CLOUDS

Finding your way out of a cave can be hard enough. Imagine if a dense "pea-soup" fog suddenly appeared! That's what happened to the famous cloud scientist Vincent J. Schaefer as he was enjoying the refreshing waters of a cave pool.

In order to conserve flashlight batteries, his companion decided to light a lamp. But the air above the lake was supersaturated with water vapor! As soon as the match was struck, the water vapor condensed into a thick fog. Smoke particles from the match flame served as nuclei on which the fog droplets formed. Schaefer is given credit for inventing cloud seeding, a method for coaxing more rain or snow from clouds by dusting them with tiny particles.

By Anne M. Rosenthal

Clouds may blanket hundreds of square kilometers of marine sky or billow tens of thousands of feet above the earth. Despite these vast proportions, cloud formation actually depends on the presence of microscopic airborne particles.

In order to understand clouds, we need to think about the properties of one of earth's most abundant compounds: water. Within our atmosphere, water is the only substance that exists naturally as a gas, liquid, and solid. When it changes from water vapor—the gaseous form—to make liquid water droplets or solid ice crystals, the water molecules rely on help from tiny suspended particles, which serve as *condensation nuclei*.

On the surfaces of these tiny suspended particles, H_2O meets H_2O. As molecules continue to gather, weak hydrogen bonds form between them. The result of all this gathering and ordering is liquid water. Or if it's really cold, solid ice crystals or snowflakes form.

The temperature at which water vapor turns to droplets or crystals depends on how much water vapor there is in the air. For a given amount of saturation, water condenses at a temperature called the *dew point*. Sometimes, however, even though the dew point has been reached, nucleation particles may be lacking to initiate the phase change. As a result, nothing visible happens.

If more and more water vapor enters the air, for example by evaporation from a mountain lake, the air may become saturated. As the air cools, it may reach *supersaturation*, an overloaded state. Then, provide the water-laden air with minute particles, perhaps the exhaust from a passing vehicle and—PRESTO!—a cloud appears.

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What types of particles contribute to cloud formation and exactly how minute are they? Sea salts are a major source of nuclei. Because of their water-attracting or *hygroscopic* quality, they can induce precipitation at temperatures above the dew point. Smoke, exhaust, soil, and even meteoritic dust contribute to cloud formation. Most of these particles have diameters less than one micrometer—that's about 0.0001 cm or 0.00004 inches.

Meteorologists know that increasing ice crystal formation within supercooled clouds results in increased precipitation. Weather modification companies apply a synthetic version of this phenomenon by seeding clouds with dry ice (solid carbon dioxide) or silver iodide (AgI) crystals. For relieving drought conditions, the process has met with only limited success; however, it has proved useful in dissipating cold fogs that might otherwise shut down airports.

I've looked at clouds from b
From up and down, and s
It's cloud illusions I
I really don't know c

When you're lying back in the grass on a balmy day, clouds passing by might resemble ponies or even monsters—"cloud illusions", as the song says. However, it's helpful to know the scientific names too, since each type of cloud has its own interesting characteristics.

While scientists differ on exactly how clouds should be categorized, here's a classification system that is often used.

Blanket-like clouds that form thick layers are called *stratus clouds*; when they occur at ground level, we call them fog. As rain clouds, the prefix "nimbo" meaning "precipitating" is added, resulting in the term "nimbostratus."

Associated with dreary days of continuous rainfall or snowfall, nimbostratus clouds tend to be dark, low storm clouds.

Cumulus clouds, also known as heap or lump clouds, may be small fair-weather puffs dotting the sky as far as the horizon. They can also become the immense blackened *cumulonimbus* clouds jutting into the upper reaches of the troposphere, the layer of Earth's atmosphere closest to the surface. The bases of these giant storm clouds, usually at 4000-5000 feet, define the point where the air is cold enough for water to condense; the tops of these clouds touch the stratosphere, where winds may further sculpt their crests into characteristic anvil shapes.

Within these cumulonimbus giants lie numerous convection cells that feed on the heat produced when water vapor condenses. Think for a moment on how "hot-and-sweaty" after a workout quickly becomes "cold-and-clammy" as your sweat evaporates into water vapor. The opposite process occurs when water vapor changes to droplets or crystals: Heat is produced. Since hot air rises, pockets of air where condensation is occurring rapidly move upward within a cloud.

These updrafts are the beginning of a chain reaction. As the air pocket rises, it expands in the thinner air and cools. This cooling triggers further condensation, which in turn heats the pocket. Heating ensures the pocket's continued buoyancy. As it continues its climb skyward, the pocket cools, more water condenses, and the cloud builds further.

n both sides now,
d still somehow,
s I recall,
/ clouds, at all.

Joni Mitchell (1969)

Storm clouds and lightning bolts

Lightning sizzles throughout these large clouds as static electricity produced by the constant movement of materials within the cloud discharges. When a large negative charge collects on the underside of the thundercloud, it induces an opposite charge known as an "electric shadow" on the ground below. As negative charges move downward from the cloud on a zigzagging path or "stepped leader", positive charges begin to travel upward from the earth's surface, often making use of a conductor such as a tree or a metal antenna—or even a person. Lightning flickers as opposite charges meet, and electricity travels along the stepped leader. So hot is a lightning bolt that it heats the surrounding air to temperatures greater than those at the sun's surface. Thunder is the shock wave produced as the air quickly expands from the heat and then contracts once the lightning has passed. On a single day, the thunderstorm-prone state of Colorado may receive 10,000–15,000 lightning strikes!

Nimbostratus clouds mean dreary days.

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Besides lightning, thunderclouds often bear numerous other hazards. Ice, repeatedly coated with water and tossed to freezing heights within the cloud, drops as hail when it becomes too heavy for upward drafts to bear. Fierce downbursts can produce winds blowing over 100 miles per hour when cooler air drops suddenly from the storm cloud toward the ground. In the United States, about 1% of severe storms—those producing winds at least 58 miles/hour, hail at least 3/4 inch in diameter, or heavy rainfall—spawn tornadoes, rapidly spinning columns of air that become visible when they carry dirt and debris.

Besides the nimbostratus and nimbocumulus clouds, another precipitating cloud is the icy web or cirrus cloud. These feathery clouds, generally composed of ice crystals, form at altitudes over 23,000 feet. Their precipitating tails are called *virgas*, which means that the precipitation never reaches the ground, but instead evaporates, changing back into water vapor.

Clouds may take particularly interesting shapes. Some of the frantic reports about aliens from outer space about to land spaceships on earth may well be related to sightings of lenticular clouds—clouds typically occurring leeward of mountain ranges when fast-moving winds tumbling over the peaks develop isolated air pockets. As the pockets move upward and cool off, "flying saucer" shapes can condense out.

Contrails—Streaks in the sky

In today's world, not all clouds result from natural causes. A significant contributor of clouds are jet airplanes, which leave linear clouds called condensation trails, or "contrails", in their wake. Contrails form when exhaust from jets flying above 30,000 feet cools rapidly in the subzero reaches of the upper troposphere and lower stratosphere. Water vapor and liquid water droplets within the jet exhaust precipitate almost instantly into ice crystals. Additionally, the tiny particles present in the exhaust seed clouds from water vapor in the surrounding atmosphere.

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Although contrails often fade quickly from the sky, the opposite is also true: Some contrails have staying power. The narrow

High, feathery cirrus clouds reflect heat back to the surface.

linear cloud tracing the airliner's path may tear into wispy cirrus or widen to a sheet of cirro-stratus clouds. Observing contrails helps us to understand a portion of our atmosphere where it is difficult to use weather instruments. Contrails are more likely to form and linger in air already saturated with water vapor.

An important aspect of clouds is their reflectivity of sunlight. Like cirrus clouds, contrails block rays that would otherwise warm the earth's surface. On the other hand, they trap radiant energy emitted by the ground, retaining heat in the atmosphere. Scientists aren't sure exactly how the equation adds up—whether contrails help cool or heat the earth's atmosphere.

A research opportunity arrived in September 2001 when commercial jets were temporarily grounded in the United States following the terrorist attacks. Atmospheric scientist David J. Travis at the University of Wisconsin-Whitewater reported in the journal *Nature* (August 8, 2002) that the average difference between daytime and nighttime temperatures during the three-day period when jets and their contrails were absent was one Celsius degree larger than normal. This occurred even though ranges for the three-day periods immediately preceding and following the hiatus were smaller than normal. The data bolstered the view that contrails may be affecting the earth's climate.

Cloud research

To help answer questions about cloud reflectivity and the trapping of infrared heat, NASA has launched two instruments called CERES (Cloud and the Earth's Radiant Energy System). The first instrument orbiting the earth on NASA's EOS Terra satellite consists of three telescopes. The first telescope measures how much solar radiation is reflected, while the other two are sensitive to longer-wavelength infrared radiation.

The second instrument launched on NASA's EOS Aqua satellite carries similar telescopes. Because Terra flies over the equator at about 10:30 a.m. and Aqua flies over at 1:30 p.m., tropical clouds are observed at two different times of day.The separated times provide an opportunity for scientists to observe how clouds build.

Then at night, Terra and Aqua cross the equator at 10:30 p.m. and 1:30 a.m. respectively. In the darkness, they continue to measure infrared radiation.Taken together, the two instruments provide better coverage of the planet than a single instrument and make it easier to study variations in earth's energy balance between day and night.

Another important area of NASA cloud research is related to ozone depletion or "ozone holes" over the two polar areas, which has left high-latitude populations especially vulnerable to increases in UV radiation and skin cancer. It is the ozone layer in the stratosphere that absorbs much of the damaging ultraviolet light and makes life on earth possible.

The primary culprits in ozone destruction are CFCs, or chlorofluorocarbons. These human-made chemicals were produced for many years as effective spray-can propellants, refrigerants, solvents, and blowing agents for plastic foams. CFCs were initially promoted because they were stable and, therefore, safe for use at the ground level. However, it was this very stability that made them dangerous over the long term. Their persistence made it possible for CFCs to rise into the stratosphere. There, solar ultraviolet radiation splits the CFC molecules, releasing ozone-destroying chlorine. Mounting evidence of the role of CFCs in destroying ozone led to unprecedented international cooperation to phase out the use and production of the chemicals by industrial nations in the 1987 Montreal Protocol and its ammendments.

But why is ozone most likely to be depleted over the Earth's poles? And why do "holes" appear and disappear? The answers to both questions may be in the clouds.

The complete story of ozone depletion involves a type of cloud called a PSC, or polar stratospheric cloud. Normally, the air over the poles is so dry that clouds don't form. But during the polar winters, temperatures become extremely low and ice crystal clouds form from the minute amounts of water vapor present in the stratosphere. The surfaces of these ice crystals are sites for chemical reactions that produce *free radicals*. Chemists define these as atoms or molecules that contain a single unpaired electron—a feature that causes them to be extremely reactive. Unfortunately, some of these reactions result in the destruction of ozone.

The seasonal appearance of ozone holes at the South Pole is further explained by long periods of light and darkness. Since ozone destruction is dependent on UV radiation, it doesn't occur until daylight reappears.

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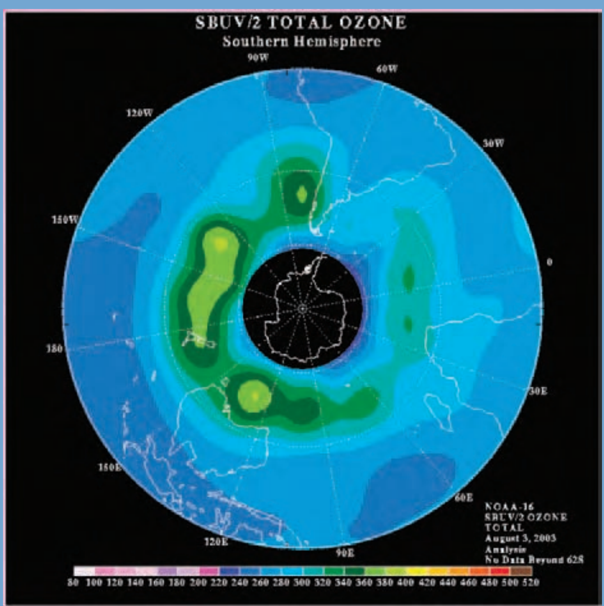

SOURCE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / NATIONAL WEATHER SERVICE WWW.NWS.NOAA.GOV

This map shows the August 2003 Southern Hemisphere total ozone from the Solar Backscattering UltraViolet (SBUV/2) instrument on board the NOAA polar orbiting satellite. In austral spring the analysis shows the "ozone hole" (values below 220 Dobson Units) over Antarctica and the Antarctic Ocean. This area of low ozone is confined by the polar vortex. Usually circular in August and September, the vortex tends to elongate in October, stretching toward inhabited areas of South America. By November, the polar vortex begins to weaken and ozone-rich air begins to mix with the air in the "ozone hole" region. The "ozone hole" is usually gone by late November/early December.
The SBUV/2 instrument cannot make observations in the polar night region because it relies upon backscattered sunlight. The blackened area centered over the pole represents the latitudes in which no observations can be made.

Land masses tend to deflect and divert winds into vertical north-south pathways. With little land-mass interference in the Southern Hemisphere, air circulates in a strong circumpolar or "horizontal" fashion. At the South Pole, the strong circulation creates a *vortex*, a whirlpool of air which prevents warm northerly air from reaching the pole. As a result, the stratosphere over the South Pole becomes very cold—cold enough to allow the formation of PSCs which accelerate the catalytic destruction of ozone. When the vortex weakens in the late spring, the ozone depleted air disperses in the atmosphere.

Ozone depletion in the Southern Hemisphere was the first to capture scientists' attention. Then, during the 1999–2000 season, scientists observed record ozone losses of 70% over the Arctic. NASA's Arctic campaign, involving over 350 scientists from around the world, studied the problem during the winter of 2003 with a combination of satellite instruments, measurements from aircraft, remote sensing, and research balloons, as well as ground-based instrumentation.

What interests atmospheric scientists the most is whether we're making any progress with our efforts to save Earth's fragile ozone layer. Is the Montreal Protocol having any effect? Or are there already so many ozone-destroying chemicals on the loose that the risk is spreading? Finding these answers may be the focus of many NASA missions to come. NASA's EOS Aura mission scheduled to launch in early 2004 will gather the most accurate information on chemistry and dynamics to date. With four instruments on board, Aura will orbit the Earth from pole to pole gathering ozone data 24 hours a day.

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REFERENCES

Anthes, R. *Meteorology*, 7th edition; Prentice Hall: Upper Saddle River, NJ, 1997.

Atmospheric Chemistry and Global Change; G. Brasseur, J. Orlando, and G. Tyndal, Eds.; Oxford University Press: New York, 1999.

Perkins, S. September's science: Shutdown of airlines aided contrail studies. *Science News*, May 11, 2002, p 291.

"Cloudman" (John Day) website, www.cloudman.com (accessed July 2003).

NASA's Earth Observatory Reference Library, http://earthobservatory.nasa.gov/Library (accessed July 2003).

Activity

"Nature is a mutable cloud, which is always and never the same."

Ralph Waldo Emerson (1803–1882)

Assemble materials.

By Bob Becker

We've all done it: lain back on a grassy hillside staring up at a multitude of puffy white clouds—one looking like an elephant, the next like Abraham Lincoln. But how often do we stop and consider why clouds form in the first place?

We know that clouds comprise small suspended droplets of water and that they have a great influence on weather patterns. But what causes their appearance and subsequent disappearance in the sky overhead? The following activity will enable you to make your own clouds in a plastic bottle and then to explore some of the factors responsible for their formation.

Safety:

Use standard precautions for any use of open flames. Strike match on safety strip; be sure the area is free of flammable material; wear safety goggles in the laboratory; be sure to have fire extinguishing equipment handy.

You will need:

- One empty 2-L soda bottle, preferably colorless, rinsed out, and allowed to dry
- 50 mL of room-temperature tap water
- One match
- One dark-colored backdrop such as a black tabletop or notebook cover
- Safety goggles

What to do:

1. Remove the label from the bottle to ensure an unobstructed view. Screw the cap on to the bottle securely. Then, using a dark backdrop to provide greater contrast, squeeze the bottle and release three to five times near the bottom as you observe the air space in the upper portion of the bottle. Since nothing has been added to the bottle, this can serve as a control for future observations.

2. Now remove the cap, and pour in 50 mL of water. Screw the cap back on securely and swirl the water around inside the bottle for 10–15 seconds. This should ensure that the air inside the bottle is well saturated with water vapor. Or, in other words, that the inside humidity is 100%. Now, repeat the squeezing technique used in step 1. What do you observe inside the bottle after the repeated squeezing?

3. Remove the cap again. In one hand, hold the bottle sideways with a slight upward tilt. In the other hand, take a lit wooden match and insert it partially into the bottle. Immediately give the bottle a quick squeeze to extinguish the match. You should see a small amount of smoke from the match trapped in the bottle. Withdraw the match, screw the cap back on, and set the bottle upright. Repeat the squeezing technique used in step 1. What do you observe inside the bottle when you squeeze? When you release the squeeze?

What's going on?

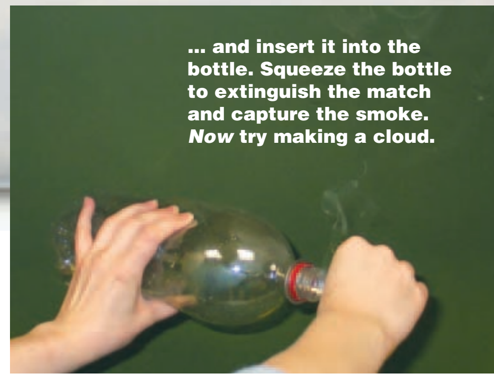
Although you couldn't tell from looking at it, there were two important changes occurring when the air-filled bottle was squeezed in **the first trial:** (1) a substantial increase in pressure, which should be obvious, because you were decreasing the volume of the bottle by squeezing it, and (2) a slight increase in temperature, although you probably didn't observe this change. This happens whenever a gas is compressed in this fashion.

When the squeeze is released, the gas molecules suddenly occupy a larger volume. Again you probably didn't notice it, but there was a slight decrease in

in a Bottle


Try making a cloud. First, use dry air, then humid air.


Next, light a match …


… and insert it into the bottle. Squeeze the bottle to extinguish the match and capture the smoke. ***Now*** **try making a cloud.**

STAFF PHOTOS

temperature. This type of cooling is quite noticeable whenever you let the air out of a pressurized tire. It cools off quite substantially, and the valve stem can become quite cold. When you increase the pressure in a tire, the exact opposite occurs.

During **the second trial,** you introduced water vapor. As you might imagine, the amount of moisture that air can hold greatly depends on the temperature; the higher the temperature, the more water evaporates. 100% humidity at 32 °C (90 ºF) translates into twice as much moisture content in the air as 100% humidity at 20 °C (68 °F). Thus, when the bottle was squeezed and the temperature increased slightly, so did the moisture content of the air as the water at the bottom and on the sides of the bottle evaporated a bit more. When the squeeze was released and the temperature dropped slightly, that extra vapor had to condense back into a liquid.

Water condenses best when it has a place to condense. The only surfaces available were the sides of the bottle and the water layer at the bottom. The total amount of moisture condensing would have been just a fraction of a drop, so this evaporating and condensing went pretty much unnoticed.

Then in **the third trial,** you introduced smoke into the bottle: not much—probably only a few millionths of a gram—but enough to create microscopic condensation sites throughout the bottle. This time when the squeeze was released and the temperature dropped, the water could condense onto the smoke particles and form miniscule water droplets suspended throughout the bottle. In other words, it formed a *cloud*. When the bottle was resqueezed and the temperature went back up, these droplets evaporated, but the smoke particles were still there, and so the whole process could be repeated. Eventually, the smoke precipitates out—onto the sides of the bottle or into the liquid layer below—and the cloud effect wears off.

In our atmosphere, clouds can form whenever warm moisture-rich air comes in contact with cooler air. There, the tiny dispersed solid particles—referred to as aerosols—act as nucleation sites for cloud formation. Although they are quite small, these particles can have huge effects on global climates and weather patterns.

Further investigation

The water you used in this activity was at room temperature. Experiment with water at a variety of temperatures and see what effect it has on the cloud formation. Also try other sources of condensation sites such as smoke from a candle, chalk dust, talcum powder, etc. Does the size and type of particle make a difference in cloud formation?

Using a slide projector or strong flashlight, shine some bright light through the bottle. Have the room as dark as possible and view the bottle from various angles. The scattering and diffraction may cause different colors to emerge, and these colors can change over time as the clouds in the bottle start to thin out.

Reprints of this activity may be purchased by calling 1–800–635–7181, ext. 8158.