Aerosol, Clouds and Climate

L’effet indirect de l’aérosol est-il détectable ?

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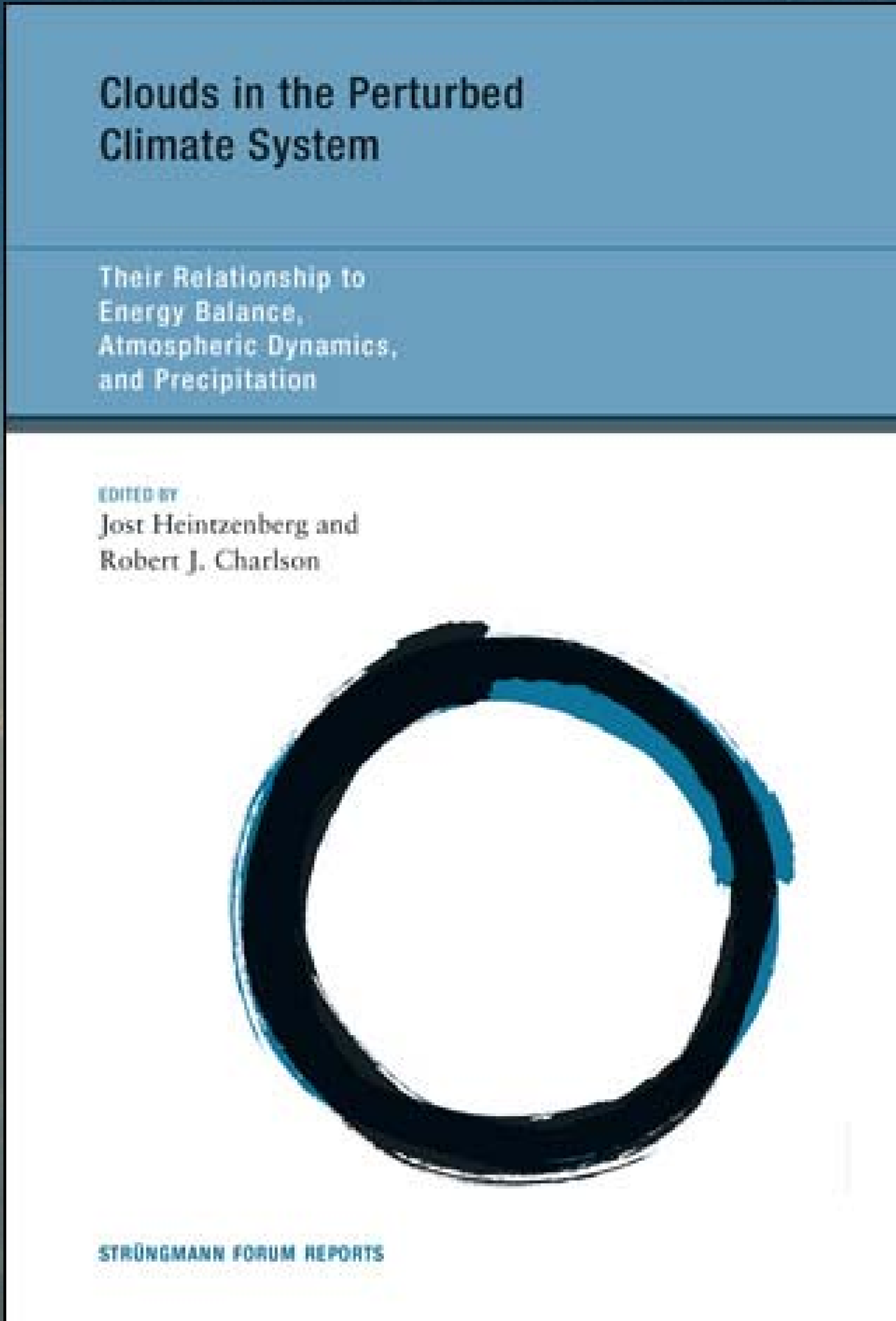


Ernst Strüngmann Forum

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

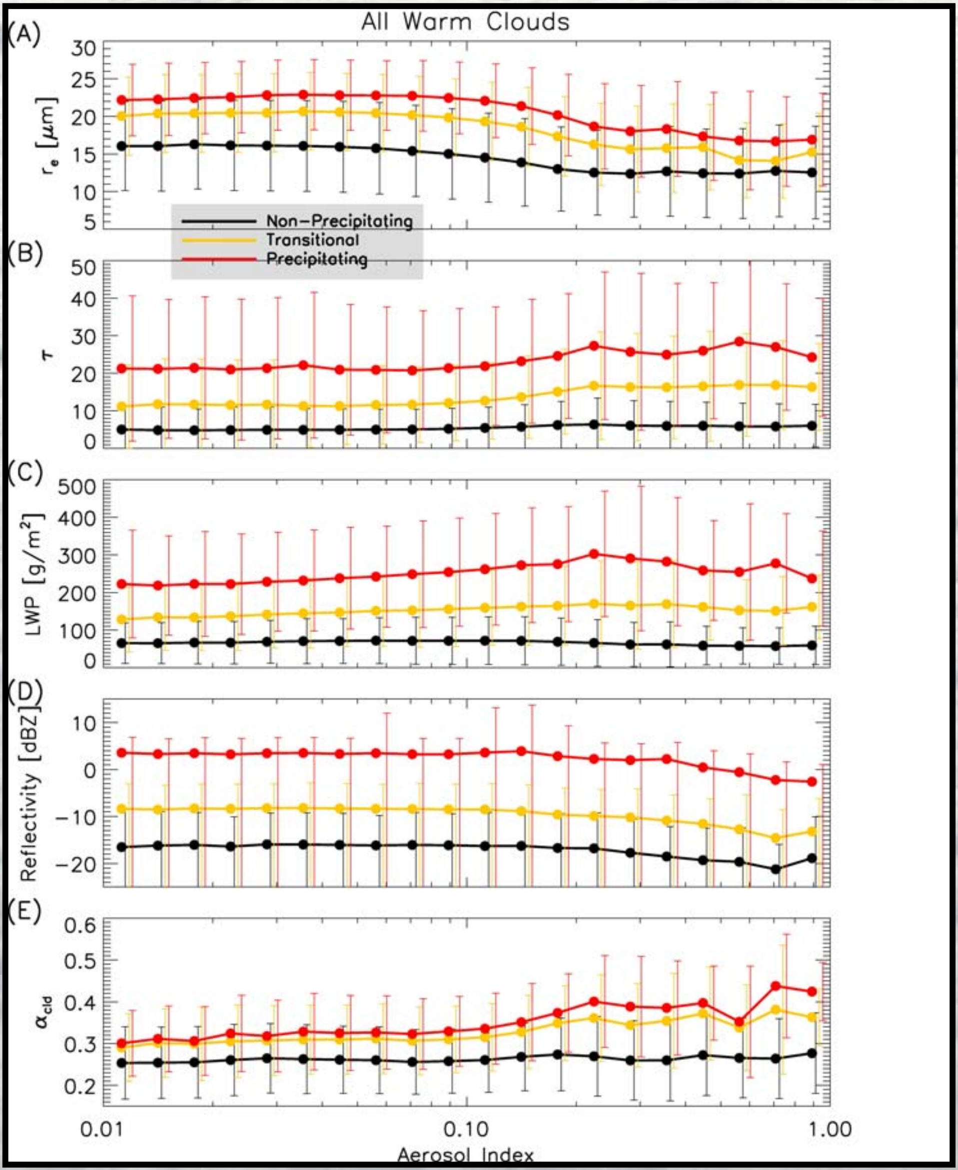
Cloud Controlling Factors—Low Clouds
B. Stevens & J. L. Brenguier

What do we learn from satellite ?

Warm oceanic clouds observed by MODIS & CloudSat

Global relationships between AI and non-precipitating, 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



What do we learn from satellite ?

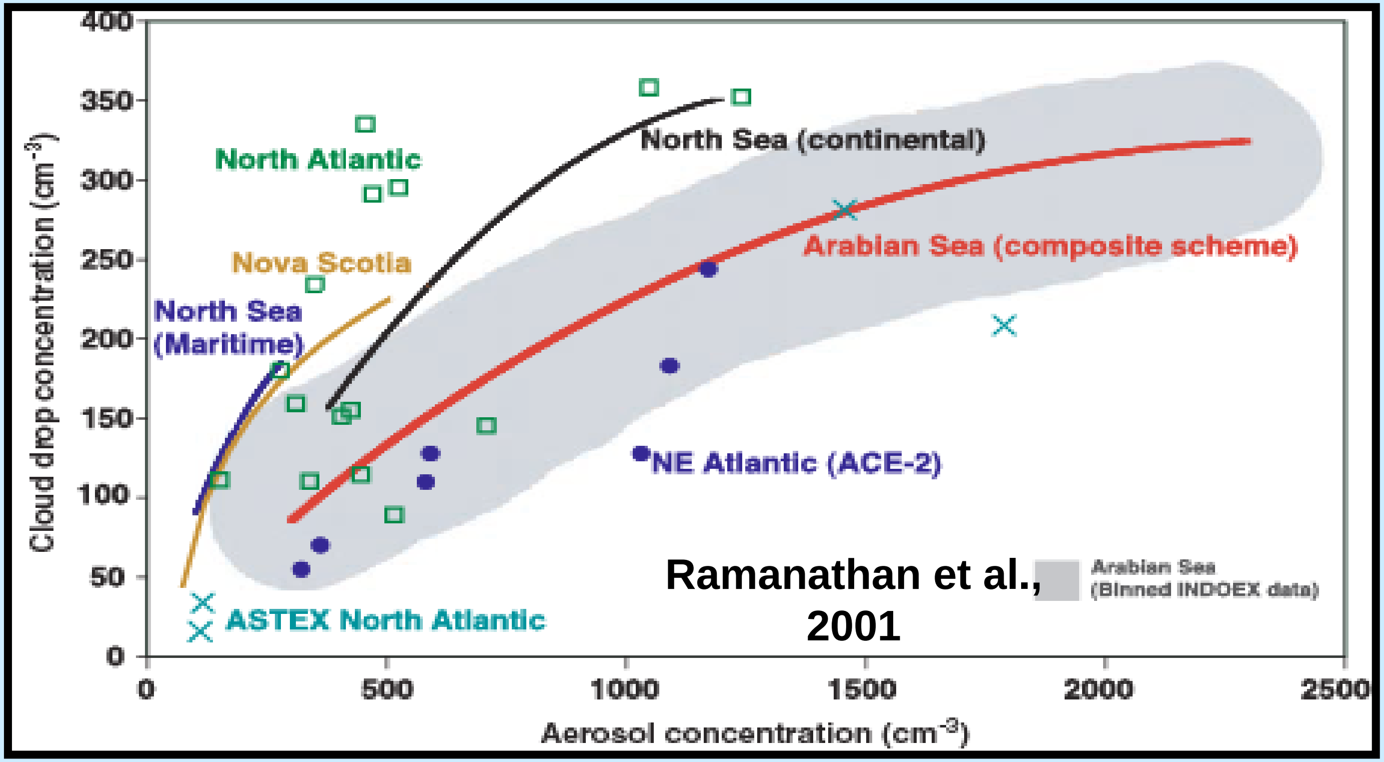
Correlations between today aerosols and cloud properties

What do we want to learn ?

How aerosols impact cloud global radiative forcing.... and how to parameterize this impact in GCMs

What do we already know ?

(I) CCN Concentration ➚ ⇒ CDNC ➚
⇒ Droplet Sizes ➘ (cst LWP)



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

What do we already know ?

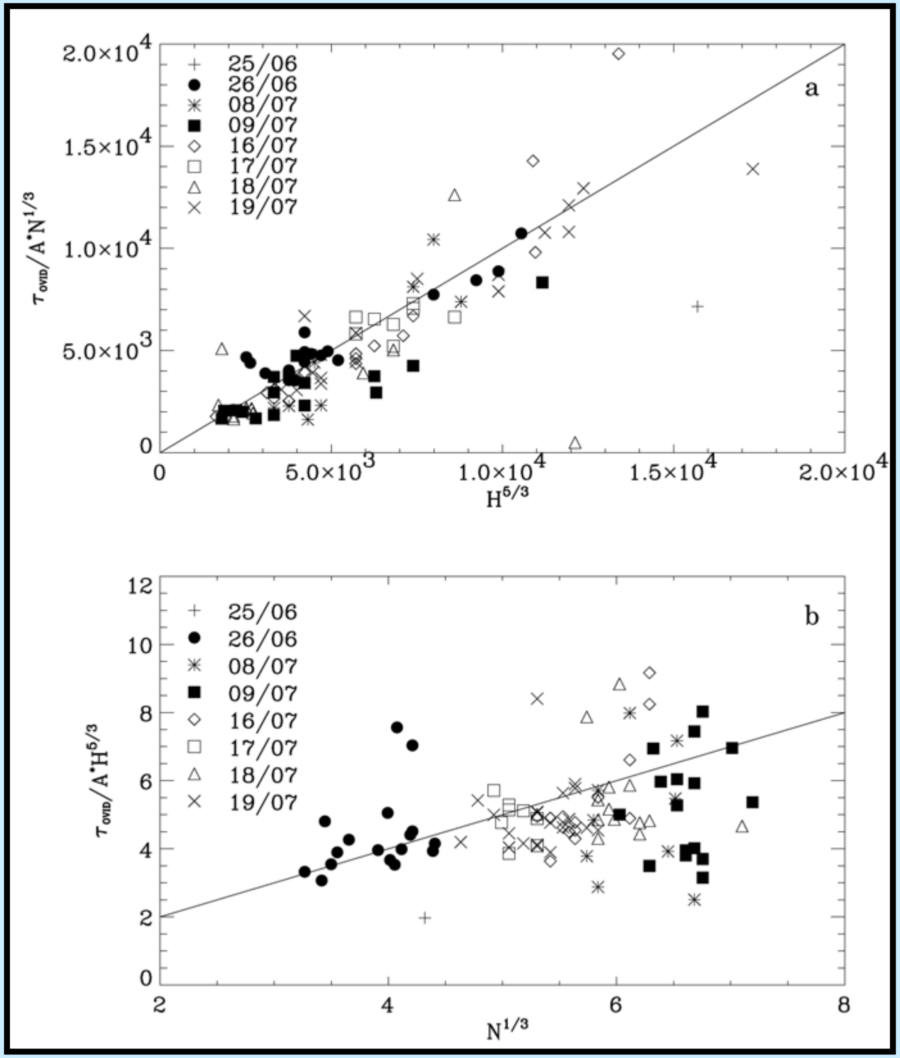
(I) CCN Concentration ➚ ⇒ CDNC ➚
⇒ Droplet Sizes ➘ (cst LWP)

(II) Droplet Sizes ➘ ⇒ COT ➚ (cst LWP)

What do we already know ?

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)



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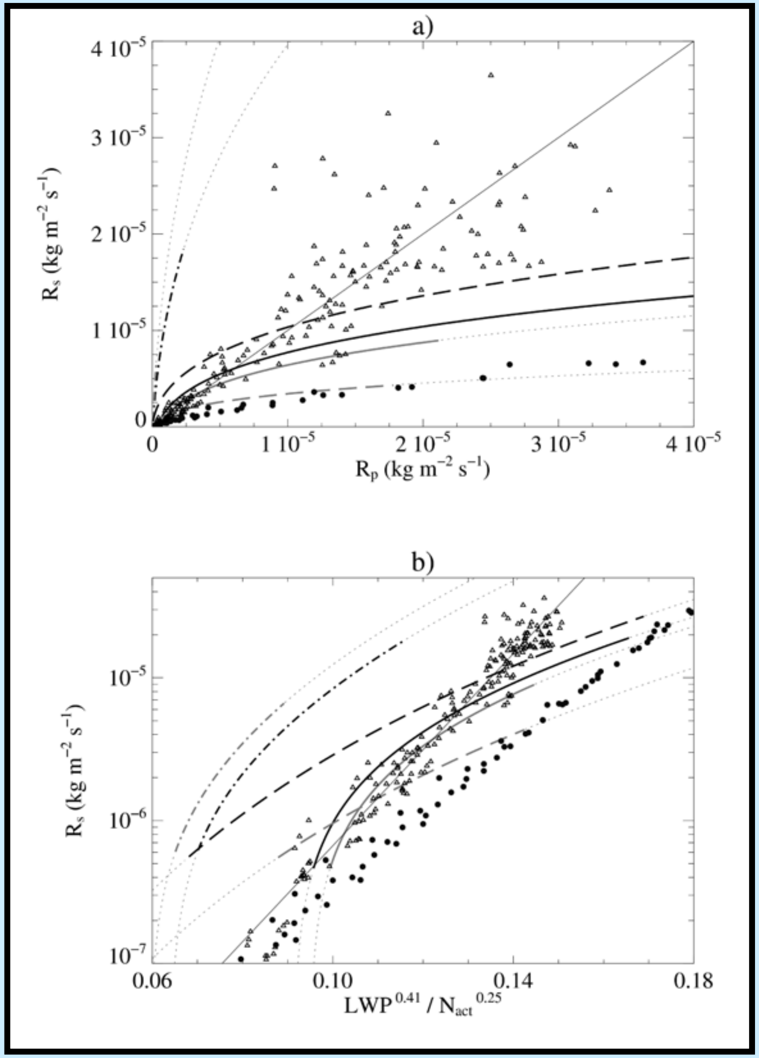
(III) Droplet Sizes ➘ ⇒ PR ➘ (cst LWP)

What do we already know ?

Comparison of LES simulated precipitation rate with parameterizations derived from observations

Data from the field experiments (ACE-2, EPIC, DYCOMS-II), and LES simulations (Geoffroy et al., 2007)



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

What do we already know ?

(I) CCN Concentration ➚ ⇒ CDNC ➚
⇒ Droplet Sizes ➘ (cst LWP)

(II) Droplet Sizes ➘ ⇒ COT ➚ (cst LWP)

(III) Droplet Sizes ➘ ⇒ PR ➘ (cst LWP)

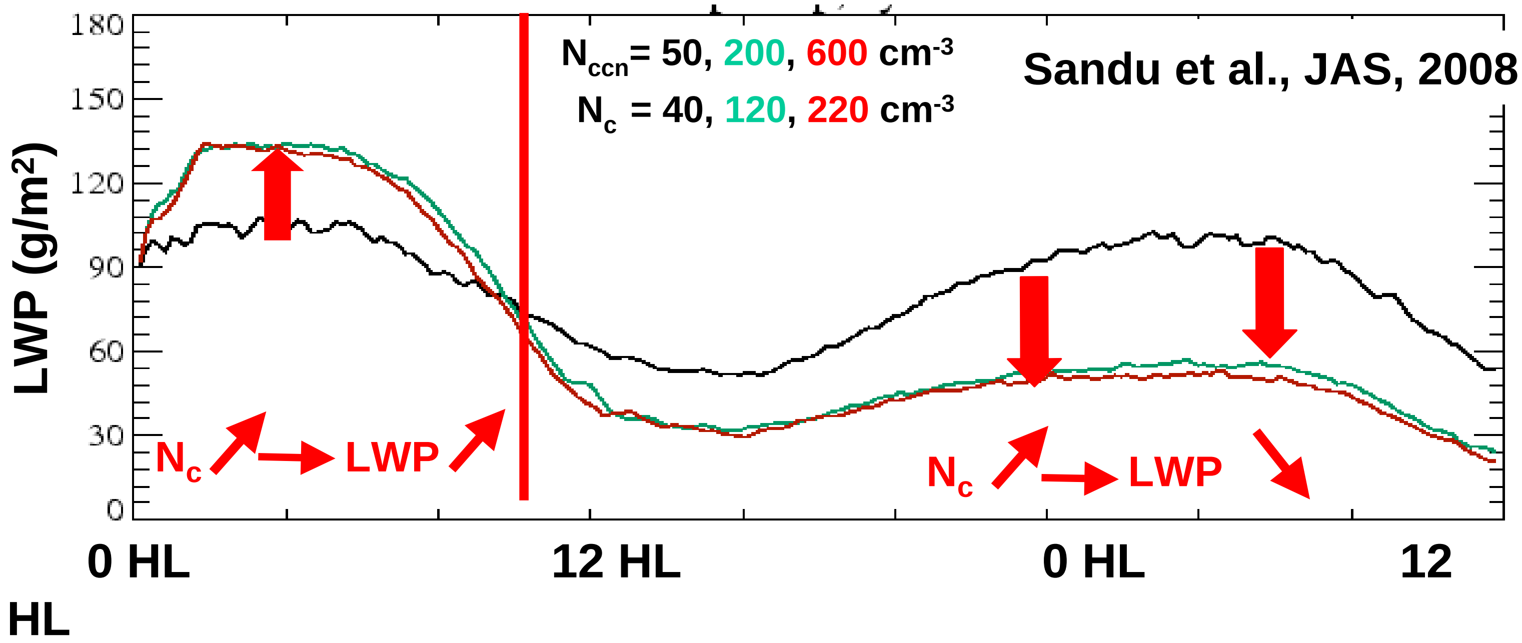
What is missing ?

(IV) Impacts on Cloud Extend and Life Time
(Varying LWP or 2nd Aerosol Indirect Effect)

CRF= f(M, A, MA)

What is missing ?

Changing cloud optical properties and precipitation efficiency is likely to impact cloud extend and life time



How can we proceed ?

To derive causal relationships from observed correlations and develop parameterizations of the aerosol impacts on cloud properties, one must first disentangle the respective contributions of the meteorology and of the aerosols.

Null Hypothesis :
Aerosols have no impact on Clouds

Cloud controlling factors are the heat and moisture (relative humidity)

Heat and moisture are scalar tracers of the general circulation

The aerosol is also a scalar tracer of the general circulation (although with slightly different diffusivity)

Within the framework of the null hypothesis, satellite observations must exhibit noticeable correlations between heat, moisture and the aerosol

Requirements for causal relationships

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

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

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

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

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 $\Delta H=H/5=80$ 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, nor predictable !

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

Aerosol → Cloud Interactions

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

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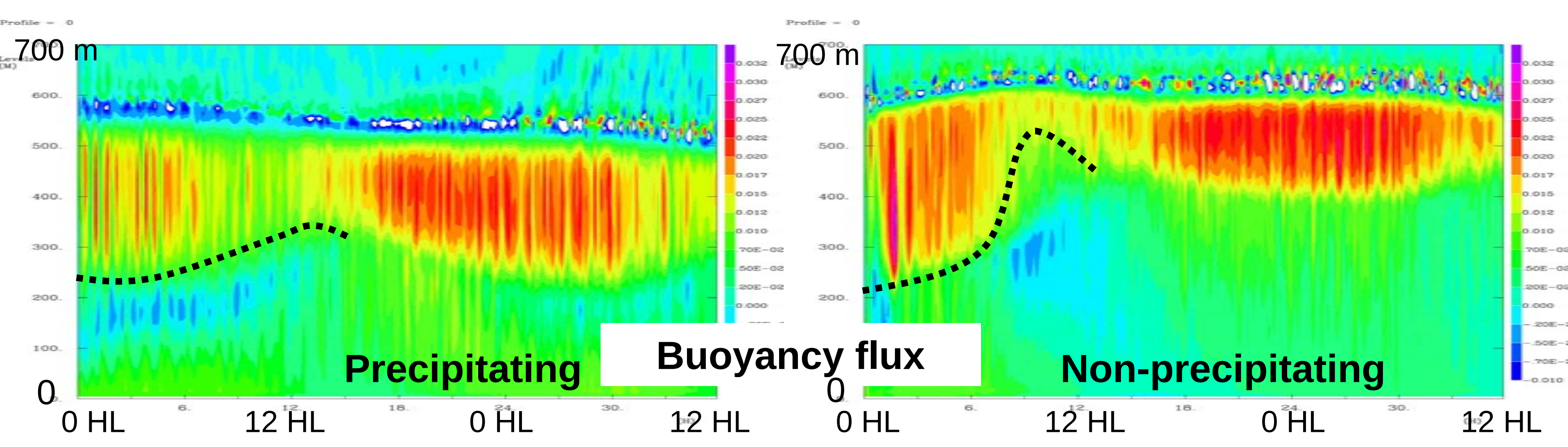
Mechanisms of the Interactions

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 (according to LES models)
- More adiabatic LWC vertical profile
- Higher vertical velocity variance at cloud top
- More coupling at night and more decoupling during the day



Aerosol ➔ Cloud Interactions

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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**

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

$$\sigma_c^2 = \lambda^2_{A_\mu}\sigma^2_{A_\mu} + \lambda^2_M \sigma^2_M + 2\lambda_{A_\mu}\lambda_M \sigma_{A_\mu}\sigma_M r$$

$\sigma^2_M \rightarrow 0$

50 years of weather modification experiments have not been sufficient to detect noticeable effects because $\lambda_M >> \lambda_A$

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)

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

Is there any aerosol source, that has no signature in term of heat and moisture, considering that $\lambda_M >> \lambda_A$?

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

Observational Strategy

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

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.

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

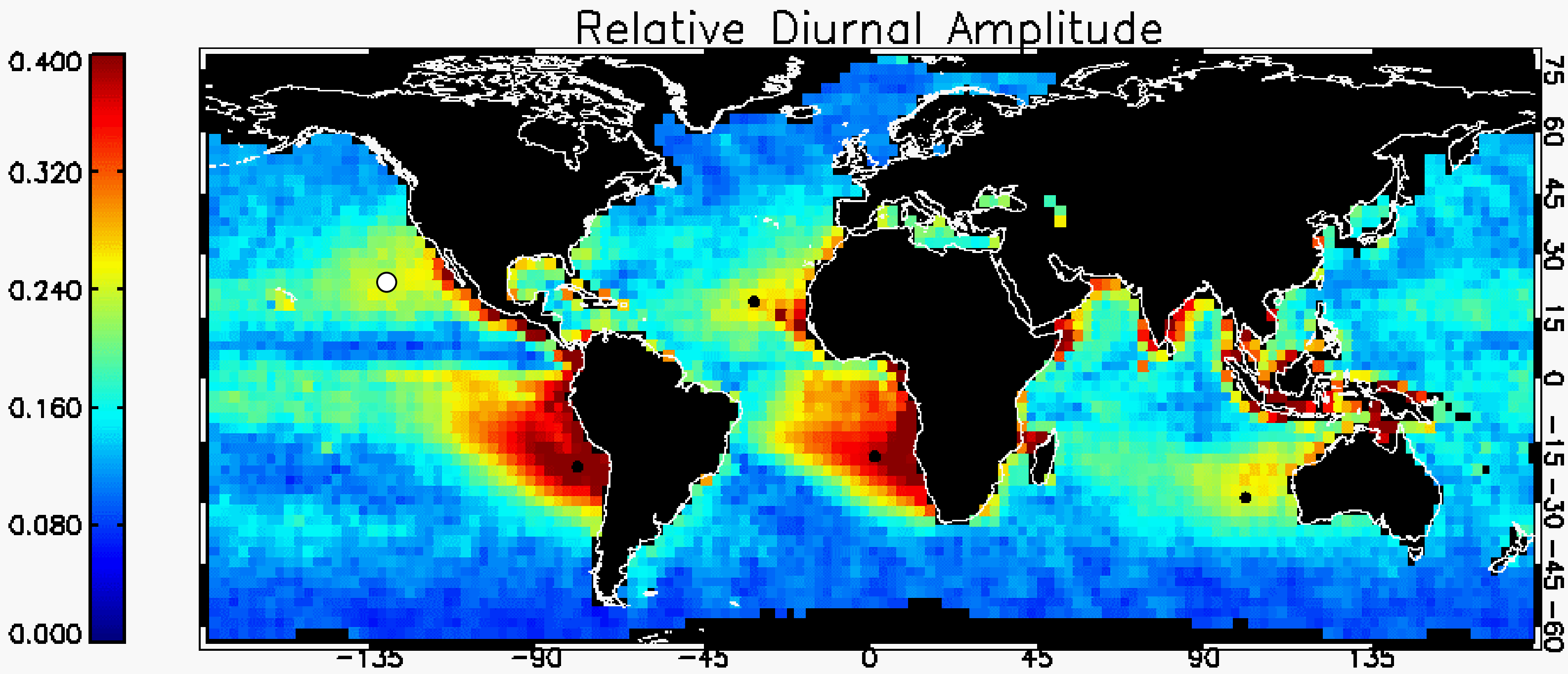
Observational Strategy

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.

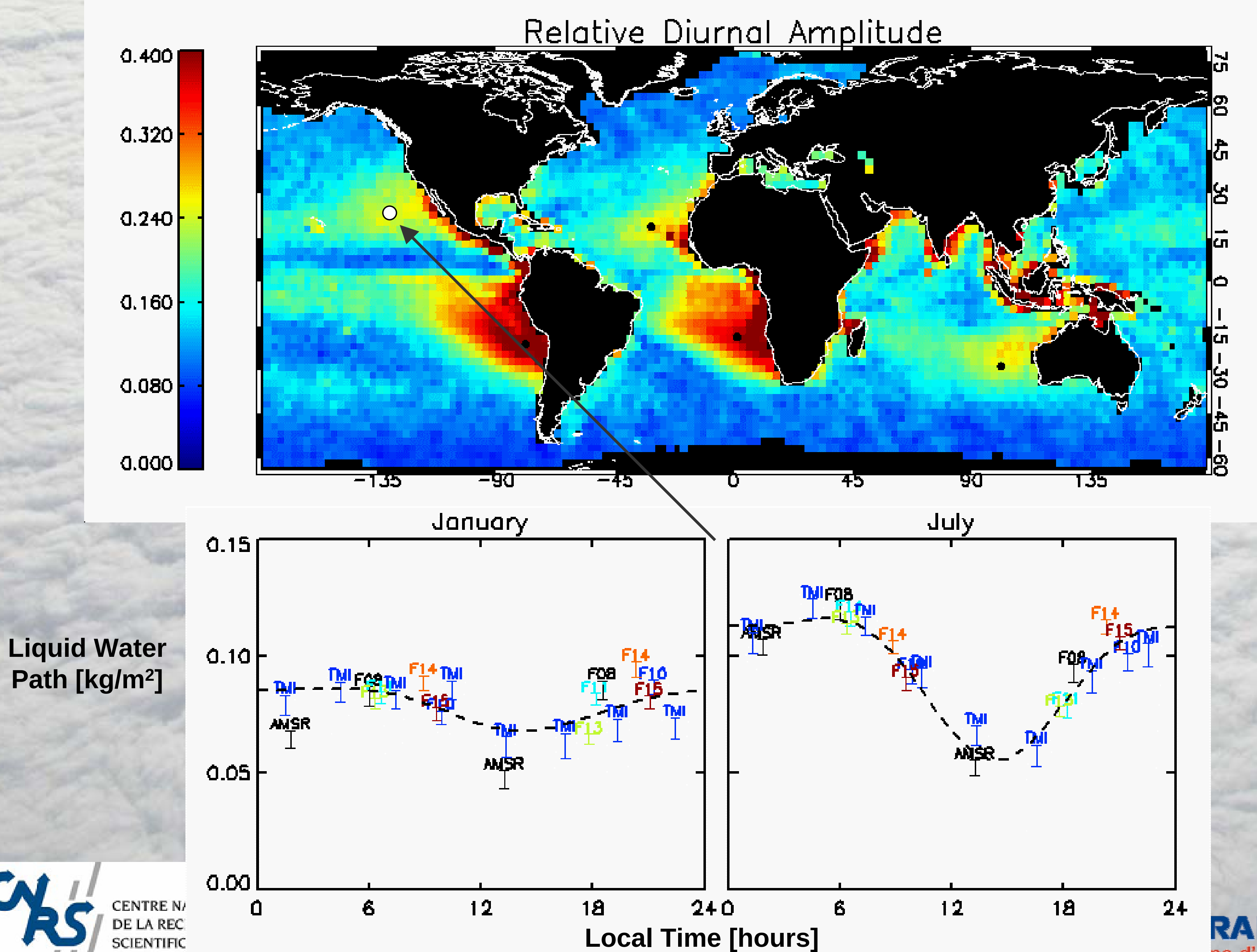
$$\delta c = \left.\frac{\partial c}{\partial m}\right|_a \delta m + \left.\frac{\partial c}{\partial a}\right|_m \delta a.$$

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

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



O'Dell, Wentz, and Bennartz, J Climate, 2008


Relative Diurnal Amplitude
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January
July
Liquid Water Path [kg/m²]
Local Time [hours]
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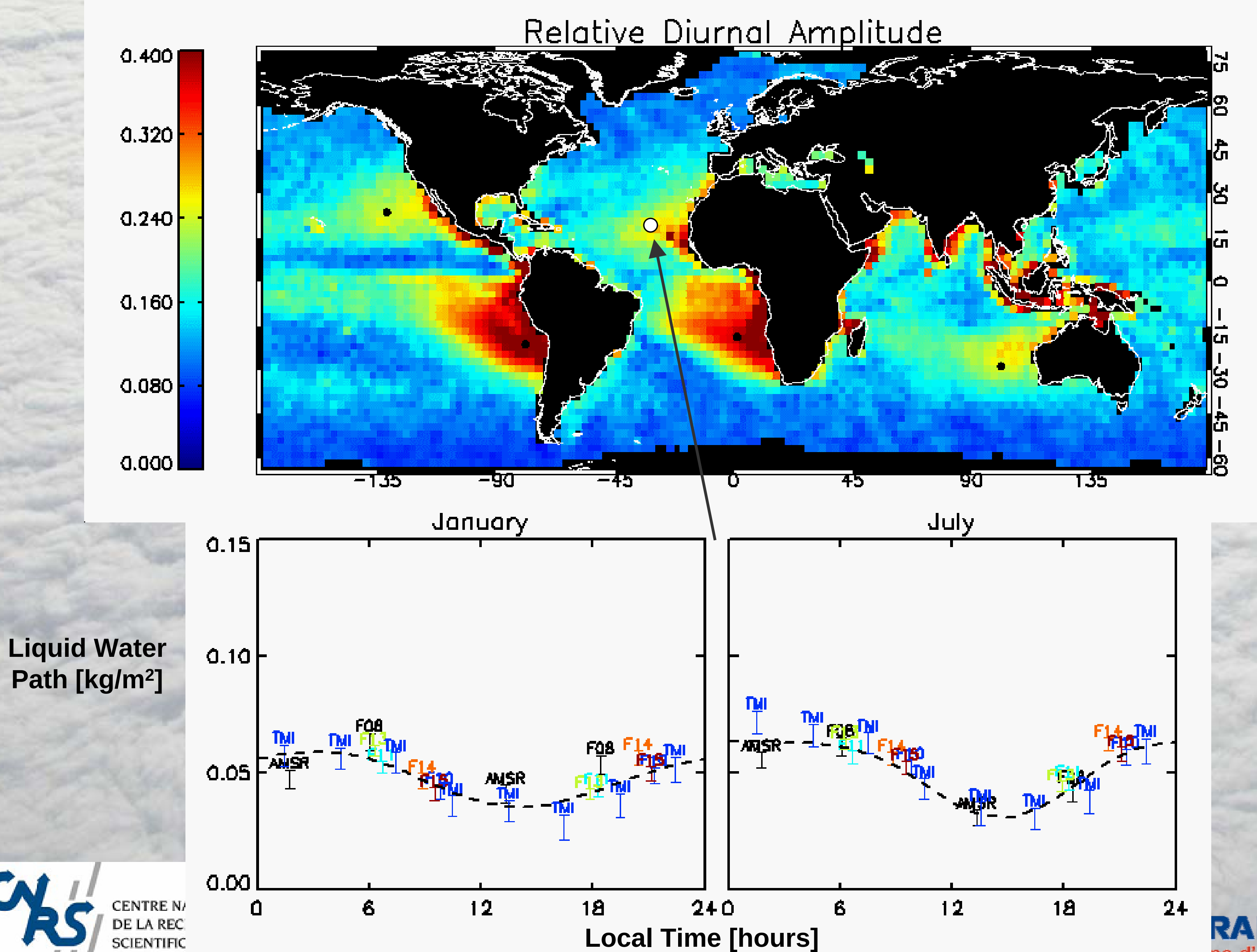

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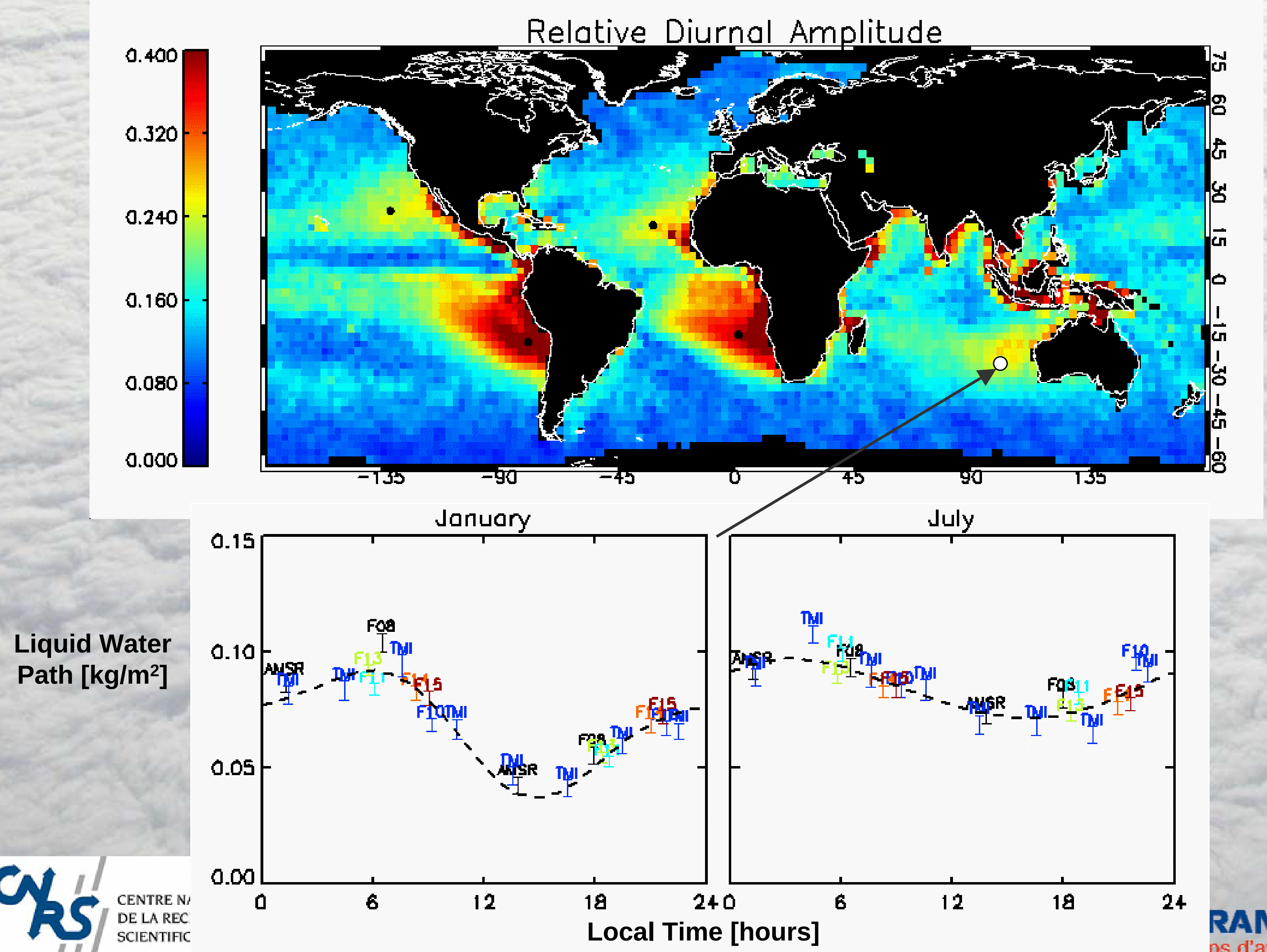

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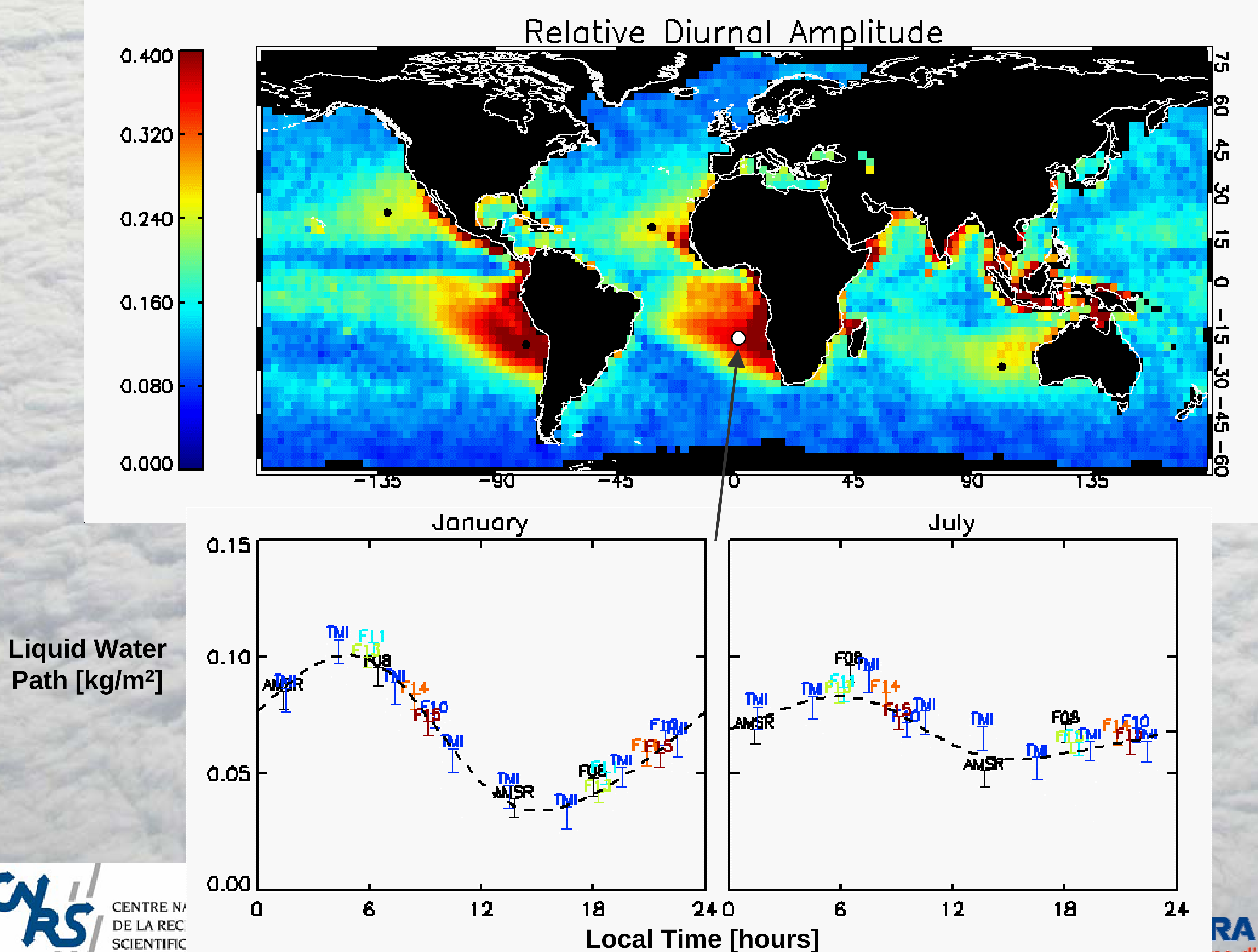
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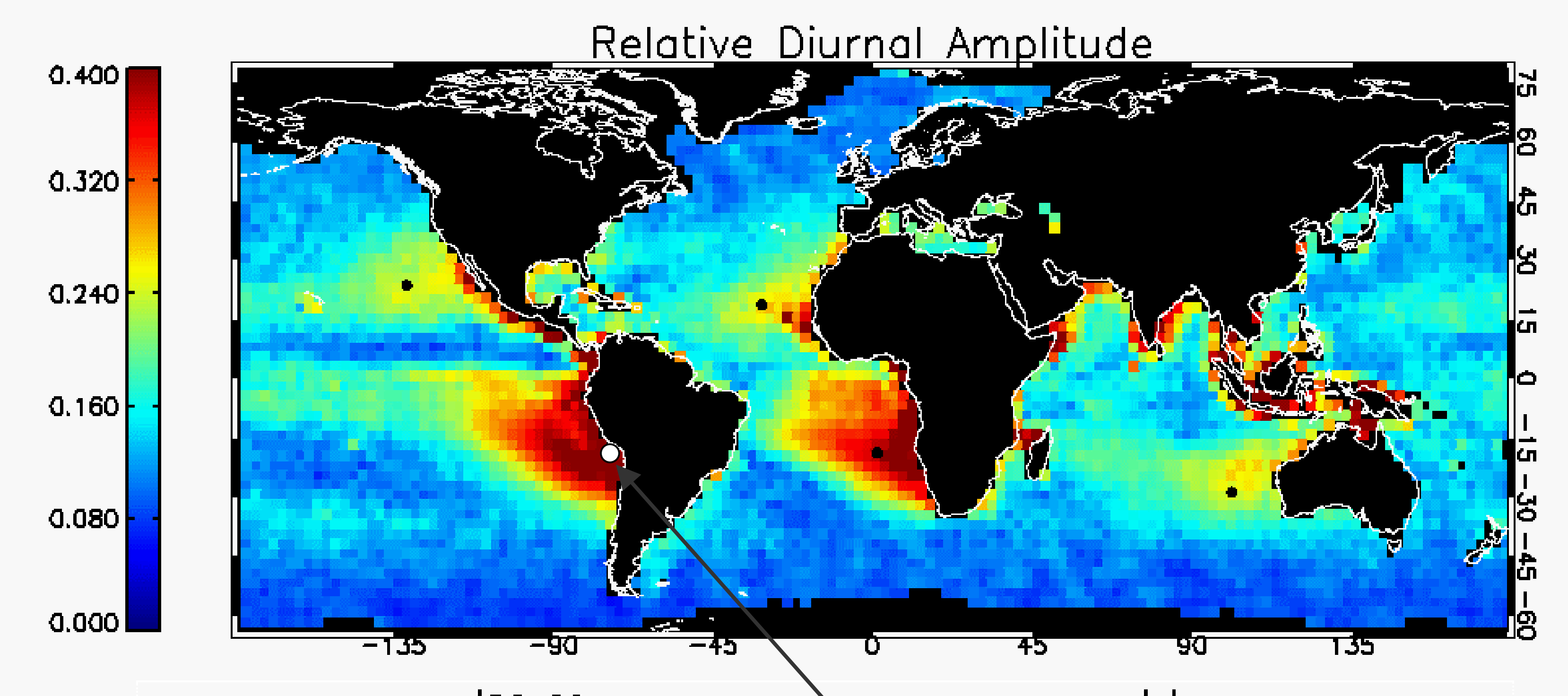
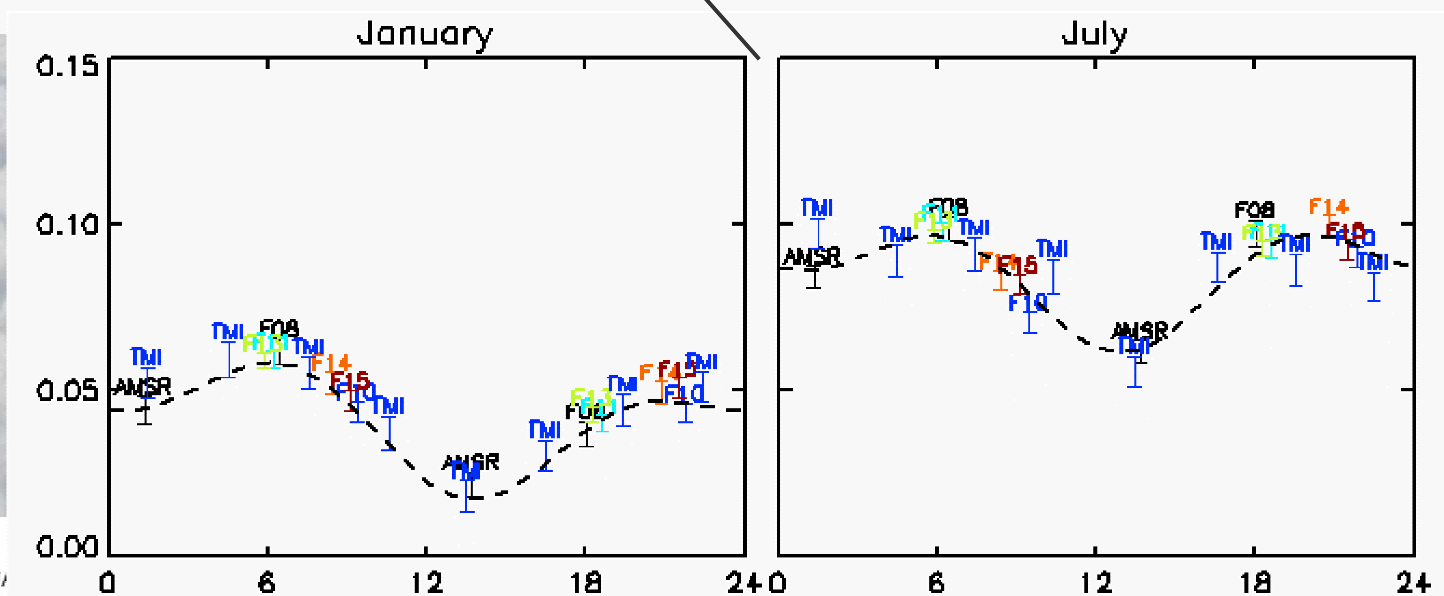


Liquid Water Path [kg/m²]



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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 susceptibility to aerosols

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

One alternative is to examine the diurnal cycle of cloud properties and its dependence on the aerosol (Meskhidze et al., 2009), 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

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

CONCLUSIONS

It is not feasible from satellite or any other measurement system to quantify the contribution of the meteorology to cloud macrophysical properties with the accuracy required to detect aerosol impacts.

Numerical simulations suggest that aerosols impacts on the cloud diurnal cycle might be detectable

The new generation of satellite data analysis shall therefore focus on the short term time evolution of the cloud systems in connection with aerosols, relying on the synergy between polar orbiting and geostationary satellite.

Thank you

for your attention