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FEATURES

every cloud has a FILTHY lining

by John Weier • September 30, 1999

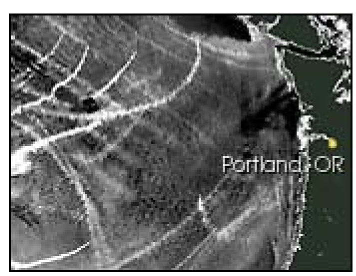
For many of us, cloud formation was one of the first scientific phenomena we understood. We were taught the sun heats up the water on the Earth's surface until the water evaporates, gently ascends into the sky, and comes together to create clouds. It was a simple concept involving just water, the sun, and the sky. As we grew, we accepted this idea as a basic, easily understood truth. We'd no sooner doubt it than doubt whether the Earth goes around the sun or whether static electricity allows a balloon to stick to a wall.

Although clouds appear pristine, aerosols—airborne grime— are required for water droplets to form. Most aerosols are generated by natural sources, but human activities are increasing their concentration in the atmosphere. As a result, the properties of clouds may be changing around the globe. (Photograph by Robert Simmon, NASA Earth Observatory)

But as it turns out, we've all been misled. Scientists have known for years that cloud formation is an extremely dirty business that depends on microscopic particles (aerosols) from the surface of the Earth. These particles allow water vapor to condense, and without them cloud droplets, mist, or fog could not form at all.

The presence of the aerosols makes matters much more complicated in that many researchers do not know exactly where all these particles come from. While the consensus is that cloud-forming aerosols mostly originate from natural sources, an increasing number of scientists believe that humans may produce a large quantity through the burning of fossil fuels. By doing so, we are making the clouds above us brighter, altering their lifetime and possibly creating huge changes in our environment.

Testing theories of man-made cloud formation has been a difficult task. In most urban areas, scientists are unable to discern exactly how pollutants contribute to forming clouds because the atmosphere over the land is too tumultuous. As an alternative, researchers from NASA's Goddard Space Flight Center and a number of universities around the country have turned to studying "ship tracks" — clouds formed from the aerosols coming from large ships. Not significant sources of pollution themselves, ships release their exhaust into the relatively clean and



The bright cloud arcs in this image are "ship tracks." They are often seen in near infrared satellite imagery of the Eastern Pacific, like this scene from a NOAA weather satellite. (Image courtesy Dr. Michael King, NASA still marine air, where the scientists have an easier time of measuring the effects of fossil fuel emissions on cloud formation.

GSFC)

What they have found is that the sulfur dioxide released from ships' smokestacks could be forming sulfate aerosol particles in the atmosphere, which cause the clouds to be more reflective, carry more water and possibly stop precipitating. This is proof that humans have been creating and modifying clouds for generations through the burning of fossil fuels. The study may go a long way towards explaining some of the climactic mysteries in the world, such as why global warming is affecting the Southern Hemisphere much more quickly than the Northern Hemisphere (King et al. 1993).

The data used in this study are available in one or more of NASA's Earth Science Data Centers.

"For the Earth's atmosphere to form clouds at all, you need particles for the water vapor to condense on," said Michael King. He is an atmospheric scientist at NASA's Goddard Space Flight Center who has studied cloud formation for more than ten years. He explained that when water evaporates into the atmosphere, it does not move together on its own to form water droplets, but spreads evenly throughout the atmosphere. Airborne particles (aerosols) that dissolve easily in water, such as ammonium sulfate and sea salt, break up this otherwise even distribution and give the water molecules something to cling to. The particles provide nuclei for cloud droplets to condense around, and together these droplets form clouds. Were it not for particles in our atmosphere, the sky would always be clear and the air around us, thick and humid (King et al. 1995).

Many areas of the globe with high water vapor concentrations (bright blue and white in the image at left) do not form clouds (white in the visible light image at far left.) (Images by Robert Simmon & the GOES Project Science Office, based on NOAA GOES data)

King said, "A greater number of aerosol particles in a cloud will lead to the production of more cloud droplets, albeit smaller in size, than would otherwise be the case. This in turn increases the brightness of the cloud." Additional particles give the water vapor more nuclei to cling to, so more smaller drops form in the cloud. These smaller drops in turn make the cloud more reflective to sunlight. The same phenomenon can be seen when ice cubes are crushed. As the ice is broken up, the once smooth surface is shattered into many tiny surfaces at varying angles to one another. These additional surfaces reflect incoming light in all directions and cause the crushed ice to appear white and opaque. Water droplets do not contain all these ridged surfaces, but their fragmentation has a similar effect on sunlight.

Whole ice cubes transmit more light than they scatter, (clear ice, top) compared to crushed ice which scatters light very well (white opaque ice, above.) This is analagous to the bright white clouds formed with high amounts of aerosols, which are composed of many very small water droplets. (Photographs by Robert Simmon, NASA Earth Observatory)

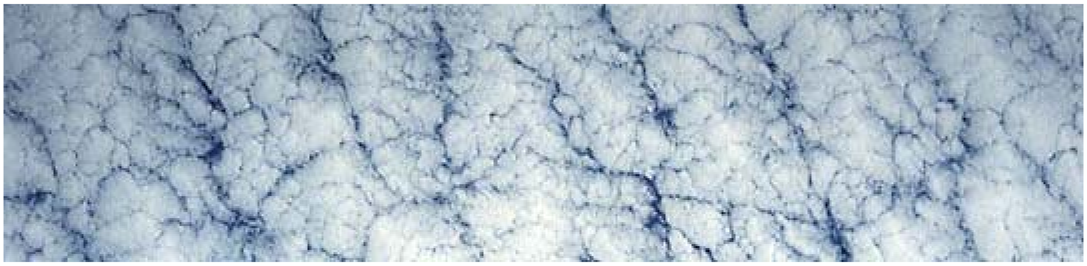
For more information, see What Are Aerosols?

A majority of cloud-creating aerosols arise from natural sources, ranging from volcanoes to microscopic ocean plants. Yet, scientists speculate that an ever growing number originate from our need for electricity and transportation. Each time we burn fossil fuels, sulfur dioxide, a gas that leads to the formation of sulfate aerosols, is released. The particles often rise into the atmosphere and create more and brighter clouds. Though no one is certain what effect this extra cloud cover may have on the environment, many scientists believe it may be cooling the atmosphere. "By modifying clouds we make them brighter," King said. "This has a cooling effect on the climate, because the clouds are reflecting more solar radiation than they normally do back into space." Any light that is reflected cannot heat the ground or the atmosphere.

Proving this hypothesis is much more difficult than measuring the brightness of the clouds over a smokestack. Above land, where most industry is located, the wind currents and convection are too tumultuous to measure cloud formation from individual pollution sources. The clouds break up and change so often that scientists have trouble monitoring the aerosols, let alone determining the precise amount of fossil fuel needed to create clouds. What the researchers needed was a pollution source that spilled contaminants continuously into a calm and relatively pristine air mass (King et al. 1995).

Searching for Ship Tracks

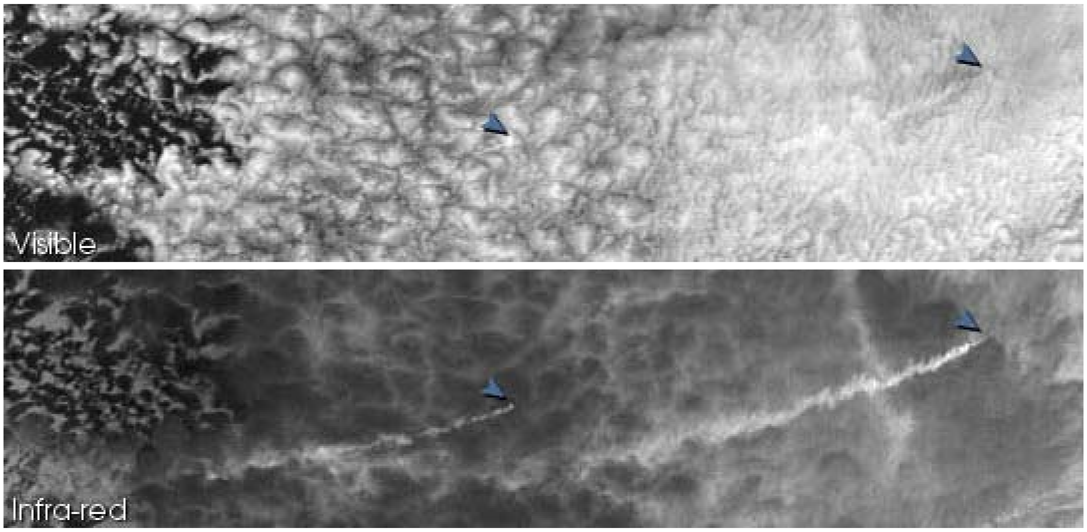
"Our interest in ship tracks came about quite by accident," said James Coakley, an atmospheric scientist at Oregon State University. He came up with the idea to study ship tracks back in 1985 while visiting Scripps Institution of Oceanography to learn about the newly-burgeoning satellite imaging technology. He said the first image shown to him was of the eastern Pacific off the coast of California. "I saw these bright streaks running through the images," he said. "Immediately I knew they were ship tracks." Coakley also saw that the ship tracks and the atmospheric conditions off of California would be ideal for studying the effects of man-made aerosols.



This photograph from the Space Shuttle shows marine layer clouds near Baja California. These clouds often stretch for hundreds of thousands of square miles in stable air just above the surface of the ocean, and provide a convenient laboratory for the study of the interaction of clouds and aerosols. (Photograph courtesy NASA Johnson Space Center)

In general, the air above the oceans suffers from less turbulence and convection than the air above land. The lower atmosphere is especially calm over the eastern Pacific in the summertime due to a layer of hot air that settles in 500 to 700 meters above that region of the ocean, Coakley explained. This effect creates a temperature inversion, placing a cap on the cooler air below, trapping pollutants and water vapor. While the inversion is responsible for the smog that reduces air quality in Los Angeles, it also allows for the formation of long lasting ship tracks. The particles bellowing from ships' smokestacks enter the air above the eastern Pacific and create long, thin clouds that remain there for days.

Coakley and his colleagues began a general survey of the ship tracks with satellite imagery. They took a number of images of the eastern Pacific using the Advanced Very High Resolution Radiometer (AVHRR). Built and managed by the National Oceanic and Atmospheric Administration (NOAA), multiple copies of this satellite instrument circle the Earth in near-polar orbits. Together, they scan the entire surface of the planet. The instruments do not simply take a picture of an area of the Earth, but use light sensors to detect specific colors (wavelengths) of light and thermal radiation coming off the Earth. These readings are beamed back to Earth in the form of data, which the scientists can manipulate to form images.



This pair of ship tracks, barely discernible in visible light (top,) stand out clearly in the near infrared (above.) (Images by Robert Simmon, based on NOAA Advanced Very High Resolution Radiometer (AVHRR) data)

When searching for ship tracks, Coakley's team looked at the near-infrared light (light which has a wavelength longer than that of red light in the visible color spectrum) coming off the clouds. At this wavelength many ship tracks appear as bright lines that can be distinguished from the surrounding, uncontaminated clouds. Once the scientists located polluted clouds, they made additional measurements of reflected light in the visible range. "On average, we found the polluted clouds reflect more sunlight than their unaffected counterparts," said Coakley.

Seeing the Clouds Close-Up

While satellite instruments can show scientists that clouds are getting brighter from ships' smokestacks, the images cannot tell them anything about the details of the processes behind the phenomenon. For that, the scientists have to take measurements inside the ship tracks themselves.

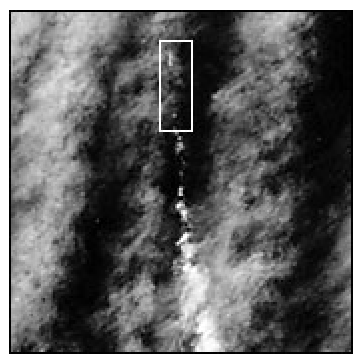
The University of Washington Convair C-131A measured aerosol, ship track, and cloud properties directly. The measurements confirm that sulfate aerosols form the ship tracks with larger numbers of smaller water droplets than contained in unpolluted clouds. (Photograph courtesy Dr. John S. Foot, U.K. Meteorological Office)

King and Coakley collaborated with researchers from the University of Washington to analyze data on solar radiation and cloud properties inside clouds that were modified by ships. "We flew an airplane through the clouds and monitored the pollution from the ships at the same time the satellite went over them," said King. The research plane was equipped with an array of gadgets that measure the light bouncing around inside the clouds, the water content there, the size of the water droplets, and many other variables. To take these measurements, the aircraft traveled 100 kilometers through the middle of the low-lying clouds (Radke et al. 1989).

As the aircraft sped out to sea, it encountered two 10-kilometer strips within the clouds that had very different properties. Across these strips, the number of water droplets per cubic centimeter more than doubled, the radius of the drops decreased by roughly six percent and the amount of water per cubic meter increased twofold (King et al 1993). "The first two results were what we expected to happen with ship tracks, but the third one was not expected," said King.

No one had predicted that this excessive cloud seeding from the ship would cause the clouds to retain more water. King explained that rain forms when cloud drops coagulate and reach a size where gravity can pull them to the ground. Yet, in the ship tracks the scientists observed, the cloud seeding made the drops so small that they could no longer easily merge together to reach the size needed to escape. Since no drizzle came out of the seeded clouds, the liquid water just kept building in the cloud. "This effect worked in exactly the same direction as the other two effects — all three made the cloud brighter and more reflective to incoming sunlight, especially in the near-infrared part of the spectrum," said King. The satellite data they received showed that the clouds that had been enhanced by the ship tracks were 13 percent brighter (King et al. 1993).

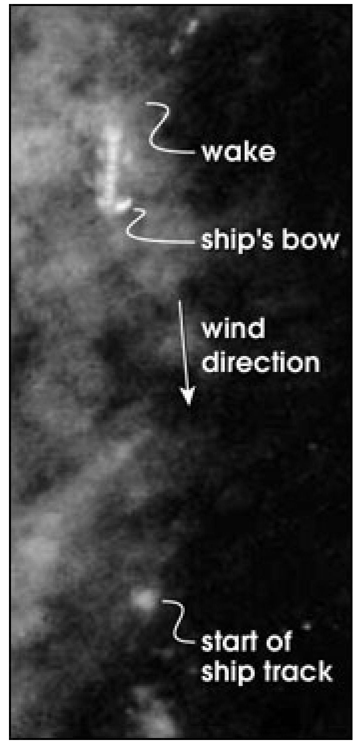
A Cloudy Future



Though these results suggested that sulfur dioxide from fossil fuels made the clouds brighter, the scientific community was not the first group to take a strong interest in the study. "The Pentagon saw the very first paper my colleagues wrote and they ran a database search on their vessels in the Pacific. They found that some of these ship tracks rose from their military ships, which were trying to hide under clouds," said King. Coakley was asked to brief the Chief of Naval Operations at the time.

Not long afterwards the scientific community began to focus on the results. Many researchers believe this study could go a long way towards explaining the temperature discrepancy between the Earth's hemispheres. Since researchers have been monitoring global warming, they have noticed a disturbing trend — the Southern Hemisphere seems to be warming up faster than the Northern Hemisphere. "The dominant hypothesis in the scientific community today is that aerosol forming pollution is greater in the Northern Hemisphere than in the Southern Hemisphere and this contributes a mitigating influence on global warming expected from the greenhouse effect," said King.

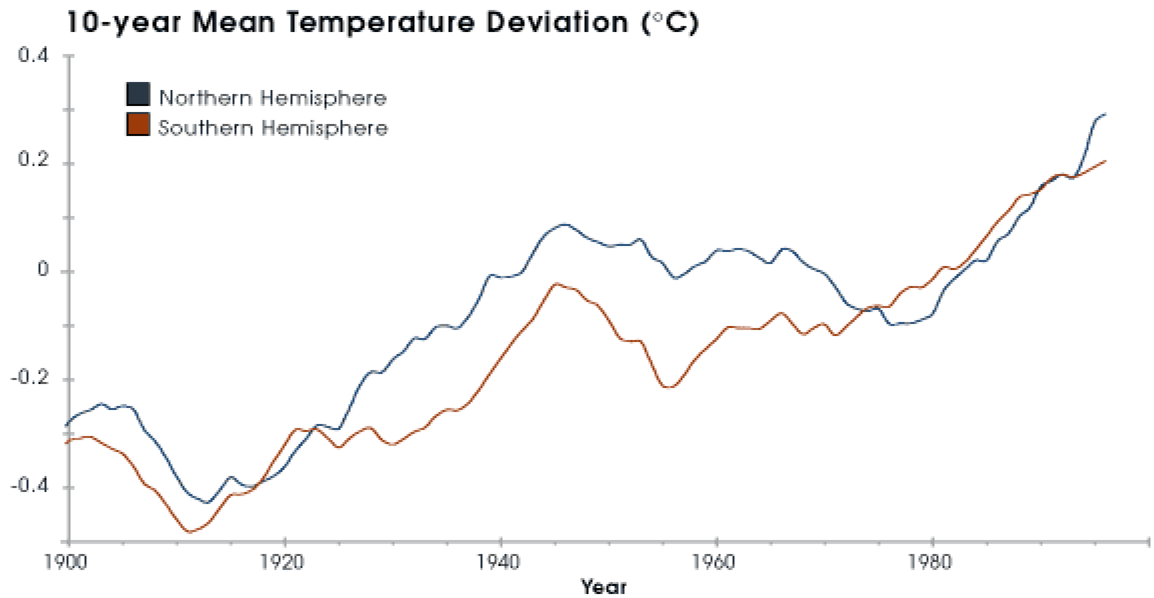
He stated that the effects of the sulfur dioxide from industry might be countering the greenhouse effect created by carbon dioxide, but only in the Northern Hemisphere. When fossil fuels are burned, both carbon dioxide and sulfur dioxide are released. As demonstrated in the ship tracks study, sulfate particles produced from sulfur dioxide creates brighter clouds, which may cool the atmosphere. Any light that is reflected cannot reach the ground and heat the surface of the Earth. This means there is less heat for carbon dioxide and other greenhouse gases to trap in the atmosphere.



This photograph from a NASA high-altitude research plane shows a ship sailing towards the bottom of the photograph with a ship track blown out ahead of it. The ship track begins about 1,400 m downwind of the ship. (Photograph courtesy Dr. Michael King, NASA GSFC)

The long-term effect of carbon dioxide and sulfur dioxide is not simply dependent on the concentration of the gases released. Rather, the amount of time the molecules spend in the atmosphere and their movement across the Earth plays a bigger role. King explained that carbon dioxide stays in the air for years and spreads out across the entire globe. Sulfur dioxide gets into the atmosphere and is converted to sulfate particles that form both a layer of polluting haze and brighter clouds. These particles dissolve and either settle back to the Earth from the forces of gravity alone or through precipitation. Rarely do the particles or the clouds they inhabit stay in the skies long enough to cross the equator, King said

So the problems created by carbon dioxide are felt globally while the "benefits" of the sulfur dioxide are felt locally. In the Northern Hemisphere, where most pollution of the world has been created, aerosol-laden clouds as well as layers of pollution could have stifled the effects of global warming. Over the Southern Hemisphere, which hasn’t had a long history of industrialization, carbon dioxide has built up unchecked. Consequently the Southern Hemisphere has been warming up more quickly (King et al. 1995).



From 1940 to 1990, meteorological records showed the Southern Hemisphere warming faster than the Northen. One hypothesis for this difference is that higher aerosol levels in the north caused clouds to reflect more energy away from the Earth's surface. In the 1990s, however, the Northern Hemisphere warmed more rapidly than the Southern. Aerosols are almost certainly affecting regional climates, but natural variability makes it hard to measure large-scale climate trends. (Graph by Robert Simmon, based on data from the Climate Research Unit (CRU) of the University of East Anglia)

"Our understanding of aerosols and cloud formation is primitive," said Coakley. "There may be a lot more to this story." Until scientists hone their knowledge of cloud formation and get an estimate of the percentage of aerosols released by humans, no one will know for certain what causes the different rates of warming between the hemispheres. Researchers have conducted many field experiments since these initial findings. They continue to answer much about man made aerosols and cloud formation, but many more questions go unanswered. No one knows, for example, just how many aerosols a given cloud can hold or the number of aerosols needed to keep a cloud from losing its contents.

Coakley warned that even if this aerosol theory of global warming is correct, we should not increase our consumption of fossil fuels. In time their full effects will catch up to the people in the Northern Hemisphere as well. Carbon dioxide will continue to remain in the atmosphere. Sulfur dioxide, once converted to sulfate particles, will keep falling to Earth. Sooner or later the effects of the carbon dioxide will far outweigh those of the sulfur dioxide.

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