud brightness, lifetime, extent, and precipitation.

**A**erosols can adversely affect air quality. These tiny particles can penetrate deep into the lungs causing allergic reactions and infections. Exposure to aerosol pollution is linked to increased risk of heart and lung disease. The U.S. Environmental Protection Agency monitors and enforces particulate air quality standards nationwide.

Long-range transport of aerosols across continents and oceans can impact air quality in normally pristine environments. Space-based observations of aerosols provide critical information on the impact of long-range pollution transport on air quality.

Unlike observations using visible light, the OMI instrument can measure aerosols over bright surfaces (like deserts and clouds), because it makes measurements in the ultraviolet (UV). Earth's surface is very dark in the UV, making it easier to observe the faint reflection of light by aerosols above the surface. Over clouds, which do reflect strongly in the UV, OMI can detect absorbing aerosols—like smoke and dust—because those aerosols absorb different amounts of light at different wavelengths.

#### California Fires 2007



During October 2007, OMI captured these images of aerosols from wildfires burning in southern California. The color indicates a satellite-derived quantity called "Absorbing Aerosol Index." Hotter (redder) colors indicate greater amounts of absorbing aerosols from the

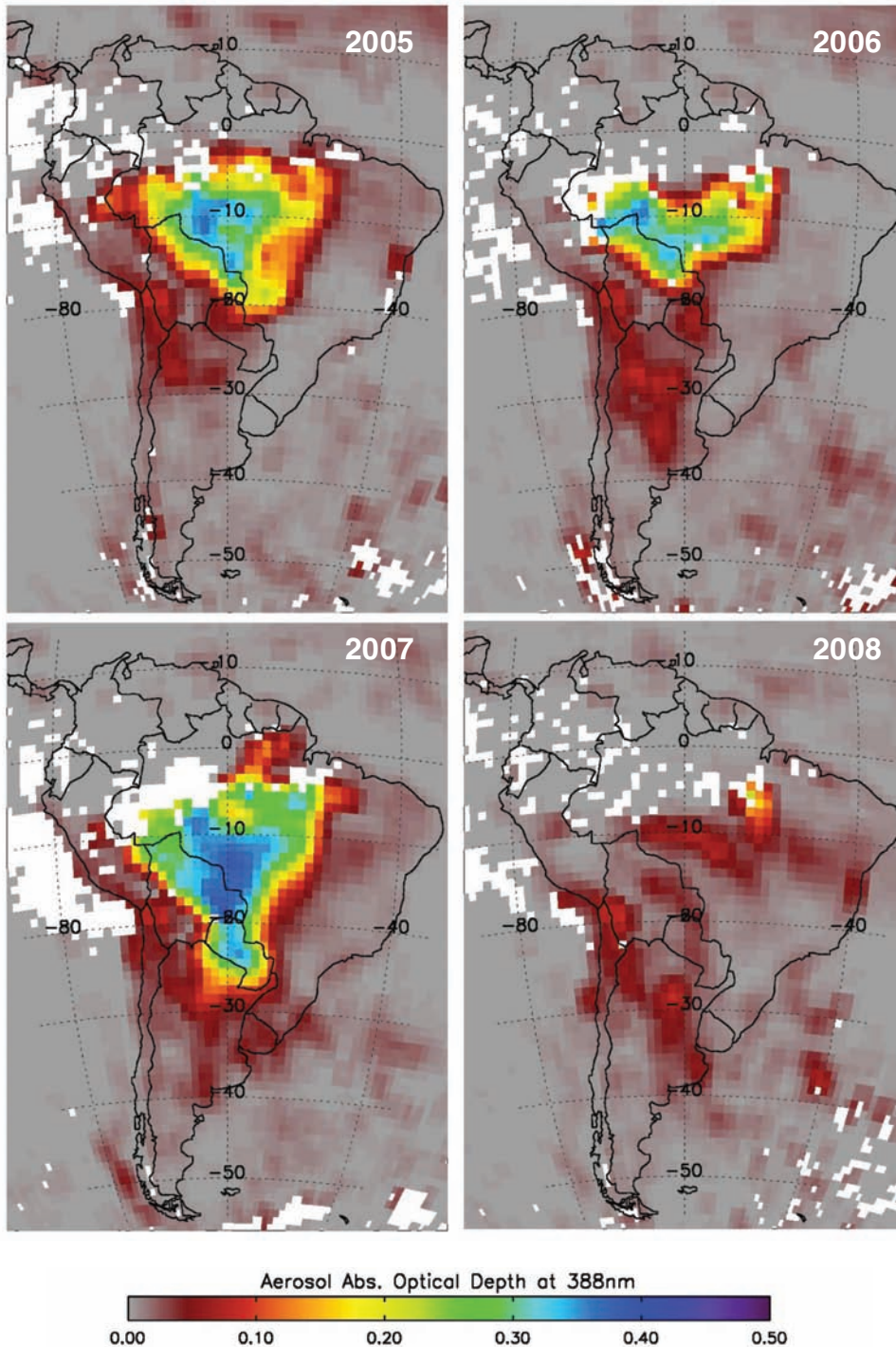
smoke plumes, while cooler colors (blues and greens) indicate fewer aerosols. The white and grey colors indicate the presence of clouds, as seen by the MODIS instrument on the NASA's Aqua spacecraft.

Other images can be found:

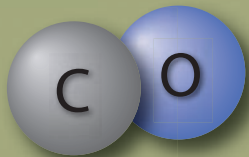
<http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=35930>

<http://alg.umbc.edu/usaq/archives/002495.html>

## OMI Observes Large Decrease in South American Biomass Burning in 2008



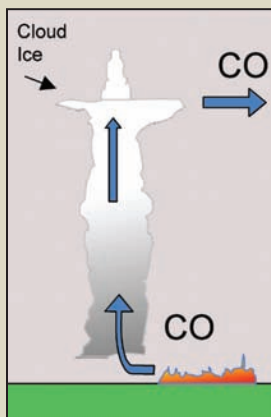
The seasonal cycle of agricultural biomass burning in South America is linked to the wet and dry seasons. Most burning takes place in September just before the wet season. The smoke aerosols produced by burning are readily detectable by OMI. The figure at left shows Aura OMI observations of aerosols over South America for September 2005 - 2008. The Absorbing Aerosol Optical Depth is a measure of aerosol concentration and sunlight absorption. The figures show that there is ~1/3 decline in biomass burning aerosol concentration in 2008 relative to other years. Other satellite instruments that measure the number of fires also show a ~50% decrease in agricultural burning in 2008 relative to 2007, with a decrease of ~62% in Brazil alone versus a ~4% decrease over the rest of South America. We do not at present have an explanation for this decline in biomass burning. It does not appear to be related to meteorology, as the precipitation in South America was not significantly different in 2008 from other years.



## CARBON MONOXIDE

### Carbon Monoxide

- Carbon monoxide is an odorless, colorless gas that is produced when there is insufficient oxygen during combustion.
- The lifetime of CO is long enough that it can be a good marker for long-range transport of polluted air.



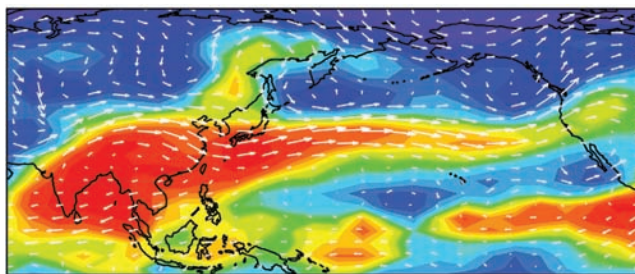
Carbon monoxide (CO) is produced at the surface by biomass burning and industrial processes. Deep convective clouds quickly transport air from the surface to upper altitudes. Since CO is not removed by rain, this transport efficiently moves CO and other insoluble gases from the surface to the middle and upper troposphere.

## Long-Range Transport of Pollution

Some pollutants, notably CO and O<sub>3</sub>, have a lifetime of a week or more. These pollutants can be transported upward into the jet stream by convective systems. At high altitudes, the pollutants spread out and may travel miles before their concentrations are reduced by chemical reactions or mixing. Is such long-range transport important for air quality? Such plumes occasionally contribute to surface air pollution, but usually their contributions are small.

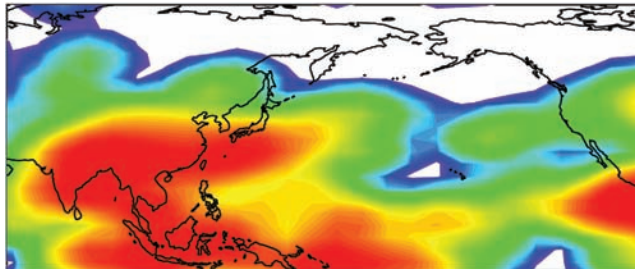
In the example on this page, TES measurements show that there are high concentrations of CO near the surface associated with urban pollution. This pollution is transported upward by convection, as signaled by elevated upper troposphere ice water concentration (IWC) over the Asian continent. Once CO arrives in the upper troposphere, the jet stream transports it across the Pacific to North America.

Aura MLS 215hPa CO



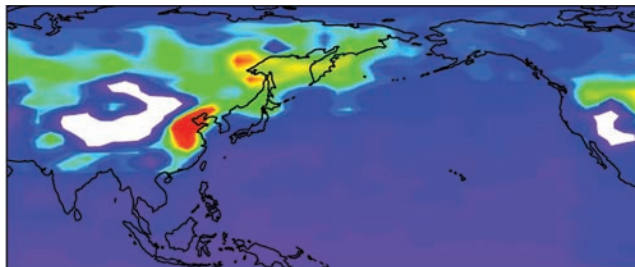
MLS CO observations in the upper troposphere (~11 km). Red indicates higher concentrations.

Aura MLS 215hPa IWC



MLS ice water content (IWC) at ~11 km. High amounts (red) indicate the location of convective clouds.

Aura TES 909hPa CO



TES measurements of CO near the surface show the locations of CO sources. Red indicates elevated concentrations. White indicates high topography.

## Changes in Air Pollution During the 2008 Olympic Games

China is now believed to be among the largest emitters of anthropogenic air pollutants in the world. Aware of China's air quality issues, the Chinese government developed the Beijing Olympic Action Plan with the goal to meet the World Health Organization air quality standards for the duration of the August - September 2008 games.

The Chinese pollution reduction strategy included: (1) reducing coal burning (the primary anthropogenic source of  $\text{SO}_2$ ); (2) restricting vehicular transportation to lower motor vehicle emissions of  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) and VOCs; and (3) curtailing metallurgical, chemical and cement industries to reduce their emissions. These emission controls were instituted from July through September 2008 in conjunction with the Olympic Games. Aura measurements show dramatic reductions in tropospheric nitrogen dioxide ( $\text{NO}_2$ ), sulfur dioxide ( $\text{SO}_2$ ), and

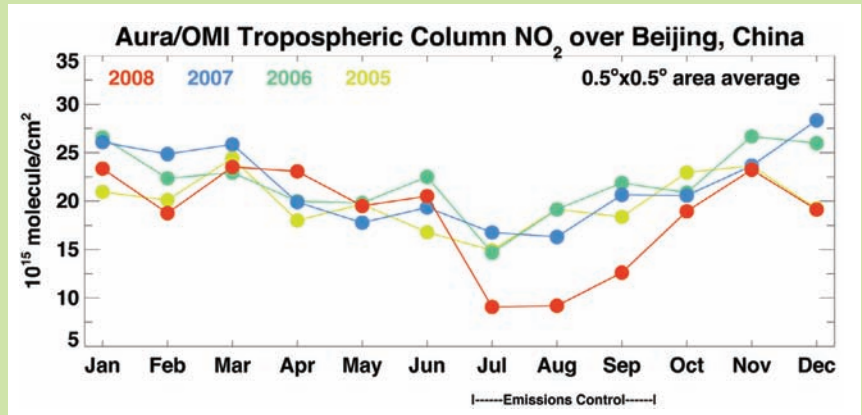
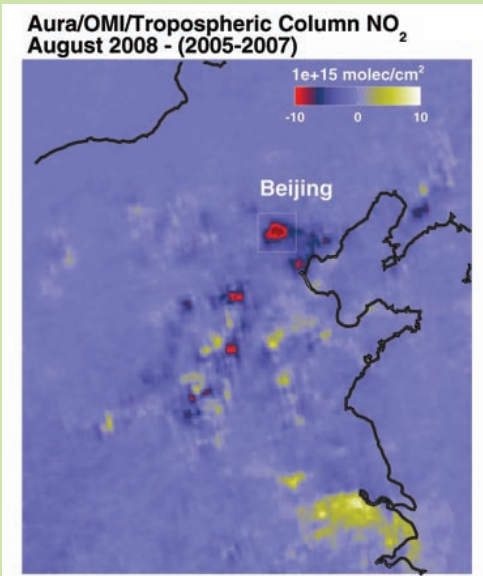
measurable reductions in tropospheric column ozone ( $\text{O}_3$ ). The MOPITT instrument onboard the Terra spacecraft also showed a reduction in CO. The drastic measures imposed by the Chinese Government appear to have successfully reduced air pollution; however,  $\text{NO}_x$  levels rose again after the Olympic Games.

The Great Wall of China, built in the 5th century, cannot stop the pollution flowing northward from Beijing.

Due to rapid industrialization, air quality in Beijing is believed to be among the worst in the world. Olympic athletes and visitors were very concerned about air quality during the games.

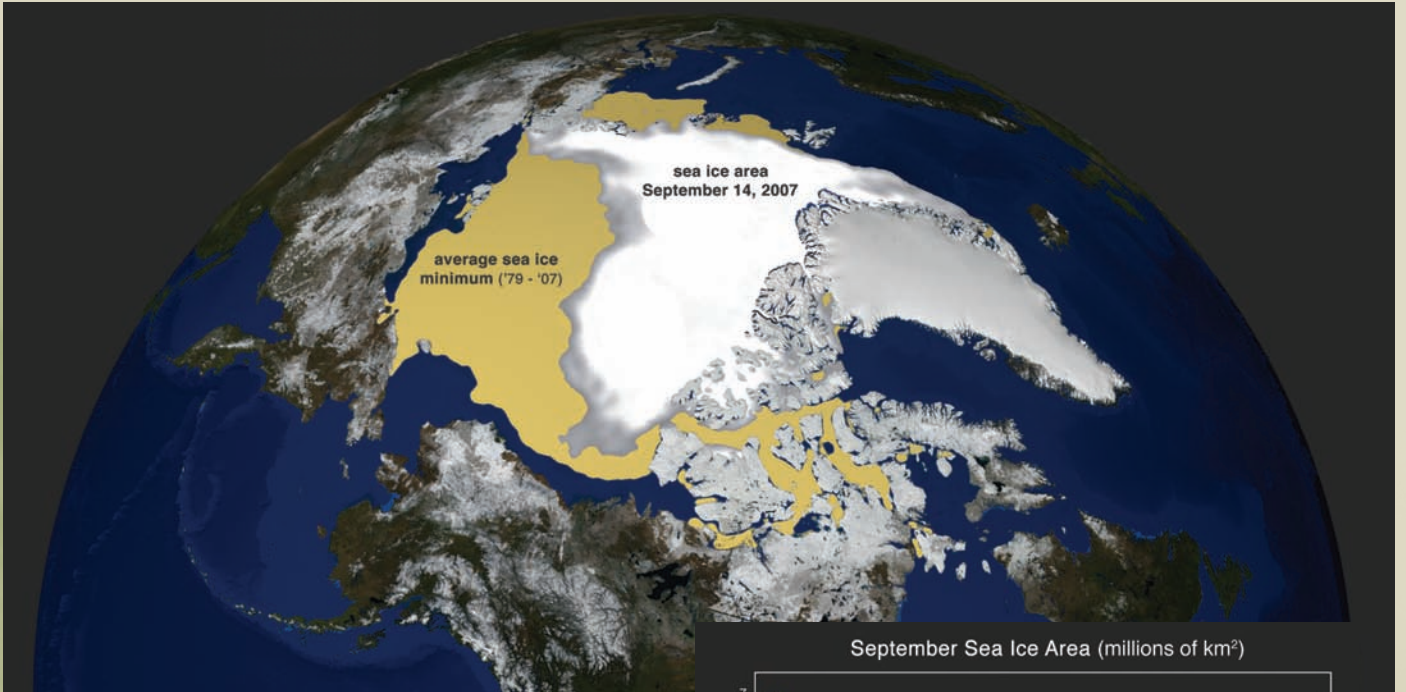


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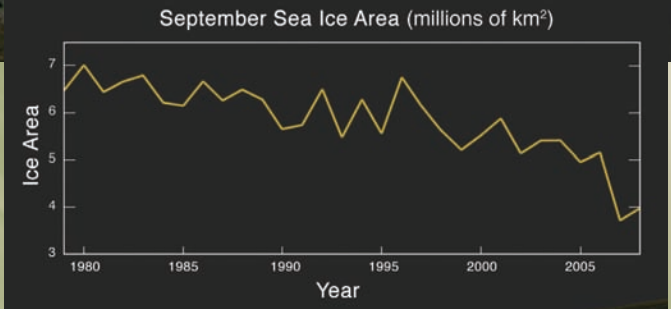


Left, map of changes in  $\text{NO}_2$  for August compared to previous years. Above, monthly mean  $\text{NO}_2$  amounts over Beijing compared with previous years. Emission controls applied during the Beijing Olympic Games reduced this pollutant.

# CLIMATE CHANGE



The Arctic sea ice area has decreased dramatically since 1979 as the climate at the North Pole has warmed.





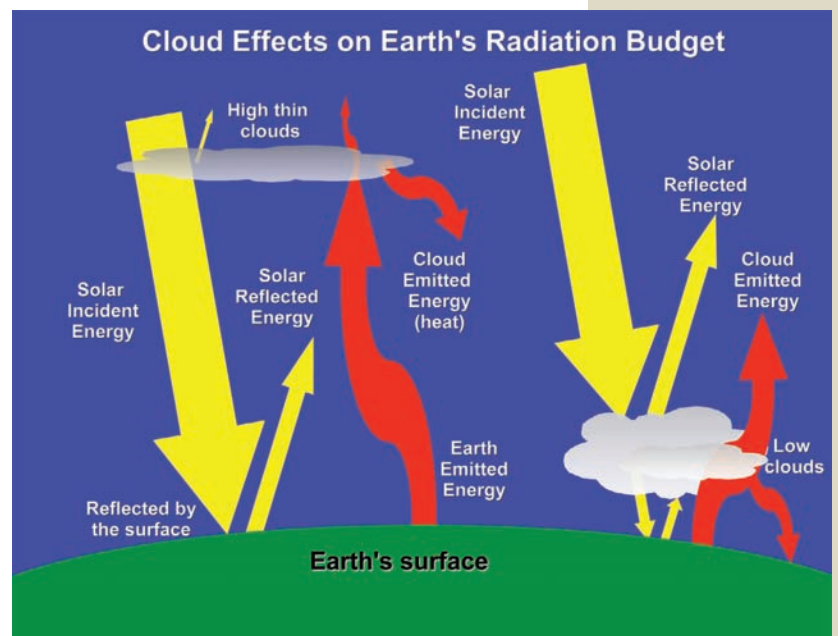
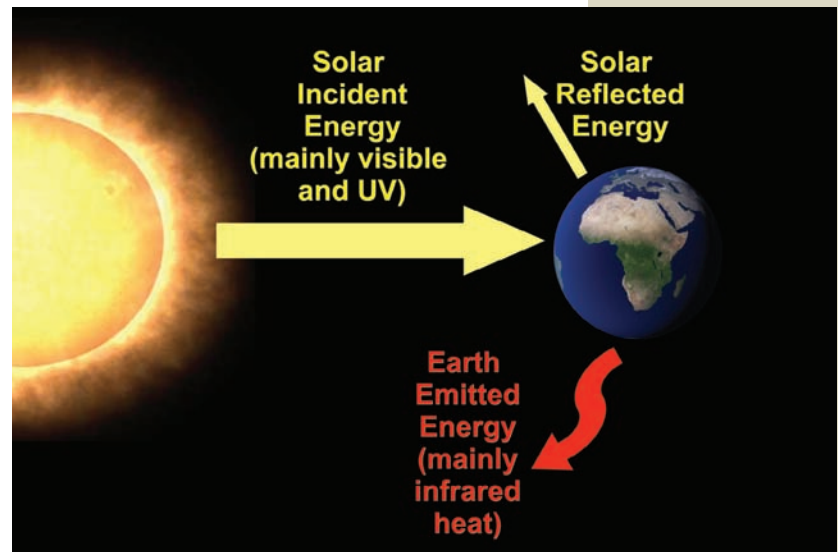
## Heating the Planet

Climate and atmospheric composition have a two-way interaction. Clouds, aerosols and greenhouse gases, such as carbon dioxide, methane, ozone and water vapor, impact Earth's climate through their effects on the radiation budget. The Earth's climate also affects the atmospheric circulation and physical processes, such as precipitation and evaporation, that in turn influence atmospheric composition. Aura measurements help scientists untangle these complex interactions.

The Earth receives energy from the Sun, mostly at visible wavelengths. About 30% of this incoming sunlight is scattered back to space by the atmosphere, the surface, clouds, and aerosols. The remainder is absorbed by the atmosphere and the surface. The Earth emits heat energy in the infrared part of the electromagnetic spectrum. Some of this heat energy is trapped by clouds and atmospheric gases and re-radiated back to the surface (the greenhouse effect).

Clouds significantly impact the Earth's heat budget and present one of the greatest uncertainties in predicting future climate. Clouds warm the Earth by trapping infrared radiation emitted by the atmosphere and the surface. They also cool the Earth by reflecting sunlight back into space. The net effect of clouds on our future climate depends on how clouds might change their location and altitude. For example, high cirrus clouds strongly warm the climate, while marine stratus strongly cool the climate. If cirrus amounts increase in the future, this will amplify global warming. Clouds also interact

radiatively with atmospheric gases. They increase the path of visible light through the atmosphere because light is scattered around and among clouds before it is scattered back to space. This increases light absorption by gases.





## Can Cloud Feedback Slow Climate Change?

### Cloud Facts

- The role of clouds is one of the greatest uncertainties in predicting future climate.
- Clouds warm the Earth by trapping infrared radiation emitted by the atmosphere and the surface. Clouds also cool the Earth by reflecting sunlight into space.
- Clouds are closely linked with water vapor, which is the most important greenhouse gas.
- The “Iris Hypothesis” stated that the area covered by tropical cirrus clouds would shrink when the ocean surface warmed. Cirrus clouds block infrared radiation from escaping to space and can amplify global warming. If the area covered by cirrus shrinks, this would be a strong negative climate feedback.
- Analysis of cirrus using measurements from Aura and other satellites show that cirrus increases as the ocean surface warms.

Climate change is likely to affect clouds and water vapor in the upper troposphere. Clouds might amplify or reduce the amount of global warming depending on their altitude. The Iris Hypothesis, illustrated by the cartoon below, shows how cloud feedbacks might blunt global warming. As sea surface temperatures rise, more energy is available for tropical storms. This would speed up the circulation and increase descending motion between clouds. Stronger and more wide-spread descent would in turn dry the air between clouds reducing cirrus

and water vapor and allowing more radiation to escape to space. The decrease of cirrus cloud coverage with increasing temperature is analogous to the opening of the eye’s iris when exposed to strong light. The net effect of this proposed feedback mechanism would be to moderate global warming.

The data from Aura MLS and other satellites (next page) show that cirrus and water vapor increase over warmer seas, contradicting the Iris Hypothesis.

### The Iris Hypothesis

**Normal**

**Iris Hypothesis**

Normal convection is shown on the top left. Iris Hypothesis: as the ocean warms, convection increases, which increases the downwelling circulation between clouds (top right). Because high altitude air is very dry, the increase in downwelling dries out the air between the clouds, suppressing cirrus formation. This would allow more radiation to escape to space. Aura data (bottom right cartoon and next page) show that cirrus and water vapor increase over warm oceans.

**What Aura Data Show**

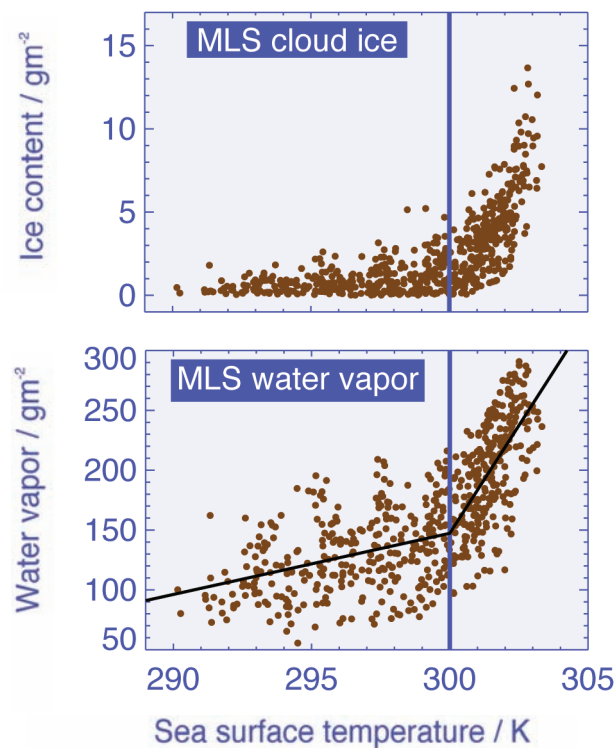
## Water Vapor and Cloud Feedback

Measurements from MLS show that cloud and water vapor feedbacks actually amplify global warming. Water vapor and cirrus increase in the upper troposphere

over warm seas. This result is inconsistent with the Iris Hypothesis. The result has now been confirmed by CloudSat.

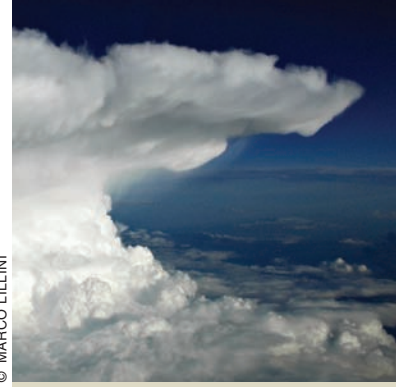
### Upper Troposphere

MLS measurements of cloud ice and water vapor over warm and cool parts of the tropical ocean. The increase in ice and water vapor as the ocean temperature increases suggests that as convection increases over warm seas, high cloud amounts [or cloud amounts] will increase. Sea surface temperatures are expected to rise as the planet warms, and this result suggests that tropical high clouds will increase, amplifying the warming.



### Cloud Facts

- Clouds play different roles in climate change depending on their altitude and extent. In the 1990s measurements from NASA satellites helped untangle the role of climate forcing by clouds.
- High, thin clouds warm the climate. They are relatively transparent to incoming sunlight, but these clouds absorb some of the Earth's outgoing heat and reradiate a portion of it back to the surface.
- Low clouds cool the climate because they radiate at roughly the same temperature as the surface and reflect sunlight as well. Low clouds act much like snow and ice.
- In the upper troposphere, MLS detects thick cirrus clouds by measuring the microwave emission of ice. Such clouds form in humid environments. The presence of high water vapor amounts confirms the presence of the clouds.





## CLIMATE CHANGE

### Ozone as a Greenhouse Gas

#### Ozone Facts

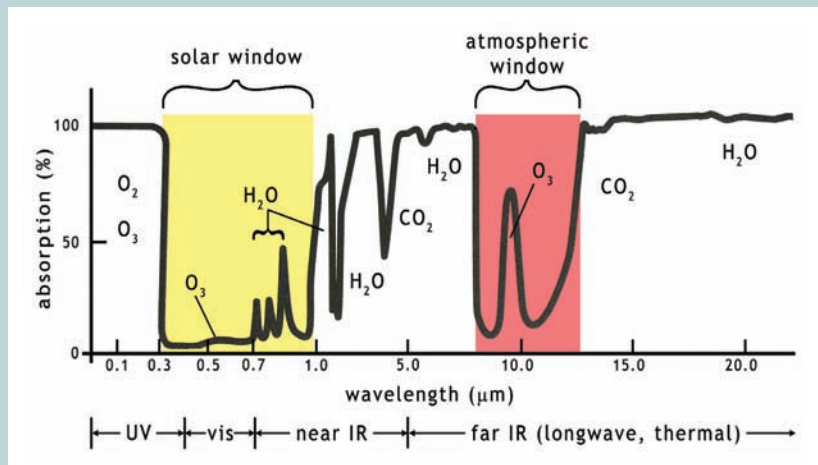
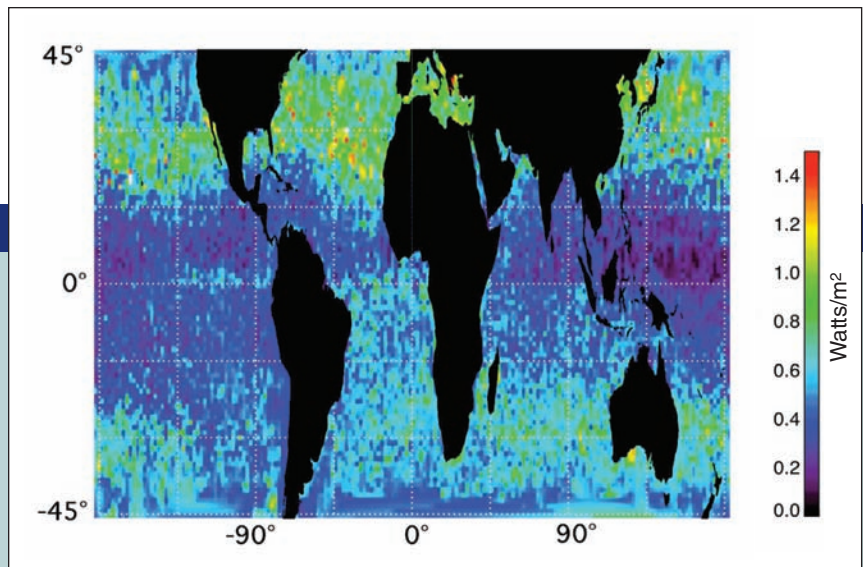
- Tropospheric ozone ranks as the third most important anthropogenic climate gas behind carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>).
- Ozone absorbs heat (infrared radiation) from the Earth's surface, reducing the amount of radiation escaping to space.
- Ozone also absorbs visible and ultraviolet radiation from the sun.

**S**tratospheric ozone is well known for absorbing harmful ultraviolet radiation. This absorption is beneficial to life on the Earth's surface. Ozone also absorbs radiation in the infrared. Tropospheric ozone can trap infrared radiation and contribute to global warming. Tropospheric ozone increased

in the last century as a result of industrial activity and biomass burning and will likely continue to increase throughout this century. The impact of anthropogenic ozone on the global radiation budget and climate has been estimated mainly using models.

#### Greenhouse Effect

This map shows the annual average trapping of outgoing long-wave (infrared) radiation (in Watts per square meter) by upper tropospheric ozone when no clouds are present, as estimated from TES IR measurements. Lofted ozone pollution in the northern middle latitudes causes greater trapping. Values are only calculated over the ocean.



Water vapor, oxygen, carbon dioxide, and ozone are among the most important gases that absorb radiation in the Earth's atmosphere. Ozone absorbs radiation in the visible (vis) and infrared (IR), indicated in yellow and red, respectively, in the figure on left, as well as in the ultraviolet (UV) parts of the spectrum. Ozone absorption in the infrared is important because ozone absorbs radiation in an "atmospheric window" region where infrared radiation would normally escape to space. Sunlight reaches the surface through the "solar window." Ozone also absorbs in this visible window region.

## Clouds and Ozone

Clouds change ozone's contribution to the radiation budget. Cloud properties from Aqua's MODIS imager and Aura's OMI can be used with daily tropospheric ozone

derived from OMI and MLS to estimate the impact of clouds on ozone absorption and its associated radiative effect.

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### Climate Change

- Climate change is caused by human and natural agents. Scientists use the concept of "net radiative forcing" to evaluate the impact of different processes that control the Earth's radiation budget.

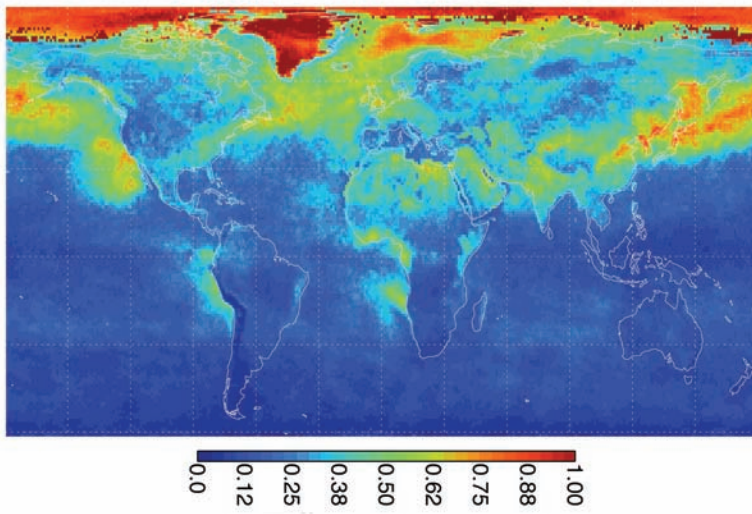
- Net radiative forcing is the total incoming minus the total outgoing radiation near the tropopause. Positive net radiative forcing leads to heating; negative net forcing leads to cooling. For the climate to stay in balance, the net radiative forcing must be zero. The net radiative forcing is measured in Watts per square meter ( $W/m^2$ ).

- Incoming radiation is from the sun. Outgoing radiation includes reflected sunlight and thermal IR radiation from the surface, the atmosphere, and clouds.

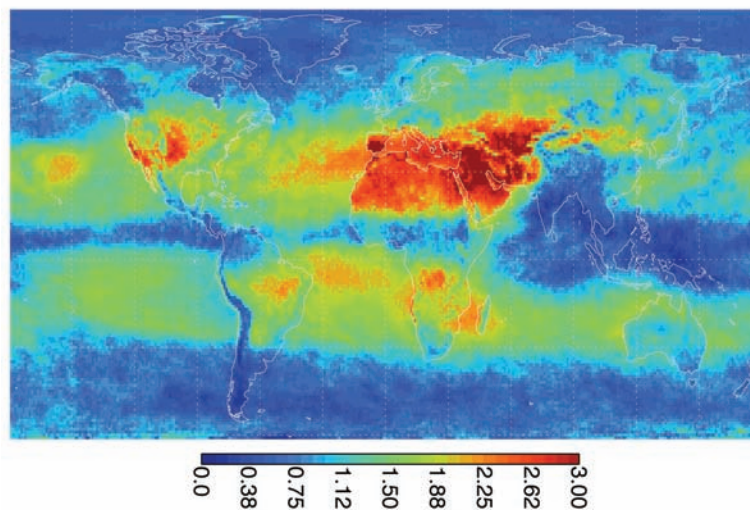
### Radiative Forcing

The map, below, shows the July 2005 average instantaneous short-wave radiative effect of tropospheric ozone absorption of sunlight. Over clouds and ice (Greenland), a portion of the reflected light is absorbed

by ozone, trapping radiation that would have otherwise escaped the lower atmosphere to space. Ozone radiation trapping occurs over polluted cloudy regions, such as off the west coasts of Africa, South and North America, and off the coast of northeast Asia.



The map, at right, shows the thermal radiative effect of tropospheric ozone in July 2005. The radiative effect of ozone is largest over the hot, dry, clear deserts where there is more thermal radiation from the surface to be absorbed. High clouds along a band near the equator decrease the radiative effect of tropospheric ozone, because the cloud tops are cold.



## Observing Dirty Clouds

**A**erosols affect the Earth's radiation budget and climate both directly and indirectly. Aerosols absorb incoming sunlight and also reflect it back to space. This is called the "aerosol direct effect." Aerosols also modify clouds and precipitation when they act as cloud condensation nuclei. This is called the "aerosol indirect effect." Although clear cases of the aerosol indirect effect have been observed, there is scant data on its overall importance to global climate.

The aerosol indirect effect is extremely difficult to observe. Aerosols inside or near clouds cannot be easily detected by satellite sensors because both aerosols and clouds scatter light. One way to infer the presence of aerosols near clouds is to use another observable pollutant as a "proxy" for aerosols. One such

aerosol proxy is carbon monoxide (CO). CO and aerosols such as smoke are both produced by incomplete combustion.

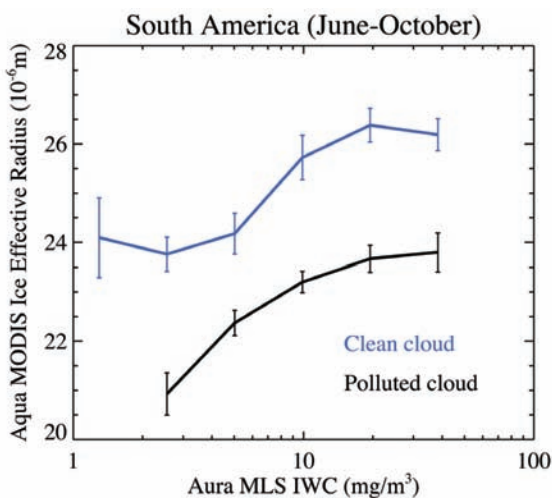
Aura's MLS can measure CO inside high altitude clouds, enabling us to identify "clean" and "aerosol polluted" clouds. Once polluted clouds have been identified by MLS, cloud particle size from Aqua MODIS and precipitation from TRMM can be used to examine the aerosol indirect effect. In the bottom left panel, polluted clouds over South America in the biomass burning season are shown to contain smaller particles than clean clouds. With the higher particle concentration, the polluted clouds reflect more light to space than clean clouds. Polluted clouds also rain less than clean clouds, as shown on the bottom right figure.

Nitrogen dioxide and aerosols form a brown layer. This cloud was observed embedded in a polluted layer over Baltimore, Maryland.

© MARK SCHOEBERL

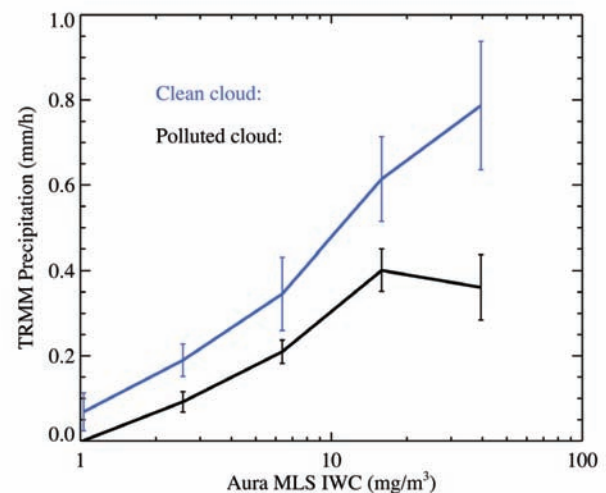
### Pollution Affects Cloud Properties

Cloud particle radius vs. cloud amount



Using MLS CO as a surrogate for clouds containing pollution, we see changes in cloud properties. The left graph shows that ice particles at the tops of clouds are smaller in polluted clouds compared to clean clouds for both thick and thin clouds (as measured by Ice Water

Precipitation vs. cloud amount



Content, IWC). The right graph relates IWC to rainfall using Tropical Rainfall Measurement Mission (TRMM) data, showing that polluted clouds produce less precipitation than clean clouds.

## The Power of El Niño

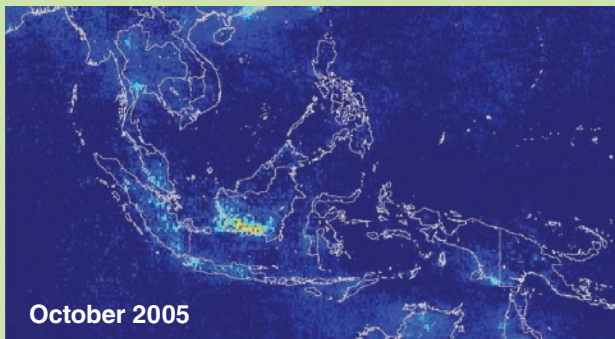
**E**l Niño is the term used to describe a variation in Earth's climate where the east tropical Pacific ocean temperatures are at least 0.5°C warmer than average for 5 months or more. The effects of El Niño include floods and droughts that can cause widespread hardships and environmental degradation.

An El Niño episode that began in September 2006 and lasted until early 2007 produced drought throughout the East Pacific. Deforestation and agricultural burning, particularly

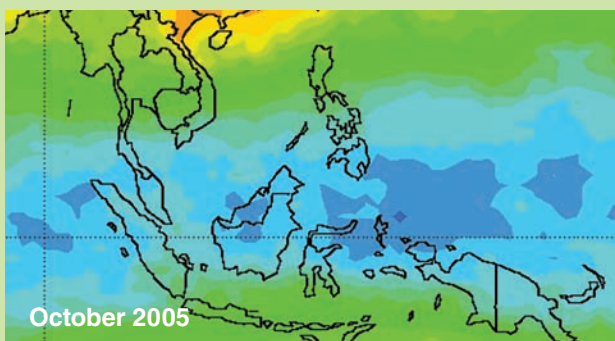
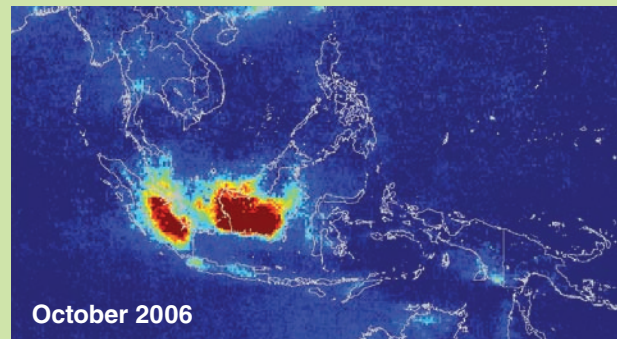
on the islands Borneo and Sumatra, triggered massive fires during the drought. The fires produced large amounts of formaldehyde (HCHO) that were observed by OMI. Large carbon monoxide plumes were observed by TES, MLS and MOPITT on NASA's Terra satellite. The fires led to elevated tropospheric ozone and poor air quality throughout the western tropical Pacific. Although the 2006 - 07 El Niño was weak, it produced the worst Indonesian fires since the devastating El Niño of 1997 - 98.



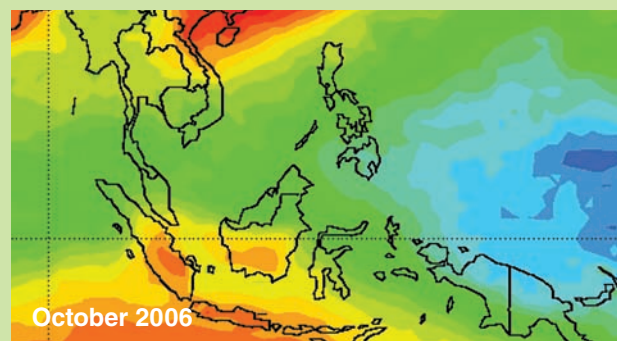
### El Niño Affects Indonesian Air Quality



OMI monthly mean column HCHO



Mean tropospheric O<sub>3</sub> mixing ratio derived from the OMI/MLS residual approach described on p. 18



Compared to a normal year (left top figure), the El Niño fires increased the production of ozone precursors such as HCHO (formaldehyde, right top figure). Tropospheric ozone is normally low in this region (left bottom figure) because convection pumps low ozone air from the

ocean surface into the mid-troposphere. The reduction of convection combined with plentiful ozone precursors significantly increased tropospheric ozone during El Niño (right bottom figure).

50  
3.0  
O<sub>3</sub> ppbv  
HCHO 1 x 10<sup>16</sup>  
molecules/cm<sup>2</sup>  
10  
<0.05

## The Water Cycle

### Water Facts

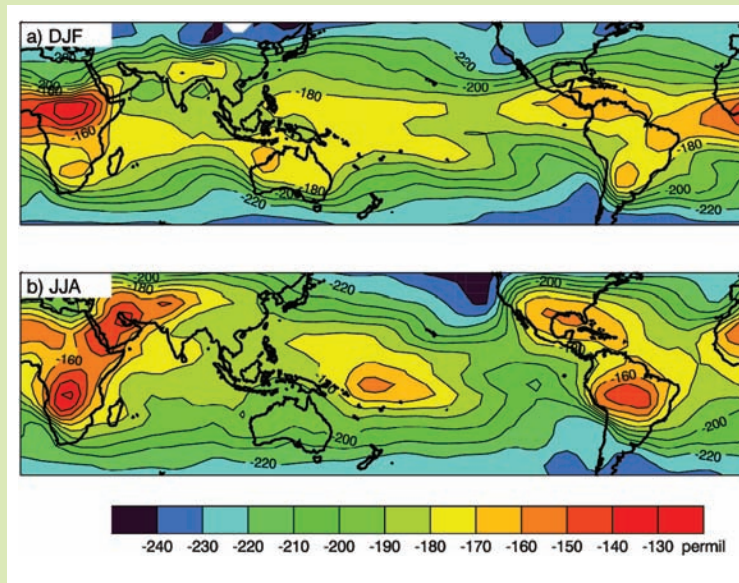
- Most water molecules are made of two hydrogen atoms and one oxygen atom ( $H_2O$ ).
- One hydrogen atom is replaced by deuterium (D, a hydrogen atom with an extra neutron) in about 0.031% of all water molecules.
- The ratio  $HDO/H_2O$  in the ocean is fairly uniform because of ocean mixing. When atmospheric water vapor condenses, it is easier to condense HDO than  $H_2O$  so rainwater has a higher concentration of HDO. The atmosphere then becomes HDO depleted.

The water cycle is the transformation of water from liquid (or solid) to gas and back again. Rain falls and flows to rivers and into the ocean. Evaporation on land and from the oceans replenishes the moisture in the air. Moist air cools as it rises, forming clouds that return the moisture to the surface as precipitation.

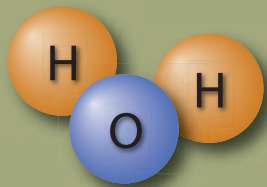
Heavy water is HDO, where D is deuterium, an isotope of hydrogen. Heavy water condenses and evaporates differently than normal light water ( $H_2O$ ). By comparing the ratio of HDO to  $H_2O$  in the atmosphere to the ratio found in the ocean, we can identify the evaporative sources of water observed in the atmosphere. TES measures both  $H_2O$  and HDO.

The heavy water to light water ratio measurements help us understand the water cycle over rainforests and over the ocean by identifying the sources of the water and how efficiently it is transformed to rainfall. The data are also helping us understand the transport of water from the equator to the poles. Ice core records stretching back hundreds of thousands of years provide us with water isotope information. By comparing these records with current observations from TES, we can find out how the water cycle has changed from the past and better predict how the water cycle will change in the future.

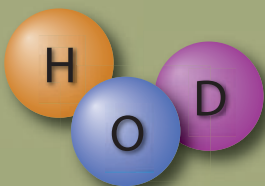
### Seasonal Cycle of HDO/ $H_2O$



The decrease in the HDO/ $H_2O$  ratio with latitude indicates condensation as the water vapor moves poleward from the warm tropics. The high HDO/ $H_2O$  ratio (reds) over land in the tropics indicates strong recycling of water through evaporation and condensation. The relatively low HDO/ $H_2O$  ratio (greens) in regions in the tropics occur where the water vapor has been HDO depleted by precipitation and then moved to drier regions.

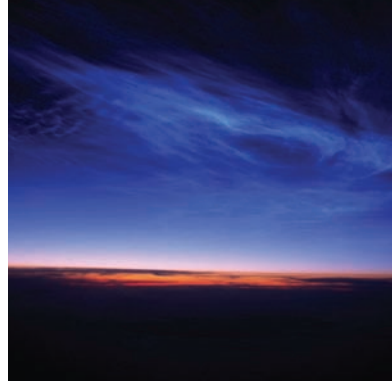


WATER



HEAVY WATER



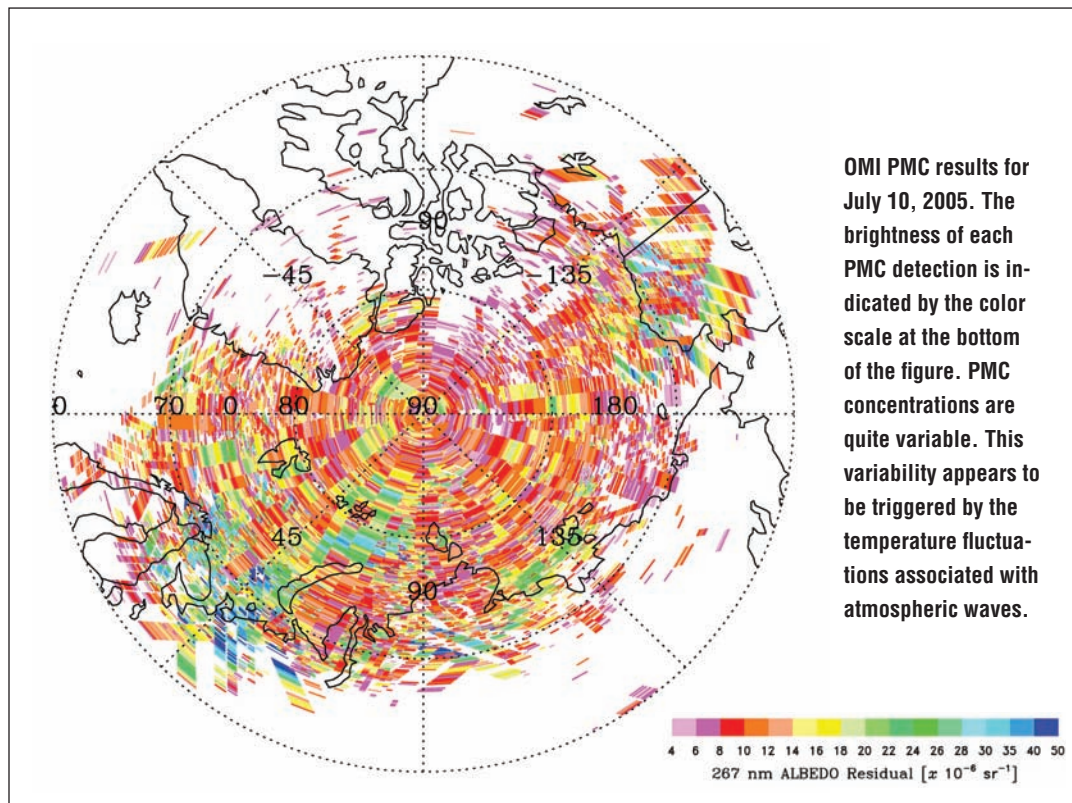


## Polar Mesospheric Clouds

**F**ar above the stratosphere in the mesosphere (~50 - 90 km), wispy noctilucent clouds form at the summer poles. Also called polar mesospheric clouds (PMCs), they form more than 80 km (50 miles) above the Earth. PMCs are believed to be microscopic ice particles that condense on meteoric dust in the very cold summer mesosphere. PMCs are visible from the ground when illuminated by the sun against the dark sky. PMCs have been observed more frequently in recent decades. There may be two reasons for this. First, the global increase in methane will lead to an increase in mesospheric water. This will increase the water vapor condensation temperature and make it easier for PMCs to form. Second, CO<sub>2</sub> has increased in the

atmosphere and the temperatures in the mesosphere have decreased, making it easier for water vapor to condense and clouds to form.

OMI is making some of the best maps of PMCs ever obtained. PMCs are so faint that they are difficult to see with a down looking instrument, but PMCs reflect enough UV sunlight that they are visible to OMI. OMI's small pixels improve the likelihood of PMC detection, and OMI's wide field of view makes it possible to identify PMC spatial structures and follow PMC evolution. With the overlapping measurement swaths above 65° latitude, OMI also measures PMC variability on time scales less than a day.



### The Highest Clouds

- Polar Mesospheric Clouds (PMCs) form in the summer mesosphere between 75 - 85 kilometers (46 to 53 miles).

- These clouds are so thin that they can only be seen from the ground when the sun goes below the horizon.

- PMCs are very tiny ice crystals probably about 0.1 micrometer in size—about 100 times smaller than fine desert dust. The ice crystals may be condensing on meteor dust.

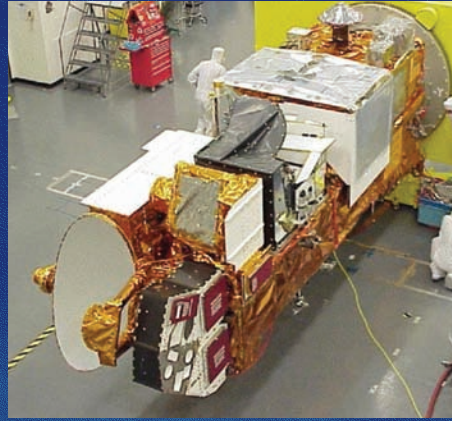
- PMCs form in the super cold summer mesosphere, where temperatures fall below -120C (-184F). The summer mesosphere is the coldest part of the atmosphere despite being in almost continual solar illumination above 65° latitude.

THE AURA MISSION

*There are no passengers on Spaceship Earth.  
We are all crew. ~*

Marshall McLuhan, 1964



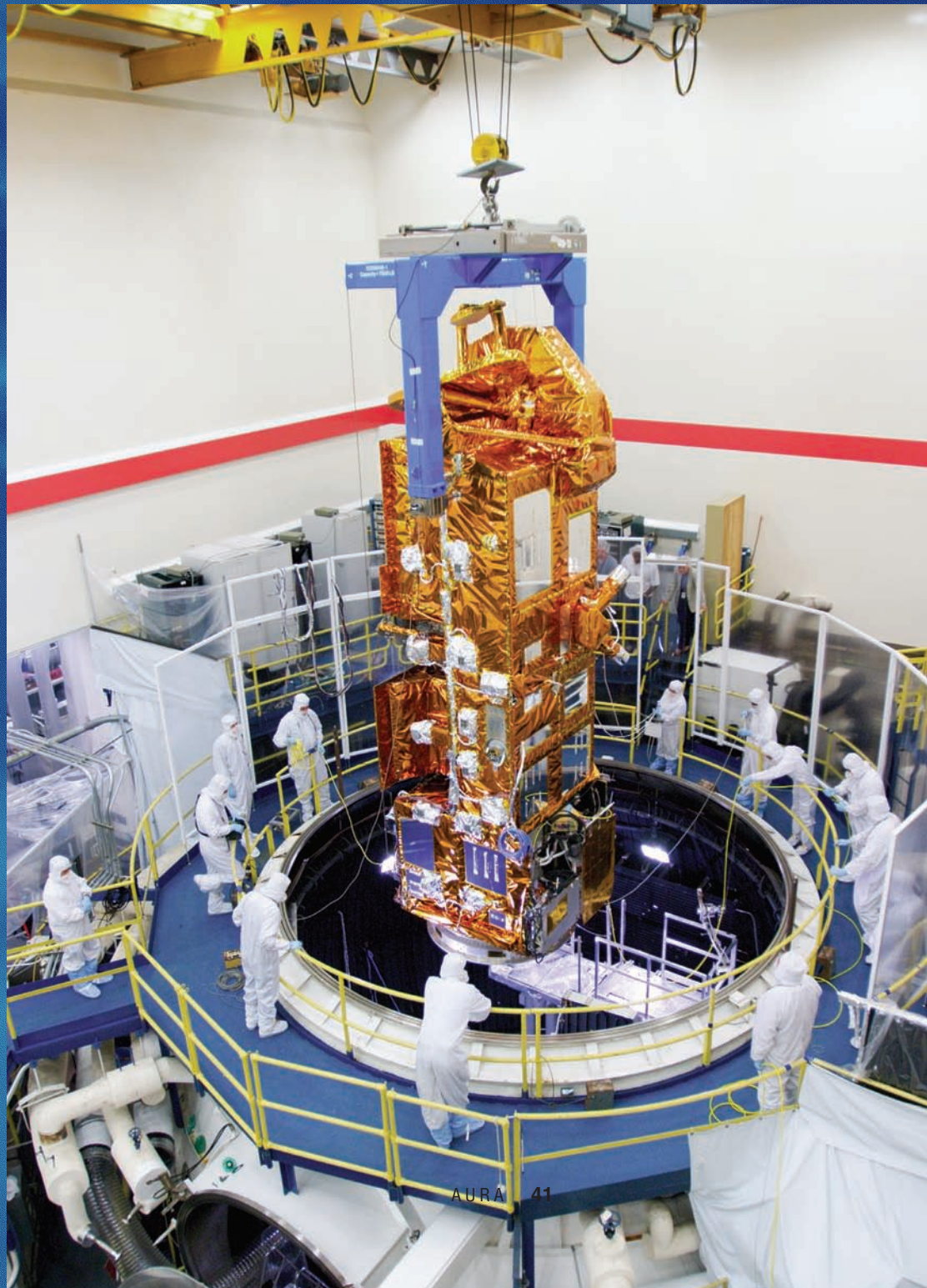


## The Aura Spacecraft

Aura was launched July 15, 2004 into an ascending node 705 km sun-synchronous polar orbit with a 98° inclination and an equator-crossing time of 13:45±15 min.

Upper right picture, Aura spacecraft during assembly. Upper picture, Aura on end. This is the position of the spacecraft when it is bolted to the top of the rocket. Right, Aura is being lowered into a vacuum test chamber.

The spacecraft is called “the bus” because it carries passengers—the instruments. The spacecraft provides power, downloads the data, controls the instruments, and provides telemetry information to the instruments. The instruments are mounted to the bus on the earth facing side except for MLS which is mounted in front. The Aura spacecraft was built by Northrop - Grumman Space Technologies.





## AURA INSTRUMENTS

### High Resolution Dynamics Limb Sounder

#### HIRDLS

#### HIRDLS Data Products

##### Temperature

O<sub>3</sub>

CFCl<sub>3</sub> (CFC-11)

CF<sub>2</sub>Cl<sub>2</sub> (CFC-12)

CH<sub>4</sub>

HNO<sub>3</sub>

H<sub>2</sub>O

NO<sub>2</sub>

##### Aerosol Extinction

##### Cloud Top Height

##### Geopotential Height

The HIRDLS instrument was built by Lockheed Martin Corporation. The data are processed at the University of Colorado and are archived at the Goddard DISC. <http://www.eos.ucar.edu/hirdls/>

The High Resolution Dynamics Limb Sounder (HIRDLS) was designed to study transport processes that influence the distributions of trace gases, especially in the lowest part of the stratosphere. HIRDLS measures profiles of temperature, ozone and other trace gases with unprecedented vertical resolution of ~1 km (0.6 miles). HIRDLS also measures cirrus clouds, important for climate change since they reflect solar radiation and emit infrared radiation (p. 30) as well as polar stratospheric clouds that play a critical role in polar ozone depletion (p. 6).

HIRDLS is a limb viewing instrument that scans the Earth's horizon. HIRDLS is a filter

radiometer that looks at the infrared emission of trace gases against the cold background of space. HIRDLS has 21 channels in the spectral range of 6.12 - 17.76 microns, and scans over the vertical range of 8 - 50 km (5 - 31 miles) with ~1 km (0.6 miles) vertical resolution.

During the Aura launch some plastic sheeting came loose inside the instrument and part of the aperture is blocked. The HIRDLS team has had to adjust their algorithm to take into account thermal radiation from the plastic, which delayed the delivery of some of their data products.

#### High Resolution Dynamics Limb Sounder



**Co-PIs: John Gille, NCAR & University of Colorado; John Barnett, Oxford University, U.K.**

HIRDLS is a limb-scanning filter radiometer that measures the IR emission of molecules against the cold background of space. HIRDLS scans the atmospheric limb.

#### HIRDLS characteristics

- 21 Channels
- Spectral Range 6.12 - 17.76 μm
- 1 km (0.6 mile) Vertical Resolution
- Vertical Range ~ 8 - 80 km (5 - 50 miles)

During launch some plastic material partially blocked the HIRDLS aperture. This has delayed the delivery of some of HIRDLS data products. The blockage restricts HIRDLS view of the atmosphere to an azimuth angle of 47° from the orbit plane on the side away from the sun (see p. 48). HIRDLS makes measurements between 65°S and 82°N.

## Microwave Limb Sounder

### MLS

The Microwave Limb Sounder (MLS) provides measurements needed to fully understand the chemistry of the stratospheric ozone layer and quantify the interactions between changes in atmospheric composition and climate. MLS also observes air pollution in Earth's upper troposphere. In addition to ozone (O<sub>3</sub>), MLS stratospheric and mesospheric profile measurements include stable and reactive forms of chlorine and other species involved in chemical ozone loss. MLS observations of long-lived trace gases are used to distinguish composition changes due to atmospheric motions from those due to chemistry. MLS upper tropospheric

profile observations include H<sub>2</sub>O, O<sub>3</sub>, CO, and HNO<sub>3</sub>. These measurements are used to study the long-range transport and chemical evolution of air pollution.

MLS cloud ice observations provide information on deep convection and climate processes. MLS is a limb-viewing spectrometer observing microwave emission of molecules from 118 GHz to 2.5 THz. MLS measures profiles for most species from about 8 km to 80 km (5 to 50 miles).



#### MLS Data Products

##### Temperature

O<sub>3</sub>

BrO

CH<sub>3</sub>CN

CH<sub>3</sub>Cl

ClO

CO

HCl

HCN

HNO<sub>3</sub>

H<sub>2</sub>O

HO<sub>2</sub>

HOCl

N<sub>2</sub>O

OH

SO<sub>2</sub>

##### Cloud Ice

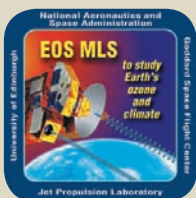
##### Geopotential Height

The MLS instrument was built by the Jet Propulsion Laboratory. The data are processed at the Jet Propulsion Laboratory and are archived at the Goddard DISC. <http://mls.jpl.nasa.gov/>

### Microwave Limb Sounder

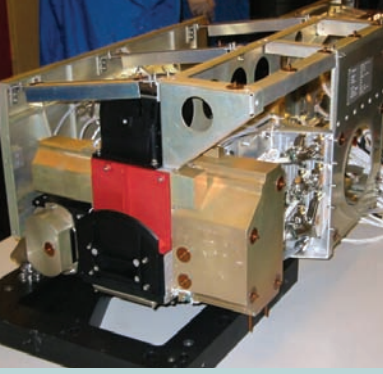
PI: Nathaniel Livesey, JPL

The Microwave Limb Sounder (MLS) is a limb sounding microwave spectrometer making observations in five spectral regions between 118 GHz - 2.5 THz and 1.5 - 3 km vertical resolution. The vertical measurement range is ~8 - 80 km (5 - 50 miles).



#### EOS MLS contains three modules

- The GHz radiometer module, which includes the 118, 190, 240, and 640 GHz receivers and a scanning antenna.
- The THz radiometer module, which contains the 2250 GHz receivers and the associated THz telescope and scan mirror.
- The spectrometer module, which receives and analyzes signals from the GHz and THz radiometer modules.



## AURA INSTRUMENTS

### Ozone Monitoring Instrument

#### OMI

##### OMI Data Products

**O<sub>3</sub> Column**

**O<sub>3</sub> Profiles**

**BrO Column**

**CHOCHO Column**

**HCHO Column**

**NO<sub>2</sub> Column**

**OCIO Column**

**SO<sub>2</sub> Column**

**Aerosol Absorption**

**Optical Centroid Cloud Pressure**

**Surface UVB**

The OMI instrument was built by Dutch Space and TNO-TPD, together with Finnish companies Patria, VTT and SSF. The data are processed in the Netherlands and at Goddard Space Flight Center and archived at the Goddard DISC. <http://aura.gsfc.nasa.gov/instruments/omi/index.html>

The Ozone Monitoring Instrument (OMI) was designed to track global ozone change and continues the column ozone record begun in 1979 by NASA's Total Ozone Mapping Spectrometer.

OMI measures the ozone layer recovery as trace gas concentrations in the atmosphere change (e.g., reduction in chlorofluorocarbons and increase in carbon dioxide). OMI measurements are used to study sources and transport of aerosols and trace gases that both affect global air quality and play a role in climate change.

Besides the ozone column and profile, OMI measures the column amounts of other trace gases including NO<sub>2</sub>, HCHO, SO<sub>2</sub>, BrO and OCIO. OMI also measures cloud pressure, maps aerosols and estimates ultraviolet radiation reaching the Earth's surface. OMI is an ultraviolet-visible (270 - 500 nm) down-looking imaging spectrograph that measures the solar radiation absorbed and

scattered by the Earth's atmosphere. The innovative optical design uses CCD solid state detectors. OMI's 2600 km (1600 miles) wide swath provides near-global coverage in one day with spatial resolution of 13 - 24 km<sup>2</sup> (5 - 9 square miles). The high spatial resolution of OMI enables almost daily detection of air pollution on urban scale resolution. OMI also provides near-real-time data for operational agencies in Europe and the U.S. for improving weather and air quality forecasts.

The Netherlands Agency for Aerospace Programs (NIVR), and the Finnish Meteorological Institute (FMI) contributed the OMI instrument to the Aura mission. The international OMI science team consists of Dutch, Finnish and U.S. team members and is led by the Netherlands Meteorological Institute (KNMI).

#### Ozone Monitoring Instrument

**PI: Pieternel Levelt (KNMI, NL)**  
**Co-PI: Johanna Tamminen (FMI, FI)**  
**US Science Team Leader: P.K. Bhartia (NASA GSFC, U.S.)**

The Ozone Monitoring Instrument (OMI) is a hyperspectral imager with spectral resolution of 0.4 – 0.6 nm.

OMI has a 2600 km ground swath and thus provides global coverage each day.

##### OMI characteristics

- Nadir Solar Back-Scatter Spectrometer
- Spectral Range 270 - 500 nm
- 13 - 24 km<sup>2</sup> (5 - 9 square miles) Footprint at Nadir
- Swath Width 2600 km (1600 miles)



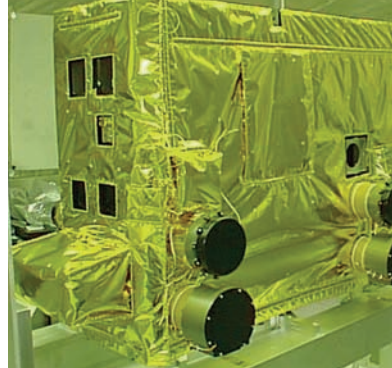
## Tropospheric Emission Spectrometer

### TES

The Tropospheric Emission Spectrometer (TES) instrument measures the vertical structure of ozone ( $O_3$ ) and carbon monoxide (CO) in the troposphere (surface to ~10 km/6 miles). Ozone contributes to poor air quality and is a greenhouse gas, trapping outgoing infrared radiation and warming the surface. CO comes from biomass burning and industrial activity, and produces ozone in the presence of nitrogen oxides ( $NO_x$ ). TES also measures water vapor ( $H_2O$ ) and isotopic water (HDO), providing information on the hydrological cycle.

TES is an infrared, high resolution, Fourier transform spectrometer covering the spectral range  $650 - 3050 \text{ cm}^{-1}$  ( $3.3 - 15.4 \text{ }\mu\text{m}$ ) at a spectral resolution of  $0.1 \text{ cm}^{-1}$ . TES has two view modes. TES can look downward

and point at specific targets, or TES can point at the horizon to make vertical profiles of trace gases. In the down-looking mode, TES can stare at a specific location for over three minutes, conduct a 400 km (248 miles) long transect, or step-and-stare over 4000 km (2485 miles) with footprints 35 km (22 miles) apart. TES has down-looking viewing resolution of  $5.3 \times 8.5 \text{ km}^2$  ( $2 \times 3.3$  square miles). TES can also view the atmospheric horizon with a higher spectral resolution of  $0.025 \text{ cm}^{-1}$ . The vertical resolution of horizon measurements is 2.5 km (1.5 miles).



#### TES Data Products

##### Temperature

$O_3$

$CH_4$

CO

$H_2O$

HDO

$HNO_3$

The TES instrument (above and on the spacecraft) was built by the Jet Propulsion Laboratory. The data are processed at the Jet Propulsion Laboratory and are archived at the Langley DAAC. <http://tes.jpl.nasa.gov/>

## Tropospheric Emission Spectrometer

PI: Anmarie Eldering, JPL

The Tropospheric Emission Spectrometer (TES) is an infrared, high resolution, Fourier transform spectrometer covering the spectral range  $650 - 3050 \text{ cm}^{-1}$  ( $3.3 - 15.4 \text{ }\mu\text{m}$ ) at a spectral resolution of  $0.1 \text{ cm}^{-1}$ .

#### TES characteristics

- Fourier Transform Emission Spectrometer
- Horizon Viewing Mode, 0 - 34 km (0 - 23 miles), 2.3 km (1.4 miles) Vertical Resolution
- Down Looking Mode,  $5.3 \times 8.5 \text{ km}^2$
- Spectral Range  $3.3 - 15.4 \text{ }\mu\text{m}$









## Launching Aura

Aura was launched on July 15, 2004 from Vandenberg Air Force Base on a Delta II rocket. The launch took place very early in the morning, and the rocket headed south so that the boosters could fall into the Pacific Ocean west of Los Angeles, California.

Shortly after launch, Aura achieved a sun-synchronous orbit at 705 km (438 miles), near its sister satellite Aqua. Over the next month, the satellite continued to fire its small rockets to adjust the Aura orbit to be 15 minutes behind Aqua. After achieving orbit, instrument check out began and within a few weeks most of the instruments began full operations.

In 2007 the Aura orbit was adjusted to move Aura closer to Aqua, CloudSat and CALIPSO. This change was made to improve the combined science from Aura and Aqua.

**Around 3 am PDT on July 15, photographer Rick Baldrige captured the launch of Aura (above). Against the stars the long trail of the Delta II rocket is seen lofting NASA's Aura spacecraft into Earth orbit from a vantage point about 321 km (200 miles) north of the Vandenberg Air Force Base. The trail represents the first five minutes of the rocket's powered flight with the ignition of additional solid fuel strap-on motors visible after liftoff, near the beginning of the track. The rocket trail curves downward as the rocket heads over the horizon. The trail ends at first stage shutdown. On the facing page is a photo of the Aura rocket seconds after ignition. Aura (right) attached to the gantry before launch. The satellite sits inside the white fairing atop the rocket.**

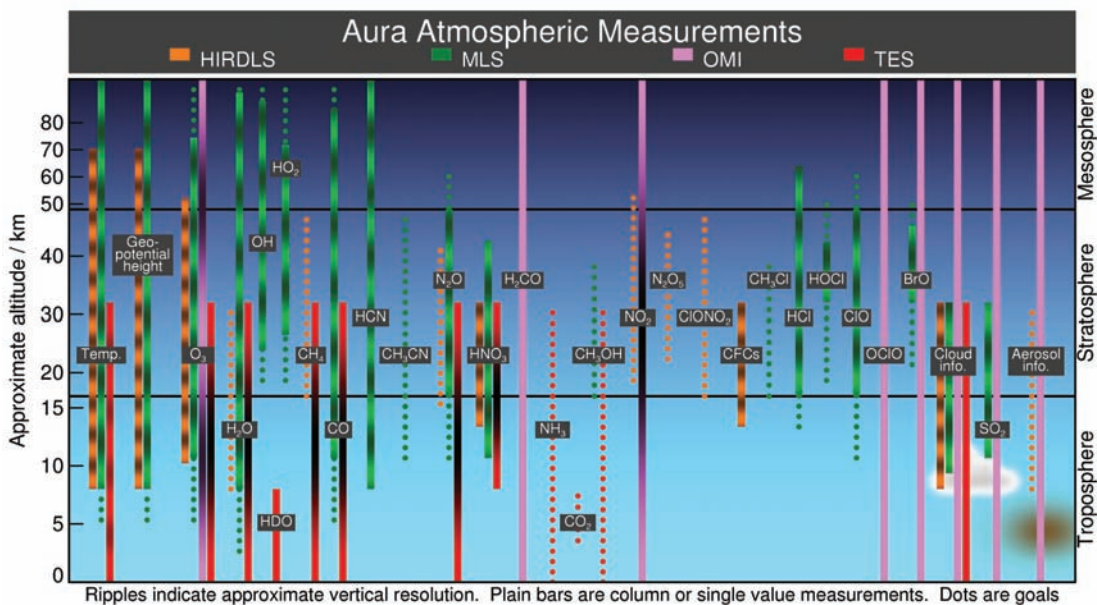
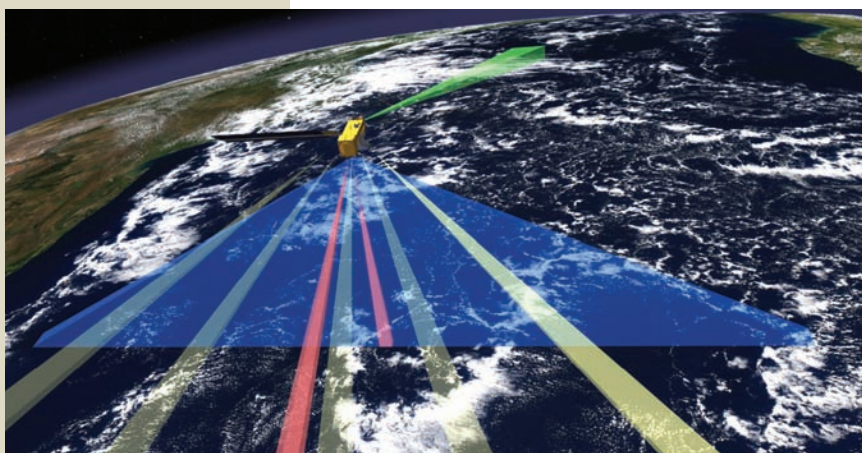


## How Does Aura Work?

**A**ura's instruments measure trace gases in the atmosphere by detecting their unique spectral signatures. MLS observes the faint microwave emissions from rotating and vibrating molecules. HIRDLS and TES observe the infrared thermal emissions also due to molecular vibrations and rotations. OMI detects the molecular absorption of backscattered sunlight in the visible and ultraviolet wavelengths.

Aura's remote sensing geometry is shown on the left. Horizon viewing (limb) instruments (MLS, TES and HIRDLS) slice through the atmosphere, profiling gases. Down-looking instruments (OMI and TES) stare at the Earth. Since MLS looks out the front of the spacecraft, it is the first to profile the atmosphere. The OMI and TES instruments then look at the same air mass as it passes beneath the spacecraft. As the spacecraft then moves on in its orbit, HIRDLS and TES profile the atmosphere again.

This unique observing geometry allows the Aura instruments to combine their measurements to get a better picture of the atmospheric chemistry. The chart below shows all the chemicals measured by Aura instruments and the altitude range of those measurements.



## A-Train Ground System

Data taken by the satellite instruments are stored on board until broadcast to a downlink facility through the spacecraft's high speed data link. Because polar orbiting satellites frequently pass over the Arctic and Antarctic, the data downlink facilities are located at high latitudes. NASA's major downlink facilities are Poker Flat, Alaska, McMurdo Base, Antarctica and Svalbard, a Norwegian archipelago in the Arctic Ocean north of mainland Europe. The Svalbard downlink antenna domes are shown below. Once the data are received at the downlink facility, they are sent via optical fiber network to processing facilities at NASA's Goddard Space Flight Center. The raw data are then distributed to the instrument teams for processing into geophysical measurements. Processed data are sent to NASA Data Active Archive Centers, where they are made available to users.

The Aura satellite also has direct broadcast capability through a smaller downlink anten-

na. This capability allows an investigator to receive data nearly instantly. The small building with the dome (on the upper right) is the Finnish direct broadcast station that receives OMI data as the satellite passes overhead. The direct broadcast data are processed at the Finnish Meteorological Institute FMI and distributed shortly after the Aura overpass.

### Where To Find Aura Data

Aura data are delivered to users through the NASA Data and Information Services Center (DISC).

For HIRDLS, MLS and OMI, the data are held at the Goddard Earth Science DISC (<http://daac.gsfc.nasa.gov/>). Data can also be accessed through the Giovanni system (<http://disc.sci.gsfc.nasa.gov/giovanni/>)

For TES, the data are held at the NASA Langley Atmospheric Sciences Data Center (<http://eosweb.larc.nasa.gov/>). The Aura instrument validation data are held at the Aura Validation Data Center at Goddard Space Flight Center (<http://avdc.gsfc.nasa.gov/Overview/>)

Aura data users should download the data user guides available at the instrument web sites, and should contact the science teams for additional questions about the data.



The Finnish Meteorological Institute (FMI) hosts a Direct Broadcast receiving station in Sodankylä, Finland, 120 km (75 miles) north of the Arctic Circle.



ANGIE KELLY, NASA

NASA's downlink facility at Svalbard, Norway located at 78° north latitude. This is an ideal site for receiving data from polar orbiting satellites like Aura, because these satellites pass within range of the station on almost every orbit.



NASA operates a highly modified McDonnell Douglas DC-8 jetliner as an airborne science laboratory. This aircraft has been used in several Aura validation campaigns.

**Validation**

Using validation data, researchers adjust their algorithms and can detect subtle instrument problems.

**Validating Aura Measurements**

How do scientists know if the measurements made from a satellite orbiting 705 km (438 miles) above the atmosphere are correct? Showing that the data are credible is called “validation.” To validate Aura data, the instrument teams compare their measurements with other satellite-, aircraft-, balloon-, and ground-based measurements.

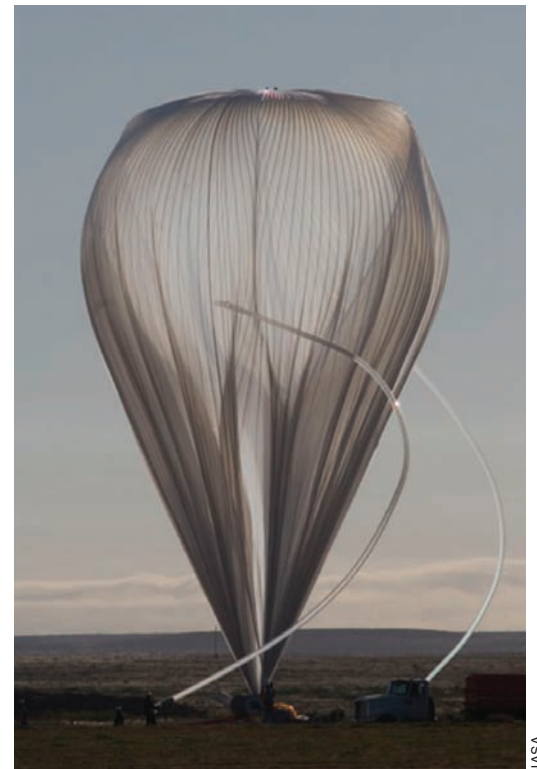
To date, the validation effort has included a series of aircraft missions and balloon launches. Validation continues throughout the life of a satellite mission because instruments can change in subtle ways while in orbit.

In its initial phase, measurement validation is simply a one-to-one comparison of Aura data with the validating data. Frequently, these validating data are obtained in a campaign environment featuring observations from aircraft or the launch of specially instrumented balloons. As time passes, the validation teams begin to build up long-term data sets. Statistical methods are used to uncover subtle differences between the Aura and validating data. The long-term data are often obtained at ground-based sites that make nearly continuous measurements during every satellite overpass.

CAMPAIGN	LOCATION	DATE	AIRCRAFT
AVE Houston	Houston, TX	Oct – Nov, 2004	WB-57
Polar AVE	Portsmouth, NH	Jan – Feb, 2005	DC-8
Costa Rica AVE	San Jose, Costa Rica	Jan – Feb, 2006	WB-57
INTEX-B	Western US, Hawaii, Alaska	Mar – May, 2006	DC-8
TC4	San Jose, Costa Rica	July – Aug, 2007	DC-8, ER-2, W-B57
ARCTAS	Canada, Alaska, Greenland	May – July, 2008	DC-8

Aircraft field campaigns in support of Aura validation. The table shows the type of aircraft used and dates of the campaign.

Balloon launch at the NASA Columbia Scientific Ballooning Facility in Ft. Sumner, New Mexico



NASA

## Aircraft Campaigns

NASA's fleet of specially equipped, high performance aircraft have been invaluable in gathering validation data for Aura. Measurements from aircraft are used to validate satellite observations over a broad range of latitudes and altitudes. Aircraft measurements are obtained in campaigns that are designed to combine validation activities with investigations of other atmospheric processes. NASA used several different aircraft for these campaigns. The aircraft observations not only help to validate the satellite data, but also provide complementary information that can be used in scientific investigations.



The WB-57 (above) and ER-2 (below) are high altitude aircraft, capable of flying into the lower stratosphere with a full payload of autonomously operated instruments.



A typical DC-8 instrument setup where a scientist flies along with his or her instrument. Air sample tubes are mounted on the wings and in windows. MLS team member Michelle Santee talks with instrument scientist Armin Kleinböhl during a DC-8 flight.



Aura will be the first satellite to use an Unpiloted Aerial Vehicle (UAV), the Global Hawk, for validation in the summer, 2010. The Global Hawk is shown above with mission lead Paul Newman.

## Balloon and Ground-Based Validation

**H**igh altitude balloons with instrumented payloads are used to validate stratospheric measurements above the reach of the highest flying aircraft. The instruments that can make the needed measurements are massive, and launching the balloons that can carry these instruments requires special facilities. There have been two Aura validation high altitude balloon launches during winter from a launch facility in northern Sweden and three launches during spring in the southwest United States. These large payloads are usually recovered.

Small balloons (balloon sondes, of the type shown on the opposite page) are launched by hand, often at sites where ground-based instruments are located or where aircraft campaigns are based. Balloon sondes provide high vertical resolution measurements up to the lower stratosphere. Small balloon instruments are limited to measurements of ozone, water vapor, temperature, and aerosols. The payloads are disposable.

Ground-based remote sensing instruments are also used for validation of satellite data. Many ground sensors are part of an international network called the Network for Detection of Atmospheric Composition Change. Ground-based instruments include lidars for profiles of ozone, aerosols, temperature, and water vapor as well as microwave radiometers, UV/Visible spectrometers, and infrared spectrometers for other trace gases. The ground-based measurements are often accompanied by balloon sonde launches for obtaining ozone, aerosols, and water vapor profile measurements. Observations most useful for validation are made when the satellite is nearly overhead. Simultaneous measurements of the same constituent using different instruments are useful in sorting out differences between the ground-based measurements and satellite measurements. This approach builds confidence in the satellite data set.



High altitude balloons can carry large payloads with complex instruments deep into the stratosphere. These balloons are launched using special equipment only once or twice a year.



The Mauna Loa observatory in Hawaii (above) has played an important role in validating Aura measurements. R. Michael Gomez (left) makes microwave water vapor measurements.



HOLGER VOMEL, UNIVERSITY OF COLORADO, BOULDER

A 1200-g latex balloon is launched from Alajuela, Costa Rica carrying the University of Colorado Cryogenic Frostpoint Hygrometer (CFH) and an Electrochemical Cell (ECC) ozonesonde. It will ascend to 30 km (19 miles), providing high-accuracy, high-resolution vertical profiles of water vapor, ozone and temperature for Aura validation.



CHUCK BARDEEN, UNIVERSITY OF COLORADO, BOULDER

Dr. Henry Selkirk and students from the Universidad de Costa Rica (UCR) steady the CFH/ECC balloon while it is filled during the Tico-sonde campaign.



The Table Mountain facility, located about 1.5 hours from the main JPL lab in Pasadena, CA houses the Fourier Transform Ultraviolet Spectrometer (FTUVS) that has been used to validate Aura data. An intercomparison of several ground-based instruments measuring NO<sub>2</sub> was also conducted there.



CHUCK BARDEEN

Karla Cerna, a student of the Universidad Nacional (UNA) in Heredia, Costa Rica, explains the preparation of the CFH/ECC sonde to former Aura project scientist Mark Schoeberl.



RICHARD MCPETERS



The SAUNA campaigns took place in Sodankyla, Finland in spring 2006 and 2007. The main purpose was to verify the accuracy of several different types of ground-based ozone measurements for satellite validation in challenging high latitude conditions.



This red oak leaf exhibits signs of ozone damage. When exposed to high concentrations of ozone over time, such plants develop characteristic tiny, evenly spaced dots known as “stippling” and also yellowing on the upper surfaces of their leaves. The stippling does not affect the underside of the leaf or the leaf veins. Eventually leaves that accumulate enough ozone damage die and fall off. Observations of ozone-sensitive plants over the course of the growing season can yield valuable information about local ozone concentrations.

## Outreach E&PO

The Aura Education and Public Outreach (E&PO) team has developed a portfolio of products geared toward formal and informal education venues using Aura data that has been distilled and distributed in various formats.

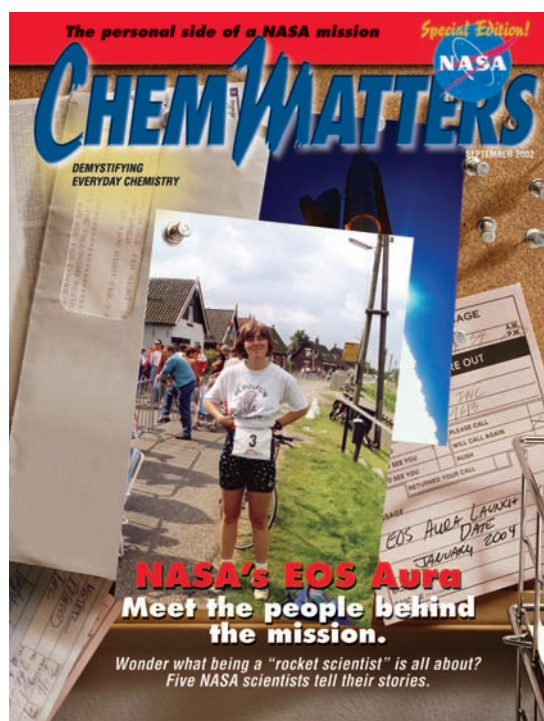
### Formal education

Air quality science and Aura data have been the focus for the formal education activities. Lessons have been developed that study connections between energy production and air quality (see right panel of p. 55 for example). All of the lessons that have used Aura data have been published in an electronic format and can be found at MY NASA DATA (<http://mynasadata.larc.nasa.gov/>) and Earth Exploration Toolbook (<http://serc.carleton.edu/eet/>).

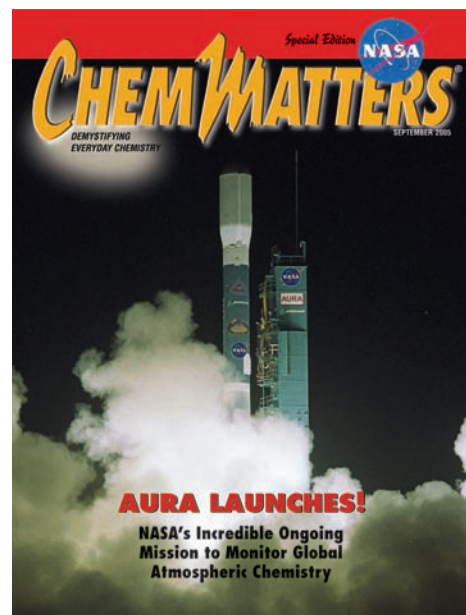
In a partnership with the Howard B. Owens Science Center in Prince George’s County, MD and Goddard’s Science On a Sphere facility, more than 1,000 students from the local area have gained a global perspective on air quality and ozone depletion. Aura scientists also participate in the Netherlands Global Learning and Observations to Benefit the Environment (GLOBE) program.

### Informal Education and Outreach

The Aura team has developed a unique approach to engaging and educating the public. In cooperation with the Smithsonian’s National Museum of Natural History, the Aura E&PO team developed an exhibit called “Change is in the Air,” displayed in 2006. The exhibit covered many features of the atmosphere that Aura is now exploring,



Covers of ChemMatters: one with Pieter Levelt, the Principal Investigator of the Ozone Monitoring Instrument, and the other of the launch.





such as the ozone hole, transport, air quality, and the atmosphere's evolution. A web site was developed capturing the features of the exhibit, which can be found at: [http://forces.si.edu/atmosphere/02\\_03\\_00.html](http://forces.si.edu/atmosphere/02_03_00.html)

Aura scientists also provide near-real-time images of Aura data for informal education settings such as museums and science centers. These images, including NO<sub>2</sub>, column ozone, tropospheric ozone residual, and aerosols, are provided to Science On a Sphere at the Goddard Space Flight Center Visitor Center and will be extended to other projection systems such as Dynamic Planet and portable planetarium domes. Aura also sponsors the "Ozone Monitoring Garden" at the Goddard Visitor Center. The Ozone

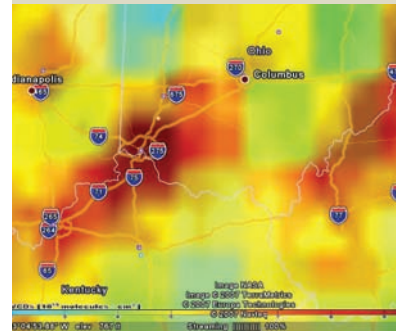
Monitoring Garden demonstrates how poor air quality can affect varieties of plants.

The Aura web site (<http://aura.gsfc.nasa.gov/>) provides the latest Aura news. The Aura team also works with the Earth Observatory to generate "Images of the Day," and the Outreach Team generated a variety of short movie clips showing the Aura orbit and instrument systems that are available through the web site.

**Aura's OMI nitrogen dioxide data are shown being projected onto the Science On a Sphere at the Goddard Visitor Center.**



**Cutleaf coneflower from the Aura Ozone Monitoring Garden exhibits a large amount of damage from exposure to ground-level ozone.**



**Data used in K-12 lessons in Google Earth to show connections between energy production and NO<sub>2</sub> concentrations.**



**Rudbeckia hirta, or black-eyed susans, are one of many species of plants that can be sensitive to ground-level ozone.**



## Acknowledgments and Credits

### Project Science Office

A. R. Douglass, J. Joiner,  
B. N. Duncan

### Past Project Scientists

M. R. Schoeberl, P. K. Bhartia,  
J. F. Gleason

### Program Scientist

K. W. Jucks

### Past Program Scientists

E. Hilsenrath, P. L. DeCola,  
R. J. McNeal

### Principal Investigators

#### HIRDLS

US Co-PI J. C. Gille  
US deputy B. Nardi

UK Co-PI J. J. Barnett  
UK deputy D. Andrews

### MLS

PI N. J. Livesey  
Deputy PI L. Froidevaux  
Past PI J. W. Waters

### OMI

Dutch PI P. F. Levelt  
Dutch Deputy PI P. Veefkind

Finnish PI J. Tamminen  
Finnish Past PI G. Leppelmeier

US team leader P. K. Bhartia

### TES

PI A. Eldering  
Deputy PI J. R. Worden  
Past PI R. Beer

### Brochure Team

**Authors:** M. R. Schoeberl, A. R. Douglass, J. Joiner, B. N. Duncan with contributions from the science teams

**Past Outreach Liaisons:** B. C. Hsu, H. Weir, L. Bleacher

**Outreach Liaison:** L. A. Layton

**Designer:** Ellen Baker Smyth, Elle Designs

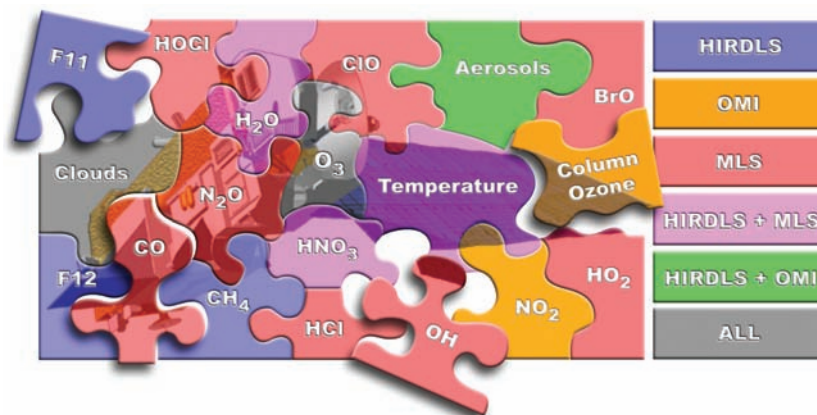
**Diagrams:** Barbara Schoeberl

We wish to acknowledge many contributions from Aura science team members, including figures and text. Without these willing contributors, this brochure would not have been possible.



**Aura Team** (L-R) R. Beer, J. Gille, P. Levelt, E. Hilsenrath, A. Douglass, M. Schoeberl, J. Waters, P. K. Bhartia, P. DeCola

## Completing the Picture of Stratospheric Chemistry



Understanding the ozone layer involves measurements of ozone and the compounds that control production and loss of ozone. The instruments on Aura provide pieces of the puzzle.

## Chemicals

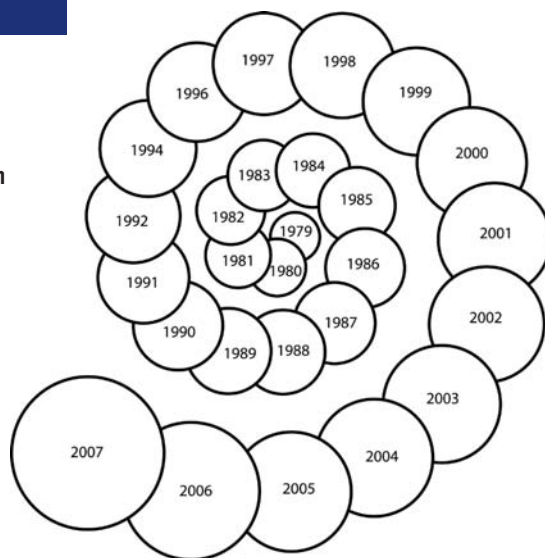
BrO	Bromine monoxide	ClONO <sub>2</sub>	Chlorine nitrate	HFI	Hydrofluoric acid	O	Atomic Oxygen
CF <sub>2</sub> Cl <sub>2</sub>	Dichlorodifluoromethane	CO	Carbon monoxide	HNO <sub>3</sub>	Nitric acid	O <sub>2</sub>	Oxygen
CFCI <sub>3</sub>	Trichlorofluoromethane	CO <sub>2</sub>	Carbon dioxide	HO <sub>2</sub>	Hydroperoxy radical	O <sub>3</sub>	Ozone
CH <sub>3</sub> CN	Methyl cyanide	H <sub>2</sub> S	Hydrogen sulfide	HOCl	Hypochlorous acid	O <sup>1</sup> D	Excited state of atomic oxygen
CH <sub>3</sub> OH	Methanol	H <sub>2</sub> O	Water	NH <sub>3</sub>	Ammonia	OCIO	Chlorine dioxide
CH <sub>4</sub>	Methane	HCl	Hydrogen chloride	N <sub>2</sub> O	Nitrous oxide	OH	Hydroxyl radical
CHOCHO	Glyoxal	HCHO	Formaldehyde	N <sub>2</sub> O <sub>5</sub>	Dinitrogen pentoxide	SO <sub>2</sub>	Sulfur dioxide
Cl	Chlorine	HCN	Hydrogen Cyanide	NO	Nitric oxide		
ClO	Chlorine monoxide	HDO	Hydrogen Deuterium Oxide (heavy isotope of H <sub>2</sub> O)	NO <sub>2</sub>	Nitrogen dioxide		
Cl <sub>2</sub> O <sub>2</sub>	Chlorine monoxide dimer			NO <sub>x</sub>	Nitrogen oxides		

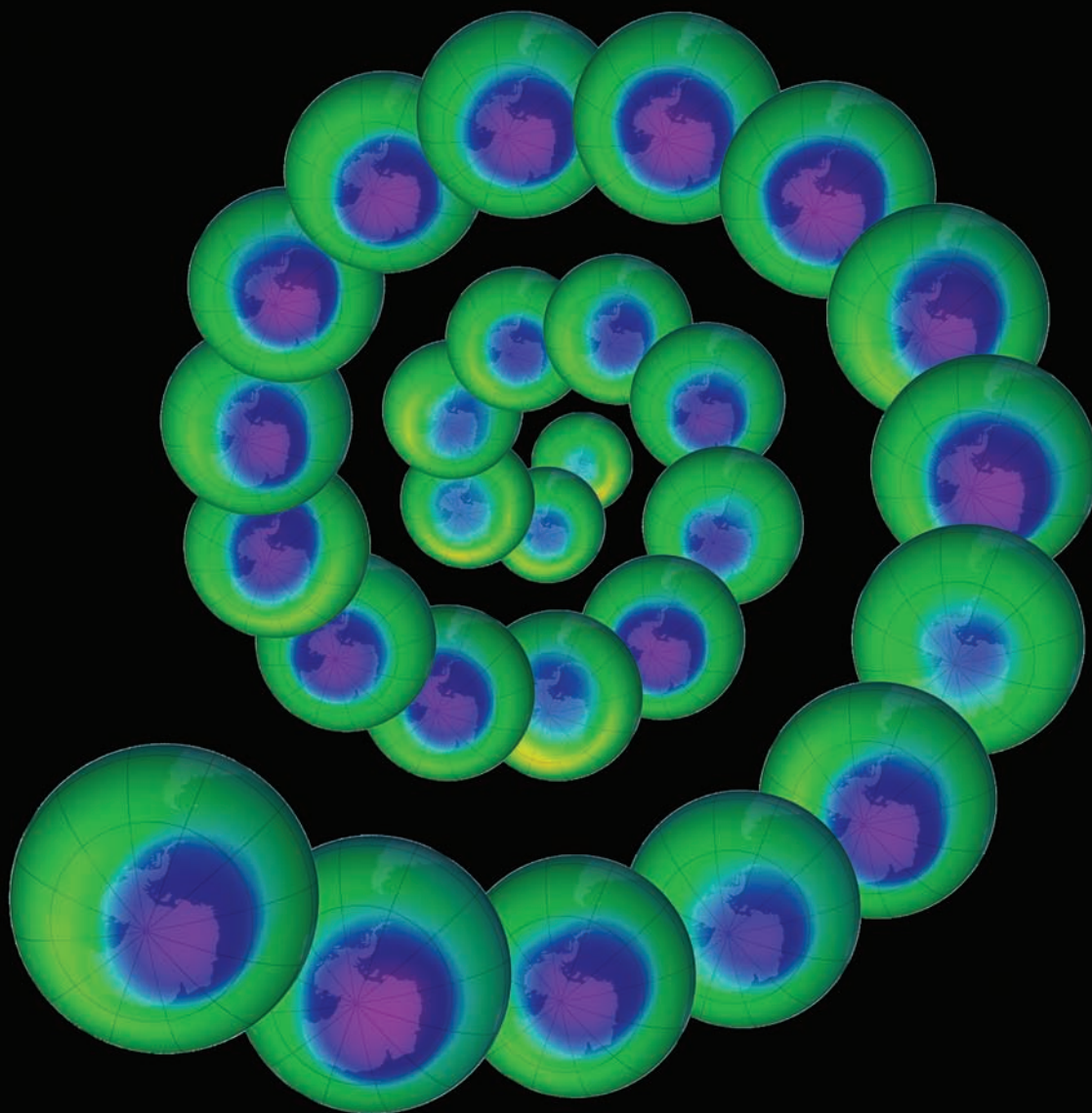
## Acronyms

AFB	Air Force Base	NCAR	National Center for Atmospheric Research	TES	Tropospheric Emission Spectrometer (One of the four Aura instruments)
AIRS	Atmospheric Infrared Sounder	NIVR	Netherlands Agency for Aerospace Programs	THz	Terahertz
BAS	British Antarctic Survey	NL	Netherlands	TNO-TPD	Netherlands Organization for Applied Scientific Research - Institute of Applied Physics
BUV	Backscatter Ultraviolet Instrument	OMI	Ozone Monitoring Instrument (One of the four Aura instruments)	TOMS	Total Ozone Mapping Spectrometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite	PARASOL	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar	TOR	Tropospheric Ozone Residual
CCD	Charge Coupled Device	PI	Principle Investigator	TRMM	Tropical Rainfall Measuring Mission
CFC	Chlorofluorocarbon	PMC	Polar Mesospheric Clouds	UARS	Upper Atmosphere Research Satellite
CFH	Cryogenic Frostpoint Hygrometer	ppbv	Parts per billion volume	UAV	Uninhabited Aerial Vehicle
DAAC	Distributed Active Archive Center	ppmv	Parts per million volume	UCAR	University Corporation for Atmospheric Research
DISC	Data and Information Services Center	PSC	Polar Stratospheric Clouds	UCR	Universidad de Costa Rica
DU	Dobson Unit	SAUNA	Sodankyla Total Column Ozone Intercomparison	UK	United Kingdom
E&PO	Education and Public Outreach	SBUV	Solar Backscatter Ultraviolet	UMBC	University of Maryland Baltimore County
ECC	Electrochemical Cell	SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography	UT	Upper Troposphere
EOS	Earth Observing System	SFF	Space Frontier Foundation	UV	Ultraviolet
ESA	European Space Agency	SOHO	Solar and Heliospheric Observatory	US	United States
FI	Finland	SOS	Science on a Sphere	VOC	Volatile Organic Compound
FMI	Finnish Meteorological Institute	SSAI	Science Systems & Applications, Inc.	VTT	Technical Research Centre of Finland
FTIR	Fourier Transform Infrared Spectroscopy				
FTUVS	Fourier Transform Ultraviolet Spectrometer				
GHz	Gigahertz				
GLOBE	Global Learning and Observations to Benefit the Environment				
GSFC	Goddard Space Flight Center				
HALOE	Halogen Occultation Experiment, instrument on UARS satellite				
HIRDLS	High Resolution Dynamics Limb Sounder (One of the four Aura instruments)				
IWC	Ice Water Content				
IR	Infrared				
JPL	Jet Propulsion Laboratory				
KNMI	Royal Dutch Meteorological Institute				
MLS	Microwave Limb Sounder (One of the four Aura instruments)				
MODIS	Moderate-resolution Imaging Spectroradiometer				
MOPITT	Measurements of Pollution in the Troposphere				
MYNASADATA	Mentoring and inquiry using NASA Data for Atmospheric and earth science for Teachers and Amateurs				
NASA	National Aeronautics and Space Administration				

## Ozone Hole

The ozone hole has been observed by NASA instruments since 1979. The years on this diagram match color images on the back cover.





**The October Antarctic total column ozone from 1979 to 2007  
as measured by TOMS instruments and Aura's OMI. See inside  
back cover to match color images with year.**

**National Aeronautics and Space Administration**

Earth Observing System Aura  
Goddard Space Flight Center  
Greenbelt, MD 20771

[www.nasa.gov](http://www.nasa.gov)

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