CLOUDS IN THE PERTURBED CLIMATE SYSTEM

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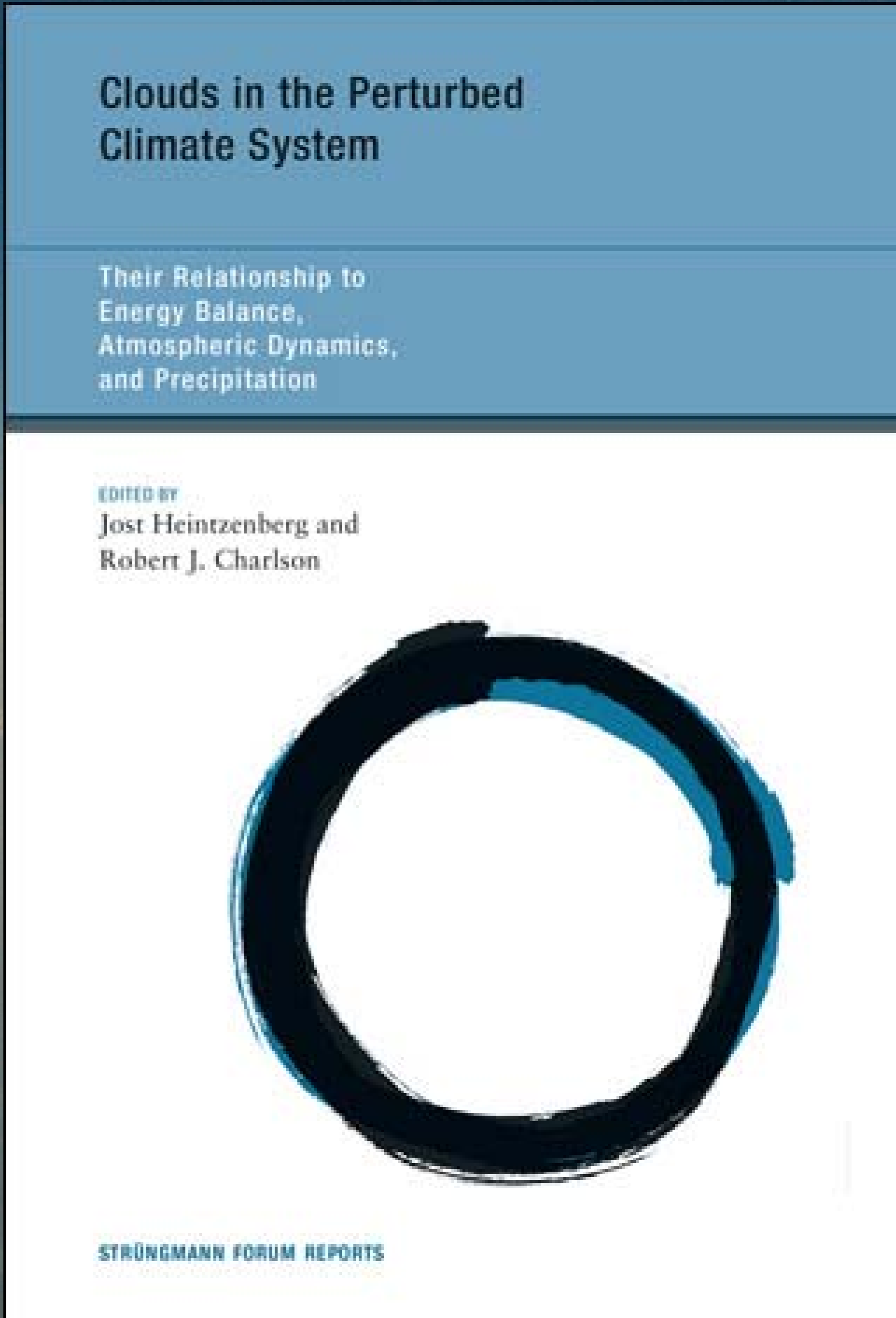
Acknowledgment: from discussions held at the ACPC (iLEAPS/IGAC) workshop (2007) and the E Strungman Forum (2008)

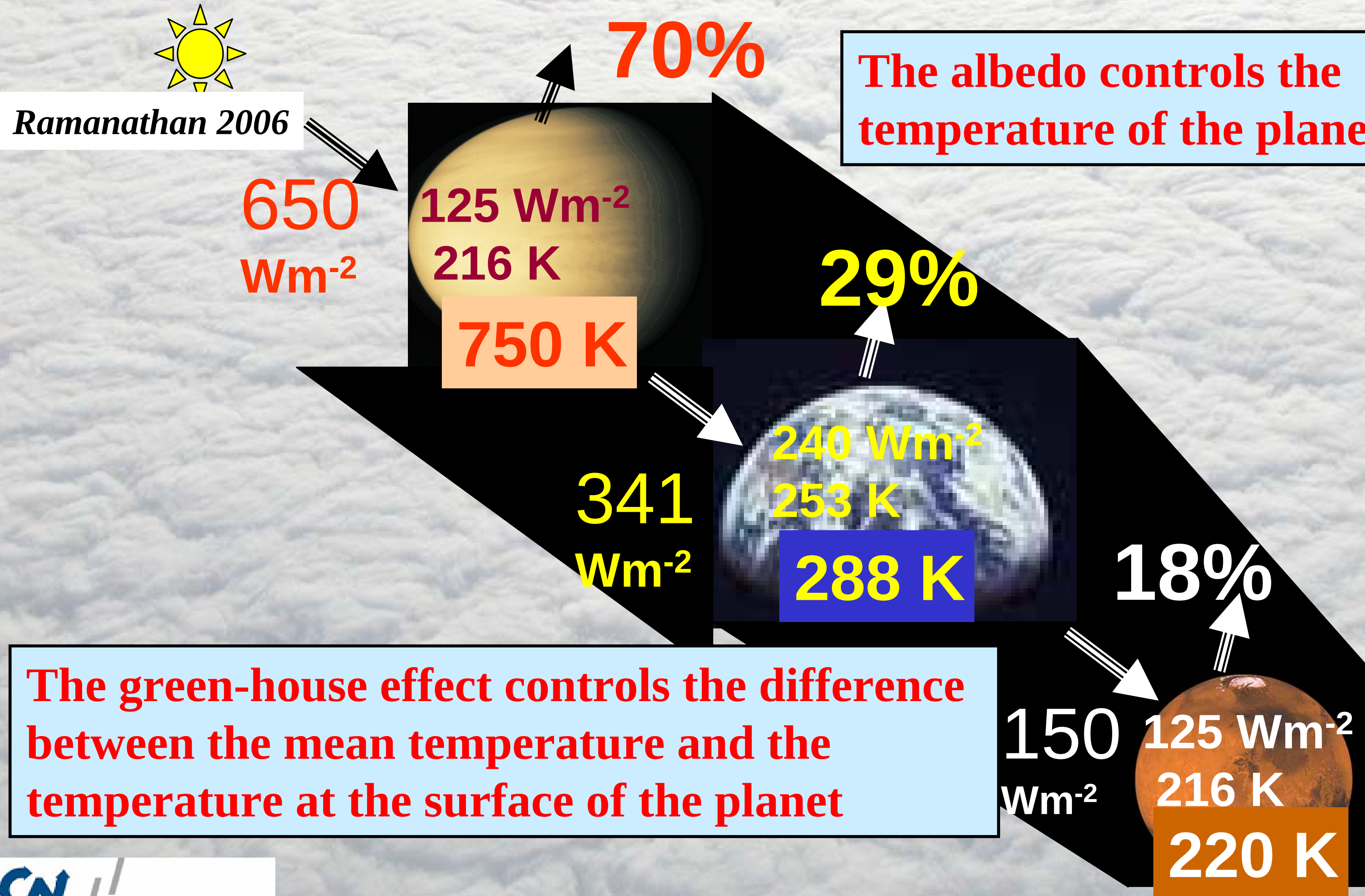


Ernst Strüngmann Forum

Observational Strategies from the Micro- to Mesoscale
J. L. Brenguier & R. Wood

Cloud Controlling Factors—Low Clouds
B. Stevens & J. L. Brenguier

Albedo & Green-House Effect



The albedo controls the temperature of the planet

The green-house effect controls the difference between the mean temperature and the temperature at the surface of the planet

Albedo & Green-House Effect

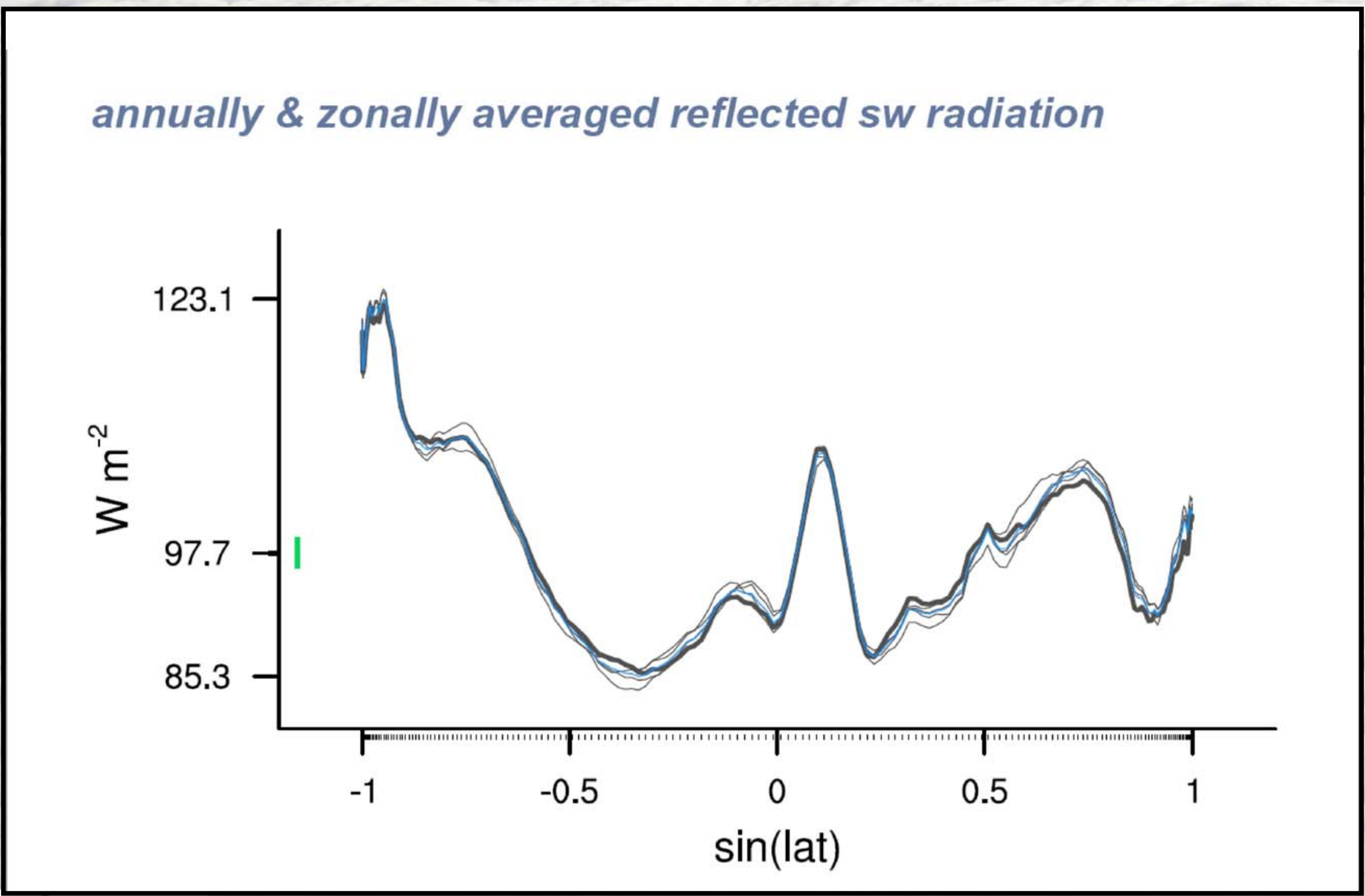
The albedo controls the temperature of the planet

The green-house effect controls the difference between the mean temperature and the temperature at the surface of the planet

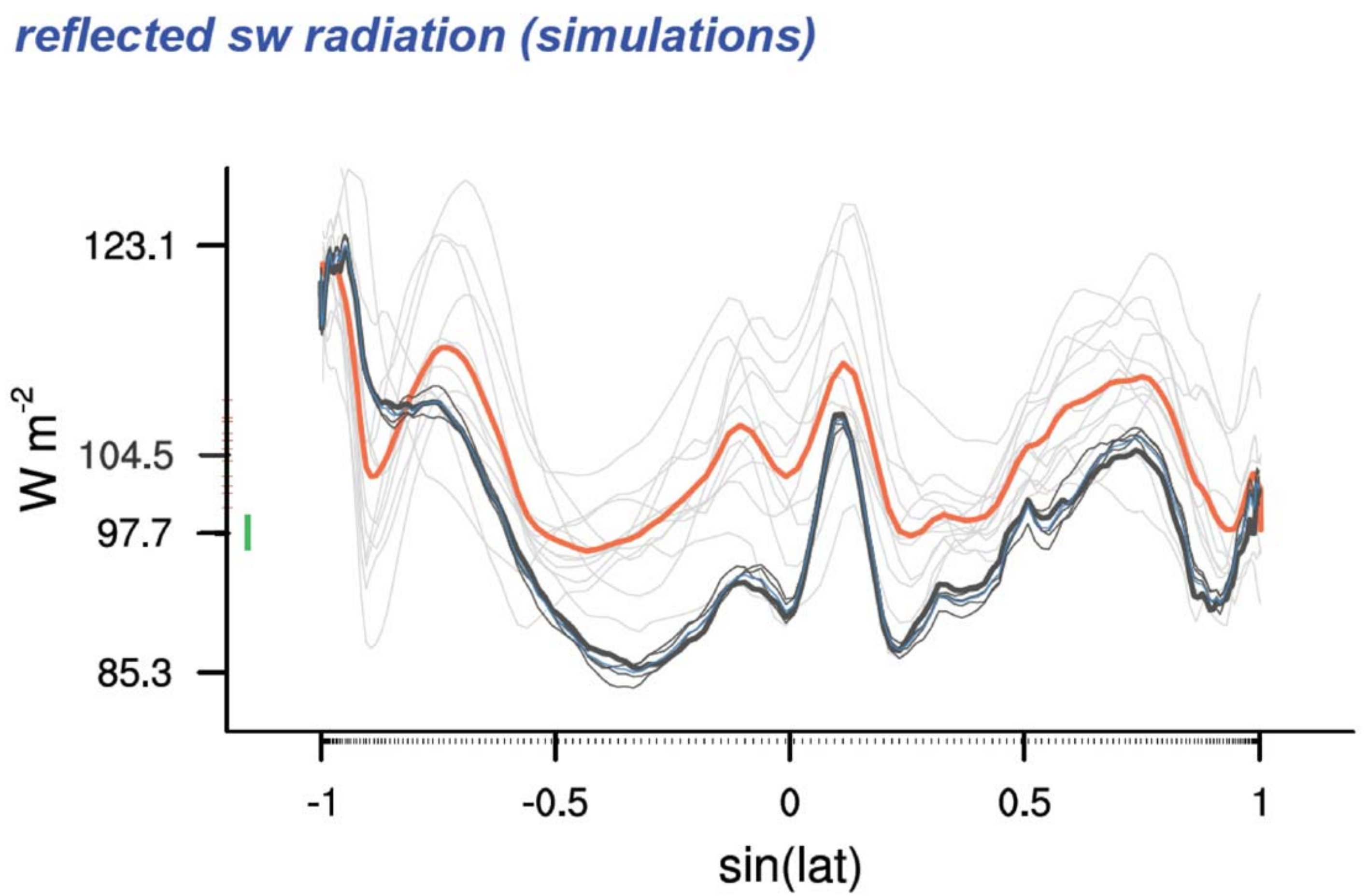
Clouds are responsible for half of the Earth albedo (- 47 Wm^{-2}) and significantly contribute to the green house effect (+ 29 Wm^{-2})

A small change in the cloud albedo/GHE balance (-18 Wm^{-2}) could either counteract or reinforce the green-house gases effect. (A doubling of the CO2 concentration corresponds to + 4 Wm^{-2})

Albedo & Green-House Effect



Albedo & Green-House Effect



- 101-106 W/m2 (Wild et al., survey)
- 107 W/m2 (Trenberth and Kiehl (ERBE)
- 101 W/m2 (CERES)

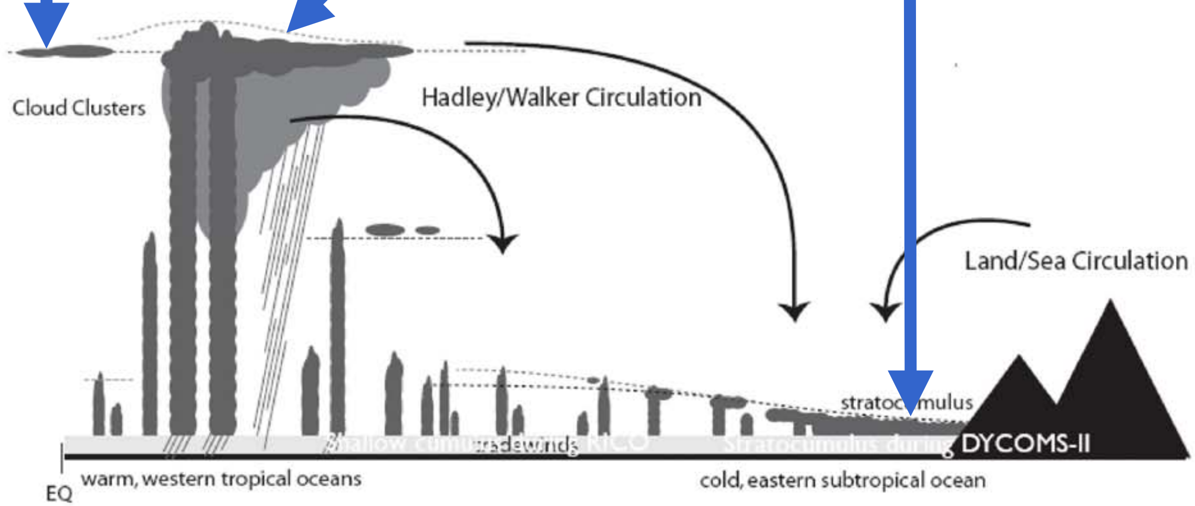
Albedo & Green-House Effect

Cloud Variability

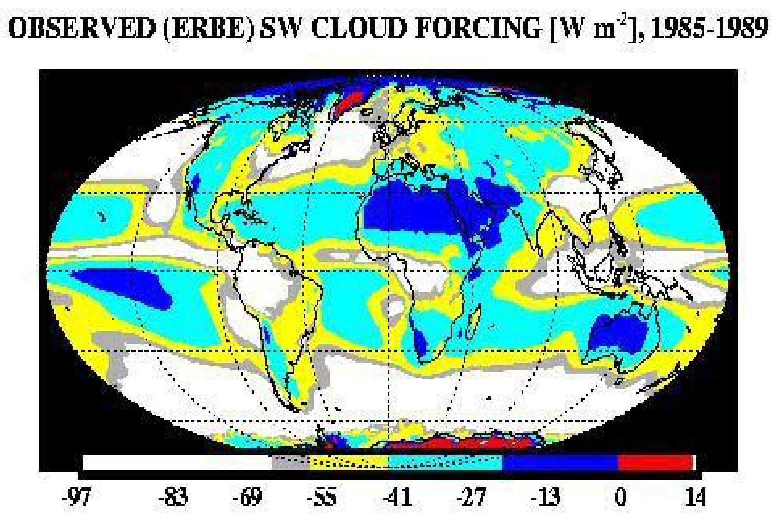
Low albedo 10%
High GHE

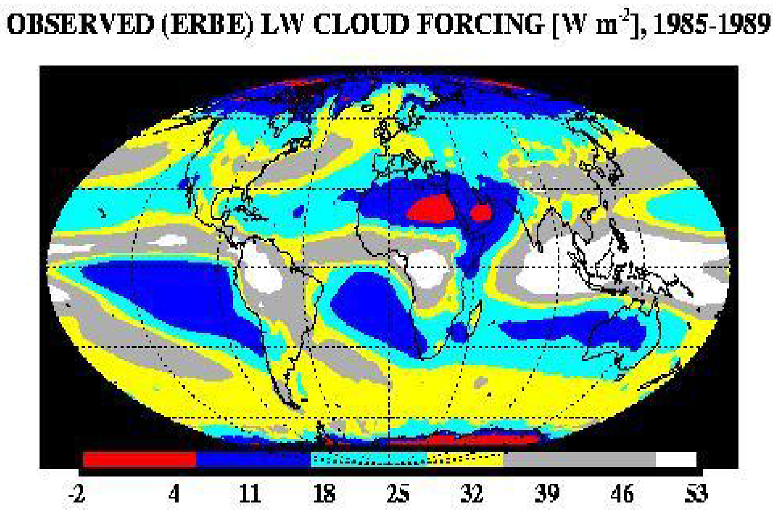
High albedo 80%
High GHE

Medium albedo 50%
No GHE



Albedo & Green-House Effect
Spatial Variability





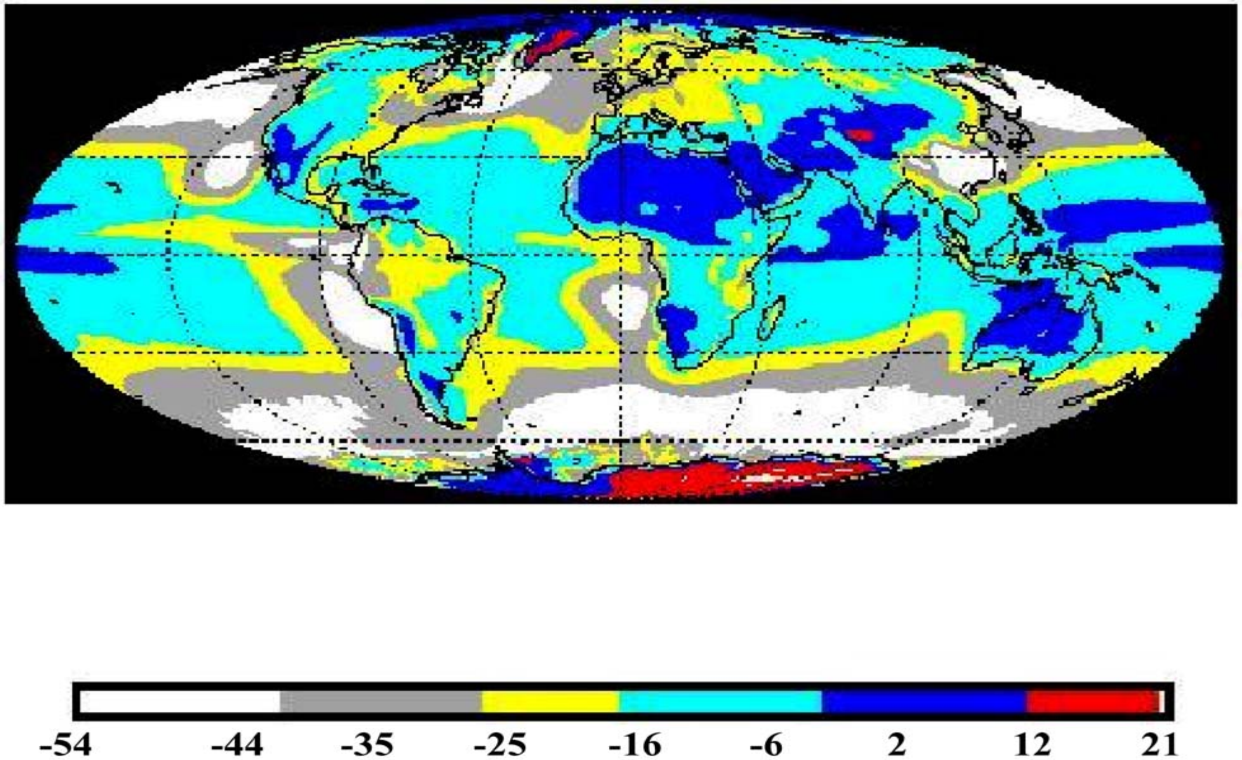
Ramanathan et al. 1989, 1991; Harrison et al. 1990

Albedo & Green-House Effect

Spatial Variability

Fig. 1. Observed (ERBE) Net Cloud Forcing [W m^{-2}], 1985-1989

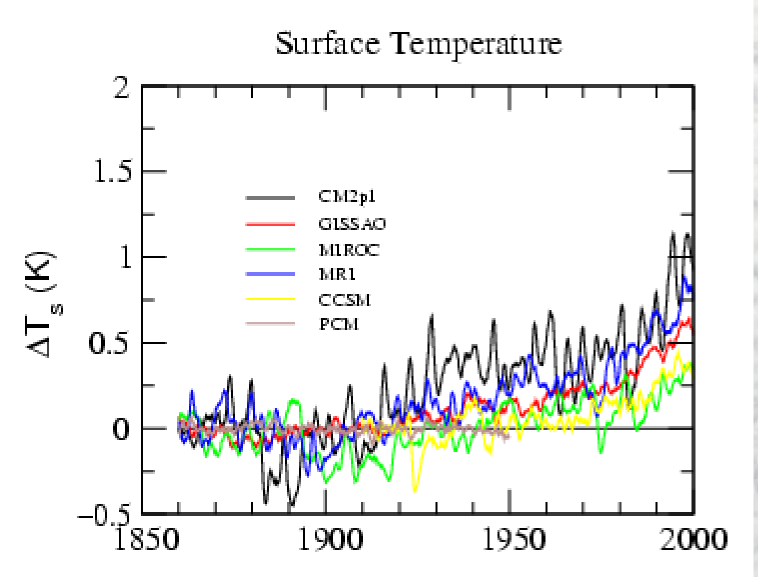
Source: Ramanathan et al, 1989; 1994; Harrison et al, 1991



The net cloud forcing is the effect of clouds on the radiation budget at the top-of-the atmosphere.

Temperature & Precipitation

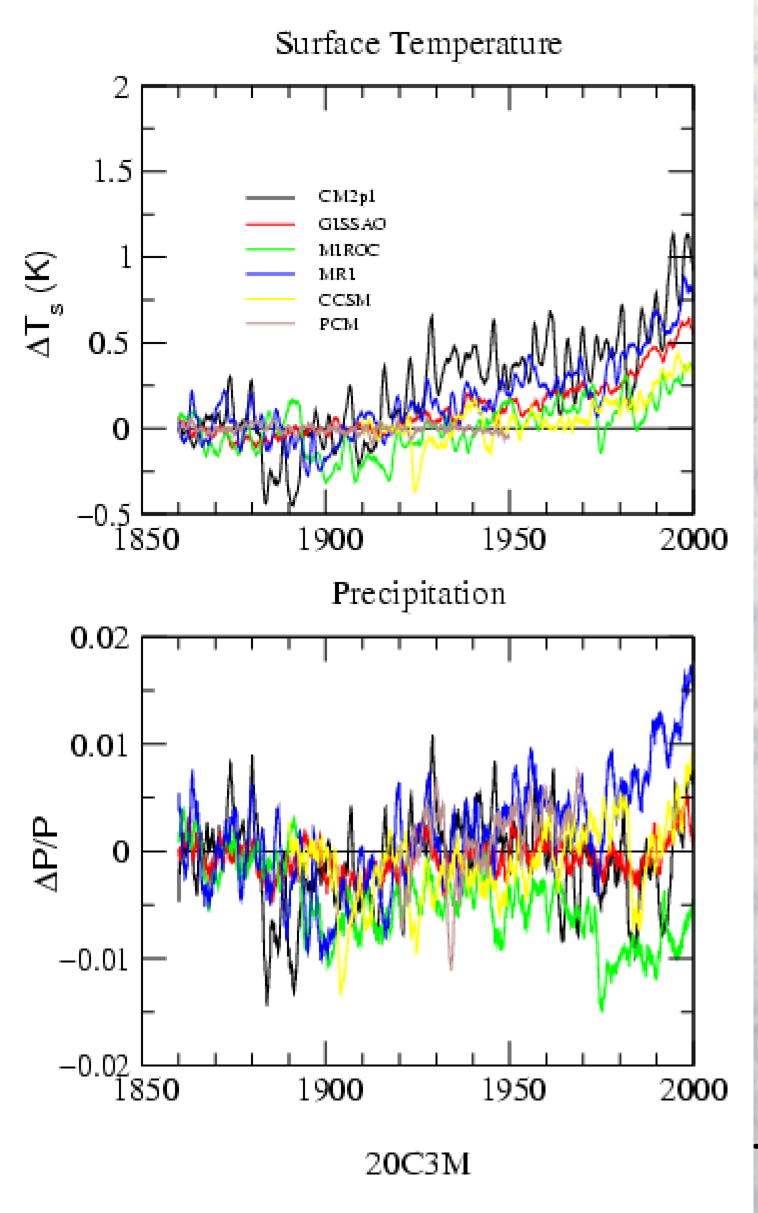
IPCC AR4 20th Century Model Projections (20C3M)



Surface temperature increases in all models.

Temperature & Precipitation

IPCC AR4 20th Century Model Projections (20C3M)



Surface temperature increases in all models.

Precipitation may increase, decrease or remain unchanged.

The Cloud in Climate Paradoxe

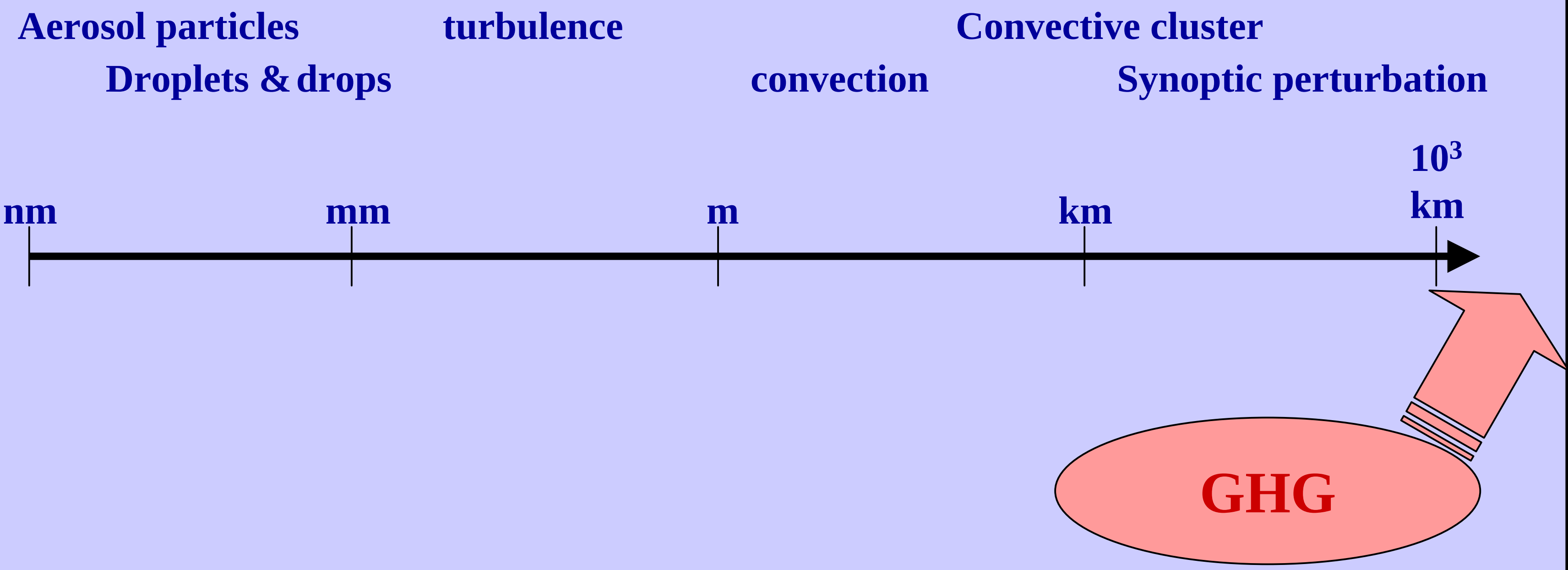
Cloud albedo varies from less than 1 % (invisible cirrus) to almost 90 % (cumulonimbus).
Their green-house effect varies from 0 to + 50 Wm^{-2}.
Their life time varies from a few minutes to days.
Their spatial distribution is very heterogeneous.

But, together, their maintain the Earth albedo constant at 29%, to better than 1 %, since thousands of years.

Climate models are able to simulate the observed global temperature change, but they are unable to place clouds at the right location, with the correct albedo and GHE properties.

What are the feed-back processes ?

Radiative forcings and feedbacks



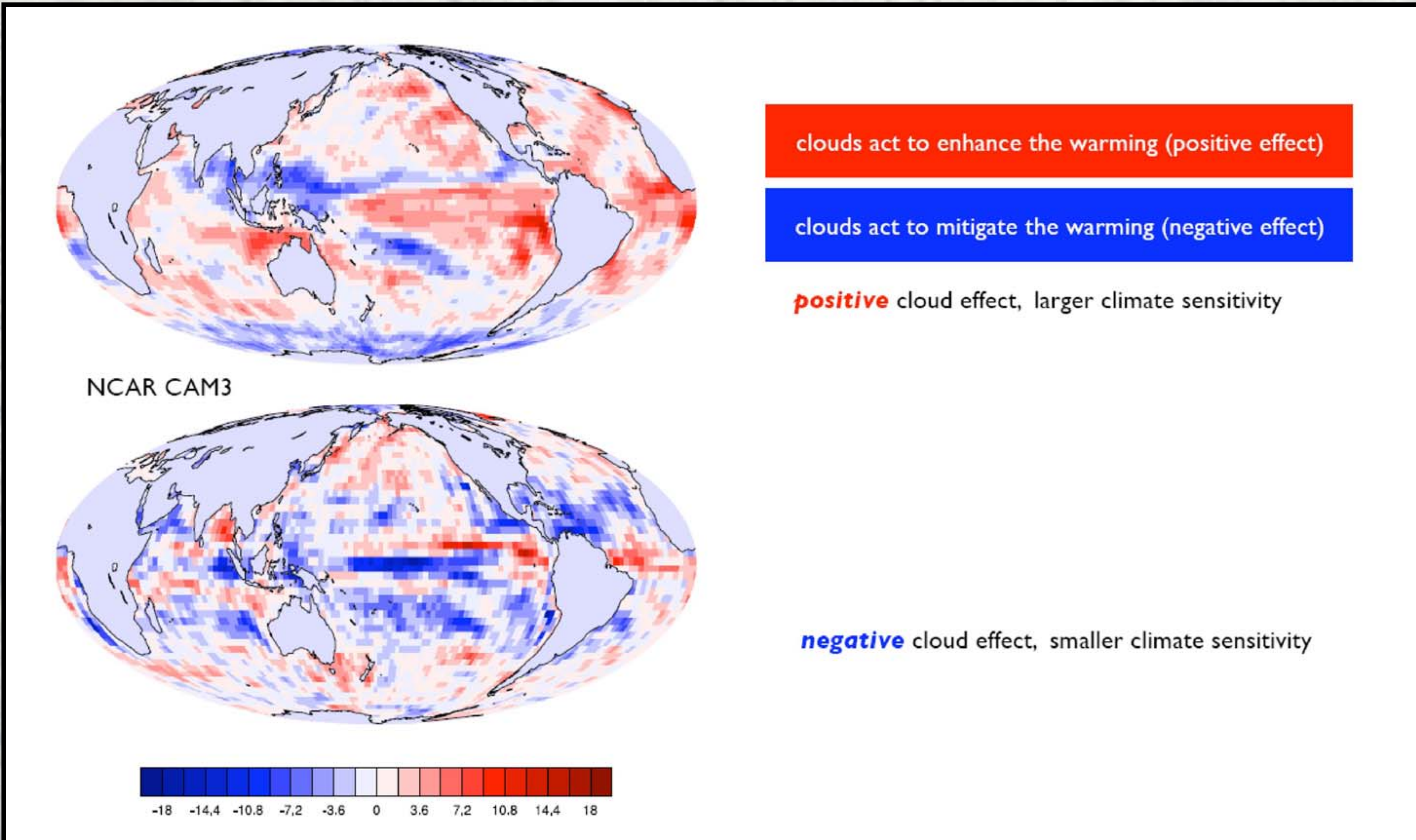
Temperature ↗

Water vapour mixing ratio ↗

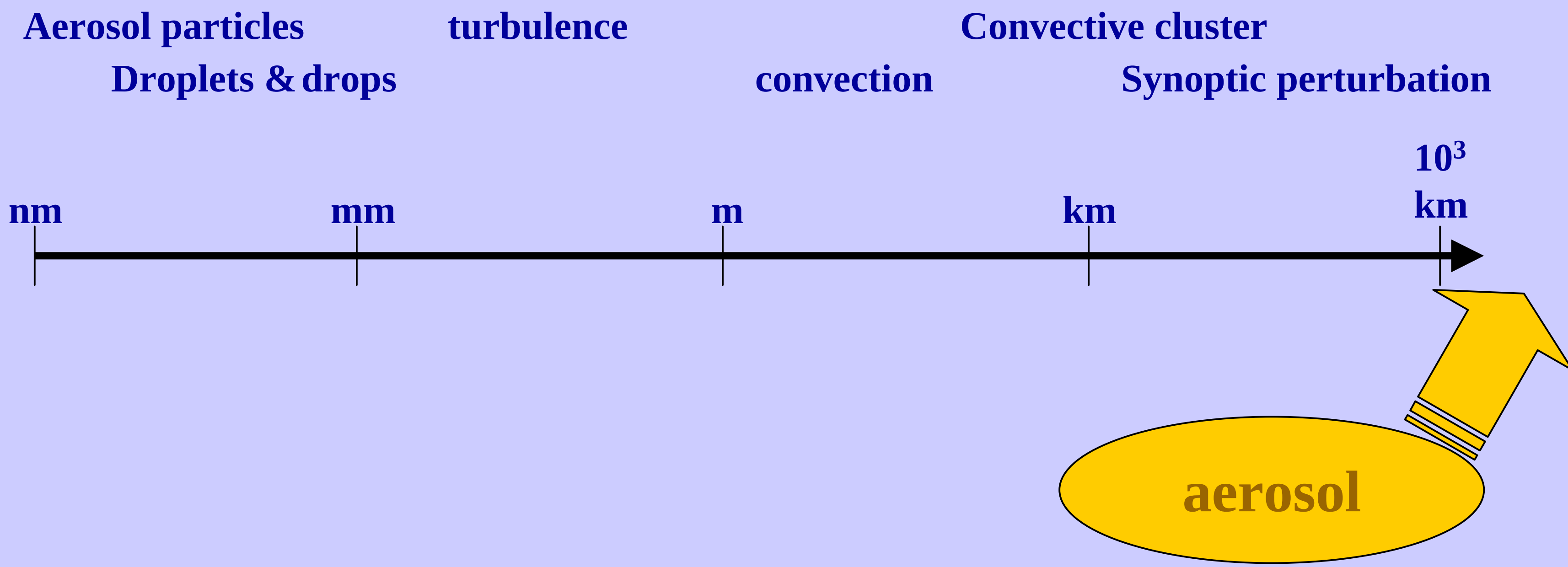
Low level cloud cover ↗ ⇒ negative feedback

High level cloud cover ↗ ⇒ positive feedback

Radiative forcings and feedbacks



Radiative forcings and feedbacks

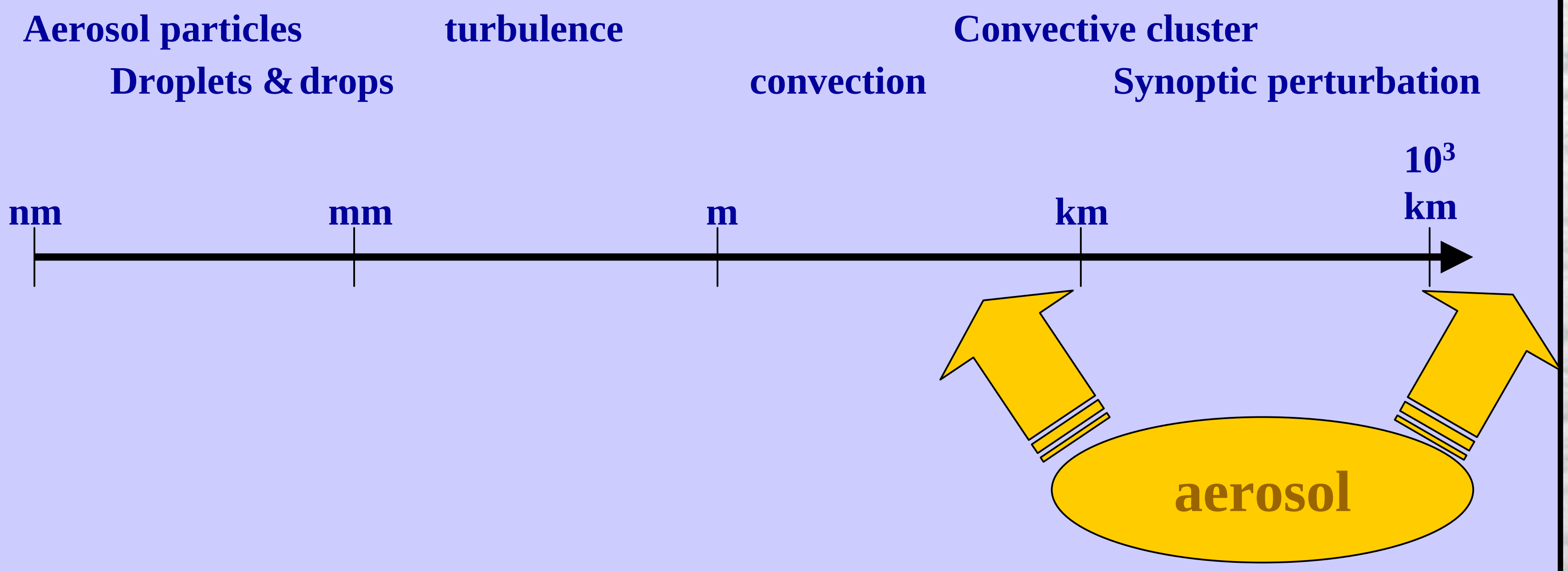


Earth albedo $\nearrow$ $\Rightarrow$ Temperature of the atmosphere $\searrow$

Absorption by aerosol $\nearrow$ $\Rightarrow$ Temperature of the atmosphere $\nearrow$

Unlike GHG, aerosol are not uniformly distributed

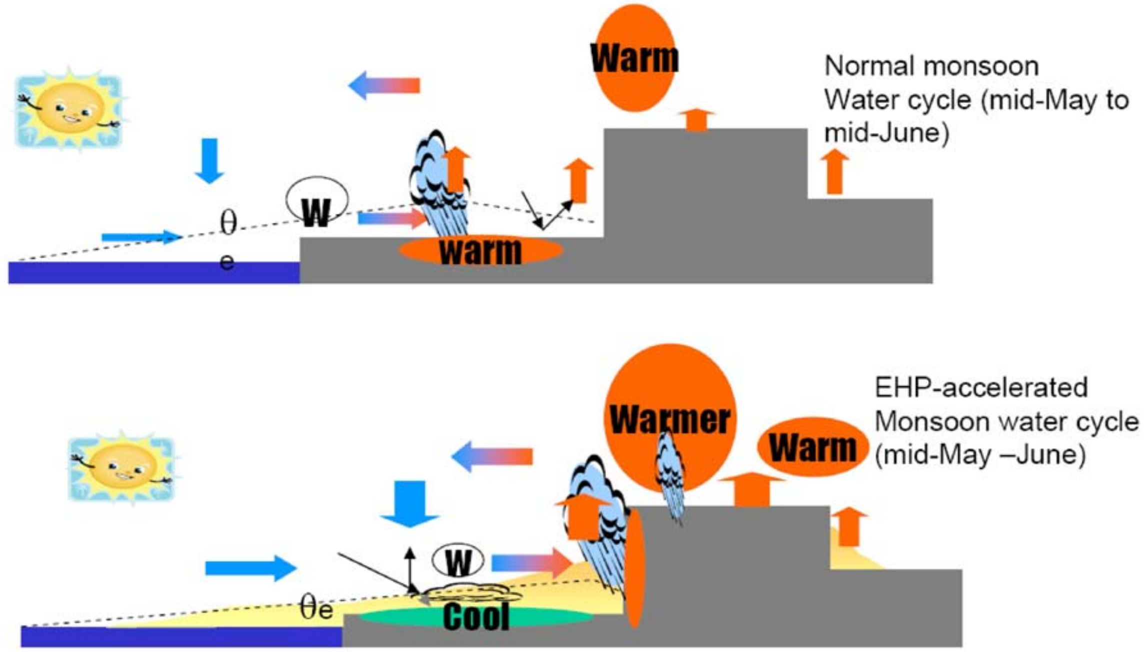
Radiative forcings and feedbacks



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

Radiative forcings and feedbacks

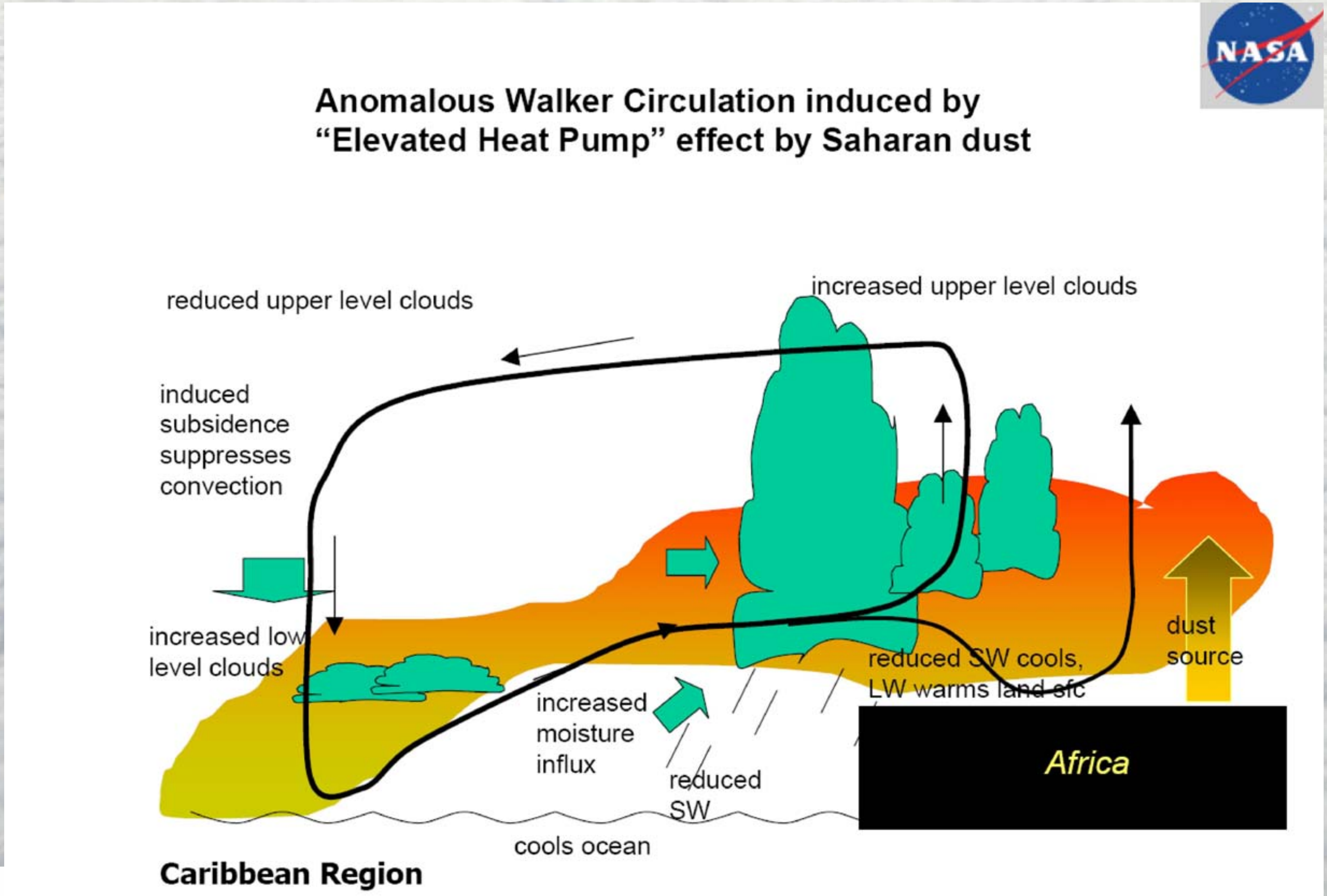
The Elevated Heat Pump (EHP) hypothesis (Lau et al. 2006, Climate Dynamics)



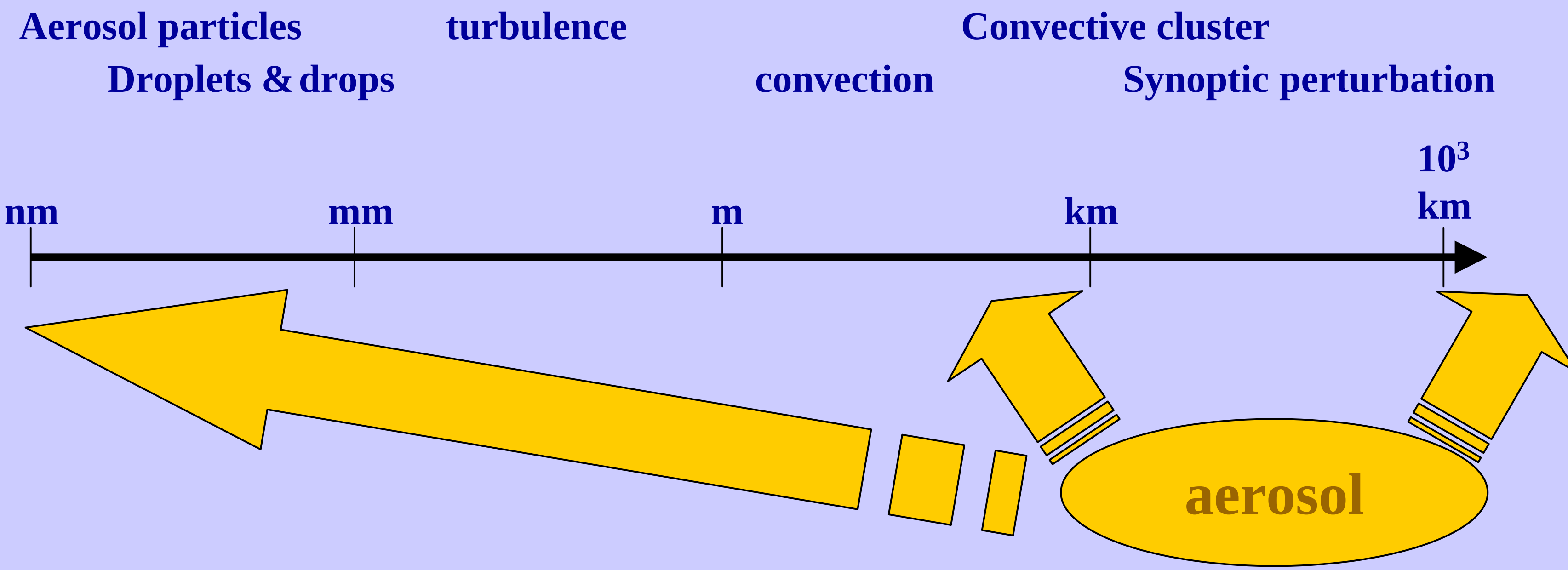
EHP postulates:
a) anomalous heating of Himalaya foohills, and warming of the upper troposphere over TP in MAM
b) an advance of the rainy season in northern India/Napal region in May-June
c) In June-July, the increased convection spreads from the foothills of the Himalayas to central India, resulting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

Lau and Kim (2006, GRL)

Radiative forcings and feedbacks



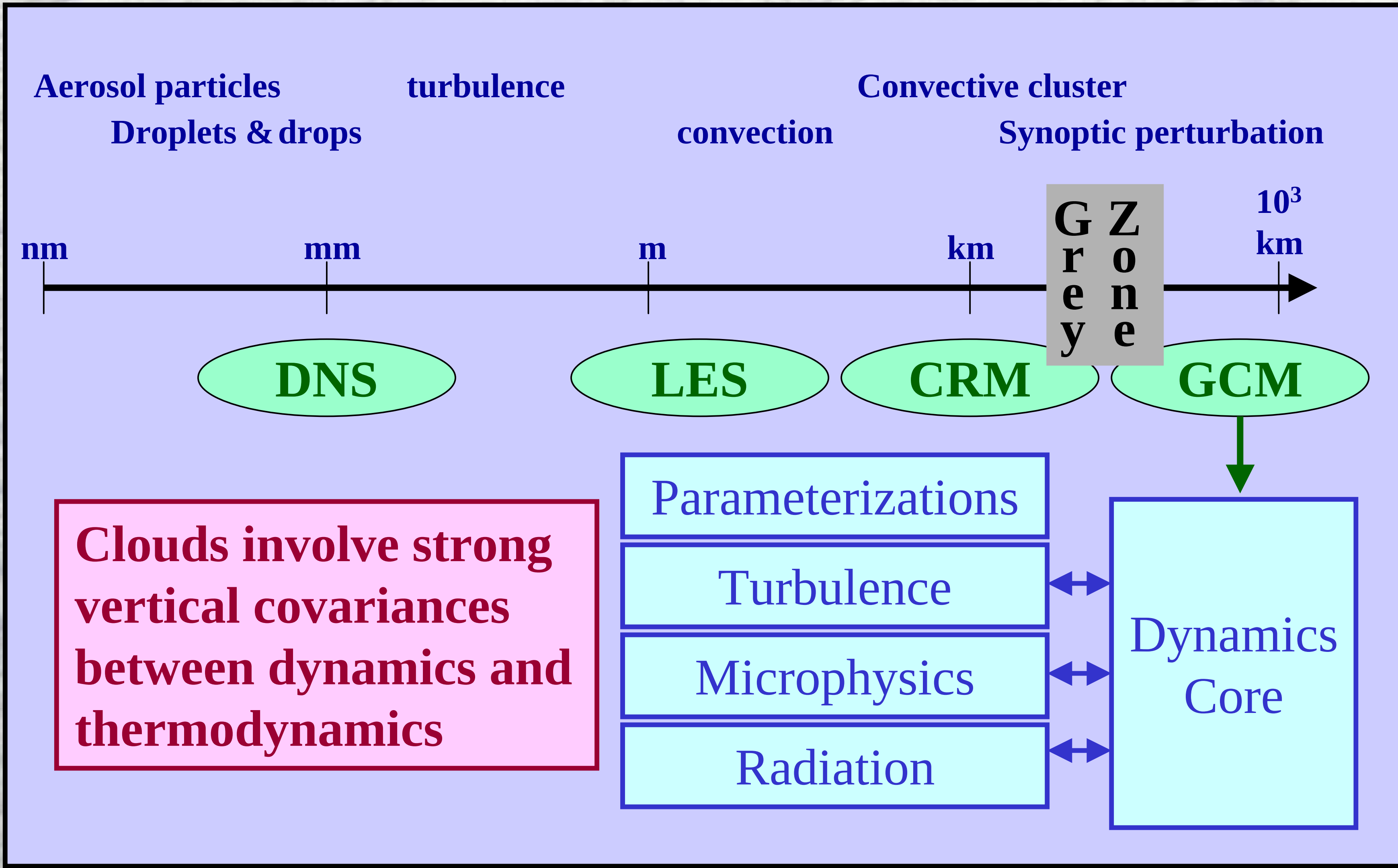
Radiative forcings and feedbacks



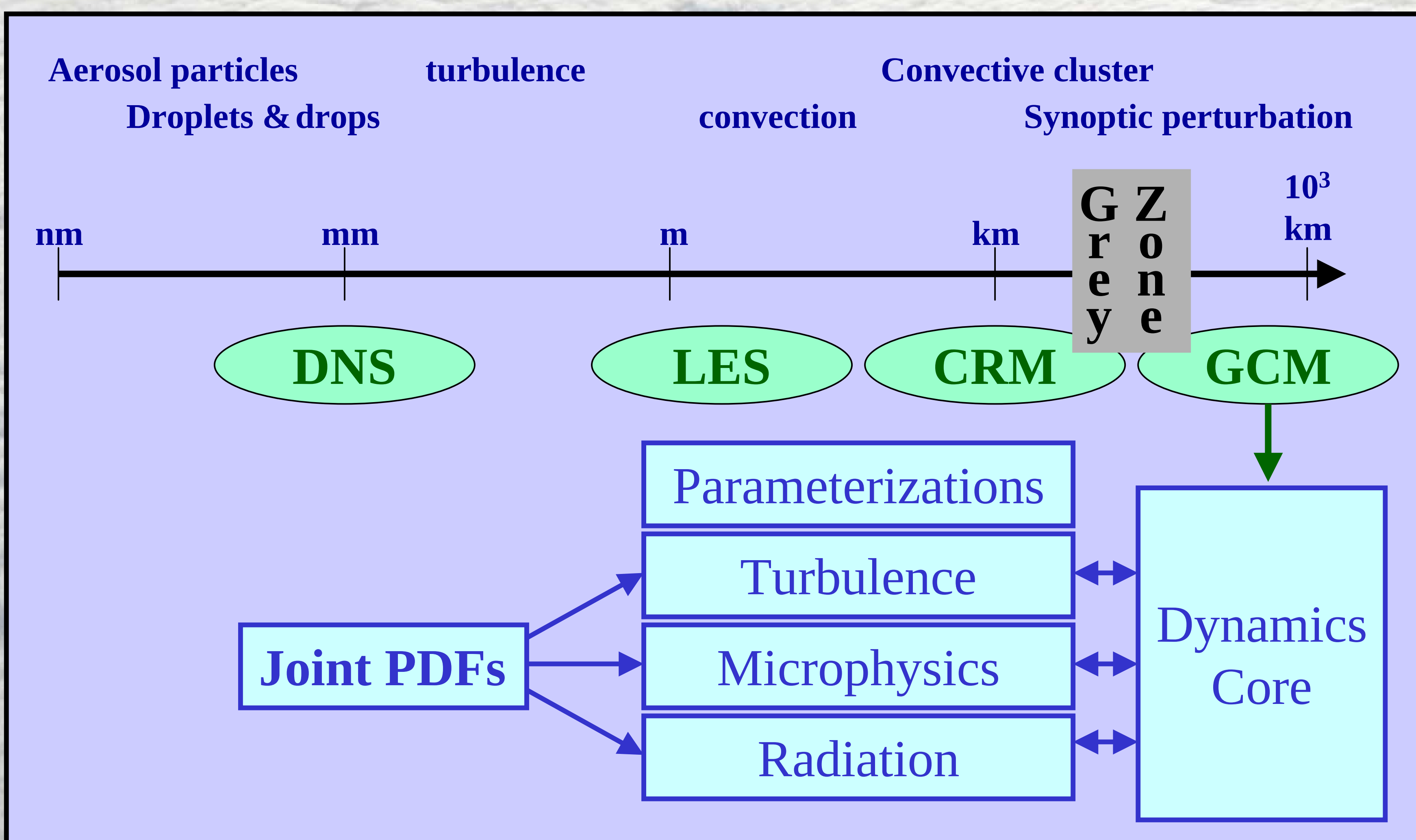
With its nucleating properties, CCN and IN, the aerosol can impact cloud microphysical properties

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

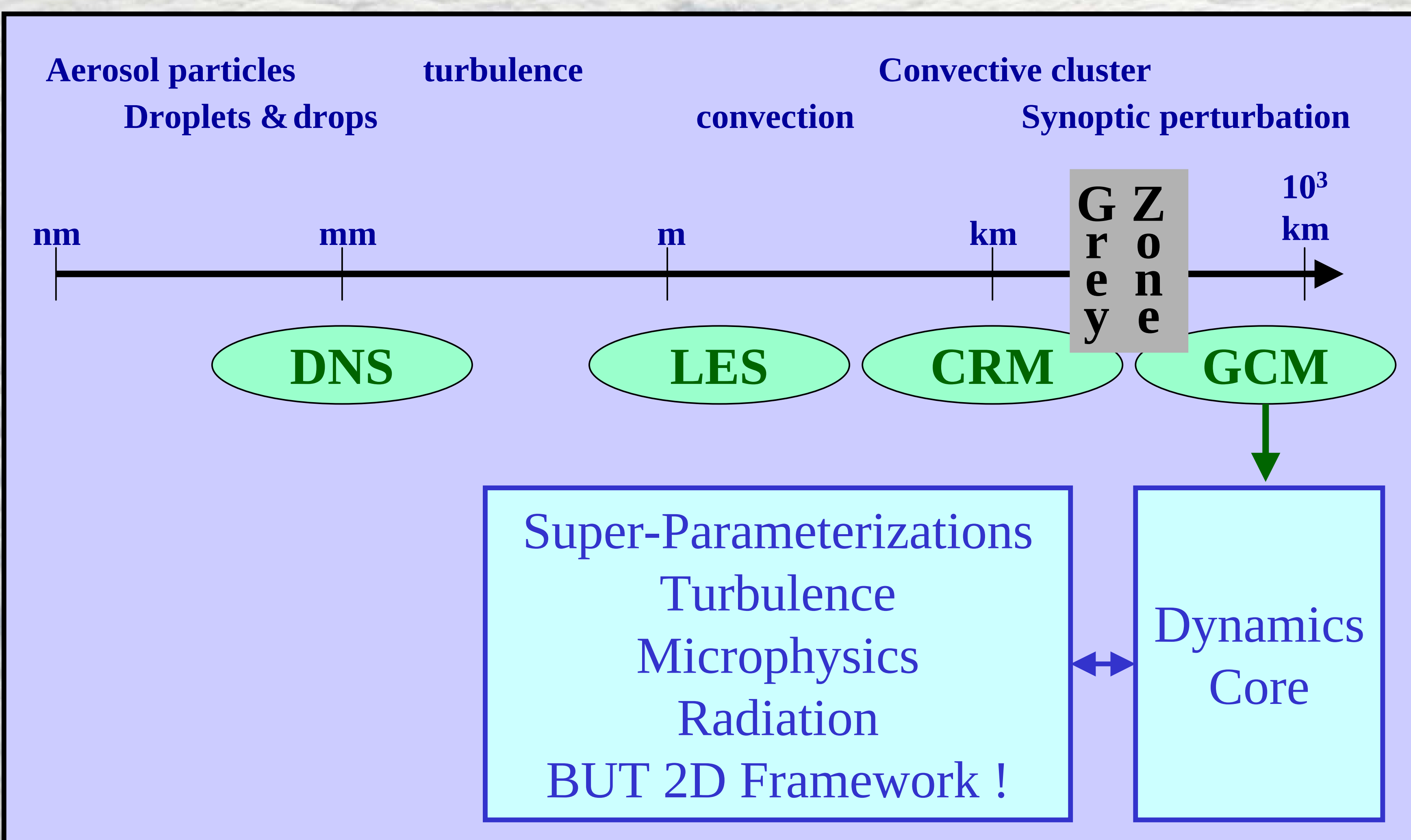
Limitations of the Modelling Systems



Limitations of the Modelling Systems



Limitations of the Modelling Systems



Limitations of the Modelling Systems

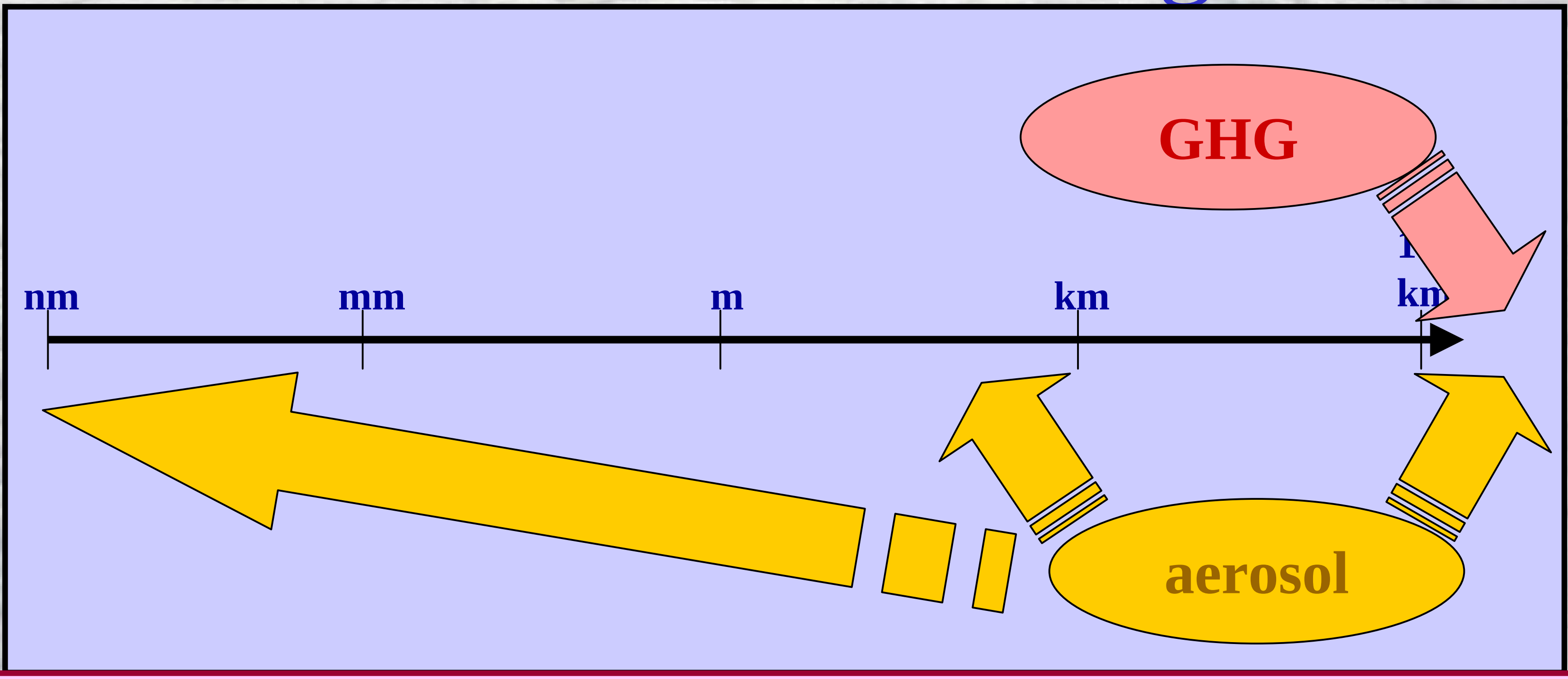
There is a significant gap in the present modelling capabilities at the transition between LES/CRM and GCM resolved scales, what is referred to as the Grey Zone (1 to 10 km), at which some clouds are resolved and others are sub-grid.

The most serious drawback is that information from the small (sub-grid) scale processes cannot be transfered to the resolved scale other than statistically on the grid mean state.

Today, GCMs are not well suited for understanding the aerosol impacts on clouds and the cloud feedback processes responsible for the regulation of the cloud radiative forcing (assuming such feedback processes act at the subgrid scale).

Aerosol Impacts versus Meteorology

Observational Strategies



Feedback processes controling cloud albedo and green-house effects are likely to propagate along all scales, from the microphysics to the global

1er Effet Indirect de l'Aérosol

Some aerosol particles act as droplet embryos (CCN).

When the CCN concentration increases, the droplet concentration generally increases.

At constant LWP, droplets in polluted clouds are smaller than in pristine clouds

More numerous and smaller droplets (cst LWP) have a higher extinction

At constant LWP, the albedo of polluted clouds is stronger than the one of pristine clouds (Twomey effect)

Can we assume that cloud microphysical and radiative properties can be modified, whithout assuming that their life cycle will also be affected

(constant LWP) ?

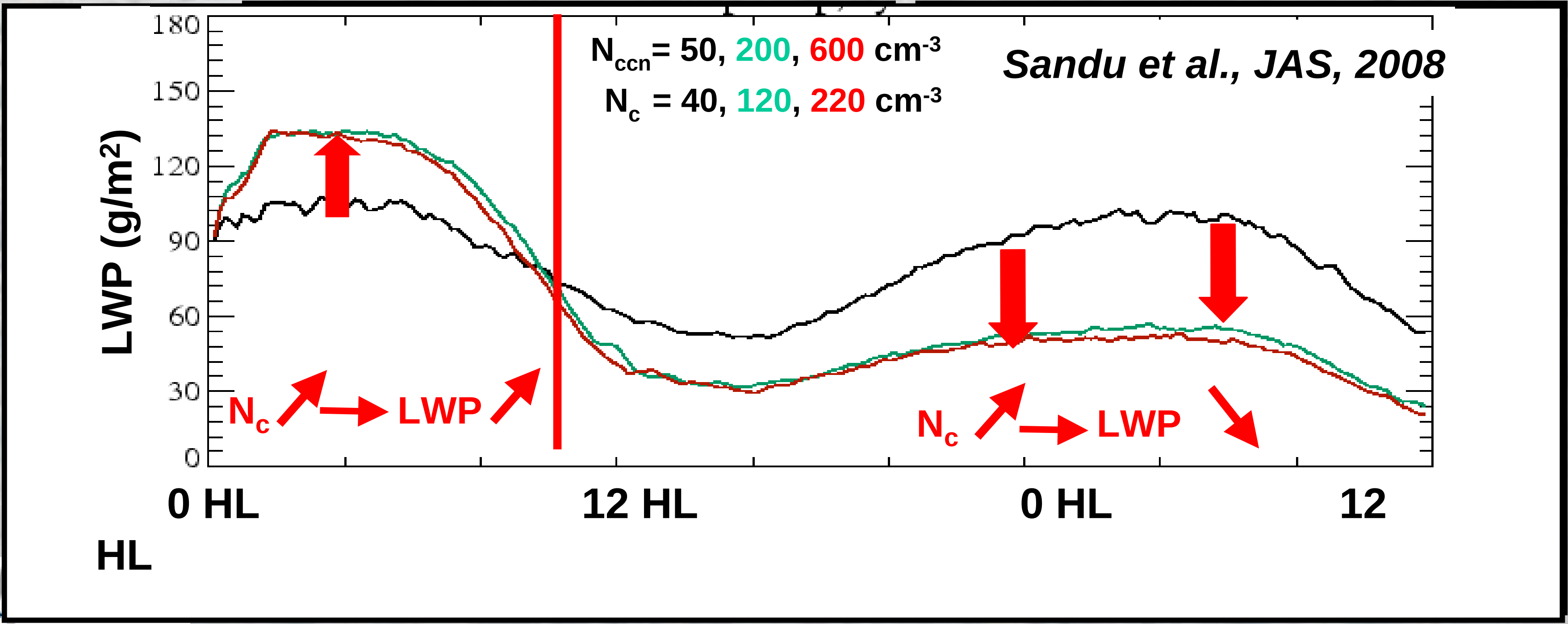
Additional Indirect Aerosol Effects

When droplets are smaller, their probability of coalescence is reduced, hence inhibiting the formation of precipitation

In boundary layer clouds, precipitation depletes the cloud water content

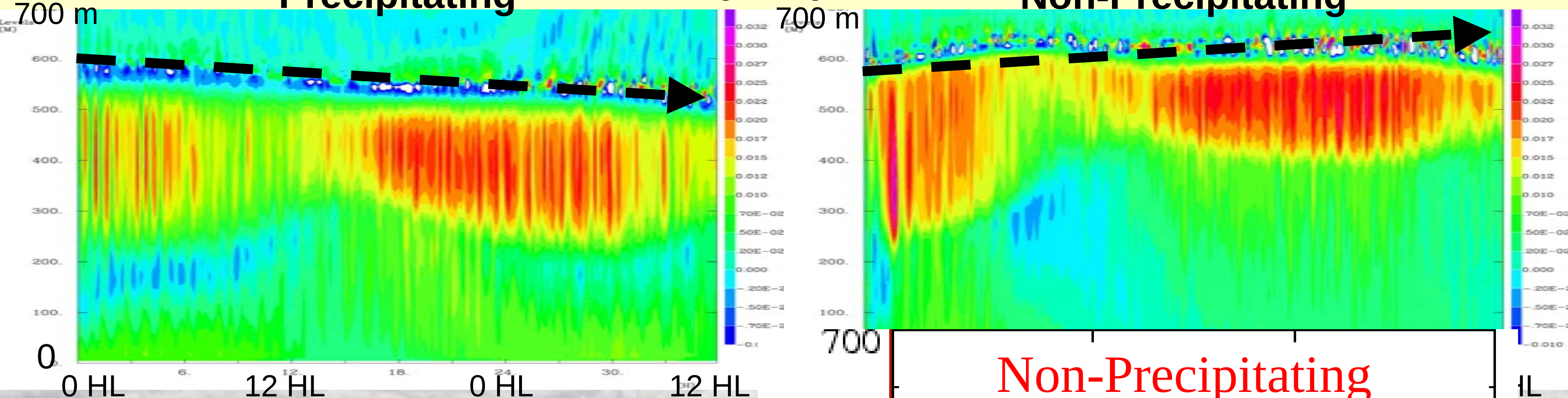
The LWP of polluted clouds shall therefore be higher than the one of pristine clouds, hence their albedo shall be higher (Albrecht effect) (negative feedback)

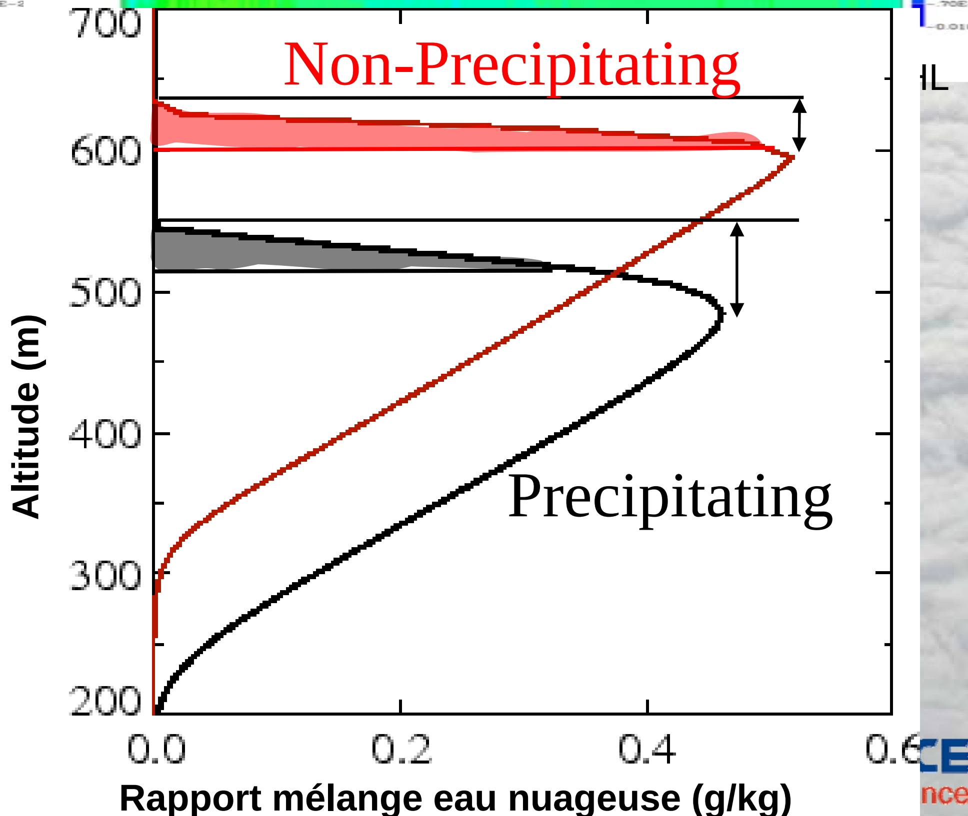
All LES simulations of this process suggest rather the opposite.



Additional Indirect Aerosol Effects

Buoyancy Flux





Précipitation Inhibited

⇒

Top entrainment reinforced

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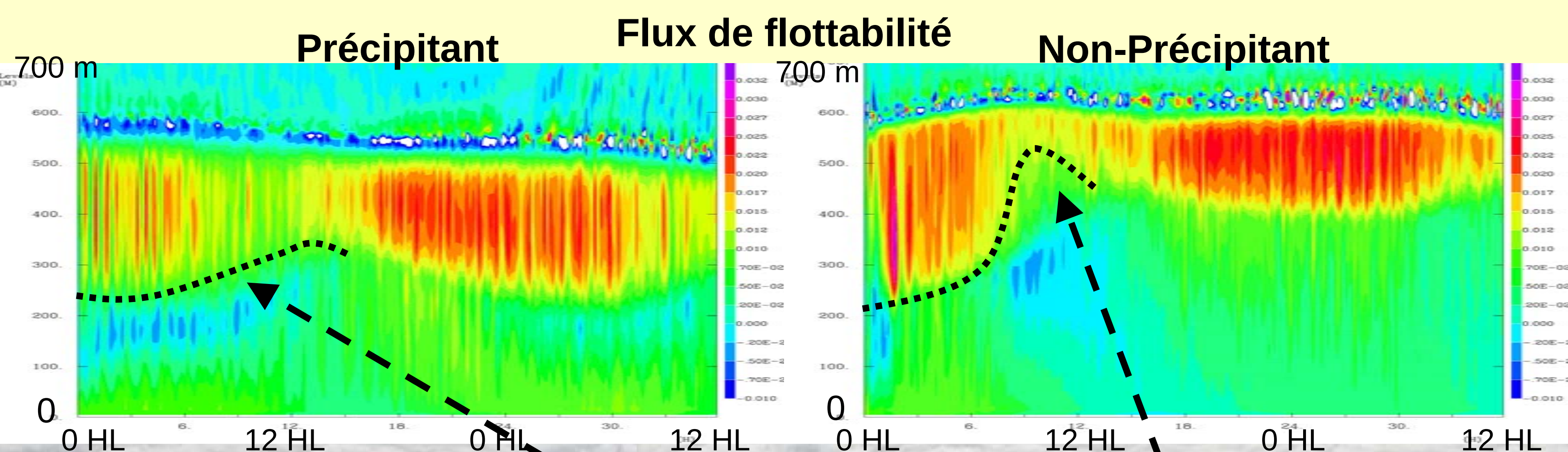
Additional Indirect Aerosol Effects



Precipitations reduce the nocturnal coupling and inhibit the diurnal decoupling

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Aerosol Impacts versus Meteorology
Observational Strategies

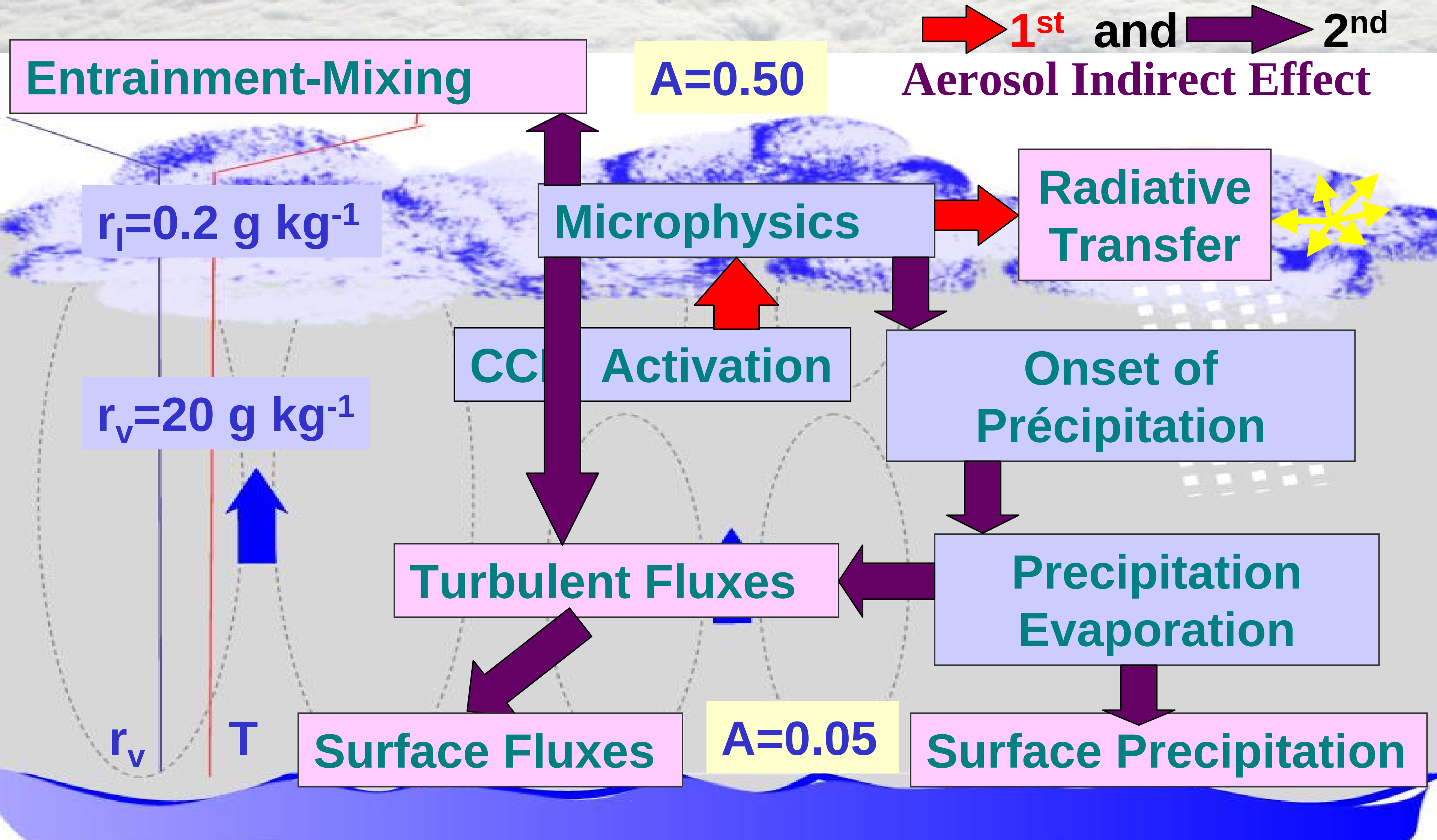
Observational evidences of the aerosol impacts on cloud microphysics (Squires, Warner, Manton, Ayers, 1960-1970) and cloud radiative properties (Ship tracks, ACE2, 1990-2000) are numerous and convincing

They rely on observation of instantaneous (20 min) cloud properties

Why is it so difficult to find observational evidence of the additional aerosol indirect effects ?

Additional aerosol indirect effects involve the time evolution of the cloud systems

Cloud Control Parameters & Aerosol Indirect Effects



Aerosol Impacts versus Meteorology
Observational Strategies

1- Measure cloud micro and macrophysical

2- Measure cloud radiative properties

3- Measure meteorological forcings

4- Examine cases with different aerosols, hence different microphysics

5- Detect differences in cloud properties, cloud cover, LWP, precipitation and radiation that might be attributed to the aerosol

Can we measure the meteorological forcings with sufficient accuracy to reject the hypothesis that they are solely responsible for the observed differences in cloud properties?

Cloud Control Parameters & Aerosol Indirect Effects

Can we measure the meteorological forcings with sufficient accuracy to reject the hypothesis that they are solely responsible for the observed differences in cloud properties?

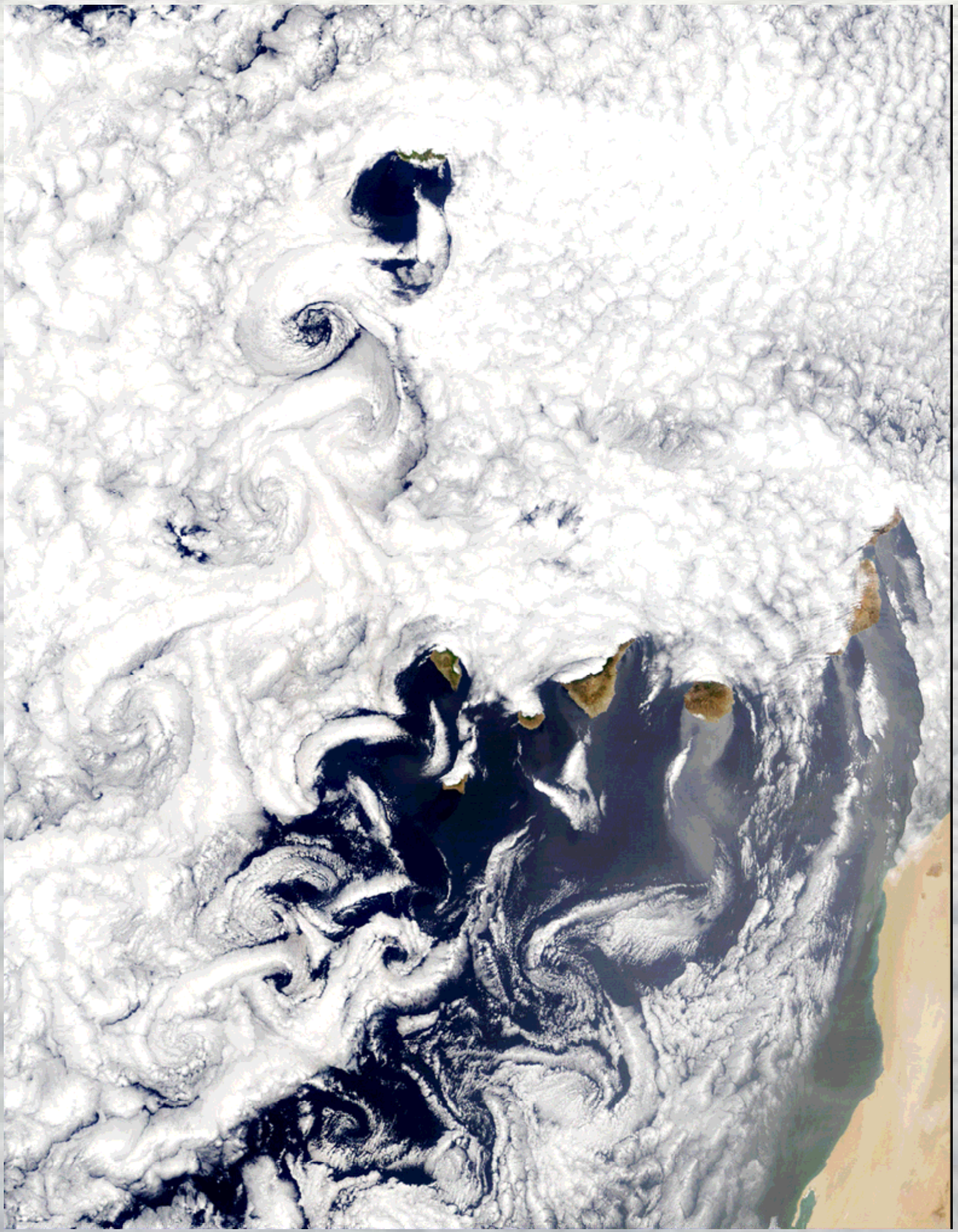
$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \delta m + \left.\frac{\partial c}{\partial a}\right|_m \delta a.$$

For instance in a subtropical stratocumulus of 100 m thickness, a drying (moistening) of 0.15 g/kg, out of a total water content of 15g/kg (1% change), is sufficient for the cloud to disappear (for a doubling of the LWP).

Cloud control parameters are not measurable, nor predictible, with an accuracy sufficient for disentangling meteorological effects on cloudiness from those of the atmospheric aerosol.

Cloud Control Parameters & Aerosol Indirect Effects

Cloud control parameters are not measurable, nor predictible, with an accuracy sufficient for disentangling meteorological effects on cloudiness from those of the atmospheric aerosol.



Cloud Control Parameters & Aerosol Indirect Effects

Alternative I: **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 almost always an indicator of their differing meteorological histories, making it nearly impossible to establish causal relationships between c and a from observations of self-perturbed systems (Metronex).

Cloud Control Parameters & Aerosol Indirect Effects

<u>Alternative II Statistical approach</u> : 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 any effect because $\lambda_M >> \lambda_A$

Not only do we need to reduce 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.

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Cloud Control Parameters & Aerosol Indirect Effects

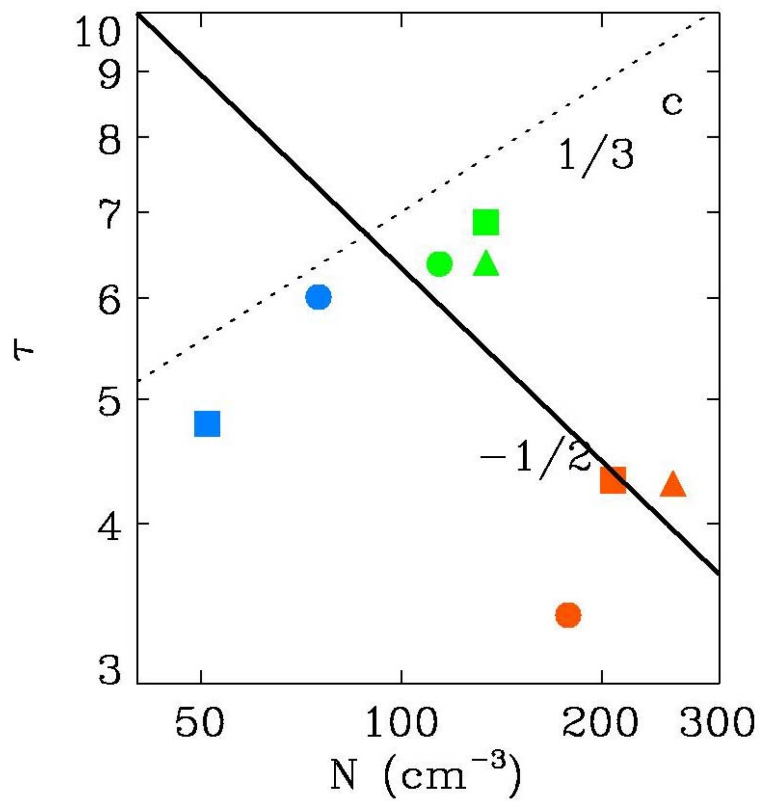
Not only do we need to understand the meteorological variability and its impact on the clouds, but we also need to understand to what extent the meteorological variability covaries with the aerosol variability.

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

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

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

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



Brenguier et al. 2003 (ACE2/PACE)

Cloud Control Parameters & Aerosol Indirect Effects

Alternative III : select situations where aerosol and meteorology vary independently (week-end effect, sugar cane burning)

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

$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \left.\frac{\partial m}{\partial m_0}\right|_a \delta m_0 + \left[\left.\frac{\partial c}{\partial a}\right|_m + \left.\frac{\partial c}{\partial m}\right|_a \left.\frac{\partial m}{\partial a}\right|_{m_0} \right] \delta a.$$

Close to the aerosol source, aerosol and meteorology are likely to be correlated. Far from the source, covariance builds up with time because of potential aerosol radiative impacts on the meteorology and potential impact of the meteorology on the aerosol (aerosol scavenging)

Cloud Control Parameters & Aerosol Indirect Effects

<u>Alternative IV</u> : select situations where aerosol properties are uniform and look at the short term meteorological variability, i.e. the diurnal cycle.

$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \left.\frac{\partial m}{\partial m_0}\right|_a \delta m_0 + \left[\left.\frac{\partial c}{\partial a}\right|_m + \left.\frac{\partial c}{\partial m}\right|_a \left.\frac{\partial m}{\partial a}\right|_{m_0} \right] \delta a.$$

0

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

Cloud Control Parameters & Aerosol Indirect Effects

Alternative V : use the synergy between models (LES) and observations. The aerosol impacts on clouds might not be detectable or distinguishable from meteorological forcings, but LES models simulate these impacts and some mechanisms by which these impacts proceed have a measurable signature: sharper liquid water content and stronger vertical velocity variance at cloud top in the polluted cases, reduced cloud base turbulence at night and increased cloud base turbulence during the day in the pristine cases.

Not an observational evidence, but it improves the confidence on the models that simulate the aerosol impacts

Recommendations

Avoid interpreting correlations seen in satellite data as cause and effect relationships

Always start with the potential impacts of the meteorology on observed cloud properties, precisely evaluate the sensitivity of the cloud system to the meteorology and the uncertainty in the measurements of the meteorological forcings, before looking at a potential aerosol impact.

A cloud is a system where meteorology and aerosol are tightly coupled. Do not limit the analysis to one way cause and effect relationships (aerosol $\Rightarrow$ meteorology), but also consider the reverse pathways (e.g. aerosol scavenging by precipitation)

Avoid enforcing relationships that have been shown to be valid at one scale on entirely other scales, or applying microphysical concepts designed for single clouds to fields of clouds.