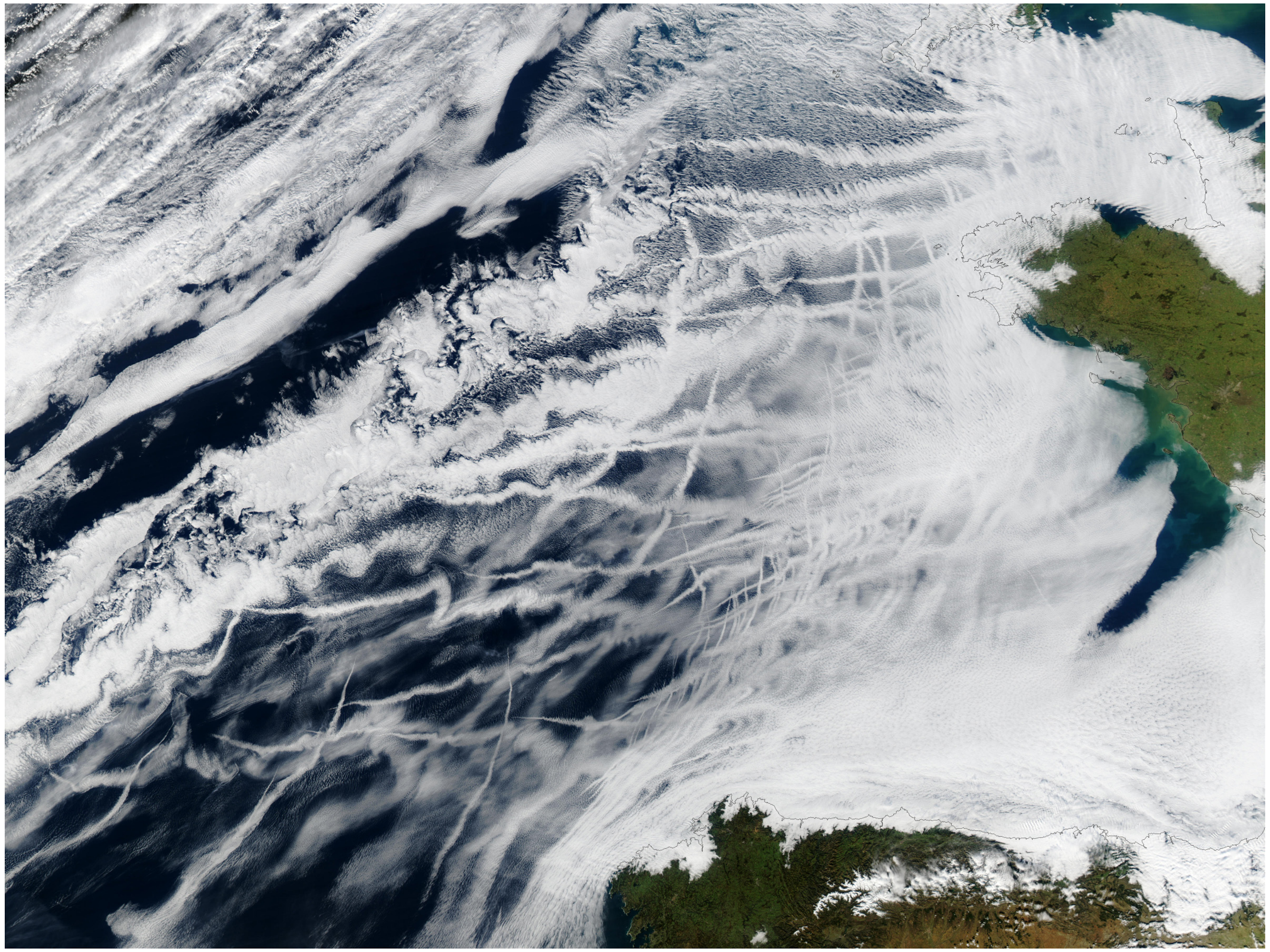
Quantifying aerosol-cloud interactions from satellite observations: opportunities and challenges



O. Sourdeval et al

Atelier LEFE; 20 Oct. 2020

Quantifying the RF_{aci} from satellites

- Due to their high temporal and spatial coverage, satellite observations are unique tools to study aerosol-cloud interactions (**ACI**).
- The impact of aerosols on the cloud albedo established by Twomey (1977) has been **quantified** from satellite observations from the past 2 decades.

Université de Lille

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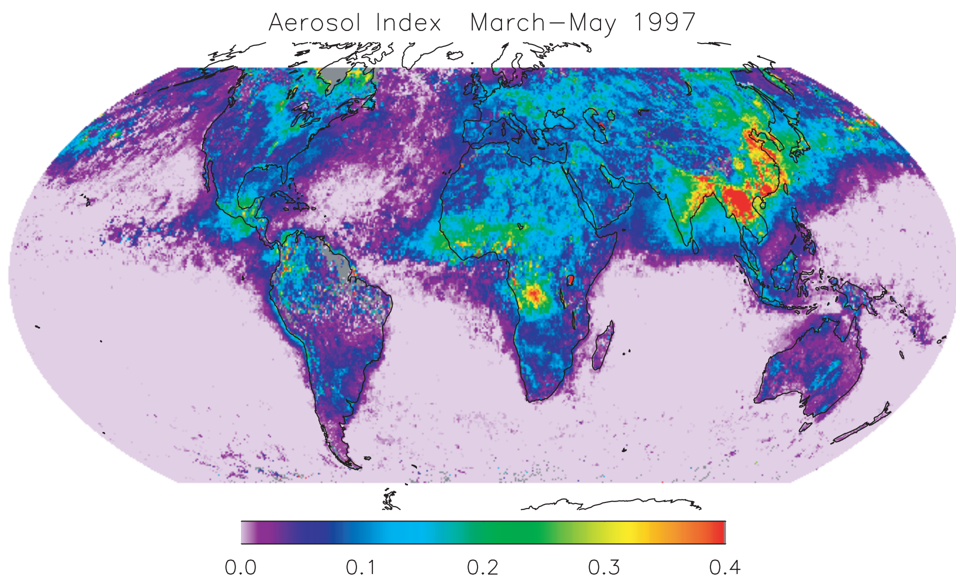

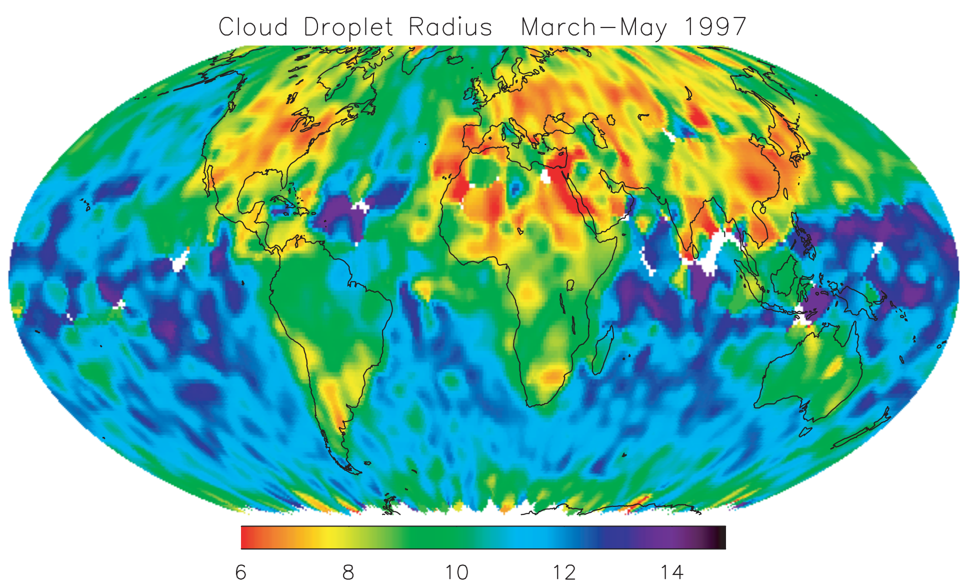

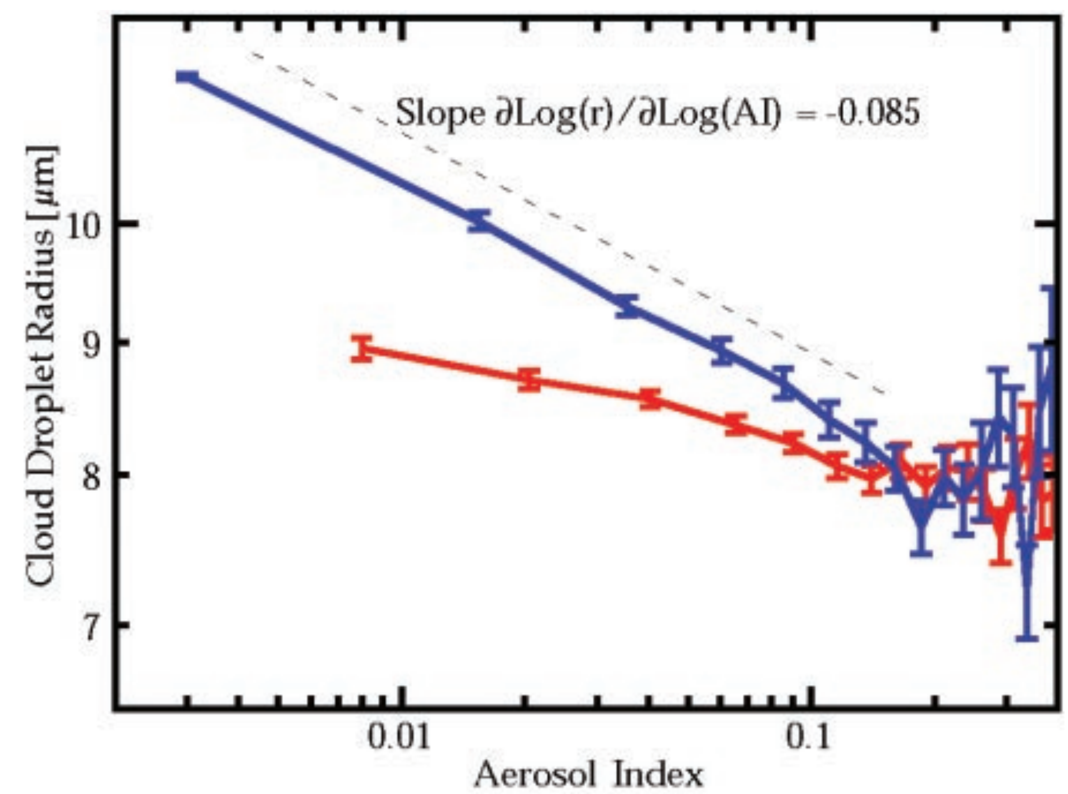

Quantifying the RF_{aci} from satellites

- The question of the **optimal cloud and aerosol properties** to study and quantify ACI from satellite has been long debated.
- Quantifying the radiative forcing related to aerosol-cloud interactions (**RF_{aci}**), or Twomey effect, requires a **cloud property X_{cld}** and **aerosol parameter** α.

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- Quantifying the radiative forcing related to aerosol-cloud interactions (**RF_{aci}**), or Twomey effect, requires a **cloud property X_{cld}** and **aerosol parameter** α.

- This translates to

Sensitivity of the cloud property X_{cld} to an aerosol parameter α

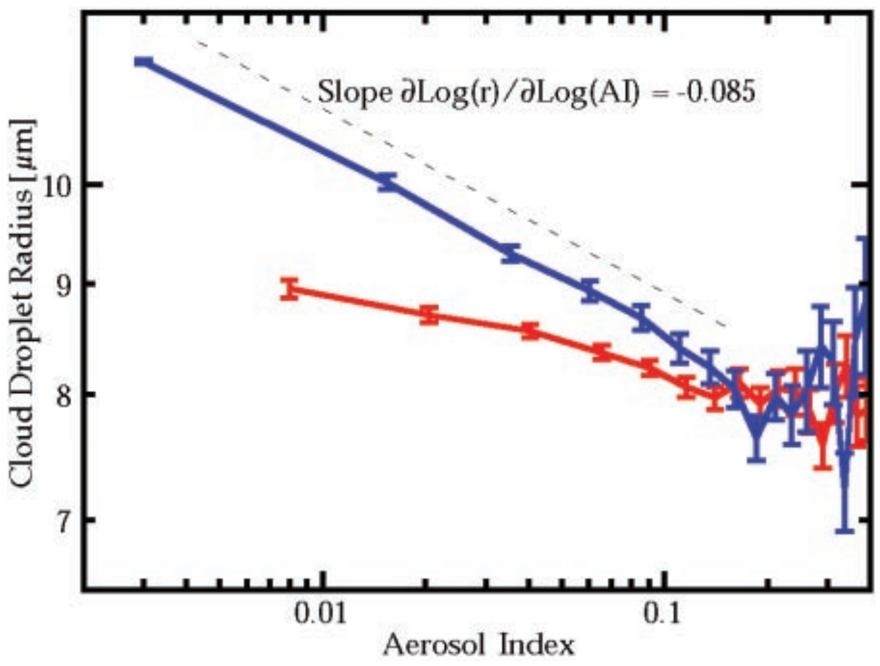
$$RF_{aci} = \frac{\partial R}{\partial X_{cld}} \frac{\partial X_{cld}}{\partial \alpha} \Delta\alpha$$

Aerosol **perturbation** (e.g. anthropogenic)

Sensitivity of the net radiative flux R to a cloud property X_{cld}. Obtained from **radiative transfer**.

Quantifying the RF_{aci} from satellites

- X_{cld} and α should both be obtained from satellite. Early studies used **available** satellite retrievals, such as the droplet effective radius (reff) and the aerosol optical depth (AOD) or index (AI).



Here, the slope provides directly the sensitivity of the effective radius to AI:

$$RF_{aci} = \frac{\partial R}{\partial r_{eff}} \frac{\partial r_{eff}}{\partial \mathrm{AI}} \Delta \mathrm{AI}$$

- These properties were then selected for convenience: they were related to radiative properties but not necessarily to the **cloud formation and growth processes**!

Aerosol and cloud properties for satellite ACI studies

- The **cloud droplet number concentration** (N_d) is most directly related to nucleation processes and changes in aerosol concentrations.
- N_d is typically **not available** in operational satellite products. Indirect N_d estimates were still obtained and used to quantify ACI

Quaas et al. (2005), ACP

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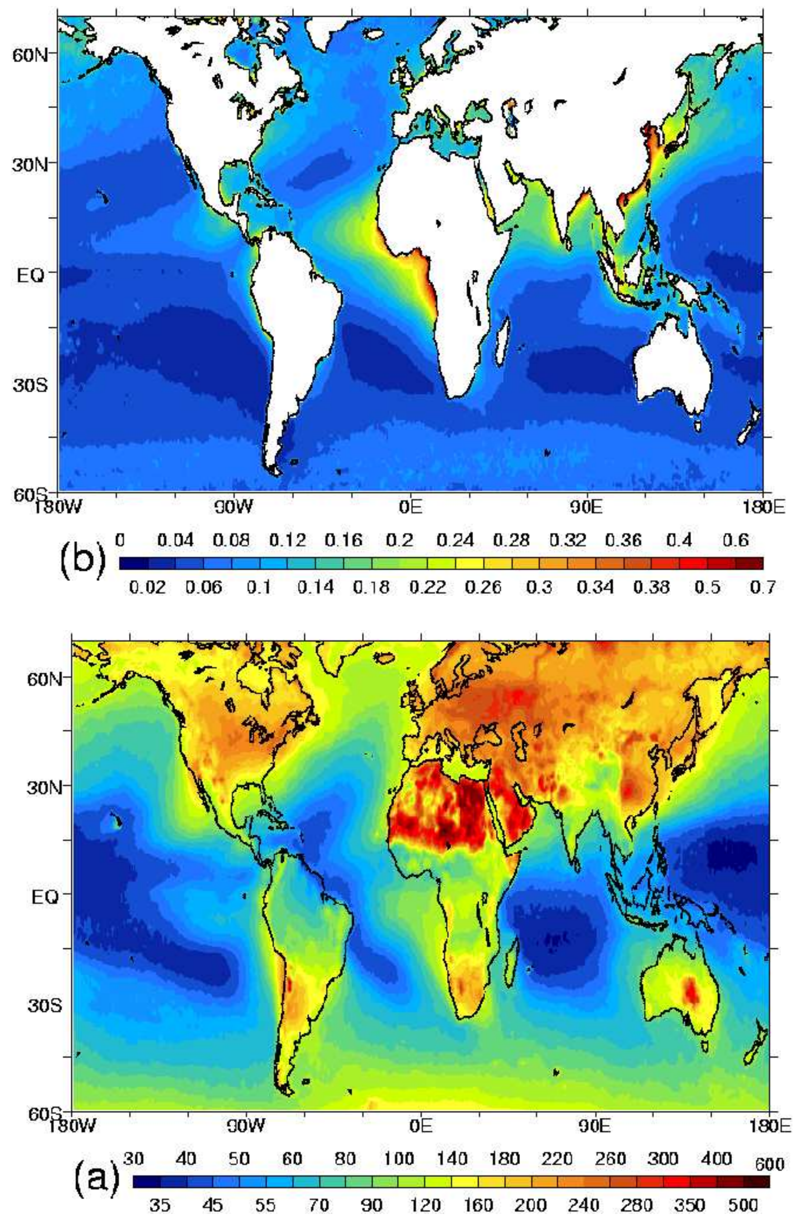
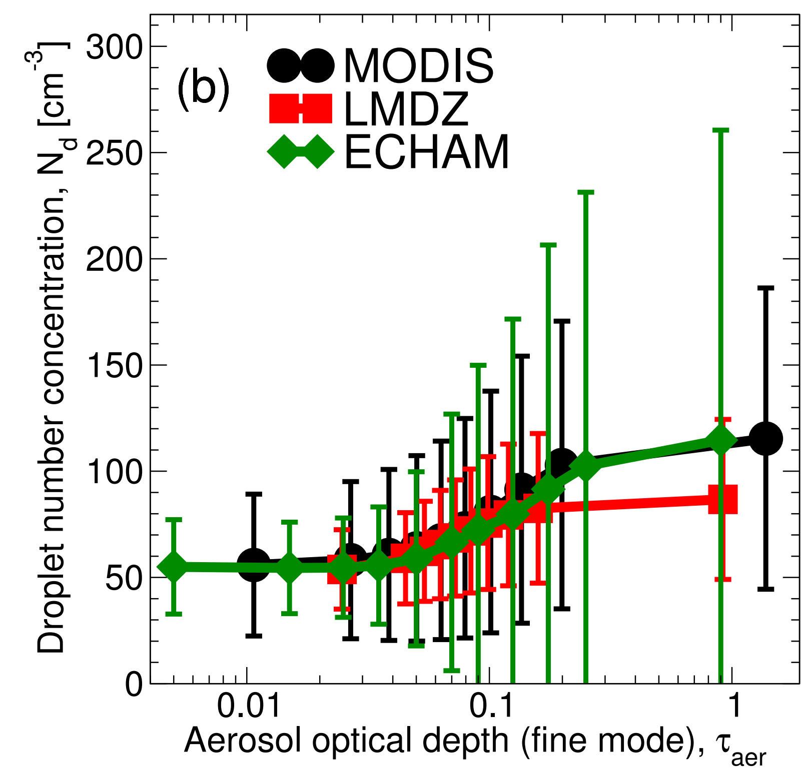


Fig. 1. Annual mean (five-year average) **(a)** cloud droplet number concentration (cm^{-3}) and **(b)** fine-mode aerosol optical depth (AODFM unitless) as derived from MODIS.



(MODIS in black, GCMs in red and green)

Quaas et al. (2005), ACP

Aerosol and cloud properties for satellite ACI studies

- This approach to estimate Nd is based on crude assumptions of **adiabatic growth** of droplets and of measurement of r_{eff} at **cloud top** (Brenguier et al, 2000).

- Under these assumptions, N_d can be related to historically retrieved cloud properties:

$$N_{\mathrm{d}} = \frac{\sqrt{5}}{2\pi k}\left(\frac{f_{\mathrm{ad}} c_w \tau_c}{Q_{\mathrm{ext}} \rho_w r_{\mathrm{eff}}}\right) \approx 1.37\, 10^{-5}\, \tau_c^{0.5}\, r_{\mathrm{eff}}^{-2.5}$$

k: shape parameter of the droplet size distribution
c_w: condensation rate
Q_{ext}: extinction coefficient
f_{ad}: adiabatic fraction
τ_c: cloud optical depth (COD)

- Grosvenor et al (2018; Rev. Geophys.) estimated that **errors** on such N_d retrievals are **at least 50%** for single-layer and homogeneous stratocumulus. They are largely unreliable in other conditions.

Aerosol and cloud properties for satellite ACI studies

- The aerosol parameter is also difficult to select. Ideally, it would be the **CCN number concentration**, however unavailable from satellite remote sensing only.
- Usual alternatives are the **AOD** and the **AI**, both radiative properties:
  - AI carries information on small particles, making it **well suited** to represent CCN! In wildly used products (e.g. MODIS) it is not available over land and considered uncertain over ocean.
  - AOD is a useful alternative, especially for the fine mode, but remains influence by the aerosol size.

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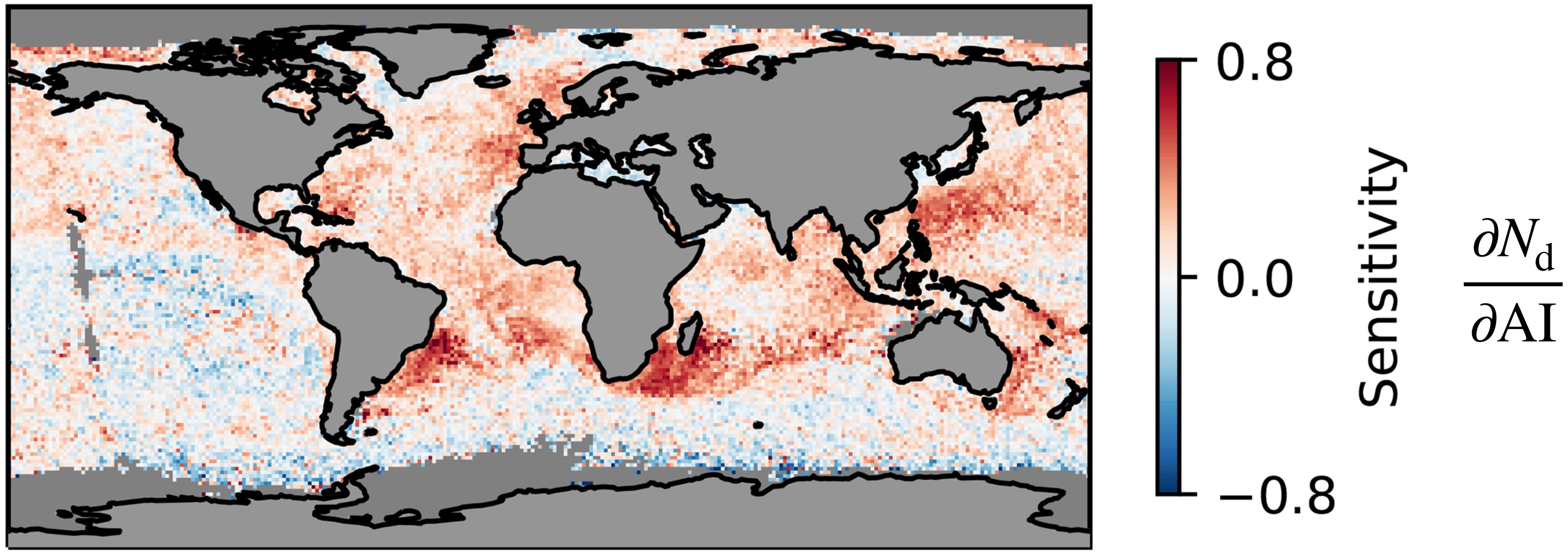
  - AOD is a useful alternative, especially for the fine mode, but remains influence by the aerosol size.
- Remains important issues for both parameters
  - No information on **speciation** and **hygroscopic growth**
  - They are **vertically integrated**, CCN are important at cloud-base.
  - Usually not exactly **co-located** with cloud properties

Aerosol and cloud properties for satellite ACI studies

- Methods combining satellite-derived Nd estimates with AI or AOD estimates constitute the core of approaches to quantify the RFaci.



- Other important issues impacting both cloud and aerosol properties are the **regime dependance** and the **aggregation scale**.

- Alternative methods are emerging, attempting to tackle these issues.

Quaas et al. (2020), ACP

Aerosol and cloud properties for satellite ACI studies

- For example, Hasekamp et al (2019) attempted an indirect satellite estimate of a **CCN burden** from polarimetric measurements.
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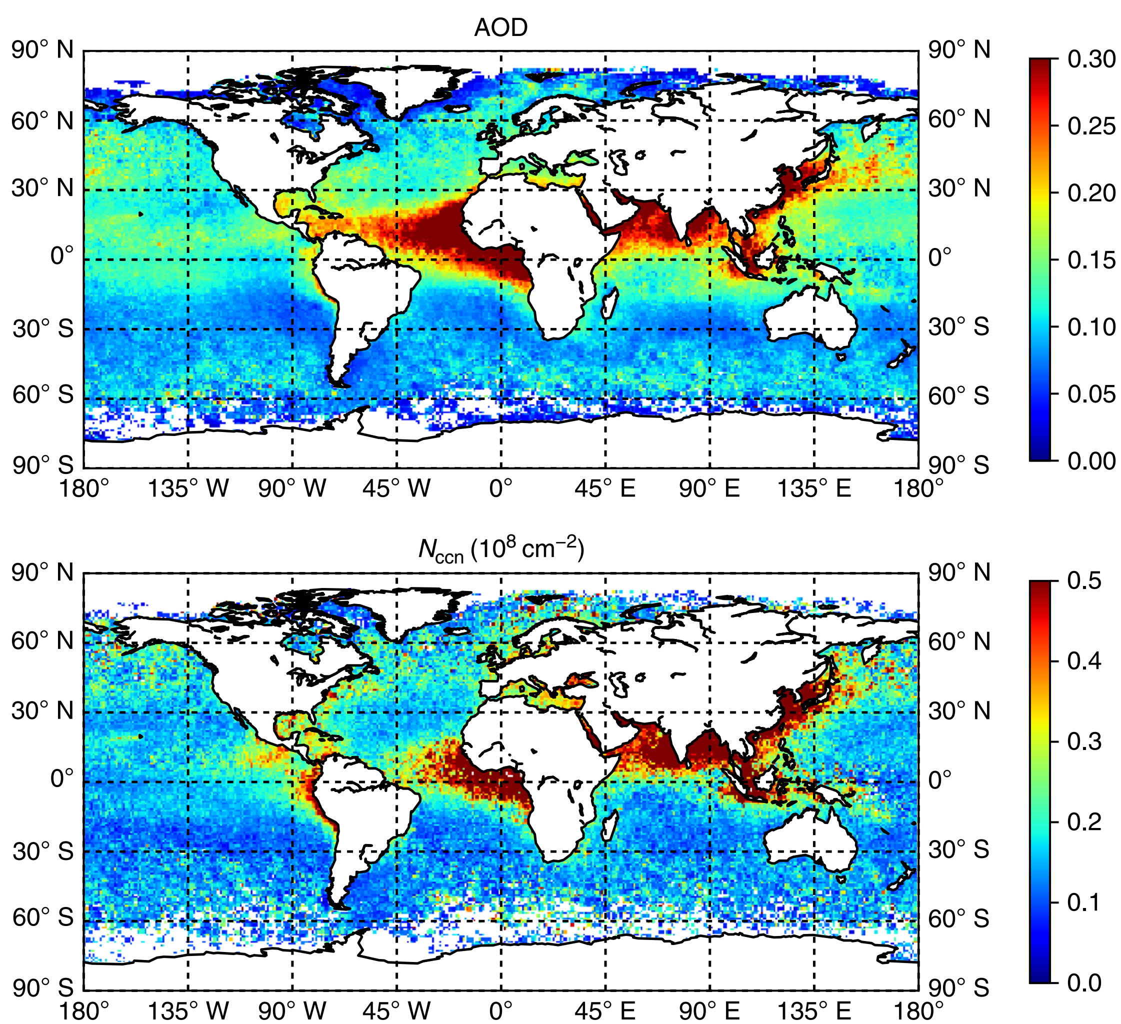
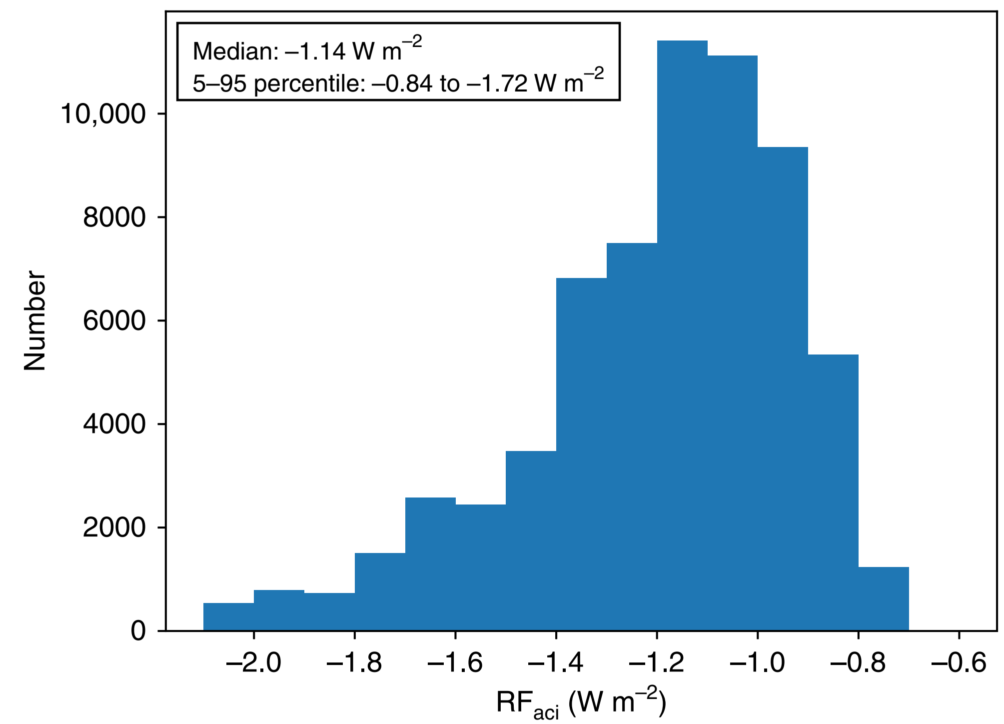


$$\frac{\partial N_d}{\partial N_{CCN}}$$



- They estimated a median RF_{aci} of **-0.33** W m^{-2} from AOD, of **-0.8** W m^{-2} from AI and of **-1.14** W m^{-2} from the CCN-burden!

Hasekamp et al. (2019), Science

The ERF_{aci} from satellite observations

- The RF_{aci} only represent a part of ACI (the better understood one!).
- **Rapid cloud adjustment** of the LWP, cloud fraction, lifetime, vertical extent and precipitation rate can also appear (among others).
- Combining adjustments and RF_{aci} leads to the effective radiative forcing, **ERF_{aci}.**

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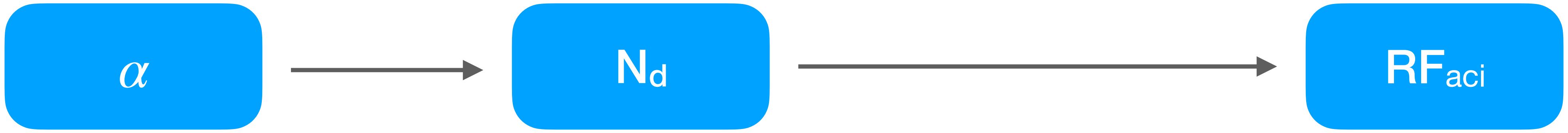

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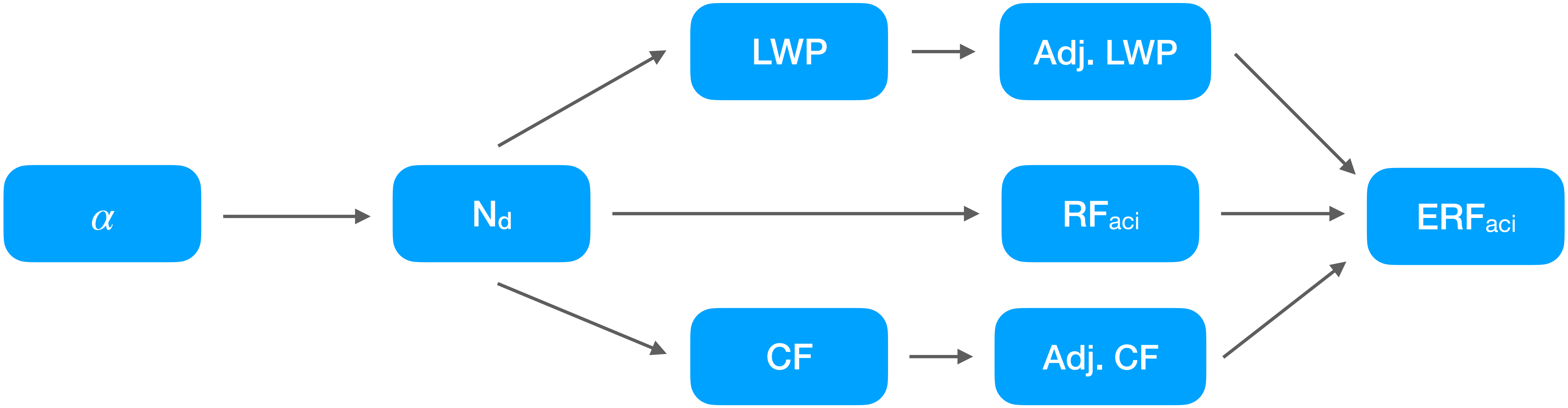

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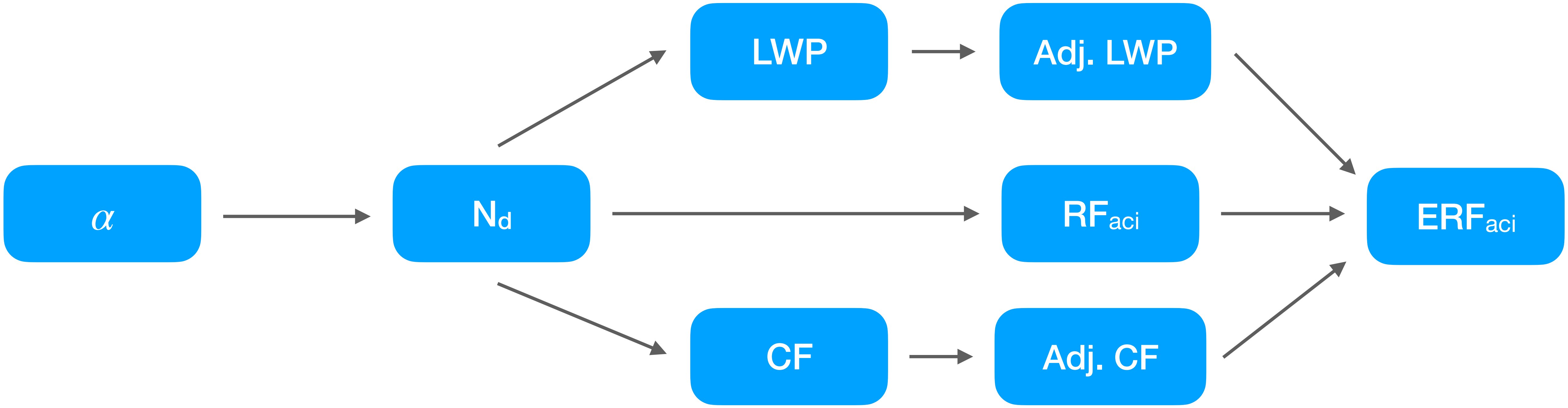

$$\mathrm{ERF_{aci}} = \left[\left(\frac{\partial R}{\partial N_\mathrm{d}} \right)_{\mathrm{LWP,CF}} + \frac{\partial R}{\partial \mathrm{LWP}} \frac{\partial \mathrm{LWP}}{\partial N_\mathrm{d}} + \frac{\partial R}{\partial \mathrm{CF}} \frac{\partial \mathrm{CF}}{\partial N_\mathrm{d}} \right] \frac{\partial N_\mathrm{d}}{\partial \alpha} \Delta\alpha$$

The ERF$_{aci}$ from satellite observations

- Adjustments are difficult to quantify using satellites because retrievals are **highly correlated** to each other and **confounding factors** are difficult to isolate.

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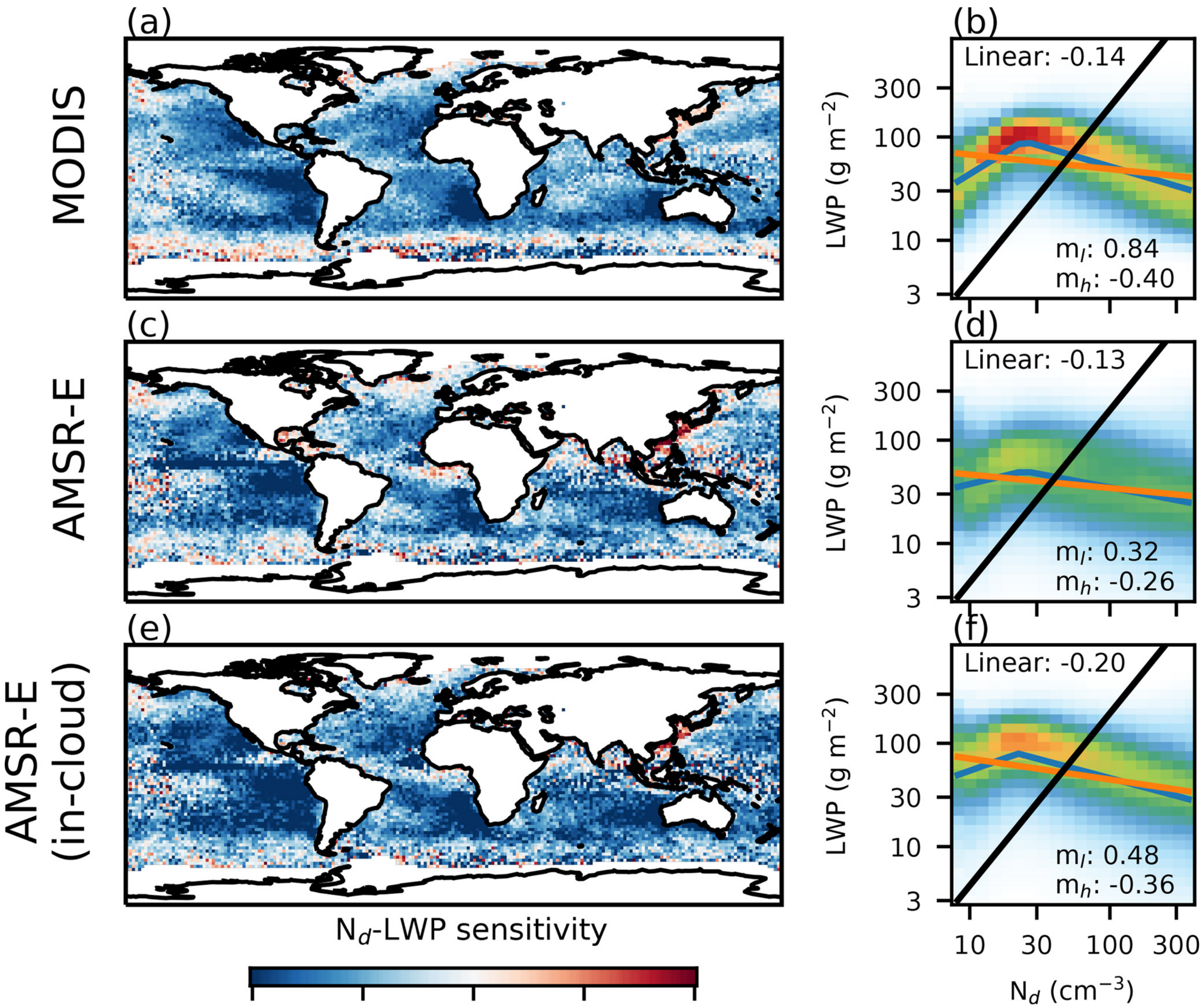
- LWP adjustments are still expected to be significant, as shown by Gryspeerdt et al:



- Global negative Nd-LWP relationship.
- Positive relationship for small Nd, consistent with precipitation suppression and cloud invigoration.
- The Nd-LWP relation appears weaker on natural experiments, setting a bound to the adjustments.
- LWP adjustments can offset the RFaci by **60%**.
- **Still very uncertain!**

Natural experiments to the rescue

- Natural experiments are becoming increasingly useful to provide a controlled setup to better understand cloud adjustments.

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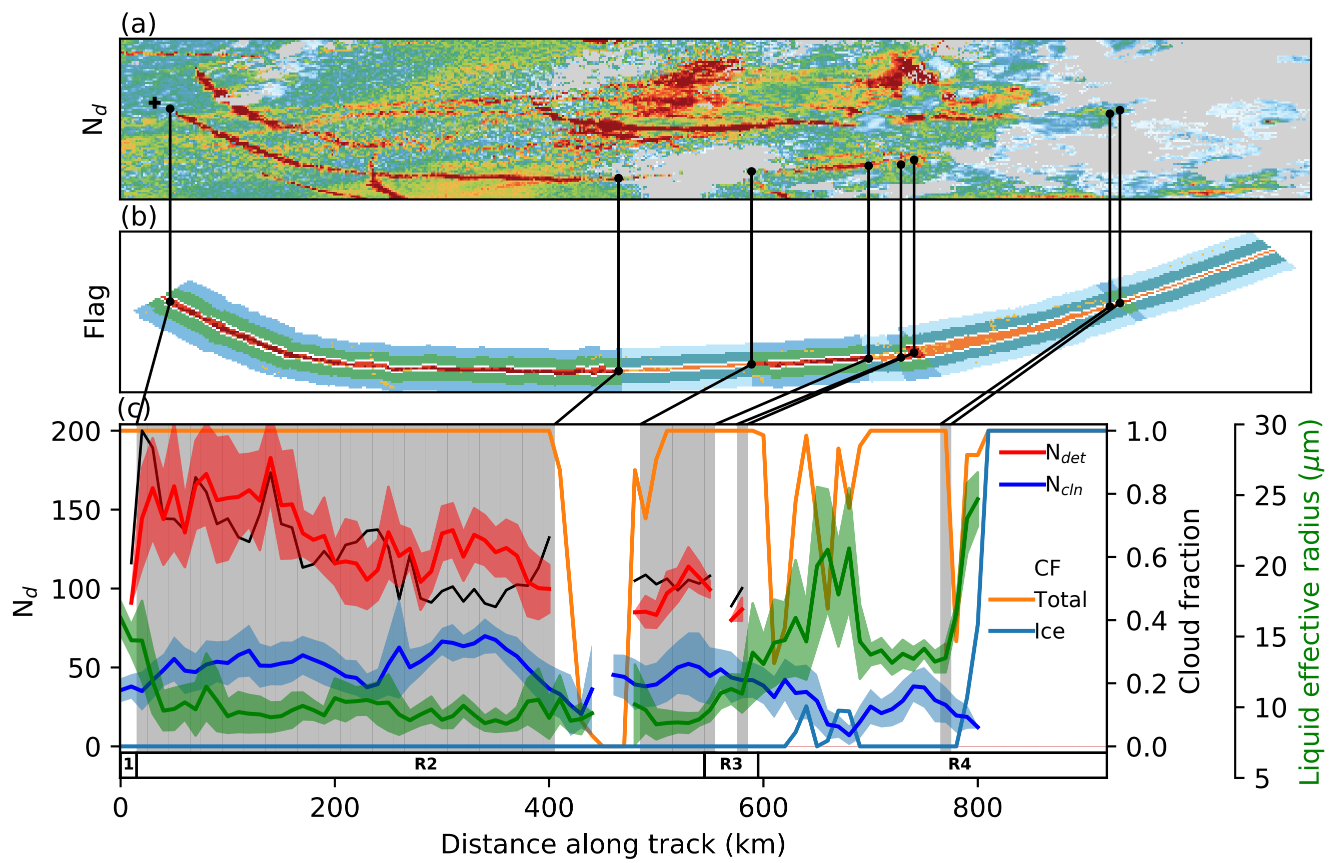
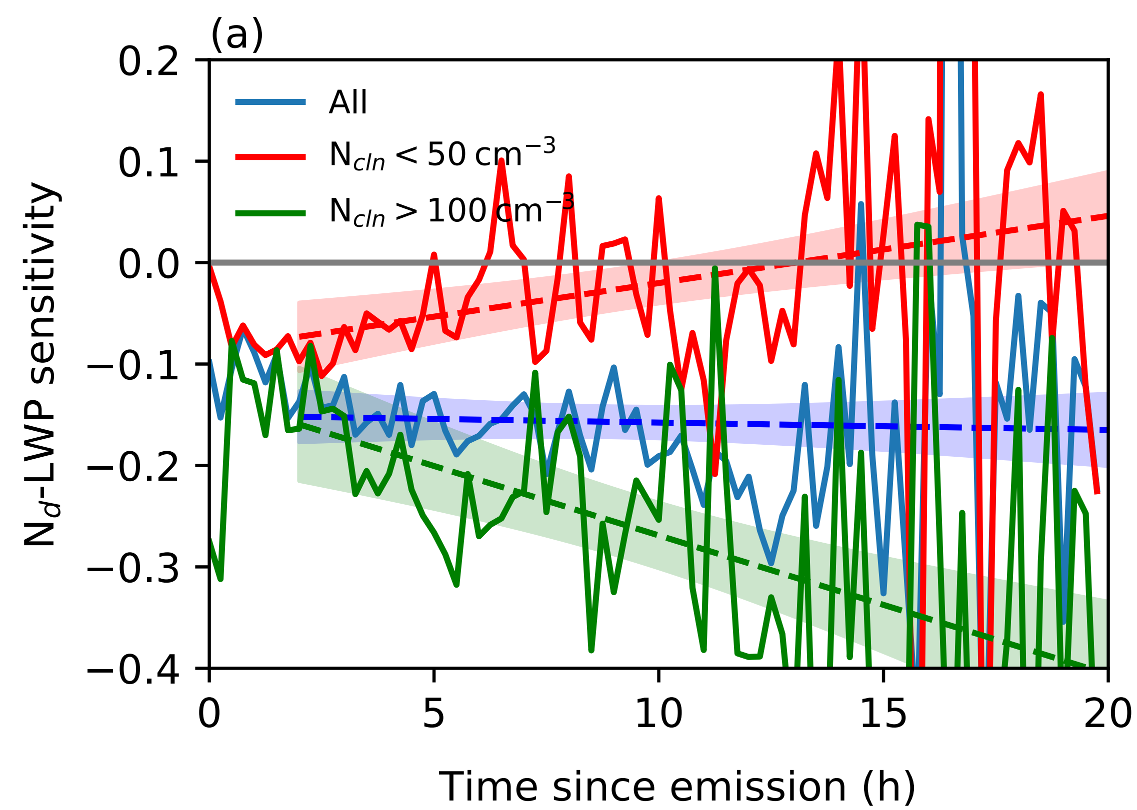
- For instance, following the previous analysis, **ship tracks** can be used to quantify the time scale of LWP adjustments





- This studies demonstrates, using natural experiments, the importance of considering **time scales** when accounting for ACI.

The challenge of ice and mixed-phase clouds

- A strong emphasis in ACI studies from satellite observation is put on **liquid clouds**!
- The ERF_{aci} associated with **ice** and **mixed-phase** clouds remains largely **unknown**, largely due to a lack of adapted cloud properties.

The challenge of ice and mixed-phase clouds

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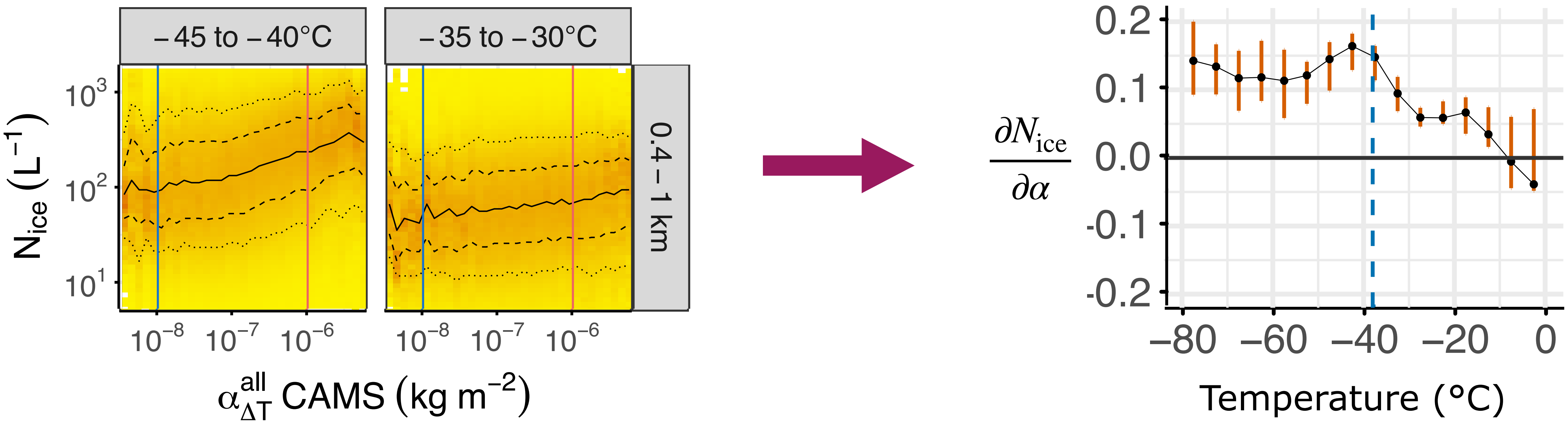
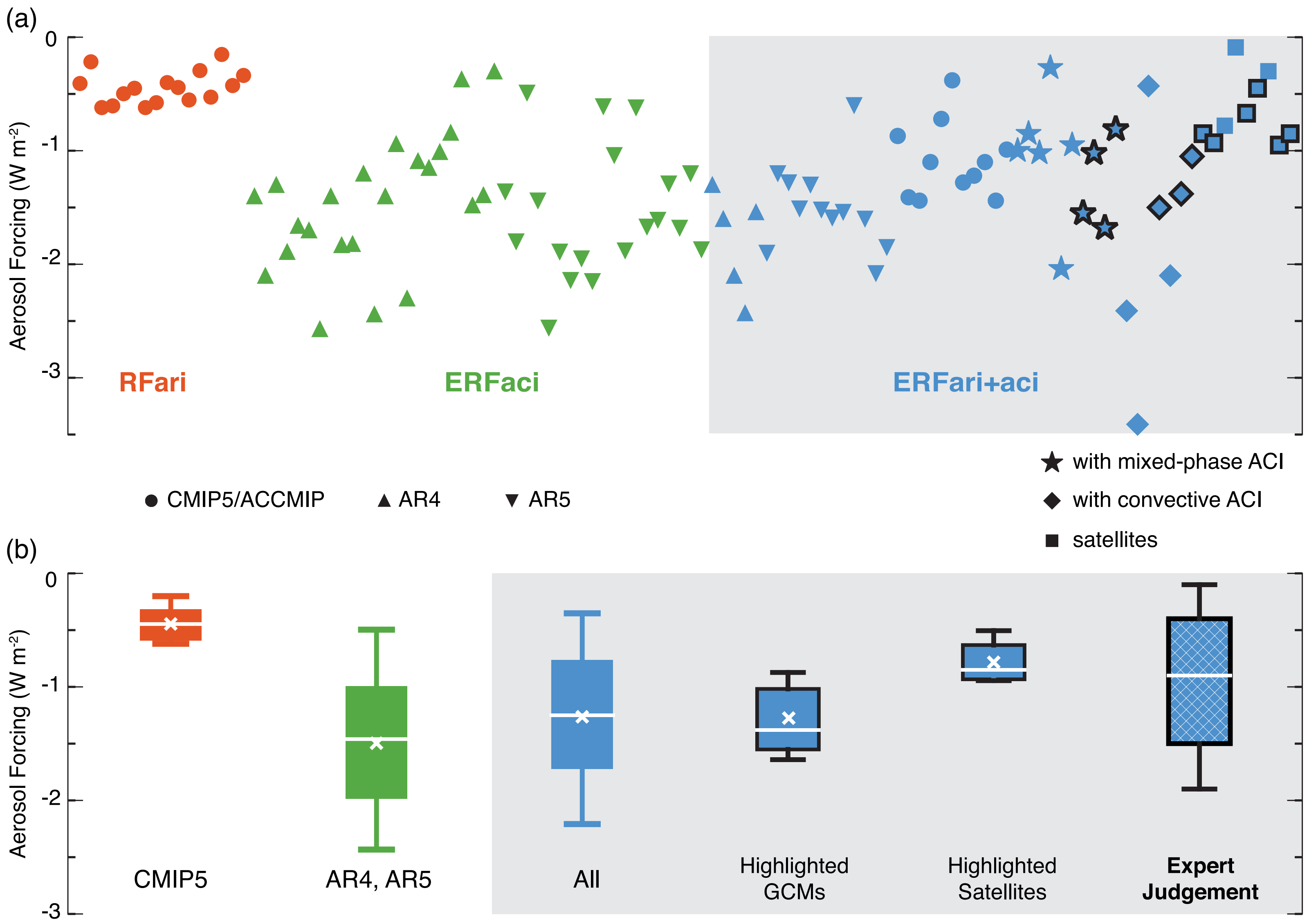
- The ERF_{aci} associated with **ice** and **mixed-phase** clouds remains largely **unknown**, largely due to a lack of adapted cloud properties.
- However, emergent methods to retrieve e.g. the **ice crystal number concentration** from satellite observations start allowing for similar studies!



Sourdeval et al (in prep)

Inconsistencies between observations and modelling

- ERF_{aci} estimates remain largely **inconsistent** between satellite observations and modelling.



- It is not yet clear if satellites provide better estimations, considering the high attached uncertainties and difficulties to assess adjustments.

Boucher et al (2013), IPCC

Inconsistencies between observations and modelling

- There are attempts to reconcile modelling and satellite values of ERFaci, especially by making their **computation** more similar (e.g. Gryspeerdt et al, 2020b; ACP)
- Other studies show **inherent limitations** to current purely satellite approaches, such as the coincidence between aerosol and cloud properties.

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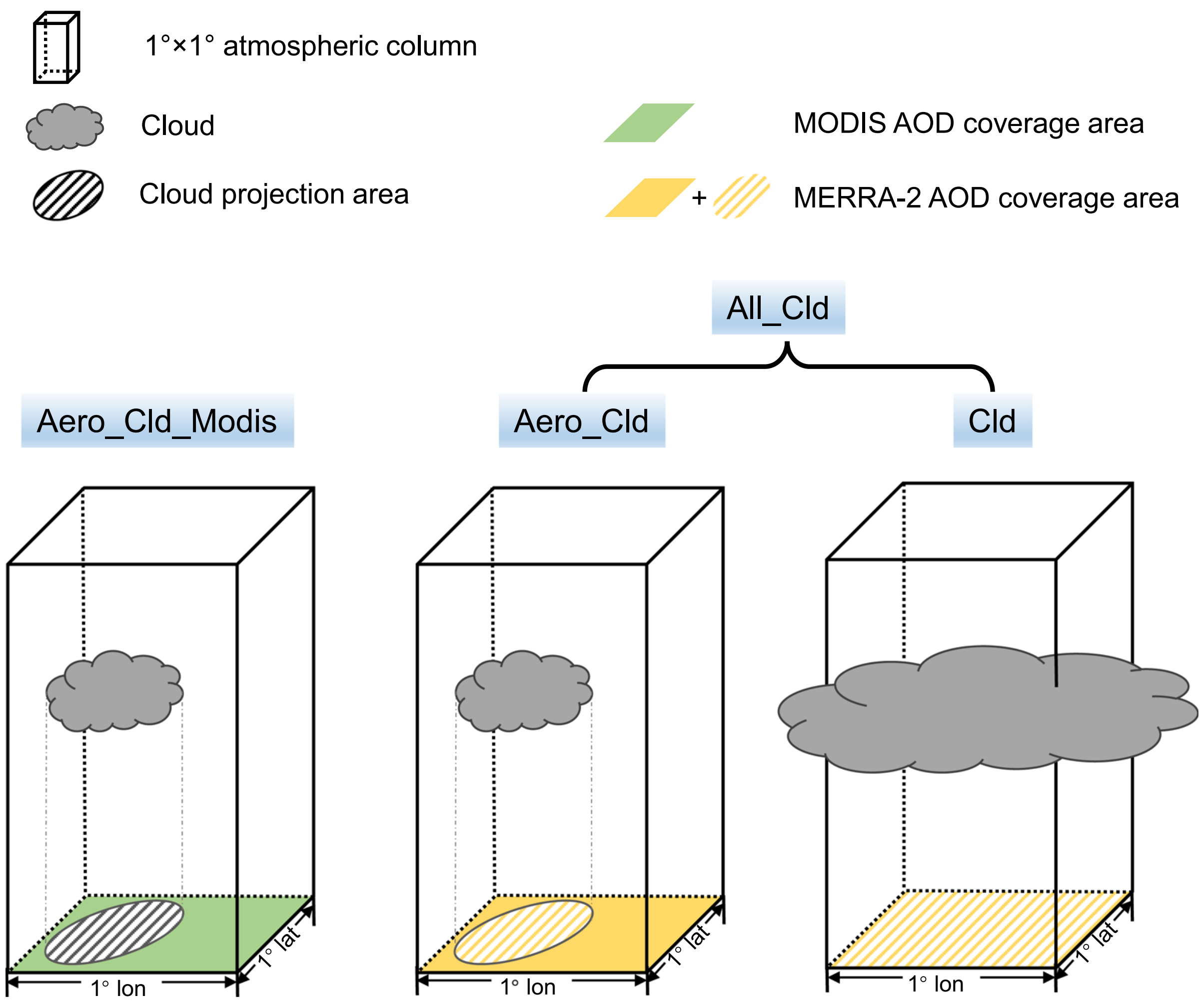

- Xia et al (2021) quantified the bias in RFaci due to sampling, by reproducing it in reanalyses data.
- They find that missed clouds typically exert a strong cooling effect
- Accounting for this bias, **RFaci increases by 55%**, making it more compatible with modelling estimates

Summary

- RFaci usually estimated from satellite using the cloud **droplet number concentration** and either the **aerosol optical depth** or **index**
- Large **uncertainties on N_d** still exist and urgently need to be reduced
- **Aerosol retrievals** are uncertain, not always adapted (hygroscopicity issue) and can be difficult to use co-jointly because of co-location problems.
- **Adjustments** are difficult to quantify using satellite observations only but progress has been made, especially using natural laboratories
- Not enough study on the ACI associated with **ice** and **mixed-phase** clouds
- **Observations and modelling** ERF_{aci} estimates remain largely inconsistent. We need to work towards unified and more robust methods to quantify ACI.