AEROSOLS AND THEIR IMPACT ON PRECIPITATION

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AEROSOLS AND THEIR IMPACT ON PRECIPITATION

- Background Review of aerosol particles
- Review of cloud formation and microphysics
- Review of interaction with radiation
- Aerosols-precipitation: observational evidence from different cloud types
- Aerosol-Cloud-Preciptiation-Climate program
- Urban heat island vs. enhanced aerosols: influence on changes in precipitation?

AEROSOLS AND THEIR IMPACT ON PRECIPITATION

Background

- Aerosols are ubiquitous in the atmosphere
- Their sizes range from a few nm to μm
- They originate through a variety of processes (primary and secondary), leading to a large variability in their sizes and composition.
- A subgroup of atmospheric aerosols, based on their size and composition can act as cloud condensation nuclei (CCN)
- Natural occurring CCN concentrations over the oceans are typically about 10-100 cm^{-3} while over the continents are about 500-800 cm^{-3}

AEROSOLS AND THEIR IMPACT ON PRECIPITATION

Background

- Also present is a subgroup (ice nuclei, IN) that serve as substrate for heterogeneous crystal growth, but are less well characterized.
- Urban areas and industrial sites may generate large concentrations of aerosols and CCN, in the range 1000-10000 cm^{-3} .
- Biomass burning and fossil fuel consumption have drastically increased the global aerosol burden

AEROSOLS AND THEIR IMPACT ON PRECIPITATION

We know that aerosols matter cloud formation… but…

Do they matter in the formation of precipitation?

- The first evidence of anthropogenic CCN affecting clouds dates back to 1960s: Cumulus clouds over smoke stacks in sugarcane plantations had altered microphysical characteristics, ***potentially*** reducing Precipitation Efficiency, although not conclusive
- Precipitation Efficiency: the fraction of water that reaches the surface from the total amount of condensed water in the volume of a cloud

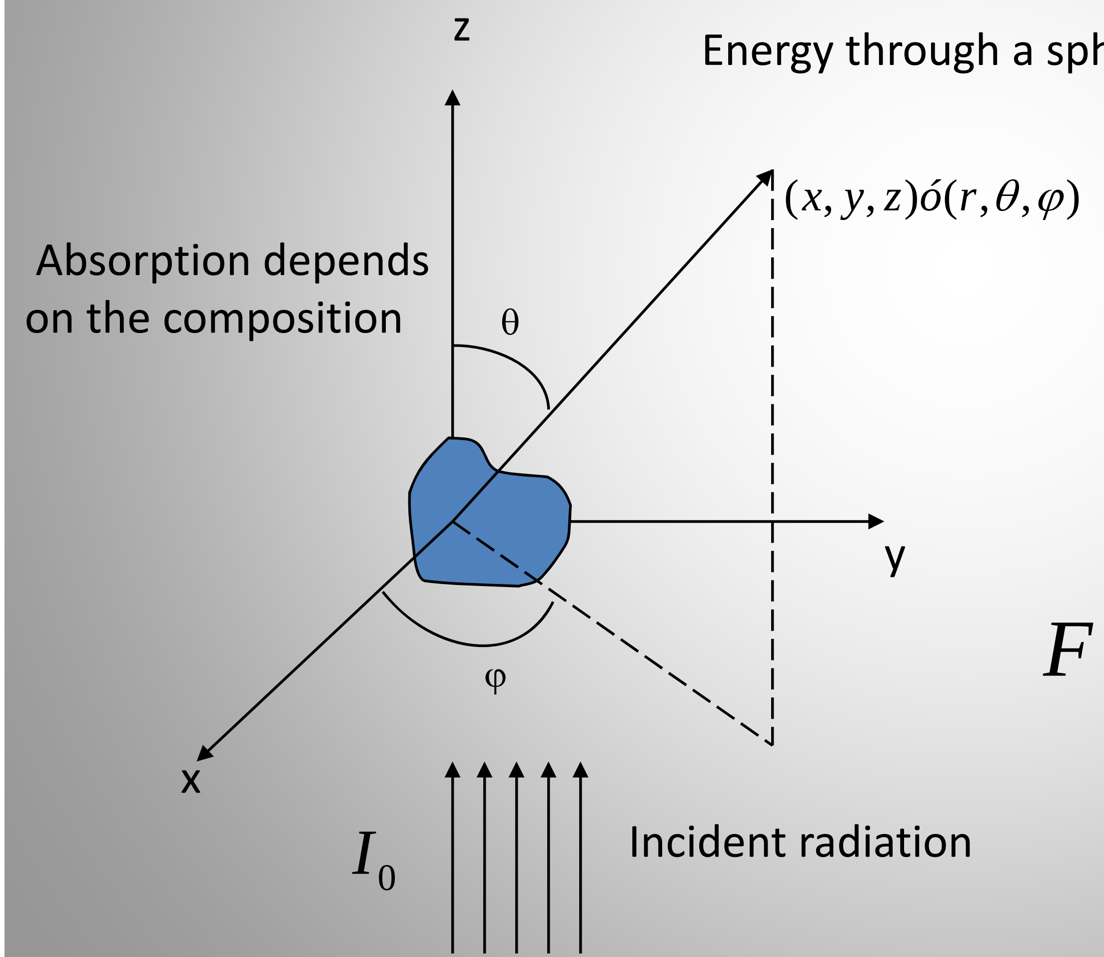
AEROSOLS AND THEIR IMPACT ON PRECIPITATION

Background

- The link between high CCN concentrations and increased cloud droplet number concentration (CNDC), and the optical properties of clouds, is supported by many in-situ observations
- However, the impact on precipitation is less well established
- More recently, “ship tracks” in stratocumulus clouds show human influence, mainly in the optical properties
- Changes in precipitation due to urban effects
- It has proven somewhat difficult to separate meteorological from purely aerosol effects, because clouds sensitivity to ambient conditions is high.

Radiation and aerosol particles: Light scattering and absorption

Background



Energy through a sphere around the particle is:

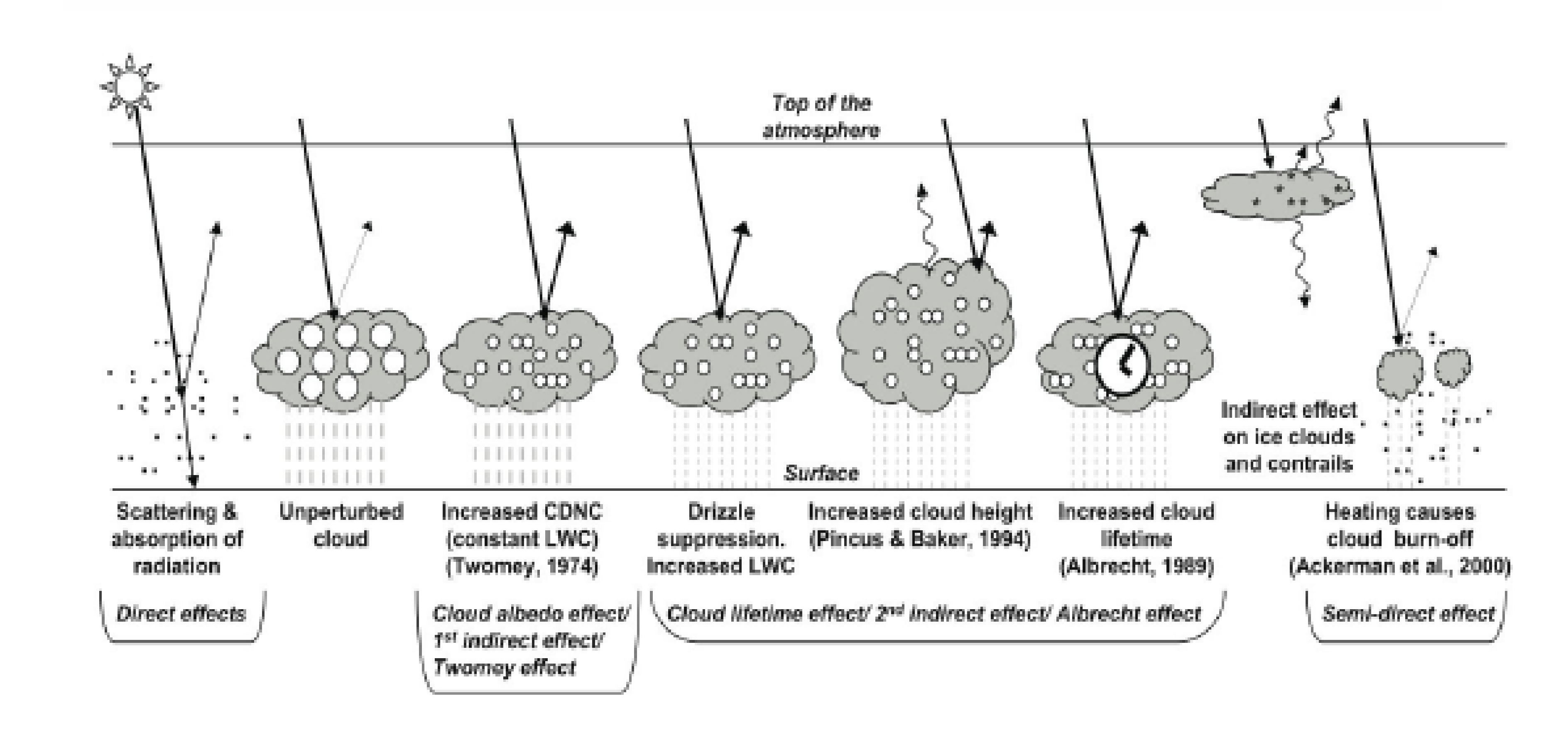
$$I \cdot r^2 \cdot \sin\theta \cdot d\theta \cdot d\varphi$$

$$I = \frac{I_0 \cdot F(\theta, \varphi, \lambda)}{(2\pi r / \lambda)^2}$$

$F(\theta, \varphi, \lambda)$ scattering function

DIFFERENT AEROSOLS EFFECTS

Background



Chapter 2, ICCP-WG1, 2007

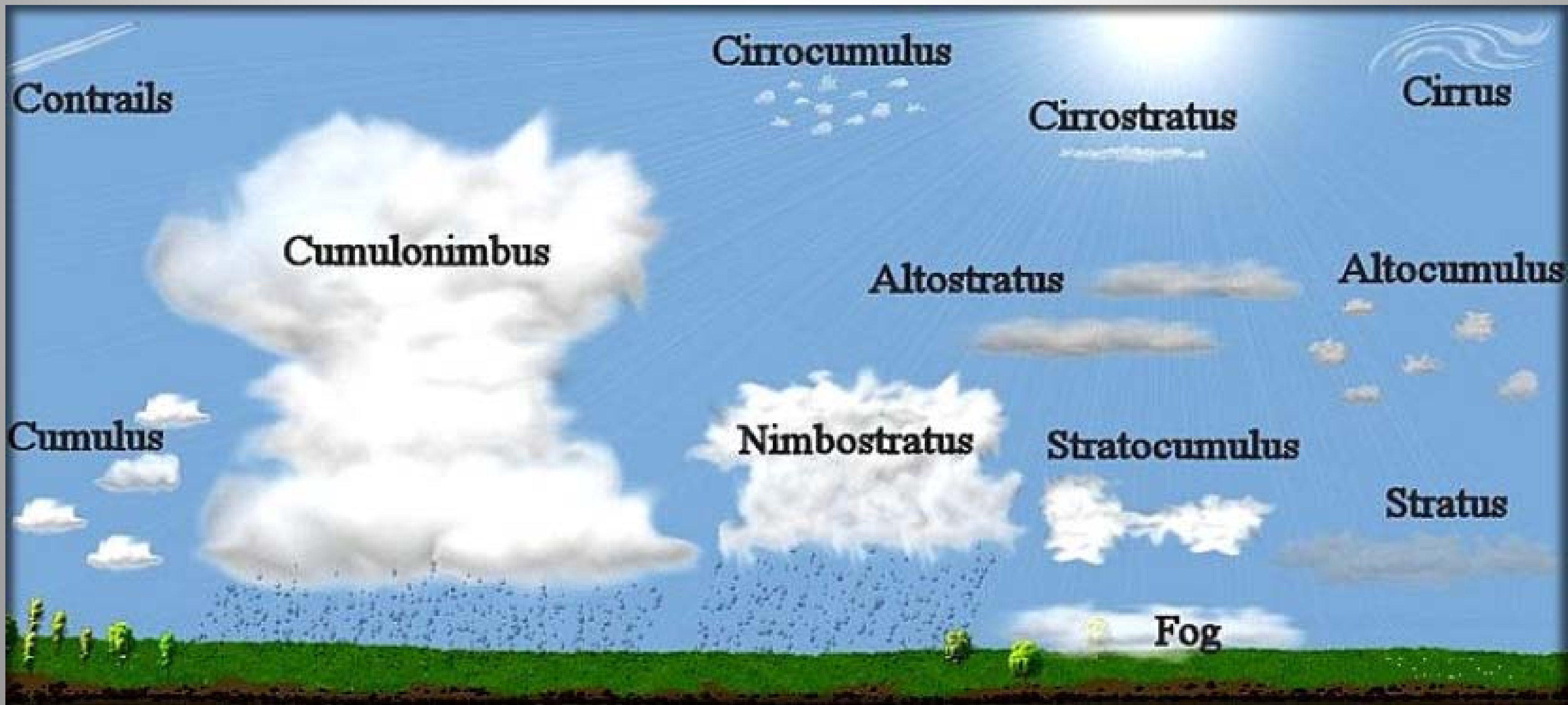
AEROSOLS AND THEIR IMPACT ON PRECIPITATION

Some relevant questions:

- How can aerosols affect precipitation in different climate zones and different cloud types?
- How different types of aerosols affect precipitation (specifics of urban pollution, biomass burning, dust)
- What are the main mechanisms (radiative vs. thermodynamic)?
- What is the empirical evidence for aerosol impacts on precipitation?

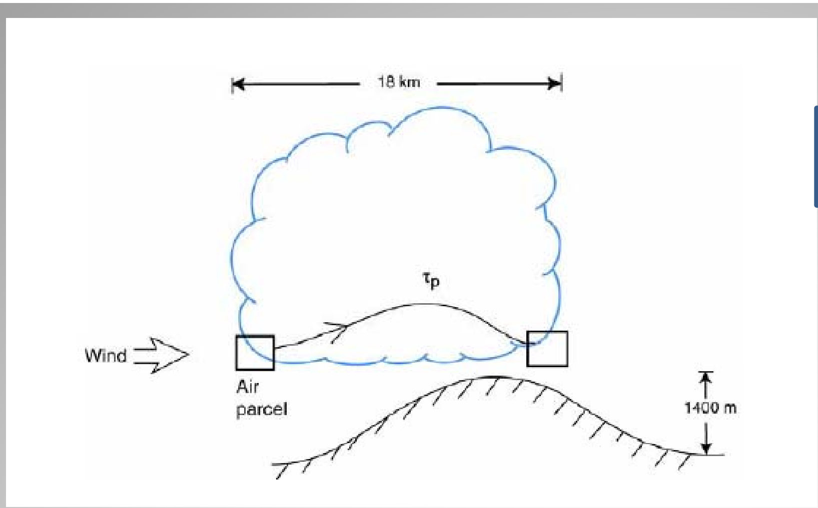
Different cloud types:

- they form by different processes
- at different altitudes, only liquid water, only ice, mixed phase
- Some precipitate to the surface and some don't



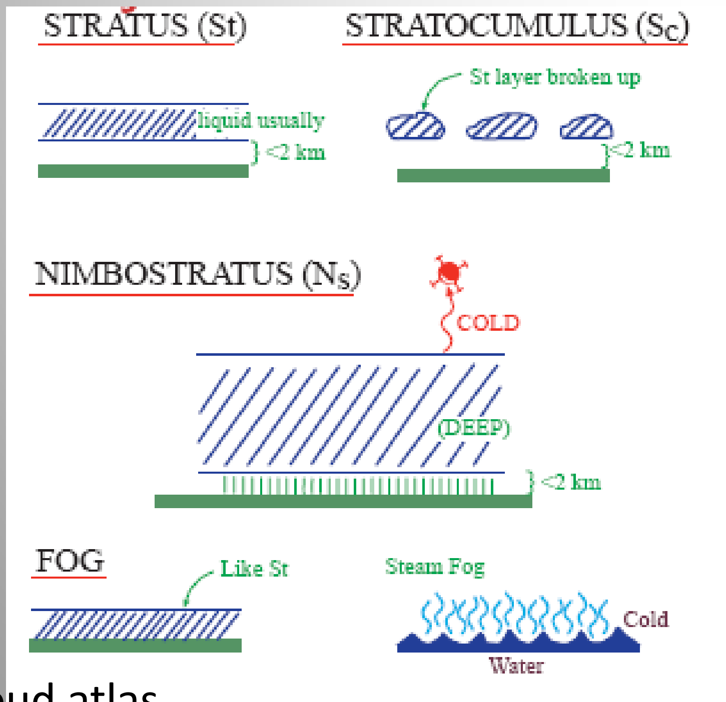
I. Sokolik

Orographically forced

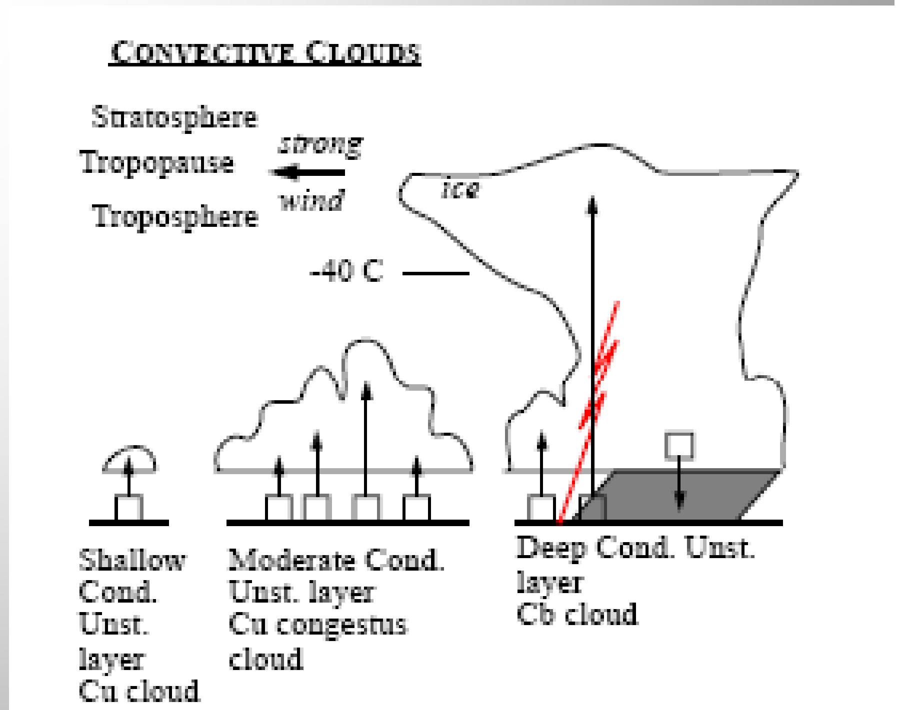


Cotton, 1990

Stratiform clouds



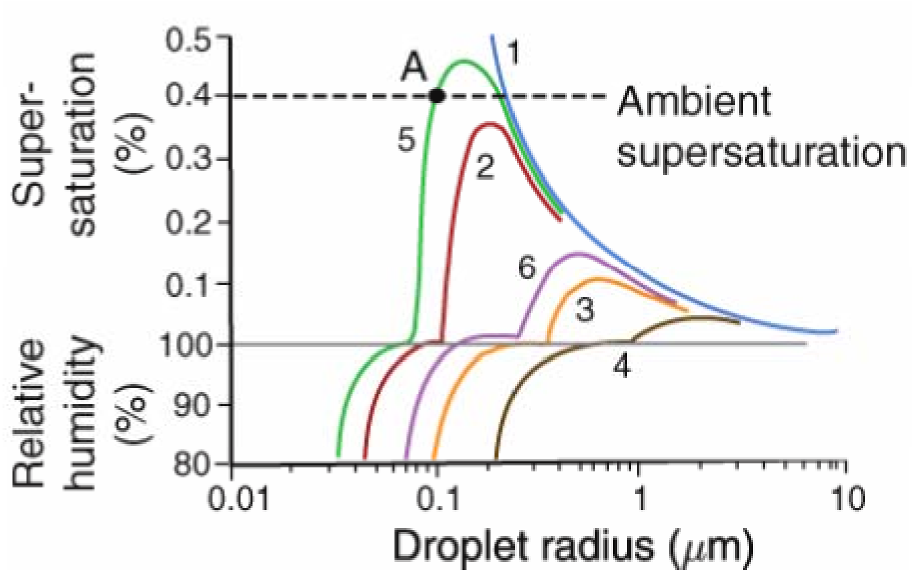
Convective clouds

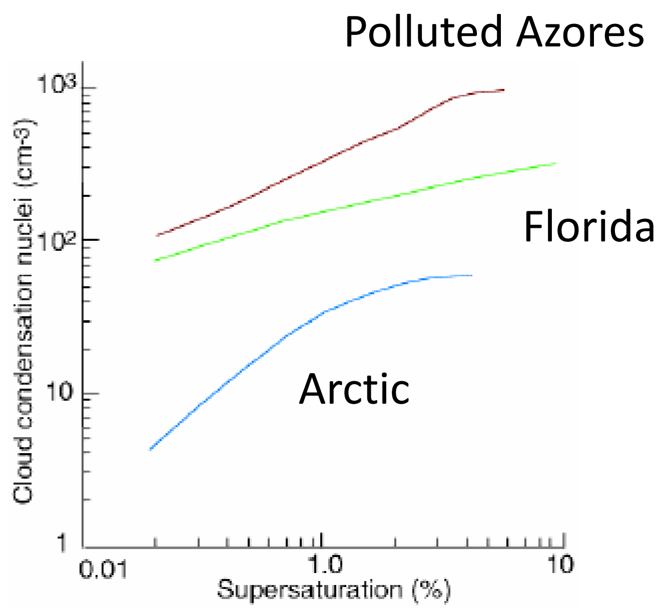


Houze cloud atlas

A bit about cloud microphysics…

Wallace and Hobbs, 2006



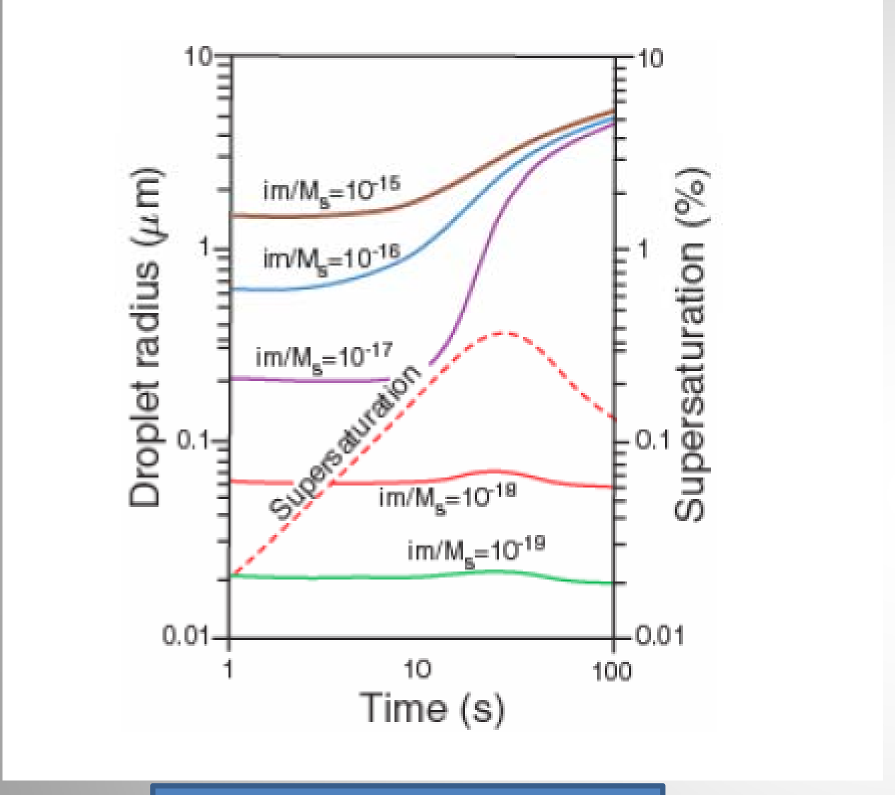


Activation is function of composition:

1. Pure water
2. m of NaCl
3. 10xm NaCl
4. 100xm NaCl
5. m of ammonium sulfate
6. 10xm of ammonium sulfate

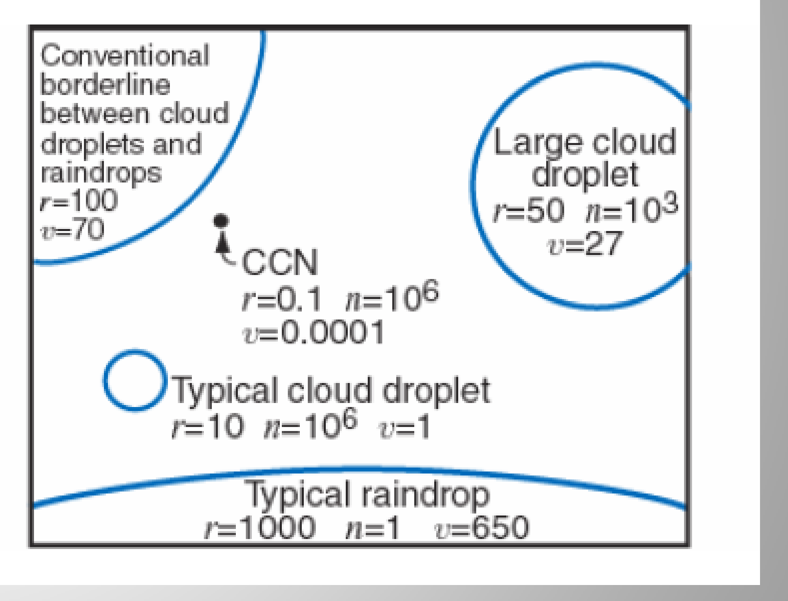
CCN spectrum: concentration vs. supersaturation

A bit about cloud microphysics…



Droplet growth for different sizes of CCN

Relative sizes of aerosols and cloud and rain droplets



r: radius in microns

n: concentration per liter

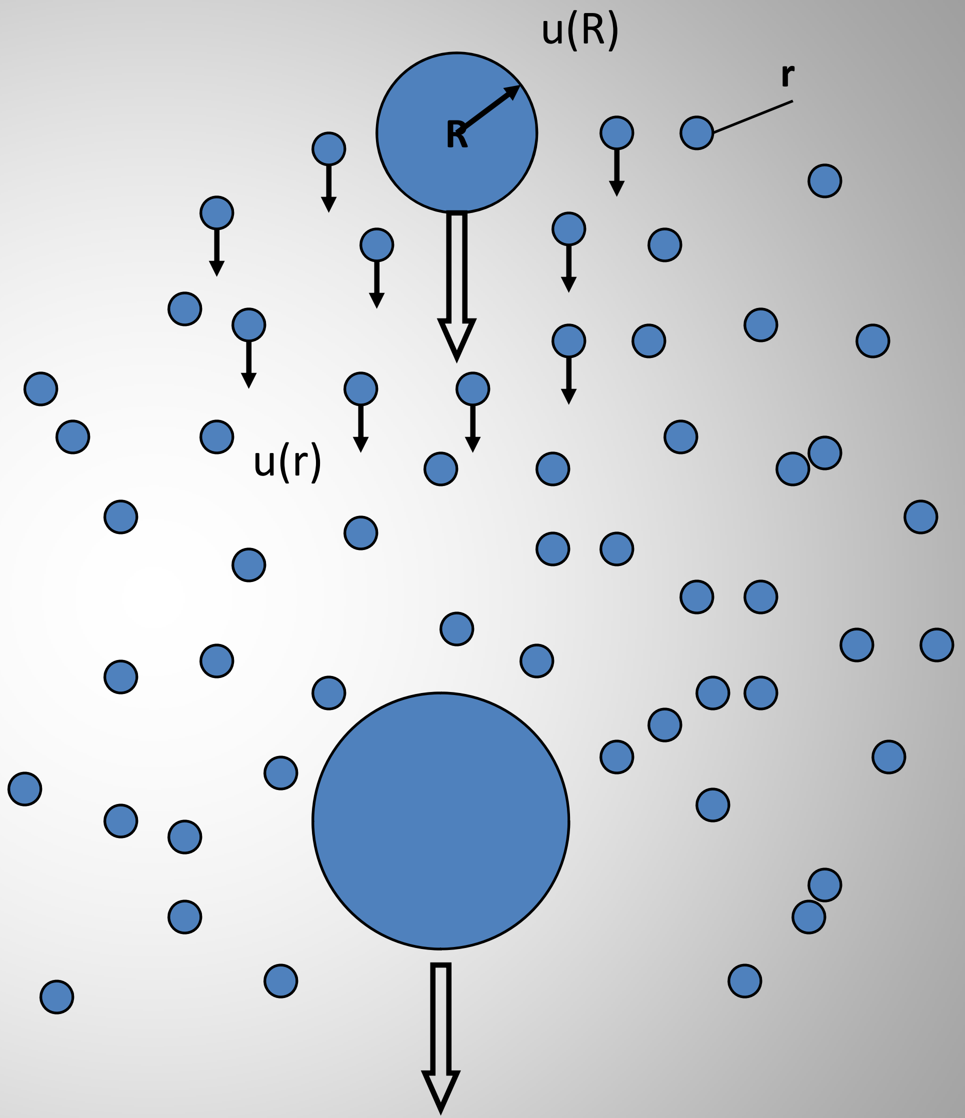
v: terminal velocity

Wallace and Hobbs, 2006

Droplet growth by collisions and coalescence.

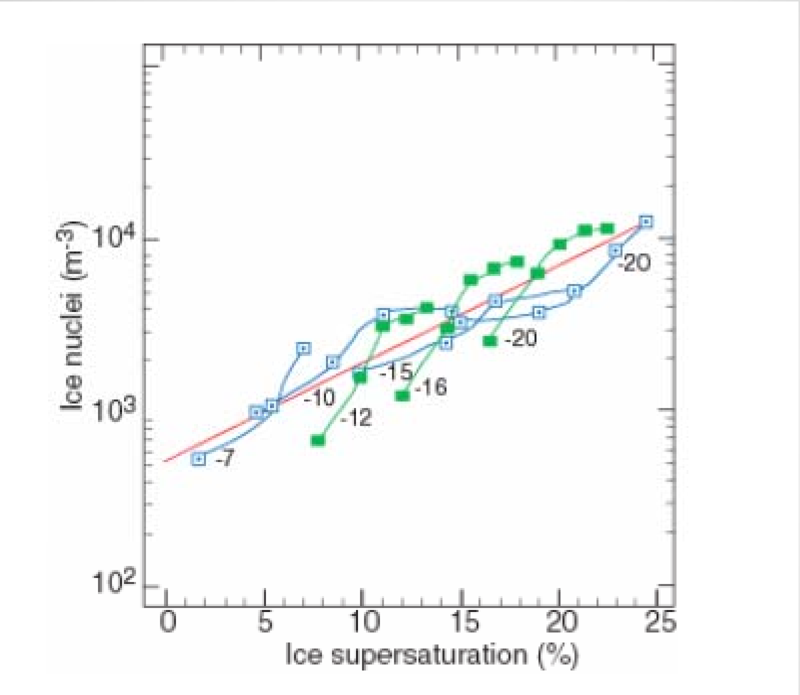
Collision efficiency

$$E \equiv \frac{y_c^2}{(r + R)^2}$$



$\pi(R+r)^2[u(R) - u(r)]$: volume swept in time

A bit about *more* cloud microphysics: when clouds are very deep, the temperature is well below freezing and ice nuclei become important

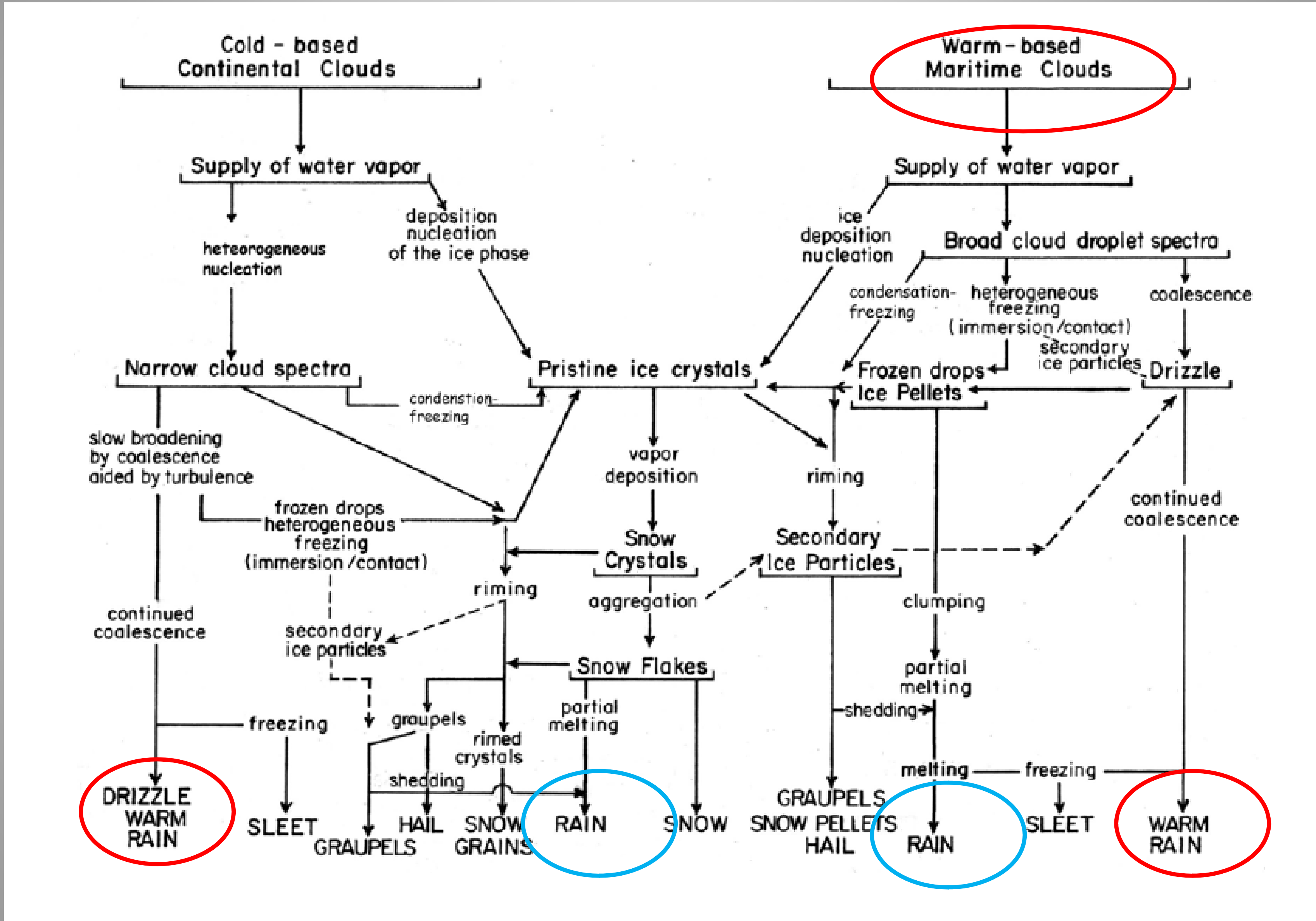


Measurements are much harder to make, so that there are few ambient observations

IN spectrum: concentration vs. supersaturation with respect to ice

Wallace and Hobbs, 2006

Summary of microphysical processes



Braham, 1968

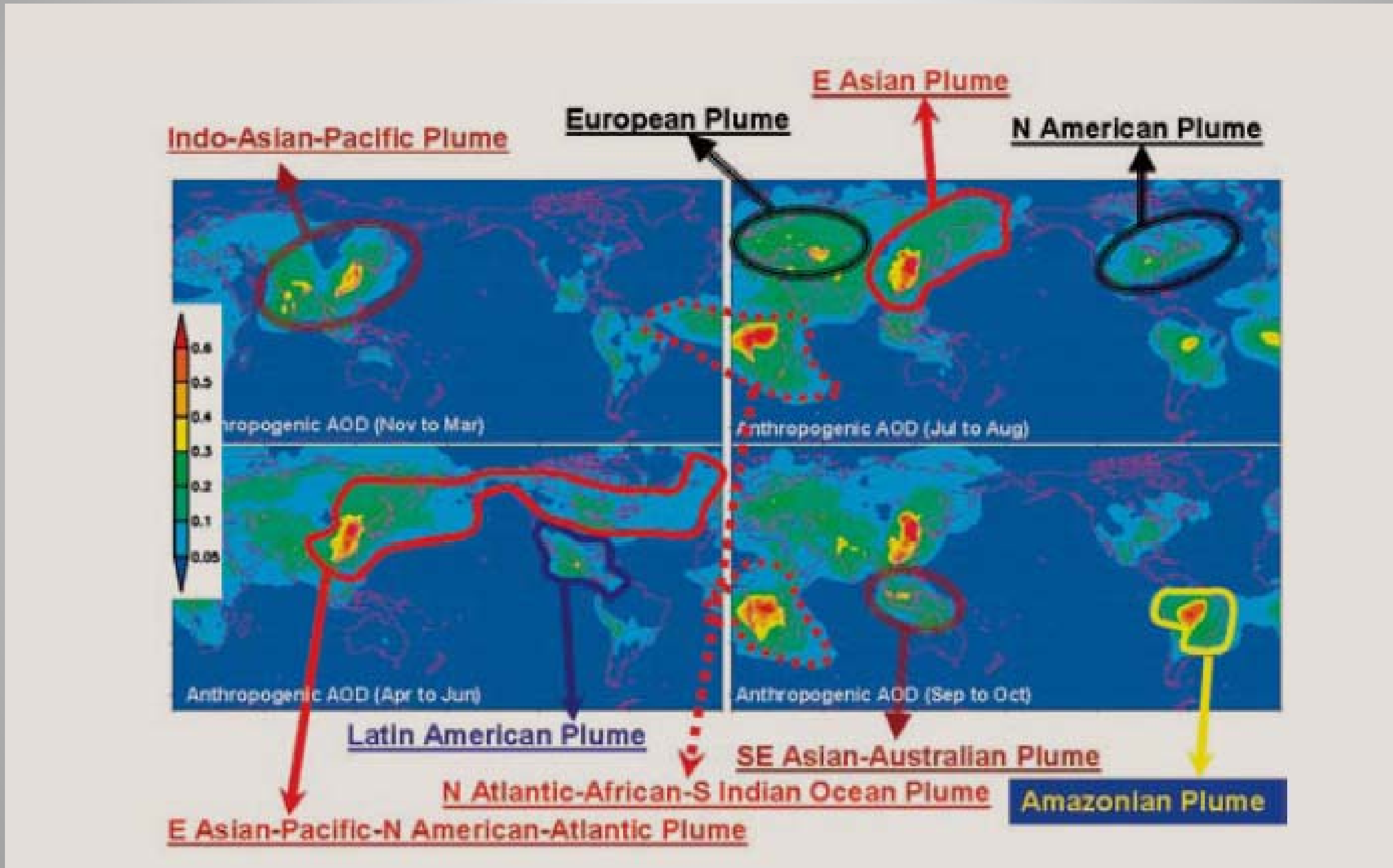
Aerosol indirect effects

Table 1. Overview of the different aerosol indirect effects and range of the radiative budget perturbation at the top-of-the atmosphere (F_{TOA}) [W m^{-2}], at the surface (F_{SFC}) and the likely sign of the change in global mean surface precipitation (P) as estimated from Fig. 2 and from the literature cited in the text.

Effect	Cloud type	Description	F_{TOA}	F_{SFC}	P
Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)	All clouds	The more numerous smaller cloud particles reflect more solar radiation	−0.5 to −1.9	similar to F_{TOA}	n/a
Indirect aerosol effect with varying water amounts (cloud lifetime effect)	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	−0.3 to −1.4	similar to F_{TOA}	decrease
Semi-direct effect	All clouds	Absorption of solar radiation by soot may cause evaporation of cloud particles	+0.1 to −0.5	larger than F_{TOA}	decrease
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay the onset of freezing	?	?	increase or decrease
Glaciation indirect effect	Mixed-phase clouds	More ice nuclei increase the precipitation efficiency	?	?	increase
Riming indirect effect	Mixed-phase clouds	Smaller cloud droplets decrease the riming efficiency	?	?	decrease
Surface energy budget effect	All clouds	Increased aerosol and cloud optical thickness decrease the net surface solar radiation	n/a	−1.8 to −4	decrease

Lohmann and Feichter, 2005

Global anthropogenic aerosol sources: Atmospheric Brown Clouds (ABC)



AOD: Aerosol optical depth (column measure of aerosol loading)

ABC Technical Summary, Ramanathan et al, 2008

Particles in different parts of the world

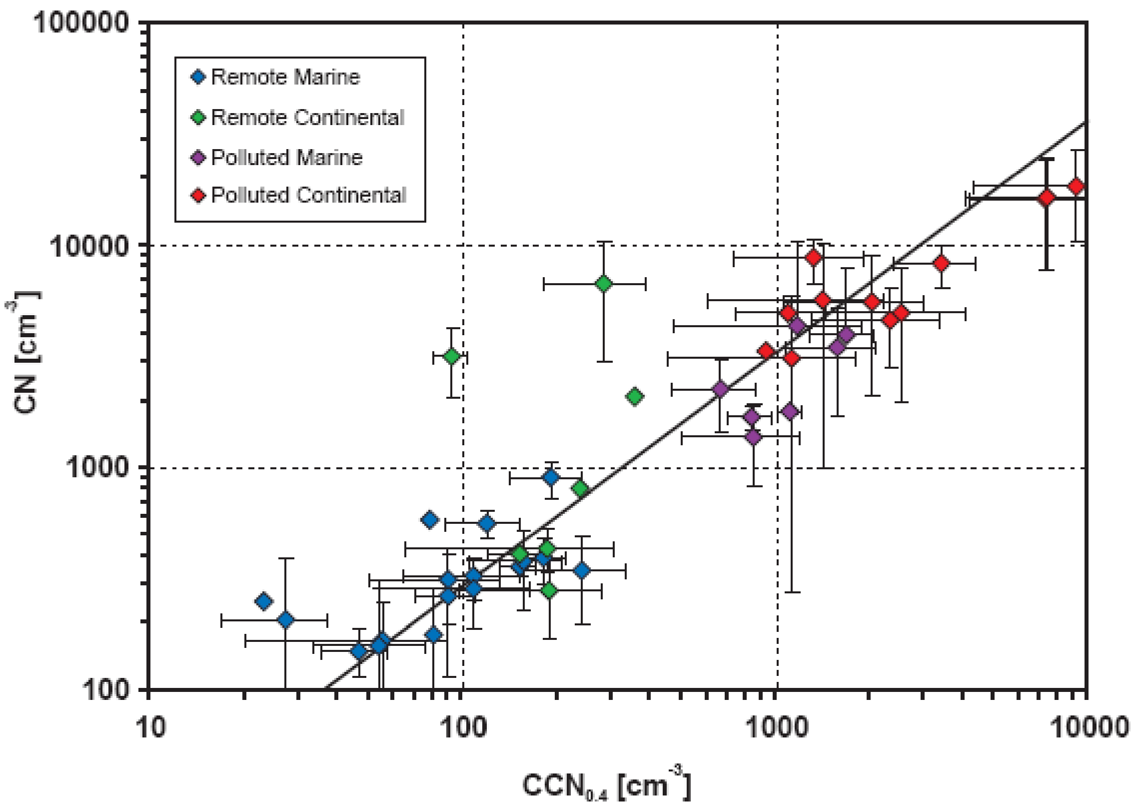


Fig. 2. Scatterplot of CN vs. $CCN_{0.4}$ based on the data from Table 2. The line represents the mean $CCN_{0.4}$/CN ratio of 0.36.

Andreae, 2008

Particles in different parts of the world

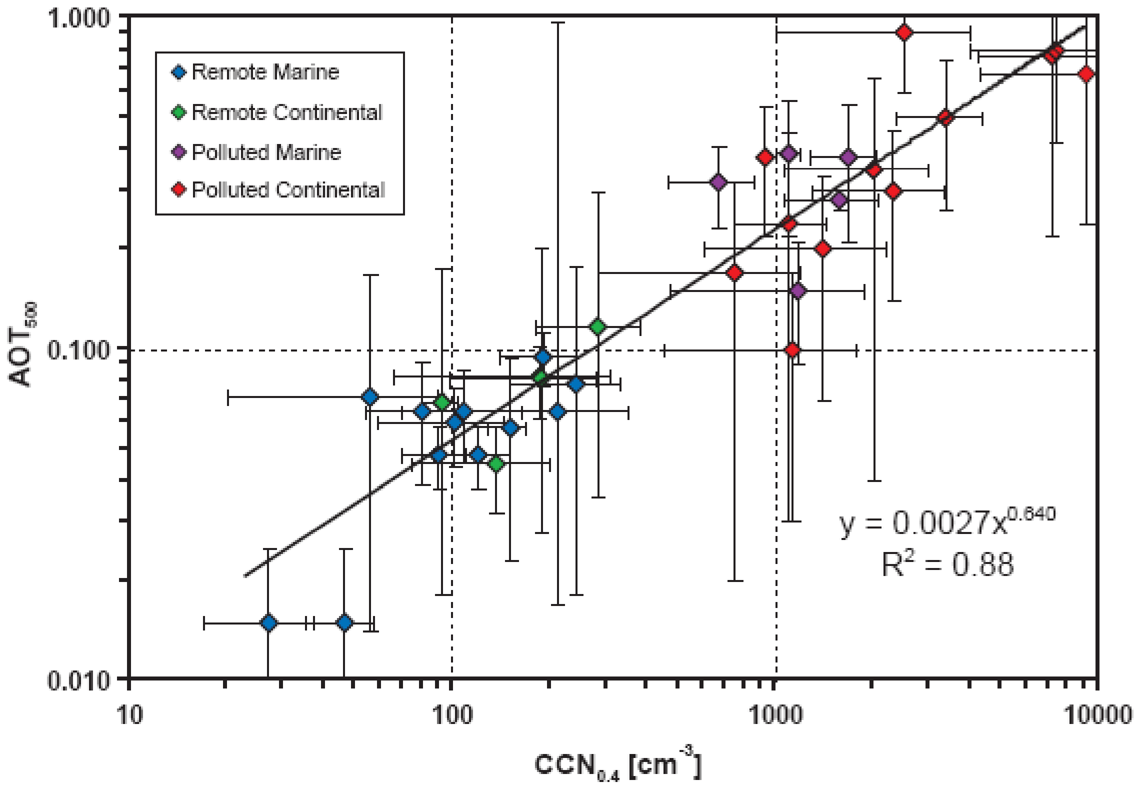


Fig. 1. Relationship between AOT_{500} and $CCN_{0.4}$ from investigations where these variables have been measured simultaneously, or where data from nearby sites at comparable times were available. The error bars reflect the variability of measurements within each study (standard deviations or quartiles).

Andreae, 2008

Particles and cloud characteristics in different parts of the world

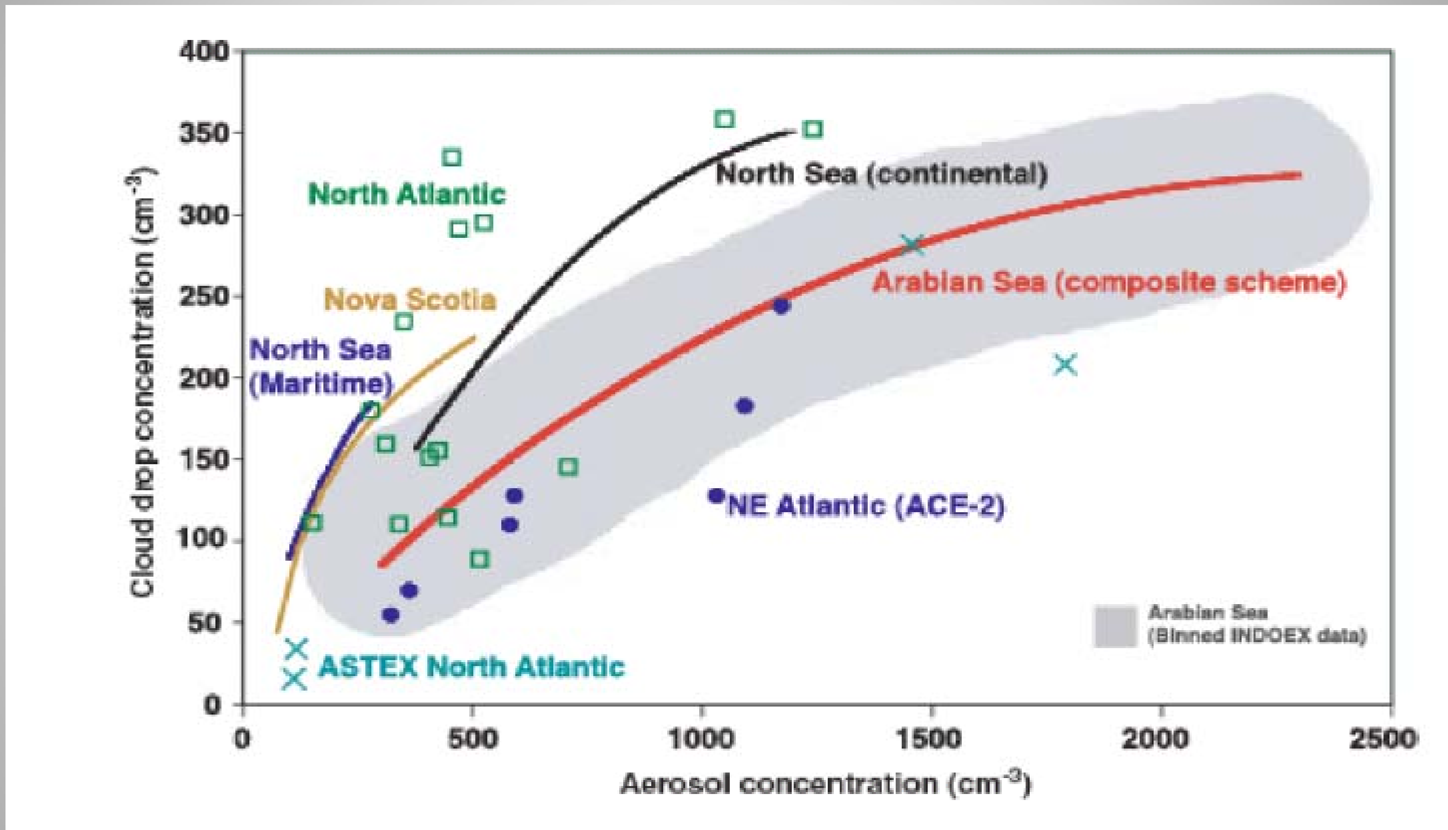


Figure 1. Aircraft measurements of CDNC aerosol number concentration. The thick red line is a theoretical parameterization based on INDOEX aircraft data for the Arabian Sea (Ramanathan et al., 2001).

Droplet distributions in stratocumuli under different CCN: Maritime (case 1) and continentally-influenced (case 2)

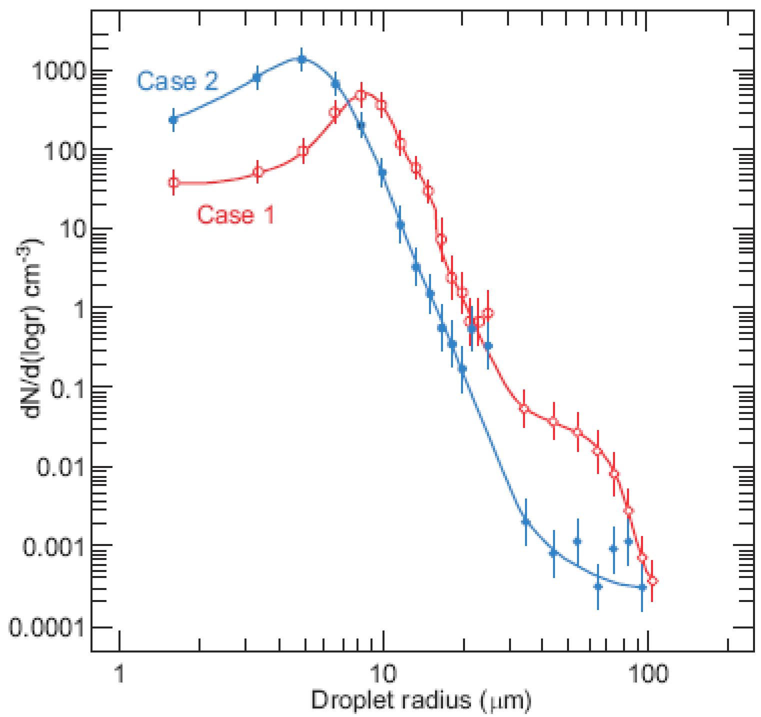


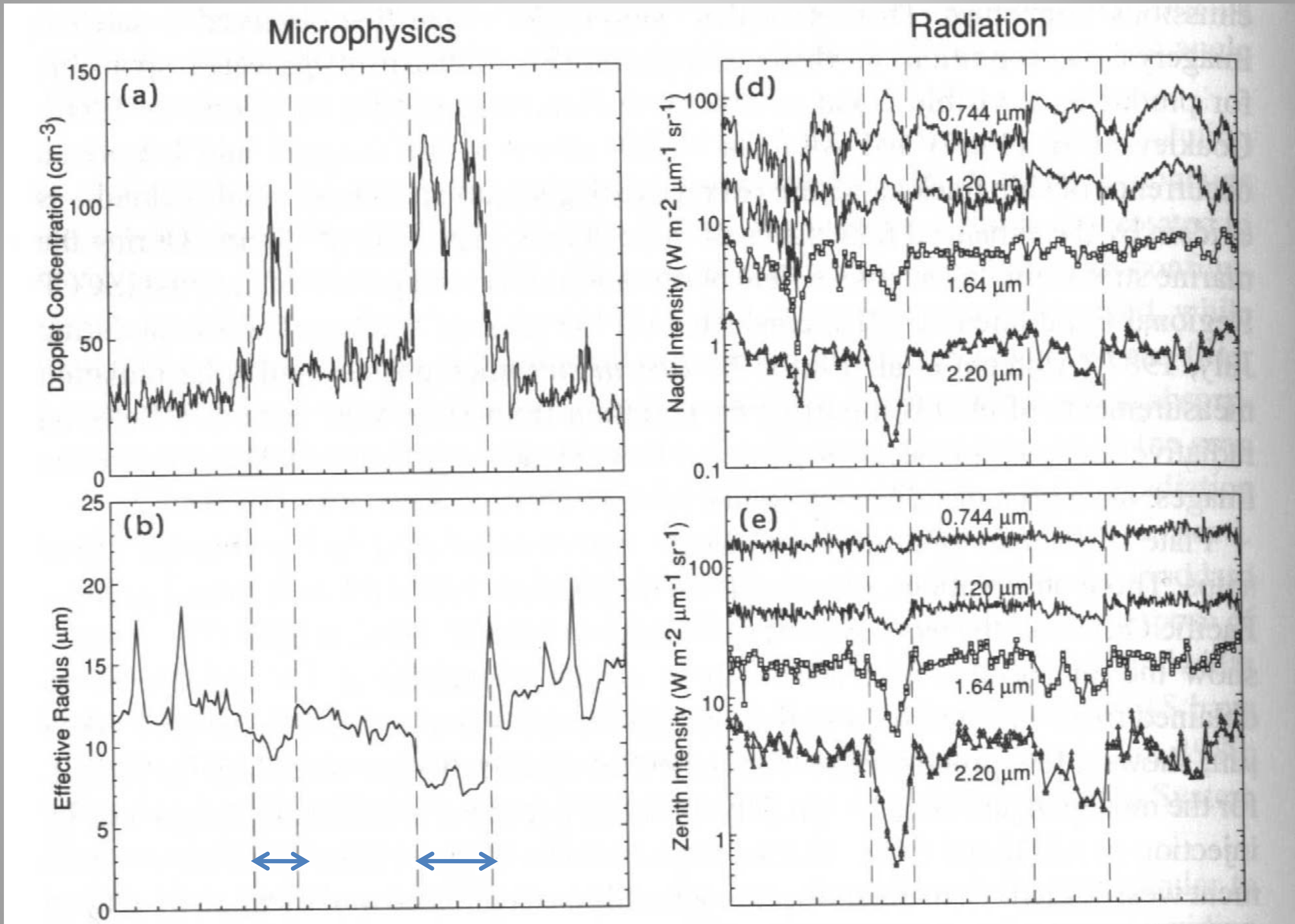
Figure 2-9. *Cloud droplet number distributions measured in stratocumulus clouds in the vicinity of the Azores by the FSSP-100 (circles) and PMS 1D (diamonds) cloud probes, averaged over 15 km of flight path for case 1—clean marine air (red symbols and curve), and averaged over 4 km of flight path for case 2—continentally influenced air (blue symbols and curve). The vertical bars are the geometric standard deviations of the droplet concentrations. From Garrett and Hobbs [1995].*

SHIP TRACKS

MODIS observations, NASA

Levin and Cotton, 2008

SHIP TRACKS



Radke et al, 1996

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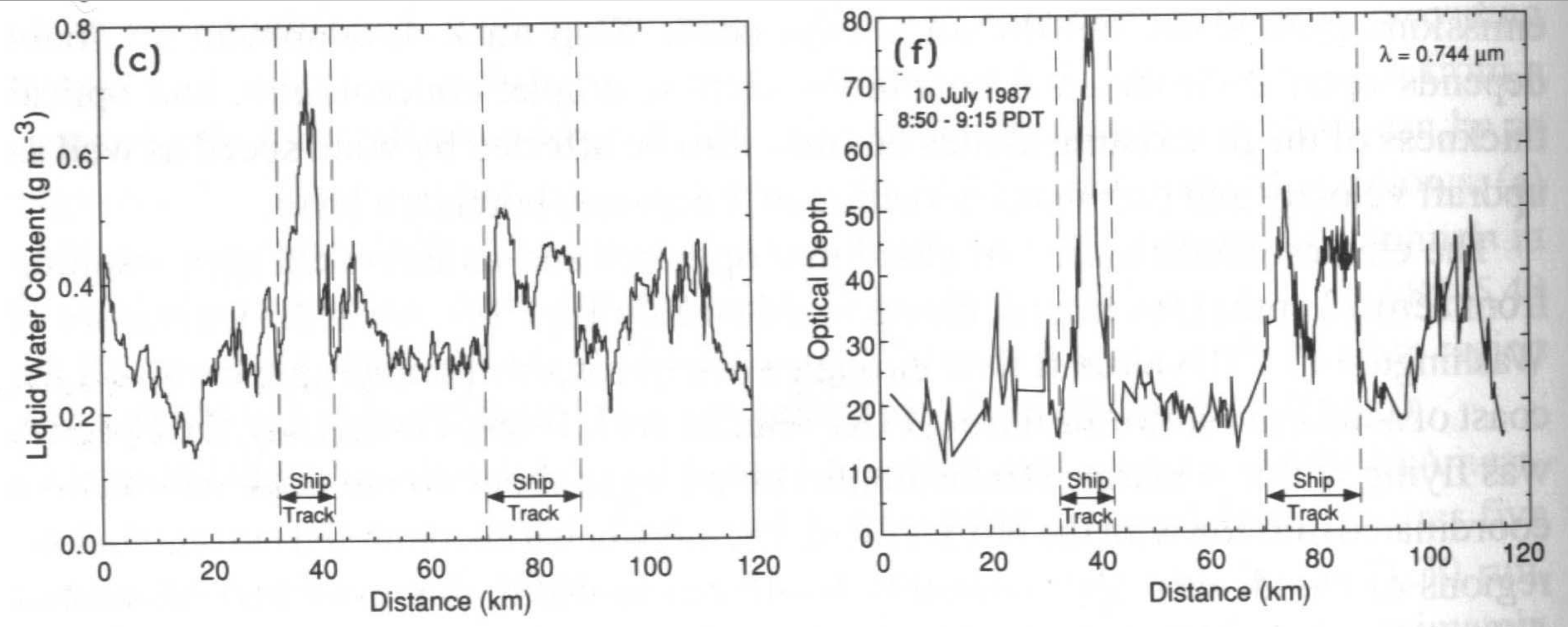

Figure 13.3 Aircraft transects of the two ship tracks on July 10, 1987, showing changes in (a) the total concentration of droplets, (b) the effective radius, (c) the cloud liquid water content, (d) the nadir (upwelling) intensities at selected wavelengths between 0.744 μm and 2.20 μm, (e) the zenith (downwelling) intensities, and (f) the total optical thickness of the cloud at 0.744 μm.

Radke et al, 1996

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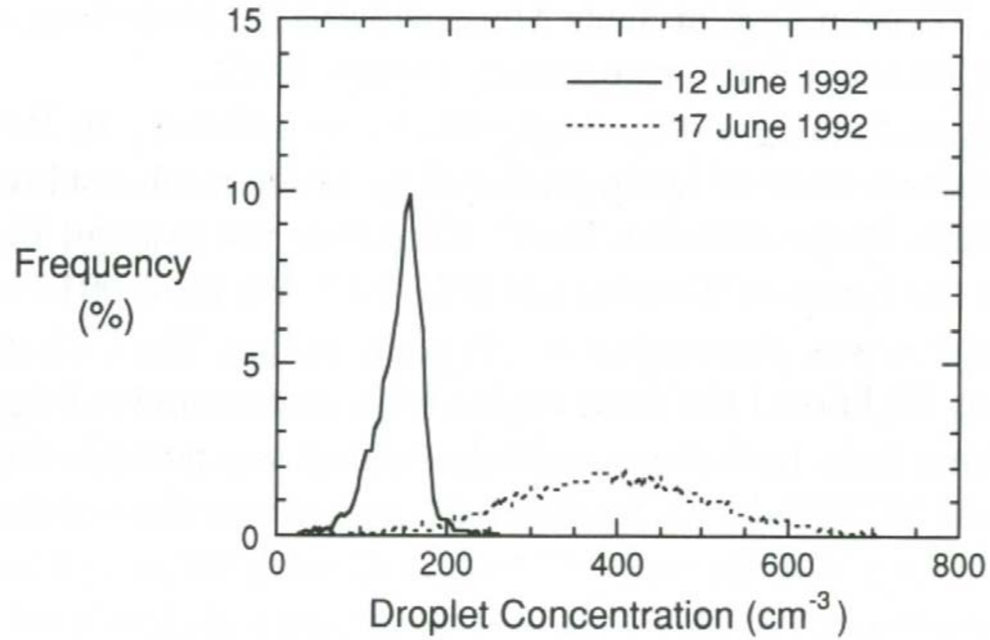
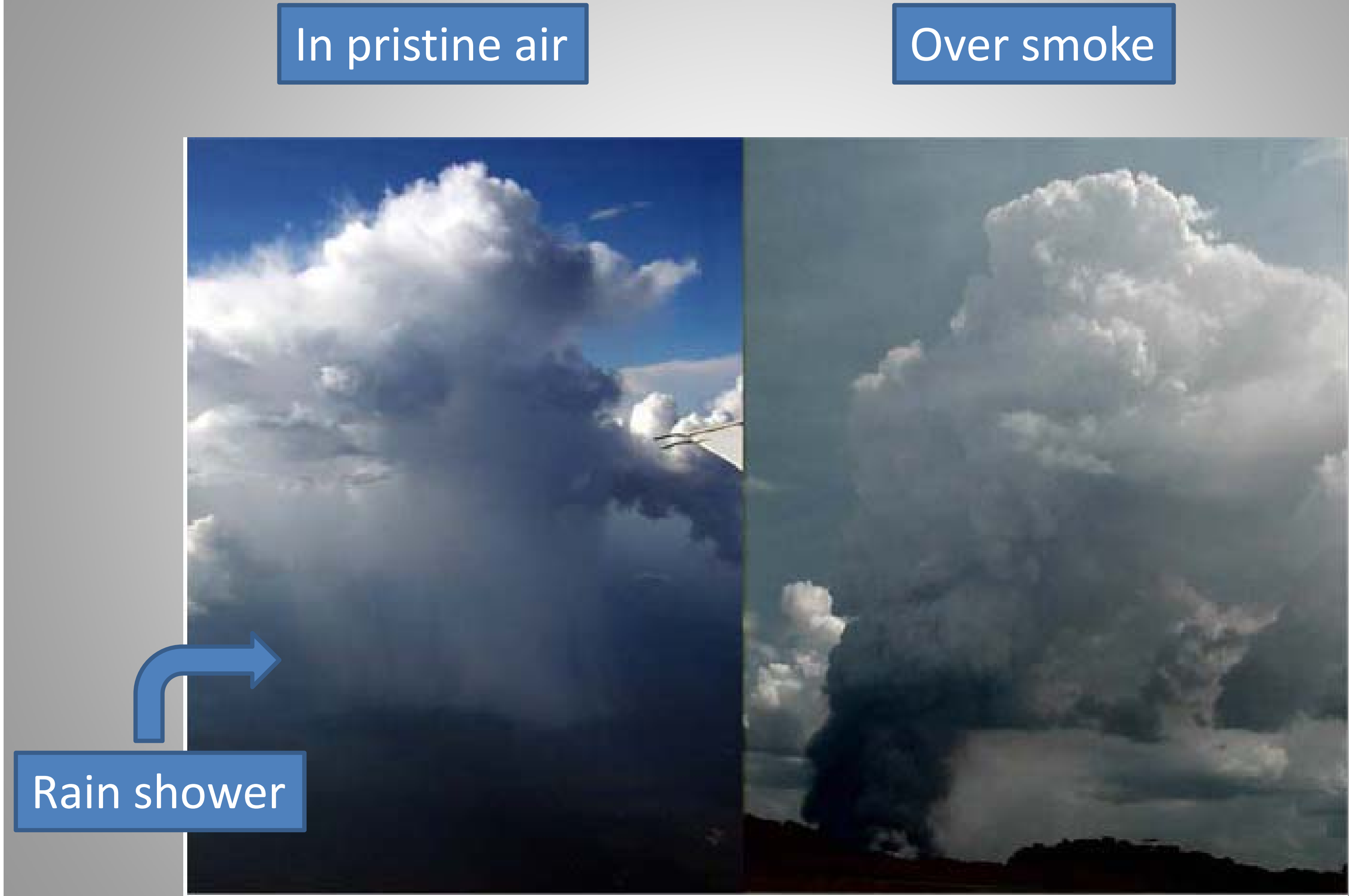


Figure 13.5 Probability distribution of cloud droplet concentration on June 12, 1992, (maritime airmass) and June 17, 1992, (continentally influenced airmass) for marine stratocumulus clouds near the Azores, Portugal, obtained from the University of Washington C–131A during ASTEX.

Radke et al, 1996

Clouds and smoke over the Amazon



Clouds sampled about 100 km apart

ACPC science plan, 2009

Clouds and smoke over the Amazon

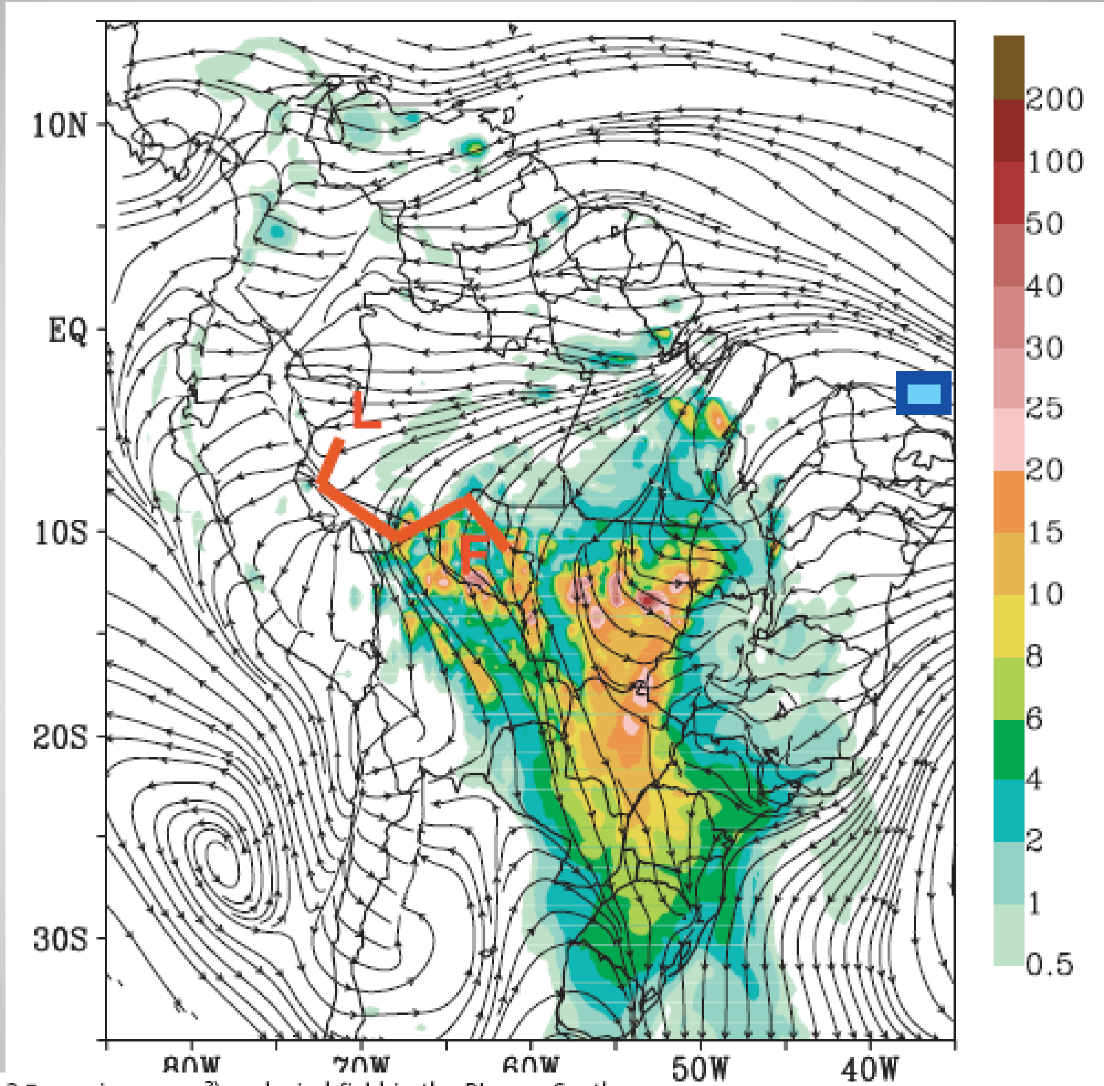
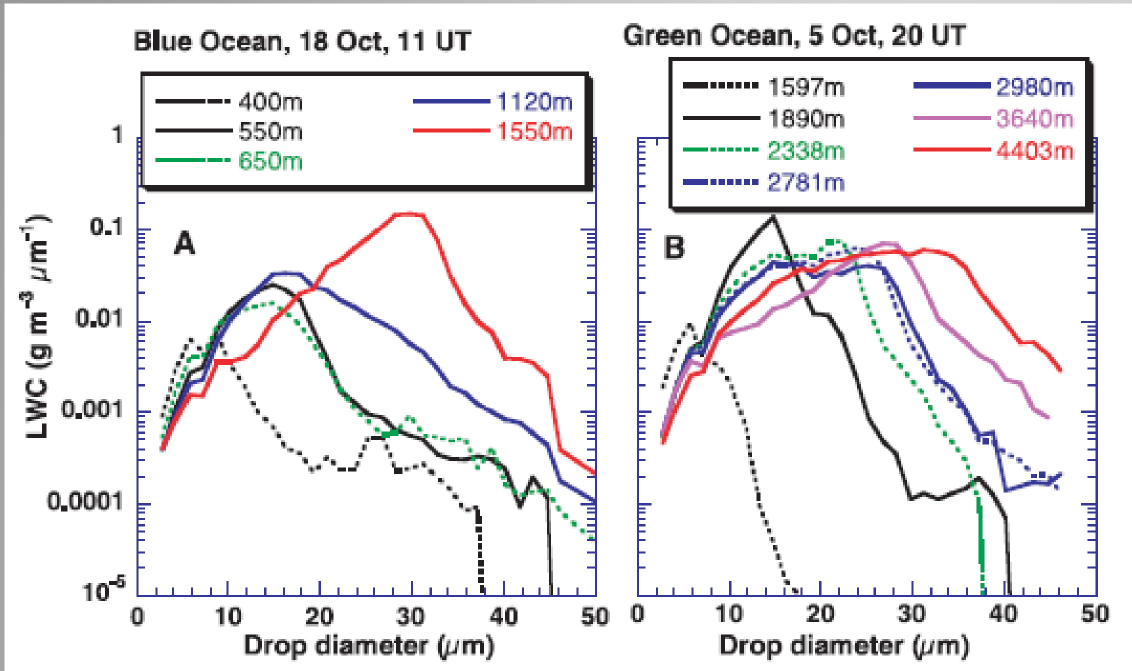


Fig. 1. Smoke aerosol distribution ($D < 2.5$ μm; in μg m^{-2}) and wind field in the BL over South America during the transect flights from Rondonia to the western Amazon. The aerosol distribution was obtained with the use of the Geostationary Operational Environmental Satellites–Automated Biomass Burning Algorithm (GOES ABBA) Fire product to estimate smoke emissions and the RAMS model to simulate their transport and removal (38). The flight track is indicated as a red line; the study area off Fortaleza, by a blue rectangle; and letters L and F represent the locations of the LET and FNS sounding sites, respectively (fig. S1).

Andreae et al, 2004

In pristine air NE

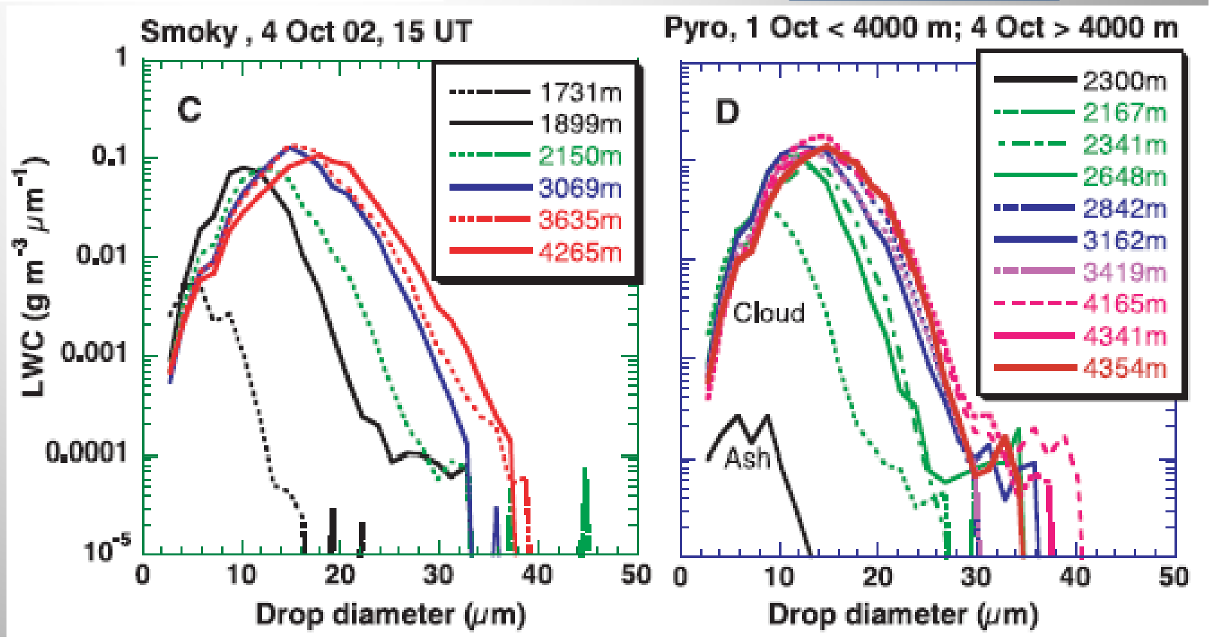
In pristine air NW



Cloud droplet size distributions in the Amazon

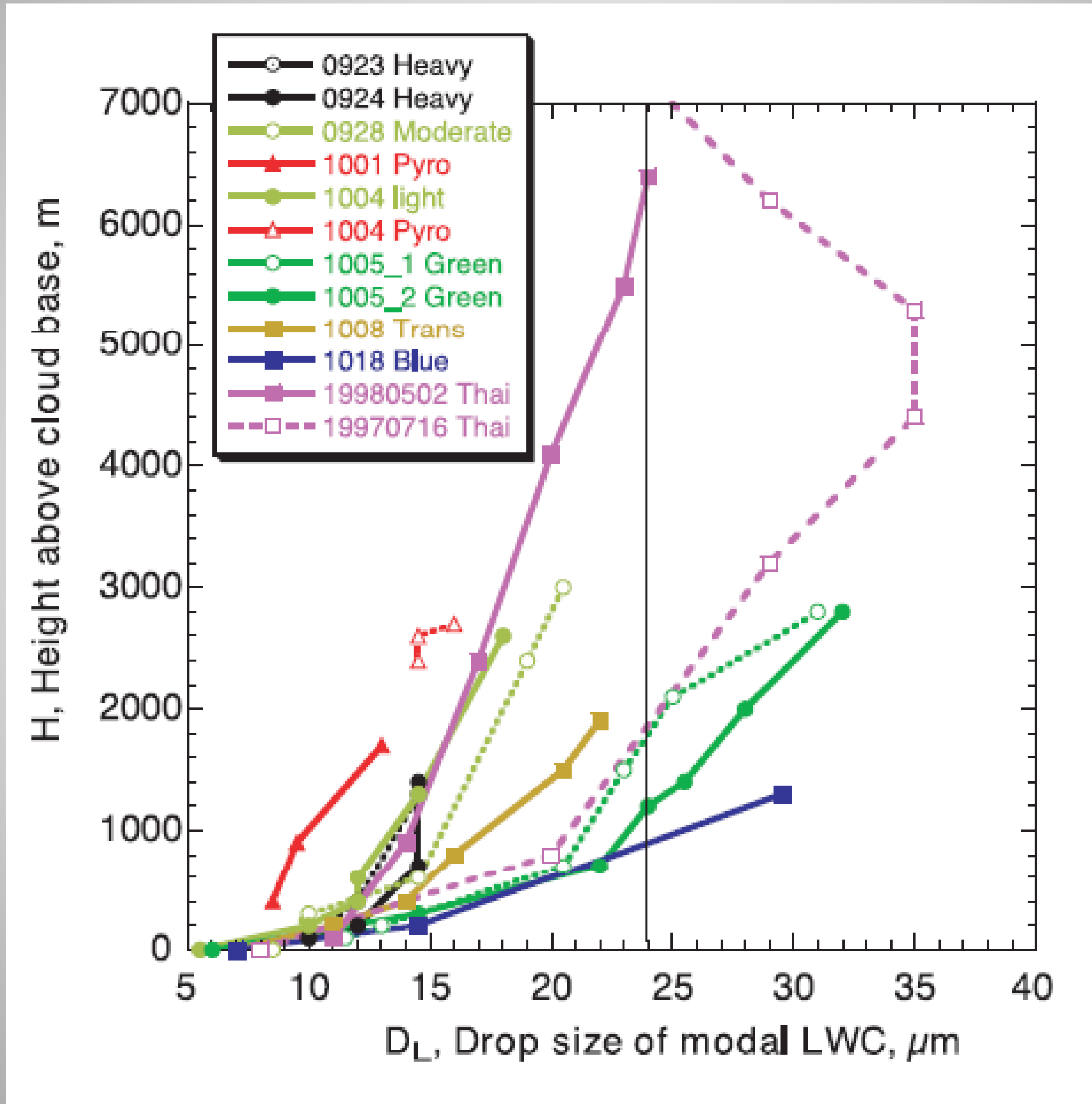
Over fire

Rondonia, SW Biomass burning in the region



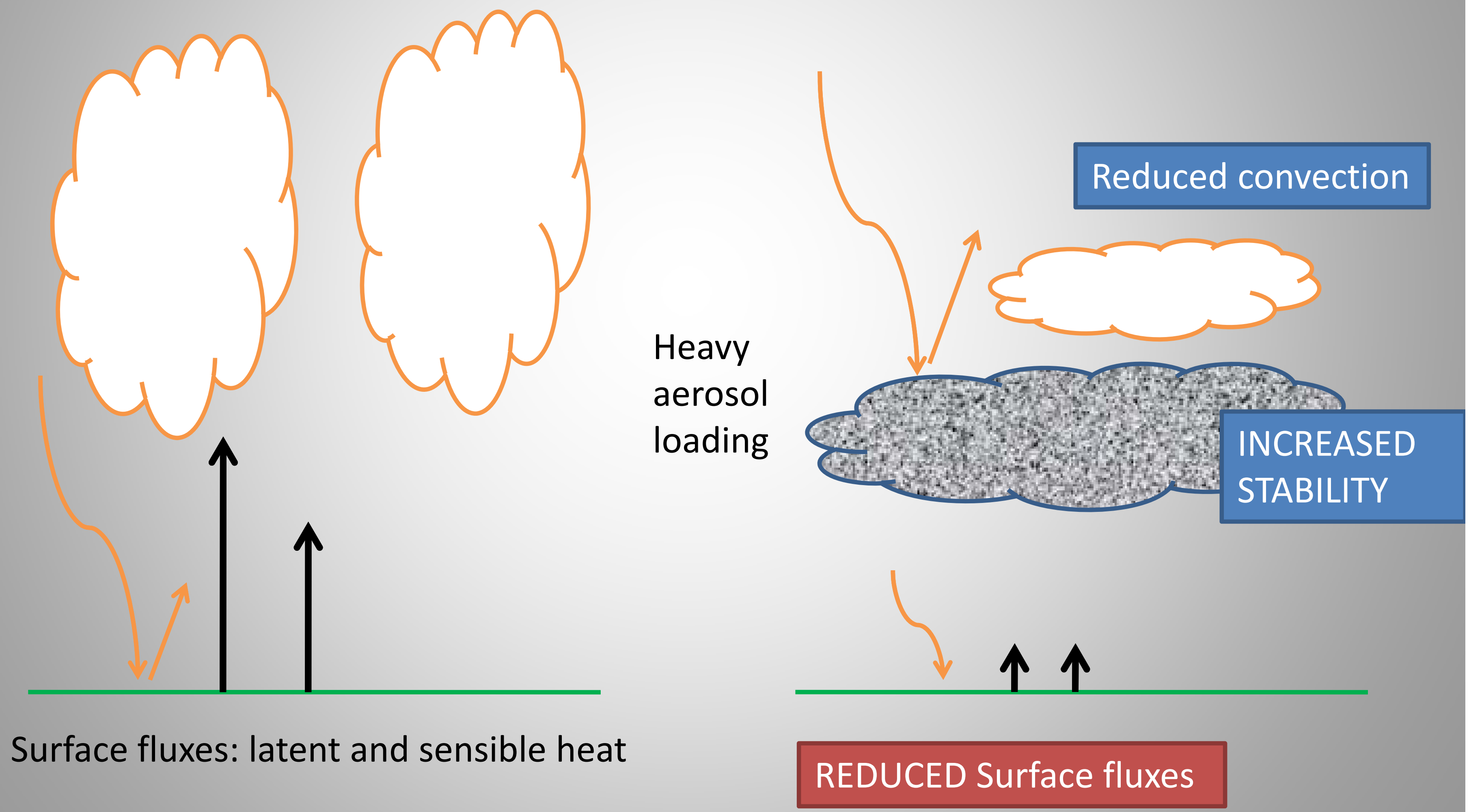
Andreae et al, 2004

Clouds and smoke over the Amazon



Andreae et al, 2004

Enhanced anthropogenic aerosols: Effects of radiation and surface fluxes



Clouds and smoke over the Amazon

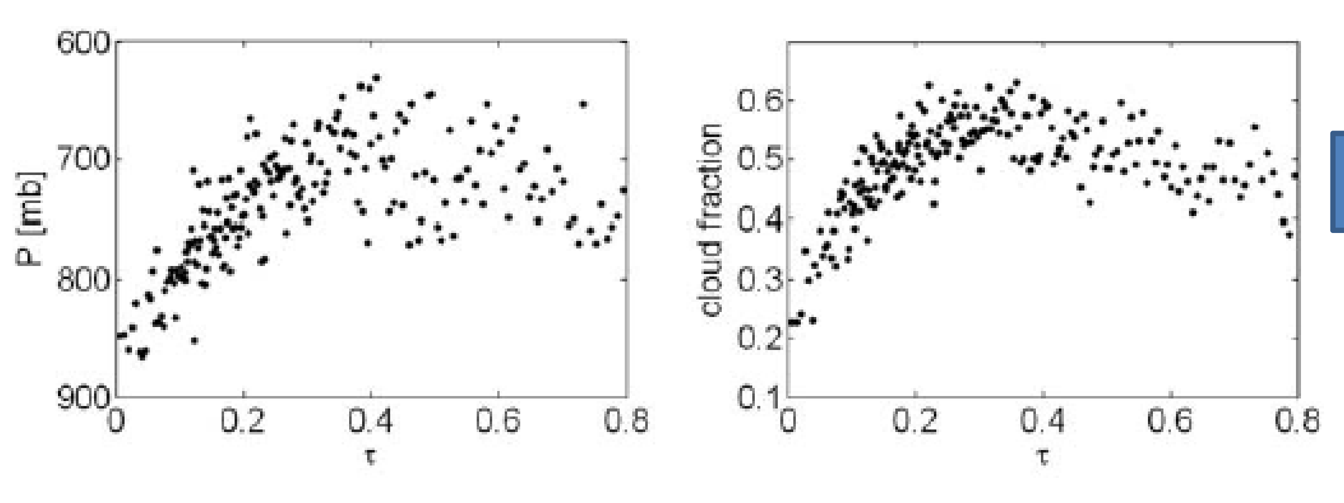
Radiative effects

Heavy smoke in the air, leading to suppression of convection in the region

NASA Columbia shuttle STS-107 flight on January 12 2003.

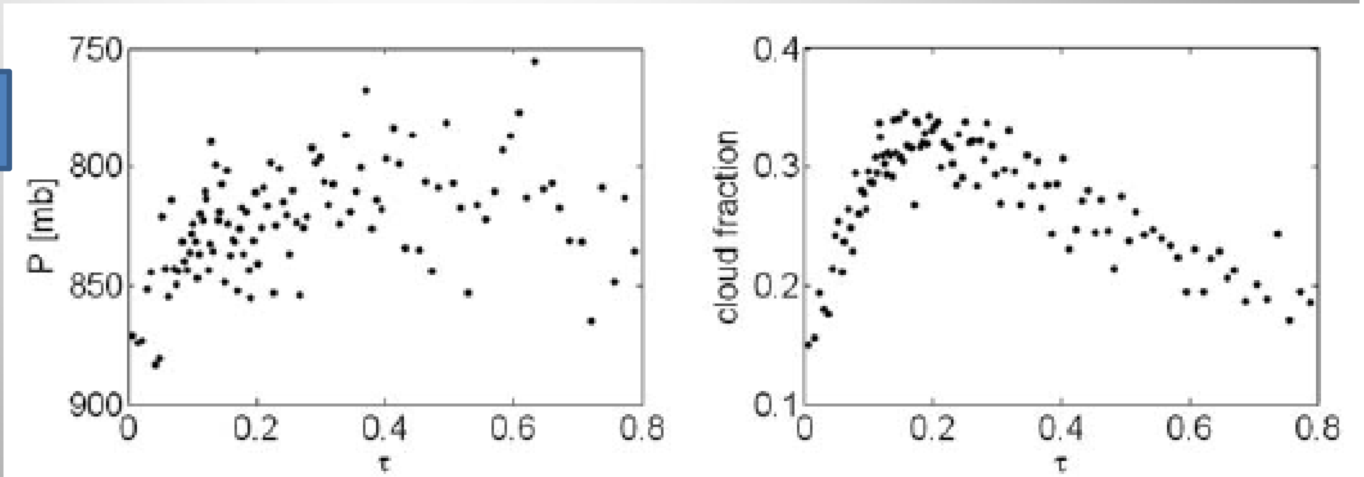
ACPC science plan, 2009

Clouds and smoke over the Amazon: Satellite observations



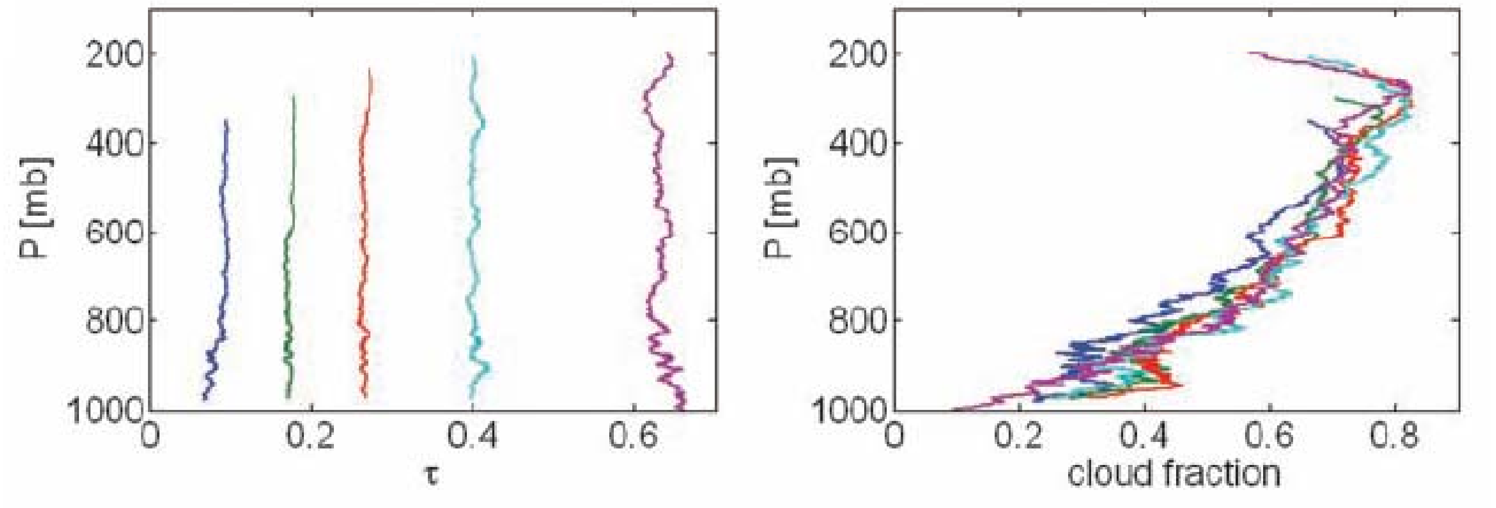
All clouds

τ < 0.5



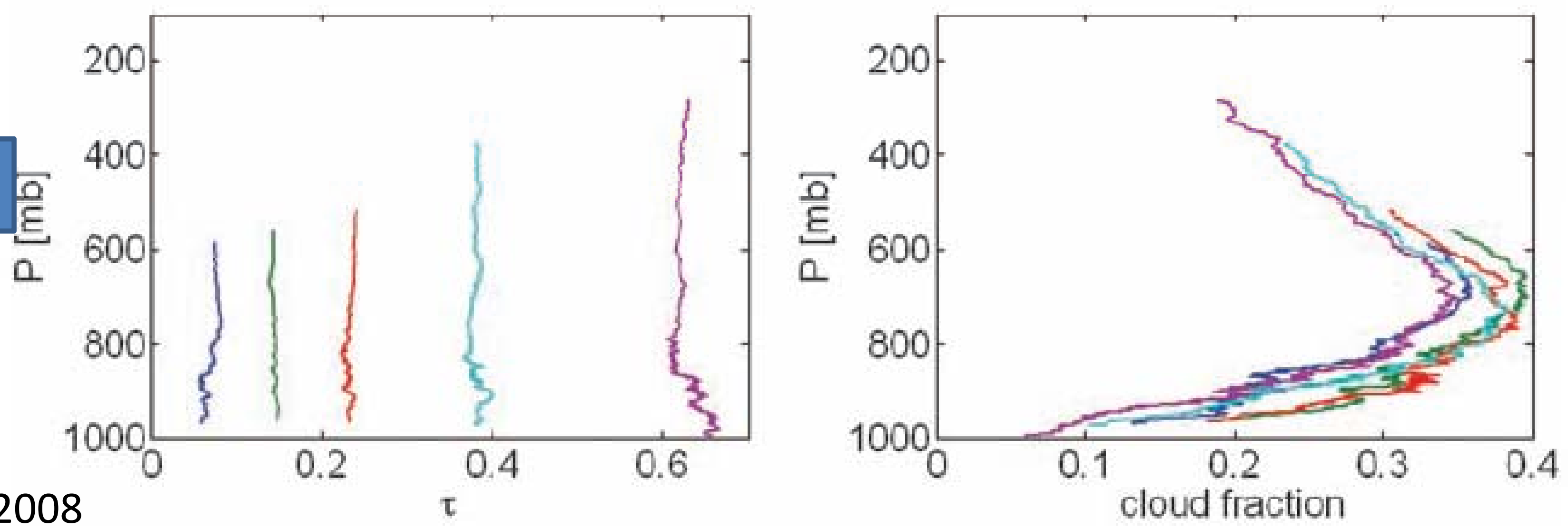
Koren et al 2008

Clouds and smoke over the Amazon: Satellite observations



All clouds

CF < 0.5



Koren et al 2008

Clouds and smoke over the Amazon: LES modelling

Feingold et al, 2005

Aerosol in BL

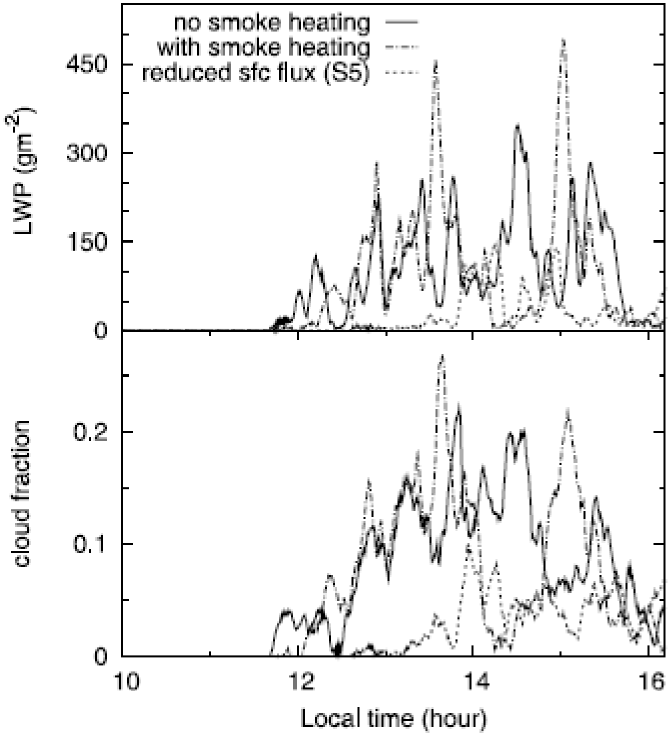
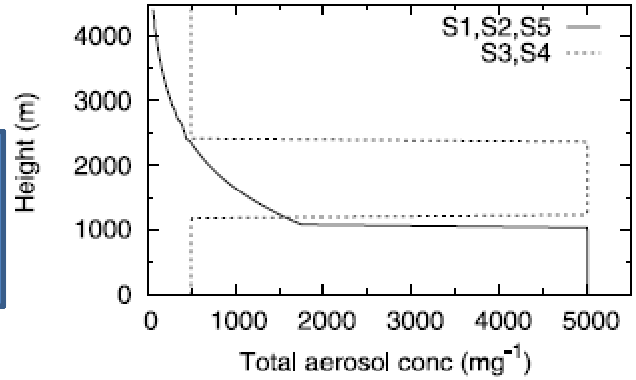


Figure 3. Time series of liquid water path LWP and cloud fraction for simulations S1, S2, and S5.

Initial aerosol profiles



Aerosol aloft

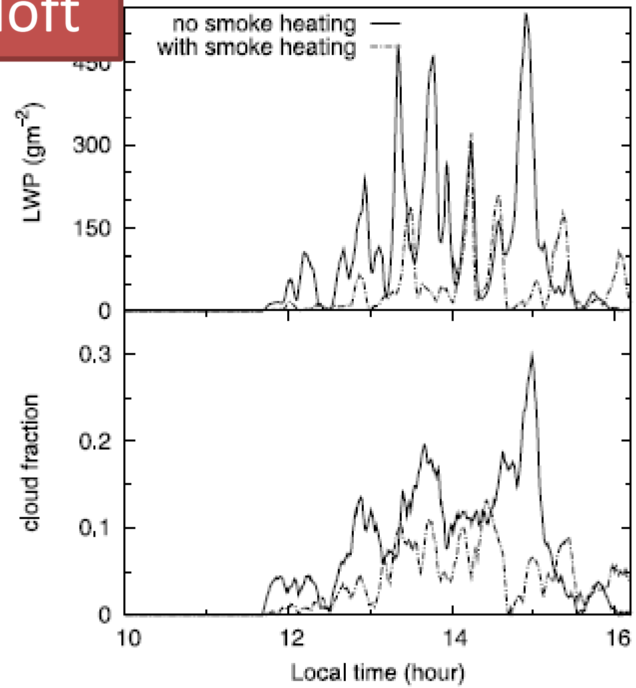
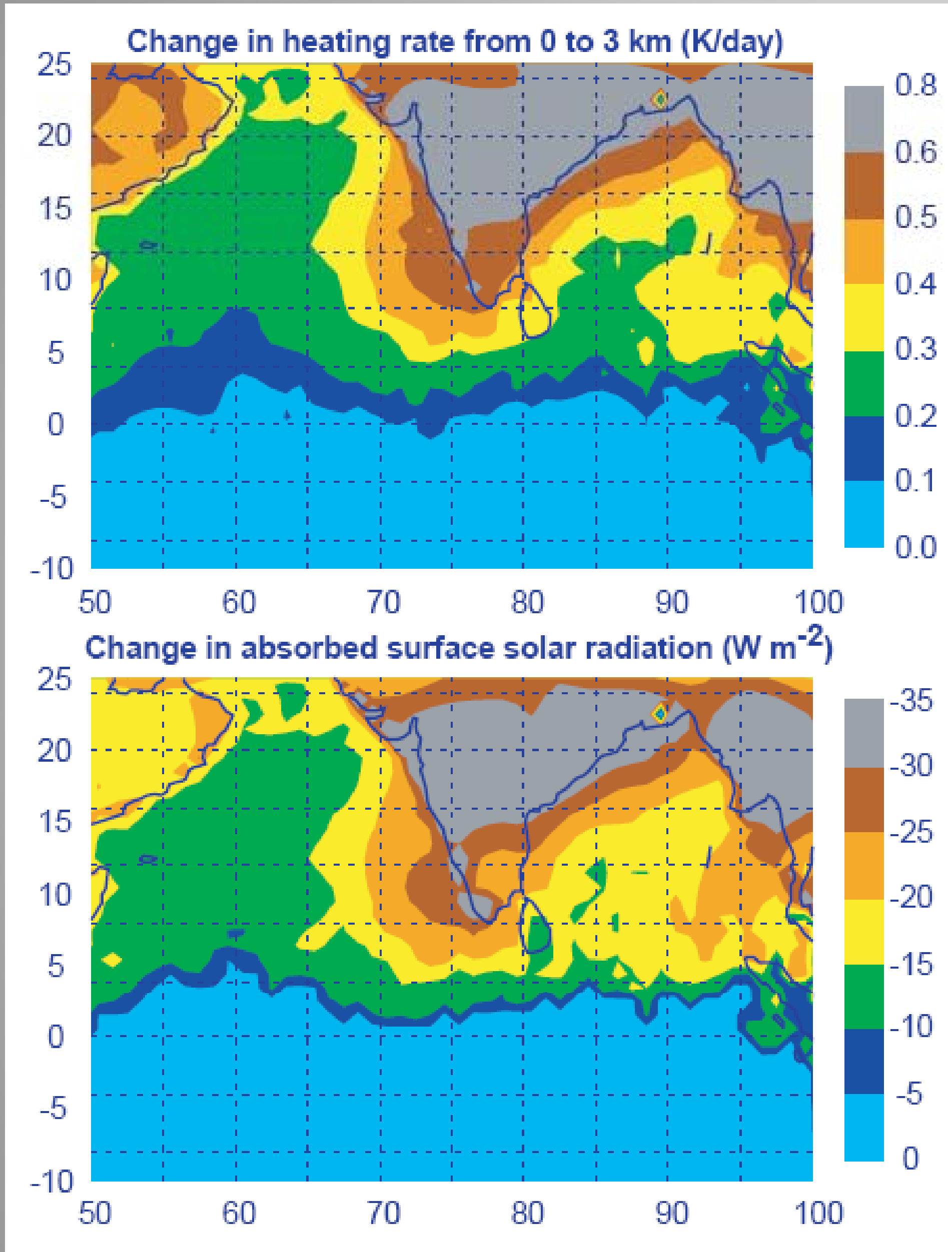


Figure 5. Time series of LWP and cloud fraction for simulations S3 (no smoke heating) and S4 (with smoke heating).

Heating by smoke leads to reduced LWP and cloud fraction



Haze in the Monsoon region

Fig. 7. The Indo-Asian haze effects on seasonal mean (January to April for 1996 to 1999) change in atmospheric solar heating rate (top panel) and the reduction in surface solar radiation (bottom panel). Results are similar to those shown in (*23*), but for a much longer period.

ABC Technical Summary, Ramanathan et al, 2008

Asian Monsoon: changes observed

Variables	South Asia and India	East Asia and China
Black carbon emissions	S Asia: Increased from under 170 Gg/yr in 1950 to about 550 Gg/Yr in 2000.	E Asia: Increased from about 250 Gg/yr in 1950 to about 1 300 Gg/yr in 2000.
SO_2 emissions	S Asia: Increased from about 1 Tg/yr in 1950 to about 7 Tg/yr in 2000.	E Asia: Increased from about 2 Tg/yr in 1950 to over 20 Tg/yr in 2000.
Dimming at surface: Solar radiation at surface	India: Trend of -4 W m^{-2} per decade from 1965 - 2000; Likely -8 W m^{-2} from 1980-2004. Total decrease of about 15 - 20 W m^{-2} since the 1960s.	China: Decrease of -20 W m^{-2} from 1960 - 1995; Reversal of trend after 1995, with a total increase of about 5 W m^{-2}.

ABC Technical Summary, Ramanathan et al, 2008

Asian Monsoon: Recent trends

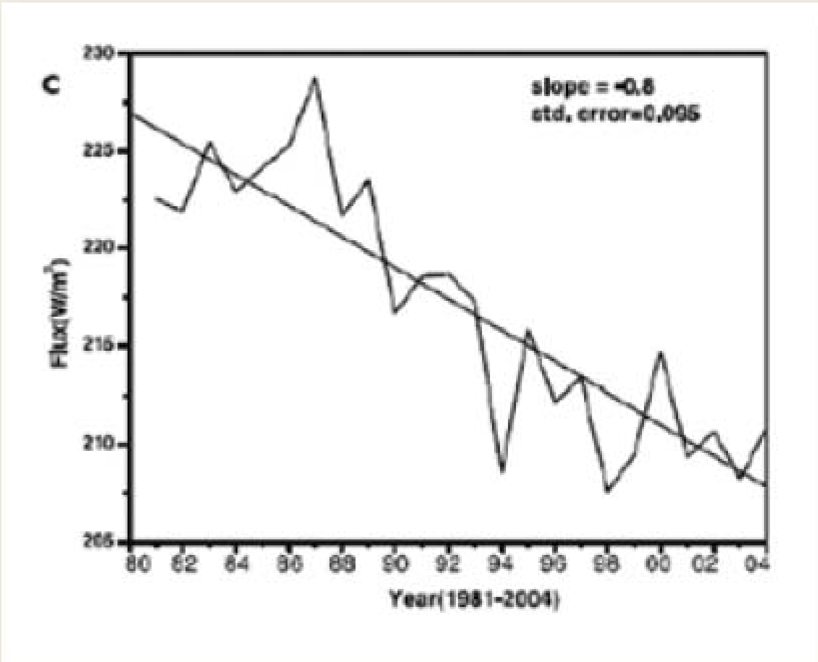


Figure TS1.5 All-India averaged annual mean surface reaching solar radiation. (Source: Kumari and others 2007). (Figure 3.1c of Part I)

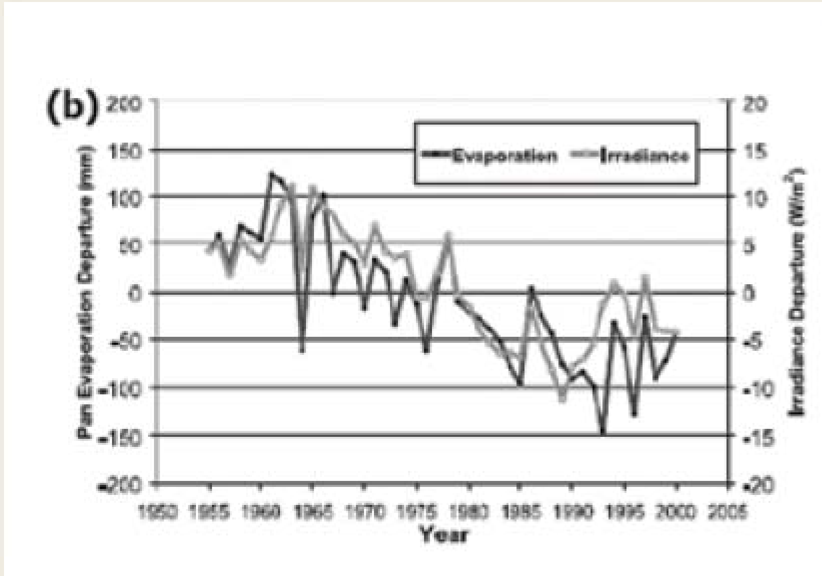


Figure TS1.6 Time-series of annual departures of pan evaporation and solar irradiance for the period 1995-2000, averaged over all stations in China (Source: Qian and others 2006). (Figure 3.2b of Part I)

ABC Technical Summary, Ramanathan et al, 2008

Asian Monsoon: changes observed

East Asian Monsoon Observed trends and attribution using models	Southward movement of monsoon belt with "north drought and south flooding". Modeling studies suggest that air pollution-induced surface cooling leads to southward shift on monsoon belt.	Xu 2001. Concluded that air pollution, that is, ABCs, is the major reason for anomalies in monsoon rainfall.
East Asian Monsoon Change from pre-industrial to present; A modelling study with fixed SST on the role of black carbon	Summer precipitation increased in Southern China and decreased northwards.	Menon and others (2002). Concluded that the northern drought and southern flooding in China are due mainly to BC aerosols intensifying circulation over Southern China with subsidence in Northern China and Southeast Asia.
East Asian Monsoon Trends in the past 25 years in surface temperature and precipitation	More frequent floods along with cooler conditions over the Yangtze River Valley; accompanied by continuing droughts and longer hot spells in Northern China in the past 25 years.	Zhao and others (2005a) reviewed available papers on this topic. After considering natural variability, GHGs and sulphate and black carbon aerosols (ABCs), concluded that GHGs and brown clouds likely account for rainfall trends.

ABC Technical Summary, Ramanathan et al, 2008

Asian Monsoon: changes observed

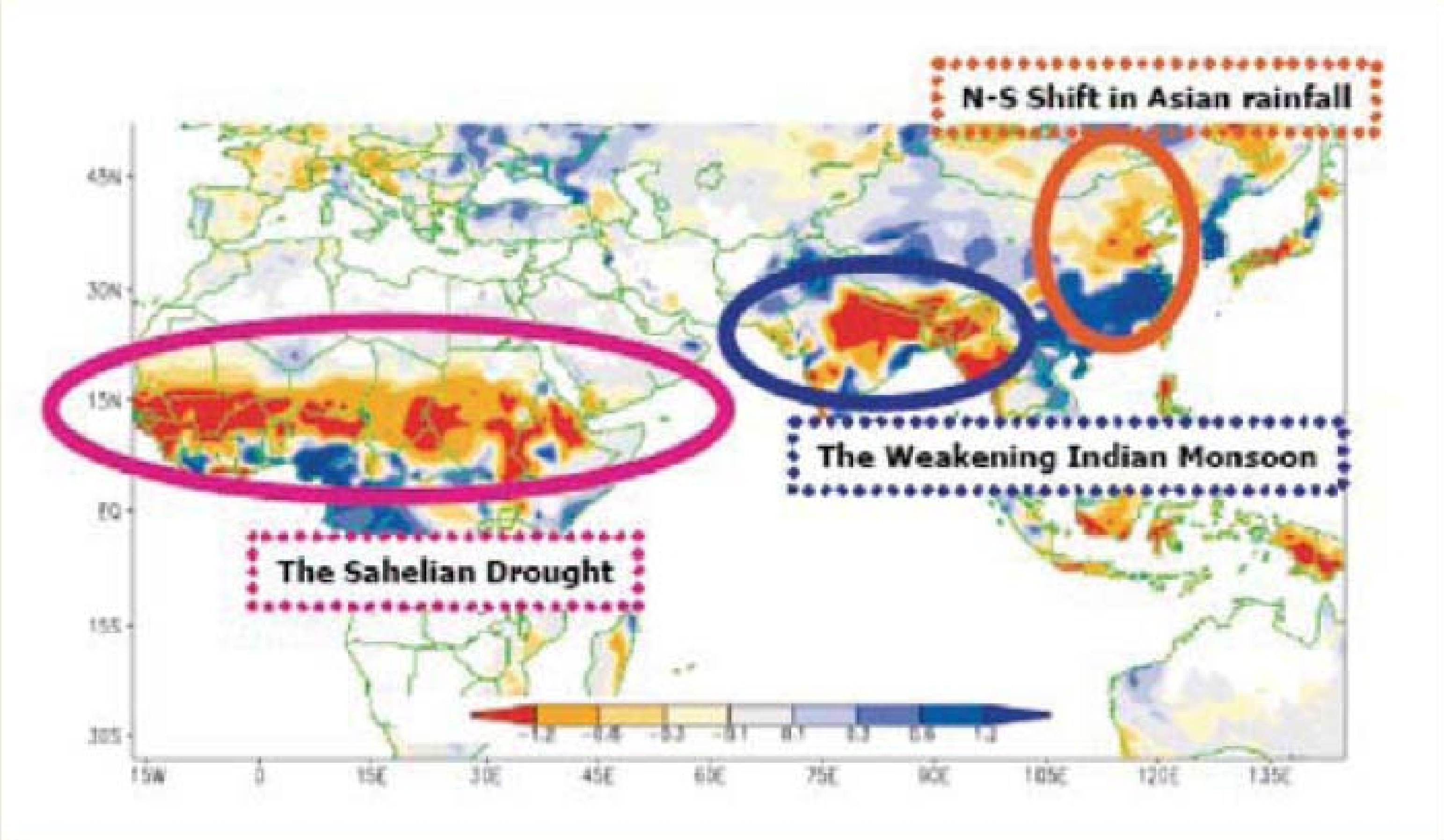


Figure TS1.8 *Observed trends in summer rainfall: 1950 - 2002. (Source: Chung and Ramanathan 2006). (Figure 3.8 of Part I)*

ABC Technical Summary, Ramanathan et al, 2008

Aerosols, Clouds, Precipitation and Climate (ACPC)

Joint Program by the International Geosphere-Biosphere Program (IGBP and the World Climate Research Program (WCRP), under core projects (iLEAPS, IGAC and GEWEX)

Objectives

The ACPC program aims to bring together a variety of communities for large observational, modeling, and theoretical efforts to understand the interplay amongst clouds, aerosol, and precipitation within a comprehensive and integrated research program. In particular, this program aims to:

- characterize aerosol-cloud-precipitation interactions for the relevant regimes by ensuring that experimental strategies address regimes where the meteorology is sufficiently constant, and aerosol variability occurs over a sufficiently wide range, so as to assist in the separation of meteorological from aerosol drivers;
- act as a forum for bringing together the diverse expertise necessary to advance our understanding;
- coordinate and synthesize the findings of various components of the program;
- help coordinate international efforts;
- provide continuity and perspective for research initiatives.

THE JOINT AEROSOL–MONSOON EXPERIMENT

A New Challenge for Monsoon Climate Research

BY K.-M. LAU, V. RAMANATHAN, G.-X. WU, Z. LI, S. C. TSAY, C. HSU, R. SIKKA, B. HOLBEN, D. LU, G. TARTARI, M. CHIN, P. KOUDELOVA, H. CHEN, Y. MA, J. HUANG, K. TANIGUCHI, AND R. ZHANG

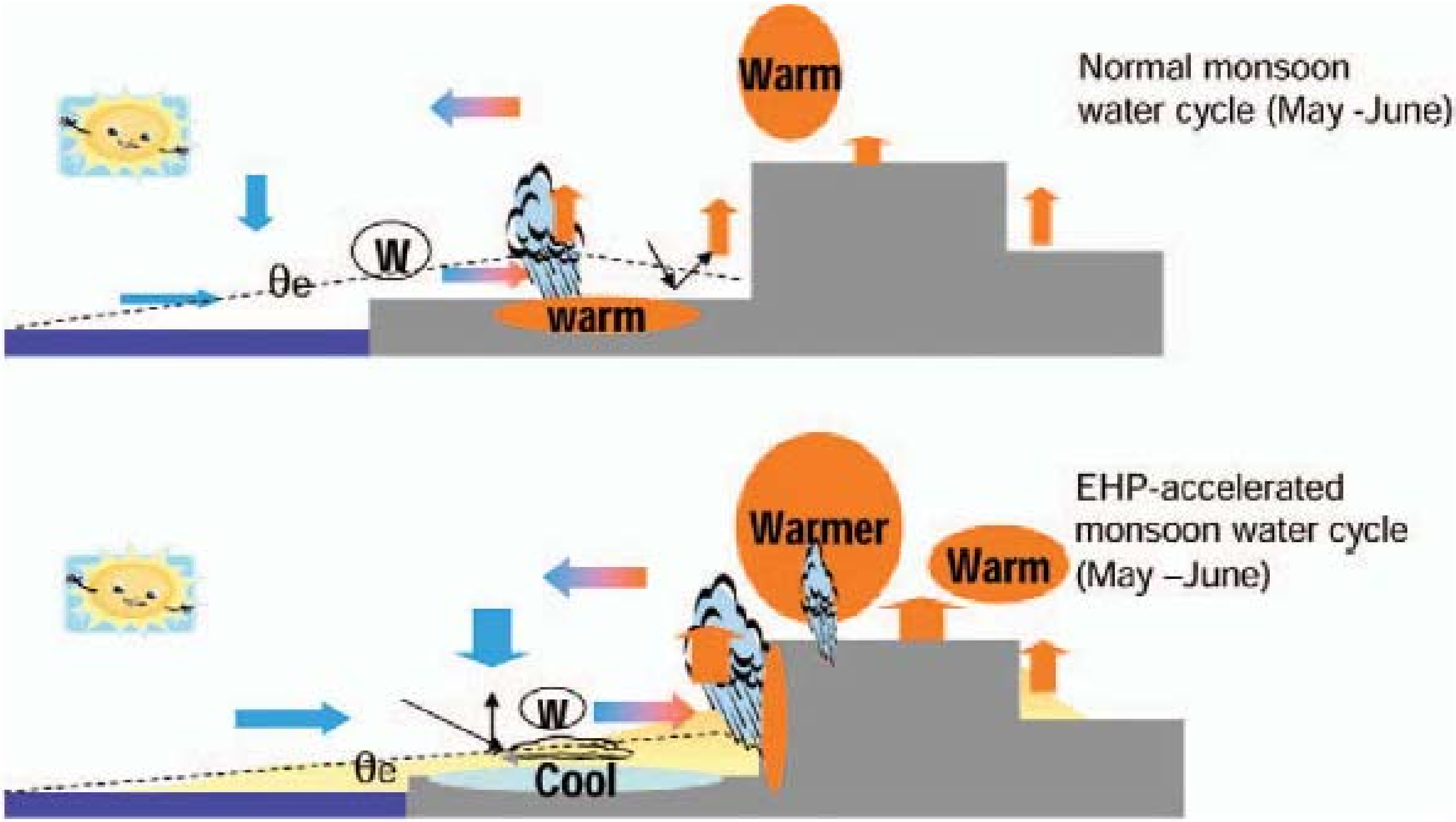
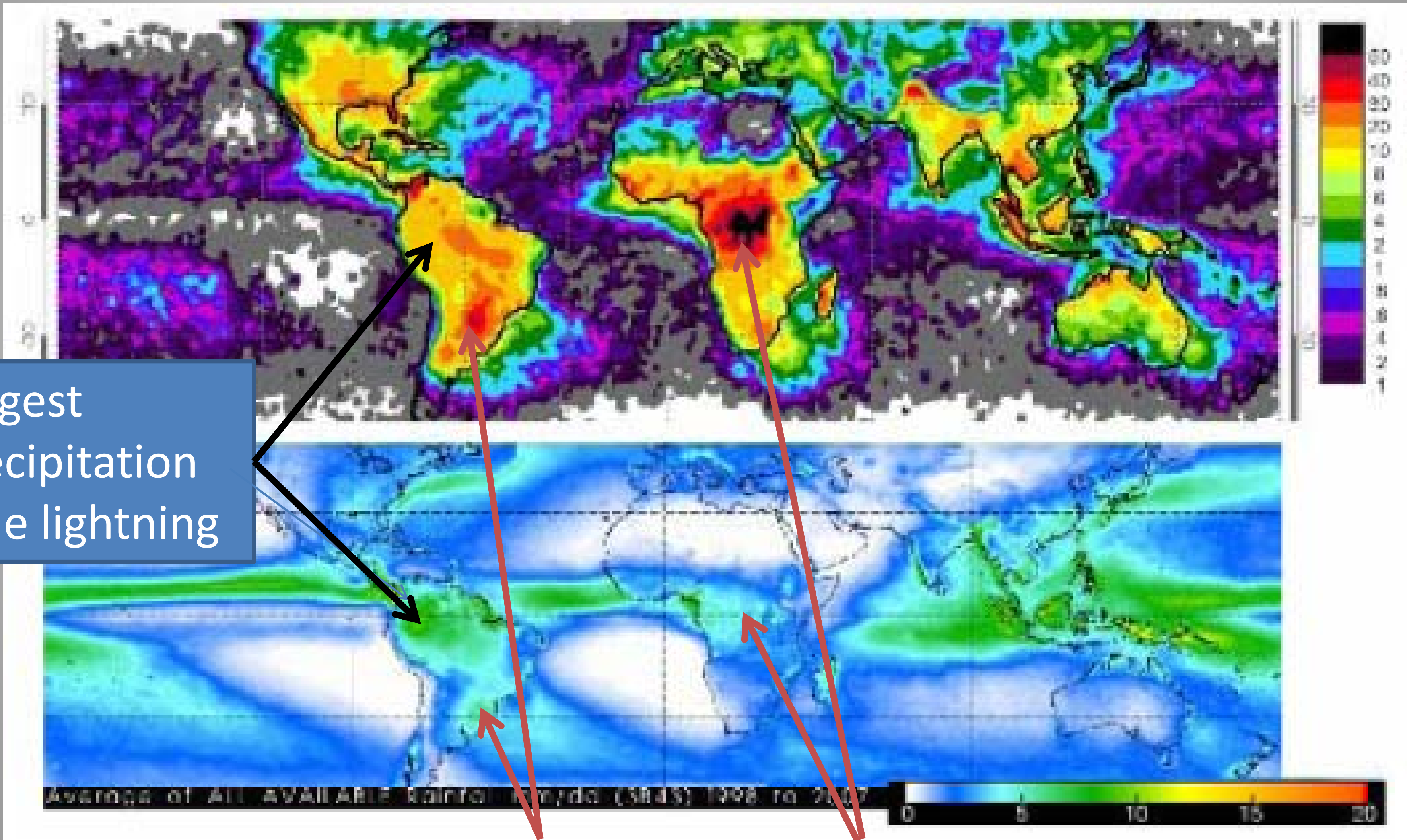


FIG. 3. Schematic showing the monsoon water cycle (top) with no aerosol forcing and (bottom) with aerosol-induced elevated heat pump effect. Low-level monsoon westerlies are denoted by W. The dashed line indicates magnitude of the low-level equivalent potential temperature θ_e. Deep convection is indicated over regions of maximum θ_e. (See text for further discussions.)

Hypothesis: High lightning in regions of aerosol-suppressed warm precipitation



Largest precipitation little lightning

Large lightning, less precipitation

ACPC science plan, 2009

Clouds-Aerosol-Precipitation in the Marine Boundary Layer (CAP-MBL):
Is variability of precipitation on diurnal-seasonal scales related to aerosols?

LES Models: Aerosol Effects on Cloud Morphology via Drizzle

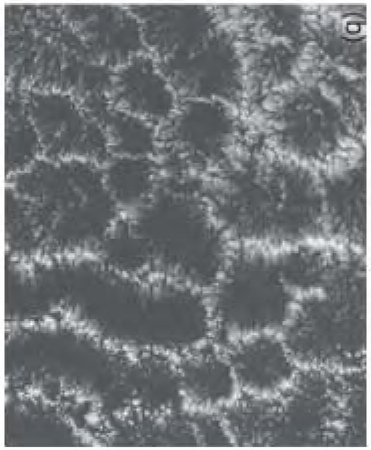
Albedo

Closed-cell
Albedo ~ 0.6
(non-precipitating)

→ high aerosol

Onset of ***drizzle*** *results in transition to open-cell convection*

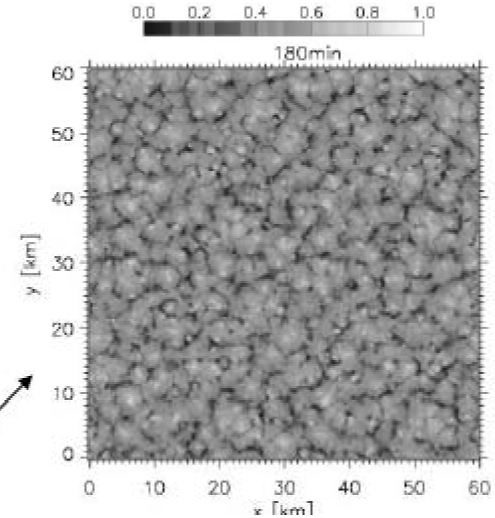
WRF Model
+ 2-moment
μphysics;
60 km domain;
$\Delta x = \Delta y = 300$ m
$\Delta z = 30$ m

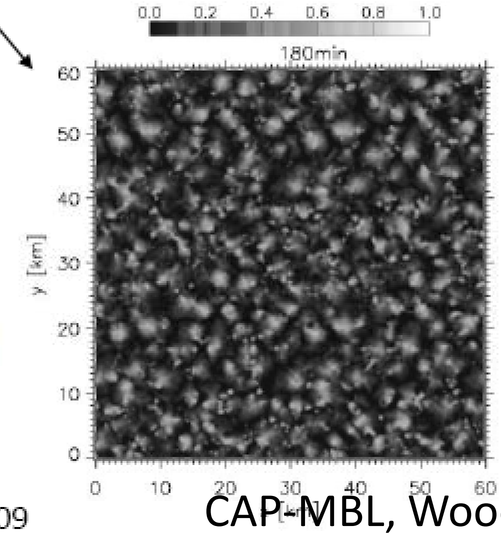


Open-cell
Albedo ~ 0.2
(precipitating)

→ low aerosol

Albedo



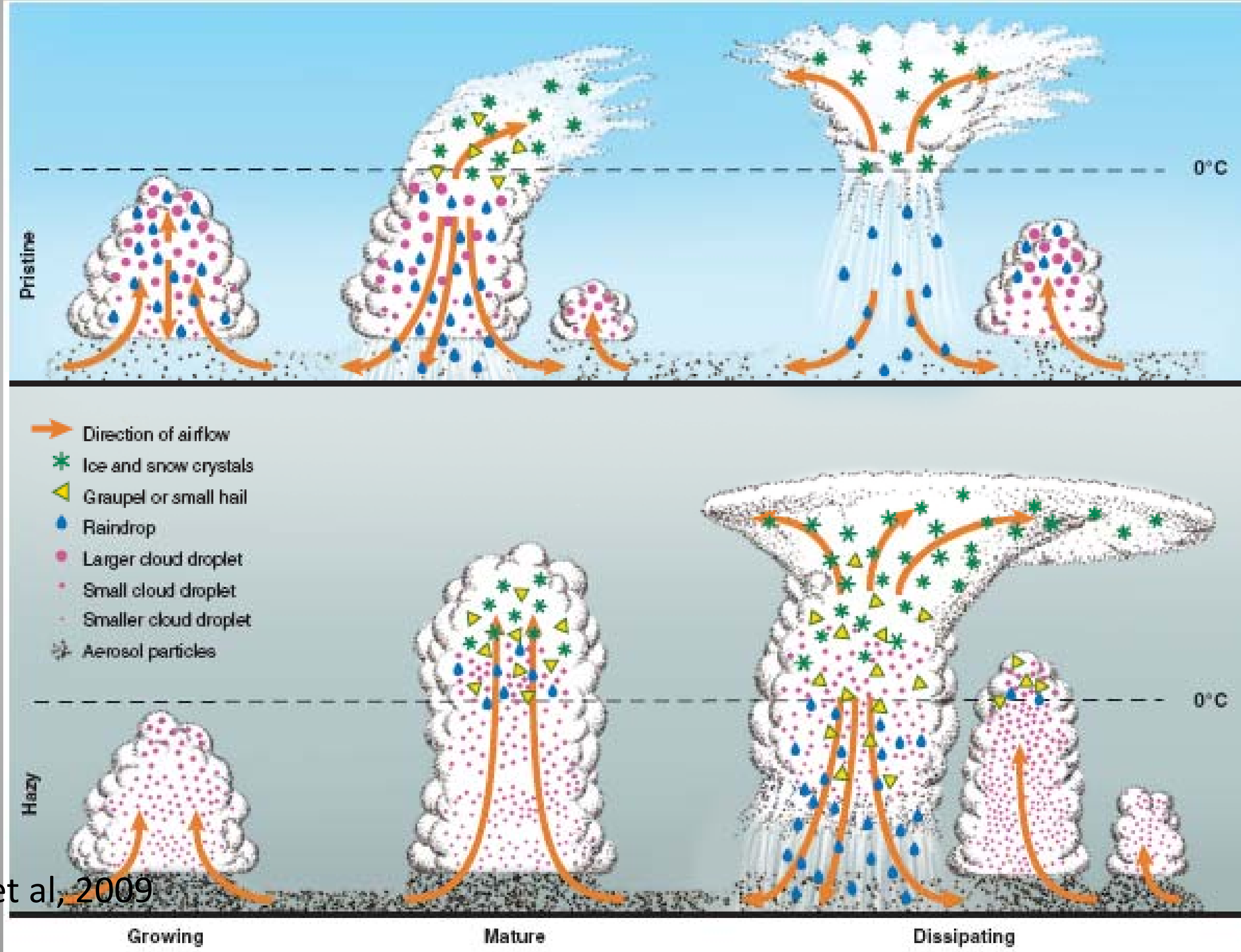


Garay et al. 2004, MISR

Wang and Feingold, 2009

CAP-MBL, Wood, 2009

Anthropogenic aerosols and precipitation:
Thermodynamic effect: Budget study in the Amazon



Rosenfeld et al, 2009

Urban heat island: evidence of man-made changes in local climate METROMEX studies (1970s)

- St. Louis exhibits a large precipitation anomaly during summer compared with surroundings.
- Much of the enhanced rainfall occurs during the afternoon (5-9 pm)
- Thunderstorms enhanced by 45% and hailstorms by 30%
- Hailstones are larger and higher in concentration
- Area experienced 58% increase in nocturnal precipitation

Changnon, 1981

Urban heat island: evidence of man-made changes in local climate

- Clouds had bases 600-700m higher than in rural areas, consistent with drier air in the city.
- cloudiness (o cloud fraction) was found greater over the urban area in the late afternoon, consistent with low-level convergence
- convective cells merged more readily, reached higher altitudes and lasted longer

Changnon, 1981

Urban heat island: evidence of man-made changes in local climate

Hypotheses for observed changes:

- urban increases in CCN and IN concentrations
- changes in surface roughness and low-level convergence
- changes in ABL caused by urban heating and land-use change
- addition of moisture from industrial sources

Modeling studies were not fully conclusive on the role of the different factors… need more field studies

AEROSOLS AND THEIR IMPACT ON PRECIPITATION

We showed some evidence of:

- Aerosols affecting precipitation different cloud types, in BL clouds: marine stratocumuli and small convective clouds in the Amazon
- Different types of aerosols may affect precipitation differently (solubility, presence of ice nuclei)
- When surface forcing is reduced clouds are inhibited (INDOEX and Amazon)

For modeling results of convective clouds in different regimes see follow up talk by Jasa this afternoon!!

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