Effects of biomass-burning-derived aerosols on precipitation and clouds in the Amazon Basin: a satellite-based empirical study

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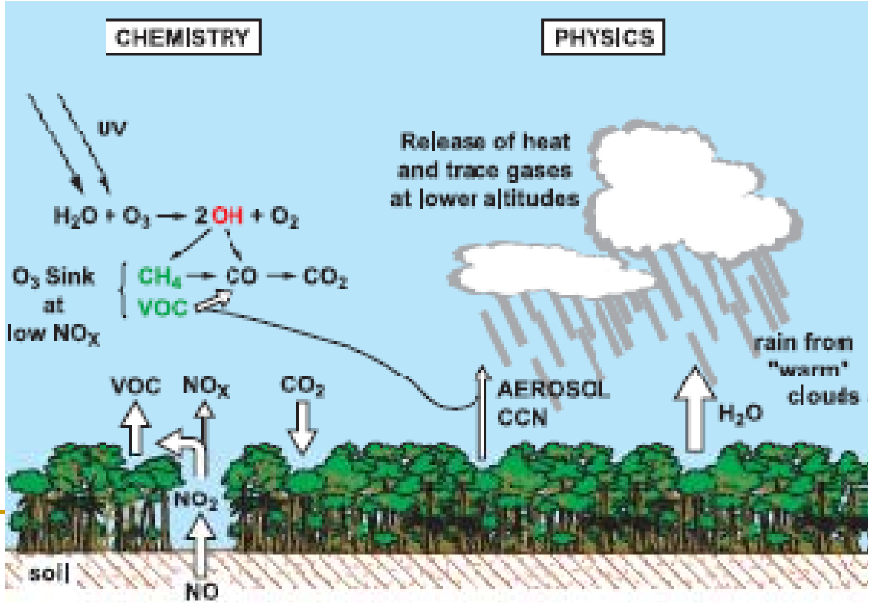
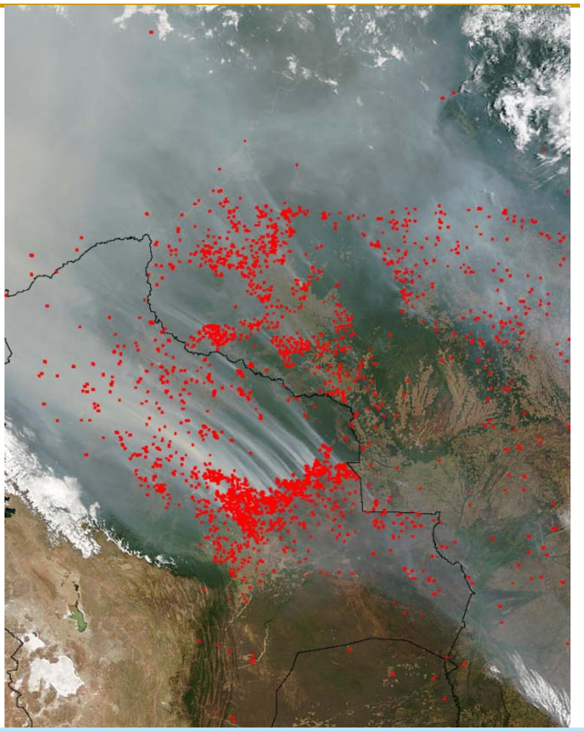
Background

1. Biogenic & Pyrogenic Aerosols

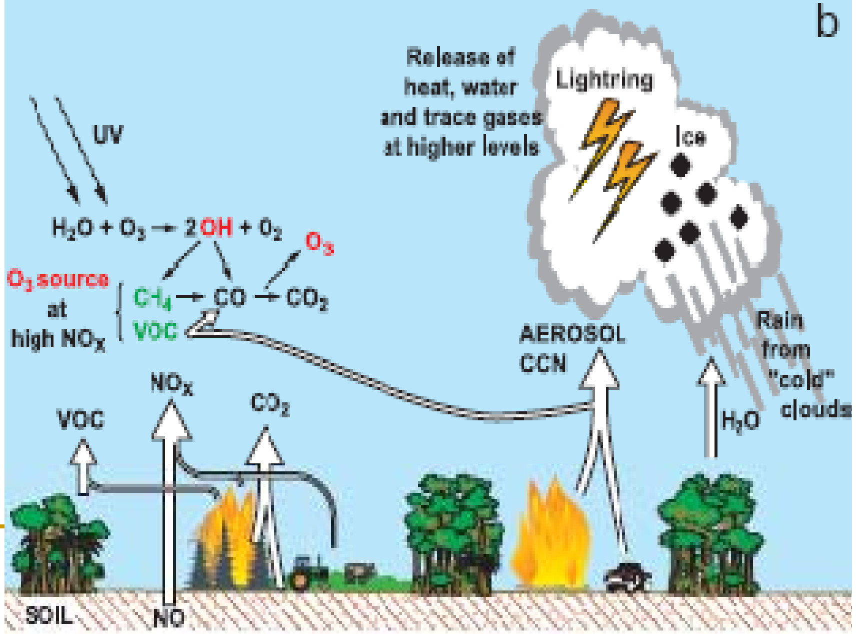
Pristine Environment: biogenic aerosols are directly emitted by vegetation (microbial particles like bacteria, fungi and pollen, etc) or indirectly from gas-to-particle conversion from biogenic gaseous precursors, or volatile organic compounds (VOC), including methane, isoprene and monoterpenes, etc. This conversion is mainly the oxidation of these VOCs by hydroxyl radical and ozone, etc.



Biomass Burning: It can emit greenhouse gases, VOC, NOx, etc. smoke is a mixture of ash particles, soot (BC), organic materials and inorganic salts. BC/OC ratio depends on plant type and combustion phase.



Both biogenic and pyrogenic aerosols consist largely of organic material (~80%), about 60% of which is water-soluble. Soluble inorganic salts represent the rest part. Thus, they are similar in composition and solubility, which results in similar CCN efficiency and CCN properties.



2. Previous Studies

- Cloud droplet radius is reduced due to biomass burning based on satellite measurements (Kaufman&Fraser 1997)
- Warm-rain processes are shut down in biomass burning event (Rosenfeld, 1999).
- Cloud droplet size is reduced and precipitation is delayed in smoky clouds, but stronger storms are produced (Andreae 2004).
- ……

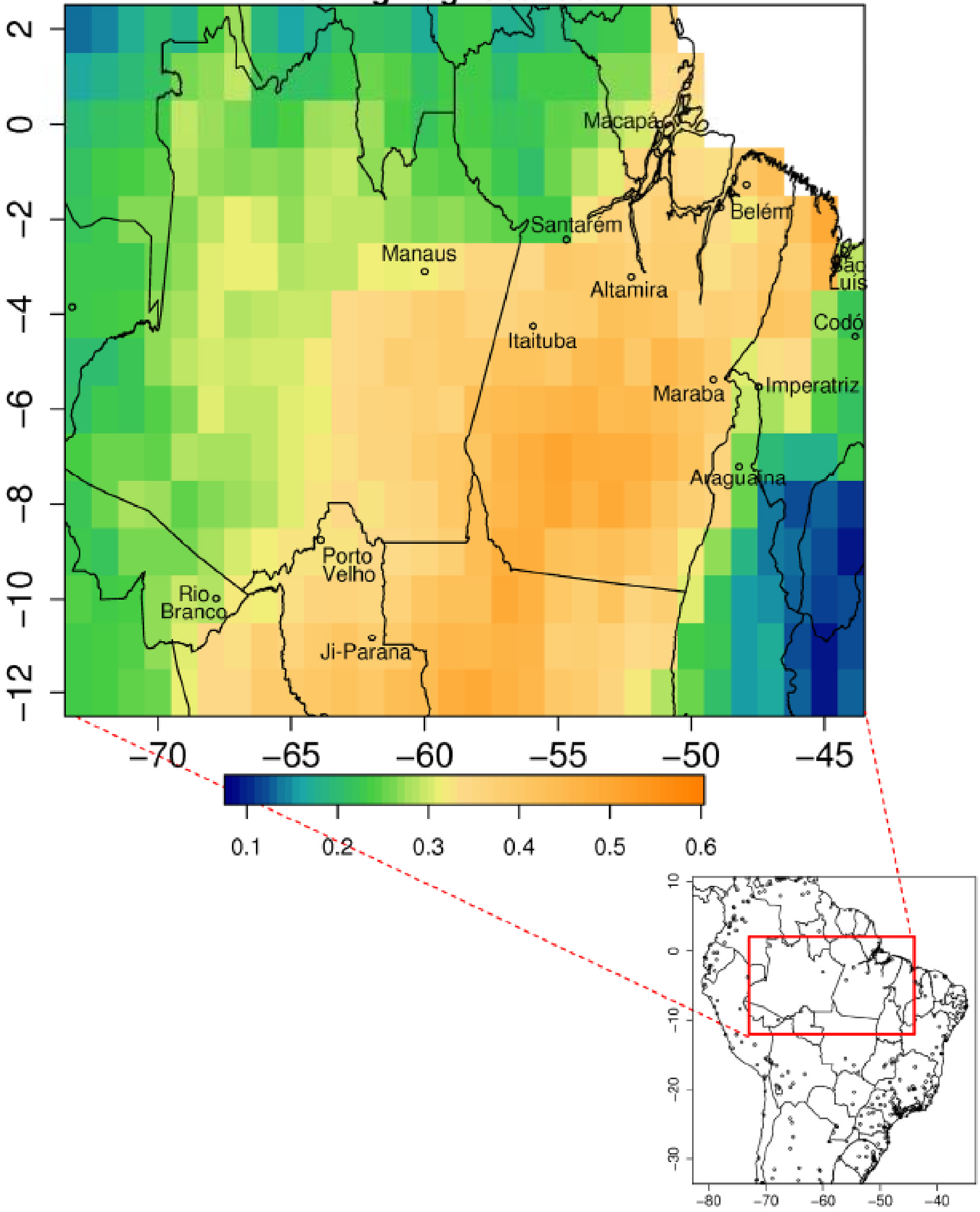
→ Net effect of aerosols on total precipitation is unknown

- The 1st indirect effect: enhanced cloud albedo (Twomey, 1977)
- The 2nd indirect effect: enhanced cloud lifetime and amount (Albrecht, 1989)
- Semi-direct effect: stabilization of atmosphere and suppression of convection (Hansen, 1997)
- Low-level cloud fraction is enhanced over the ocean (sekiguchi, 2003)
- Scattered cumulus cloud cover is reduced due to biomass burning aerosols in Amazon (Koren, 2004)
- ……

→ Inconclusive relationship between coverage of all cloud types and aerosols; no studies on cloud top temperature and pressure

3. This Study

1. All clouds are included; only dry season (Aug-Oct, 2000& 2003) is considered to ensure large signal of aerosol loading and reduce the effect of seasonal variability.
2. This paper focuses on the statistical relationship between the aerosol optical depth and precipitation and cloud properties (cloud fraction, cloud top pressure and temperature, etc.)


Spatial Distribution of Average MODIS Aerosol Optical Depth during Aug~Oct 2000

Data

1. Precipitation

TRMM 3G68 land product (TMI 2A12 & PR 2A25)

TRMM Microwave Imager (passive):

Channel: 10.7, 19.7, 21.3, 37, 85.5 GHz

Resolution: 63km*37km ~ 7km*5km

Measurement: over ‘cold’ oceans, high SNR enables measurement of clouds and rain drops; over ‘warm’ lands, low accuracy except at 85.5GHz channel, the land emitted microwave is scattered by ice, used to measure ice content.

Algorithm: Bayesian inverse method

Precipitation Radar (active):

Channel: 13.8 GHz

Resolution: 4km; 215km swath

Measurement: it measures backscattered signal and produce vertical profile of precipitation.

2. Aerosol Optical Depth (AOD):

MOD04_L2, Collection 4 (at 0.55um)

Algorithm: dark land target method, *Kaufman et al 1997*

Coverage: global over oceans; nearly global over lands

Resolution: daily; 10km*10km (nadir)

Primary data format: HDF-EOS

Processing level: 2 (geophysical values derived from level 1 calibrated and geolocated raw radiance)

Additional information: collection 4 represents a significant improvement over collection3, particularly in southern Africa, where there was an underestimate of AOD due to an underestimation of aerosol absorption in this region.

3. Clouds

MOD35_L2, Collection 4

Cloud fraction: 1km*1km; cloud mask method, *Ackerman etal 1998, 2002*

Cloud top P/T: 5km*5km; radiance ratio method, *Kidder&Vonder Haar, 1995*

Cloud phase: 5km*5km; bispectral infrared algorithm, *Platnick etal 2003*

Cloud droplet effective radius and water path (liquid+ice): 1km*1km *Platnick etal 2003*

The contaminated pixels by aerosols are removed in calculating cloud fraction, Re and water path in the cloud mask method.

4. Atmospheric Conditions

NCEP/NCAR reanalysis data

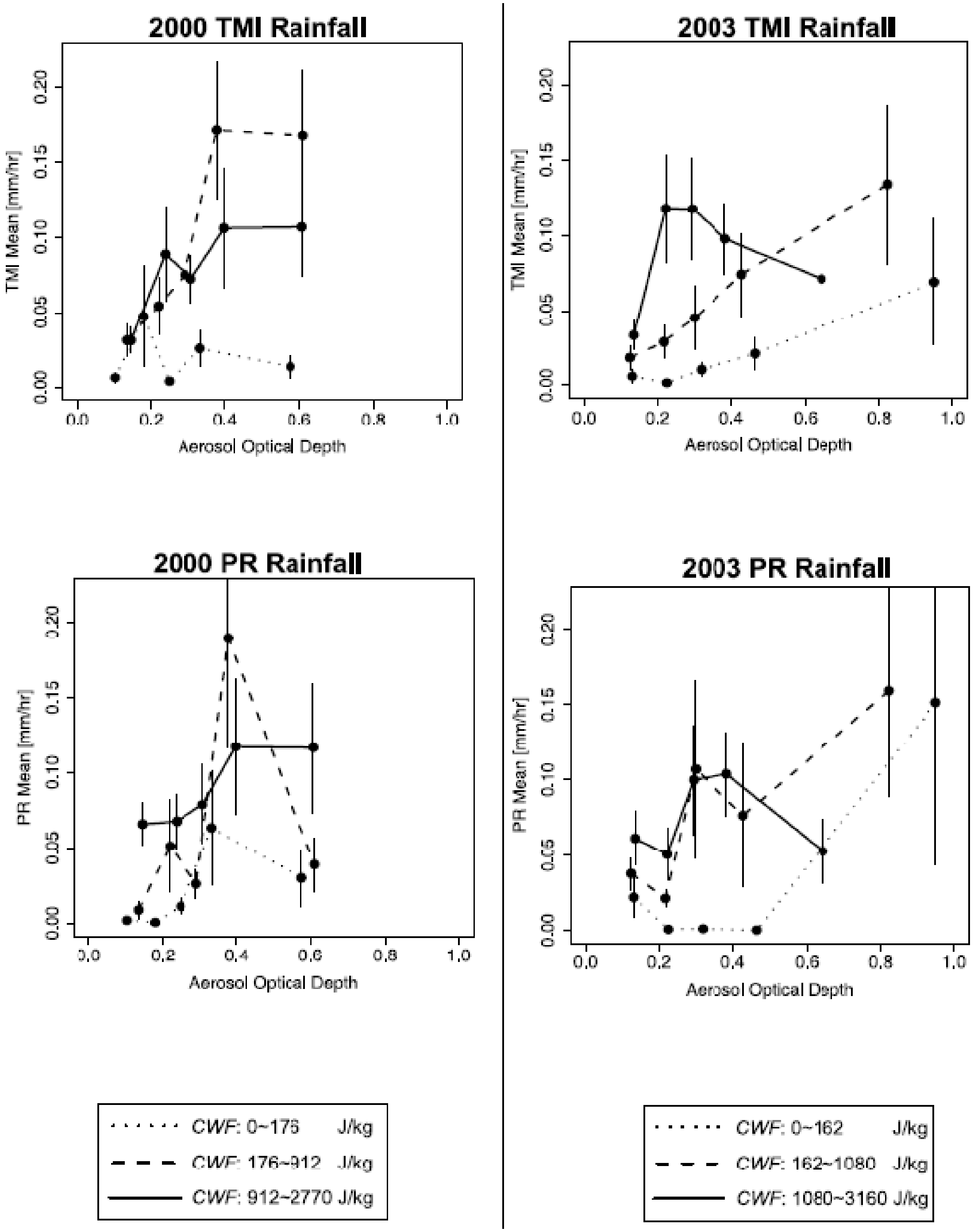
Resolution: 2.5° * 2.5°, 6 hourly

Usage: to account for synoptic-scale forcing of buoyancy generation and precipitation, and to separate such factors from aerosol effects.

Criterion: cloud work function (CWF) is a measure of both CAPE (positive buoyancy) and the effect of entrainment (negative buoyancy). It's used to divide the data into several groups accounting for different levels of synoptic-scale forcing (buoyant convection).

Statistics

1. Generally, rainfall increases with AOD. large scatter may result from uncertainty in observations and low resolution of CWF.
2. Low CWF → weak buoyant convection → low rainfall
3. High CWF doesn’t necessarily cause large rainfall, due to increased AOD

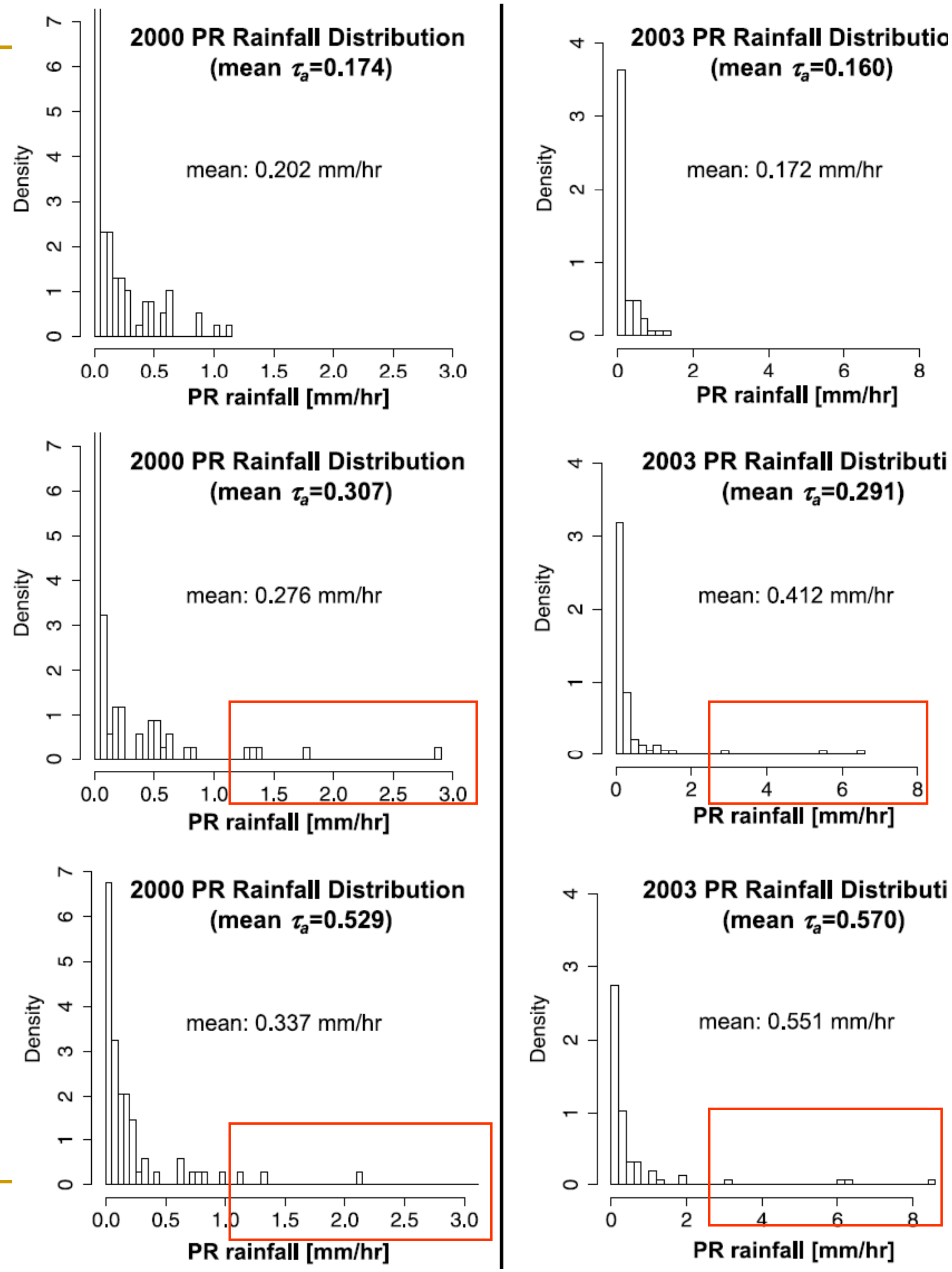


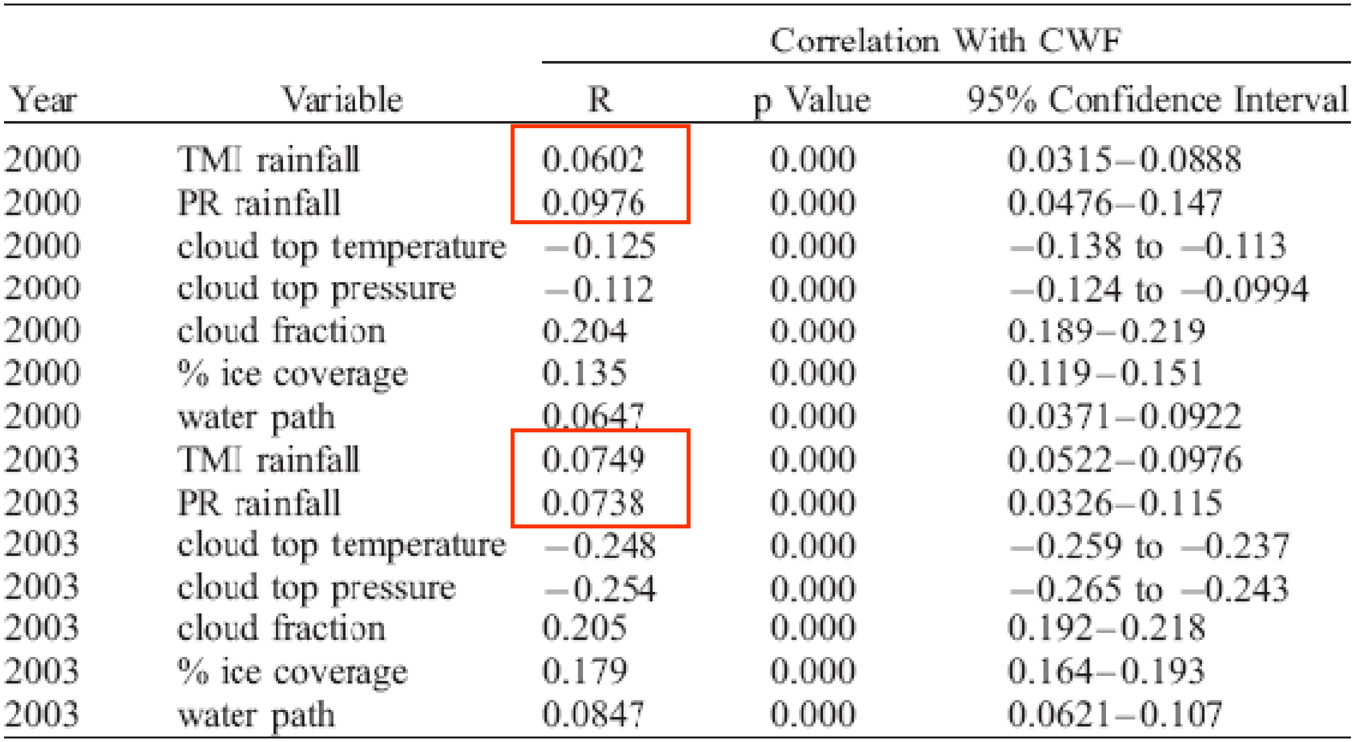
1. The increase of precipitation with larger AOD ← early suppression of warm-rain process; but more intense cold-rain process induced by the transportation of moisture upward and latent heat released from freezing.

2. Uncertainties:

TMI signal is obscured by surface emission.

PI detects rainfall in only one frequency.

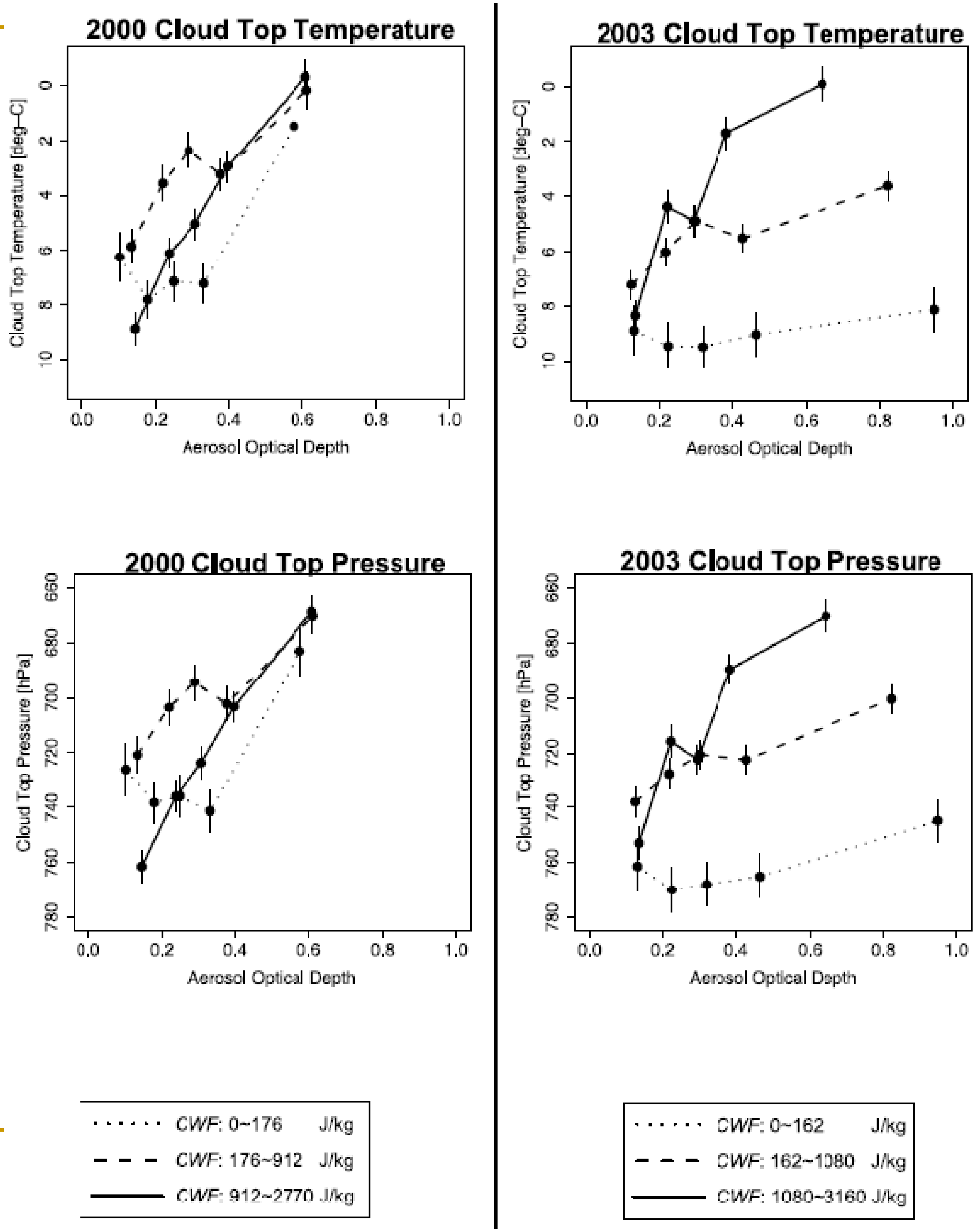




Year	Variable	Correlation With CWF R	 p Value	 95% Confidence Interval
2000	TMI rainfall	0.0602	0.000	0.0315–0.0888
2000	PR rainfall	0.0976	0.000	0.0476–0.147
2000	cloud top temperature	−0.125	0.000	−0.138 to −0.113
2000	cloud top pressure	−0.112	0.000	−0.124 to −0.0994
2000	cloud fraction	0.204	0.000	0.189–0.219
2000	% ice coverage	0.135	0.000	0.119–0.151
2000	water path	0.0647	0.000	0.0371–0.0922
2003	TMI rainfall	0.0749	0.000	0.0522–0.0976
2003	PR rainfall	0.0738	0.000	0.0326–0.115
2003	cloud top temperature	−0.248	0.000	−0.259 to −0.237
2003	cloud top pressure	−0.254	0.000	−0.265 to −0.243
2003	cloud fraction	0.205	0.000	0.192–0.218
2003	% ice coverage	0.179	0.000	0.164–0.193
2003	water path	0.0847	0.000	0.0621–0.107

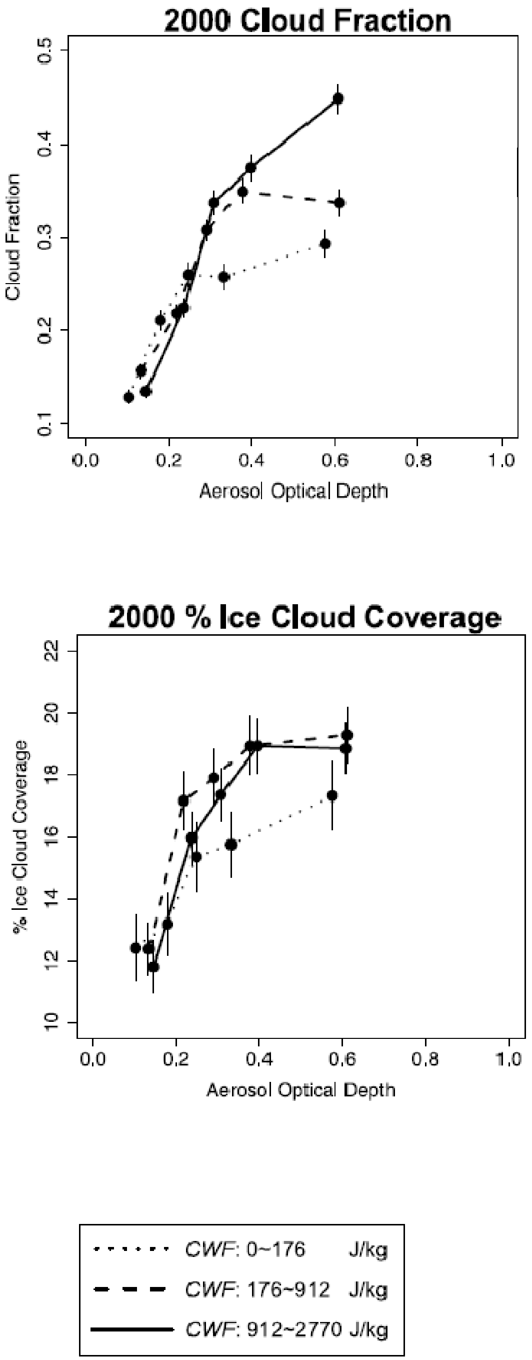
1. Generally, lower rainfall is associated with smaller CWF values.
2. But, the correlation between CWF and rainfall is weak. This may result from the coarse grid and time spacing (2.5° * 2.5°, 6 hourly) of NCEP reanalysis data, which fails to capture the subgrid scale convective clouds and precipitation.
3. Large errors also exist in the reanalysis moisture fields in the tropics.

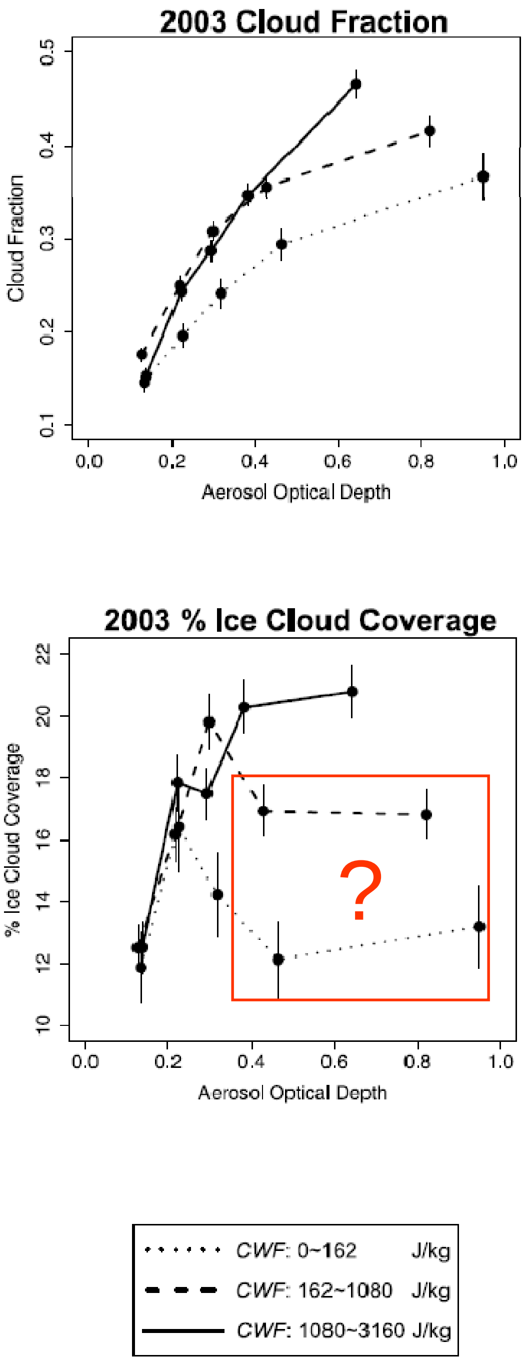
1. Increase AOD → increase cloud top height → lower cloud top T&P
2. Higher CWF → stronger updraft motion →higher cloud top → lower cloud top T&P

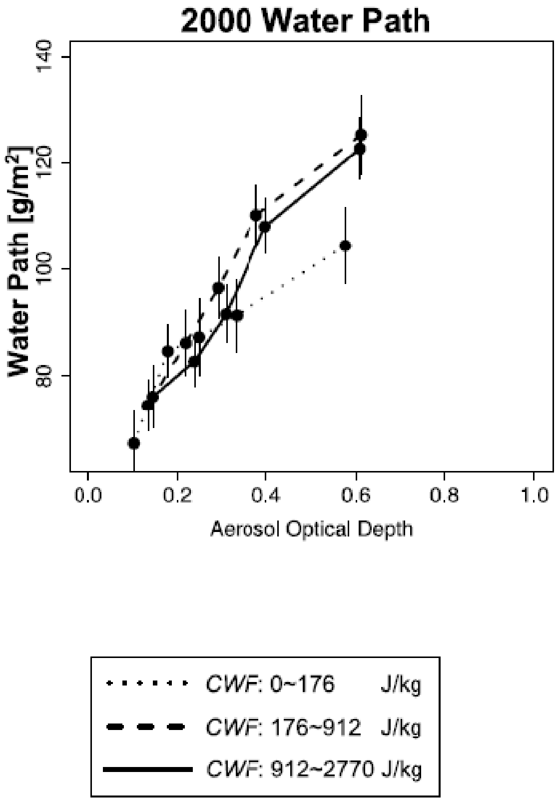


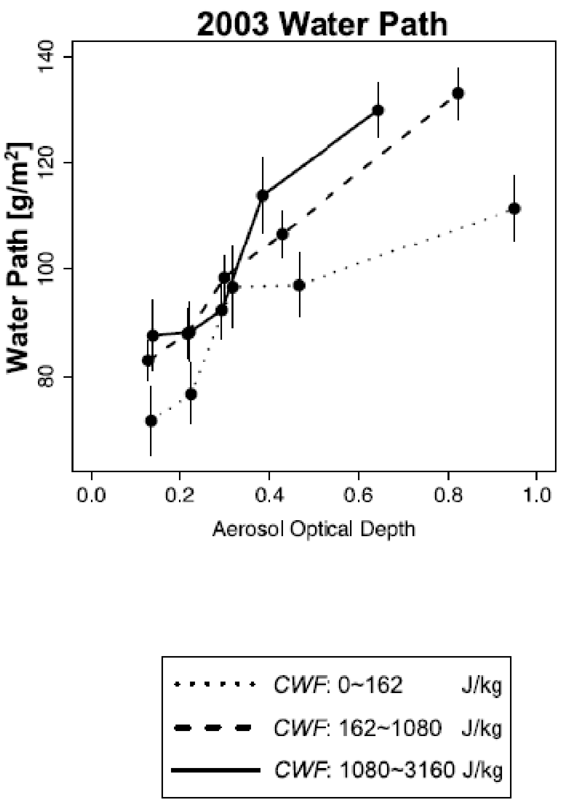
1. With larger AOD, cloud fraction increases (to 30%).
2. With larger CWF, cloud fraction increases faster (to 40%).
3. Ice cloud coverage increase with AOD.

4. Low-level cumuli was found to decrease with higher AOD (Koren, 2004), but the total cloud fraction increases with larger AOD in this study, which suggests that increased cloud fraction occurs at high altitude due to strong deep convection. This is also consistent with lower cloud top temperature and pressure, and higher ice cloud coverage.







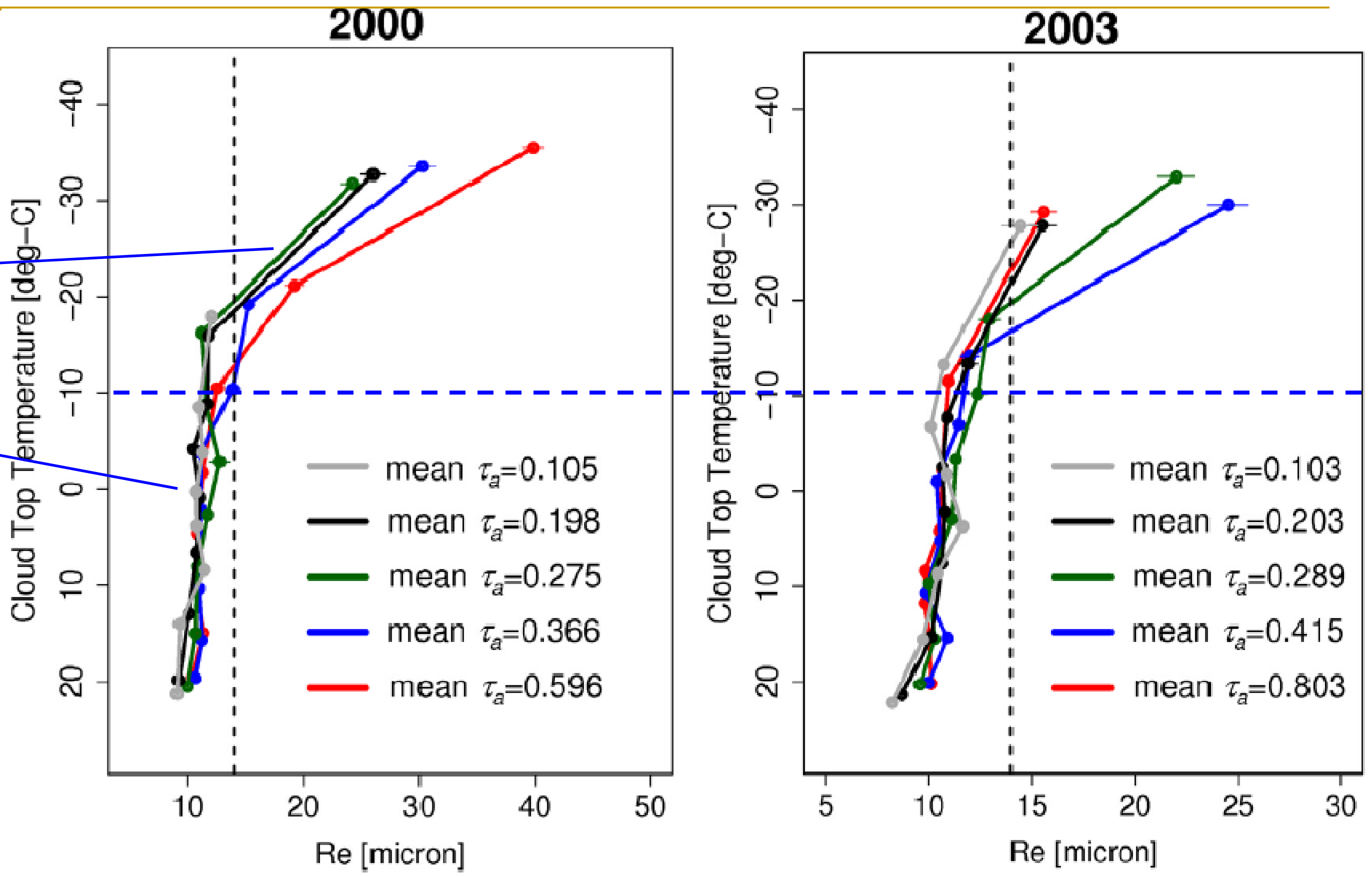


1. Integrated water path increases with AOD.
2. This may result from the increase of high-level clouds.

Significant test shows the distribution of rainfall, cloud top P/T, cloud fraction, water path and 2003 ice cloud coverage are altered with change AOD and CWF.

Droplet coalescence & ice formation

Diffusional growth



1. dRe/dT increases at higher altitude, indicating ice formation and mixing phase clouds.
2. Only slight decrease of Re with AOD in 2003 may result from strong convection and so increased water path and cloud fraction. Also, this study uses data from all regions and on all cloud types, differing from previous studies.

Summary

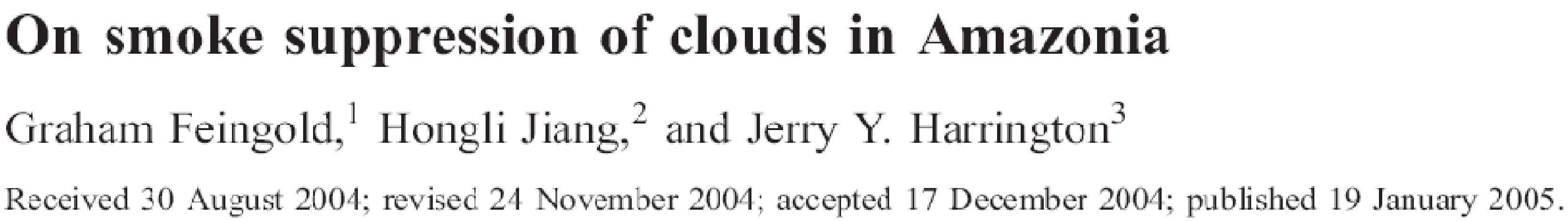
1. This study uses data on AOD, precipitation, cloud properties and atmospheric conditions to statistically analyze the relationships between rainfall&cloud and enhanced AOD.
2. This study focuses on (1) amazonian region covered mainly by tropical rainforest and affected only by biomass burning; (2) only the dry season in 2000 and 2003.
3. In the case of increase AOD, the observed results are (1) increased rainfall; (2) increase occurrence of intense rainfall events; (3) enhanced cloud cover; (4) elevated cloud top; (5) increased water path and (6) greater formation of ice.

Extended Thinking

It’s hard to explore the feedback of rainfall to aerosol concentration (precipitation scavenging), since this study uses averaged data over the whole dry season. But in individual rainfall event, there exists a bi-stability *(Andreae etal 2004):*

Pristine environment → warm rain process → efficient washout of aerosol particles → pristine environment favorable for warm rain process

Polluted by biomass burning → suppression of early rainfall → accumulation and vertical transport of aerosol



On smoke suppression of clouds in Amazonia

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Motivation

1. Semi-direct effect of absorbing aerosols (*Hansen etal 1997*) decreases the cloud fraction due to the stabilization of atmosphere and thus suppression of convection.
2. The location of absorbing aerosol is important: it reduces cloud water when residing in the boundary layer, and increase cloud water by reducing dry air entrainment when lying above the cloud layer (*Johnson etal 2004*).
3. Observations in Amazonia (*Koren etal 2004*) shows a reduction of cloud fraction due to absorbing smoke. The smoke can stabilize the atmosphere, and suppress the surface turbulent heat fluxes.
4. This study uses detailed LES model to evaluate the relative importance of different physical processes in changing cloud fraction, including atmospheric stabilization, droplet heating and surface flux modification.

3D Large Eddy Simulation

1. Model

Domain: 6km*6km*4.5km

Resolution: 100m*100m*50m

Running Time: 500 min with a step of 2 sec

Initialization: atmospheric sounding at local time 07:38, Sept.26, 2002, Fazenda, Brail

Cloud formation: 14 size bins for aerosol and 12 bins for cloud drops; CCN activation/drop condensation&evaporation/coalescence/sedimentation

Radiation scheme: 8 bands; smoke as a mix of soot and ammonium sulfate; lognormal size distribution; Qext&w0 (composition, H); w0 = 0.9 at 0.47um →quite absorbing!

2. Simulation Scenarios

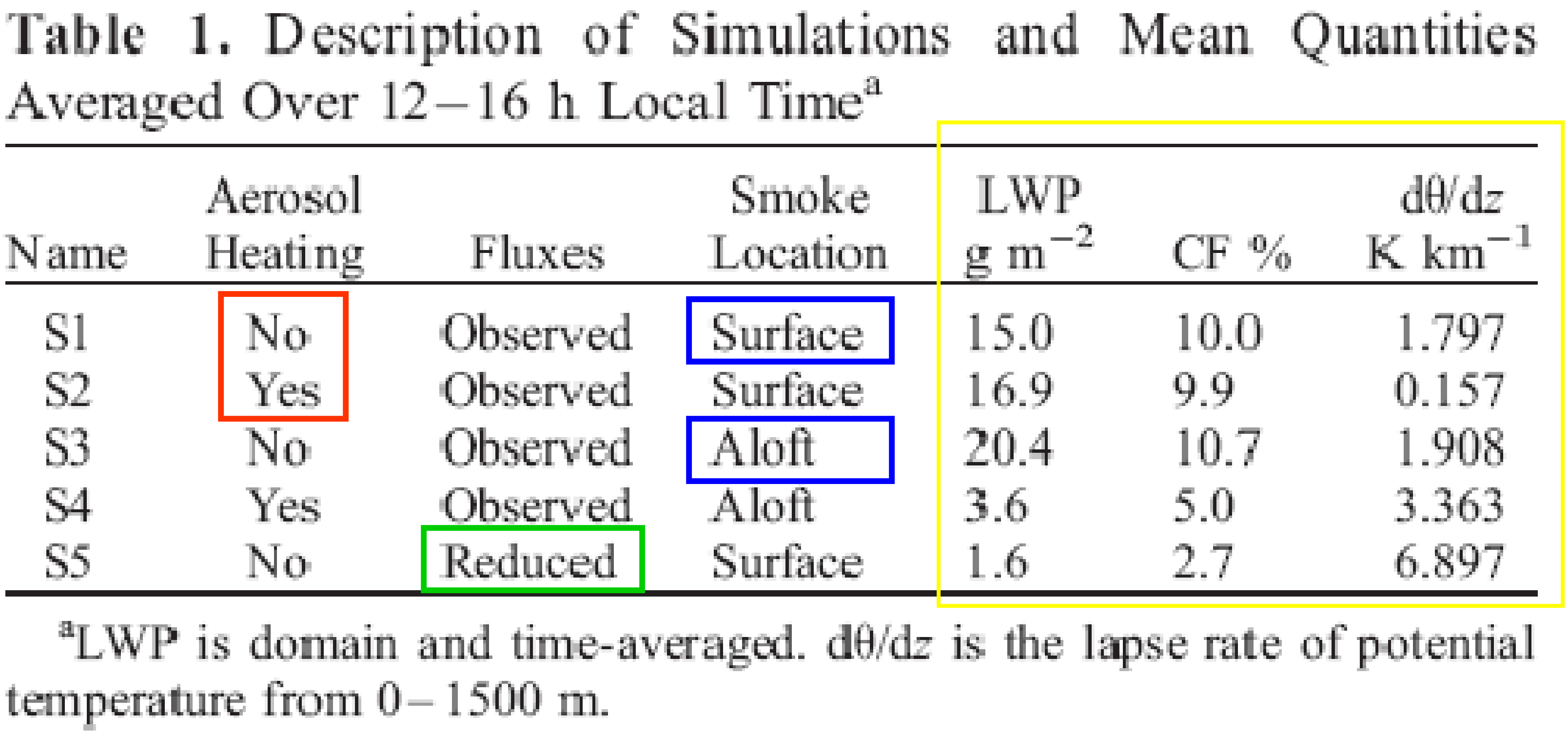


Table 1. Description of Simulations and Mean Quantities Averaged Over 12–16 h Local Time[a]

Name	Aerosol Heating	Fluxes	Smoke Location	LWP $g\ m^{-2}$	CF %	$d\theta/dz$ $K\ km^{-1}$
S1	No	Observed	Surface	15.0	10.0	1.797
S2	Yes	Observed	Surface	16.9	9.9	0.157
S3	No	Observed	Aloft	20.4	10.7	1.908
S4	Yes	Observed	Aloft	3.6	5.0	3.363
S5	No	Reduced	Surface	1.6	2.7	6.897

[a] LWP is domain and time-averaged. $d\theta/dz$ is the lapse rate of potential temperature from 0–1500 m.

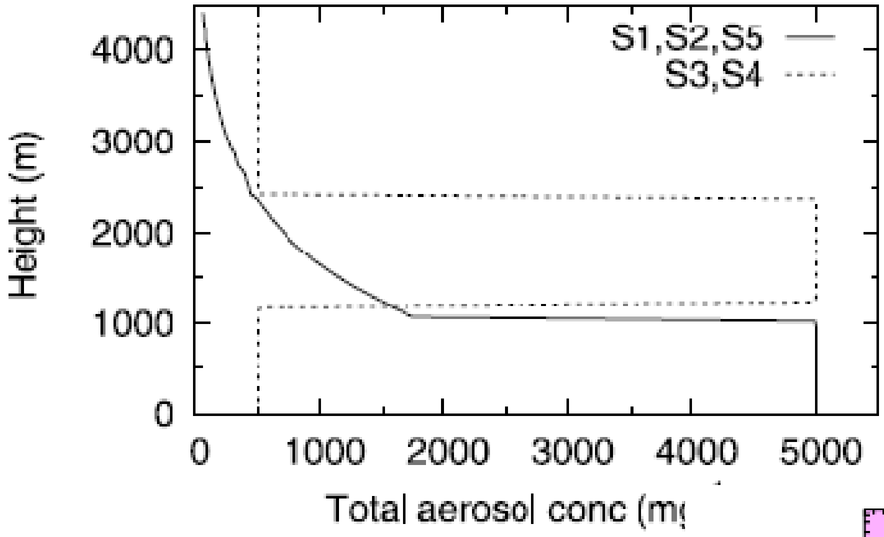


Figure 1. Initial aerosol profiles for sim
described in Table 1.

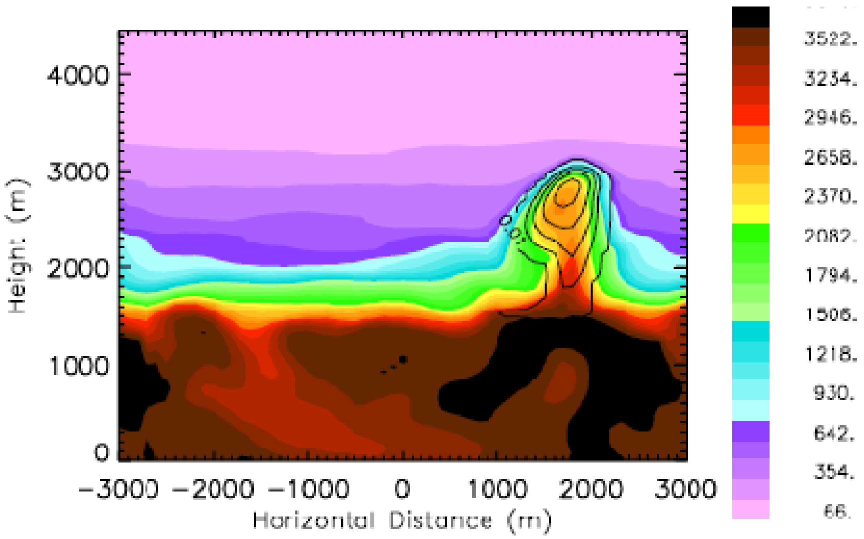
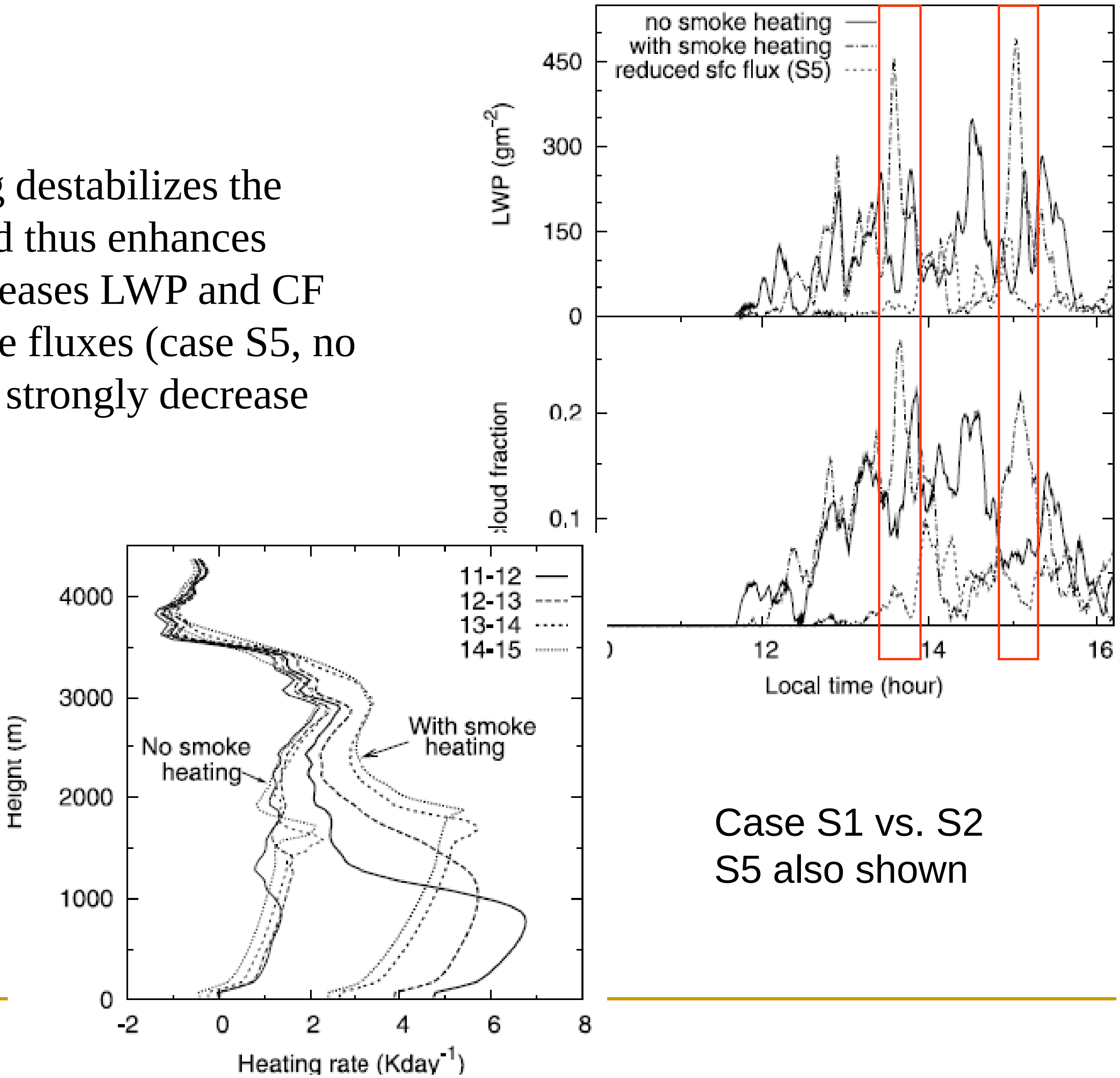


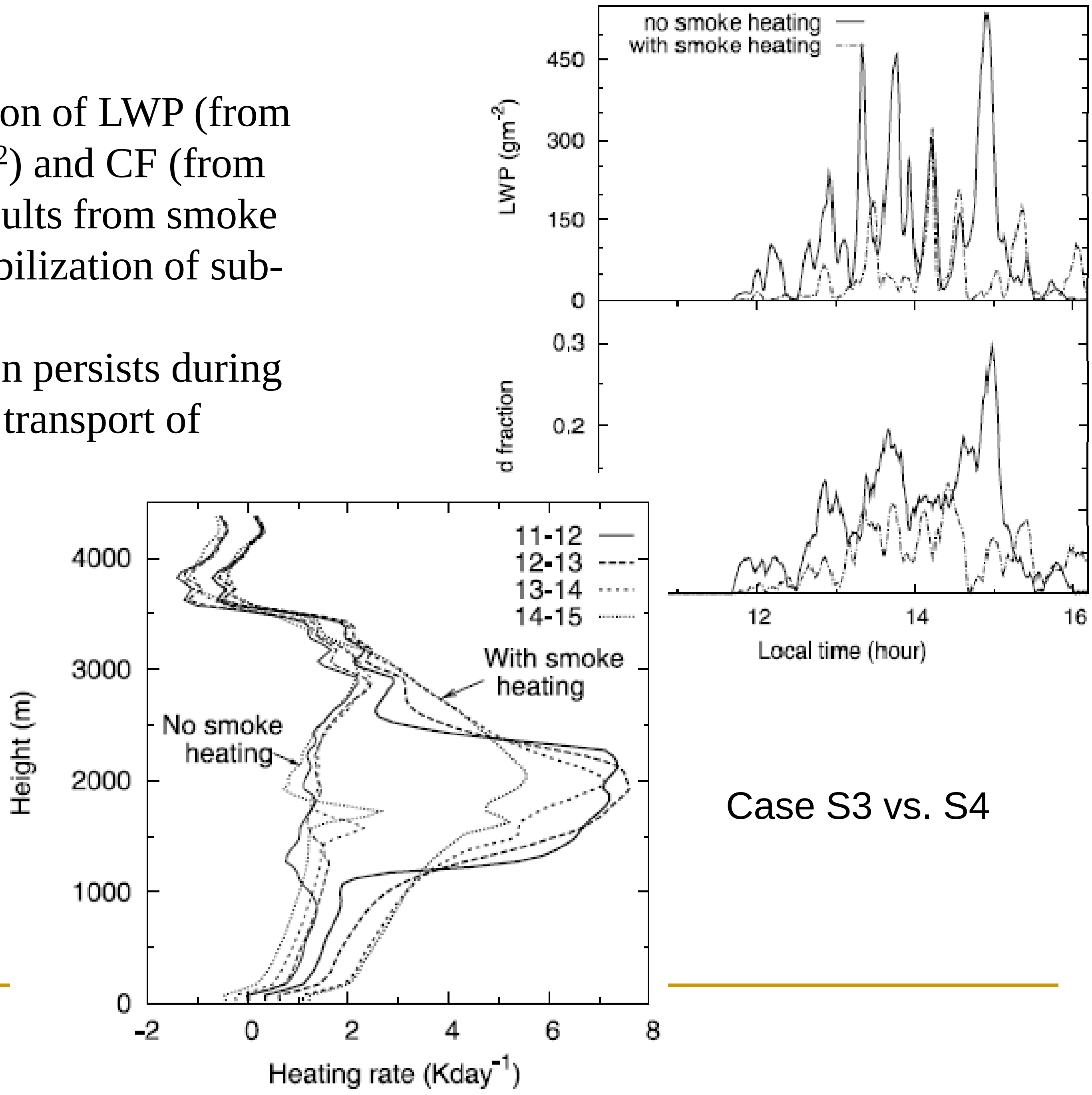
Figure 2. Aerosol and smoke cross sections at 14 h illustrating typical clouds and vertical redistribution of smoke as initialized in S1. Color-flooded contours indicate aerosol concentration (unactivated + activated) in mg ^{1} and solid contours indicate LWC in g kg^{-1} (contour interval 0.5 g kg^{-1})

1. Aerosol heating destabilizes the atmosphere, and thus enhances convection increases LWP and CF
2. Reduced surface fluxes (case S5, no smoke heating) strongly decrease LWP and CF.



Case S1 vs. S2
S5 also shown

1. Evident reduction of LWP (from 20.4 to 3.6 gm^{-2}) and CF (from 10% to 5%) results from smoke heating and stabilization of sub-cloud layer.
2. The stabilization persists during the mixing and transport of smoke.



Case S3 vs. S4

Discussion and conclusions

1. Whether the absorbing smoke from biomass burning increase or decrease the cloud LWP and fraction depends on the location of the aerosol layer: (1) smoke in the sub-cloud layer destabilize the lower atmosphere and increase convection, and thus enhance LWP and CF; (2) smoke within the cloud-layer reduces LWP and CF by stabilizing the atmosphere and suppress convection.
2. In the case of smoke residing in the cloud layer, the primary reason for the reduction of LWP and CF is the increased stability and suppression of convection due to smoke heating, NOT the smoke heating inside the drops, which enhances the evaporation.
3. The decrease of surface turbulent fluxes and thus buoyant convection and moisture transport (due to less solar heating and ET) can alone substantially decrease cloud LWP and fraction **(Case S1 vs. S5: LWP 15→1.6; CF 10%→2.7%).**

NOTE: the aerosol heating and surface fluxes are coupled together, which is not included in this simulation. A full coupling of these effects is not expected to produce qualitative change.

Extended Thinking

Giant CCNs is not included in the simulation.

How smoke can affect clouds and precipitation?

Microphysical&Dynamic effects:

1. Early rainfall (warm-rain processes) is suppressed and strong updraft transport more moisture into high altitude and supercooled region, where additional latent heat is released from freezing (cold-rain processes). More intense rainfall is formed dominant with ice phase. This can cause a net increase in rainfall amount, cloud fraction and LWP, etc.
2. Giant CCN from the smoke (especially fresh smoke) is efficient for rainfall formation.

Radiative effects:

1. The location or vertical distribution of the smoke layer determines how it alters the atmospheric stability and convection strength. When the smoke is within the lower layer, it heats and destabilizes the atmosphere, thus increasing convection; when the smoke resides in the cloud layer, it stabilize the atmosphere and suppress convection; when the smoke layer lie above the cloud top, it inhibits the dry air entrainment and thus maintain a moist cloud layer.

Thank You

Questions?