Smoke (BC) from Pyro-Cb fires in Alaska.

9 July 2004, 14:54 UT, 36,000 feet, North Labrador
Ship tracks over the North Pacific

Red: Visible reflectance
Green: 3.7 µm reflectance
Blue: 11 µm temperature
Suppression of Rain and Snow by Urban and Industrial Air Pollution
(Rosenfeld, 2000, Science)

VIRS painting yellow pollution tracks in the clouds over South Australia, due to reduced droplets size. PR shows precipitation as white patches only outside the pollution tracks, although clouds have same depth.

PR shows bright band in clean clouds. Therefore, pollution suppressed rain and snow in polluted clouds.

TMI shows ample water in the polluted clouds.

VIRS retrieved effective radius does not exceed the 14 µm precipitation threshold in polluted clouds within area 2 in the Australia image.
Red: Visible reflectance
Green: 3.7 µm reflectance
Blue: 11 µm temperature

23 May 2003
Northeast China
Visible

Hot spot of forest fire
23:30 UT, 28 May 2001

3-km Reflectivities

Echo Top Heights
3-km Reflectivities

Echo Top Heights

23:40 UT, 28 May 2001
3-km Reflectivities

Echo Top Heights

00:10 UT, 29 May 2001
Blue Ocean
DSD20021018_1a

Drop diameter [µm]
Warm rain evolution over the western tip of the Amazon, afternoon.
Smoky conditions
North of JPR, Noon.

DSD20021004_H1
DSD with height in Pyro cumulus
2002 10 01 < 4000 m
2002 10 04 > 4000 m
Aircraft measured Modal LWC cloud drop diameter as a function of height above cloud base, for the various aerosol regimes in Brazil [Thailand].

Andreae, M. O., D. Rosenfeld, P. Artaxo et al., 2004: Smoking rain clouds over the Amazon. *Science, 303*, 1337-1342.
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Deep convective clouds with sustained supercooled liquid water down to –37.5 °C

Daniel Rosenfeld & William L. Woodley

The burned Amazon
Dry and dark surface, Strong updraft

Moist surface, Weak Updraft

- Cloud drop
- Rain drop
- Ice crystal
- Ice precipitation

0°C

Updraft

- Moist surface
- Dry and dark surface
- Strong updraft
- Weak updraft
Cloud drop
Rain drop
Ice crystal
Ice precipitation

Dry and dark surface, Strong updraft

Moist surface, Weak Updraft

0°C

Updraft

0°C
The effect of aerosols on precipitation in clouds was calculated from the data of the image above. The **warm colors** represent efficient precipitation processes, while the **cold colors** represent suppressed precipitation, due to the pollution. The scale is the maximal cloud top temperature [°C] required for onset of precipitation.
Cloud drop
Rain drop
Ice crystal
Ice precipitation

Continental: Polluted, Suppressed rain, Strong updraft

Maritime: Clean, Fast rain, Suppressed updraft

0°C

Cloud drop
Rain drop
Ice crystal
Ice precipitation
Annual average lightning density [flashes km$^{-2}$]
Lightning prevail mostly over land, whereas rainfall is similar over land and ocean, indicates fundamental differences between continental and maritime rainfall.

*Can aerosols help explaining the fundamental differences in Continental vs. Maritime convection?*
Contrasting convective regimes over the Amazon: Implications for cloud electrification

E. Williams,¹ D. Rosenfeld,² N. Madden,¹ J. Gerlach,³ N. Gears,³ L. Atkinson,³ Et al.

“1.3. The Aerosol Hypothesis” [for cloud electrification]

“[8] The present study tests a distinctly different hypothesis for the contrast in lightning activity in continental and maritime clouds. This explanation, as proposed by D. Rosenfeld for this study, is based on another well-established contrast between continental and maritime boundary layers: the aerosol concentration.”

“[9] The aerosol hypothesis for the land-ocean lightning contrast is illustrated in Figure 2. In contrast with the dominant role of large particles in the traditional hypothesis, this idea focuses on the behavior of the smaller cloud droplets. Air drawn from the clean (polluted) boundary layer air will contain a small (large) number of large (small) droplets. Active coalescence and rainout of the cloud prevail in the warm portion of the maritime cloud, leading to the depletion of liquid water from the colder mixed phase region. A dominance of diffusional droplet growth and suppressed coalescence prevail in the continental CCN-rich clouds, preventing rainout and allowing liquid water to ascend to the mixed phase region where it plays a dual role. First, it can contribute to cloud buoyancy and the updraft strength by the latent heat of freezing. Second, it can contribute to the growth of graupel particles and catalyze the process of charge separation by ice particle collisions.

[10] In clouds with very large concentrations of small CCN the formation of the ice phase can be delayed to very high altitudes and low temperatures [Rosenfeld and Lensky, 1998; Rosenfeld,2000; Rosenfeld and Woodley,2002; Khain et al.,2001]. The delay in the ice formation to above the -20°C isotherm is likely to deprive the lower part of the mixed phase region of a key ingredient for charge separation in a temperature range where it is most potent [Takahashi,1978], and thereby addition of aerosols beyond a certain “optimum” may not enhance any more lightning, and may even decrease it with respect to that “optimum.””
Heavy smoke from forest fires in the Amazon was observed to reduce cloud droplet size and so delay the onset of precipitation from 1.5 kilometers above cloud base in pristine clouds to more than 5 kilometers in polluted clouds and more than 7 kilometers in pyro-clouds. Suppression of low-level rainout and aerosol washout allows transport of water and smoke to upper levels, where the clouds appear “smoking” as they detrain much of the pollution. Elevating the onset of precipitation allows invigoration of the updrafts, causing intense thunderstorms, large hail, and greater likelihood for overshooting cloud tops into the stratosphere. There, detrained pollutants and water vapor would have profound radiative impacts on the climate system. The invigorated storms release the latent heat higher in the atmosphere. This should substantially affect the regional and global circulation systems. Together, these processes affect the water cycle, the pollution burden of the atmosphere, and the dynamics of atmospheric circulation.
The hypothesis of dynamic invigoration by delaying precipitation:

“(i) Blue ocean: Low concentrations of cloud condensation nuclei (CCN) in the clean atmosphere over the ocean produce clouds that are microphysically “maritime,” i.e., have relatively few but large drops that coalesce rapidly into raindrops. In addition, the typically weaker updrafts over the ocean allow more time for raindrops to grow and precipitate before reaching the freezing level. Early precipitation further suppresses the updraft and vigor of the convection.”

“(iii) Smoky clouds: Vegetation burning produces high concentrations of aerosols, a large fraction of which are capable of nucleating cloud droplets. This results in high concentrations of small cloud droplets that are slow to coalesce and precipitate. The lack of precipitation, except from the deepest clouds, keeps the particles in the air and creates a positive feedback for maintaining the smoky and rainless conditions. The lack of early precipitation allows updrafts to accelerate and transport cloud water in deep convection to the high and supercooled regions, where it can release additional latent heat of freezing, which it would not have delivered in the maritime case of early rainout. The added water is available for production of intense ice precipitation, hail, and lightning, creating more violent convective storms.”
Figure 2. Twelve-year (1989–2000) mean annual lightning flash density in flashes km$^{-2}$ yr$^{-1}$, centered on Houston, Texas (outlined in white), at a spatial resolution of 5 km. Galveston Bay is located to the southeast of the Houston urban area. The coordinates in decimal degrees of the bottom left corner are 28.75°N, 96.55°W and the top right, 31.1°N, 94.05°W.

Steiger et al., JGR 2002
Cloud-to-ground lightning enhancement over Southern Louisiana

Scott M. Steiger and Richard E. Orville  
GRL  2003

Figure 1. The fourteen-year (1989–2002) mean annual cloud-to-ground (CG) lightning flash density in flashes km$^{-2}$ yr$^{-1}$ at a spatial resolution of 5 km. The urban areas of Lake Charles (LCH) and Baton Rouge (BTR), LA are outlined in black. The coordinates in decimal degrees of the lower left corner are 28.81 N, 95.1 W and the upper right, 33.56 N, 90.05 W.

Figure 5. The density (km$^{-2}$) of sources that emitted particulate matter less than 10 μm in diameter (PM10) over Louisiana in 1999. The outlines are the same as for Figure 1. The coordinates in decimal degrees of the lower left corner are 29.0 N, 94.34 W and the upper right, 33.1 N, 89.54 W.
Disdrometer measured DSD of continental and maritime rainfall, as micophysically classified by VIRS overpass. The DSD is averaged for the rainfall during +- 18 hours of the overpass time. The disdrometers are in Florida (Teflun B), Amazon (LBA), India (Madras) and Kwajalein.

Application of TRMM Z-R shows a near unity bias in maritime clouds, but overestimates by a factor of 2 rainfall from continental clouds.

Rosenfeld and Ulbrich, Met. Monog., 2003
Continental aerosols increase convective updrafts and downdrafts. (Khain et al., 2003)

Equatorial maritime air mass: GATE QUADRA Day 261
Smoke suppresses rainfall only initially while strongly invigorating the updrafts. (Khain et al., 2003)
Simulation of extremely continental high base (11° C) clouds  
(West Texas, August 1999)
The “polluted” Cb can have nearly adiabatic water until –38°C Therefore, it has very low precipitation efficiency.

**Letters to Nature**

**Deep convective clouds with sustained supercooled liquid water down to –37.5 °C**

Daniel Rosenfeld & William L. Woodley†

Vertical profiles of maximum values of (a) cloud water content (CWC), (b) the mean volume diameter and (c) droplet concentration observed in the control run at 250 m below the growing cloud top, presented on the background of the aircraft observations (Rosenfeld and Woodley, 2000), shown in green (CWC>0.2 gm\(^{-3}\) and black (CWC<0.2 gm\(^{-3}\)). The blue and red squares denote model calculated values for the low and high CCN concentrations. The black square in the concentration panel (c) denotes the model ice concentrations.
West Texas: rain accumulation

Depletion of rain in smoky air
Simulation of PRESTORM Alabama squall line
Prestorm Alabama:

Time evolution of accumulated rain

Squall line forms in smokey air!

No squall line forms in clean air!
Scheme of aerosol effects on precipitation

Accumulated rain

Aerosol concentration

Maritime & moderate (wet)
continental clouds
(like GATE and PRESTORM)

Dry unstable situation
(like Texas clouds)
AEROSOL IMPACT ON THE DYNAMICS AND MICROPHYSICS OF CONVECTIVE CLOUDS

A. Khain, D. Rosenfeld and A. Pokrovsky

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The Role of Sea Spray in Cleansing Air Pollution over Ocean via Cloud Processes

Daniel Rosenfeld, Ronen Lahav, Alexander Khain, Mark Pinsky

Particulate air pollution has been shown to strongly suppress precipitation from convective clouds over land. New observations show that precipitation from similar polluted clouds over oceans is much less affected, because large sea salt nuclei override the precipitation suppression effect of the large number of small pollution nuclei. Raindrops initiated by the sea salt grow by collecting small cloud droplets that form on the pollution particles, thereby cleansing the air. Therefore, sea salt helps cleanse the atmosphere of the air pollution via cloud processes. This implies that over oceans, the climatic aerosol indirect effects are significantly smaller than current estimates.
The difference between the cloud clear air equivalent anthropogenic aerosol sulfate concentrations on the two days is nearly an order of magnitude, but in absolute terms it is only 1 µg m⁻³. Astonishingly, this small amount of aerosol can reduce the snowfall rate up to 50%.

Evidence is presented to demonstrate the possible magnitude of the secondary indirect aerosol effect on precipitation rates from cold mixed-phase clouds in mountainous regions where a seeder-feeder cloud couplet is present. Changes as small as 1 µg m⁻³ in CCN aerosol concentration can cause significant changes in cloud properties and precipitation efficiencies. (Quoted from Borys et al., GRL 2003).
Legend

1. Ukiah
2. Lake Spaulding
3. Bowman
4. Boca
5. San Francisco
6. Sacramento
7. Pacific House
8. Cluster of snow packs in the divide line downwind to Sacramento
9. Woodfords
10. Fresno
11. Grant Grove

Cluster of stations: Hills downwind L.A / L.A
Ending / Starting ratio = 1.80 / 2.14 = 0.84

\[ y = 14.25 - 0.006x \quad R = 0.27 \quad P = 0.03 \]

Ratio between Lake Spaulding to Ukiah
Ending / Starting ratio = 1.85 / 1.85 = 1.00

\[ y = 1.5703 + 0.00001x \quad R = 0.02 \quad P = 0.90 \]
Analysis of the orographic factor trends according to the synoptic conditions:

- 3°C: Expected Clouds Temperatures at 700 mb on rainy days - Los Angeles and San Diego areas

![Analysis Diagram](image)
The annual ratios of precipitation (Ro) between Cuyamaca and San Diego for clouds occurring when T > -3°C at 700 hpa (mainly frontal and warm air mass) and when T ≤ -3°C (mainly cyclonic post frontal clouds).
Cluster of stations: Judean Hills / Judea plains
Ending / Starting ratio = 1.17 / 1.38 = 0.85

\[ y = 10.7 - 0.005x \quad R = 0.54 \quad P = 0.0006 \]

Startind / End ratio = 1.6/1.63 =0.98

\[ y = -0.41486 + 0.0010528x \quad R = 0.05304 \]
Topographic cross section showing the effects of urban air pollution on precipitation as the clouds moves from west to east across the mountains.
Changes in precipitation ratio and trends:

Western United States
Winter:
The ratio between Ogden Sugar factory to Pine View
Ending / Starting ratio = 0.90

Ratio Ogden Sugar factory to Pine View Ending / Starting ratio = 0.90

Ratio Silver Lake Tooele Ending / Starting ratio = 0.67

Summer:
Ratio Ogden Sugar factory to Pine View Ending / Starting ratio = 1.07

Ratio Silver Lake Tooele Ending / Starting ratio = 1.00

Ratio Salt Lake City salt lake plant Ending / Starting ratio = 1.01

Winter:
The ratio between City plant and Salt Lake City
Ending / Starting ratio = 0.89

\[ y = 11.813 - 0.005x \]
\[ R = 0.32 \]
Long-range trends of the winter (October – April) precipitation measured in Tooele (A) and in the downwind hilly station of Silver Lake (B); the correlation between these two stations (C) and the ratio of precipitation (Ro) measured between them (D).

Winter: Trend analysis for Tooele
Ending / Starting ratio = 12/8.5 = 1.23

\[ y = -120.12 + 0.066072x \quad R = 0.41 \]

Winter: Trend analysis for Silver Lake Brighton
Ending / Starting ratio = 26.83/30.01 = 0.86

\[ y = 194.24 - 0.083525x \quad R = 0.21 \]

Ratio Silver lake Tooele
Ending / Starting ratio = 2.30/3.45 = 0.67

\[ y = 16.626 + 1.1993x \quad R = 0.46 \]
Winter:
Ending / Starting ratio = 1.38 / 1.71 = 0.81

\[ y = 13.462 - 0.0060374x \]
\[ R = 0.42 \]

Summer:
Ending / Starting ratio = 1.23 / 1.27 = 0.97

\[ y = 2.1305 - 0.0004339x \]
\[ R = 0.03 \]
Long-range trends of the winter precipitation (Oct- April) measured in Hayden (A) and in the downwind hilly station of Steamboat springs (B); the correlation between these two stations (C) and the ratio of precipitation (Ro) measured between them (D)

Congress noted with concern the new additional evidence, also presented at the 8th WMO Scientific Conference on Weather Modification, that was pointing to an apparent substantial reduction of the rainfall efficiency of clouds by plumes of smoke caused by biomass burning (agricultural practices, forest fires, cooking and heating) and industrial processes. Congress also noted the evidence that some non-raining clouds could regain their raining ability once they moved over oceans or large bodies of water (such as the Aral Sea) because sea-salt was then mixed into the clouds and overrode the detrimental effect of the smoke particles. Therefore, Congress recommended CAS to establish an ad-hoc Group on Biomass Burning and Smoke Plumes in general, charge it to prepare a summary report for information of the Members, addressing relevant issues such as (1) the climatology of smoke and weather active aerosol (Cloud Condensation Nuclei or CCN) plumes, (2) the in situ and remote measurement of CCN and cloud droplet concentrations, (3) strategies to reduce biomass burning and hence the density of smoke plumes, and (4) the seeding procedures and evaluation methods to re-establish raining ability of clouds affected by smoke plumes, and CAS to report to Fifteenth Congress.
IUGG Resolution Sapporo 10 July 2003:

Considering biomass burning from agricultural practices, household consumption and wildfires produces substantial quantities of aerosol particles that can increase small cloud droplet number concentration.

Realizing that higher concentrations of small cloud droplets affect their coalescence and the formation of precipitation and thus the water supply.

Welcoming the recognition of the potential effect of all aerosol sources on precipitation by Congress XIV of the World Meteorological Organization, WMO, in May 2003 and its projected actions focused on biomass burning plumes.

Urges the scientific community to undertake systematic studies of the impact of biomass burning aerosol on precipitation formation on all scales. Feedback effects on climate as well as the competing effects of industrial fine particle aerosols and natural coarse particle aerosols such as sea salt and soil dust should be included.

Recommends that a body be established to undertake an international program of study and assessment of the rain related effects of biomass burning in collaboration with WMO and other international organizations.

that this body creates a mechanism to assemble the scientific evidence needed to lay the groundwork for a UN sponsored conference on pollution effects on precipitation and hence water supply.

that this body reports in the IUGG Newsletters and the GA in 2007 on the step taken and the progress made.