AEROSOL, CLOUDS & RADIATION

from Radiation to Cloud Physics

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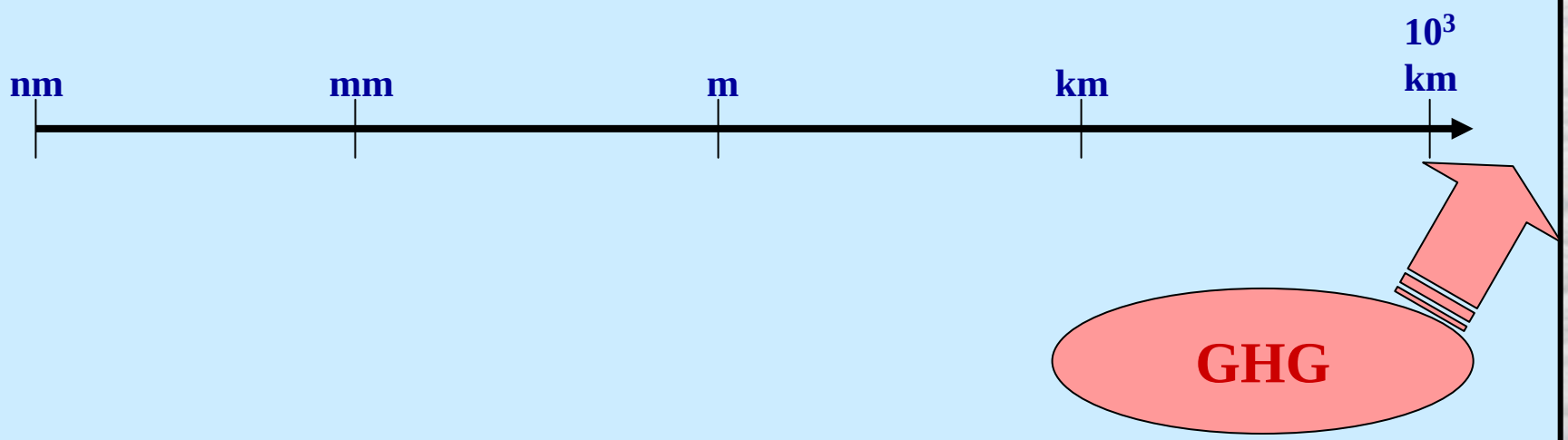
Aerosol – Cloud Interactions

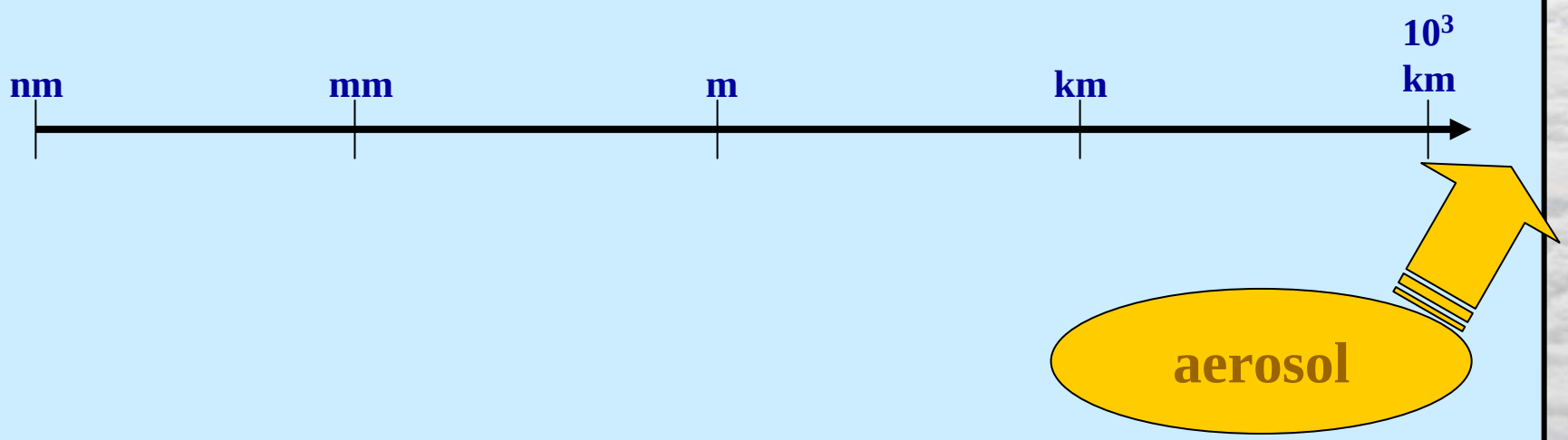
The Global Perspective

Forcings & Feedbacks



Temperature ↗ ⇒ Water vapour mixing ratio ↗
Low level cloud cover ↗ ⇒ negative feedback
High level cloud cover ↗ ⇒ positive feedback

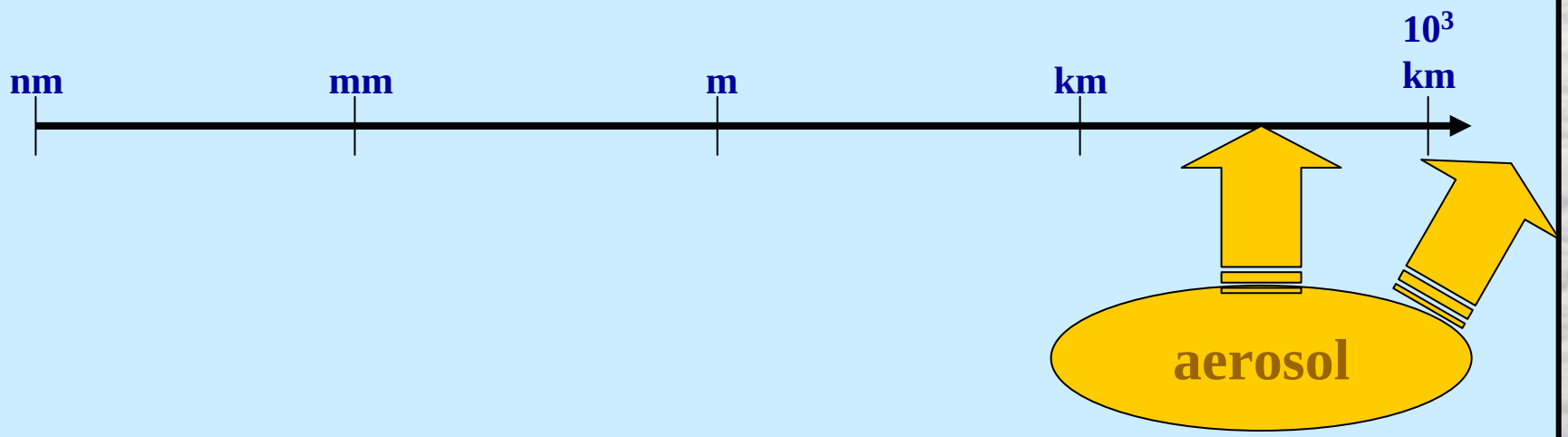
Forcings & Feedbacks



Albedo ↗ ⇒ Temperature of the atmosphere ↘
Absorption ↗ ⇒ Temperature of the atmosphere ↗

Unlike GHG, aerosol are not uniformly distributed

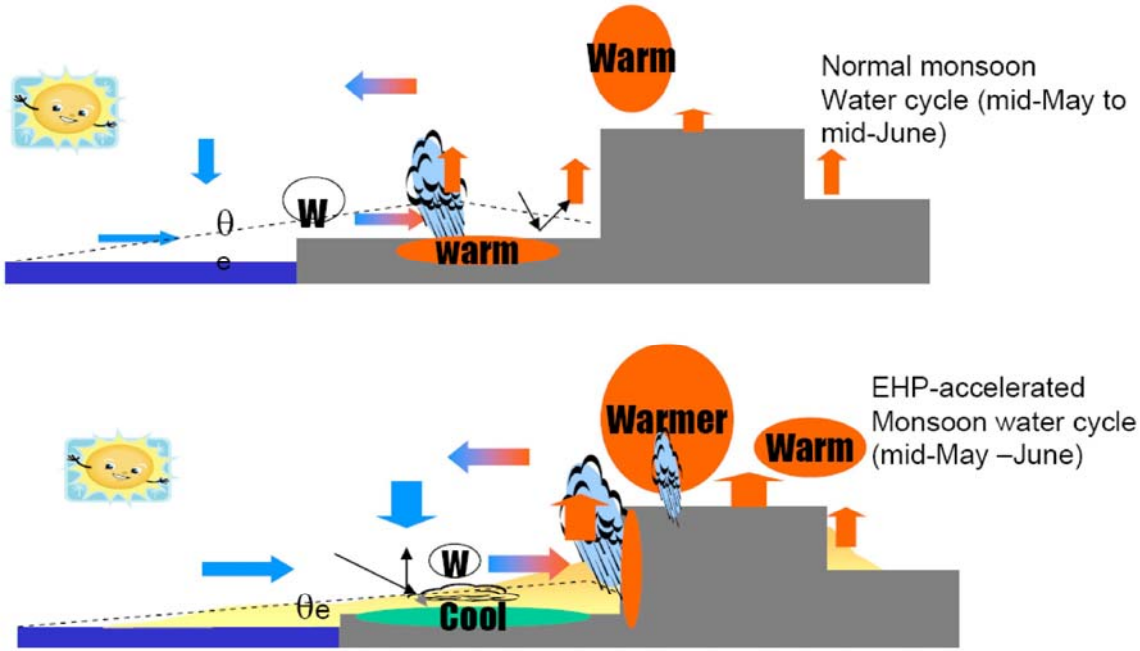
Forcings & Feedbacks



At the regional scale, aerosol can impact the general circulation by heating/cooling specific atmospheric layers

Forcings & Feedbacks

The Elevated Heat Pump (EHP) hypothesis (Lau et al. 2006, Climate Dynamics)

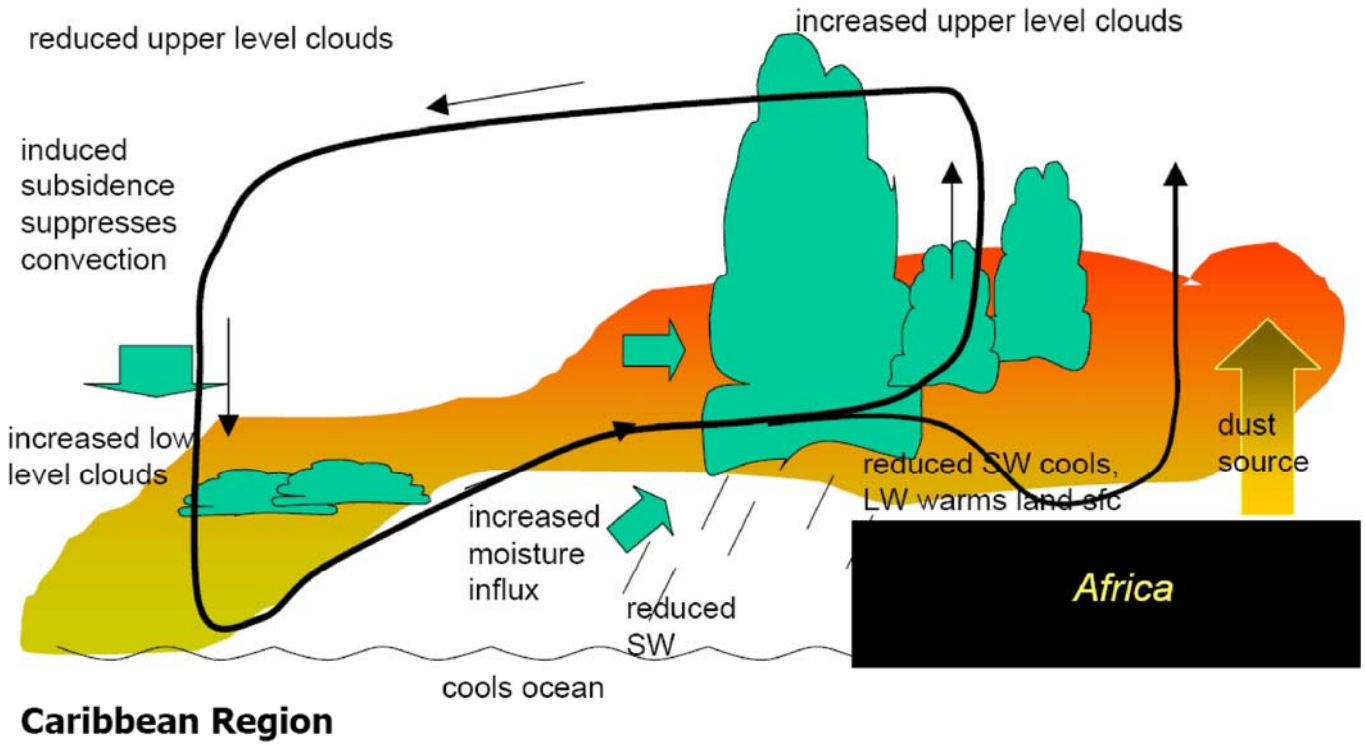


EHP postulates:

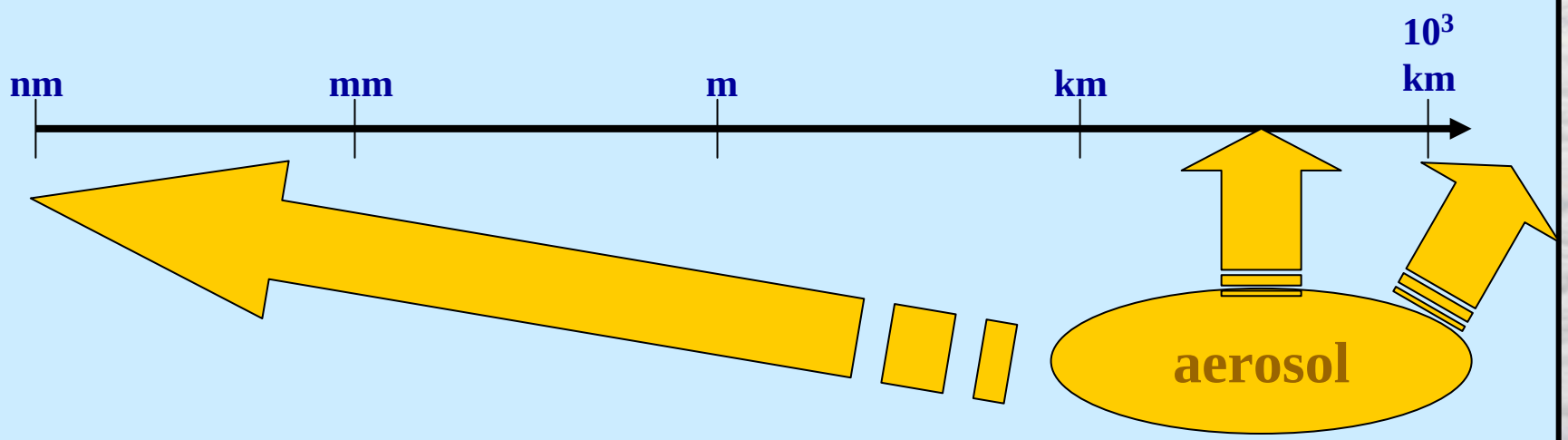
a) anomalous heating of Himalaya foohills, and warming of the upper troposphere over TP in MAM
b) an advance of the rainy season in northern India/Napal region in May-June
c) In June-July, the increased convection spreads from the foothills of the Himalayas to central India, resulting in an intensification of the Indian monsoon.

Lau and Kim (2006, GRL)

Forcings & Feedbacks



Forcings & Feedbacks



With its nucleating properties, CCN and IN, the aerosol can impact cloud microphysical properties

Do cloud microphysical changes have an impact on cloud radiative properties ?

Aerosol Impacts on Cloud Microphysics

CCN & Cloud Droplet Concentration

(I)

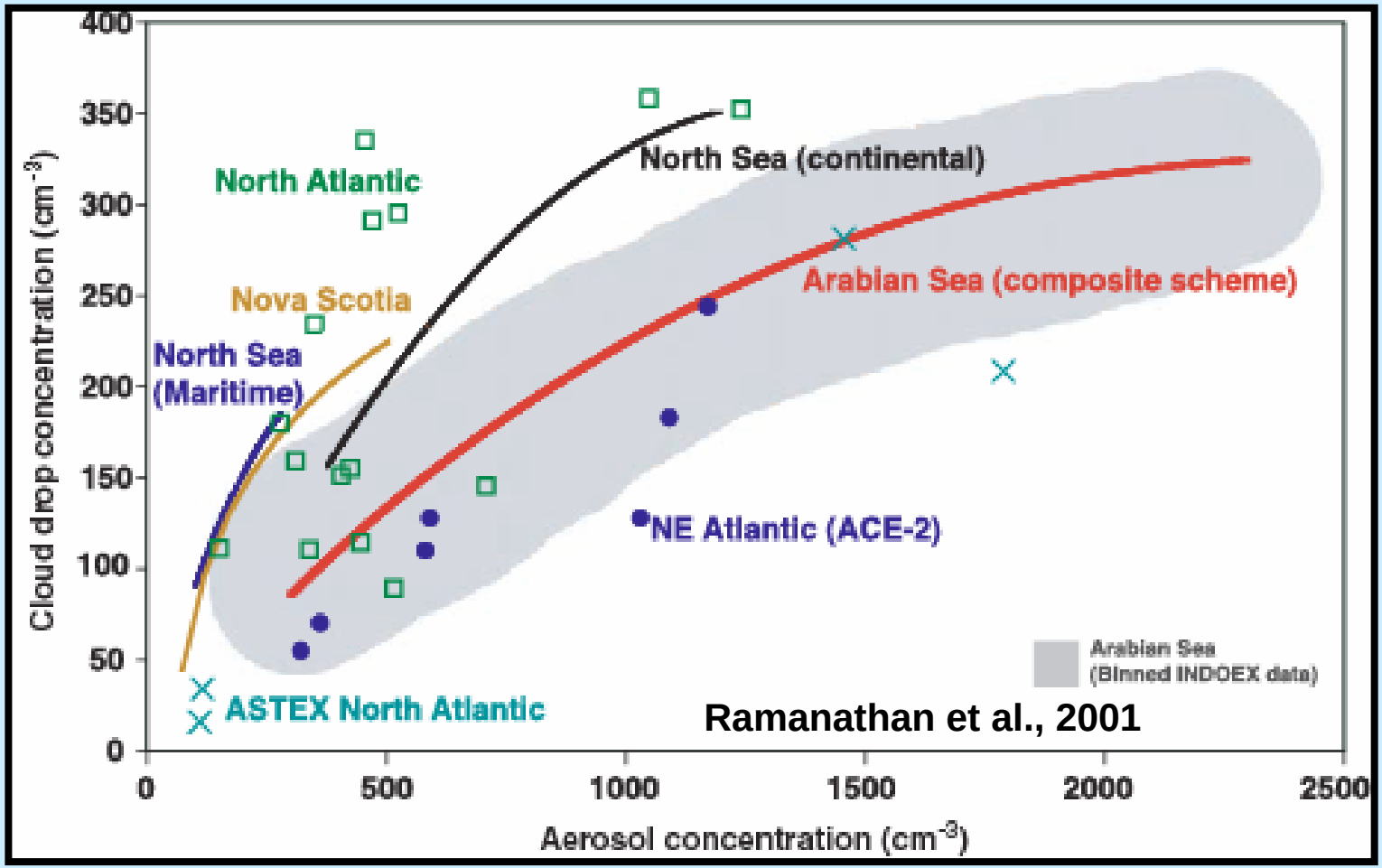
Increased Aerosol concentration

⇒

Increased CDNC

although the scaling factor depends on the fraction of the aerosol that acts as CCN and on the ability of clouds to activate the CCN (cloud dynamics)

Aerosol Impacts on Cloud Microphysics



Gunn & Phillips, 1957; Squires, 1958; Squires & Twomey, 1961; Warner & Twomey, 1967; Warner, 1968

Aerosol Impacts on Cloud Microphysics

CDNC & Droplet Sizes

(II)

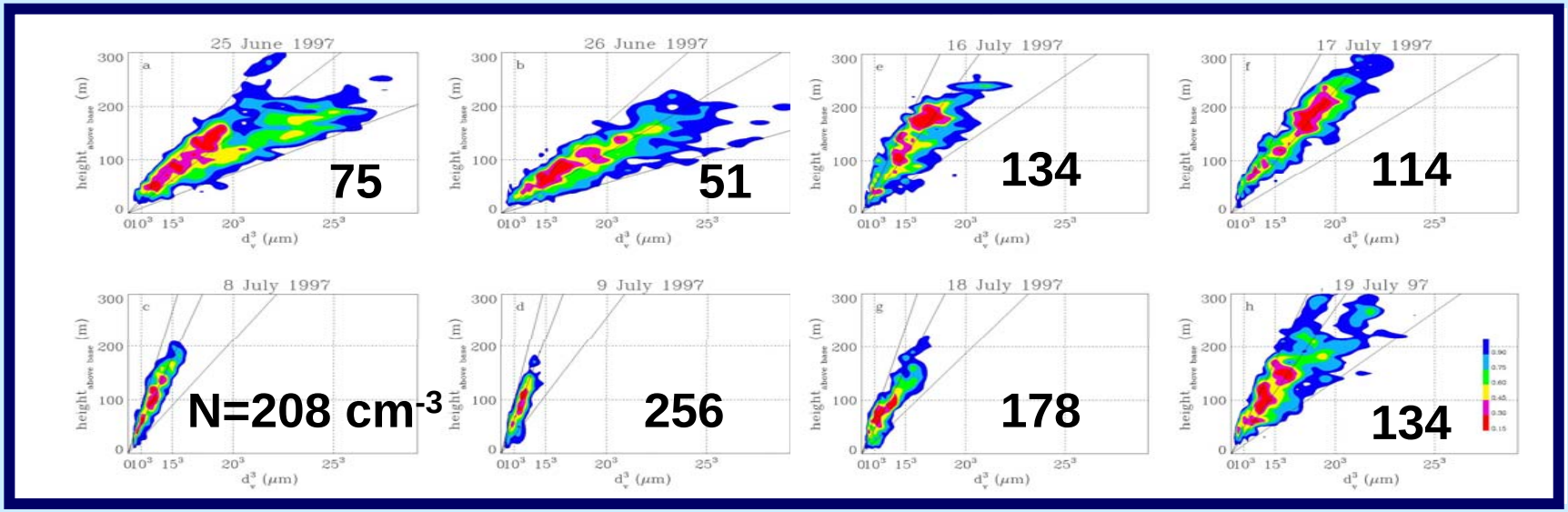
Increased CDNC

$\Rightarrow$

Smaller droplet sizes (cst LWC)

$$(LWC = 4/3\pi\rho_w N r_v^3)$$

Aerosol Impacts on Cloud Microphysics



Comparison of vertical profiles of the microphysics in pristine and polluted marine stratocumulus clouds.

Data from the ACE-2 field experiment (Brenguier et al., 2003)

Aerosol Impacts on Cloud Radiation

CDNC & Cloud Radiative Properties

(III)

Increased CDNC

$\Rightarrow$

Increased COT (cst LWC)

(Twomey Effect)

$$q_c = C_w h = 4/3\pi\rho_w N r_v^3$$

$$k = (r_s/r_v)^6 = (r_v/r_e)^3$$

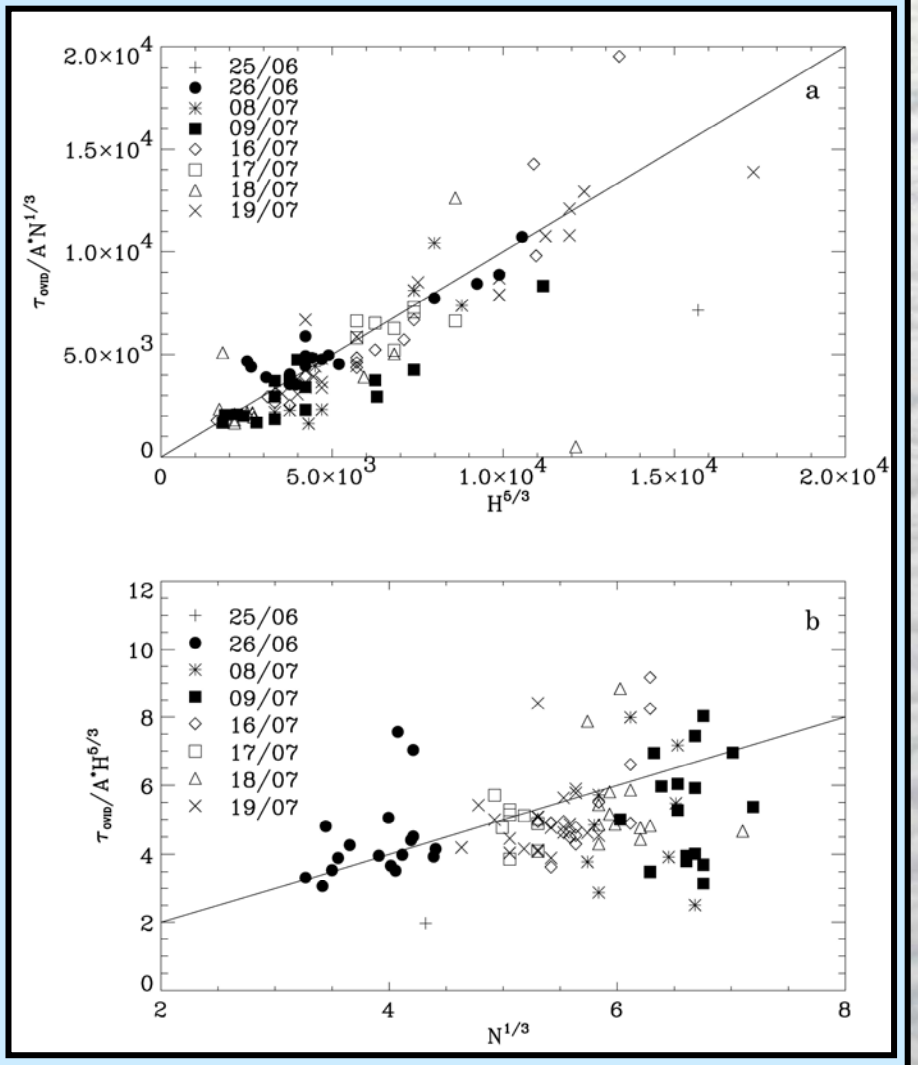
$$\tau = \pi Q_{ext} N r_s^2 H \qquad \Rightarrow \tau = A(kN)^{1/3} H^{5/3}$$

$$W = \tfrac{1}{2} C_w H^2 \qquad = A(kN)^{1/3} W^{5/6}$$

Aerosol Impacts on Cloud Radiation

Comparison of optical thickness derived from in situ measurements with the one derived from independent radiance measurements from above the cloud layer.

Data from the ACE-2 field experiment (Brenguier et al., 2000)



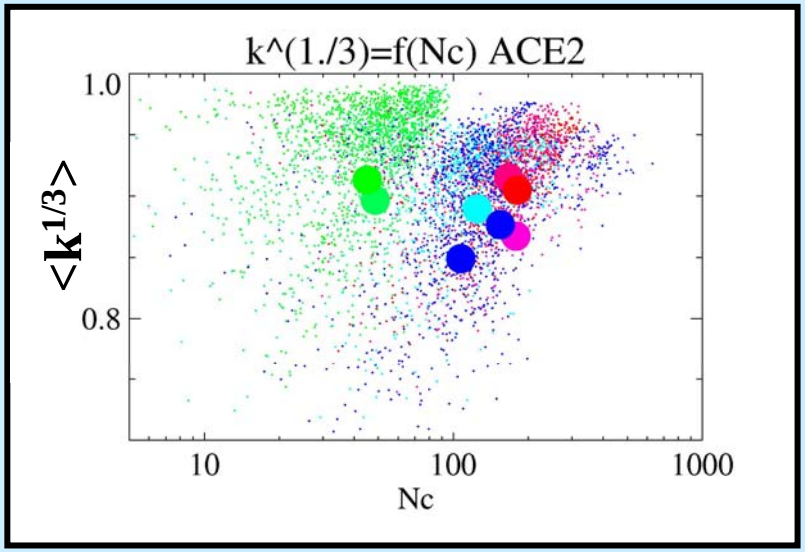
STRAYINGS : the k Warming Effect

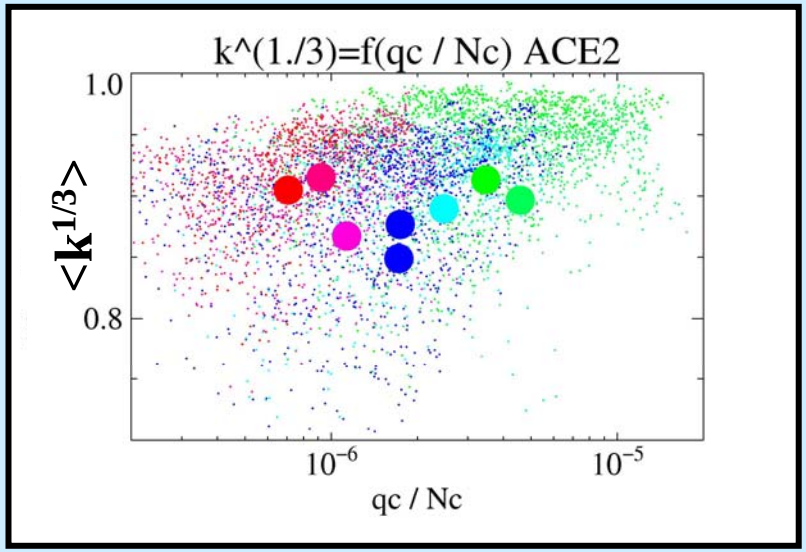
$\tau = A(kN)^{1/3}H^{5/3} = A(kN)^{1/3}W^{5/6}$ 0.67 < k < 0.80 (Martin et al., 1994)

$0.84 < k^{1/3} < 0.93$

k decreases when N increases, hence reducing the Twomey effect cooling (Liu& Daum, 2000).

k varies with q_c/N (Liu et al., 2008), as $\beta=1/k^3 = 0.07(q_c/N)]^{-0.014}$





0.67 < k < 0.80 (Martin et al., 1994); 0.61 < k < 0.77 (ACE-2)

Just replace the diagnostic of N by kN

Satellite Retrievals : τ & r_e

Optical thickness & Effective Radius

Multispectral radiances (VIS+NIR) provide information about the COT and the droplet effective radius

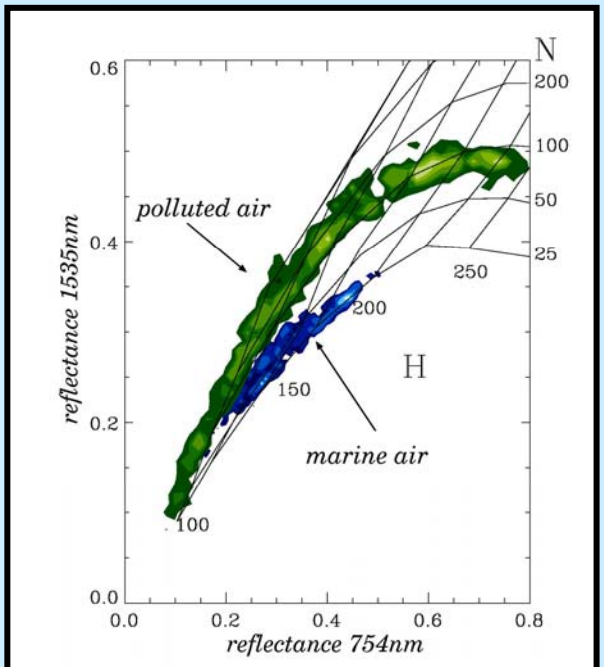
$$\tau = \int \sigma_{ext}(h)dh \qquad r_e = r_v^3 / r_s^2$$

The interpretation of τ & r_e in term of cloud properties depends on the cloud model that has been used to develop the retrieval look-up table (most commonly plane-parallel, vertically uniform cloud layer)

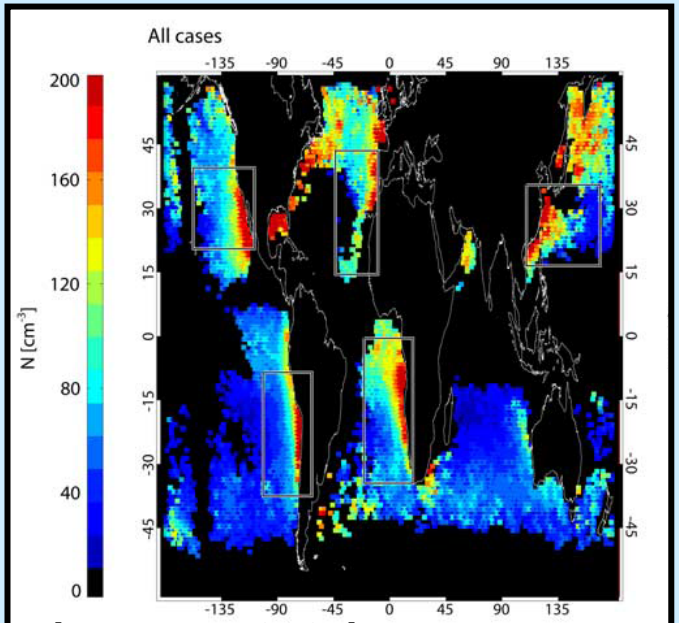
Satellite Retrievals : τ & r_e

Marine boundary-layer clouds

For the specific case of MBL clouds, an adiabatically stratified cloud model can be used to relate τ & r_e to cloud state variables, such as CDNC and LWP (Brenguier et al., 2000, Schüller et al., 2005; Boers et al., 2005; Bennarz, 2007)



(Brenguier et al., 2000)



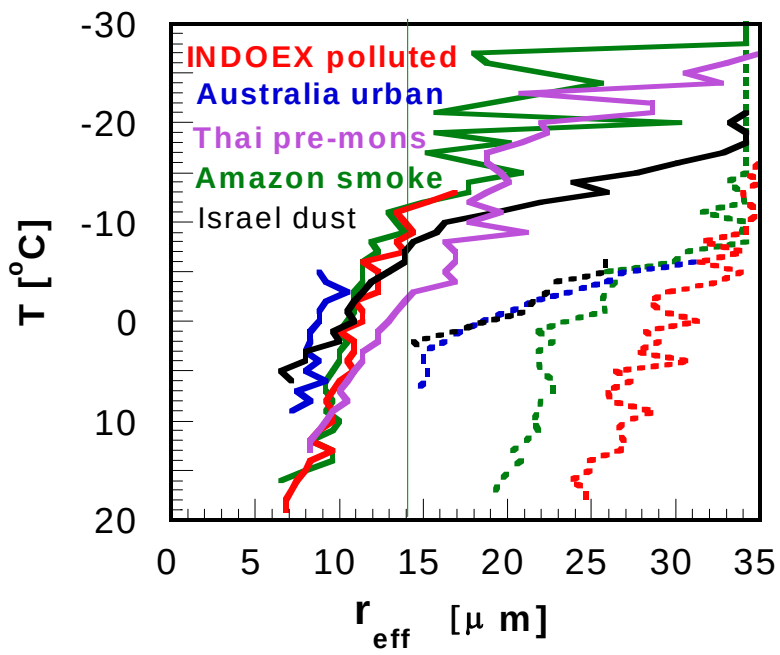
(Bennarz, 2007)

Satellite Retrievals : τ & r_e

Cumulus clouds

For the specific case of cumulus cloud systems, with varying cloud top altitudes, the vertical profiles of retrieved τ & re can be interpreted as the τ & re profiles within the clouds (Rosenfeld and Lensky, 1998; Rosenfeld, 2000)

Satellite retrieved median effective radius of particles near the top of deep convective clouds at various stages of their vertical development, as a function of the cloud top temperature, which serves as a surrogate for cloud top height, in polluted (solid lines) and pristine air (broken lines).



Satellite Retrievals : τ & r_e

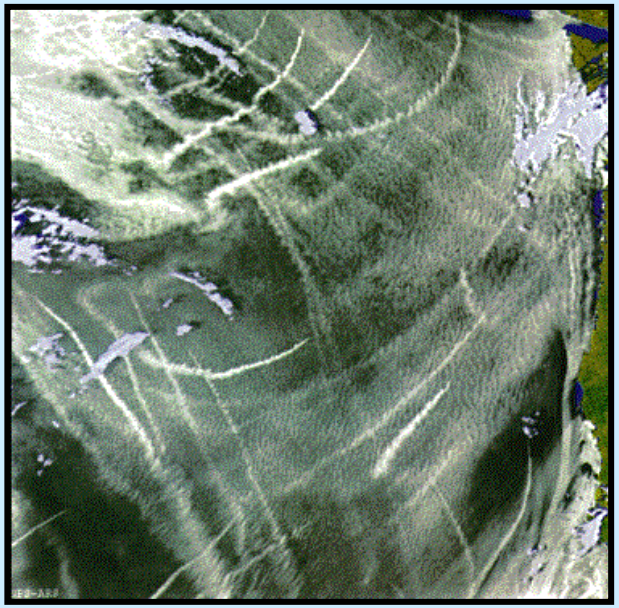
Observational Evidence

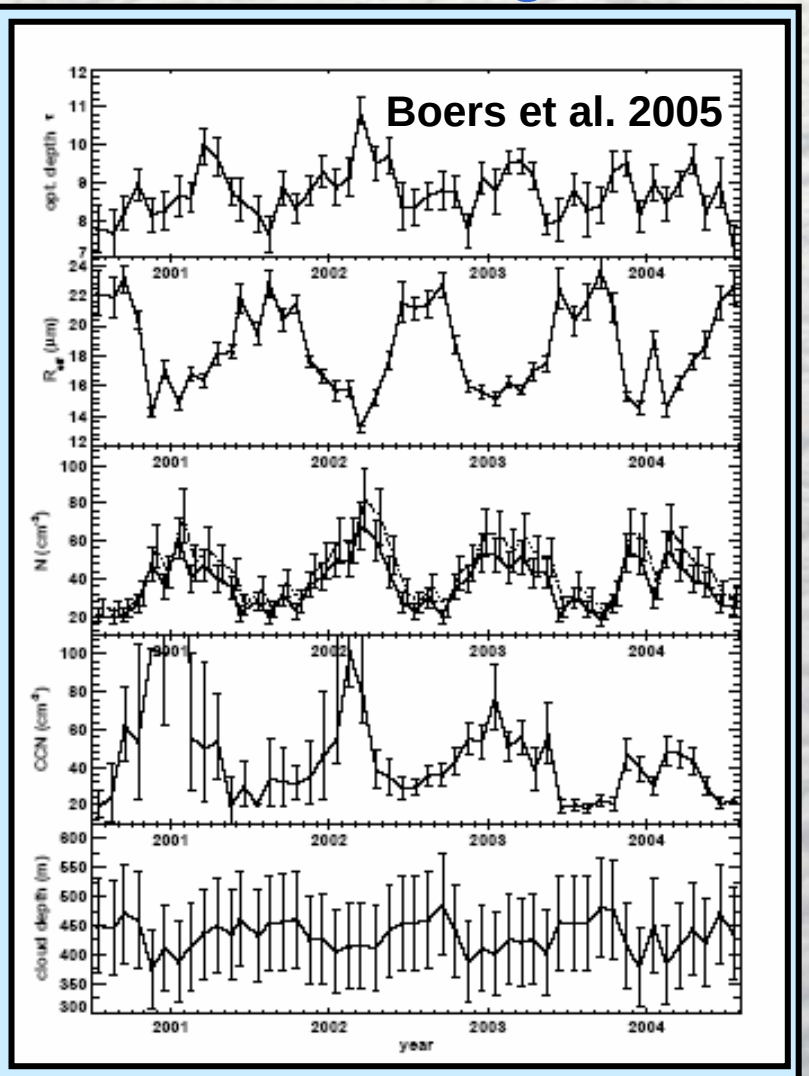
(I) Increased Aerosol concentration

$\Rightarrow$ Increased CDNC

(II) $\Rightarrow$ Smaller droplet sizes (cst LWC)

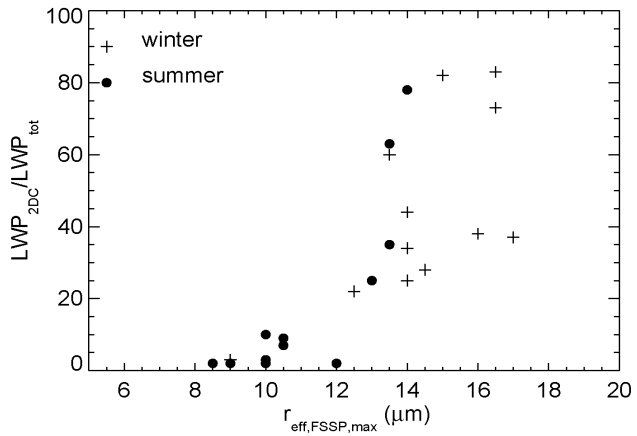
(III) $\Rightarrow$ Increased COT (cst LWC)



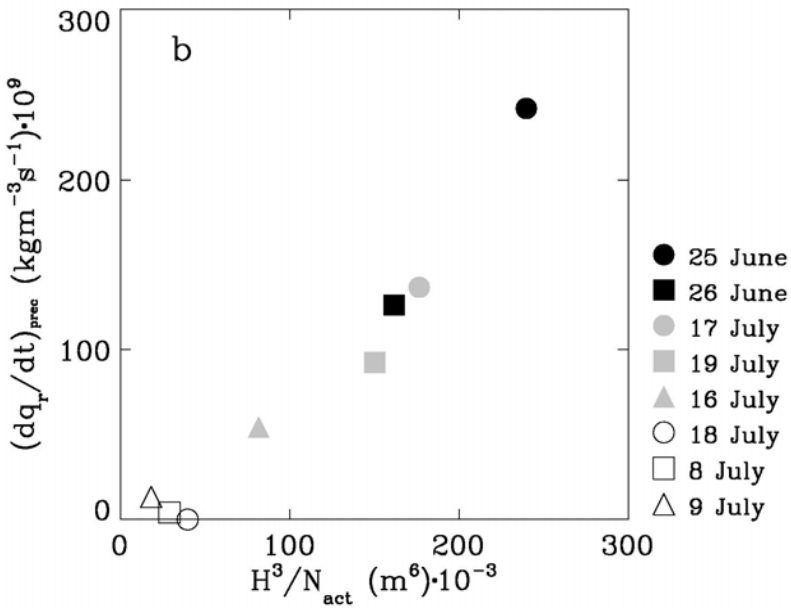


Aerosol Impacts on Precipitation

In MBL clouds, precipitation starts when droplets reach a radius bigger than 10~12 µ.



Boers et al., 1998



Pawlowska & Brenguier, 2003

!! Not valid in cumulus clouds if they can grow deep enough for droplets to reach the critical size, regardless of CDNC !!

Aerosol, Clouds and Climate

Summary of our present understanding

Aerosols induced changes on cloud microphysics have an impact on cloud radiative properties.

Parameterization of the 1st aerosol indirect effect in climate models is presently limited by the model performance for LWP, and for sub-grid vertical velocity that drives the CCN activation process

Aerosols induced changes on cloud microphysics have an impact on precipitation in MBL clouds.

!! Aerosol should therefore significantly impact the hydrological cycle and the Earth radiation budget !!

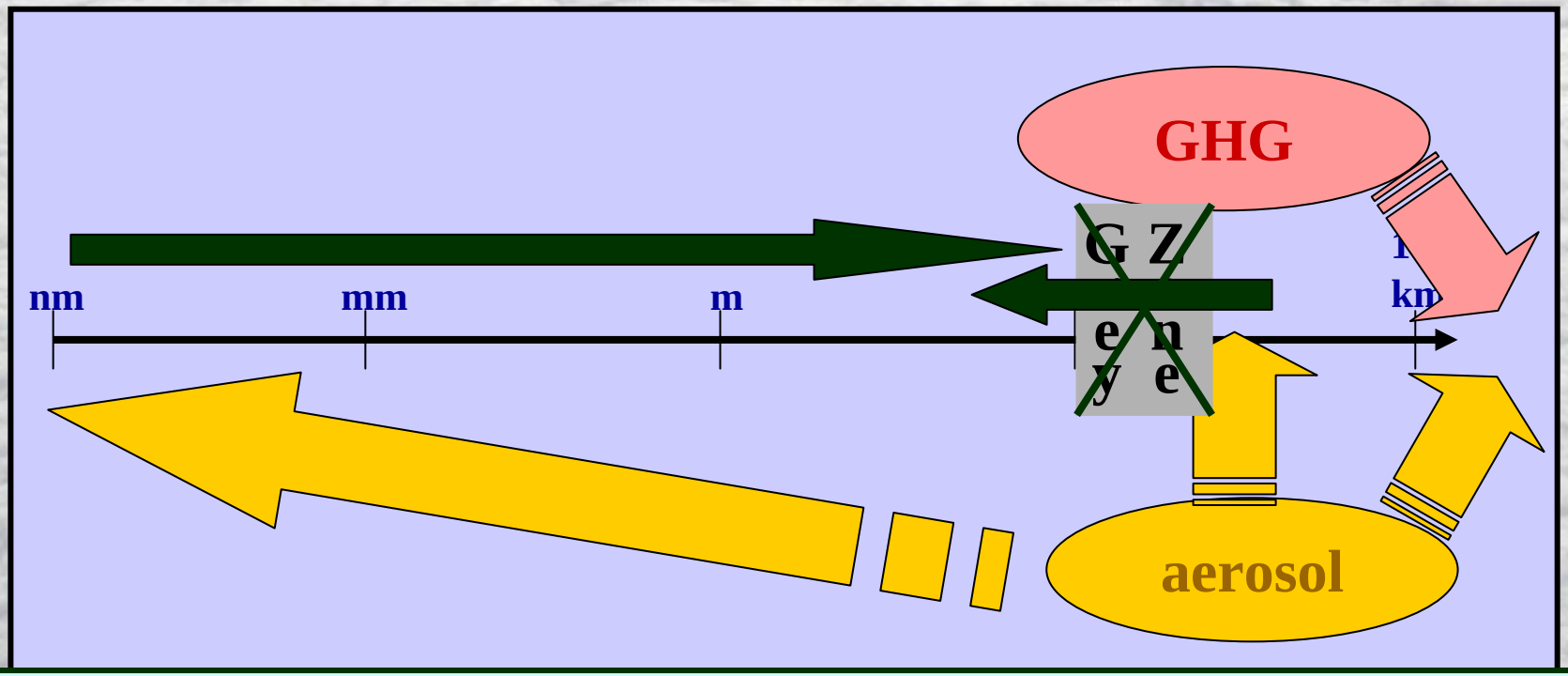
Aerosol, Clouds and Climate

Aerosol Pollution Impact on Precipitation: A Scientific Review – IUGG & WMO

Levin and Cotton

Summary: From this report it is clear that aerosol-pollution affects the amount, and spatial and temporal distribution of clouds, in general agreement with our physical understanding of cloud processes. However, much uncertainty remains regarding these processes. Moreover, because of the complex interactions between environmental meteorological parameters, aerosols, cloud microphysics and dynamics, clear causal relationships between aerosols and precipitation are difficult to identify and moreover, even the sign of the precipitation changes by aerosols are hard to determine in a climatological sense. Based on many observations and model simulations the effects of aerosols on individual clouds (particularly in ice-free clouds) are more clearly understood than the effects on precipitation.

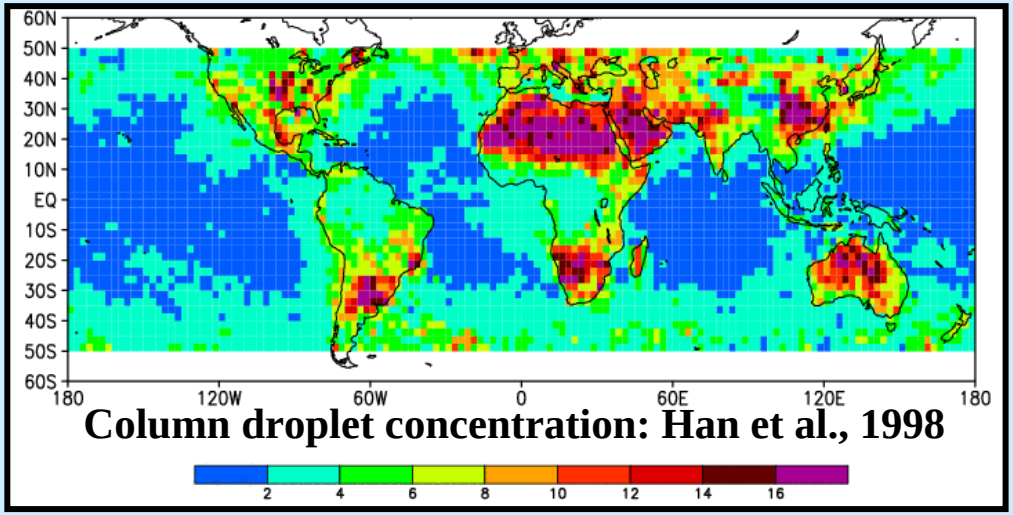
Aerosol Impacts versus Meteorology



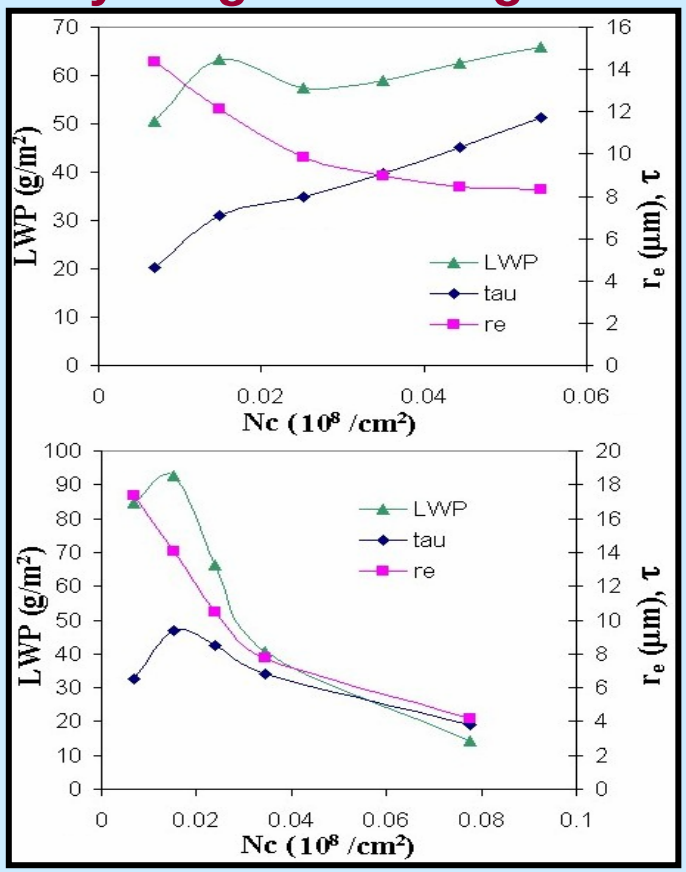
Are aerosol induced cloud microphysical changes mitigated or amplified by large scale feedback processes ?

Satellite Retrievals : global τ & r_e dist.

Beyond MBL and cumulus cloud systems, τ & re climatology is difficult to interpret in term of cloud properties because information about cloud depth, LWP and layering is missing.



Column droplet concentration: Han et al., 1998

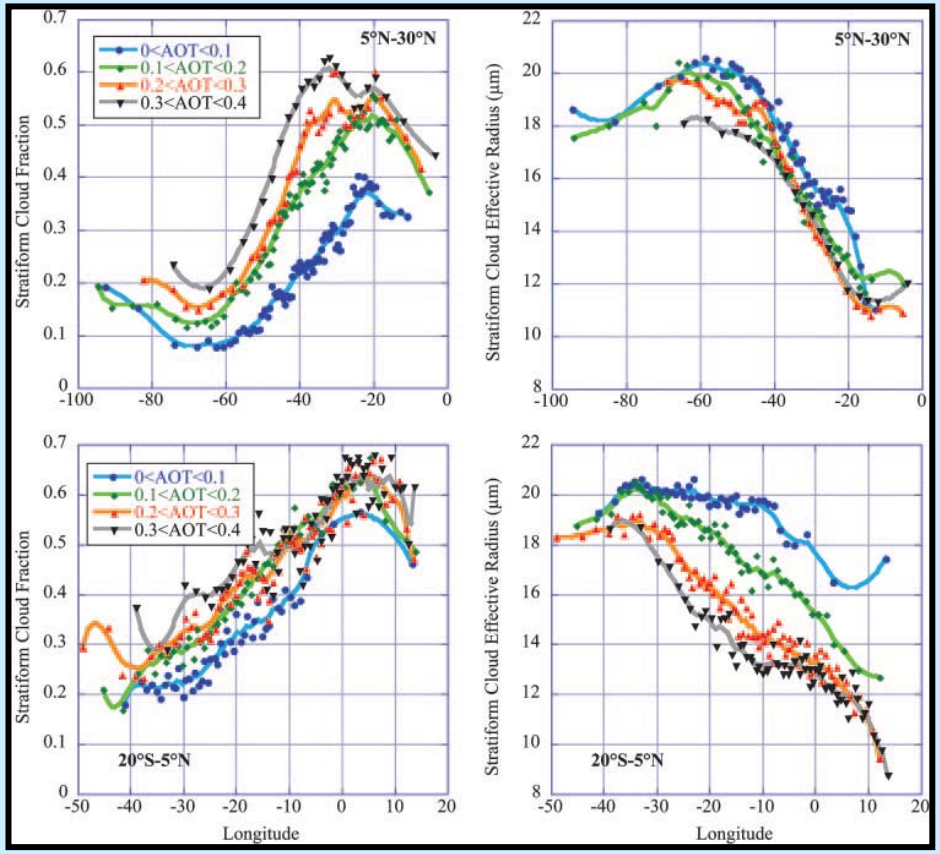


Satellite Retrievals : global τ & r_e dist.

Beyond MBL and cumulus cloud systems, τ & re climatology is difficult to interpret in term of cloud state parameters because information about cloud depth and LWP is missing.

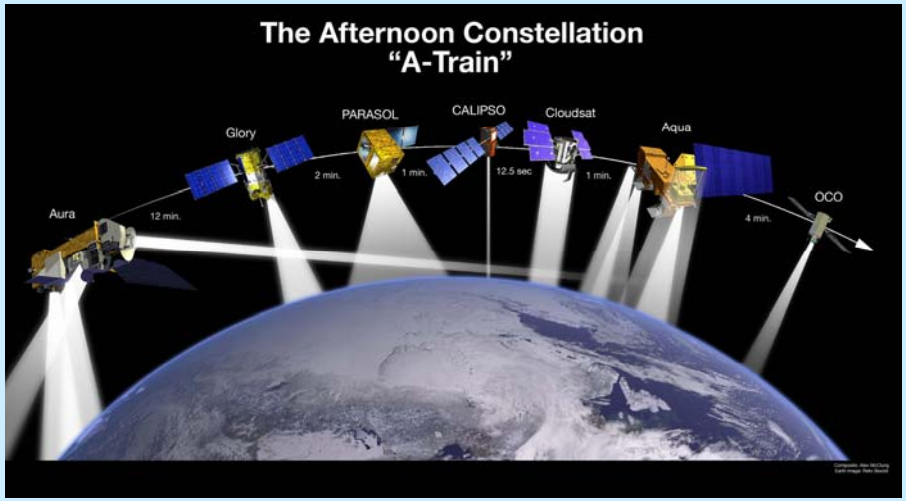
Longitudinal dependence of the shallow cloud fraction (*Left*) and droplet effective radius (*Right*) for the northern tropical Atlantic with dust intrusions (*Upper*) and southern tropical Atlantic with smoke intrusion (*Lower*).

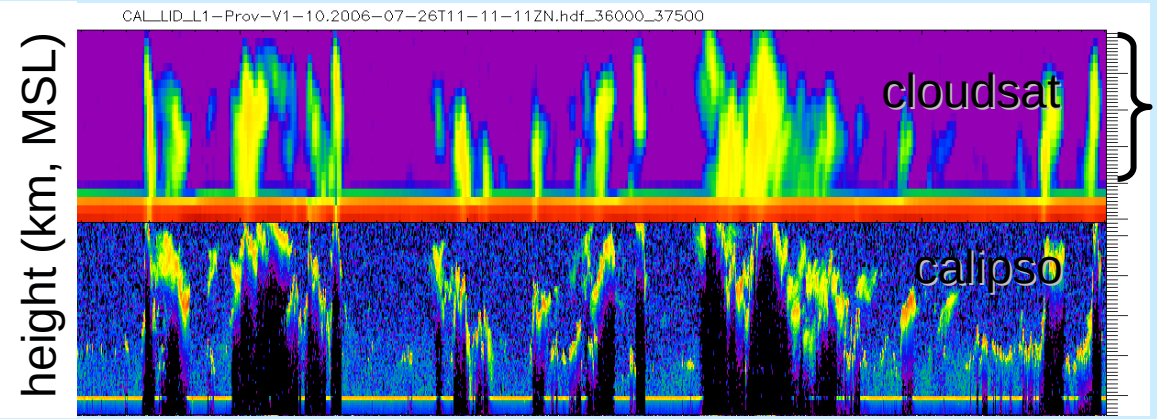
The results are shown for four ranges of the aerosol optical thickness (AOT). The dots are average of 50–200 1° 1° grid boxes located in similar longitude location and for the same AOT range. (Kaufman et al., 2005)



Satellite Retrievals : A-Train

The situation has significantly progressed with active remote sensing from the A-Train





4 km

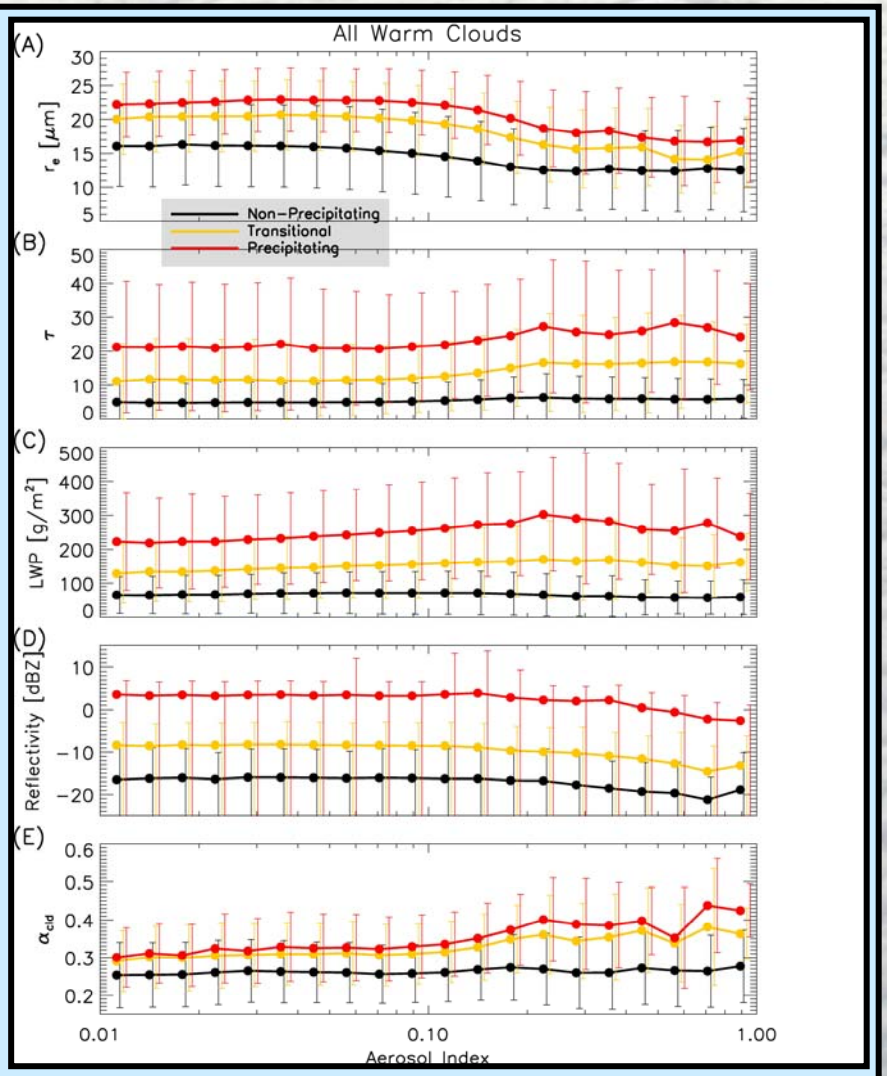
Shallow convection over the Pacific

Satellite Retrievals : A-Train

Warm oceanic clouds derived observed jointly by MODIS and CloudSat

Global relationships between AI and nonprecipitating, transitional, and precipitating cloud parameters. Circles represent the mean values and error bars show the standard deviation. The LWP estimate is for the cloud component only. The reflectivity is the CPR vertical cloud mean reflectivity factor.

Lebsock et al, 2008



Aerosol-Cloud Interactions

Global correlations between aerosols, cloud properties and precipitation do not reflect necessarily a causal relationship between aerosol and clouds, as often concluded. They might also reflect cloud and precipitation impacts on aerosols, and most likely the fact that aerosol and cloud controling factors shall be correlated because of their common origin.

Cloud controling factors are the temperature and the humidity, that determine RH, i.e. heat and moisture that both are scalar tracers of the general circulation, like aerosols are.

Within the framework of the null hypothesis of no causal relationships between aerosols and clouds, both shall thus be tightly correlated.

Aerosol ➔ Cloud Interactions

Time is a crucial ingredient of causal relationship studies.
"Do aerosol changes precede cloud changes or the contrary ?"

The second ingredient is the set of physical mechanisms by which aerosols might impact clouds. To identify them and be able to simulate them in numerical models.

The third ingredient is the susceptibilty of clouds to the aerosols compared to their susceptibility to other cloud controling factors. The former being expected to be much higher than the later !

Cloud Susceptibility to Meteorology versus Aerosol

$$\tau = AN^{1/3}W^{5/6} \qquad W = 1/2\, C_w H^2 \quad \Rightarrow \quad \frac{d\tau}{\tau} = \frac{1}{3}\frac{dN}{N} + \frac{5}{6}\frac{dW}{W} = \frac{1}{3}\frac{dN}{N} + \frac{5}{3}\frac{dH}{H}$$

$$H = z_t - z_b \qquad z_t = cst \quad \& \quad q_t = q_{vs}\left[(T(z_b)\right]$$

$$\frac{dz_b}{dq_t} = \left(\frac{dq_{vs}}{dz}\right)^{-1} = \left(\frac{dq_{vs}}{dT}\frac{dT}{dz}\right)^{-1} = \left(\frac{q_{vs}}{e_s}\frac{de_s}{dT}\Gamma_d\right)^{-1} = \left(q_{vs}\frac{\varepsilon L_v}{R_a T^2}\frac{de_s}{dT}\Gamma_d\right)^{-1}$$

FIRE 14-15 July 2009 case study θ **= 287 K,** q_t **= 10 g/kg**

z_t**=600 m,** z_b**=200 m, H=400 m, W=220 gm**$^{-2}$**,** dz_b/dq_t**=150 m/gkg**$^{-1}$

A CDNC doubling is balanced by a decrease of the cloud thickness of ΔH=H/5=80 m, i.e. Δq_t=-0.5 g/kg, equivalent ΔT=0.8 K. (Δq_t=-0.12 g/kg or ΔT=0.2 K for a 100 m thick cloud layer).

Cloud Susceptibility to Meteorology versus Aerosol

In MBL clouds, the susceptibility to the meteorology is two orders of magnitude greater than to the aerosols.

Assuming we observe a pristine and a polluted cloud system, and detect different trends in LWP, it is difficult to attribute these differences to the aerosols because the small differences in meteorological forcings that could also explain the LWP changes are not measurable !

Statistical approaches are necessary to filter out the variability of the meteorology (same methodology as in weather modification assessments)

Aerosol ➔ Cloud Interactions

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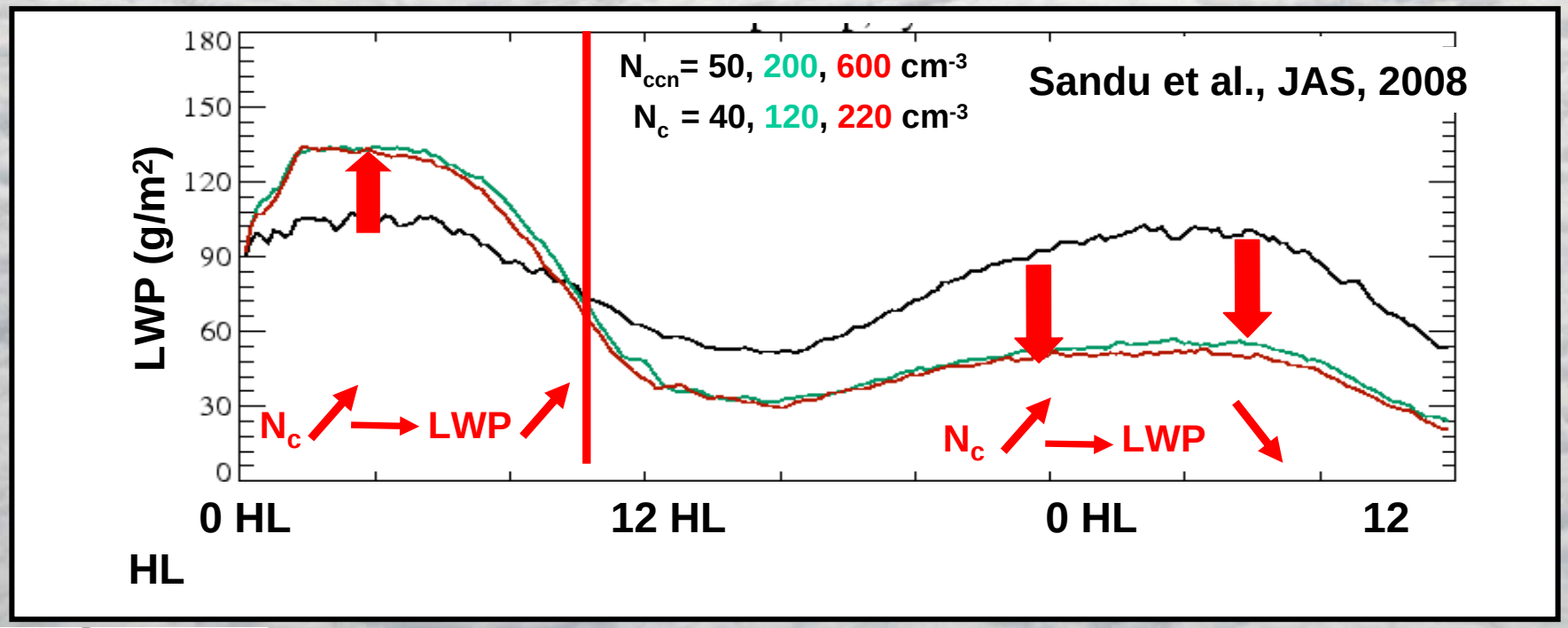
Mechanisms of the Interactions

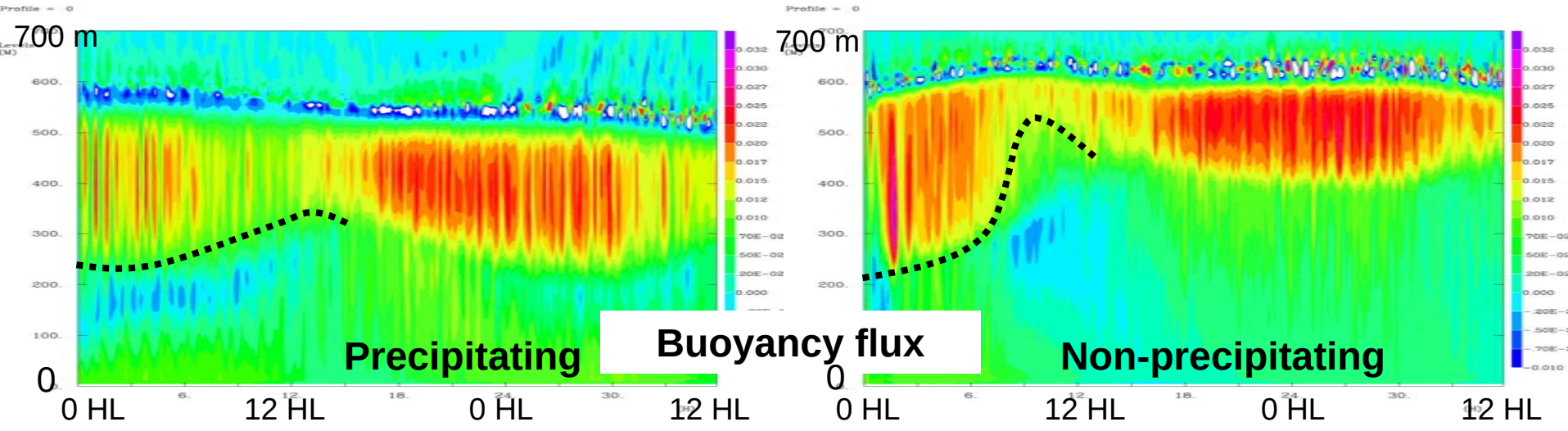
2nd order reasoning : LES simulations of the BL coupled system :
- CCN increase inhibits precipitation
- Cloud top entrainment is increased, surface fluxes are reduced
- LWP decreases in response to increased CCN concentration



Mechanisms of the Interactions

Meteorological forcings are not measurable with the accuracy required to disentangle aerosol from meteorological impacts, BUT

The mechanisms by which aerosols are supposed to impact cloud dynamics have specific measurable signatures.
Increased CCN concentration results in :
- More adiabatic LWC vertical profile
- Higher vertical velocity variance at cloud top
- More coupling at night and more decoupling during the day



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Time and Time Scales

Heat, moisture and aerosols are tightly coupled in the climate system. To identify causal relationships, a hierarchy of timescales shall be established.

fsec	Droplet Extinction → Radiation
20 min	CCN → CDNC → Droplet Extinction
hour	CDNC → Precipitation
hours	Precipitation → CCN (scavenging)
hours	Precipitation → Cloud Dynamics
hours-days	Aerosol → Atmospheric stability profile
1 Day	**Solar cycle (empirically proven !!)**

Observational Strategy

I.: Case Study approach: Look at cloud systems with different aerosols and the « same » meteorology:

$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \underbrace{\delta m}_{\to 0} + \left.\frac{\partial c}{\partial a}\right|_m \delta a.$$

Likewise, the fact that two air-masses have differing aerosol properties is an indicator of their differing meteorological origins and trajectories. Most of the aerosol sources are also sources of heat and moisture.

Observational Strategy

II. Statistical approach : examine a large sample of cases with significant aerosol variability and a reduced meteorological one. Same methodology as for weather modification experiments

$$\sigma_c^2 = \lambda_{A_\mu}^2 \sigma_{A_\mu}^2 + \lambda_M^2 \underbrace{\sigma_M^2}_{\to 0} + 2\lambda_{A_\mu} \lambda_M \sigma_{A_\mu} \sigma_M r$$

50 years of weather modification experiments have not been sufficient to detect noticeable effects because λ_M >>

Not only do we need to reduce the meteorological variability and its impact on clouds, but also to understand to what extent the meteorological variability covaries with the aerosol variability.

Observational Strategy

II : Statistical approach : Select situations where aerosol and meteorology vary independently (week-end effect, sugar cane burning)

$$\sigma_c^2 = \lambda_{A_\mu}^2 \sigma_{A_\mu}^2 + \lambda_M^2 \sigma_M^2 + 2\lambda_{A_\mu} \lambda_M \sigma_{A_\mu} \sigma_M \underbrace{r}_{\to 0},$$

Is there any aerosol source, that has no signature in term of heat and moisture, considering that λM >> λ A ?

Where to look ? Close to or far from the source ?

Observational Strategy

$$\sigma_c^2 = \lambda_{A_\mu}^2 \sigma_{A_\mu}^2 + \lambda_M^2 \sigma_M^2 + 2\lambda_{A_\mu} \lambda_M \sigma_{A_\mu} \sigma_M \underbrace{r}_{\to 0},$$

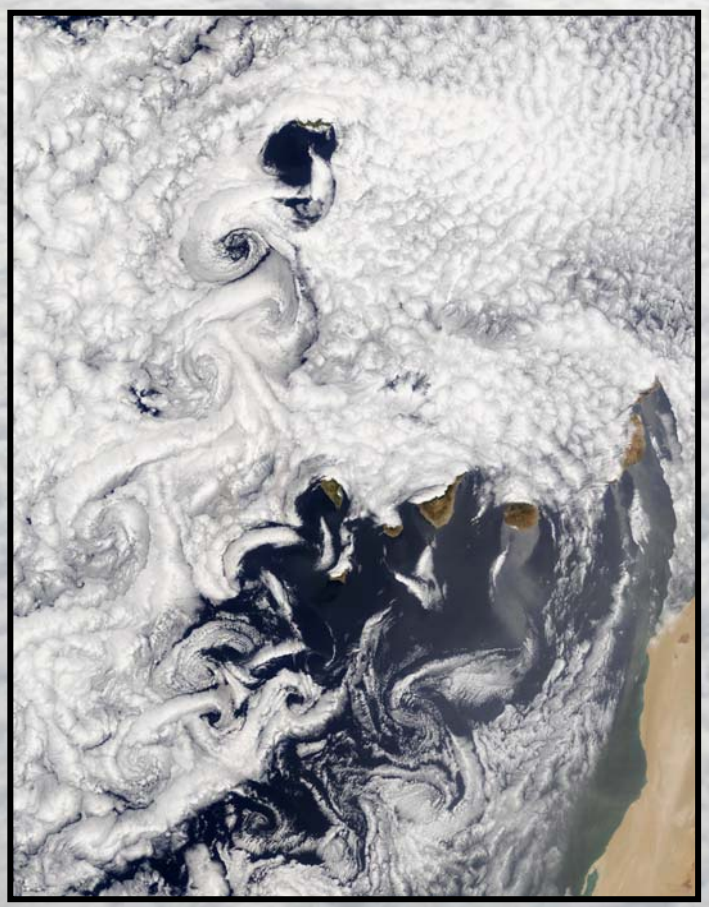
Close to the source, the heat and moisture signature is likely to be too large

Far from the source, can we expect that the heat and moisture signature vanishes, while the aerosol signature is still noticeable. Heat, moisture and aerosols are, however, all scalar tracers of the air mass, hence their dilution time scales are similar.

How long does it takes for the boundary layer to forget its origin

Observational Strategy

$$\sigma_c^2 = \lambda_{A_\mu}^2 \sigma_{A_\mu}^2 + \lambda_M^2 \sigma_M^2 + 2\lambda_{A_\mu} \lambda_M \sigma_{A_\mu} \sigma_M \underset{\rightarrow 0}{r},$$



Moreover, far from the source, correlations have time to develop, that have nothing to do with the aerosol microphysical effect, i.e. cloud and precipitation impacts on aerosols and aerosol direct effects on the airmass

Observational Strategy

IV. : System Dynamics approach: select situations where aerosol properties are specified and look at the short term meteorological response of the cloud system to the diurnal cycle.

$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \delta m + \left.\frac{\partial c}{\partial a}\right|_m \delta a.$$

$\propto \cos(2\pi t/24)$

The diurnal cycle provides the opportunity of a meteorological forcing that is well characterized and reproducible

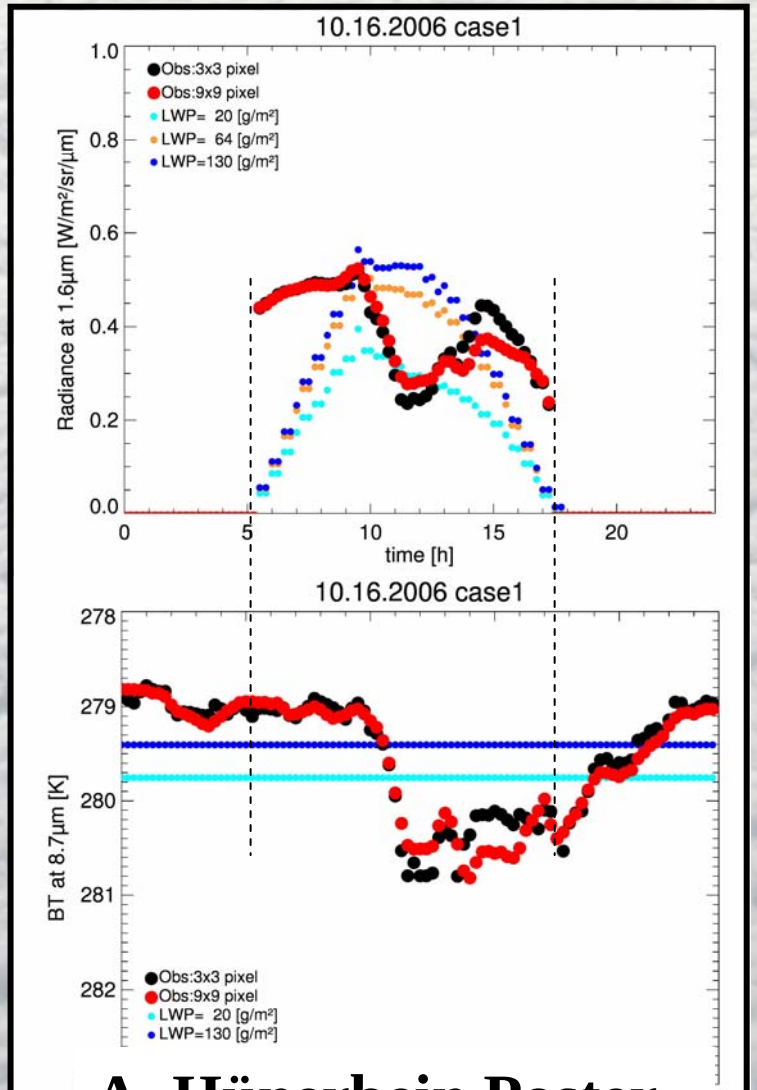
Observational Strategy

Select homogeneous areas in the regions of subtropical marine Sc

Follow the area using BL winds

Use the combination of VIS, NIR and IR channels on geo-stationnary satellites (MSG, GOES) to retrieve LWP.

Examine various diurnal cycles, precipitating and non-precipitating, to identify specific signatures of the precipitation on the cloud diurnal cycle



A. Hünerbein Poster

Summary

The detection of an aerosol impact on clouds is difficult because of the high susceptibility of clouds to meteorology (heat and moisture) compared to their susceptibili

$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \delta m + \left.\frac{\partial c}{\partial a}\right|_m \delta a.$$

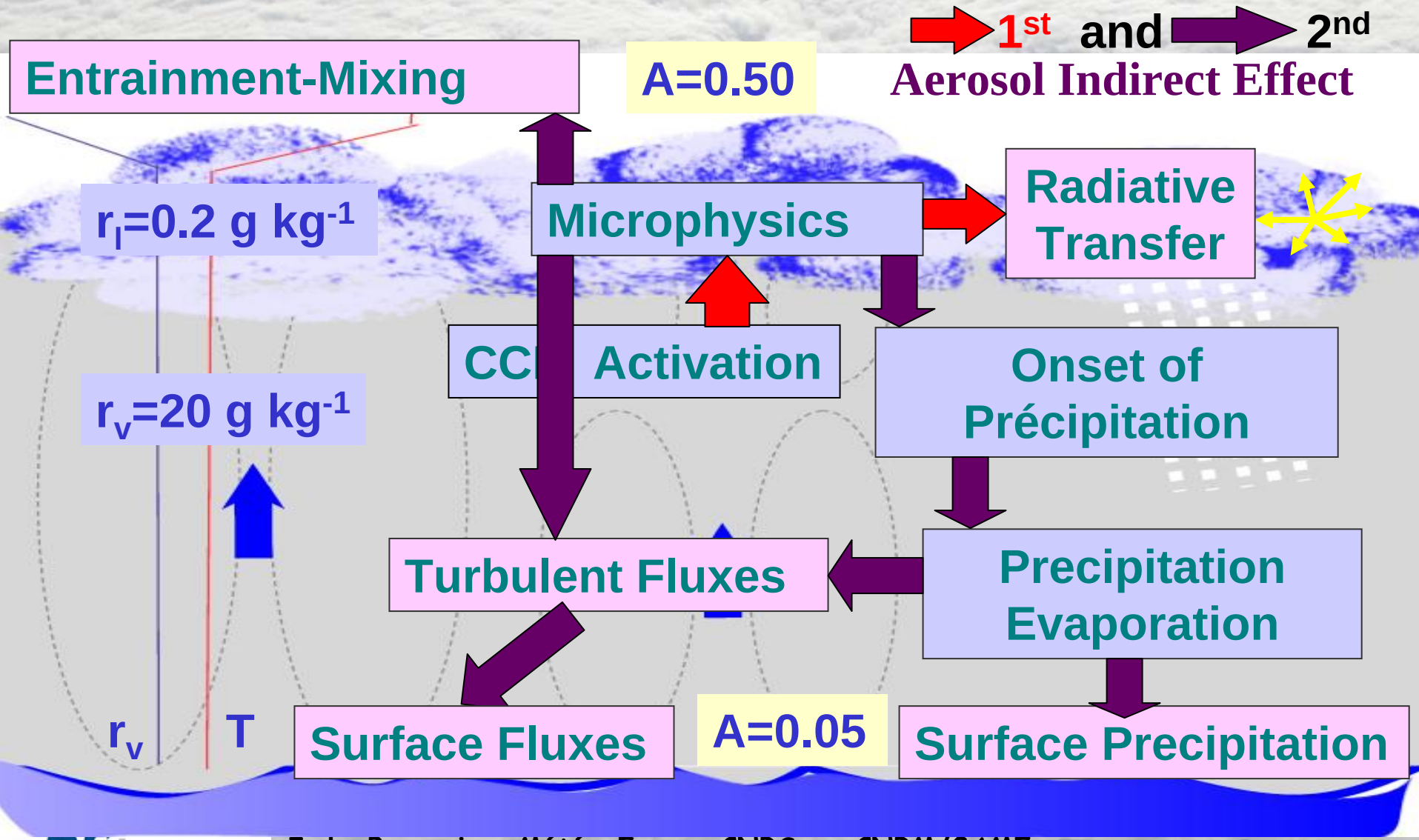
One alternative is to examine the diurnal cycle of cloud properties and its dependence on the aerosol, with the expectation, supported by LES, that the susceptibility of the diurnal cycle to the aerosol is comparable to its susceptibility to changes in meteorological forcings

$$\frac{\partial(dc/dt)}{\partial m} \approx \frac{\partial(dc/dt)}{\partial a}$$

Thank you

for your attention

Cloud Control Parameters & Aerosol Indirect Effects



Cloud Control Parameters & Aerosol Indirect Effects

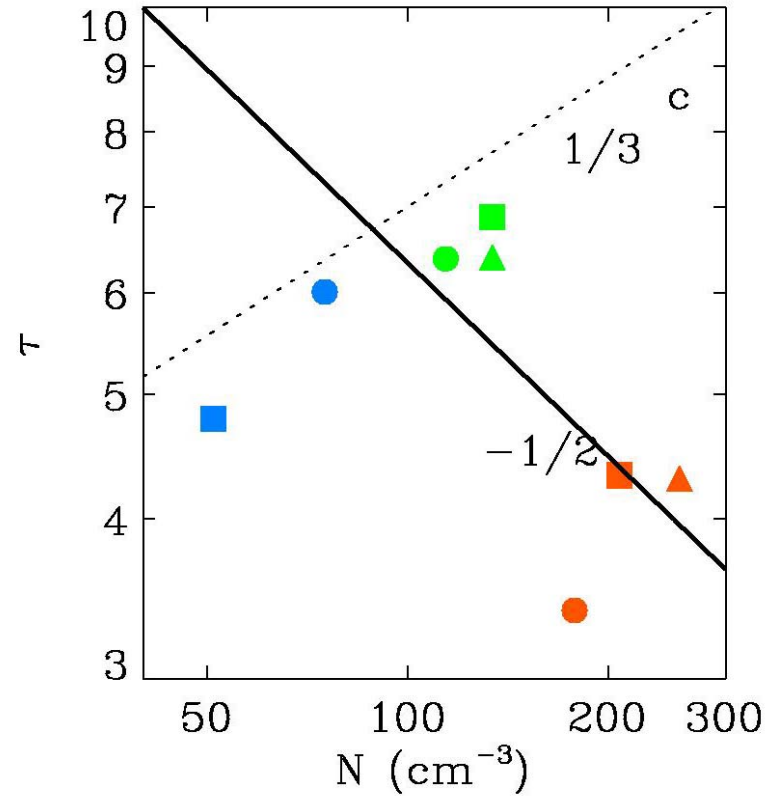
Not only do we need to understand the meteorological variability and its impact on the clouds, but we also need to understand to what extent the meteorological variability covaries with the aerosol variability.

$$\tau \propto N^{1/3} H^{5/3} \qquad r_e \propto N^{-1/3} H^{1/3}$$

$$H \propto N^{\gamma}$$

$$-1/5 \le \gamma \le 1 \;\Rightarrow\; \frac{d\tau/\tau}{dr_e/r_e} < 0$$

$$\gamma \le -1/5 \;\text{ or }\; \gamma > 1 \;\Rightarrow\; \frac{d\tau/\tau}{dr_e/r_e} > 0$$



Brenguier et al. 2003 (ACE2/PACE)