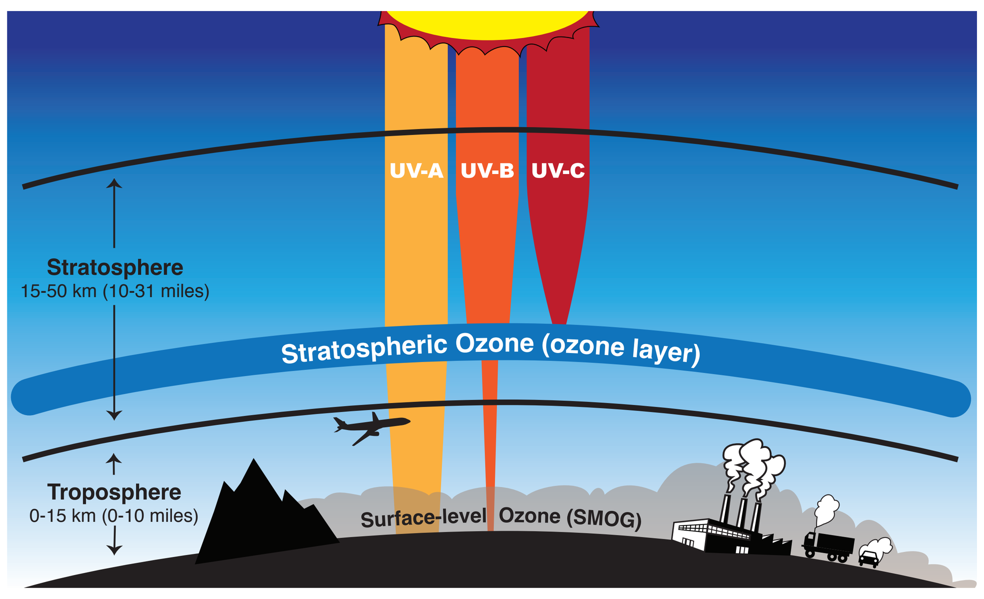
# What is Ozone?

Ozone ($O_3$) is a molecule made up of three atoms of oxygen (O), and is mostly found in the stratosphere, where it protects us from the Sun's harmful ultraviolet (UV) radiation. Although it represents only a tiny fraction of the atmosphere, ozone is crucial for life on Earth.

Ozone in the stratosphere—a layer of the atmosphere between 15 and 50 kilometers (10 and 31 miles) above us—acts as a shield to protect Earth's surface from the sun's harmful ultraviolet radiation. Without ozone, the Sun's intense UV radiation would sterilize the Earth's surface. With a weakening of this shield, more intense UV-B and UV-A radiation exposure at the surface would lead to quicker sunburns, skin cancer, and even reduced crop yields in plants.

However, near the surface where we live and breathe, ozone is a harmful pollutant that causes damage to lung tissue and plants. This "bad" ozone forms when sunlight initiates chemical reactions in the air involving pollutants, particularly a family of gases called nitrogen oxides (released from vehicles and industry during the combustion process) and with volatile organic compounds (carbon-containing chemicals that evaporate easily into the air, such as petroleum products).

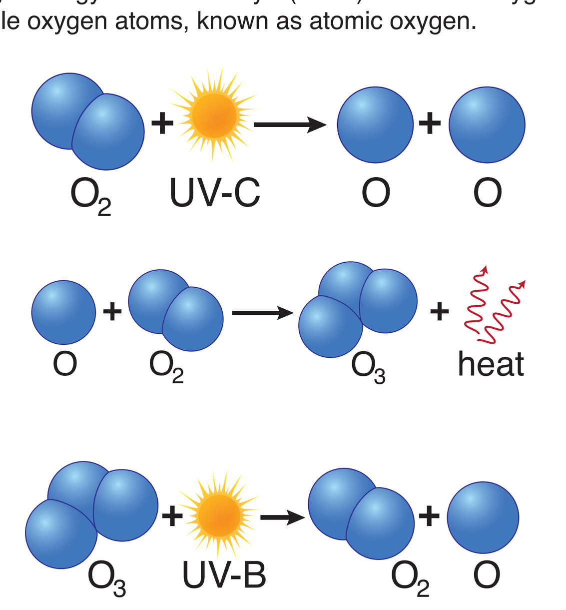



*Ozone is good in the stratosphere because it absorbs all of the most energetic ultraviolet radiation (UV-C), most of the UV-B radiation and some of the least energetic UV radiation (UV-A). Ozone is "bad" in the troposphere because it is harmful to breathe and is the primary component of smog in summer.*

# Chemistry of the Ozone Layer

There are natural processes that create and destroy ozone in the stratosphere. These processes regulate a balance of ozone and form the ozone layer.

Ozone is created primarily by sunlight. When high-energy ultraviolet rays (UV-C) strike an oxygen molecule ($O_2$), they split the molecule into two single oxygen atoms, known as atomic oxygen.



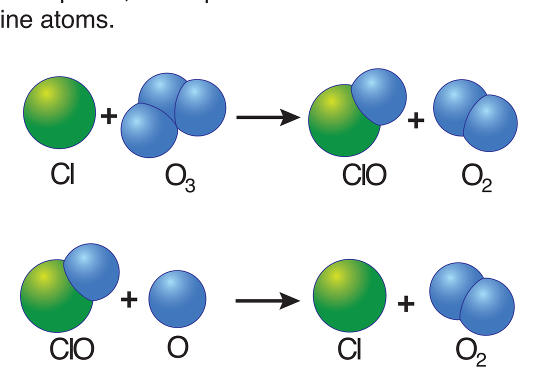

A freed oxygen atom then combines with another oxygen molecule to form a molecule of ozone ($O_3$). Because there is so much oxygen in our atmosphere, this "ozone-oxygen cycle" is continuously absorbing high-energy ultraviolet radiation (UV-C) and completely blocking it from reaching the Earth's surface. This process creates heat which warms the upper part of the stratosphere

Ozone is very reactive, and attacks other molecules in the air, often regenerating oxygen in the process. Also—and this is why ozone is important to us—ozone in the stratosphere absorbs much of the sun's UV-B rays, splitting back into molecular and atomic oxygen. No matter how the oxygen atoms are produced, they almost always quickly react with oxygen molecules, reforming ozone. So, while ozone is continually being replenished, it is also continually being destroyed. Sometimes an ozone molecule reacts with an oxygen atom, creating two oxygen molecules, thus ending the cycle. If the rate of ozone creation is equal to the rate of destruction, the total amount will remain the same. This is like a leaky bucket: If you pour water into the bucket at the same rate that it's leaking out, the level of water in the bucket will stay the same.

Scientists have found that ozone levels change periodically with regular natural cycles such as the changing seasons, winds, and long time scale sun variations. Ozone also responds to some sporadic solar events such as flares. Moreover, volcanic eruptions may inject materials into the stratosphere that can lead to increased destruction of ozone.

In the 1970's, scientists suspected that reactions involving man-made chlorine-containing compounds could upset this balance leading to lower levels of ozone in the stratosphere. Think again of the "leaky bucket." Putting additional ozone-destroying compounds into the atmosphere is like increasing the size of the holes in our "bucket" of ozone. The larger holes cause ozone to leak out at a faster rate than ozone is being created. Consequently, the level of ozone protecting us from ultraviolet radiation decreases. The ozone destroyed by manmade emissions is comparable or more than the amount destroyed by natural processes.

Human production of chlorine-containing chemicals, such as chlorofluorocarbons (CFCs), has added an additional factor that destroys ozone. CFCs are molecules made up of chlorine, fluorine and carbon. Because they are extremely stable molecules, CFCs do not react with other chemicals in the lower atmosphere, but exposure to ultraviolet radiation in the stratosphere breaks them apart, releasing chlorine atoms.

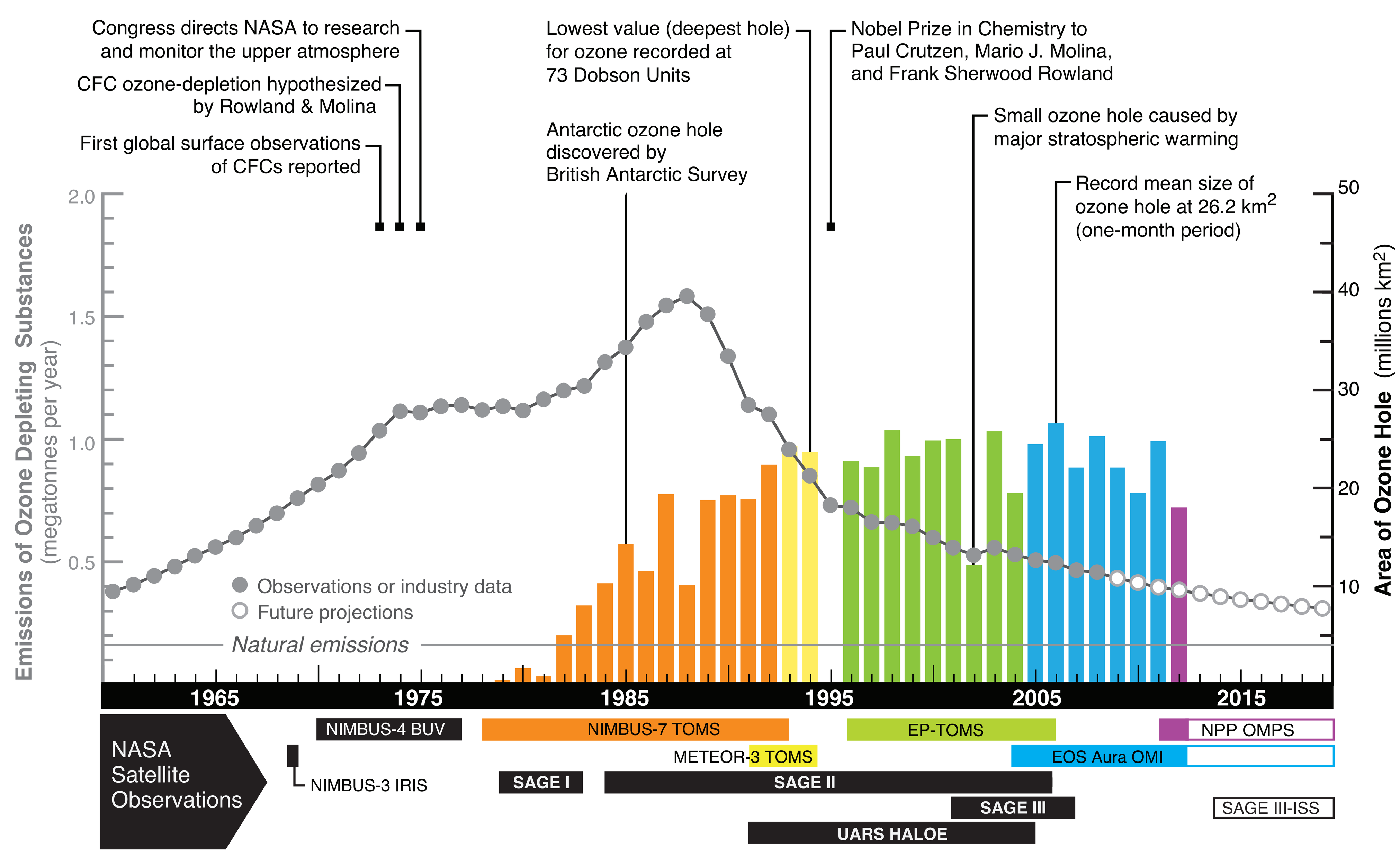



Free chlorine (Cl) atoms then react with ozone molecules, taking one oxygen atom to form chlorine monoxide (ClO) and leaving an oxygen molecule ($O_2$).

If each chlorine atom released from a CFC molecule destroyed only one ozone molecule, CFCs would pose very little threat to the ozone layer. However, when a chlorine monoxide molecule encounters a free atom of oxygen, the oxygen atom breaks up the chlorine monoxide, stealing the oxygen atom and releasing the chlorine atom back into the stratosphere to destroy another ozone molecule. These two reactions happen over and over again, so that a single atom of chlorine, acting as a catalyst, destroys many molecules (about 100,000) of ozone.

Fortunately, chlorine atoms do not remain in the stratosphere forever. Free chlorine atoms react with gases, such as methane ($CH_4$), and get bound up into hydrogen chloride (HCl) molecules. These molecules eventually end up back in the troposphere where they are washed away by rain. Therefore, if humans stop putting CFCs and other ozone-destroying chemicals into the stratosphere, stratospheric ozone will eventually return to its earlier, higher values.

# Timeline of Stratospheric Ozone Depletion and Observations




This timeline highlights the average area of the ozone hole between September 7th and October 13th as observed by NASA spaced-based instruments (see colored bars and scale on right), and the emissions rates of human-produced ozone-depleting substances (ODSs) combined with natural emissions of halogen source gases (grey, see scale on left). The Montreal Protocol and it's amendments, which allowed regulators to limit the amount of ODSs released, had a major impact on the emissions, as seen by their timing indicated by the red squares. In the meantime, the ODS burden (ODS remaining in the stratosphere) is decreasing slowly because of the long lifetimes of ODS in the atmosphere. Ozone recovery, in turn, will further lag the ODS decrease and likely occur in the 2050-2060 time frame.

In 1975, the United States Congress recognized the importance of understanding such atmospheric phenomena and directed NASA to research and monitor the upper atmosphere in order to better understand the chemical and physical integrity of the Earth's upper atmosphere. Daily space-based observations of global stratospheric ozone levels–particularly over Antarctica—started in 1978 with the Total Ozone Mapper (TOMS). The TOMS instruments on board multiple platforms provided observations of the ozone hole for nearly 29 years, with the exception of 1995 after the TOMS instrument on METEOR-3 stopped sending data in December of 1994. The historical record of ozone depletion provided by NASA instruments shows the slowing of this depletion after emissions of ODSs were reduced.

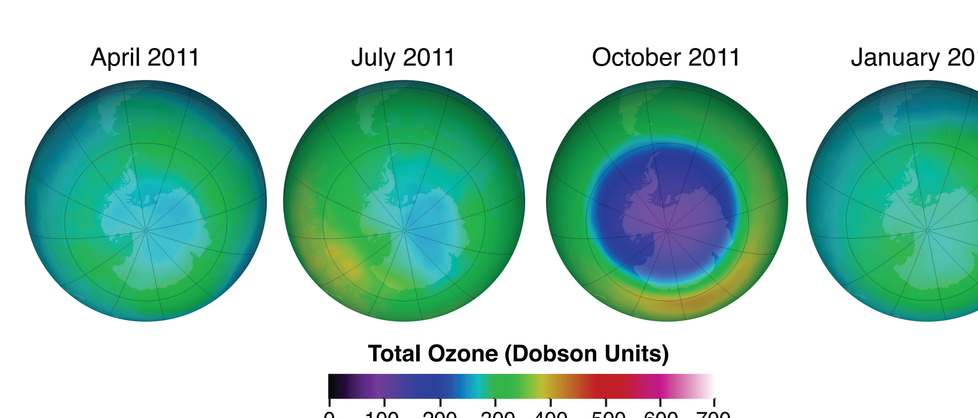
The Vienna Convention was agreed to in 1985, and called out ODSs as an ozone threat. Faced with the strong possibility that ODSs—gases containing halogens such as CFCs—could cause serious ozone depletion, policy makers from around the world signed the Montreal Protocol treaty in 1987, limiting CFC production and usage. As a result of the Montreal Protocol and its subsequent Amendments and Adjustments, ODS emissions decreased substantially between 1990 and the present.

# How the Ozone Hole forms

The Ozone Hole is not really a "hole" but a thinning of the ozone layer over the south polar region. Every year, since at least 1978, there is a sudden, rapid decrease in the stratospheric ozone levels at the end of the Antarctic winter.

During the long winter months of darkness over the Antarctic, atmospheric temperatures drop, creating unique conditions for chemical reactions that are not found anywhere else in the atmosphere. The wind in the stratosphere over the polar region intensifies and forms a polar vortex, which circulates around the pole. The transition from inside to outside the polar vortex creates a wind barrier that isolates the air inside the vortex and also results in very cold temperatures.

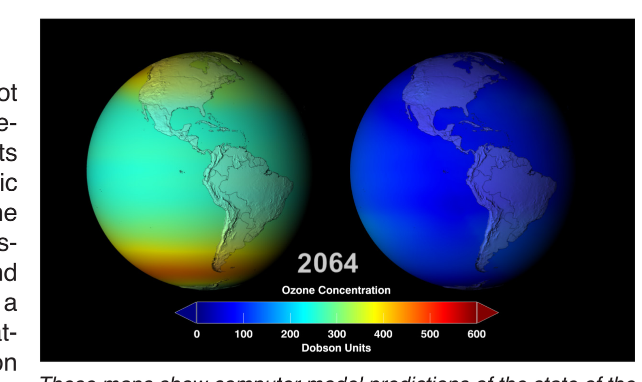
At temperatures below -78°C, thin clouds made of mixtures of ice, nitric acid, and sulfuric acid form in the stratosphere. Chemical reactions on the surfaces of these ice crystals convert chlorine-containing compounds like HCl, which is harmless to ozone, into more reactive forms. When the sun rises over the Antarctic in the Spring (September), light rapidly releases free chlorine atoms into the stratosphere. A new ozone destroying cycle begins. The chlorine atoms react with ozone, creating ClO. The ClO molecules combine with each other, forming a compound called a dimer. Sunlight releases chlorine atoms from the dimer, and the cycle begins again. The polar vortex keeps the ozone-depleted air inside from mixing with the undepleted air outside the vortex.




*Southern Hemisphere ozone concentration for four months, representing the four seasons, as measured by the OMI instrument on the Aura satellite. The feature of very low ozone concentrations over a very well-defined region over Antarctica and beyond in the Austral Spring is called the "Ozone Hole." (The Dobson Unit is the most commonly used unit for expressing ozone concentration. It's the amount of ozone that would make a 0.01 millimeter deep layer of pure ozone if it were all brought down to the Earth's surface. The ozone layer's average thickness is about 300 Dobson Units, or a surface layer 3 mm deep.)*

The ozone destruction continues within the polar vortex until the ozone levels approaches zero at the altitudes where reactions on the thin clouds have released chlorine atoms. Once ozone has reached such a low level, the chlorine atoms react with methane, filling the vortex with HCl. The low ozone persists until the vortex weakens and breaks apart. Then the ozone levels in the polar stratosphere begin to return to pre-September levels due to the increase in solar UV and the mixing of polar and nonpolar air.

# A World Avoided



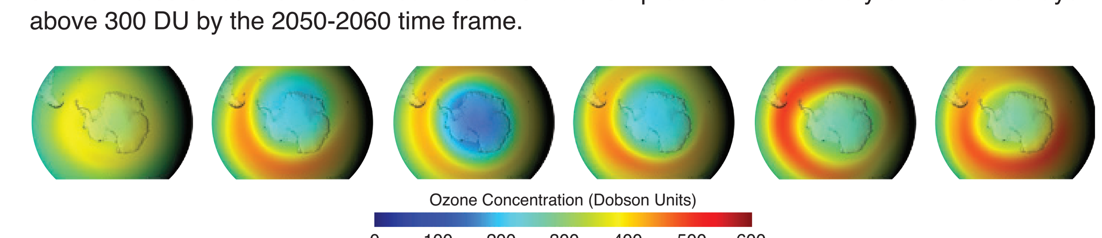

*These maps show computer model predictions of the state of the ozone layer in 2064 with (above left) and without (above right) the effects of international agreements to curb ozone-destroying chemicals in the 1980s and 90s. (NASA images by the GSFC Scientific Visualization Studio.)*

What if the countries of the world had not agreed to phase out production of ozone-depleting substances? Were scientists right about predictions of catastrophic ozone loss, which led to the signing of the Montreal Protocol? To answer these questions, atmospheric scientists at NASA and other research centers decided to create a model using computers to simulate the atmosphere with and without restrictions on ODSs.

In the "World Avoided" model, the emissions of CFCs and other ODSs were assumed to grow at a rate of 3% per year, about what they had been doing over the decade prior to the Montreal Protocol's regulations. Scientists used an earth system model that accounts for variations in solar energy, atmospheric chemical reactions, temperature changes and winds, and interactions between the stratosphere and troposphere, and let the calculations simulate the atmosphere from 1975 to 2065. Then, they repeated the simulation, this time using actual and forecast ODS emissions.

By the year 2020 in the "World Avoided" simulation, 17 percent of global ozone was destroyed, and an ozone hole formed each year over the Arctic as well as the Antarctic. By 2040, the ozone hole—ozone levels less than 220 Dobson Units—was global. The UV Index in mid-latitude cities reached 15 around noon on a clear summer day (10 is considered extreme today). By the end of the simulation in 2065, global ozone dropped to less than 110 DU, a 67 percent drop from the 1970s. Arctic ozone values remained between 50 DU and 100 DU the whole year around (down from 500 DU in 1960).

In the real world, emissions of ODSs ended in 1992. However, their abundance is only now beginning to decline because the chemicals stay in the atmosphere for 50 to 100 years. The peak abundance of CFCs in the atmosphere occurred around 2000, and has decreased by roughly 4 percent to date. Stratospheric ozone was depleted by 5 to 6 percent at middle latitudes, but has rebounded a little in recent years. The largest recorded Antarctic ozone hole was recorded in 2006, with slightly smaller holes since then. The "Real World" simulation predicts the recovery of the ozone layer to above 300 DU by the 2050-2060 time frame.

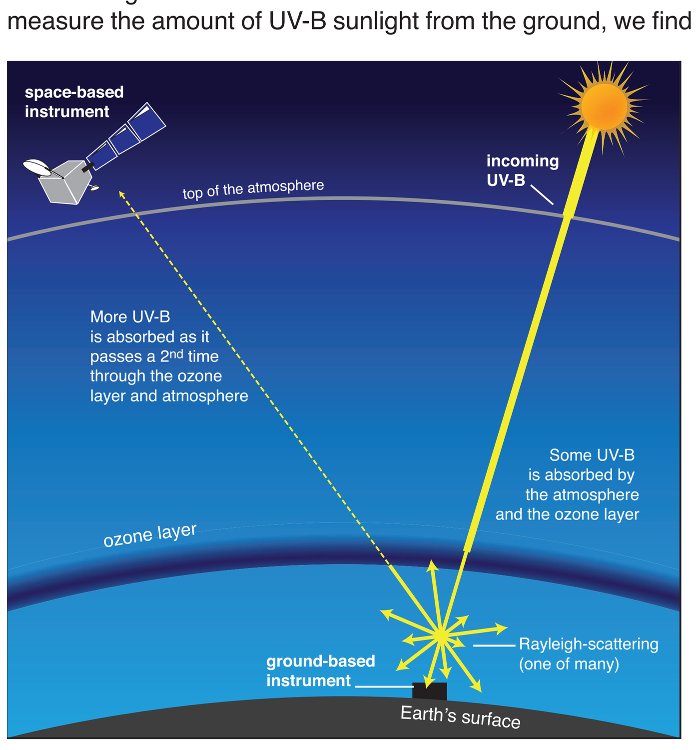



*The Antarctic ozone hole (blue areas), which first appeared in the early 1980s and peaked in the 2000s, is expected to shrink markedly by 2064. International agreements successfully mitigated the threat posed by CFCs and other ozone-destroying chemicals. (NASA images by the GSFC Scientific Visualization Studio.)*

# Measuring Ozone in the Earth's Atmosphere

Scientists have been measuring ozone since the 1920's using ground-based instruments that look skyward. Data from these instruments, although useful in learning about ozone, only tell us about the ozone above their sites, and do not provide a picture of global ozone concentrations. To get a global view of ozone concentrations and its distribution, scientists use data from satellites.

The principle of measuring ozone is simple. We know from measurements how much incoming UV-B sunlight arrives at the top of the Earth's atmosphere every second. We also know how much light (including UV-B) is scattered by air molecules in the atmosphere--this is called "Rayleigh scattering," and this is the same phenomenon that makes the sky appear blue. So we can calculate the amount of UV-B sunlight that would make it to the Earth's surface if there were no ozone to absorb it. When we measure the amount of UV-B sunlight from the ground, we find it is much less than what we calculated.




The difference is the amount of UV-B absorbed by ozone, and from that we can calculate the amount of ozone.

Measuring ozone from space is similar, but you have to know the amount of the solar UV-B light that is backscattered, or bouncing, off molecules in the atmosphere (Rayleigh scattering, again) in the direction of the satellite. This measurement technique is depicted in the figure on left. We can calculate how much UV-B light the space-based instrument would observe if there were no ozone. However, the amount of UV-B measured is much less because UV-B is passing through the atmosphere a second time. Again, from the amount of UV-B that's "missing," we can calculate the amount of ozone.

The longest satellite record of ozone data has been from instruments using this backscatter method. The first measurements were taken by the BUV instrument on Nimbus-4 satellite in 1970 followed by the Total Ozone Mapping Spectrometer (TOMS) instruments on the Nimbus-7, Earth Probe, and Meteor-3 satellites, several SBUVs on NOAA satellites, the Ozone Monitoring Instrument (OMI) onboard the EOS Aura satellite, and the Ozone Mapping and Profiler Suite (OMPS) on the Suomi NPP satellite. The Europeans also flew BUV-type instruments on their environmental satellites.

Another type of instrument uses occultation to measure ozone, such as the Stratospheric Aerosol and Gas Experiment (SAGE) instruments including the upcoming SAGE-III-ISS onboard the International Space Station, the Atmospheric Chemistry Experiment (ACE), and Halogen Occultation Experiment (HALOE) on the UARS satellite. Other techniques include measuring the radiation emitted from the atmosphere in the infrared and microwave wavelengths where ozone also absorbs and allows instruments to detect the radiation change.

In addition to the OMI instrument, the Aura satellite carried three other ozone-measuring instruments, the High Resolution Dynamics Limb Sounder (HIRDLS), the Tropospheric Emission Spectrometer (TES) using infrared emission, and the Microwave Limb Sounder (MLS). (Note: All these instruments measure several other atmospheric constituents in addition to ozone.)

# Visualizing the Ozone Hole

This activity will introduce students to the use of color maps to visualize data about stratospheric ozone. Scientists use colors and other representations for data to help interpret and visualize information. Data are mapped to colors and other representations to help the mind interpret this information. Sometimes this means creating an image that looks much like an aerial photo of the planet's surface, but other data are best mapped to a color scale. In this lesson, students will discover that selecting a good color scale is both essential to understanding data and to accurately communicating science.

## Objectives

After completing this activity, students should be able to

- describe why color maps are used to visualize data
- interpret data using a color mapped image
- compare and evaluate different color scales

## Standards (Grades 9-12)

NGSS: Practice 4 Analyzing and Interpreting Data
AAAS: 12E/H2 Check graphs to see that they do not misrepresent results by using inappropriate scales.
AAAS: 11C/H4 Graphs and equations are useful ways for depicting and analyzing patterns of change.
NSES: Unifying Concepts and Processes Standard: Evidence, models, and explanation.
NSES: Content Standard E: Understandings about science and technology

## Engage

Ask questions about the front of the poster. When was the ozone hole the smallest? (1979) When did the ozone hole grow the fastest? (1981–1985, pattern of growth, no shrinking) What year had the largest ozone hole? (2006) Ask students to provide evidence for their answers. (the graph, the globes, the colors) Ask how these helped answer the questions.

## Explore

Using the "Color by Number" worksheet, ask students to create a visual representation that accurately communicates the size of the ozone hole. Invite students to make up their own color scale. The seven ranges of ozone data may be divided any way they like. Ranges don't have to start at zero and don't have to be even units. They can choose any colors or shades of colors they like. If only one student is participating, color two maps with different scales. Encourage students to think about the range and why they choose it.

## Explain

Post drawings on the wall and compare. Do any look like there is almost no hole? Which one is easiest to understand? Why? Hardest to understand? Why? Why not use the same color for all types of data? Explain how the different color scales help us to visualize data by drawing attention to what is important, such as the location of the ozone hole. However, color can also be deceptive, such as a break in a color scale that stands out where there is nothing really unique about the data.

## Evaluate

Looking back at the poster, ask students "Why was this particular color scale chosen?" (There is a noticeable break from light to dark blue at 220 DU, where values lower than 220 DU are considered to be the "ozone hole.") Ask students to think about their scales and describe why they choose certain colors and data ranges. Which data were emphasized or de-emphasized in their color maps?

## Extension

For extended activities, additional resources, and adaptations for other grades, visit http://aura.gsfc.nasa.gov/outreach/ozoneholeposter/.

# Color by Number Worksheet

NASA's fleet of Earth observing satellites produce 1500 Terabytes of data each year, enough to fill 3000 laptops, each with a 500 GB hard drive. To help interpret this wealth of data, scientists rely on techniques to visualize information such as mapping data values to colors. Create your own color map using data from Aura's OMI instrument of total ozone from October 2012.

**Total Ozone October 2012**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 274 | 289 | 291 | 300 | 305 | 307 | 312 | 314 | 312 | 320 | 318 | 319 | 309 | 302 | 296 | 292 |
| 280 | 289 | 296 | 304 | 309 | 311 | 314 | 314 | 323 | 330 | 334 | 329 | 330 | 317 | 307 | 297 |
| 279 | 292 | 308 | 313 | 312 | 310 | 306 | 311 | 322 | 331 | 345 | 343 | 346 | 332 | 324 | 308 |
| 293 | 305 | 311 | 315 | 310 | 289 | 283 | 279 | 290 | 314 | 336 | 359 | 360 | 353 | 339 | 320 |
| 305 | 314 | 317 | 318 | 300 | 259 | 236 | 232 | 236 | 257 | 291 | 342 | 374 | 372 | 356 | 332 |
| 305 | 316 | 325 | 325 | 289 | 242 | 208 | 194 | 196 | 217 | 247 | 301 | 368 | 386 | 370 | 347 |
| 321 | 325 | 321 | 330 | 288 | 232 | 195 | 179 | 169 | 180 | 216 | 280 | 357 | 400 | 376 | 352 |
| 322 | 328 | 326 | 325 | 304 | 253 | 210 | 187 | 177 | 186 | 219 | 287 | 359 | 402 | 388 | 364 |
| 324 | 326 | 327 | 328 | 327 | 297 | 247 | 224 | 216 | 222 | 254 | 306 | 375 | 408 | 386 | 358 |
| 320 | 329 | 331 | 332 | 342 | 340 | 304 | 285 | 279 | 283 | 307 | 353 | 395 | 403 | 383 | 362 |
| 315 | 325 | 340 | 348 | 359 | 368 | 363 | 352 | 357 | 347 | 366 | 399 | 409 | 397 | 376 | 357 |
| 315 | 326 | 331 | 356 | 362 | 381 | 397 | 402 | 401 | 407 | 415 | 415 | 406 | 390 | 369 | 348 |
| 311 | 323 | 341 | 349 | 366 | 385 | 404 | 412 | 424 | 423 | 423 | 413 | 396 | 378 | 359 | 340 |
| 304 | 322 | 330 | 345 | 361 | 376 | 395 | 406 | 411 | 408 | 397 | 388 | 376 | 358 | 341 | 326 |
| 302 | 320 | 327 | 339 | 354 | 368 | 378 | 389 | 397 | 389 | 381 | 367 | 359 | 342 | 331 | 316 |
| 292 | 306 | 318 | 329 | 338 | 347 | 352 | 361 | 368 | 367 | 361 | 356 | 342 | 330 | 320 | 306 |

**Color Scale (Dobson Units)**

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| ______ | ______ | ______ | ______ | ______ | ______ | ______ |

**Directions:** Create your own color map. Color in the color scale with any colors or shades of colors you choose. Label the data ranges for each color. Ranges do not have to start at zero or be segmented evenly. Your challenge is to create a color scale that will accurately represent the size of the ozone hole.

**About the Front:** These data can be found on NASA's Ozone Watch web site (http://ozonewatch.gsfc.nasa.gov). The globes are October averages of daily total ozone. The graph shows averages of daily ozone hole areas for 7 September to 13 October—a period that usually spans the largest areas of the ozone hole. Note that an average of daily values in the graph is not equal to the area taken from the averaged globe over the same period.

**For further reference:**

NASA's Earth Observatory:
http://earthobservatory.nasa.gov
EOS Aura mission:
http://aura.gsfc.nasa.gov
SAGE II mission: http://sage.nasa.gov
NASA Science Visualization Studio:
http://svs.gsfc.nasa.gov
Ozone Layer Twenty Questions: http://www.esrl.noaa.gov/csd/assessments/ozone/2010/twentyquestions/

*Ozone facts: The average ozone levels over the entire globe is 300 Dobson Units. Values lower than 220 Dobson Units are considered part of the ozone hole. In 2006, the worst year for ozone depletion to date, the lowest values of 84 Dobson Units were observed.*

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