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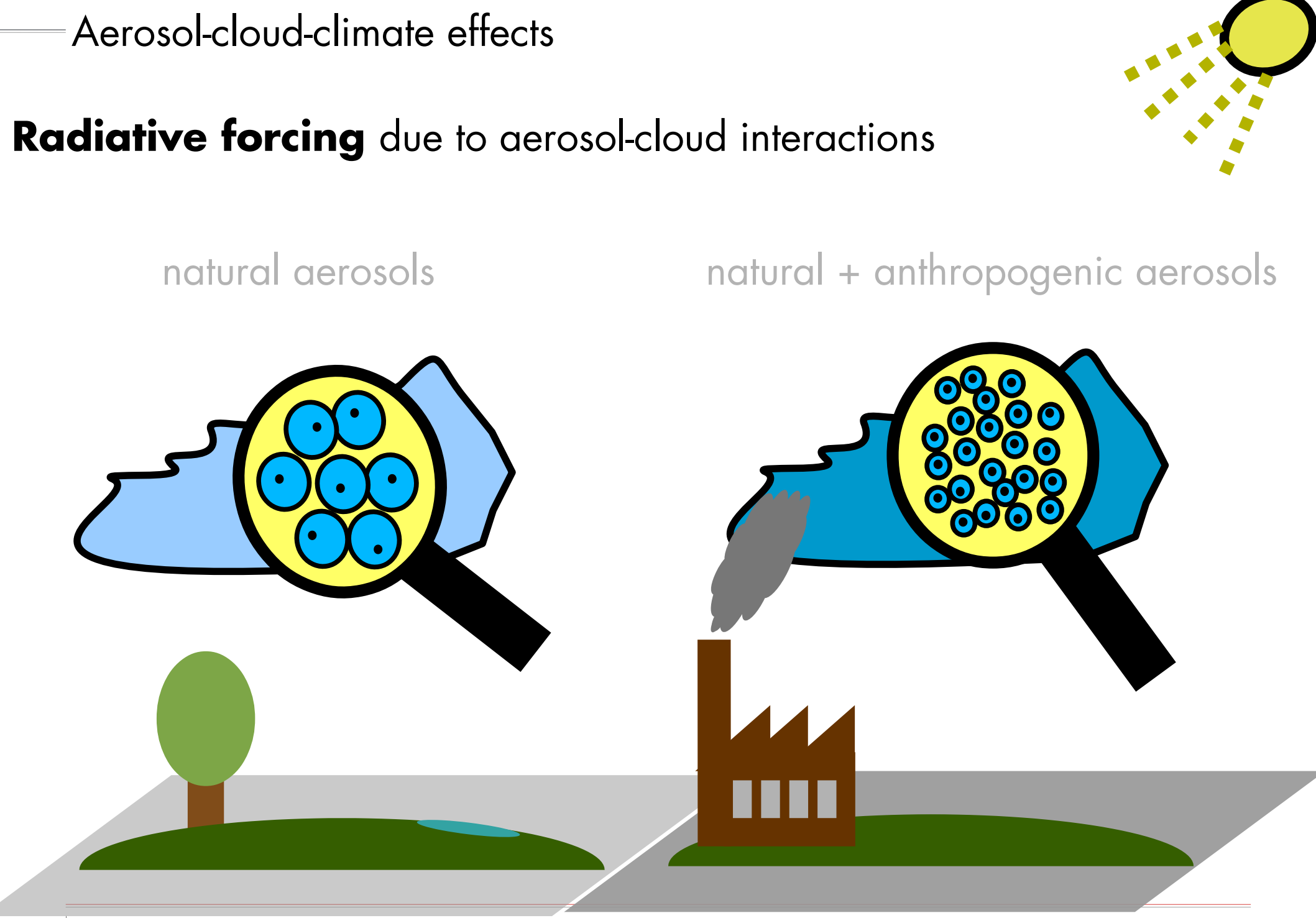
Tailoring satellite retrievals towards assessment of clouds and aerosol-cloud interactions

Johannes Quaas | http://research.uni-leipzig.de/climate

With Ed Gryspeerdt (now Imperial College London), Johannes Mülmenstädt, Marc Salzmann, and Odran Sourdeval (now Univ. Lille)

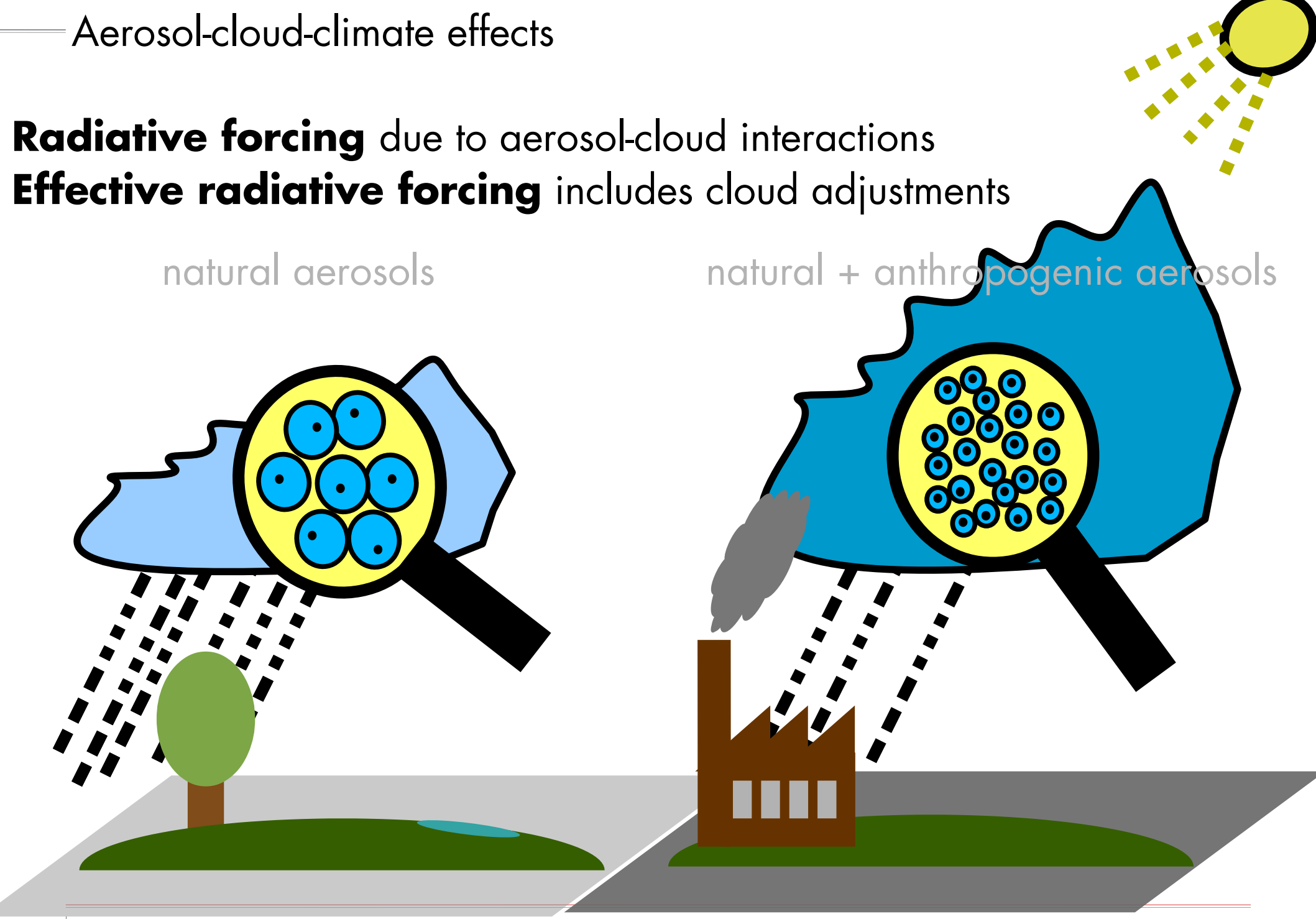
as well as Nicolas Bellouin and Velle Toll (Univ. Reading)

Radiative forcing due to aerosol-cloud interactions



Aerosol-cloud-climate effects

Radiative forcing due to aerosol-cloud interactions
Effective radiative forcing includes cloud adjustments



Aerosol-cloud-climate effects

Radiative forcing | Radiative perturbation | Cloud particles | Aerosol-perturbation

$$\mathrm{ERF_{aci}} = \frac{\mathrm{d}R}{\mathrm{d}\ln N_\mathrm{c}} \cdot \frac{\mathrm{d}\ln N_\mathrm{c}}{\mathrm{d}\ln \alpha} \cdot \Delta \ln \alpha_\mathrm{ant}$$

Quaas et al., J. Geophys. Res. 2008; Bellouin, Quaas, et al., submitted to Rev. Geophys.

Aerosol-cloud-climate effects

Radiative forcing | Radiative perturbation | Cloud particles | Aerosol-perturbation

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$$= \underbrace{\frac{\partial R}{\partial \ln N_\mathrm{c}}} + \underbrace{\frac{\partial R}{\partial f}\frac{\mathrm{d}f}{\mathrm{d}\ln N_\mathrm{c}} + \frac{\partial R}{\partial L}\frac{\mathrm{d}L}{\mathrm{d}\ln N_\mathrm{c}} + \frac{\partial R}{\partial T_\mathrm{top}}\frac{\mathrm{d}T_\mathrm{top}}{\mathrm{d}\ln N_\mathrm{c}}}$$

Radiative forcing **$\mathrm{RF_{aci}}$**

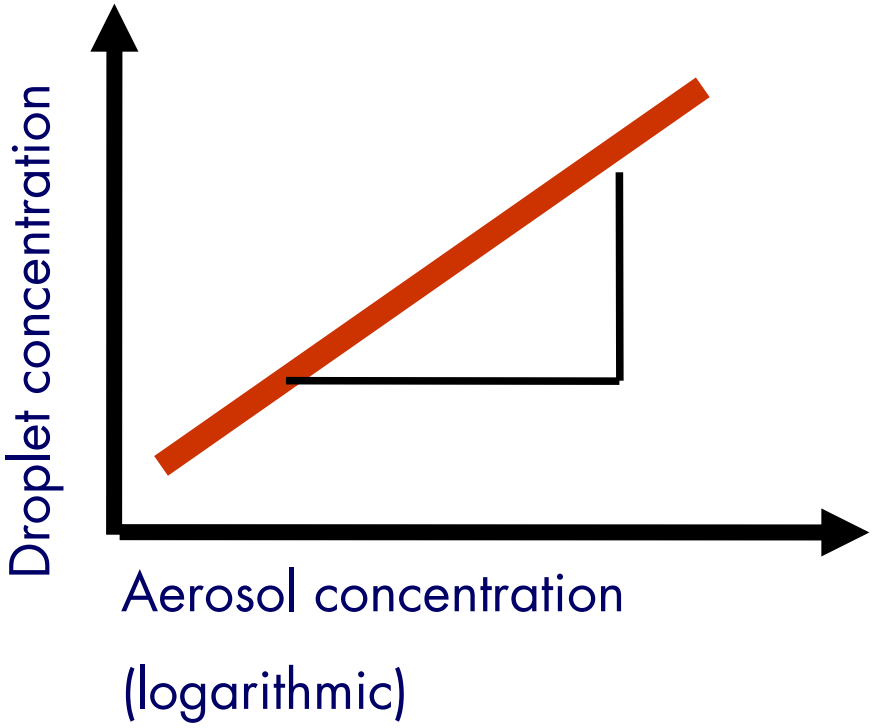
(1st effect)

Effective radiative forcing **$\mathrm{ERF_{aci}}$**
(Adjustments / 2nd effect)

Cloud fraction ***f***, Cloud water path ***L***, Cloud top temperature $\boldsymbol{T_\mathrm{top}}$

Quaas et al., J. Geophys. Res. 2008; Bellouin, Quaas, et al., submitted to Rev. Geophys.

Aerosol-cloud-interaction metric



Slope of regression as metric

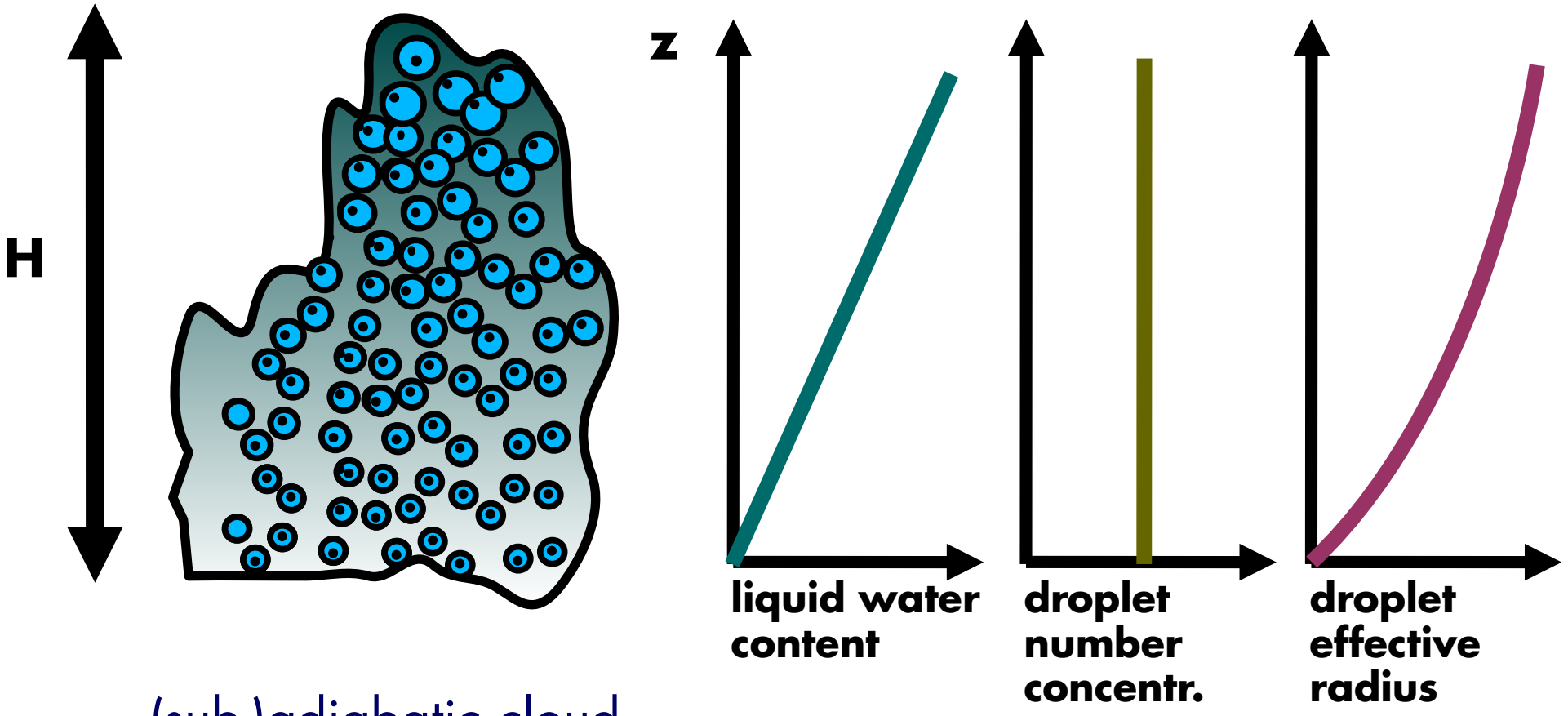
$$\frac{\mathrm{d}\ln N_\mathrm{d}}{\mathrm{d}\alpha} \approx \frac{\Delta N_\mathrm{d}/N_\mathrm{d}}{\Delta\tau_a/\tau_a}$$

N_d – Cloud droplet number concentration

τ_a – Aerosol optical depth

Klein and Hall, CCCR 2015; Feingold et al., Geophys. Res. Lett. 2003

Droplet number concentration



(sub-)adiabatic cloud

Operational satellite retrievals: Optical Depth (τ_c) and effective radius at cloud top, r_e

Brenguier et al., J. Atmos. Sci., 2000; Quaas et al., Atmos. Chem. Phys, 2006

Droplet number from satellites

k – droplet spectrum dispersion

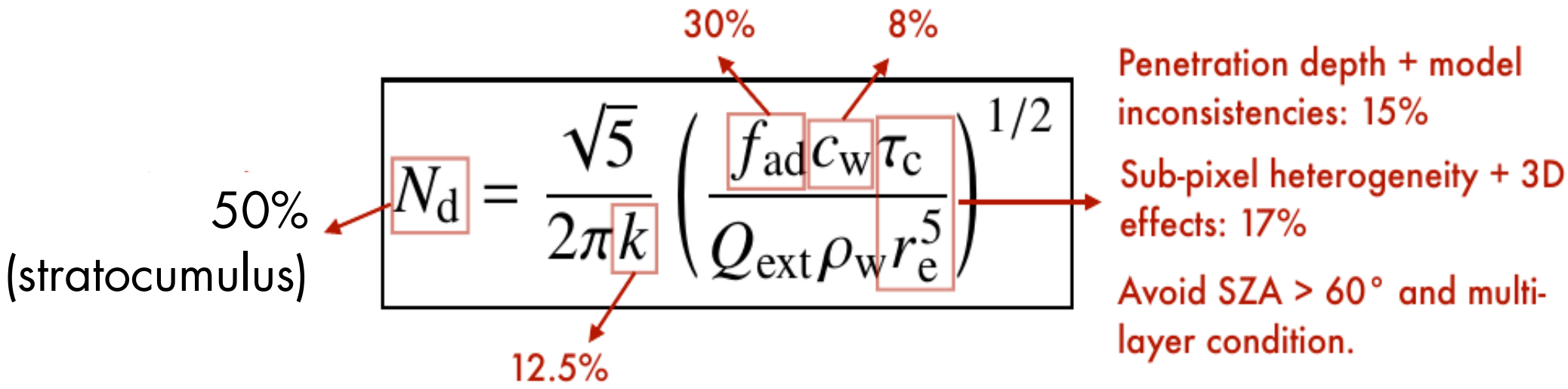
f_{ad} – sub-adiabatic fraction

c_w – adiabatic condensation rate

Q_{ext} = 2 extinction coefficient

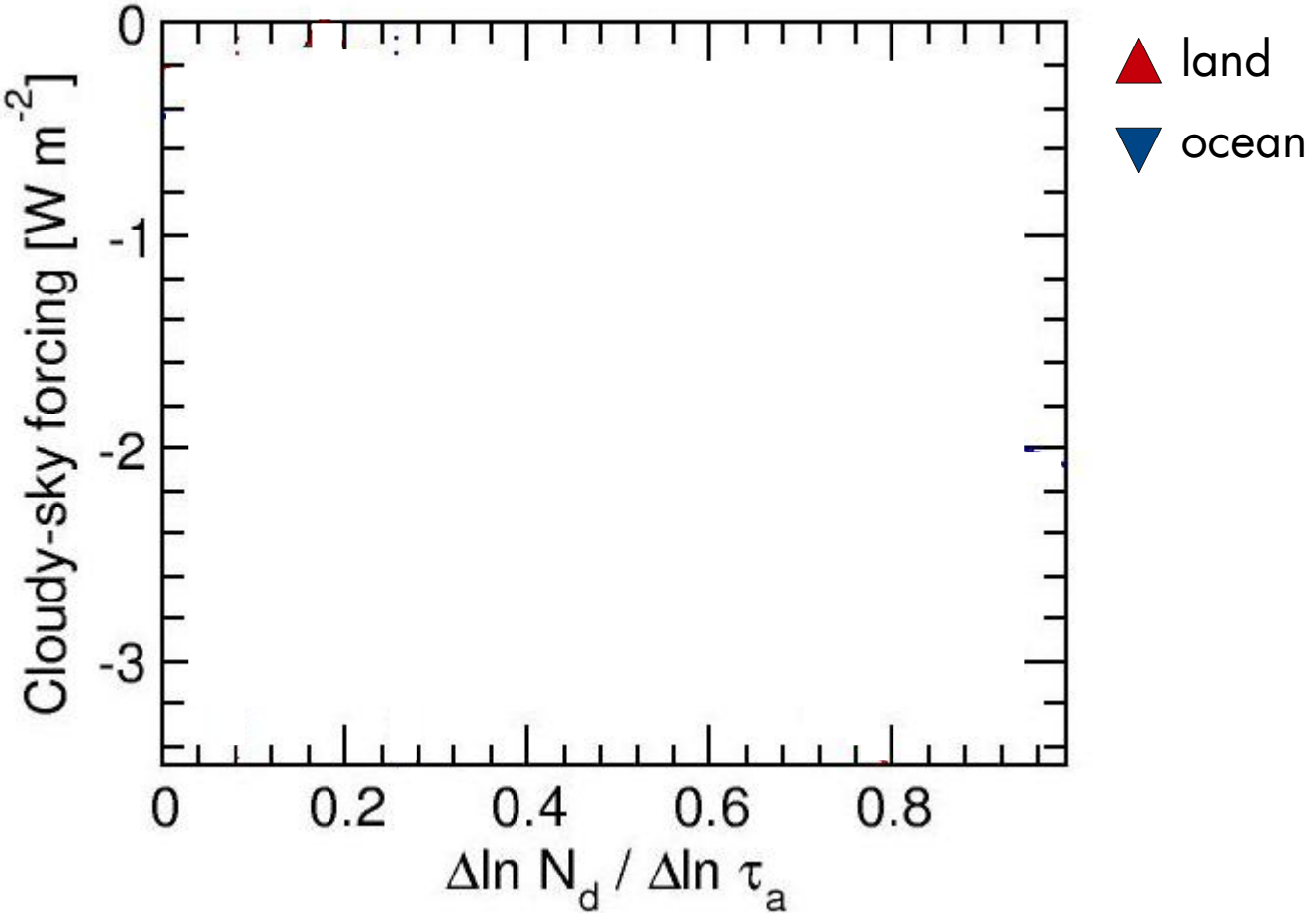
ρ_w = 1000 kg m^{-3} density of water

Final estimation of the error



Grosvenor et al. Rev. Geophys. 2018

ACI metric relevant to constrain forcing



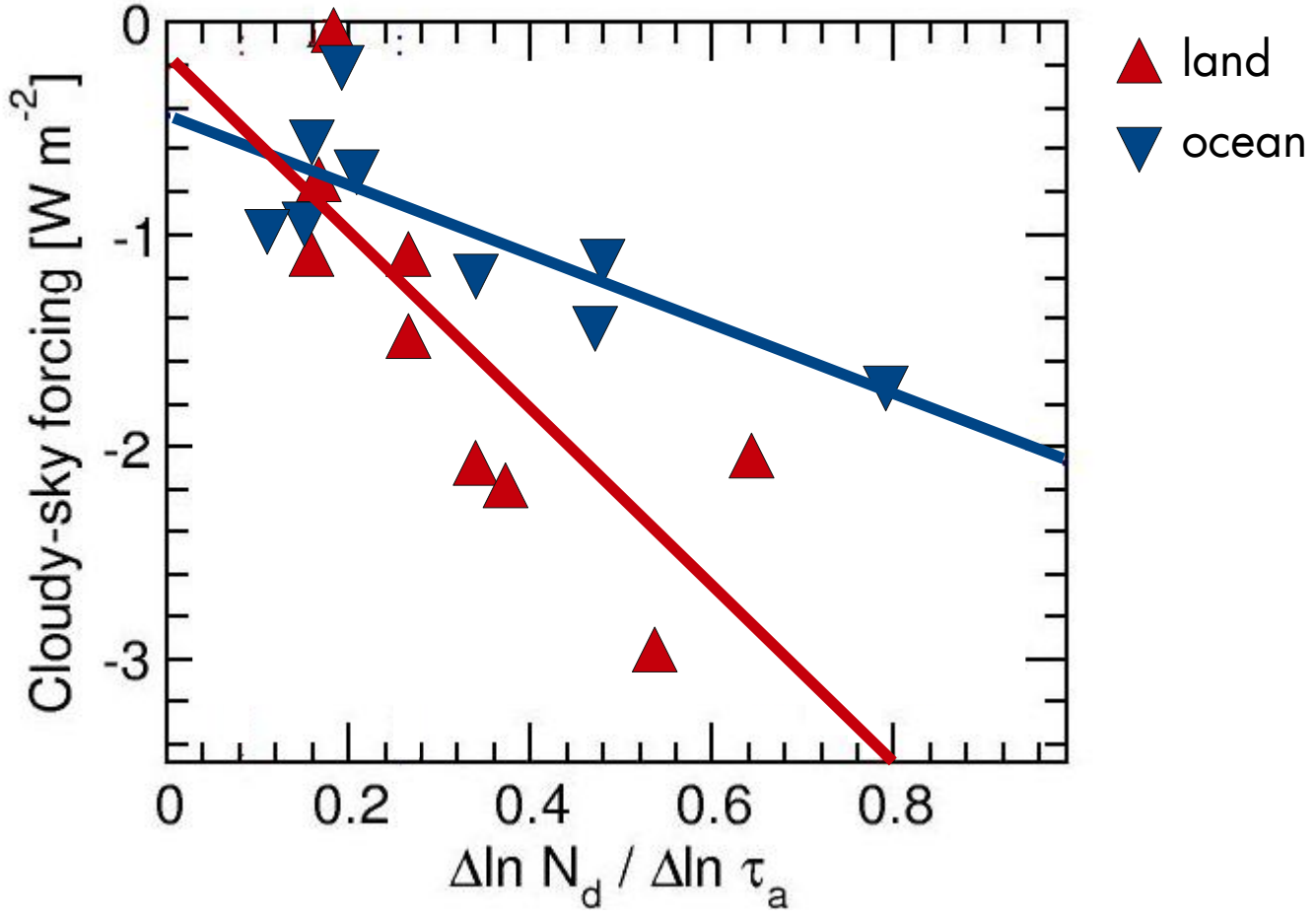
Climate models
AEROCOM initiative

Cloudy-sky effective radiative forcing

vs. ACI metric

Quaas et al., Atmos. Chem. Phys. 2009

ACI metric relevant to constrain forcing



r = -0.79

r = -0.80

Climate models
AEROCOM initiative

Cloudy-sky effective radiative forcing

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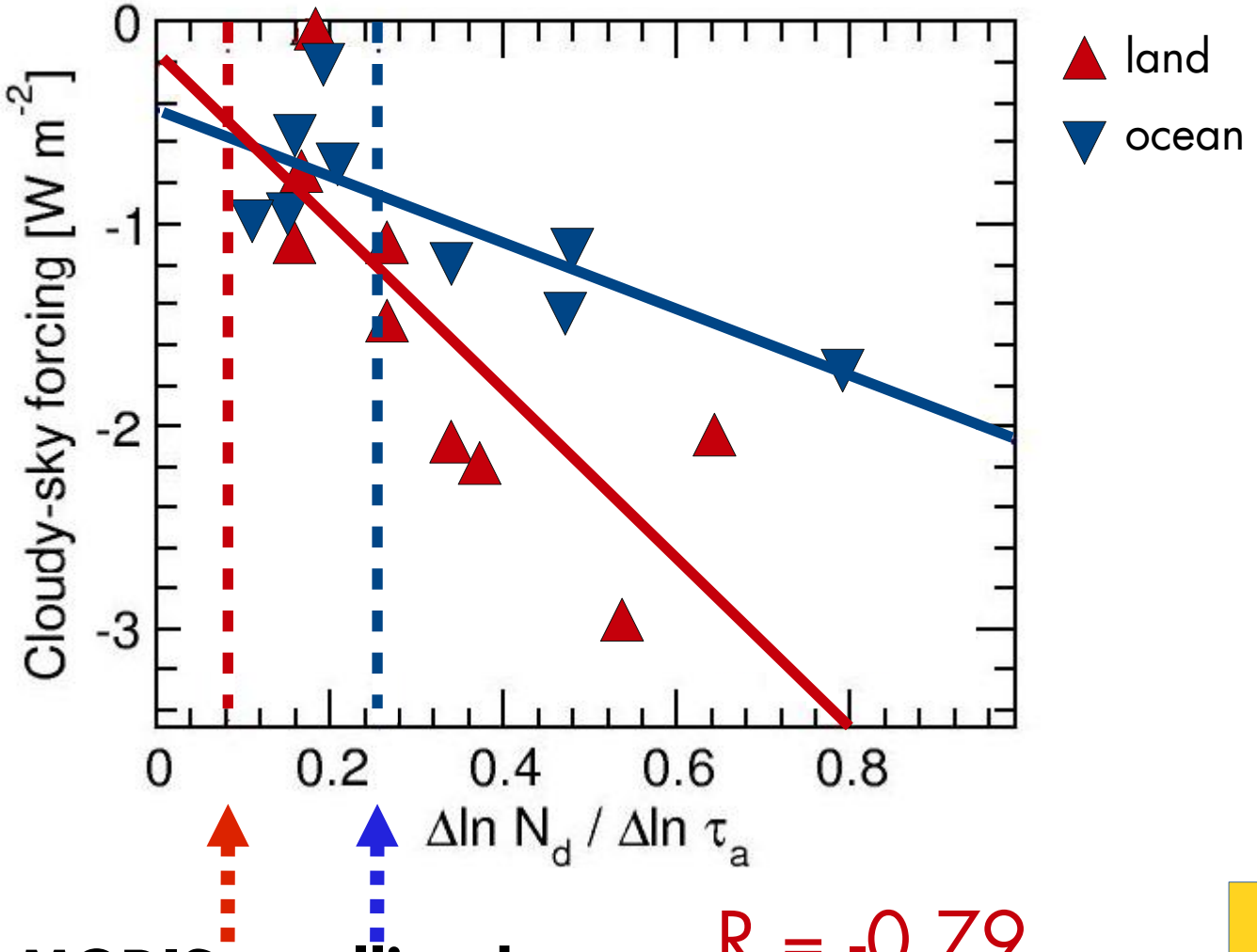
ACI metric relevant to constrain forcing



MODIS satellite data
Land and ocean

R = -0.79
R = -0.80

Climate models
AEROCOM initiative

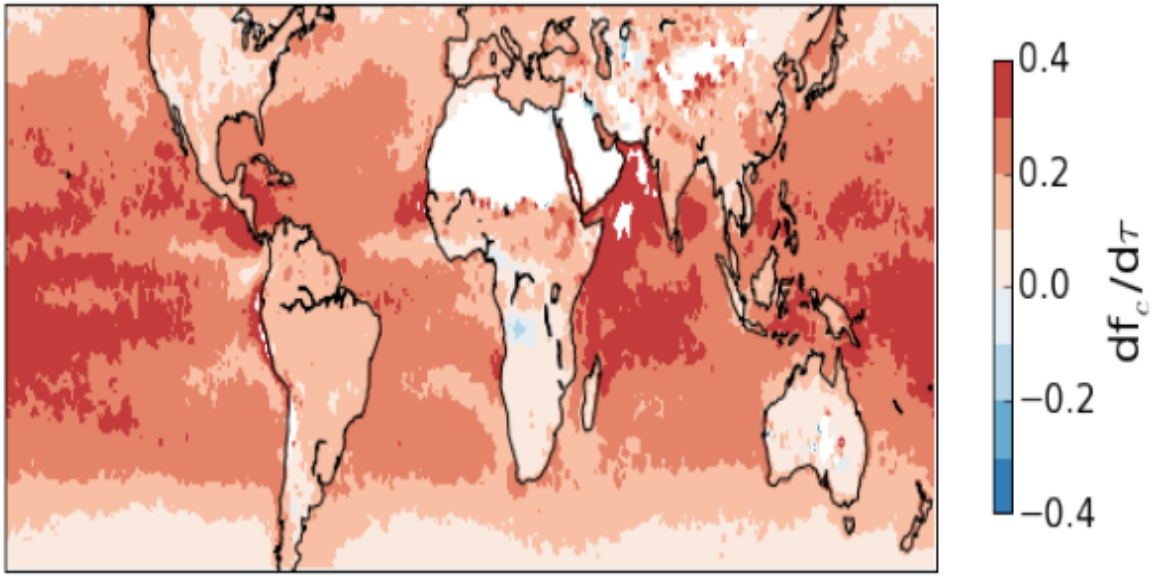
Cloudy-sky effective radiative forcing

vs. ACI metric

→ -1.2±0.4 Wm^{-2}
total ERF$_{aer}$

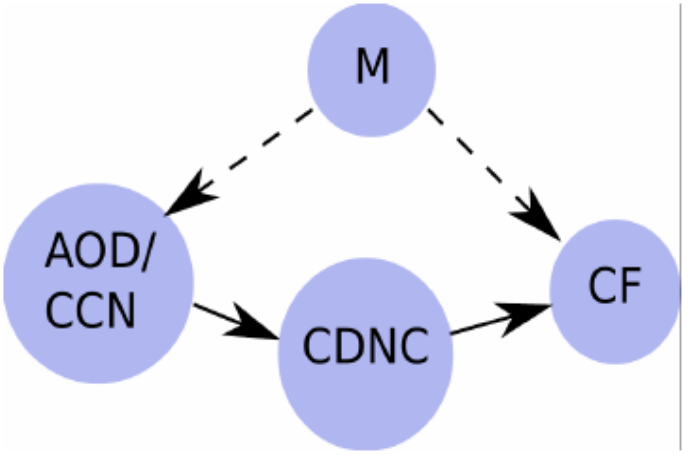
Quaas et al., Atmos. Chem. Phys. 2009

Cloud cover – aerosol relationship



Data from MODIS Aqua (used throughout this work)

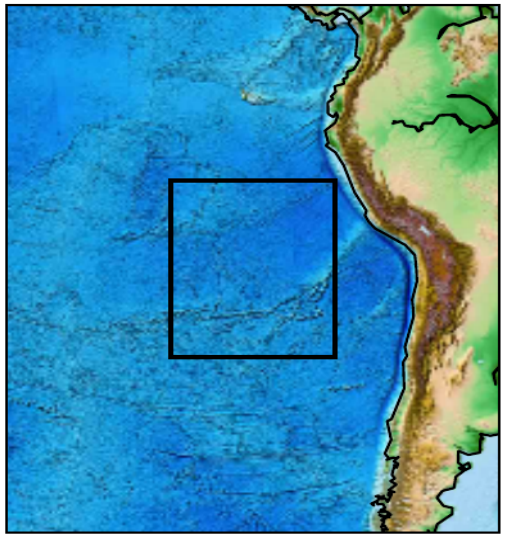
Regression coefficient cloud fraction (CF) vs. AOD
6 years of MODIS data at 1°x1° resolution

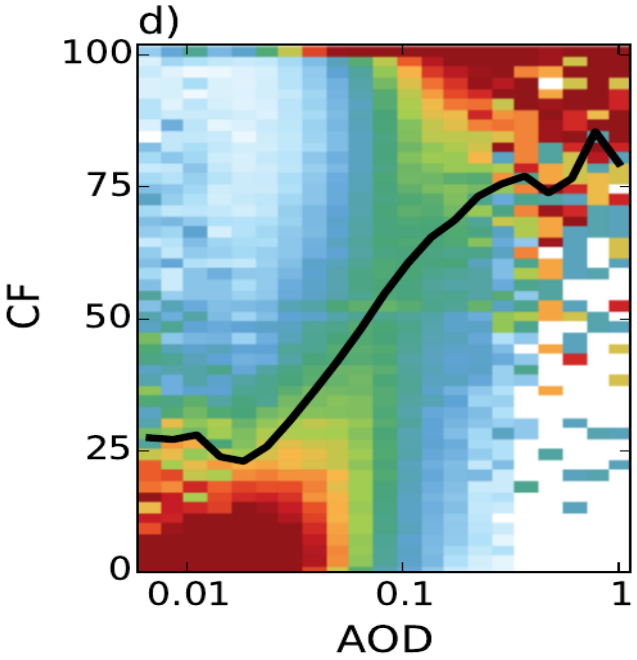


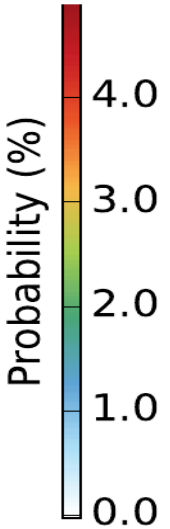
Microphysical pathway: via cloud droplet concentration changes (~ independent of RH)

Gryspeerdt, Quaas, Bellouin J. Geophys. Res. 2016

Cloud cover – aerosol relationship: decompose joint PDF

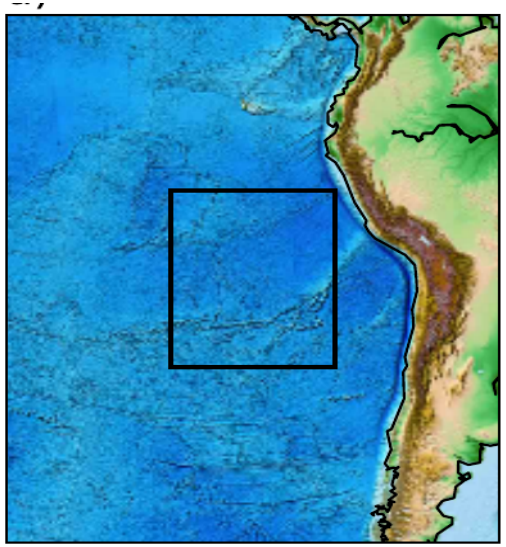


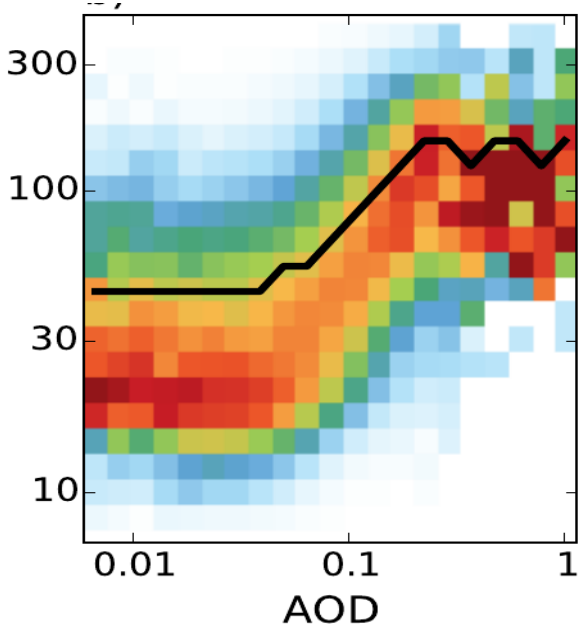


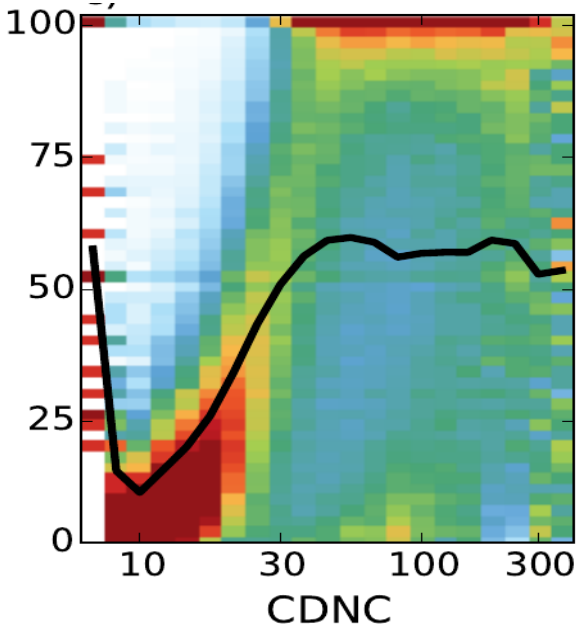


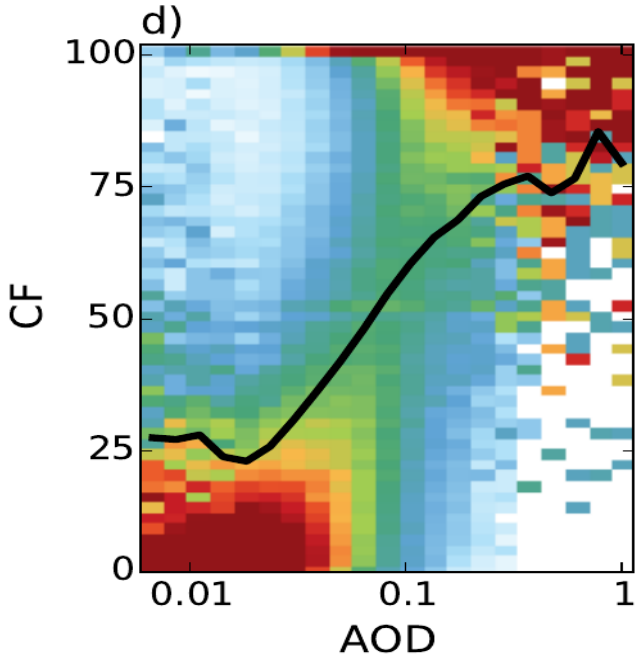
Gryspeerdt, Quaas, Bellouin J. Geophys. Res. 2016

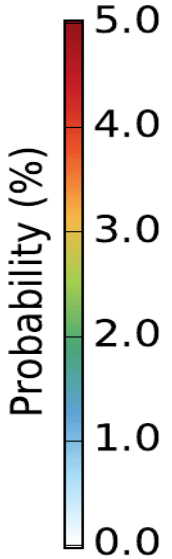
Cloud cover – aerosol relationship: decompose joint PDF





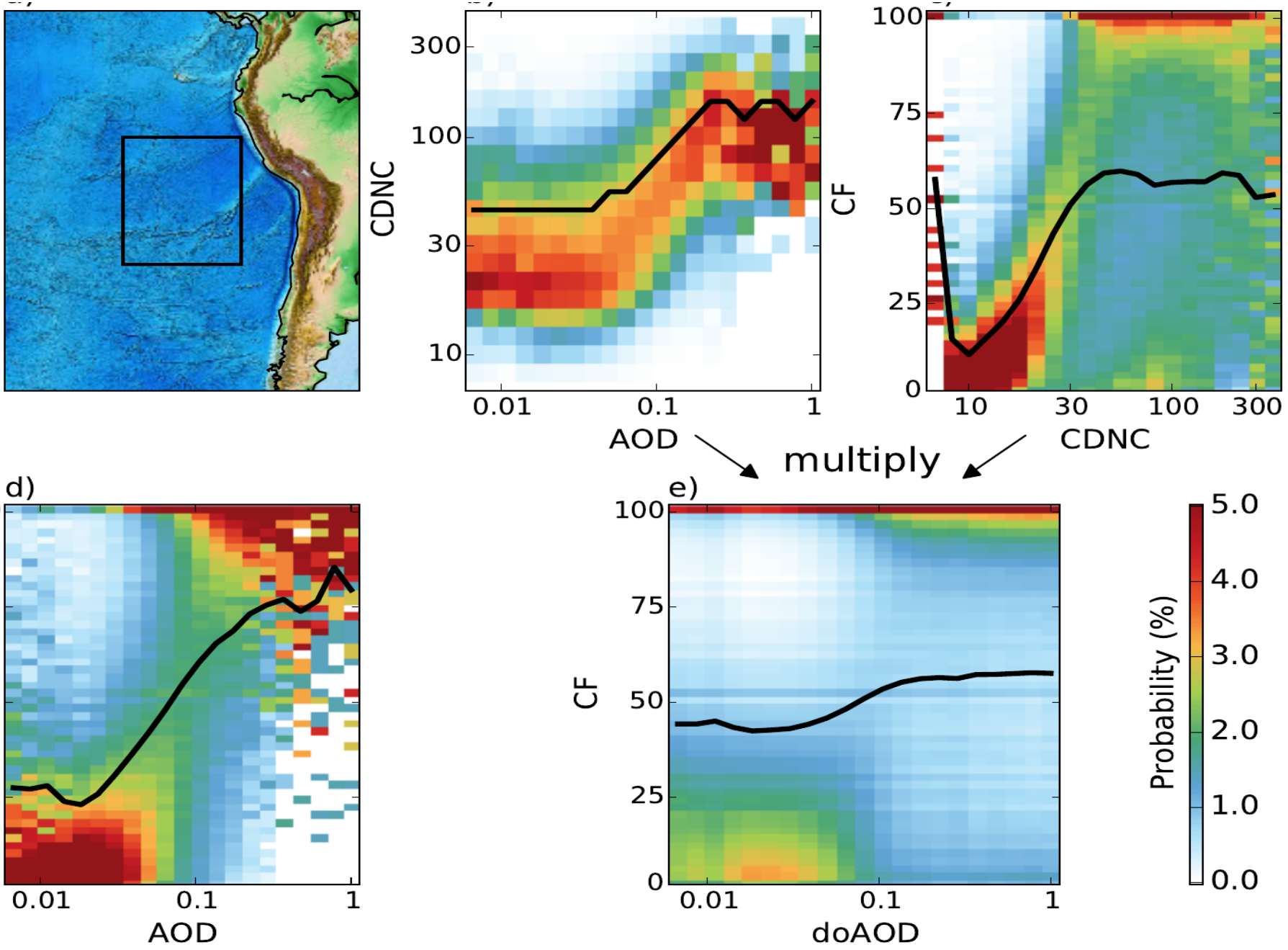






Gryspeerdt, Quaas, Bellouin J. Geophys. Res. 2016

Cloud cover – aerosol relationship: decompose joint PDF



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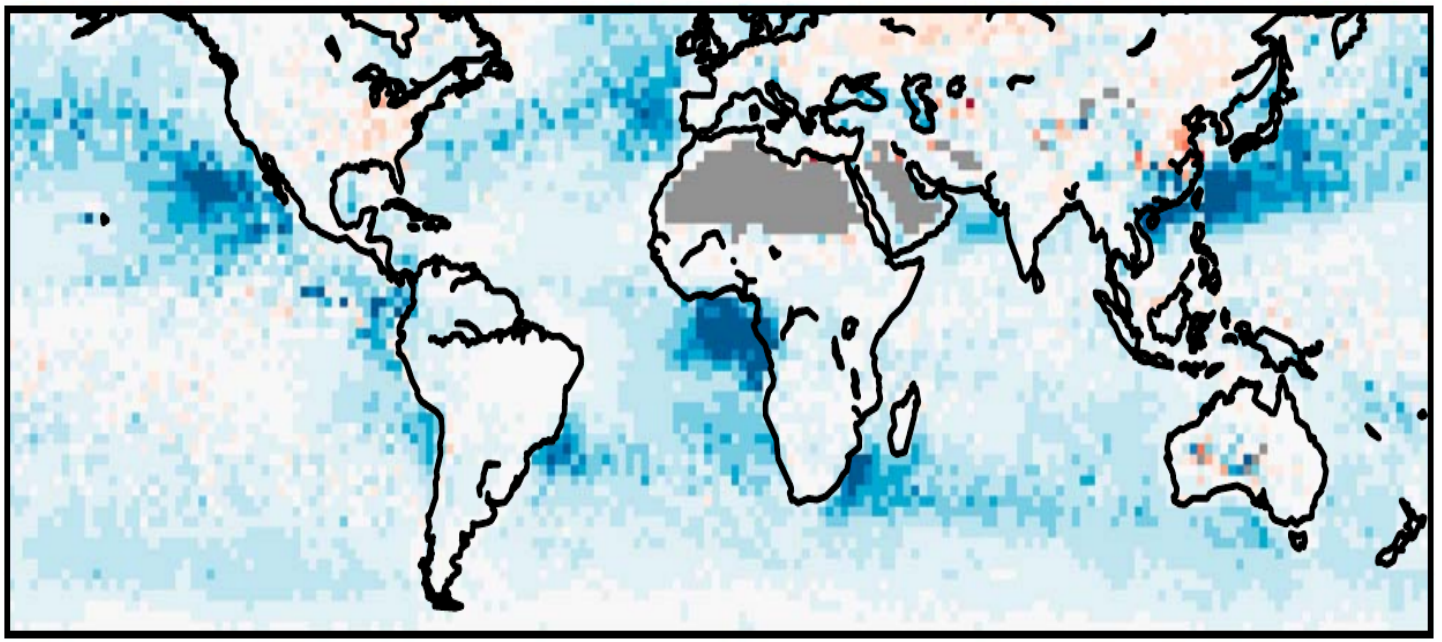
Cloud cover – aerosol relationship



Δ TOA SW (Wm^{-2})

-2.4 -1.2 0.0 1.2 2.4

Anthropogenic AOD from *Bellouin, Quaas, Morcrette and Boucher (ACP 2013)*

Lohmann & Feichter ACP 2005:

$ERF_{aci} \approx 2xRF_{aci}$

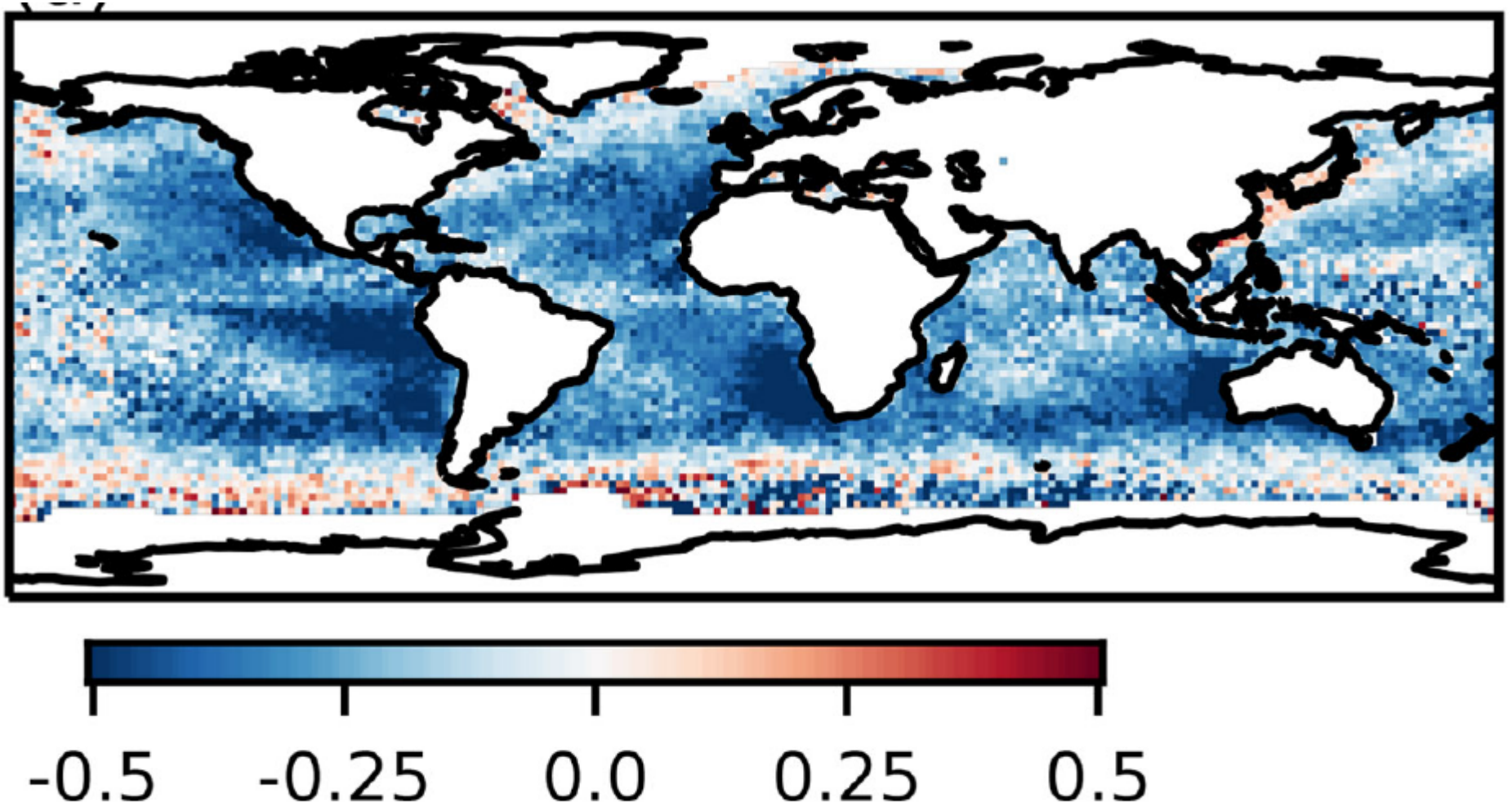
Caveat: N_d retrieval uncertain

Global annual mean forcing implied

- by AOD – Cloud fraction relationship: **-3 Wm^{-2}**
- by AOD – CDNC – cloud fraction relationship: **-0.48 Wm^{-2}**

Gryspeerdt, Quaas, Bellouin J. Geophys. Res. 2016

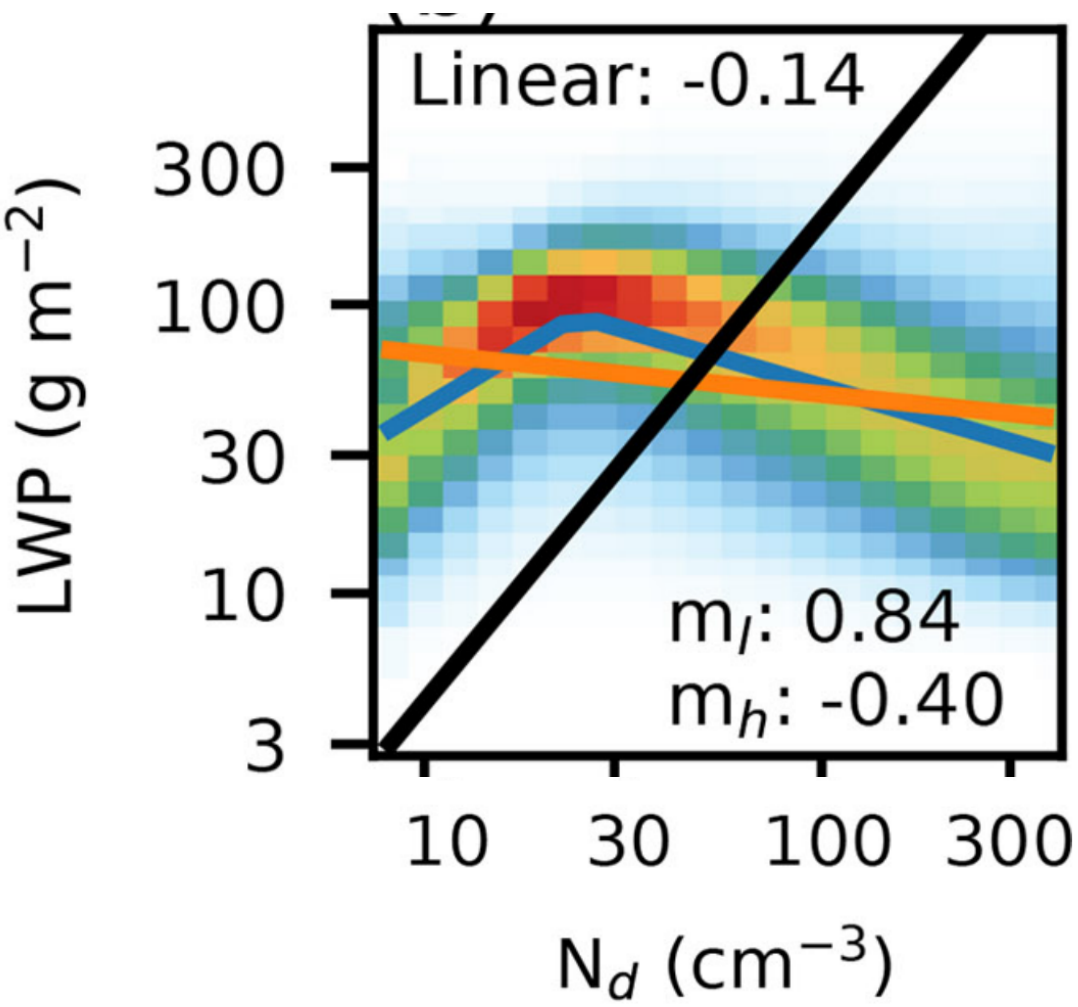
Liquid water path – aerosol relationship



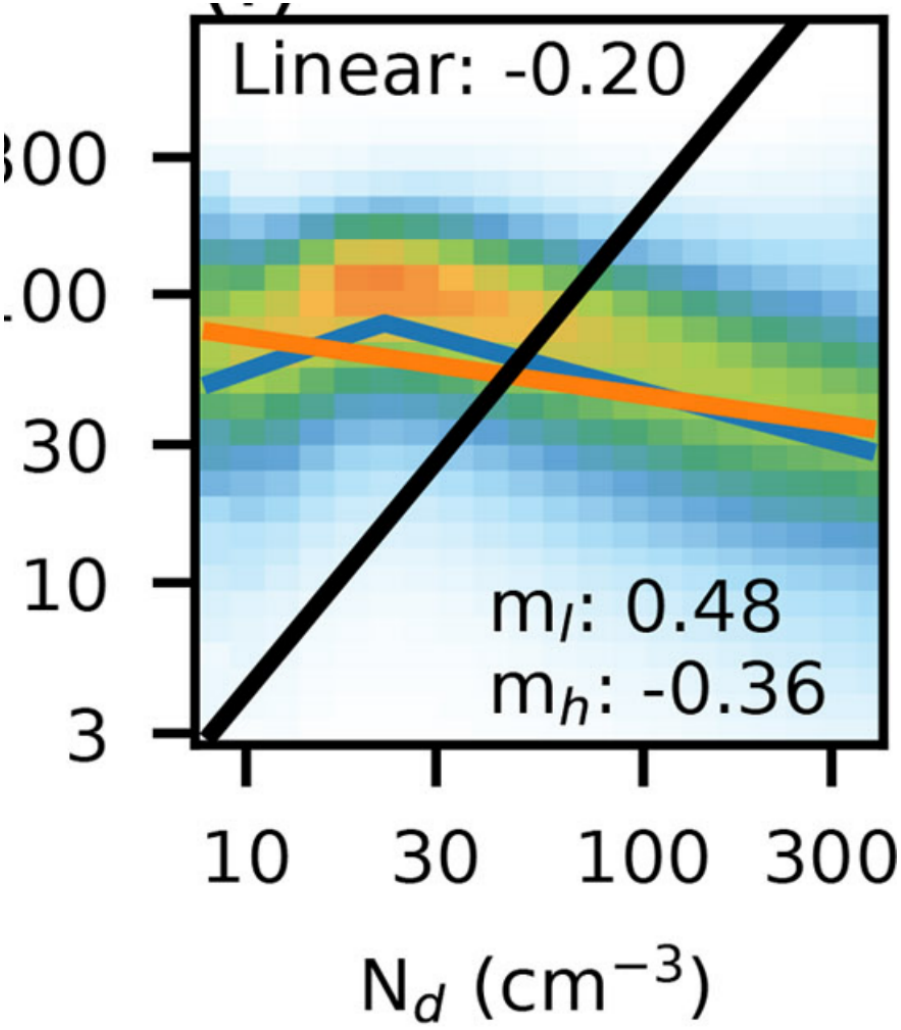
$\Delta \ln LWP / \Delta \ln N_d$ from MODIS

Gryspeerdt et al. Atmos. Chem. Phys.. 2019; Michibata et al., Atmos. Chem. Phys. 2016

Liquid water path – aerosol relationship



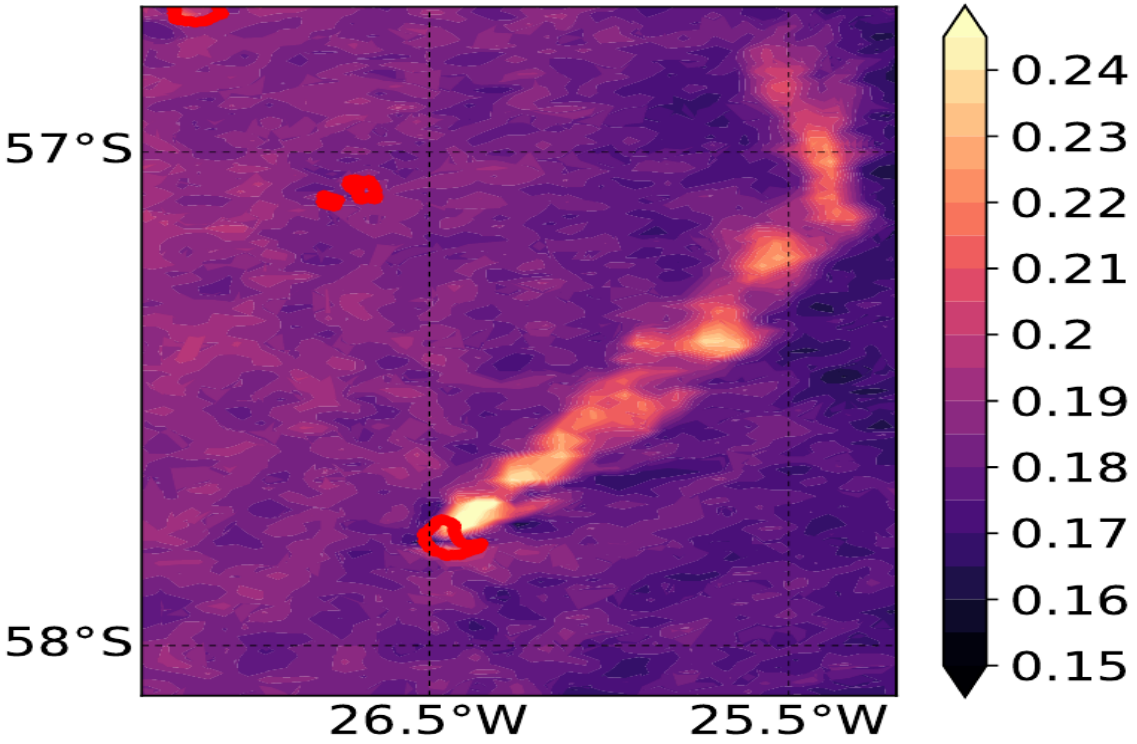
LWP from MODIS
(visible-near infrared)

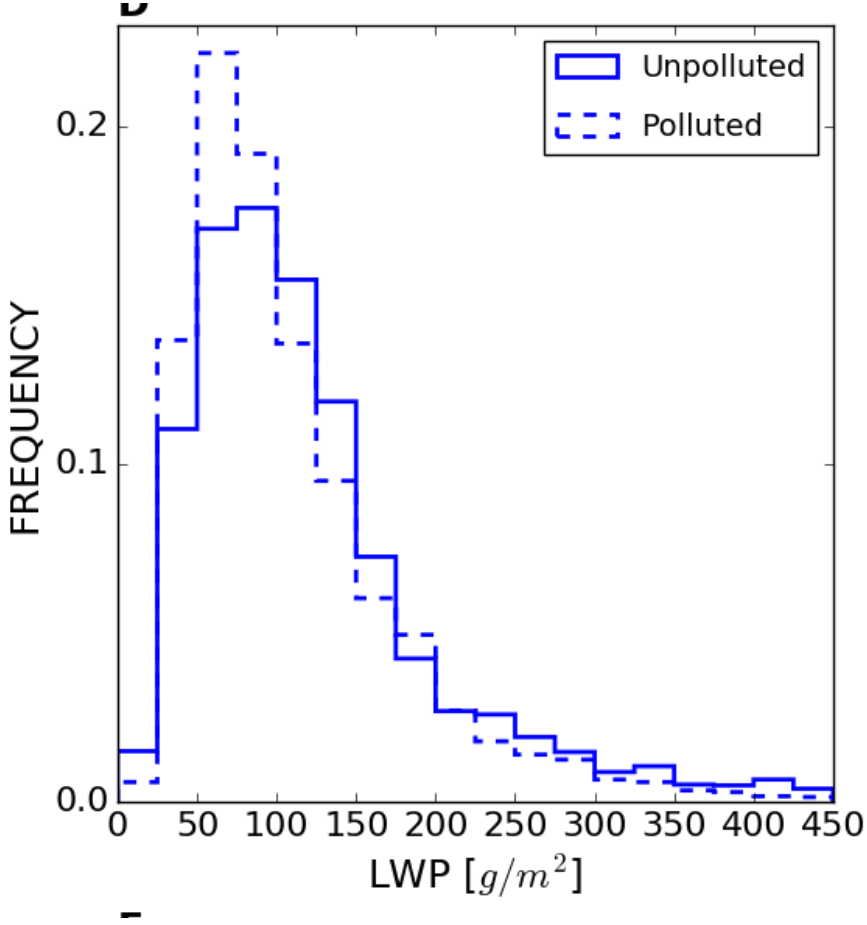


LWP from AMSR-E
(microwave)

Gryspeerdt et al. Atmos. Chem. Phys.. 2019

Liquid water path – aerosol relationship



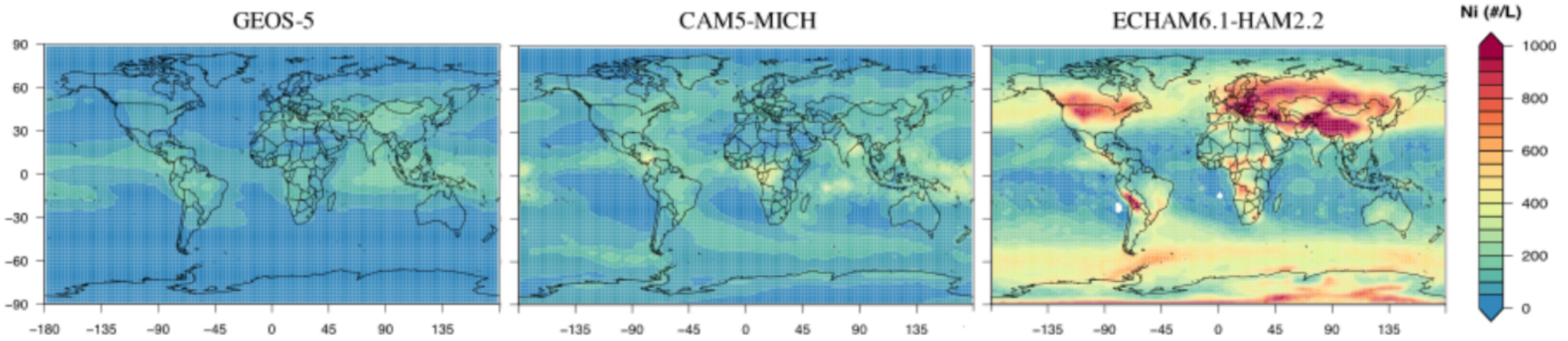


Net effect: offsets ~10% of Twomey effect

Toll et al. Geophys. Res. Lett. 2017; Toll et al. submitted

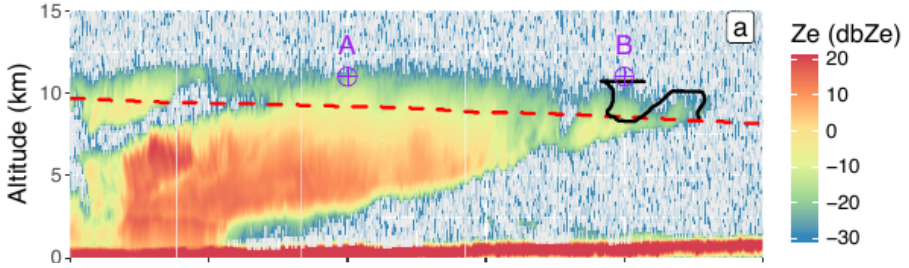
What about ice clouds? - *Ice crystal number concentration*

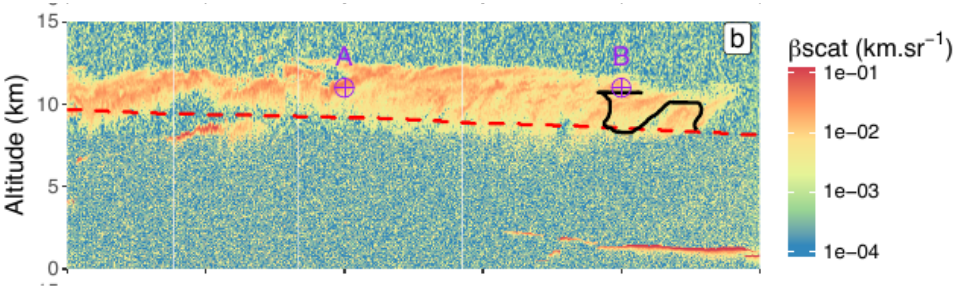
→ Climate models (AEROCOM)
→ Isotherm –45°C



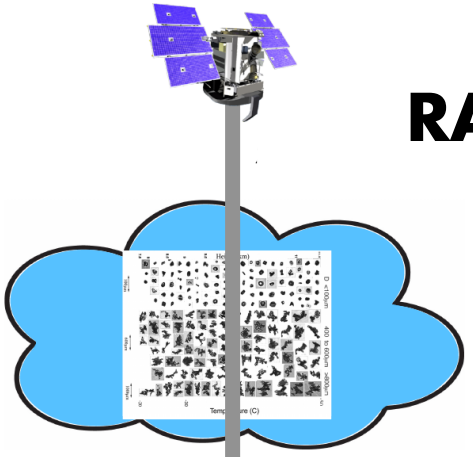
Global distribution of the ICNC between -40 and -50 °C in the simulations of 3 models for the AEROCOM-IND3 experiment (2006-2013 average; F. Hemmer, Bachelor thesis)

What about ice clouds? - *Ice crystal number concentration*

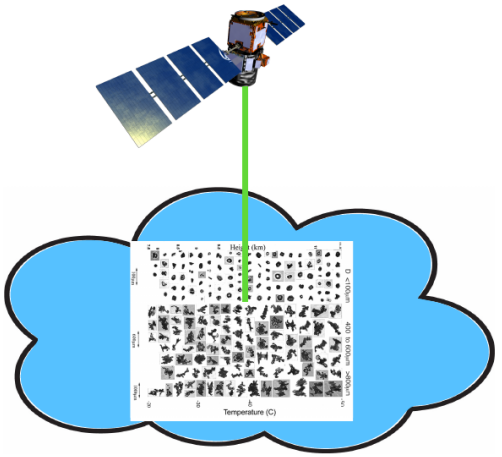


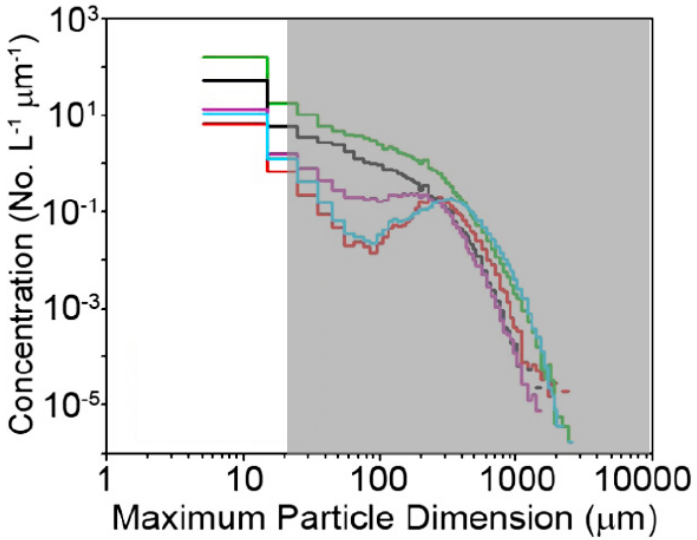


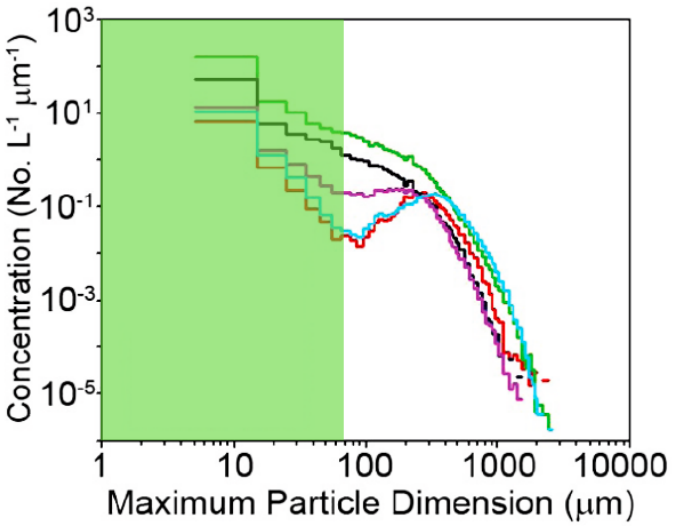
RADAR



LIDAR

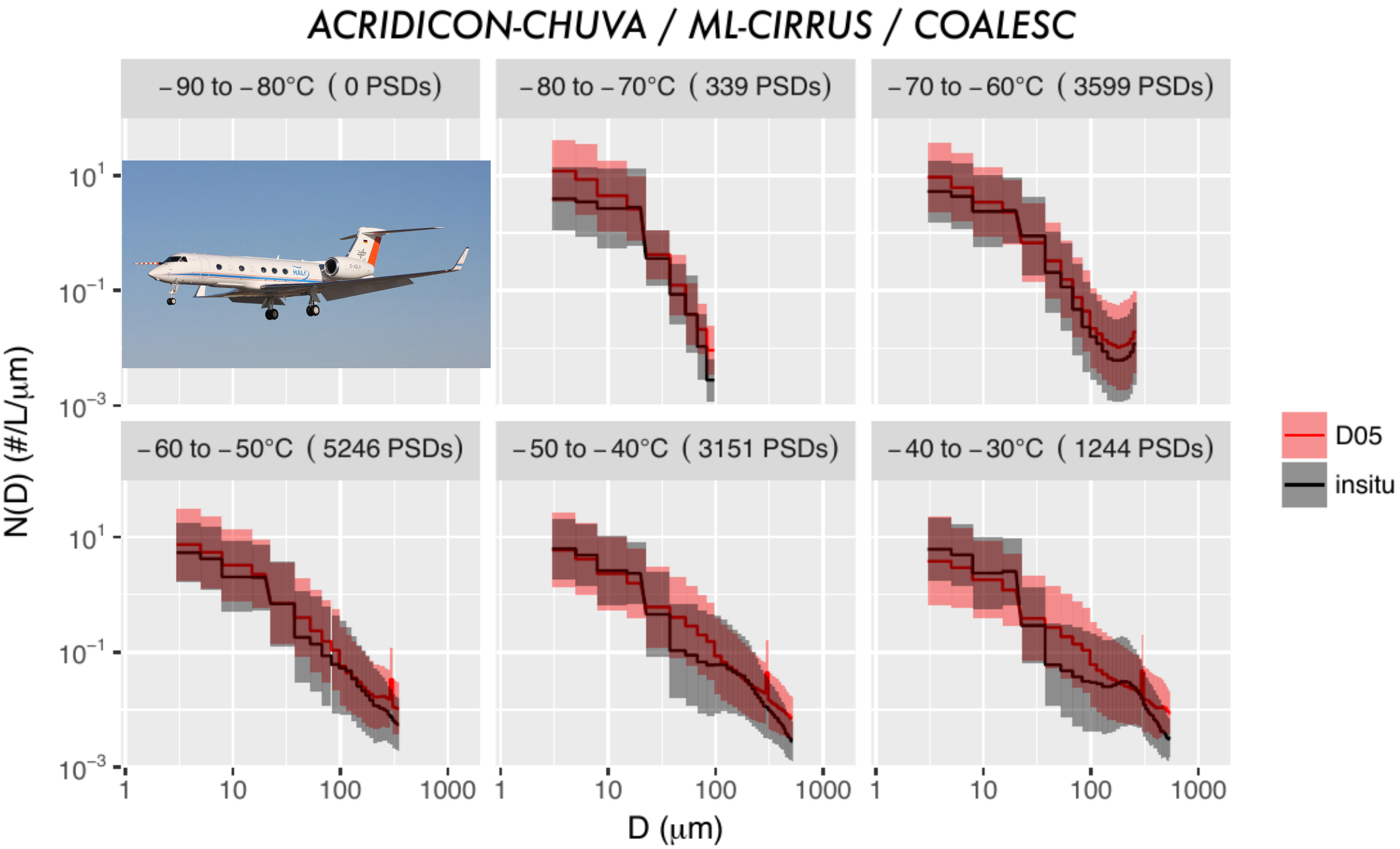






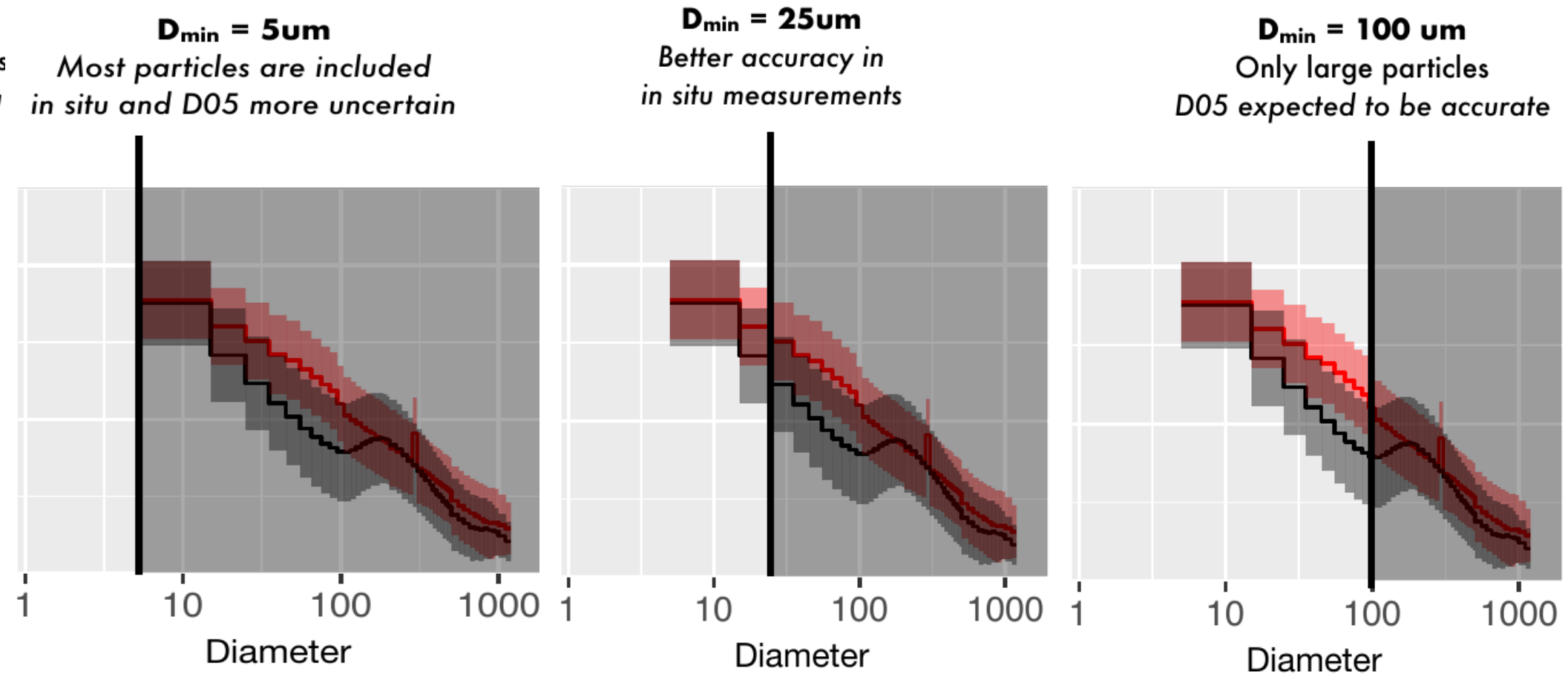
Sourdeval et al. Atmos. Chem. Phys. 2018

Size distributions vs. in-situ observations



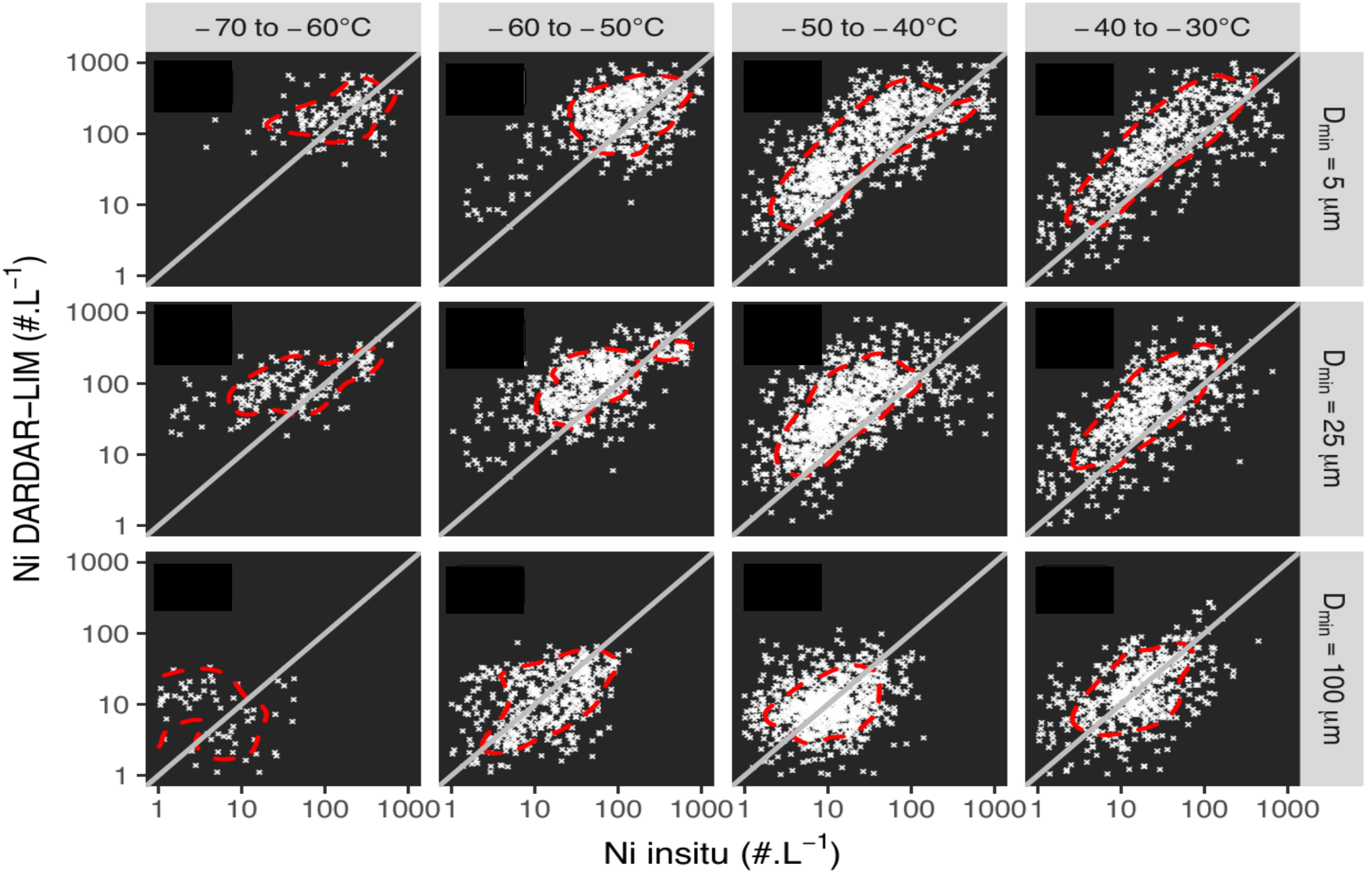
Sourdeval et al. Atmos. Chem. Phys. 2018

Gamma-distribution → lower cutoff very relevant!



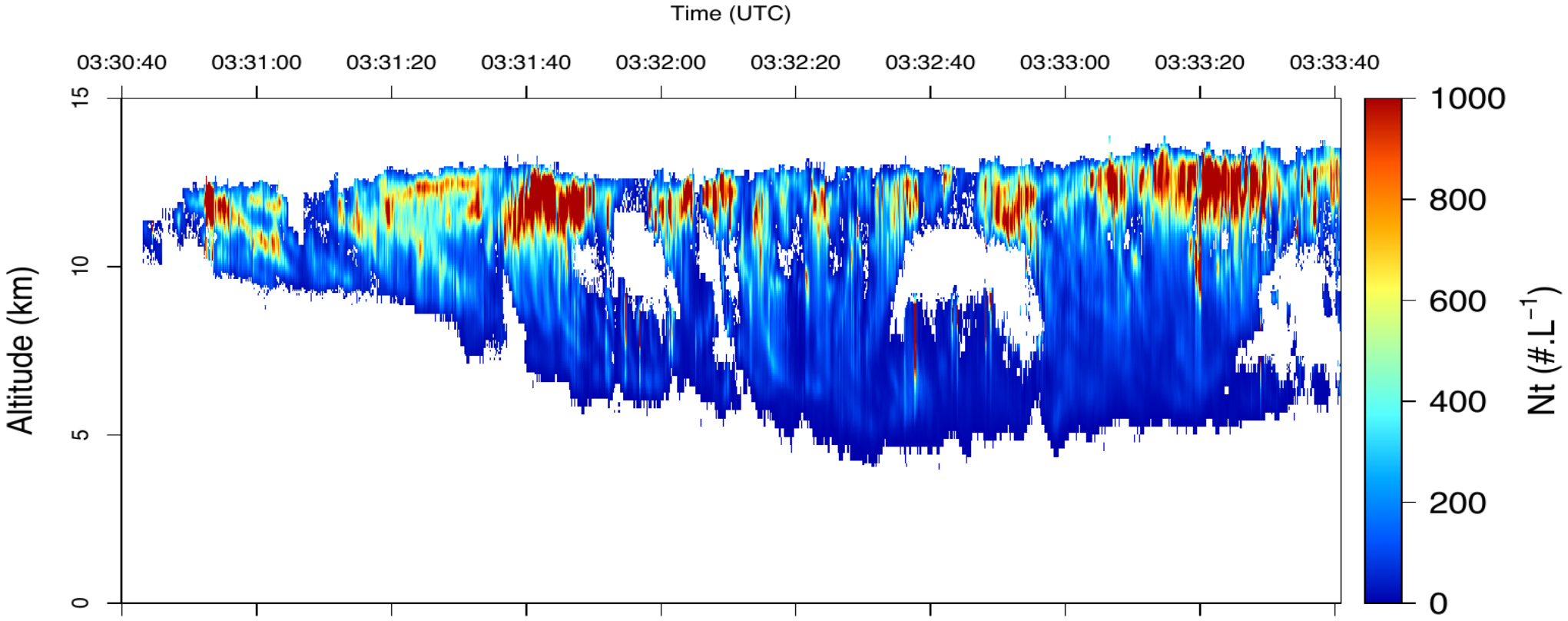
Sourdeval et al. Atmos. Chem. Phys. 2018

Directer comparison to in-situ data



Sourdeval et al. Atmos. Chem. Phys. 2018

Derived vertical profile



Sourdeval et al. Atmos. Chem. Phys. 2018

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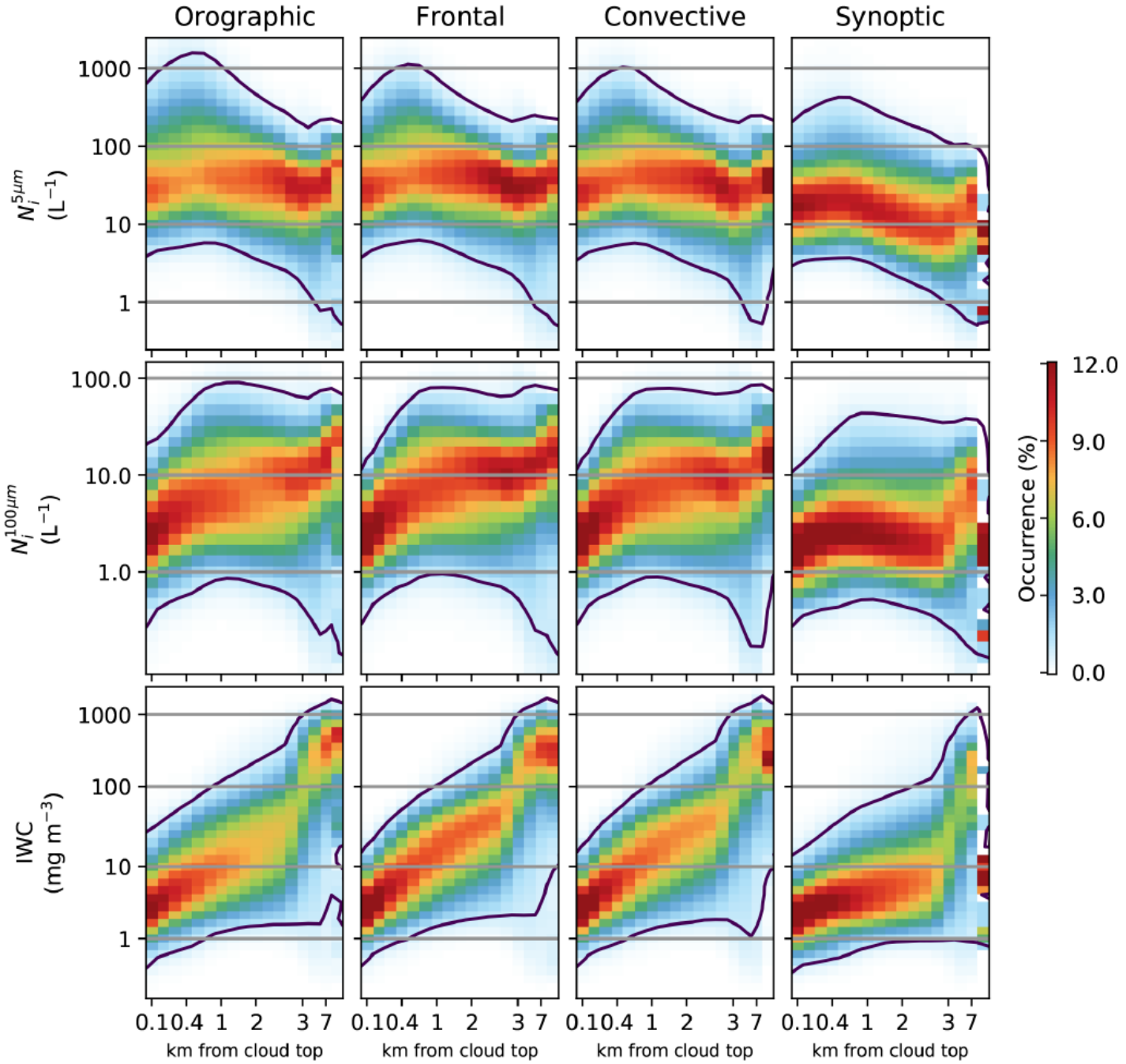


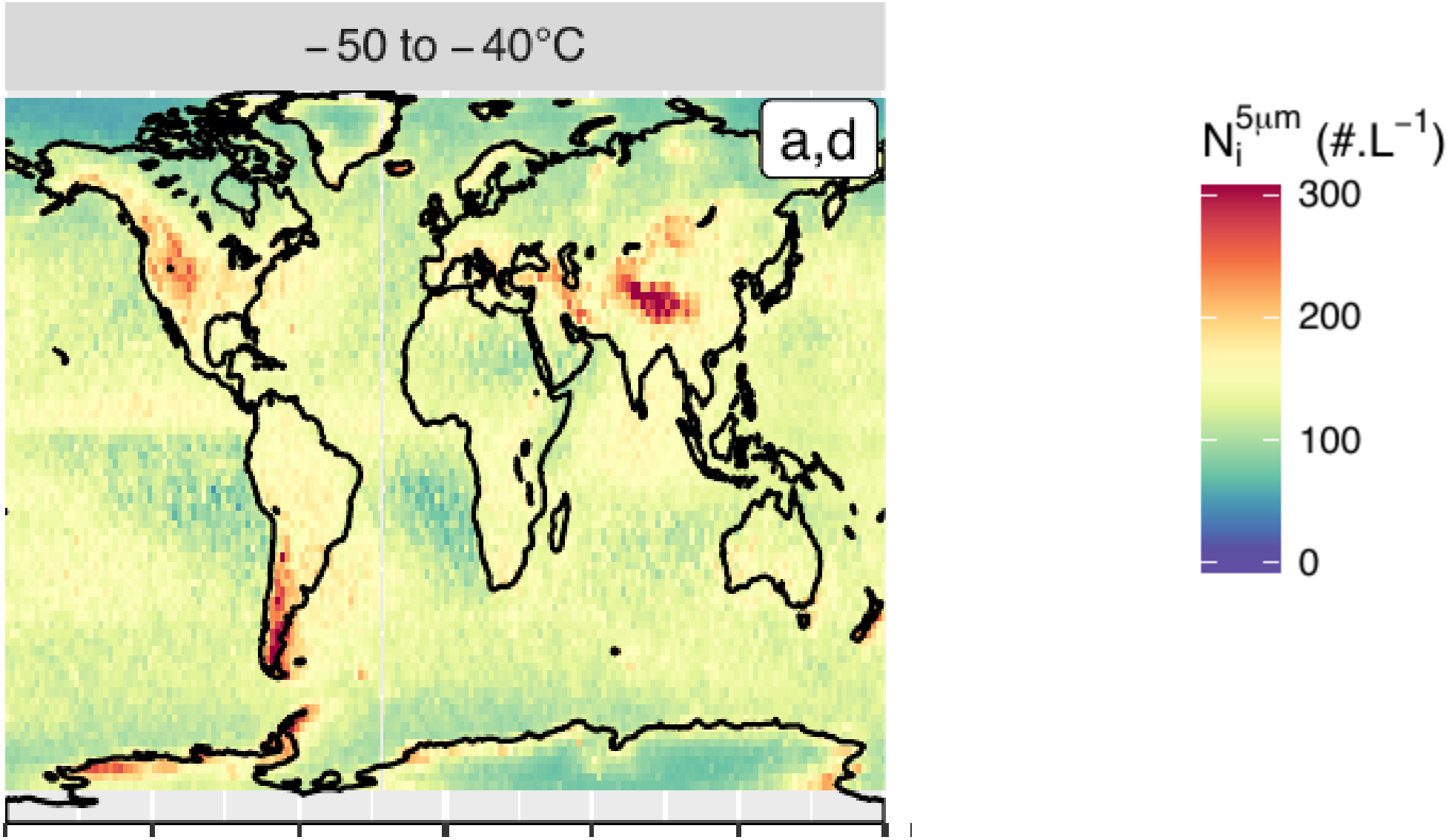
All crystals

Large crystals

Specific ice mass

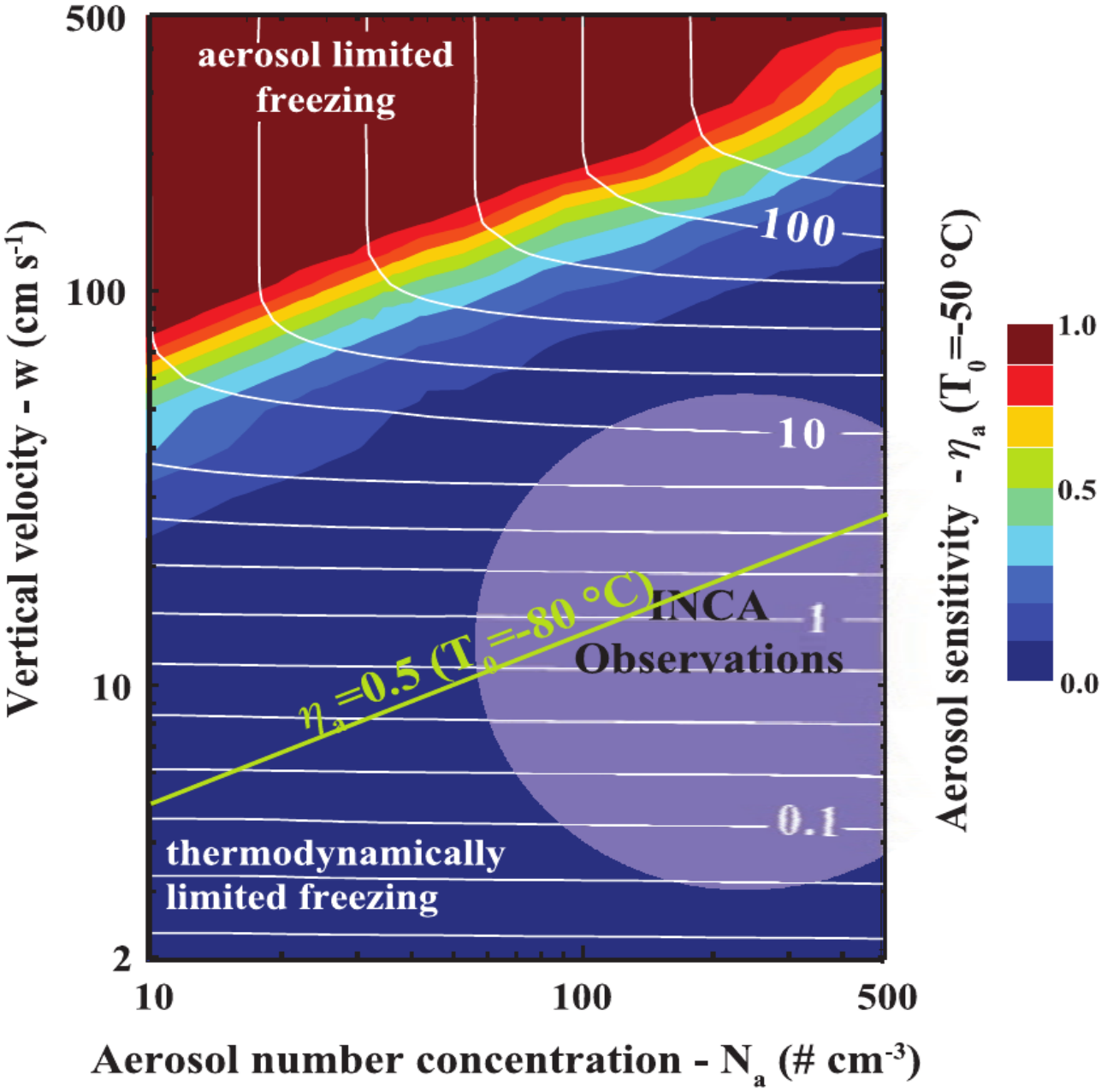
Gryspeerdt et al. Atmos. Chem. Phys. 2018

Geographical distribution



Sourdeval et al. Atmos. Chem. Phys. 2018

Ni – Sensitvities



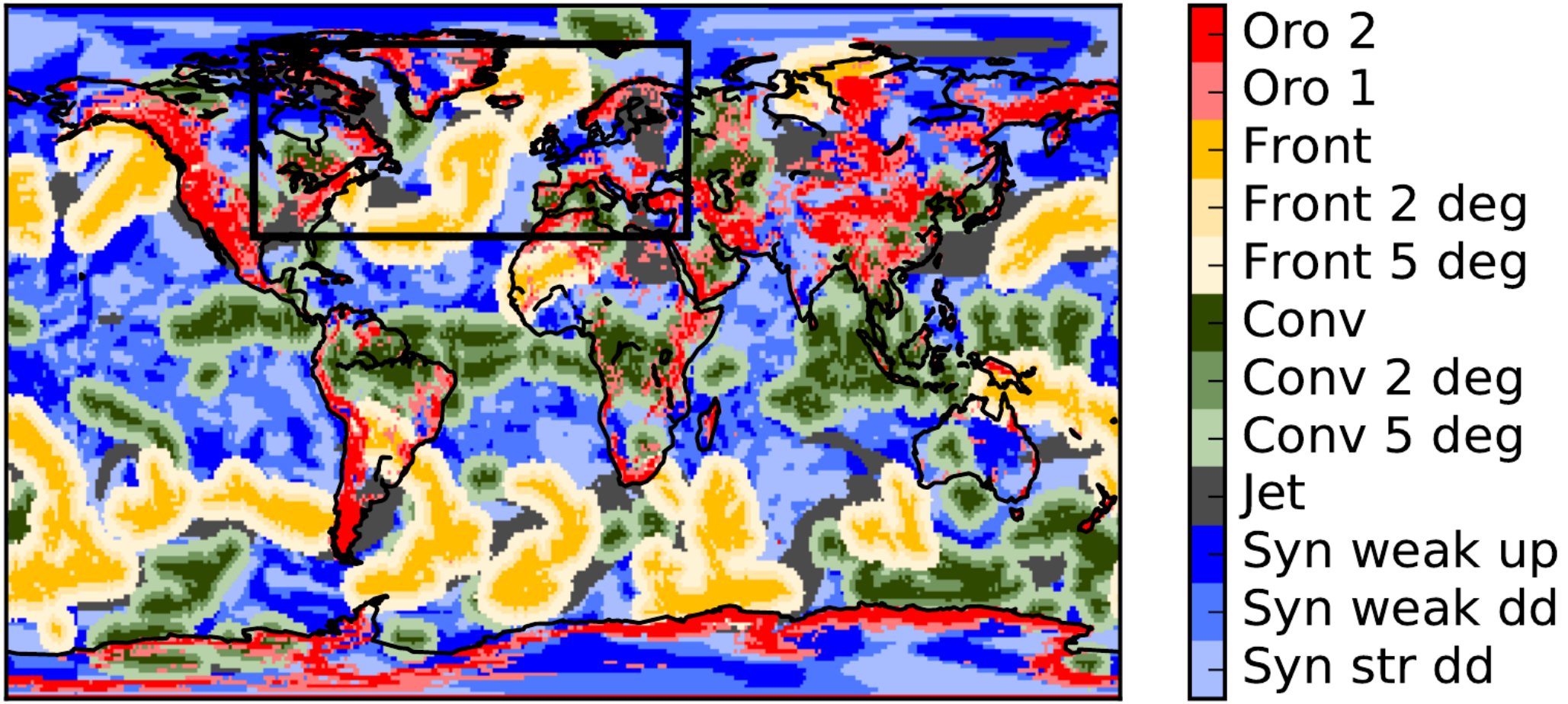
Kay and Wood, Geophys. Res. Lett. 2008

Dynamical forcing = Vertical wind

→ No measurements / retrievals avaibale

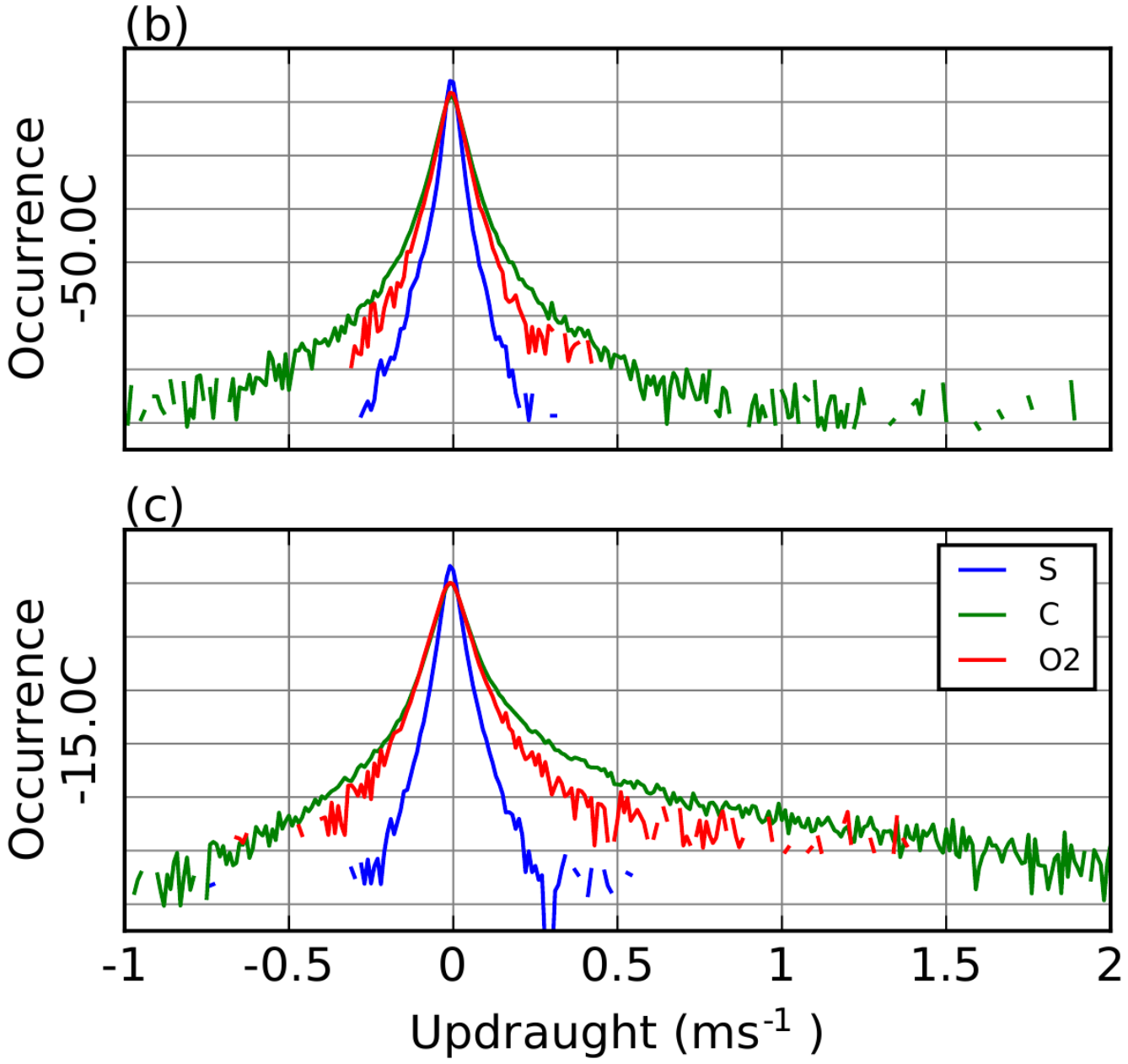
→ Classification of weather condition

(c)



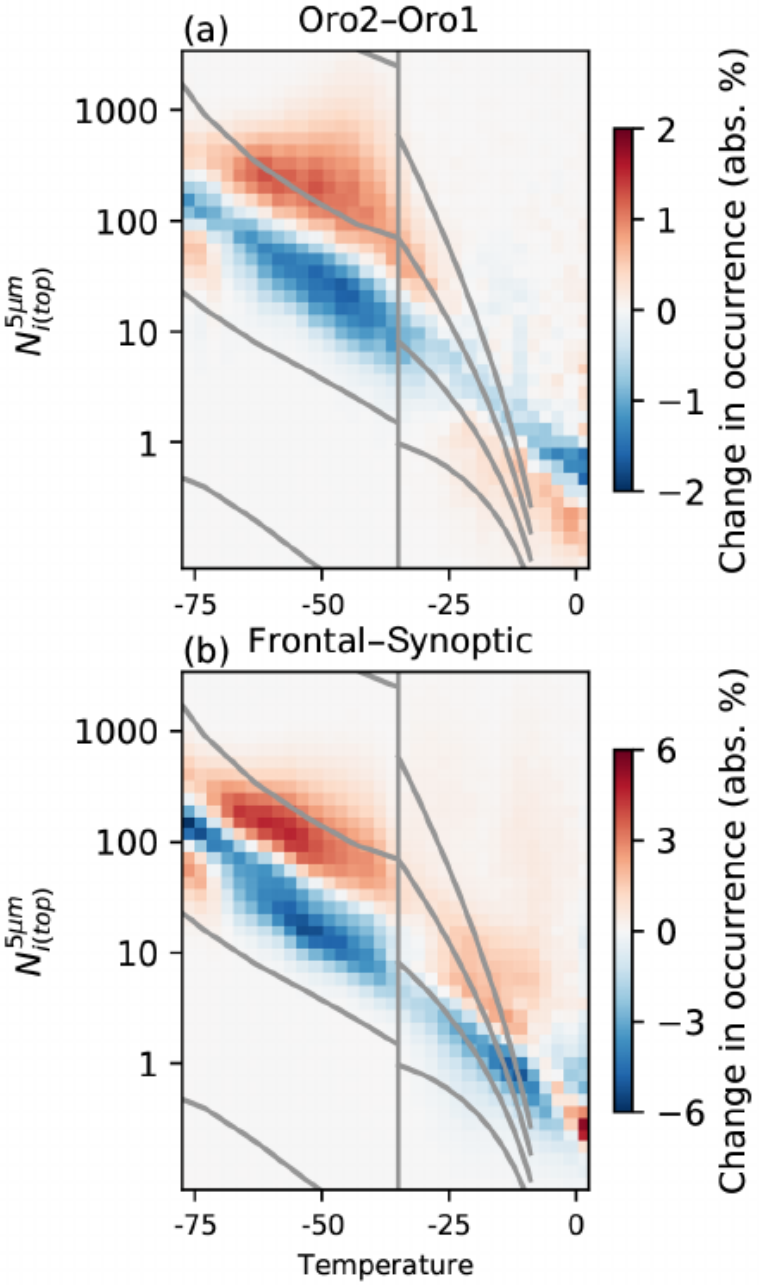
Gryspeerdt et al. Atmos. Chem. Phys. 2018

Distribution in HD(CP)² / NARVAL – simulations with ICON (2 km)



Gryspeerdt et al. Atmos. Chem. Phys. 2018

Sensitivities: vertical wind



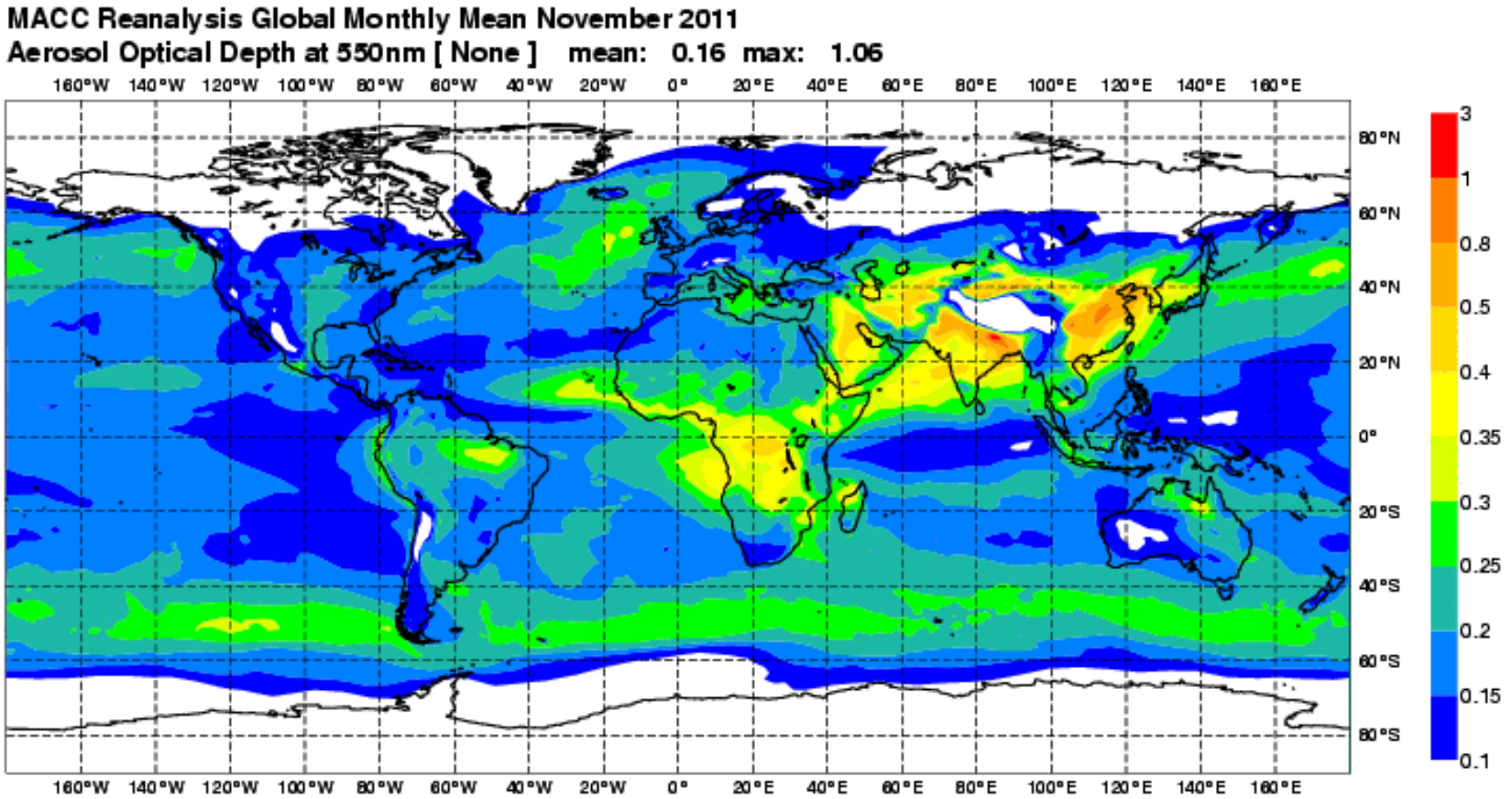
Steep orography (Oro2) vs. less steep orography (Oro1) → weaker updraught

Frontal cirrus vs. synoptic cirrus (without strong dynamical forcing)

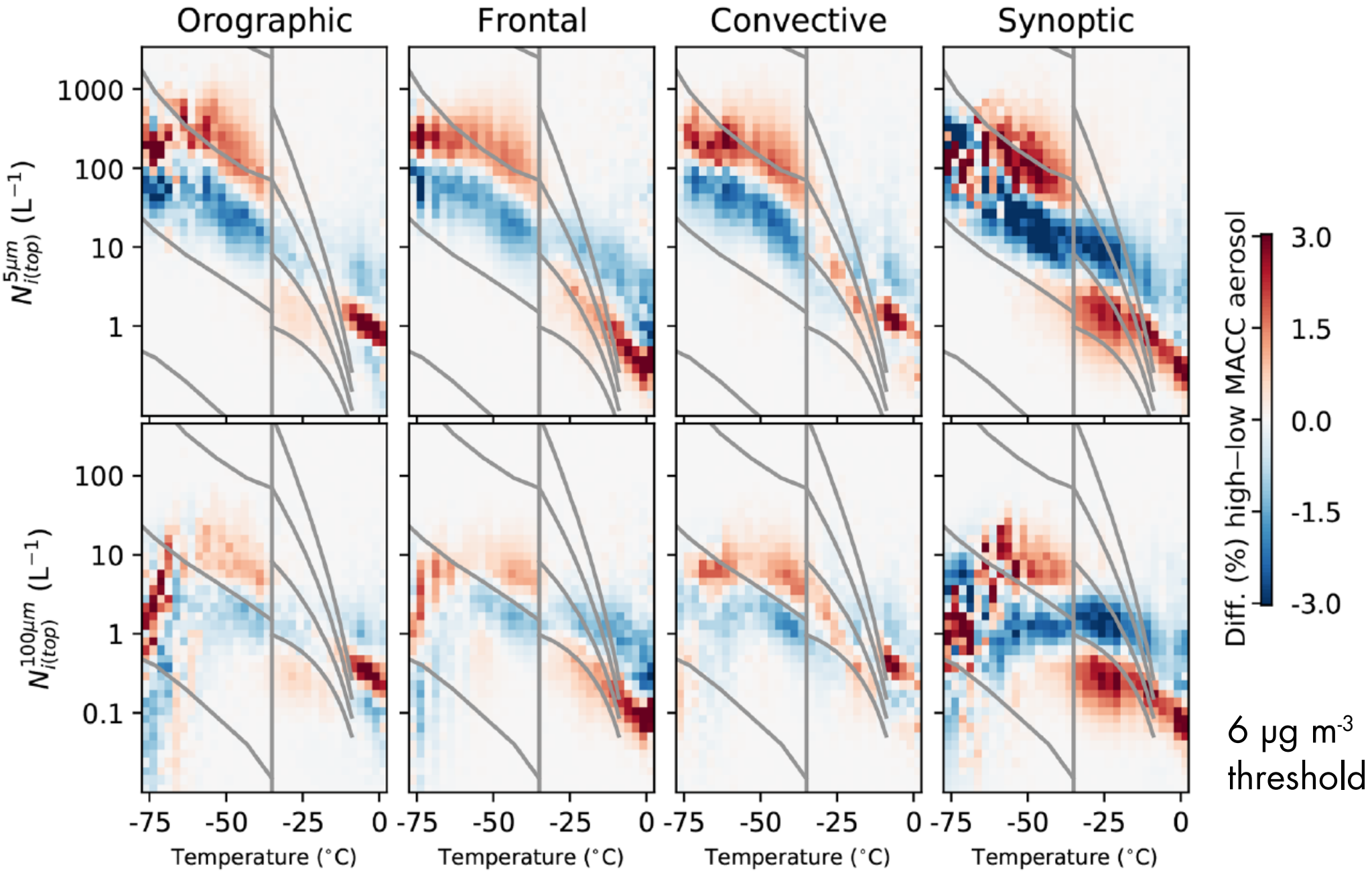
Gryspeerdt et al. Atmos. Chem. Phys. 2018

Aerosol: COPERNICUS Atmospheric monitoring service

→ Assimilation of MODIS-aerosol optical depth
→ ECMWF-model + aerosol module
→ 4D-distribution of specific aerosol mass



Sensitivities: Aerosol (homogeneous freezing)



Gryspeerdt et al. Atmos. Chem. Phys. 2018

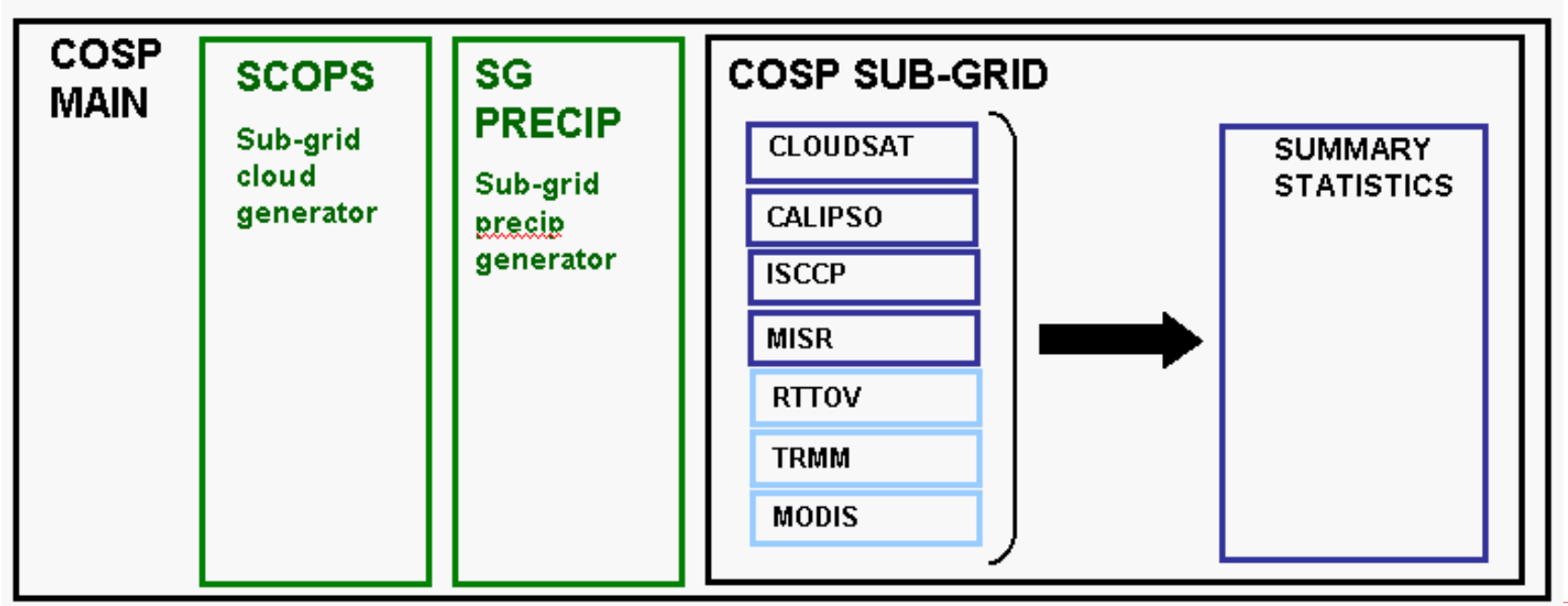
Satellite simulators

CFMIP

Cloud Feedback Model Intercomparison Project

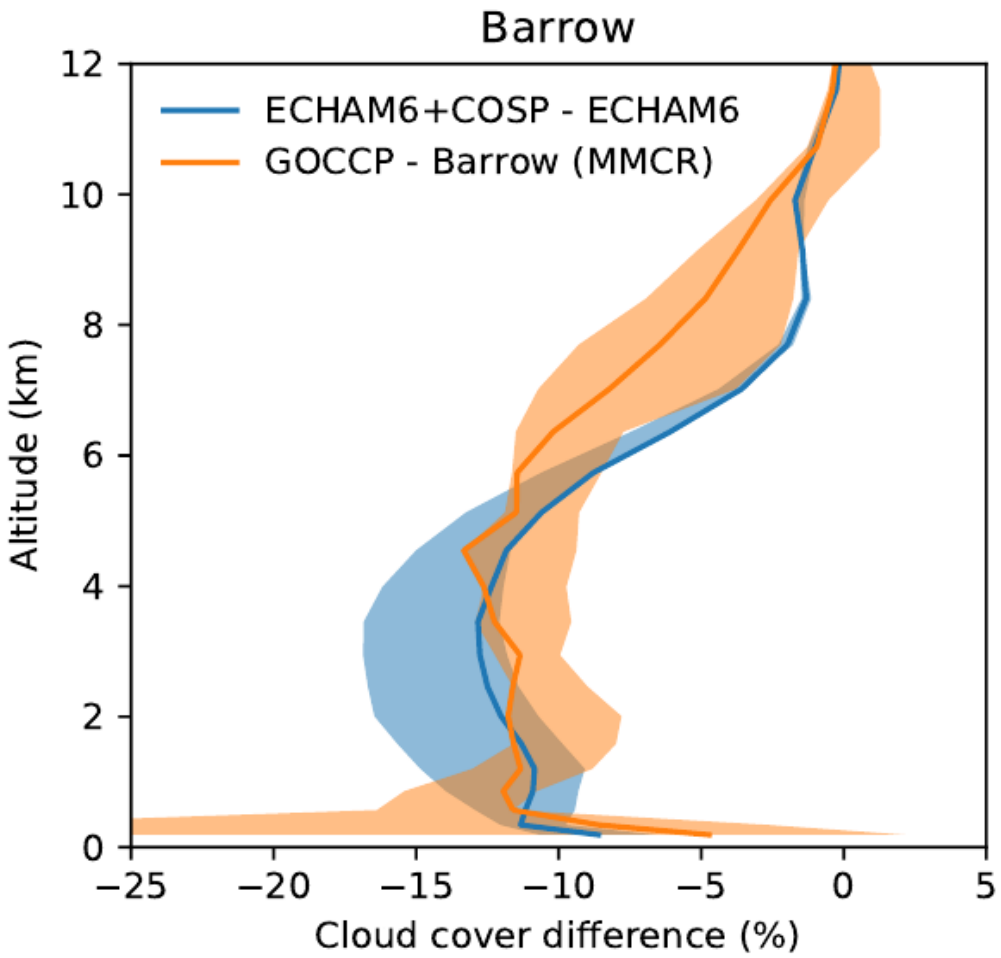
CFMIP Observational Simulator Package (COSP)

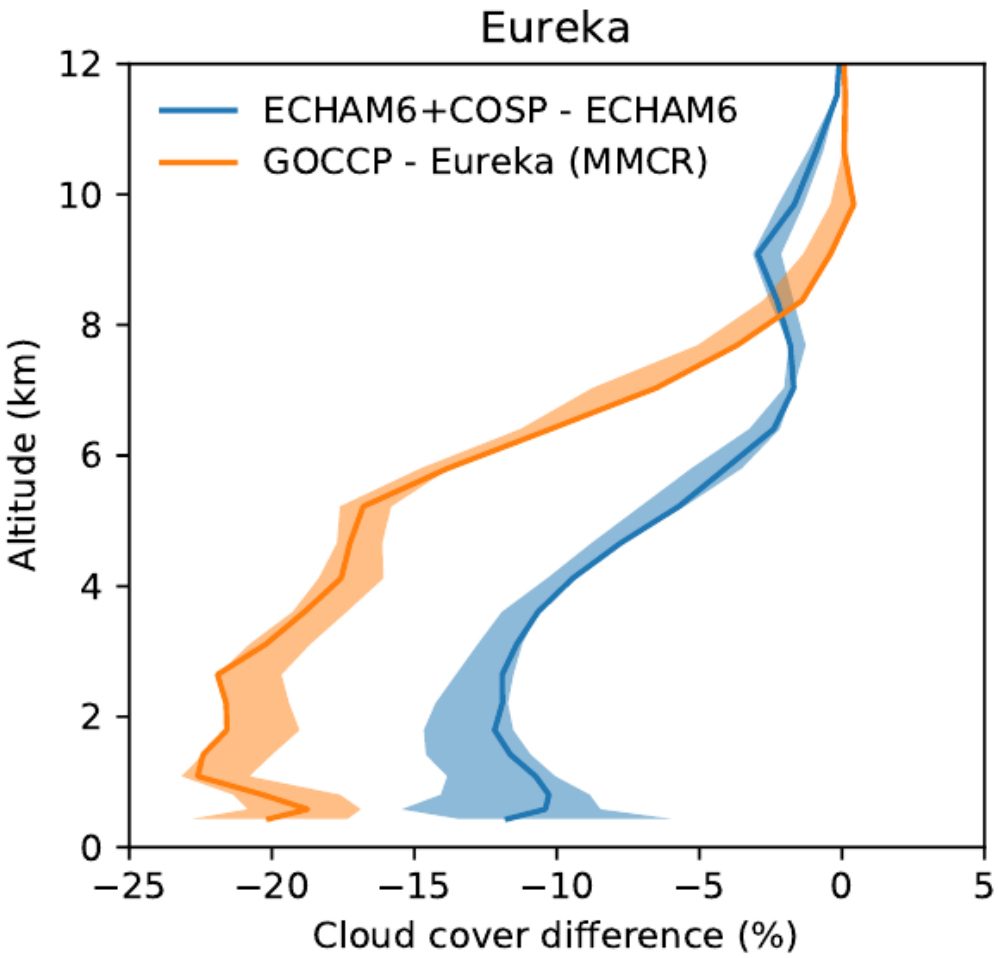
1) subgrid sampling
2) mimic retrievals
3) summary statistics



Bodas-Salcedo et al., BAMS 2008; Nam and Quaas, J. Climate 2012

Model evaluation: need to apply simulators

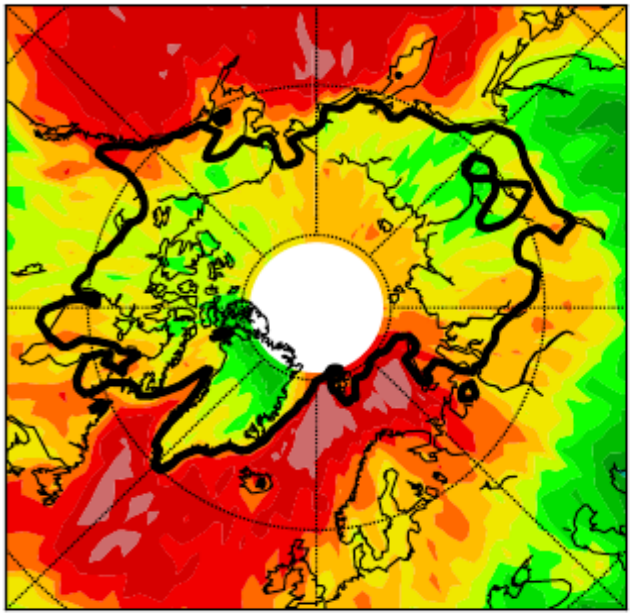




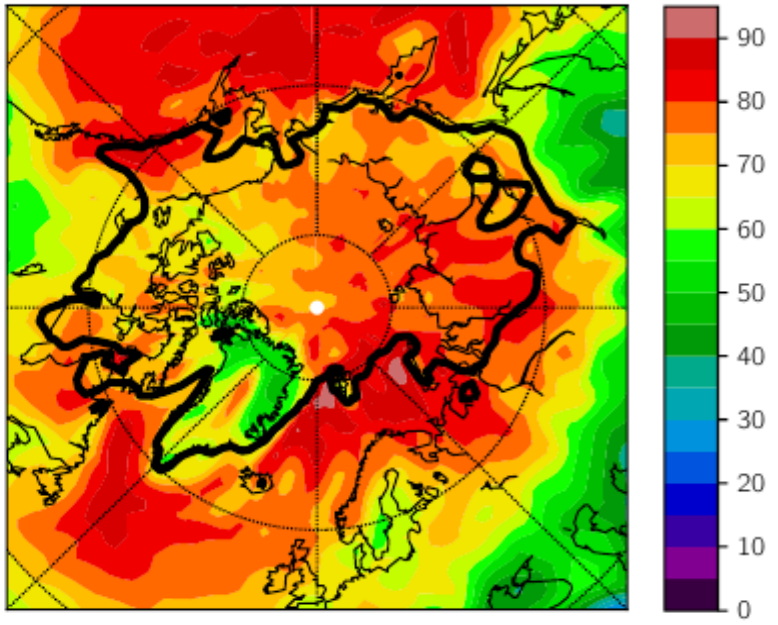
Kretzschmar et al. Atmos. Chem. Phys. Discuss.

Model evaluation in the Arctic: cloud bias

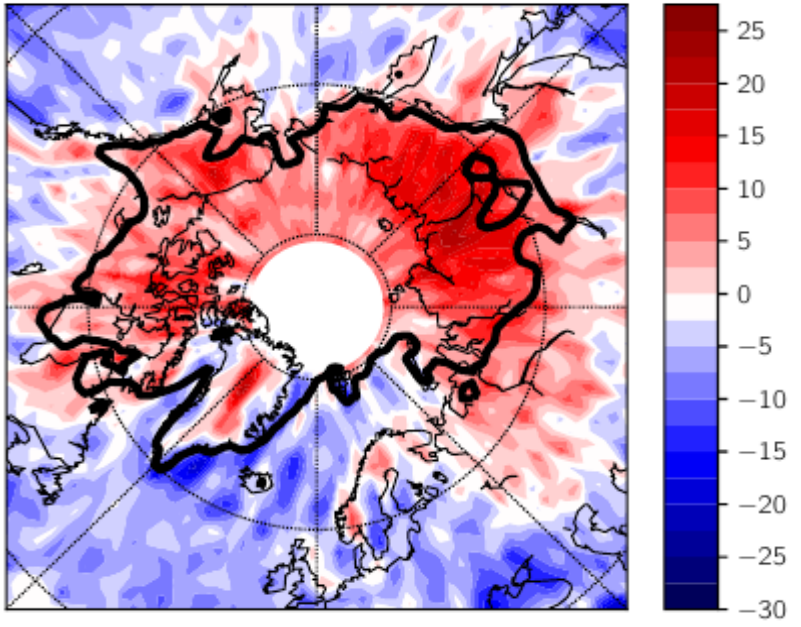
CALIPSO total cloud cover



ECHAM6+COSP total cloud cover



Difference total cloud cover



> ice supersaturation
> surface fluxes
> Bergeron-Findeisen

Kretzschmar et al. Atmos. Chem. Phys. Discuss.

Conclusions

- **Droplet number concentration**

  → Necessary for assessment of aerosol-cloud interactions
  → Allows to constrain the radiative forcing in models
  → Relationship with cloud fraction positive, with liquid water path both signs
  → Using external aerosol sources (volcanoes, ship tracks): on average no LWP change

- **Ice crystal concentration**

  → From radar-lidar synergy (DARDAR-Nice)
  → Very sensitive to vertical wind
  → some sensitivity to aerosol for strongly forced, cold cirrus

- **Model evaluation in the Arctic**

  → Requires satellite simulator in the model
  → Cloud bias vs. lidar
  → Adjust various cloud-related parameterisations

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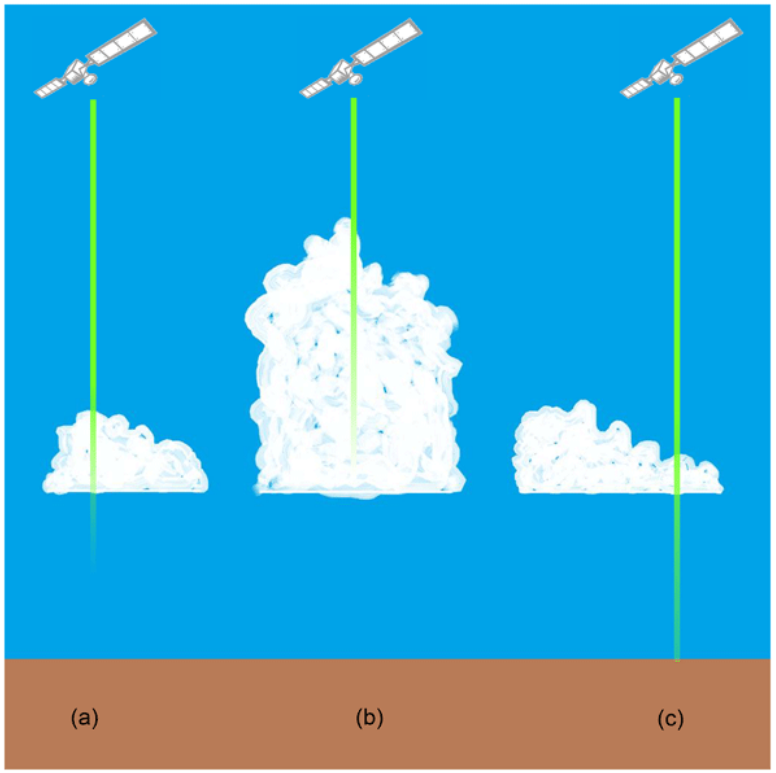
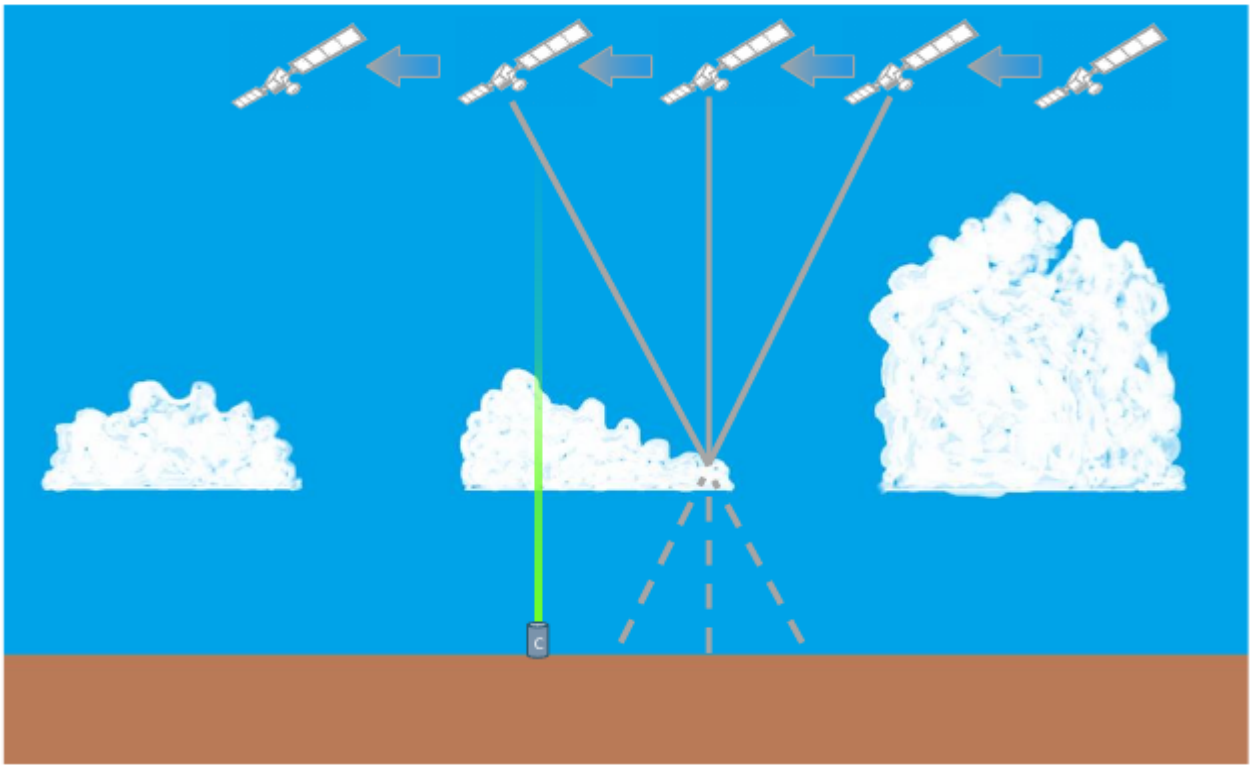
Thank you

Johannes Quaas
research.uni-leipzig.de/climate

Cloud-base height retrieval

idea: lowest cloud-top height in a field = approximate cloud base





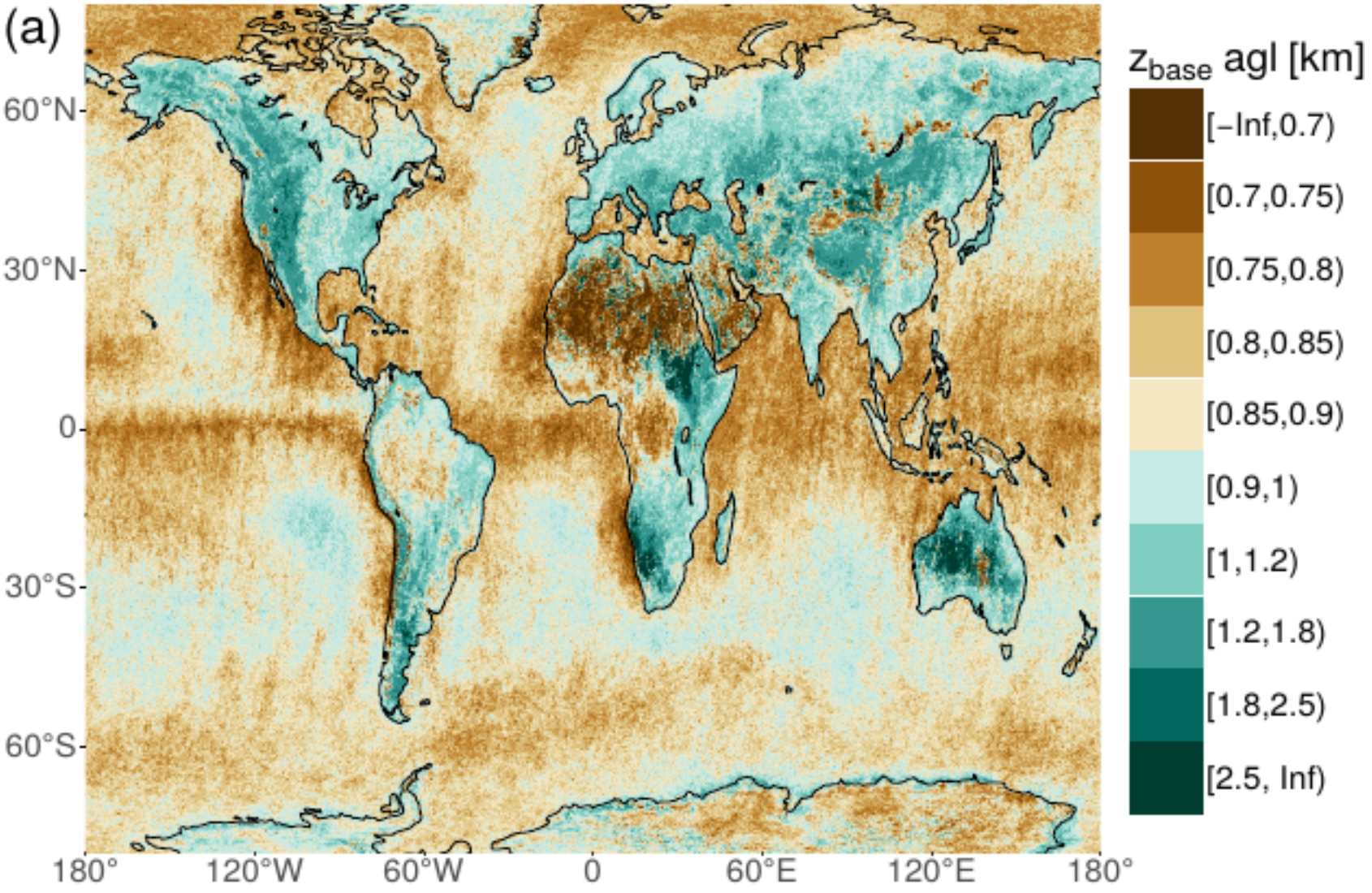
CALIPSO lidar

Mülmenstädt et al. ESSD 2018

MISR multi-angle

Böhm et al. AMT 2019

Cloud-base height retrieval



Applications: - surface energy budget
- cloud regime