Satellite-based observations are providing new insights into the detrimental impact of air pollution on rain-forming processes in clouds

Pollution and clouds

Daniel Rosenfeld and William Woodley

THESE days almost everything seems to be bad for your health – smoking, eggs, fast food, alcohol. But who would have thought that smoking could affect the health of clouds? The more we look, however, the more concerned we are about the effects of smoke and air pollution. We now realize that they can adversely affect the rain-forming processes in certain types of cloud.

Scientists first became concerned about this problem when they began studying multispectral images from meteorological satellites, which allowed them to see things that previously they never thought possible. Their work horses have been the polar-orbiting satellites of the US National Oceanic and Atmospheric Administration (NOAA), which have been operational since 1985. These carry Advanced Very High Resolution Radiometer (AVHRR) sensors that do not simply take a picture of an area of the Earth, but record visible and infrared solar radiation that has been reflected off the Earth's surface, atmosphere and clouds, as well as thermal radiation emitted by these objects. The readings are beamed back to Earth, where they are then manipulated to form images.

Polluted clouds produce less rain than clean clouds and also reflect more sunlight back into space

In 1987 James Coakley and colleagues at Oregon State University in the US were studying AVHRR images and were surprised to find "tracks" in stratocumulus clouds that lay several hundred metres above the surface of the Pacific ocean. The tracks were detected by on-board sensors that measured infrared light reflected by the clouds at wavelengths of about 3.7 μm. The tracks appeared as bright lines that could be distinguished from surrounding regions of cloud (figure 1).

The tracks, it transpired, were formed by sulphate aerosols spewed out by the smokestacks of large ocean-going ships. It was a turning point in our ability to infer cloud processes using satellite data. As later studies revealed, these dirty cloud tracks reflect more light because they contain more water in higher concentrations of smaller drops than nearby uncontaminated clouds. Imagine the shock senior naval officers around the world must have felt when they realized that anyone with access to AVHRR satellite data could quite easily spot their ships hiding below the clouds! Such are the effects of pollution.

The nature of clouds

We may all be familiar with clouds, but what exactly are they? Clouds in the Earth's atmosphere are composed of tiny drops of water, just a few hundredths of a millimetre in diameter. The cloud drops are so small, in fact, that they float in air and do not fall much under gravity. At sub-zero temperatures, clouds can even be made of tiny ice crystals.

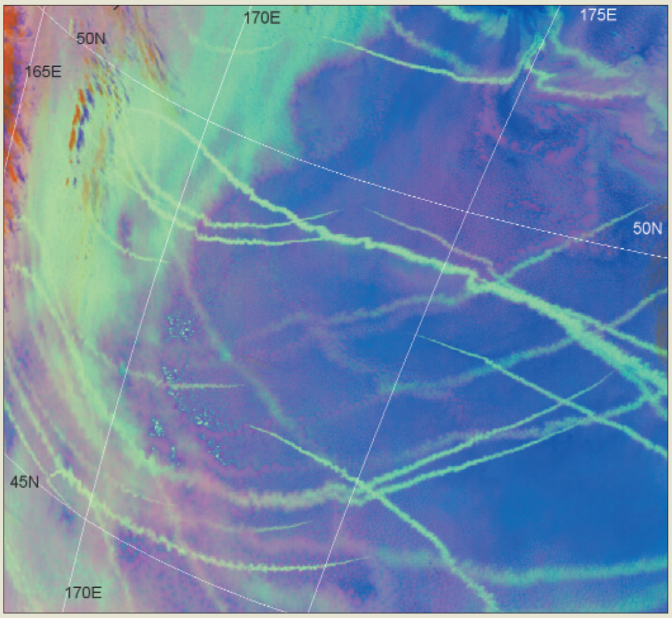
Clouds are formed when water vapour cools to below its condensation point. The cooling takes place as the vapour-laden air climbs to higher altitudes, where the pressure is lower and the atmosphere is cooler. The way in which the air rises determines the shape and properties of the resulting clouds.

The sloping motion of large sheets of air leads to extensive layered clouds – tens or hundreds of kilometres across. These so-called "stratiform" clouds adopt different forms, depending on how high in the atmosphere they exist. From the Earth's surface up to altitudes of 1 km, they appear as fog and stratus clouds. From 2–6 km they are altostratus and rain-producing nimbostratus, while from 7–10 km they are icy cirrus and cirrostratus clouds.

Vertical air motions, in contrast, tend to be much stronger than those responsible for stratiform clouds, and are limited to areas of just a few hundred metres to several kilometres across. These "convective" clouds are much taller than they are wide. They look like cauliflowers, with bright, white tops and dark bases, and are known as "cumuliform".

Cumulus clouds vary greatly in depth, ranging from small, benign "fair-weather" cumuli to huge cumulus clouds, known as cumulonimbus, with tops that climb to heights of 16 km or more. Cumulonimbus clouds produce most of the rainfall in the tropics and most of the rainfall in the mid-latitudes during the summer season. Cumulonimbus clouds are also the main components of thunderstorms, hailstorms, tornadoes and hurricanes. This article will look at the effect of pollution on this type of cloud.

1 Tracks in the ocean



A satellite image of the North Pacific Ocean, observed over the course of a few minutes by the NOAA's Advanced Very High Resolution Radiometer at 03:25 GMT on 22 June 2000. Red – visible sunlight reflected from the Earth (0.65 μm) – represents clouds with large drops. Yellow – reflected sunlight in the mid-infrared band at 3.7 μm – indicates clouds with small drops. The bright-green bands show the path of ocean-going ships. Pollution emitted by the ships leads to smaller water droplets in the clouds above (see text), which reflect more infrared light. These tracks can last for a day or more and can spread to widths of several tens of kilometres. The blue background, which corresponds to emitted thermal infrared radiation (10.8 μm and 12 μm), represents the ground surface below the clouds.

Impact of pollution on clouds

The reason why dirty clouds, such as those polluted by the aerosols from ship stacks, are brighter than clean clouds is straightforward. Basically, polluted clouds have higher concentrations of tiny water and ice droplets, which reflect more solar radiation back into space than unpolluted clouds (see box on page 35). In fact, the effect of pollution on clouds counteracts the hypothesized global warming due to the build-up of carbon dioxide and other greenhouse gases in the atmosphere. As early as 1974, Sean Twomey at the University of Arizona in the US had predicted that the pollution of clouds by enormous quantities of cloud-droplet-forming aerosols would offset the predicted global warming. The polluted clouds would return a higher fraction of incoming solar radiation to space than uncontaminated clouds. Thus, he argued, pollution would cool the atmosphere.

Some have even claimed that the so-called Twomey effect explains why the southern hemisphere, which is less polluted than the northern hemisphere, is warming more rapidly. The reason is that greenhouse gases last for hundreds of years and spread themselves evenly in both hemispheres, inducing equal amounts of warming. Particulate air pollution, however, is relatively short-lived, surviving for less than a week. It is therefore more abundant close to the energy-guzzling centres of population in the northern hemisphere, where pollution inhibits the potential warming due to greenhouse gases. It is a perverse world indeed when one must rely on pollution to offset the effects of global warming due to the build-up of greenhouse gases in the atmosphere.

The present authors have examined false-colour AVHRR images of land all over the world and found plumes emanating from cities and major industrial sources. For example, we found a gigantic area of pollution extending all the way from the industrialized Great Lakes region of North America to the Atlantic coast. It could be detected almost every time that pollution-revealing clouds were present. We even found pollution tracks above the relative wilderness of north-central Manitoba in Canada, created by emissions from a huge smelting plant (figure 2).

Through these findings, we became more and more interested in discovering how pollution affects rain-forming processes in clouds. We feared that pollution would be bad for the health of the clouds and hamper their ability to produce precipitation. In a world where fresh water is our most important resource, we can ill afford anything that compromises its quantity and quality.

How air pollution suppresses precipitation

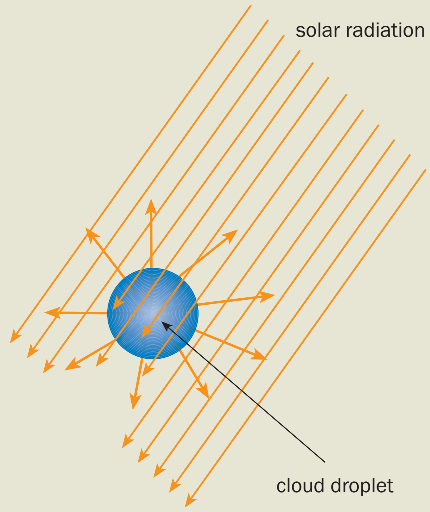
Clouds precipitate when they survive for long enough to grow water and/or ice particles that are large enough to fall to Earth. This can happen in two ways. At temperatures above freezing, droplets low in the cloud – just above the base – grow by attracting water vapour through diffusion, until their "effective radius" – the ratio of the total volume of all the drops in a particular region divided by their total surface area – reaches a value of about 14 μm. After this point, the droplets continue to grow by colliding and coalescing with other water droplets. Eventually, when the drops are bigger than about 200 μm in diameter, they fall through the cloud and reach the Earth's surface as rain. This precipitation process is, however, highly sensitive to the size of the initial cloud droplets. Those with diameters less than about 30 μm are so small that they float in air and have a low probability of growing into raindrops by colliding and coalescing with other droplets. Larger droplets, on the other hand, coalesce much faster.

The other way in which a cloud can grow particles to precipitation size is through ice processes, which operate when droplet coalescence processes are absent. Ice particles are first formed either when water droplets freeze as they are carried to temperatures well below 0 °C, or when ice crystals are nucleated on aerosol particles called ice nuclei. The ice particles collect any unfrozen drops faster than any other particles can snap them up, and also evaporate more slowly. If these processes carry on for long enough, the ice particles grow so big that they reach precipitation size. They then fall to Earth, melting to form rain if they reach temperatures above 0 °C. If the falling ice particles are large, they may not melt at all before reaching the ground; this is hail. (Snowflakes are not formed from frozen water droplets at all – but from aggregates of ice crystals.)

Pollution affects these precipitation processes because all cloud droplets – whether formed through the water or ice route – must initially form around an existing aerosol particle, known as a "cloud condensation nucleus". But the number of these nuclei depends on the purity of the air. Clean air has relatively few cloud condensation nuclei per unit volume, which means that only about 100 cloud droplets are formed in every cubic centimetre of air. Polluted air, in contrast, has more than 1000 cloud condensation nuclei per cubic centimetre – mainly in the form of additional smoke and aerosol particles. Since the total amount of water in polluted and unpolluted clouds at a particular height is about the same, the water in dirty clouds is distributed over a much larger number of smaller droplets. In other words, there are lots of very small droplets in polluted clouds, which cannot easily grow into larger drops of precipitation size during the lifetime of the cloud (figure 3). Pollution hinders rainfall.

Pollution can also affect the growth of precipitation that forms through the ice phase. The reason is that the tiny droplets in polluted clouds freeze more slowly at sub-zero temperatures than the larger drops found in clean clouds. Droplets that are smaller than 30 μm tend to remain in a supercooled liquid state until about –25 °C, and can even remain in this form down to a chilly –38 °C if the cloud contains very small droplets in vigorously ascending air currents. These supercooled liquid droplets float in the air flowing around the falling ice-precipitation particles, and therefore manage to avoid being captured. The ice particles, in other words, fail to collect enough water to grow to precipitation size. Once again, pollution slows down rainfall.

Detecting the size of microscopic cloud droplets



Look out of an aeroplane window during a daytime flight and the clouds below are a bright, white colour. That's because water is transparent to visible light, which is scattered by water drops in all directions without being absorbed. However, water also absorbs infrared light from the Sun. The relative amounts of reflected and absorbed light provides information on the size of the drops.

Incident light is scattered from the surface of the drops, which means that the total amount of scattered radiation is proportional to the total surface area (i.e. $\sim r^2$) of the drops in a particular volume of cloud, where r is the radius of a drop. The absorption of radiation, however, occurs inside the drop and is therefore proportional to the total volume ($\sim r^3$) of the drops. In other words, the net reflected radiation – the total amount of scattered light divided by the total amount of absorbed light – is inversely proportional to the size of the cloud droplets ($\sim r^{-1}$).

Clouds with smaller water drops therefore reflect more infrared solar radiation back to space than clouds with larger drops. This dependence of the reflectance on drop size can be used to calculate the size of a drop simply by measuring the brightness of the cloud in the infrared. The resultant size, termed the "effective radius", is the total volume of all the drops divided by their total surface area.

Take to the air

Cloud-physics measurements are usually made using an aircraft equipped with suitable instruments. Indeed, these are now so routine that common standards apply. However, there is a snag when trying to work out the rain-forming processes inside clouds: it is impractical to make reliable measurements over large areas and short periods of time. A new approach was therefore needed.

In 1998 one of us (DR) and his graduate student Itmar Lensky developed a technique to meet this need. We used data in the visible band (at 0.65 μm) to select only the bright and therefore thick clouds, which are candidates for producing precipitation. We also used near-infrared radiation to infer the effective radius of the droplets by analysing the relative amount of absorbed and reflected light at that wavelength. Finally, using thermally emitted radiation at 10.8 μm and 12 μm, we measured the temperature at the tops of the clouds. Because colder temperatures exist at greater heights, we could use the measurements for relating the composition of the clouds to their heights. False colour was then assigned to the various absorption and emission bands to produce the images in figures 1 and 2.

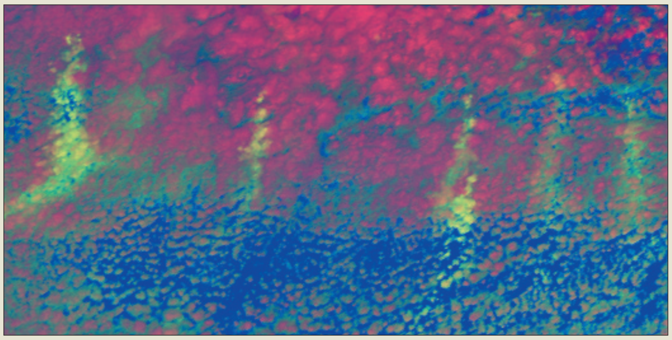
Our method was unique in that we could use it to work out how the size of droplets varied with temperature and height. We did this by looking at an area of the atmosphere that contained clouds at nearly every stage of development – from birth, through vertical growth, to maturation and dissipation. We were somewhat restricted in that the satellite used produced only one image of a given area every time it orbited the Earth. We therefore had to assume that studying clouds at different heights would give the same result as probing an individual cloud at different stages of its vertical development. This approach allowed us to obtain the characteristic droplet radius as the cloud developed and to define various regimes of droplet growth and precipitation. It thereby provided us with insights into the physical processes in clouds. We could also establish the temperature at which freezing first began in the cloud and when glaciation (i.e. conversion of water into ice) was complete. Most important of all, we could determine the temperature at which particles of precipitation size first develop in a cloud.

Our approach triggered a new era in cloud physics and led to immediate payoffs. For example, it indicated that, contrary to conventional wisdom, deep cumulonimbus clouds in many regions of the globe remain supercooled to nearly –38 °C. We then used a Learjet cloud-physics aircraft to try to validate comparable satellite inferences for clouds in Texas and Argentina. In both regions, we found that the clouds had as much as 5 g m^{-3} of water near –38 °C – the temperature at which water drops spontaneously freeze without the need for ice nuclei. At lower temperatures, virtually all of the water was found to be frozen, in agreement with theory and laboratory measurements.

We then examined clouds that were ingesting smoke from huge fires raging in Indonesia, as well as pollution from three industrial sources in Australia. In all of the cases, the clouds developed no particles of precipitation size until very low temperatures were reached. Coalescence of droplets was almost entirely absent. Ice processes were badly affected, with ice forming only at great heights and low temperatures. These studies suggest that the amount of rain produced by cumulonimbus clouds in such circumstances can be cut in half – although because the method looked at only the tops of clouds, it did not actually *prove* that the amount of precipitation is directly affected by pollution aerosols.

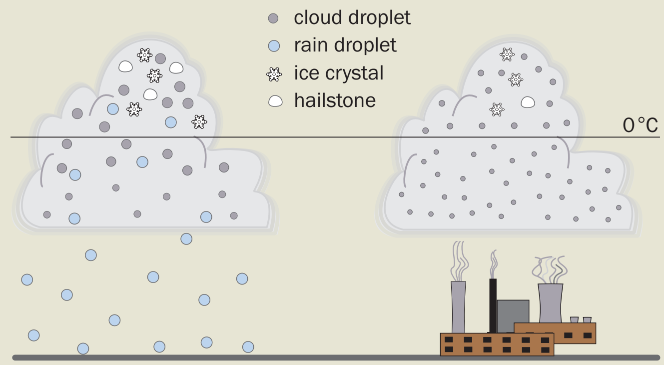
The launch of NASA's Tropical Rainfall Measuring Mis-

2 Pollution over Canada



An AVHRR image taken at 20:12 GMT on 20 July 2000, showing five pollution tracks staining an otherwise pristine cloud deck in north-central Manitoba, Canada. Polluted regions (clouds with tiny water drops) are light green and yellow, while unpolluted regions (clouds with larger drops) appear pink, magenta and purple. After receiving and processing this image, we identified the sources of the pollution, the largest (extreme left) being a huge smelting plant. The image is 550 km by 250 km.

3 Effects of pollution



Clean clouds have fewer water droplets per unit volume than polluted clouds, although the size of the droplets in clean clouds increases quickly with height above the base of the cloud. Polluted clouds have a larger number of smaller drops, and their size increases only slowly with height. The small size of the drops in the polluted clouds slows their conversion into rainfall.

sion (TRMM) satellite changed all of that. It can measure rainfall levels at various heights in the tropics, providing a way of estimating how the latent heat of condensation varies with altitude in different areas. This information helps us to understand how this heat drives the circulation of the global atmosphere. The TRMM satellite orbits the Earth between 35 degrees latitude north of the equator and 35 degrees south, observing the clouds and precipitation over the global tropics and subtropics. It carries a Visible and Infra Red Sensor (VIRS), which is similar to the Advanced Very High Resolution Radiometer sensors on the NOAA's polar-orbiting satellites. Our technique, however, works equally well with VIRS images.

Unique features of the TRMM satellite are its precipitation radar (PR) and its passive microwave imager. The PR works like a weather radar, transmitting radio waves that penetrate the clouds; the difference being that the waves are reflected back by precipitation inside and beneath the cloud. The PR receives the precipitation echoes and creates a three-dimensional map of the precipitation in the atmosphere. The passive microwave imager (TMI), meanwhile, measures the thermal radiation emitted at microwave frequencies. In contrast to the infrared that is emitted mostly from the top of the cloud, the longer-wavelength microwaves penetrate much further through the clouds, thereby revealing information about the whole cloud volume. The most interesting parameter that the imager provides us with is the total amount of water in the cloud.

Effects of cities

After the TRMM satellite was launched, our first step was to repeat the AVHRR studies of polluted areas using the satellite's VIRS data. As expected, the results were the same. Smoke and industrial air pollution were found to decrease the size of cloud particles, shut off collision-coalescence processes, delay in-cloud glaciation and slow the formation of precipitation. The PR data showed that precipitation was diminished or eliminated altogether in the polluted regions in clouds, while the TMI results showed that the clouds still retained their water in the form of cloud droplets (figure 4). Even though the polluted clouds were brighter and contained more water than the unpolluted clouds, they produced little or no precipitation – just as in the case of the ship tracks. Clearly smoking is hazardous to the precipitation health of the clouds.

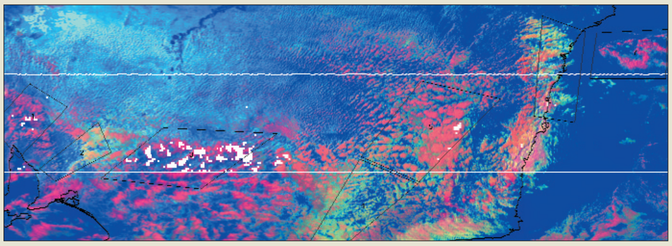
The effect of huge urban areas on clouds and precipitation is a separate issue. Studies by scientists at the Illinois State Water Survey and the University of Chicago have shown that precipitation and the frequency of thunderstorms and lightning are enhanced over and downwind of large urban areas, such as St Louis and Chicago. Such results appear to contradict the findings that pollution suppresses precipitation. However, attempts to correlate the urban-enhanced rainfall to air-pollution sources failed to show any relation. Analyses suggest that the urban-enhanced rainfall is instead due to the "heat-island effect" and to increased friction, both of which increase the tendency for air that has converged at a certain location for some time to rise and make room for more air to converge. The increased rising motion results in more cloud growth and rainfall over and downwind of urban areas. Under such conditions, any pollution sources within a city that might act to decrease the rainfall are overwhelmed by these more powerful dynamic forces. The dynamical effects diminish at short distances, but the pollution remains in the air and is transported large distances, where the detrimental effects of pollution on precipitation-forming processes in the clouds take over.

There is now no question that, in the absence of compensatory dynamic forces, pollution is bad for the precipitation health of clouds. This is true whether or not the pollution comes from industry or from massive conflagrations such as the Indonesian and Malaysian fires of 1997, or the forest fires that raged in the western US last summer. The focus now is on how extensive this problem might be, and on how it might affect the global climate.

Concerned future

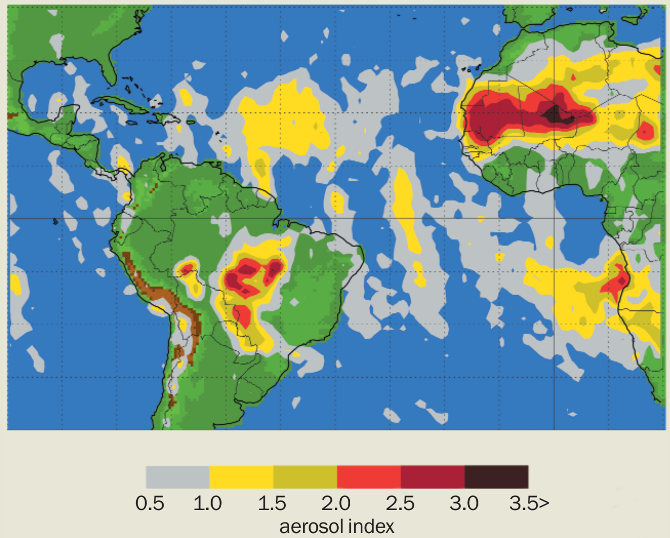
The more we look, the more we are convinced that pollution is much more of a problem than we thought. Studies of the daily variation in aerosol levels, as measured by NASA's Total Ozone Mapping Spectrometer, give us some idea of the extent of the problem (figure 5). Africa is an anomaly when it comes to pollutants and aerosols, especially on the northern and southern margins of the equatorial areas of the contin-

4 Slowing down precipitation



An image from NASA's Tropical Rainfall Measuring Mission at 04:44 GMT on 21 October 1998 over south-eastern Australia using data from the satellite's Visible and Infra Red Sensor. Our analyses showed that the effective radius of the cloud droplets in the polluted areas (yellow and green) remained below the minimum size of 14 μm required for precipitation, but that they were above this threshold in the unpolluted regions (dark pink and magenta). The white patches, which show precipitation echoes picked up by the satellite's Precipitation Radar, confirm the view that pollution hinders rainfall. No precipitation echoes were recorded in the polluted areas, whereas extensive areas of precipitation occur in the cleaner clouds. Further analyses of the radar data show that the pollution also shuts off the ice precipitation processes.

5 Smoke and dust in Africa and the Amazon



Relative amount of aerosols several kilometres above ground, as quantified by the "aerosol index". Data were obtained by NASA's Total Ozone Mapping Spectrometer on 13 September 1998. The relatively high levels of pollution above the Amazon and Congo basins are caused by smoke from forest fires in these regions.

ent. The relatively high levels of pollution can be explained by the almost continual presence of fires and dust-storms on the fringes of the "inter-tropical convergence zone", which moves north and south of the equator with the seasons. One can readily imagine these aerosols being drawn toward the equator into the migratory weather disturbances that move from east to west across the African continent. These aerosols certainly could influence the rainfall. The Amazon basin, on the other hand, has less aerosol pollution relative to Africa, except for the seasonal episodes of smoke from forest fires.

The higher pollution burden in Africa may explain why it only rains a little more than half as much in the Congo basin of Africa as it does in the Amazon basin of South America – even though satellite rainfall estimates for the two regions, based on their infrared presentations and on passive microwave rainfall algorithms, are about the same. Alan McCollum, Arnold Gruber and Mamoudou Ba from the NOAA, who made these observations, used our satellite technique to compare the cloud properties over the Amazon and equatorial Africa. They found that droplet coalescence occurs in 90% of the observed clouds above the Amazon, compared with just 50% for those above the Congo. This is a big difference, and – since clouds with coalescence typically produce twice as much rainfall as those without – could explain the disparity in rainfall. This disparity can be explained by greater aerosol pollution in Africa.

The Amazon and Congo basins together make up a significant fraction of the world's deep tropics over the continents. If natural and/or human pollution is shown to account for the differences in rainfall and lightning between the two regions, its effect on climate may be able to be quantified through computer simulations. Preliminary calculations by Hans Graf at the Max Planck Institute for Meteorology in Hamburg, Germany, reveal that the climate system is very sensitive to the impact of air pollution on precipitation.

Responding to pollution

We must therefore live with the fact that pollution is bad for the precipitation health of clouds. This has serious potential implications for the availability of water resources, which might be compromised, especially in the most densely populated areas of the tropical and subtropical world, where people depend on this water for their livelihoods. It also has serious implications for the global climate by decreasing and/or redistributing the rainfall, particularly where precipitation originates from convective clouds.

The changes in precipitation distribution must be linked to changes in the release of latent heat, which drives the global circulation. A change in the global circulation is a likely outcome. If this happens, these changes must already be with us and could possibly explain some of the oddities of recent climatic events. These changes are in addition to those induced by the increased greenhouse gases, which were at the focus of the recent climate-change conference in the Hague. These new insights will no doubt feature in future debates on climate change and the impact of pollution on the environment, with water resources at the top of the list.

Further reading

J A Coakley, R L Bernstein, and P R Durkee 1987 Effects of ship stack effluents on cloud reflectivity *Science* **237** 1020

H F Graf, D Rosenfeld and F Nober 2000 The possible effect of biomass burning on local precipitation and global climate *13th Int. Conf. on Clouds and Precipitation (Reno, NV)* (World Meteorological Organization) p882

D Rosenfeld 1999 TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall *Geophysical Res. Lett.* **26** 3105

D Rosenfeld 2000 Suppression of rain and snow by urban and industrial air pollution *Science* **287** 1793

D Rosenfeld and I Lensky 1998 Space borne based insights into precipitation formation processes in continental and maritime convective clouds *Bulletin American Meteorological Soc.* **74** 2457

D Rosenfeld and W L Woodley 2000 Convective clouds with sustained highly supercooled liquid water down to –37.5 °C *Nature* **405** 440

Tropical Rainfall Measuring Mission Web site trmm.gsfc.nasa.gov

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