Updating satellite-based ACI estimates with refined CCN approximation

Yohei Shinozuka (Yohei.Shinozuka@nasa.gov), Ralf Bennartz, Arlindo M. da Silva, Ravi C. Govindaraju, Oleg Dubovik, David Fuertes, Pavel Lytvynov, Anne Jefferson, Robert Wood, Brent Holben, Rick Wagener, Laurie Gregory, Lynn Ma, Andrew M. Sayer

NASA Ames, GSFC; BAERI; Vanderbilt University; SSAI; Université de Lille; BNL; CIRES NOAA; University of Washington

We use

ground-based measurements (e.g., ARM, AERONET)

passive satellite and model products (e.g., MERRA-II, PARASOL GRASP, MODIS).

Background

On the responses of droplet concentration and size to increases in aerosol, Boucher et al. (2013) say “aircraft measurements (e.g., Twohy et al., 2005; Lu et al., 2007, 2008; Hegg et al., 2012) tending to show **stronger responses than satellite-derived** responses (McComiskey and Feingold, 2008; Nakajima and Schulz, 2009; Grandey and Stier, 2010)”.

Background

On the responses of droplet concentration and size to increases in aerosol, Boucher et al. (2013) say “aircraft measurements (e.g., Twohy et al., 2005; Lu et al., 2007, 2008; Hegg et al., 2012) tending to show **stronger responses than satellite-derived** responses (McComiskey and Feingold, 2008; Nakajima and Schulz, 2009; Grandey and Stier, 2010)”.

Our main findings

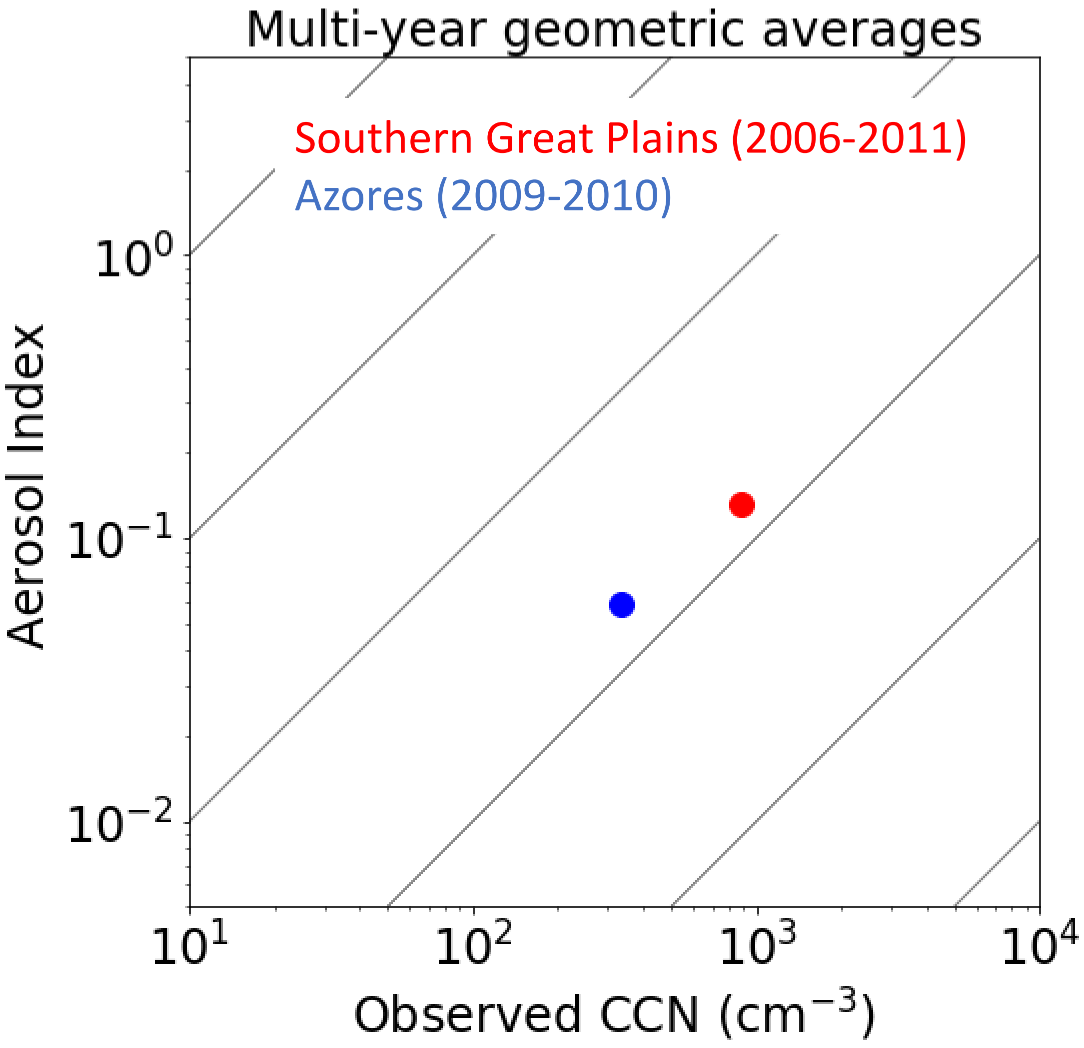
Satellite-based estimates may have been underestimated, because of:

- exaggerated CCN variability
- the use of standard least-squares regression

besides the scale problem (Grandey and Stier, 2010; McComiskey and Feingold, 2012).

Is AI proportional to CCN?

500 nm AOD * Angstrom (440/870)
AERONET V2
Holben, Wagener, Gregory, Ma



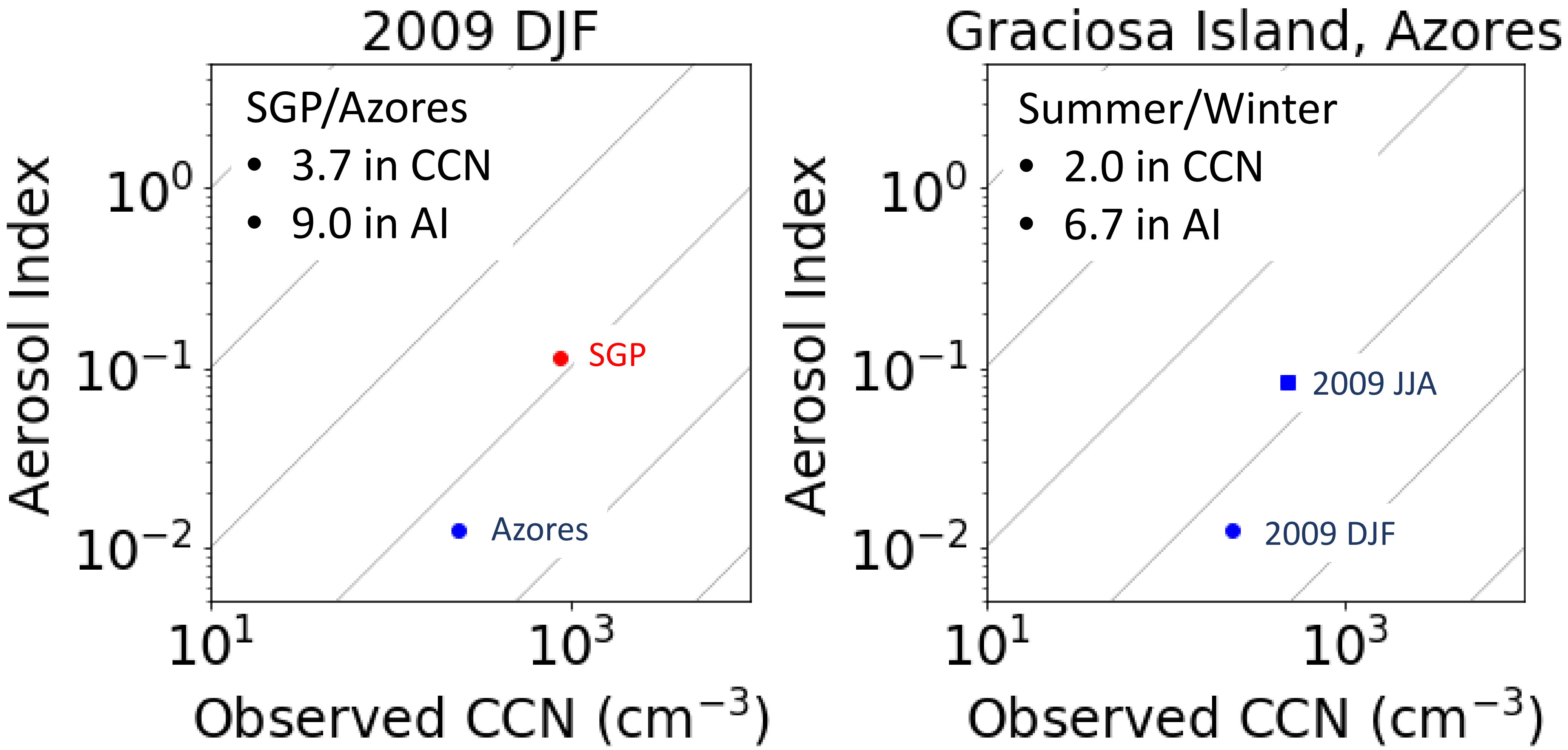
At 0.4% supersaturation
Jefferson, Wood

SGP/Azores
- 2.7 in CCN
- 2.3 in AI

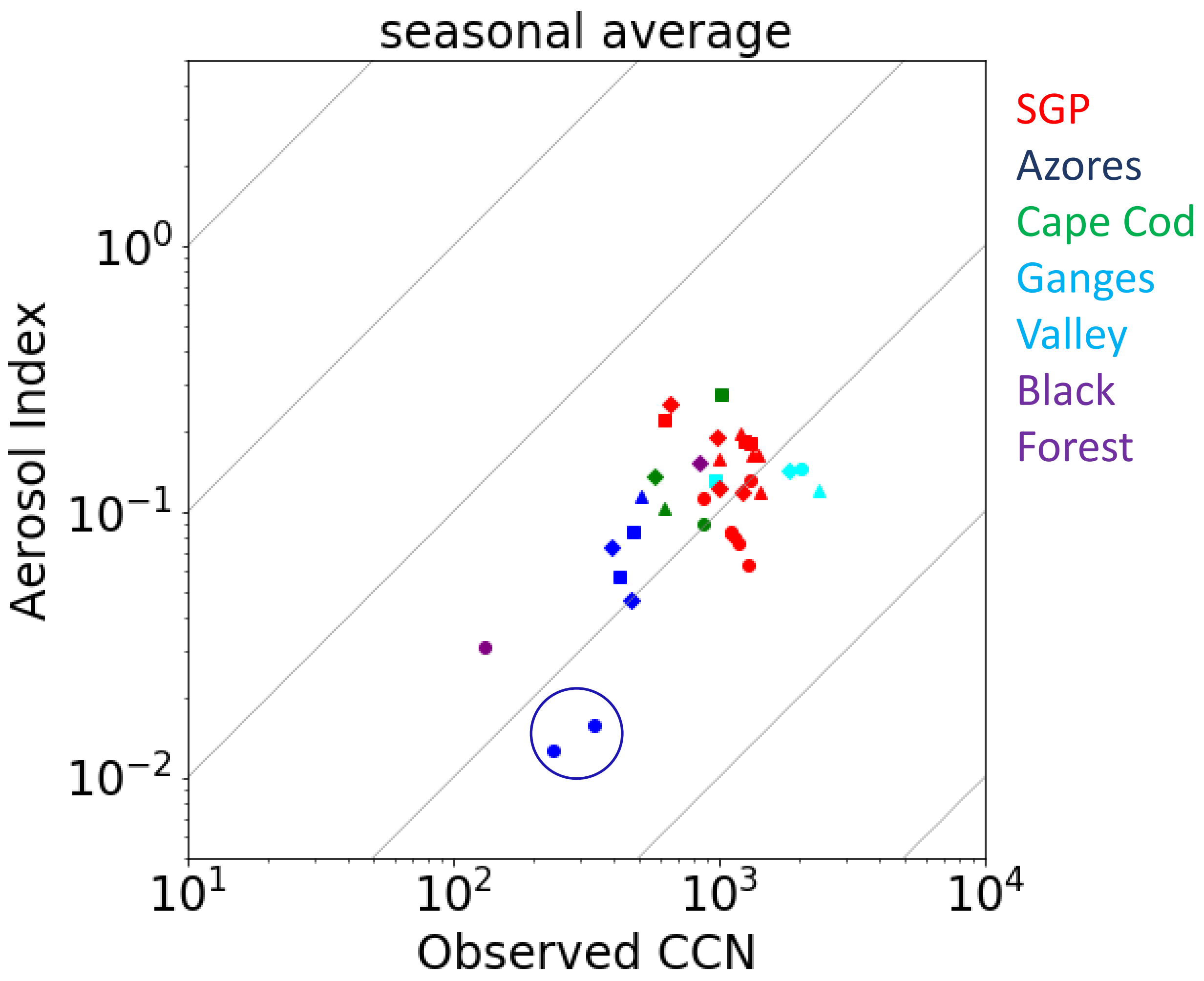
AI scales with CCN fairly well.

Not so well on a seasonal average basis (next slide).

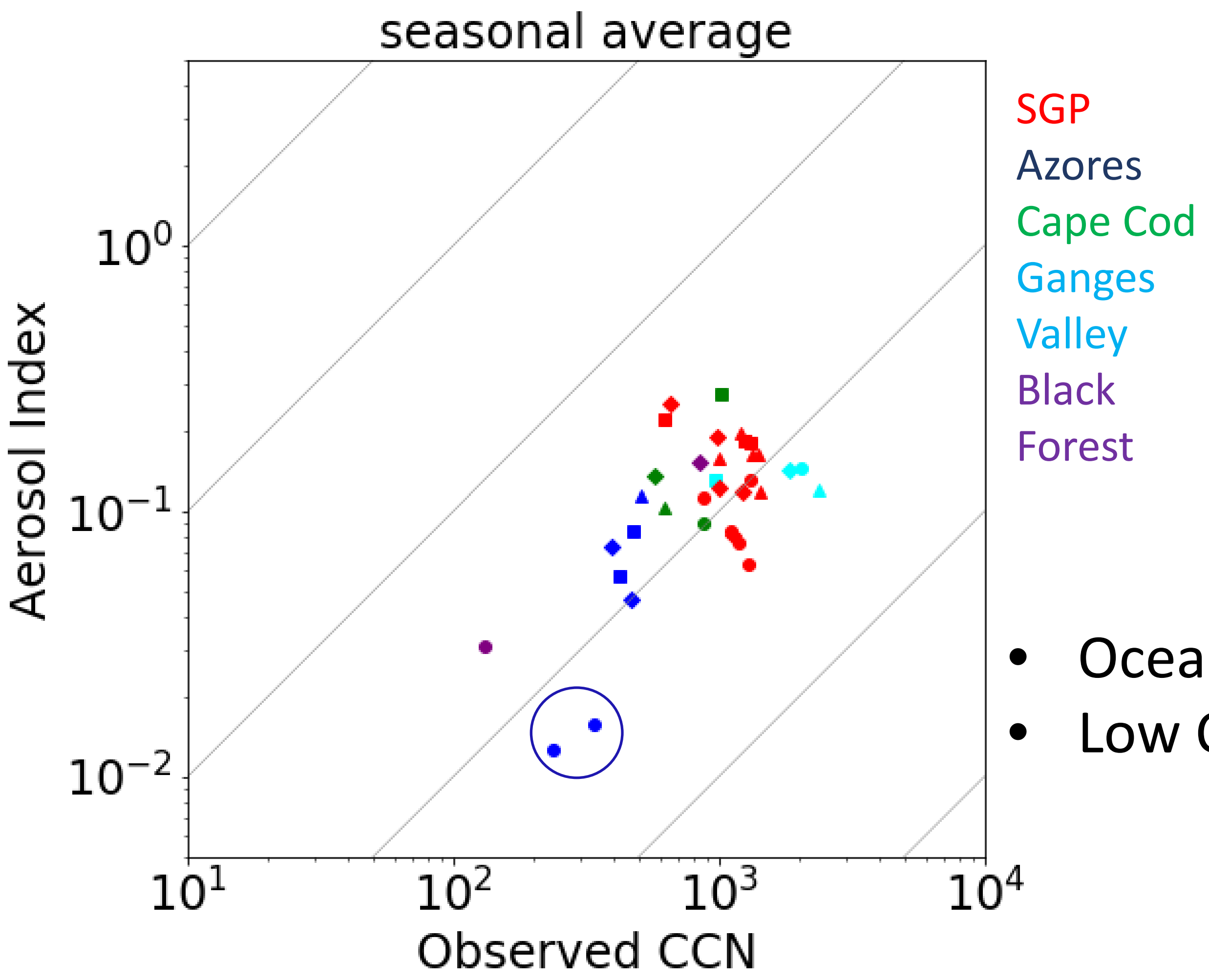
Is AI proportional to CCN?



AI exaggerates CCN’s site- and season-dependence…



AI exaggerates CCN’s site- and season-dependence…
for winter Azores

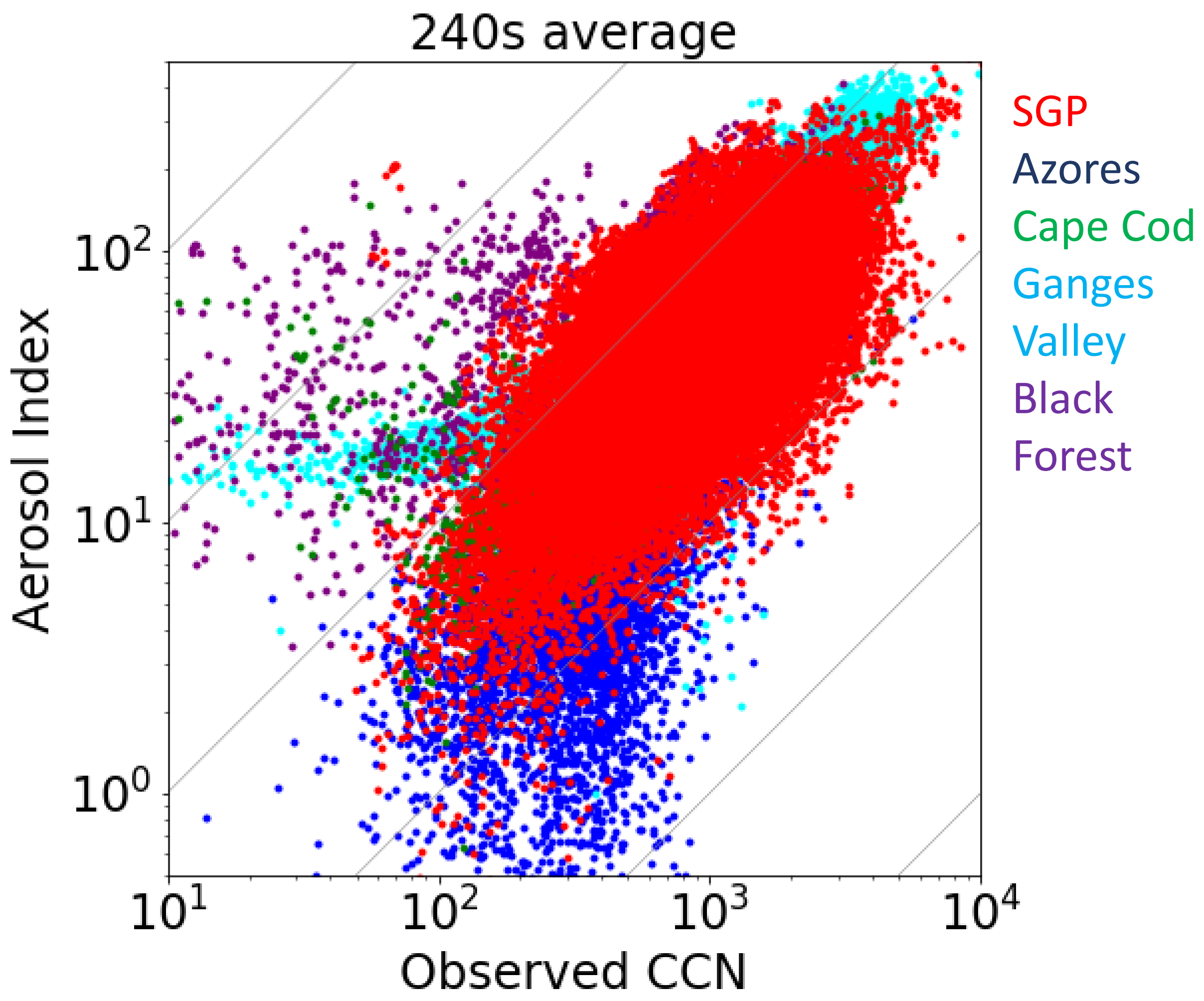


- Oceans underrepresented
- Low CCN values important

AI exaggerates CCN's site- and season-dependence…
for winter Azores

In situ dry AI-CCN relationship

500 nm dry extinction (Mm^{-1}) * Angstrom (450/700)
Jefferson



At 0.4% supersaturation
Jefferson, Wood

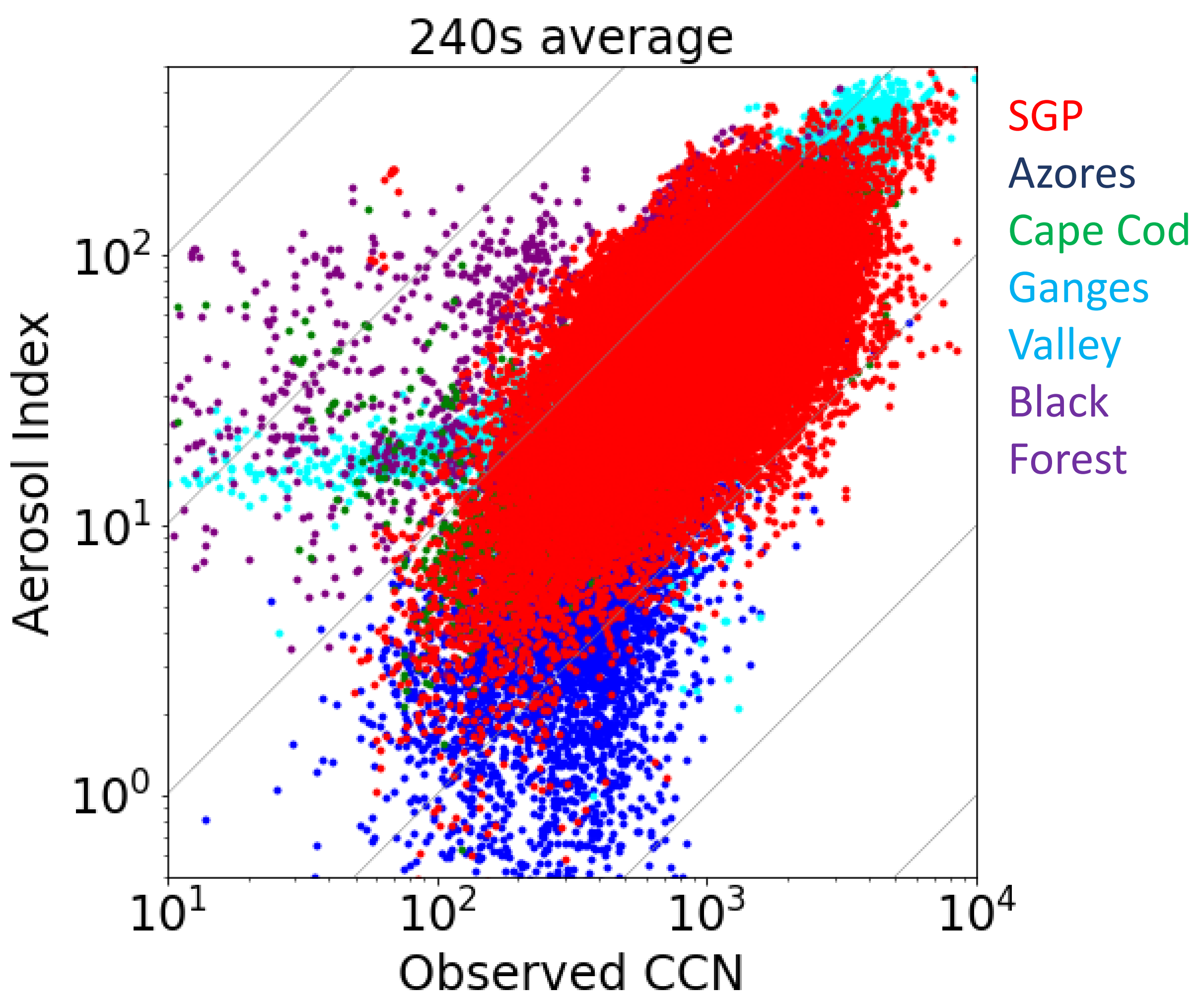
CCN Proxies

Aerosol Index AOD × Angstrom (α)	Derived from an AVHRR algorithm (Nakajima et al., 2001)	Total aerosol	Can be negative
CCN Index $10^{0.3\alpha+1.3}\sigma^{0.75}$ where σ is dry extinction	Fitted to in situ measurements (Shinozuka et al., 2015)	CCN at 0.4% supersaturation (variants at 0.2% and 0.6% also)	Always positive

Neither addresses the dependence on humidity and altitude; uncertainty in the input including Angstrom exponent; pre-industrial values

In situ dry AI-CCN relationship

500 nm dry extinction (Mm^{-1}) * Angstrom (450/700)
Jefferson

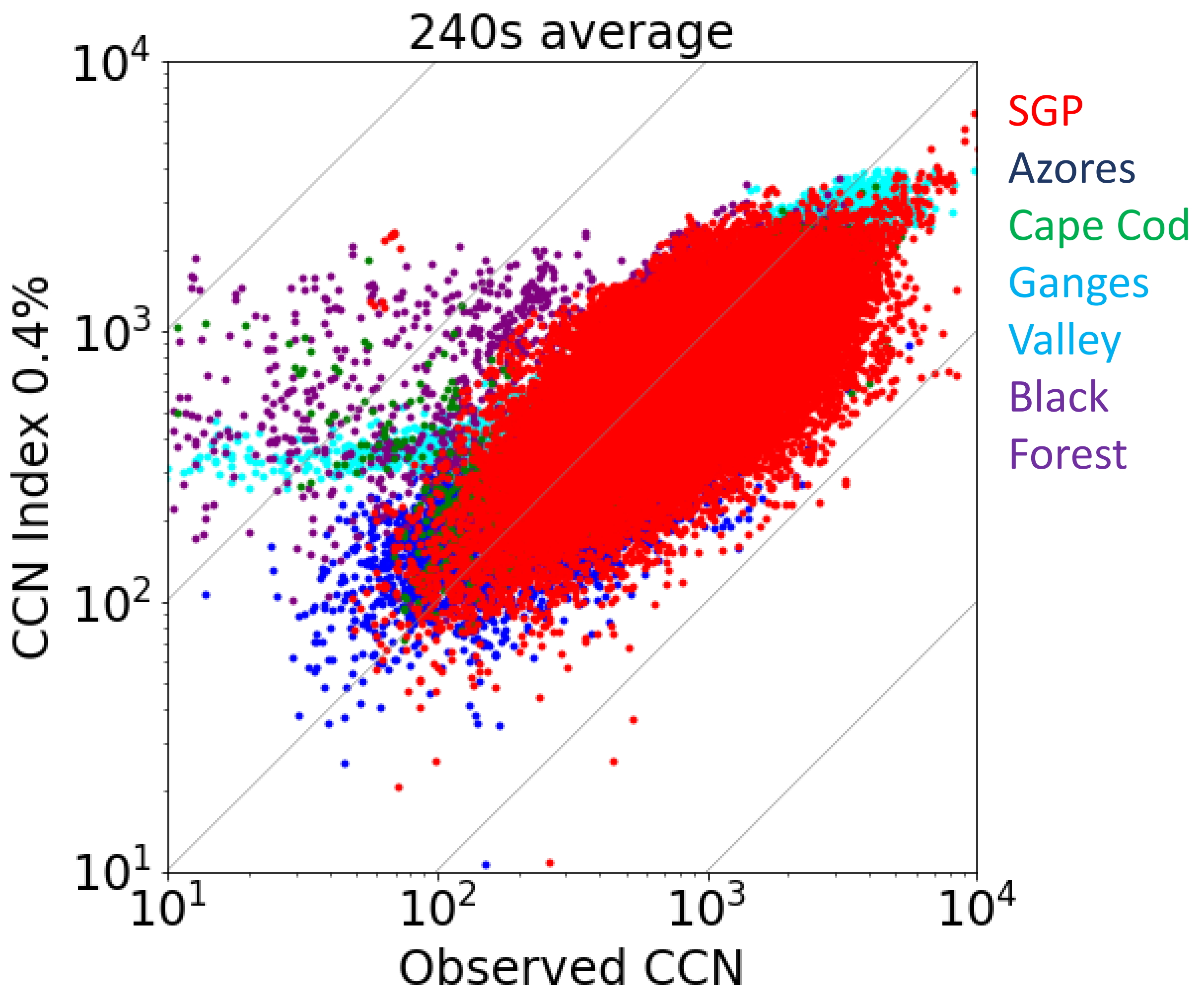


At 0.4% supersaturation
Jefferson, Wood

In situ dry CCNI-CCN relationship

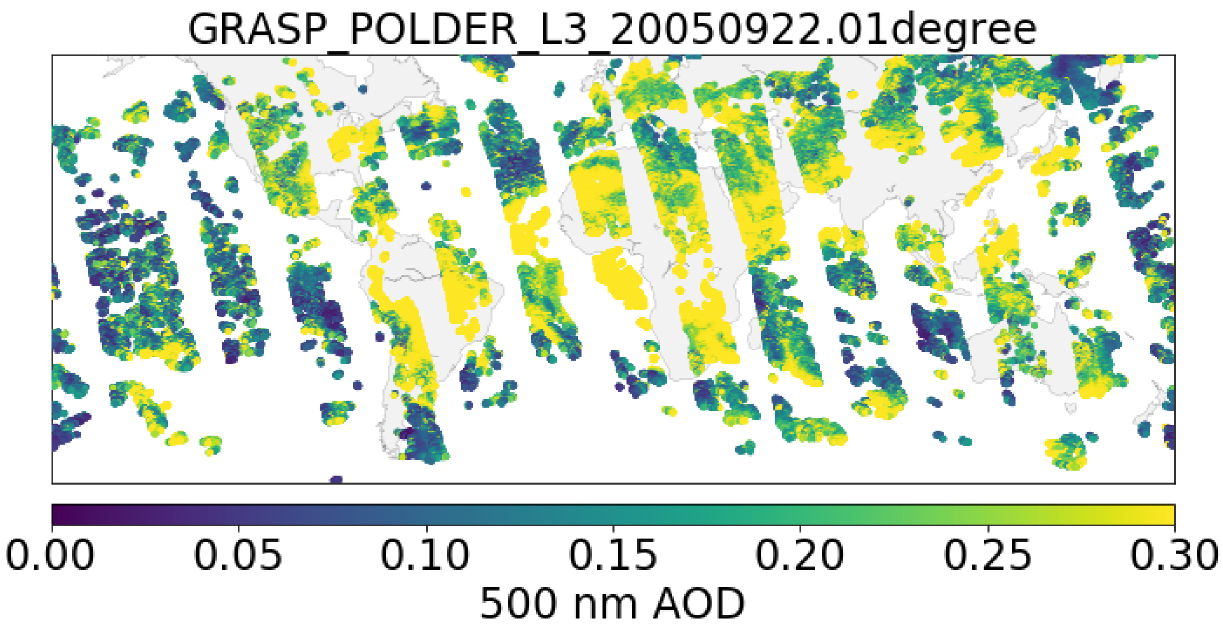
$10^{0.3\alpha+1.3}\sigma^{0.75}$

σ =500 nm dry ext (Mm^{-1}), α=Angstrom (450/700)
Jefferson

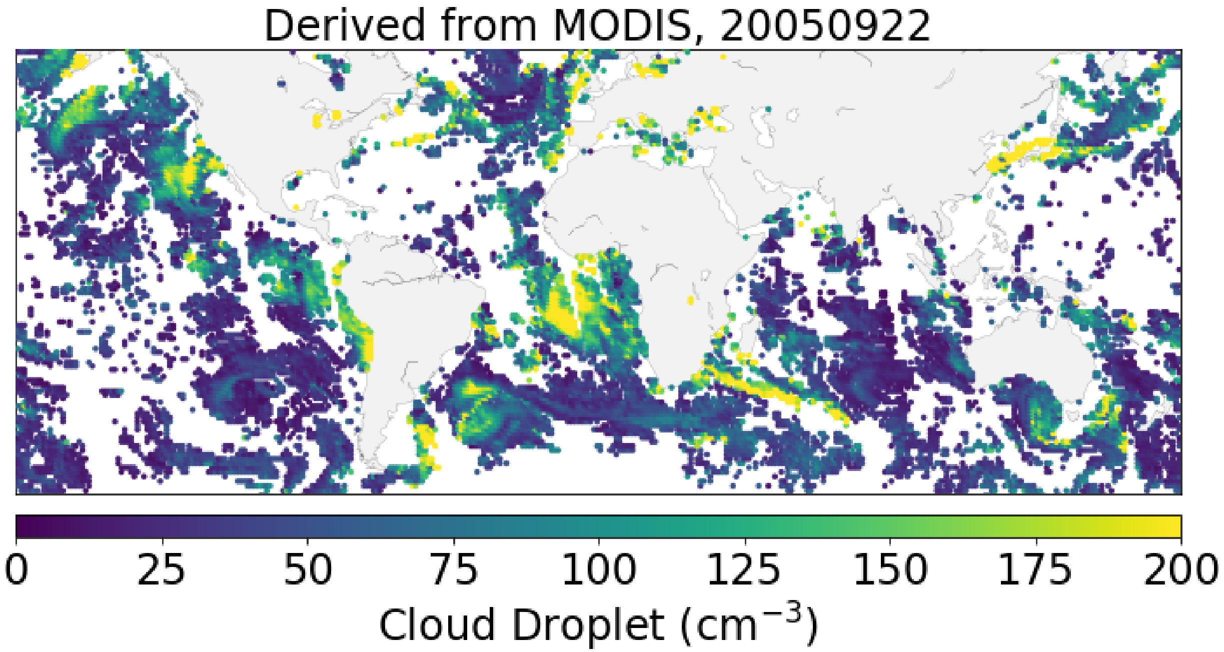


At 0.4% supersaturation
Jefferson, Wood

Regression for ACI

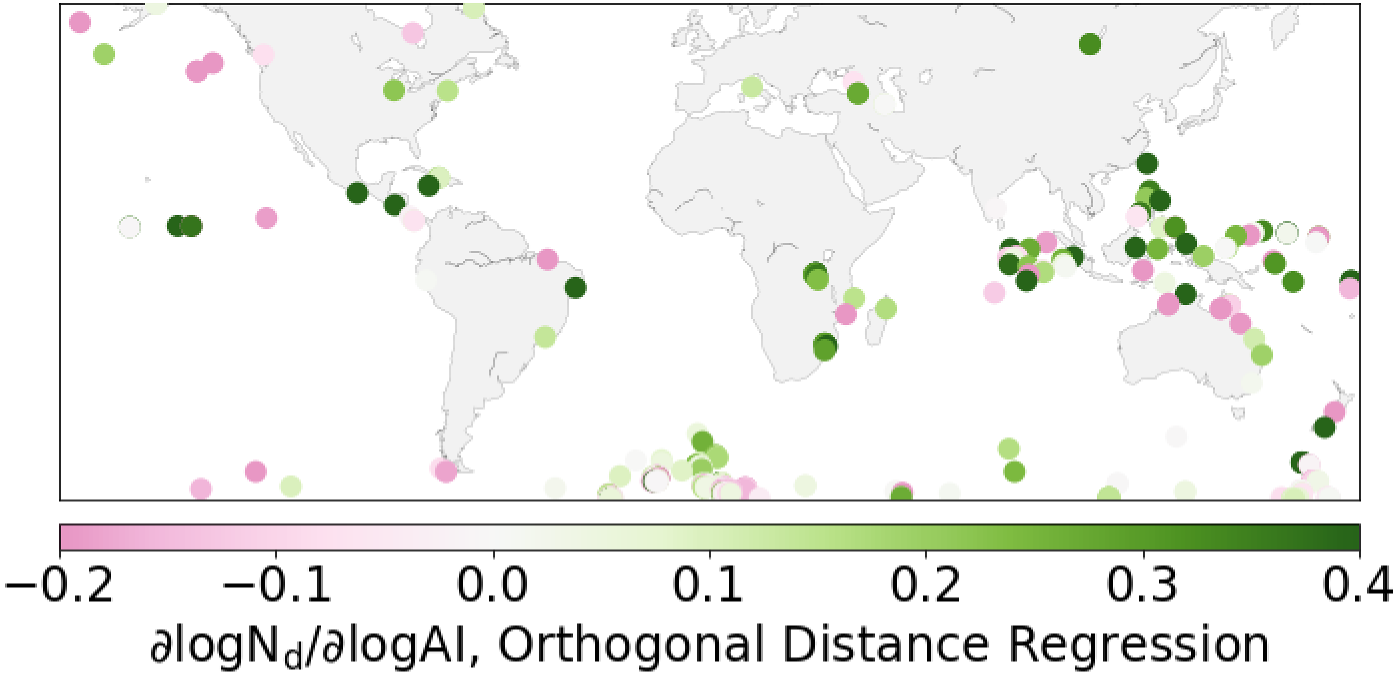


Dubovik, Fuertes and Lytvynov



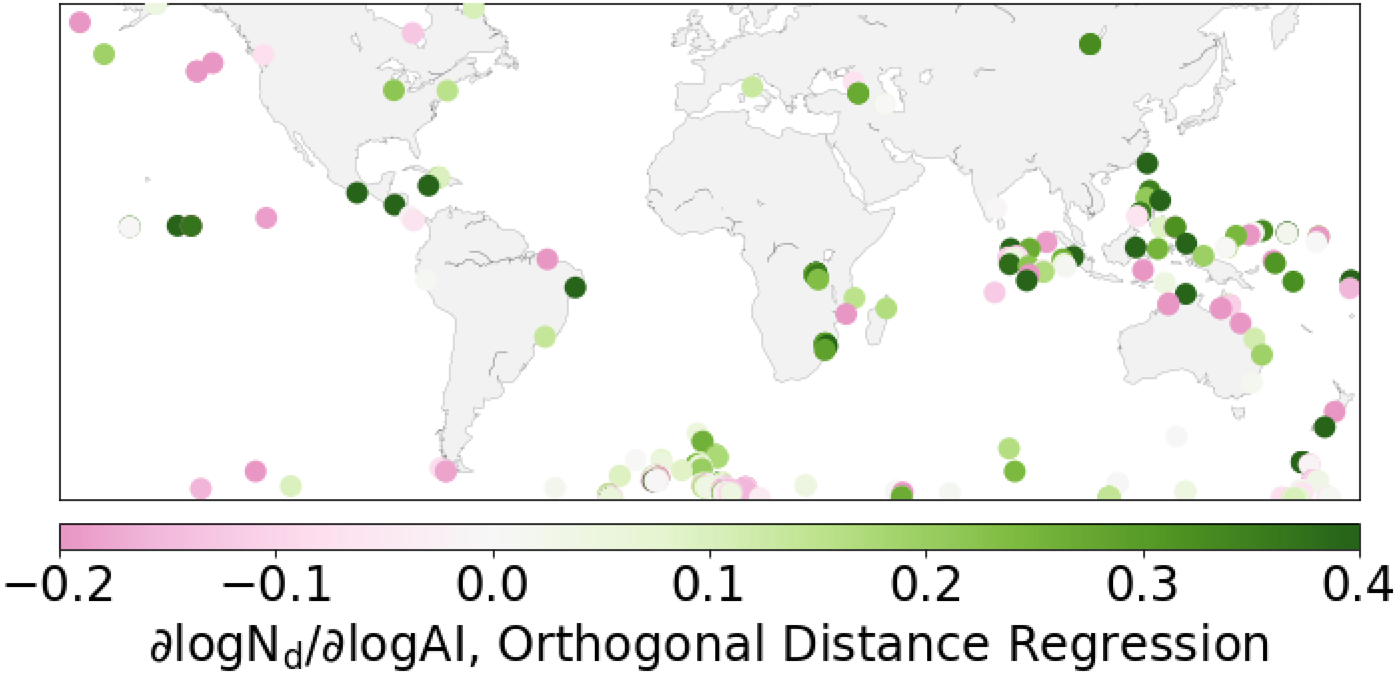
Bennartz and Rausch (2017)

Regression for ACI



Locations with a wide range of CCN proxy (gstd>0.5) only

Regression for ACI



Locations with a wide range of CCN proxy (gstd>0.5) only

Calculation to be repeated

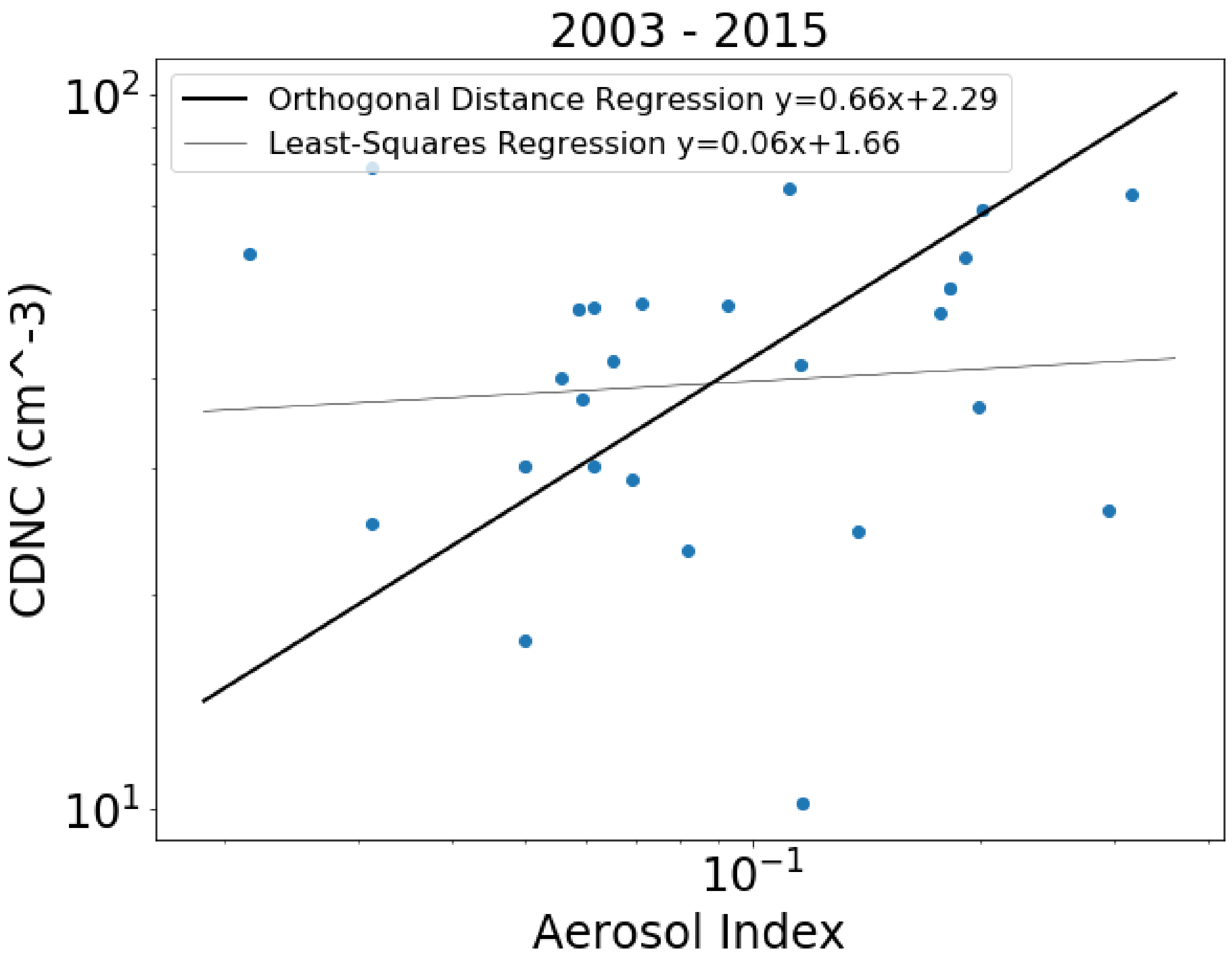
- with CCNI in place of AI
- by standard least-squares regression in place of orthogonal distance regression
- with a variety of uncertainty estimates
- with MODIS and MERRA-2 instead of PARASOL GRASP
- on a regional basis instead of 0.1 degree
- with land data
- on a seasonal basis instead of multi-year

Regression for ACI

We want to estimate the relationship with the true CCN concentration, not with a CCN proxy (CCNI or AI).

Errors in the CCN approximation must be considered.

Minimize the orthogonal distance, not the vertical.



Reference:

Technical Note: Review of methods for linear least-squares fitting of data and application to atmospheric chemistry problems

C. A. Cantrell

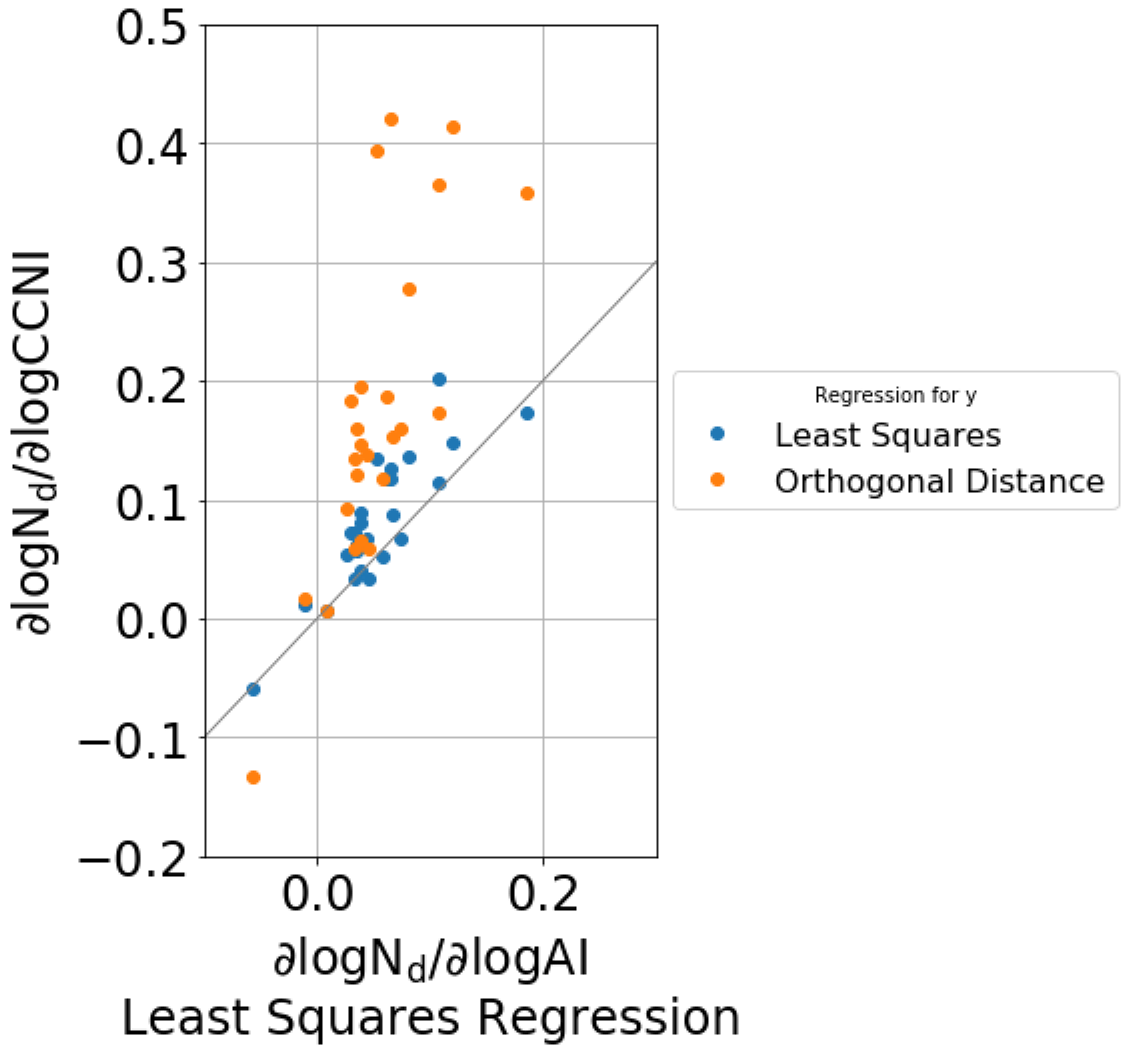
ACP, 2008

National Center for Atmospheric Research Atmospheric Chemistry Division 1850 Table Mesa Drive Boulder, CO 80305, USA

Regression for ACI

ACI (the partial derivative) is stronger with:

- CCNI in place of AI
- ODR in place of LSR

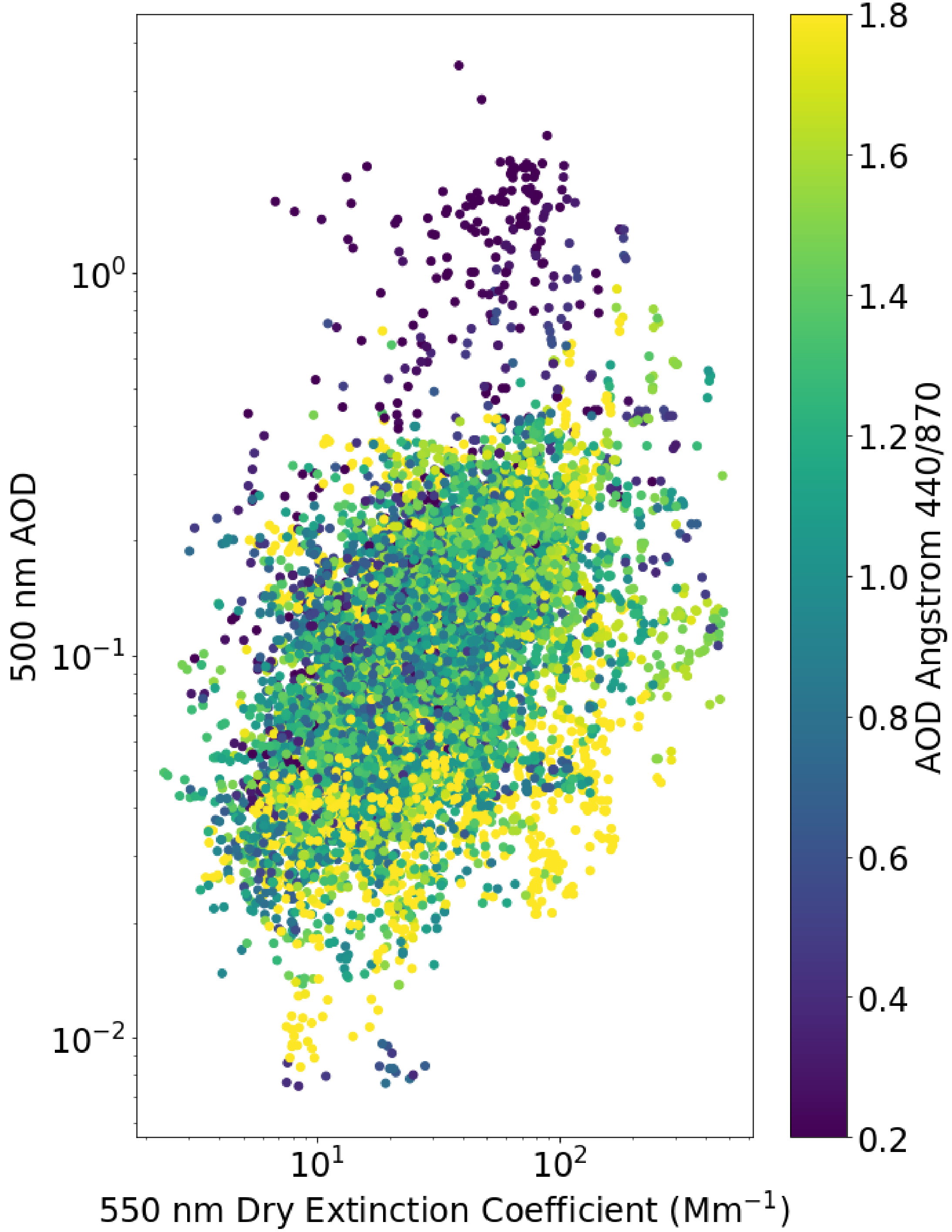


Locations with a wide range of CCN proxy (gstd>0.5) only

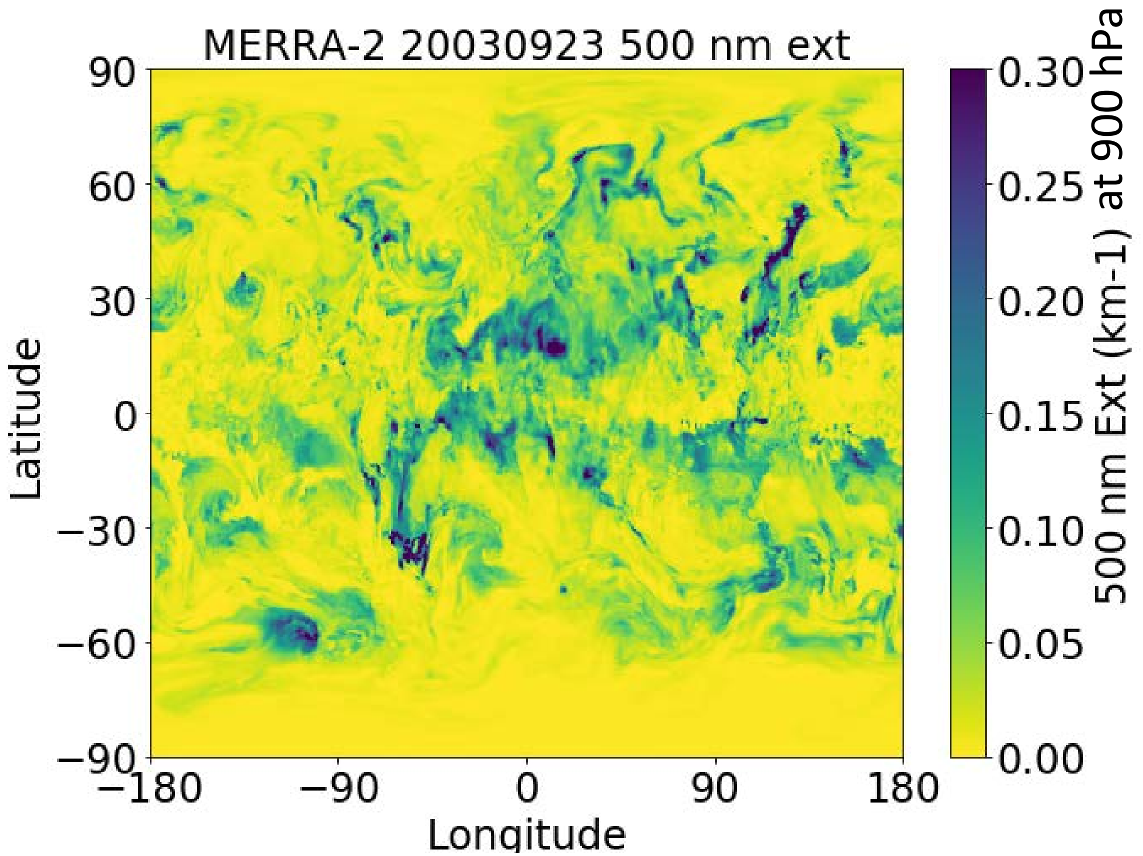
Coincident measurements of AOD and dry extinction at ARM/AERONET sites

•Positive correlation
•High variability
•A weak trend with Angstrom exp., possibly the effects on Azores marine aerosols of:

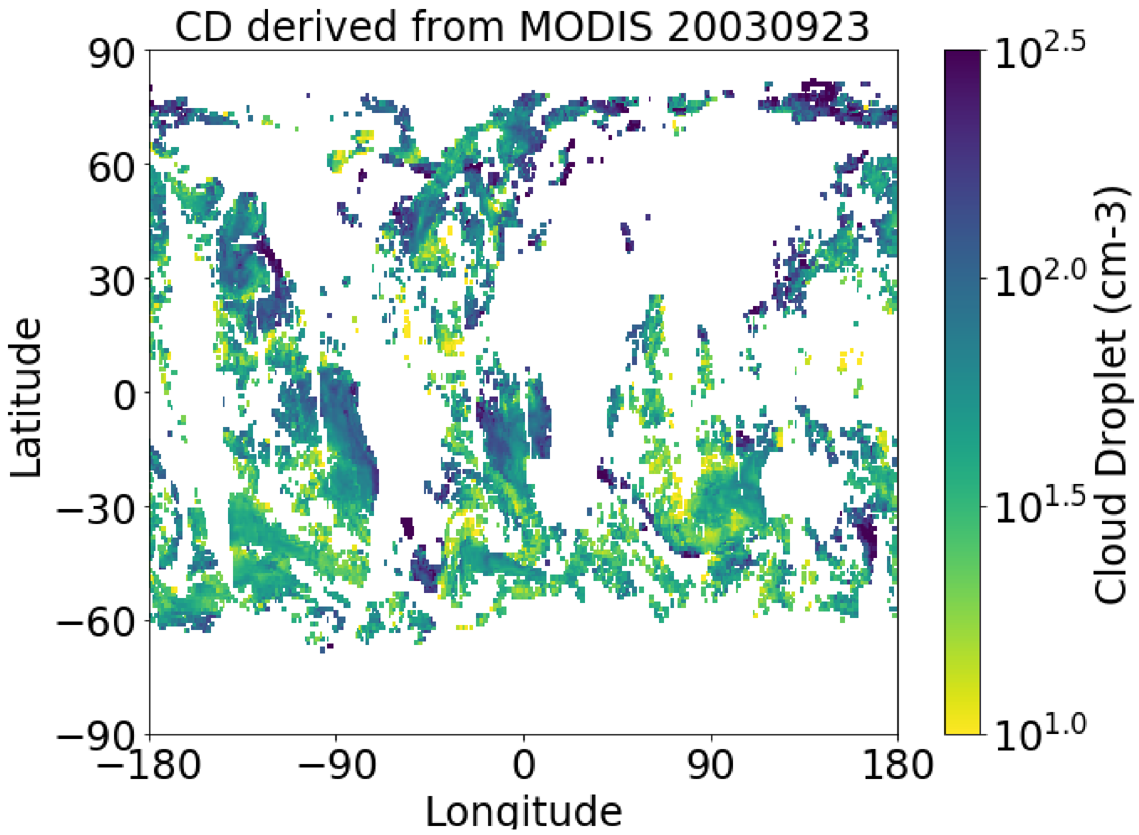
- removal of **particles >10 um** upstream of in situ instruments
- imperfect **cloud masking** of AERONET V2
- high **humidification**
- deeper **boundary layer height** (???)



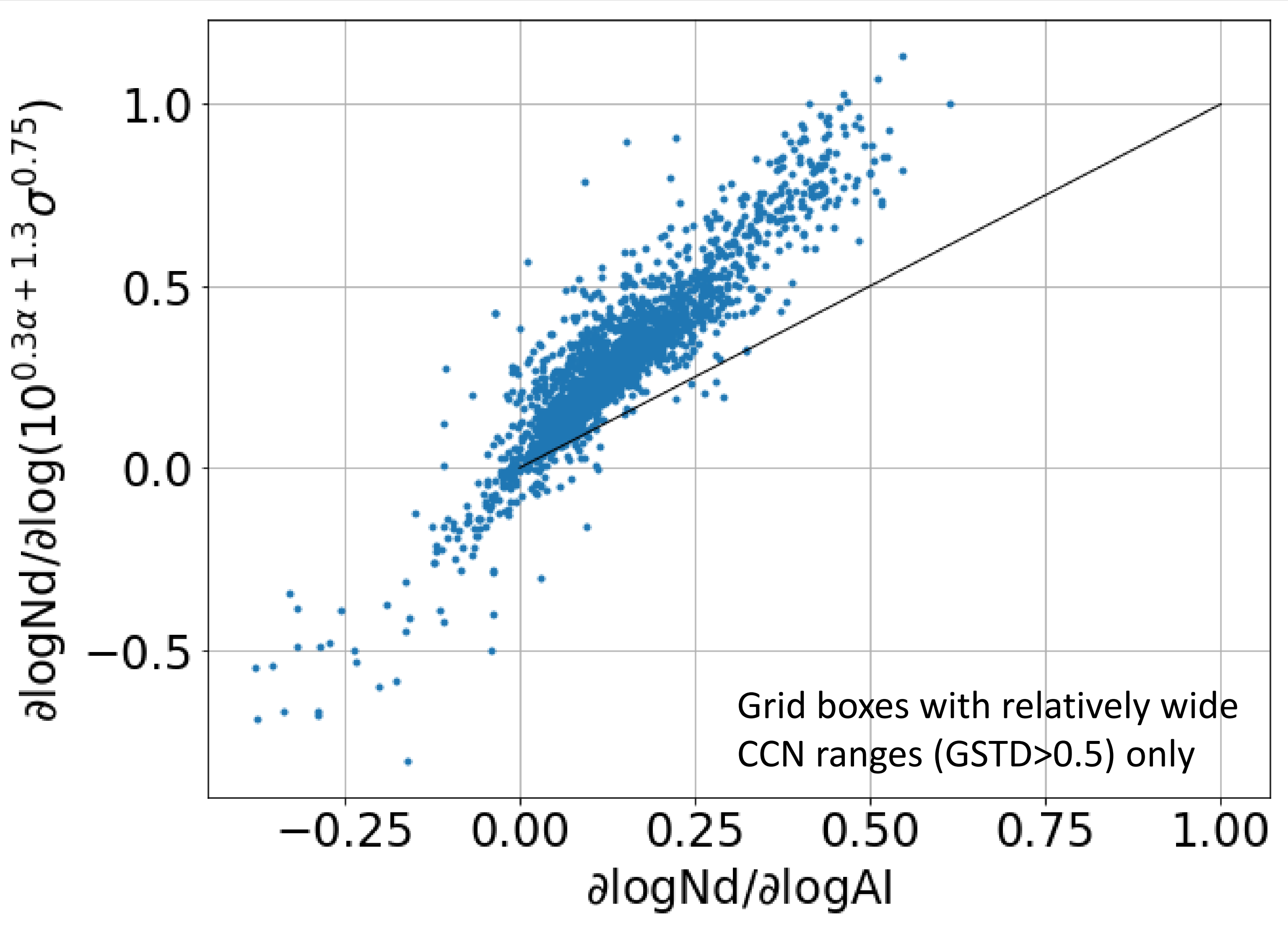
Altitude-resolved aerosol products, with a possibility to compute humidification



Arlindo M. da Silva, Ravi C. Govindaraju



Bennartz and Rausch (2017)



- The partial derivative is higher with the CCN Index (y axis).
- The use of AI may lead to an underestimate of aerosol-cloud interactions (ACI).

Summary

Satellite-based estimates may have been underestimated, because of:

- exaggerated CCN variability
- the use of standard least-squares regression

besides the scale problem (Grandey and Stier, 2010; McComiskey and Feingold, 2012).

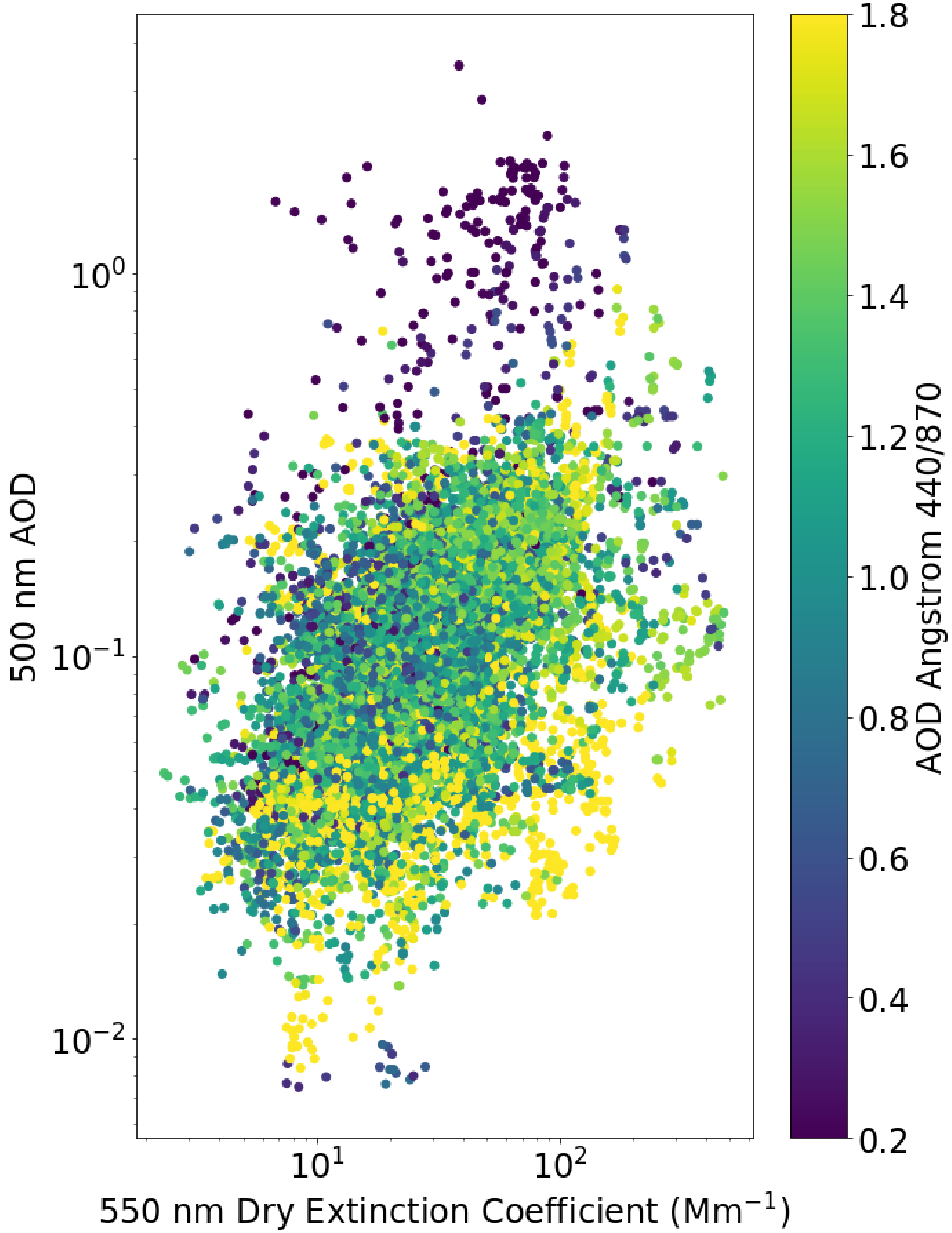
Next steps

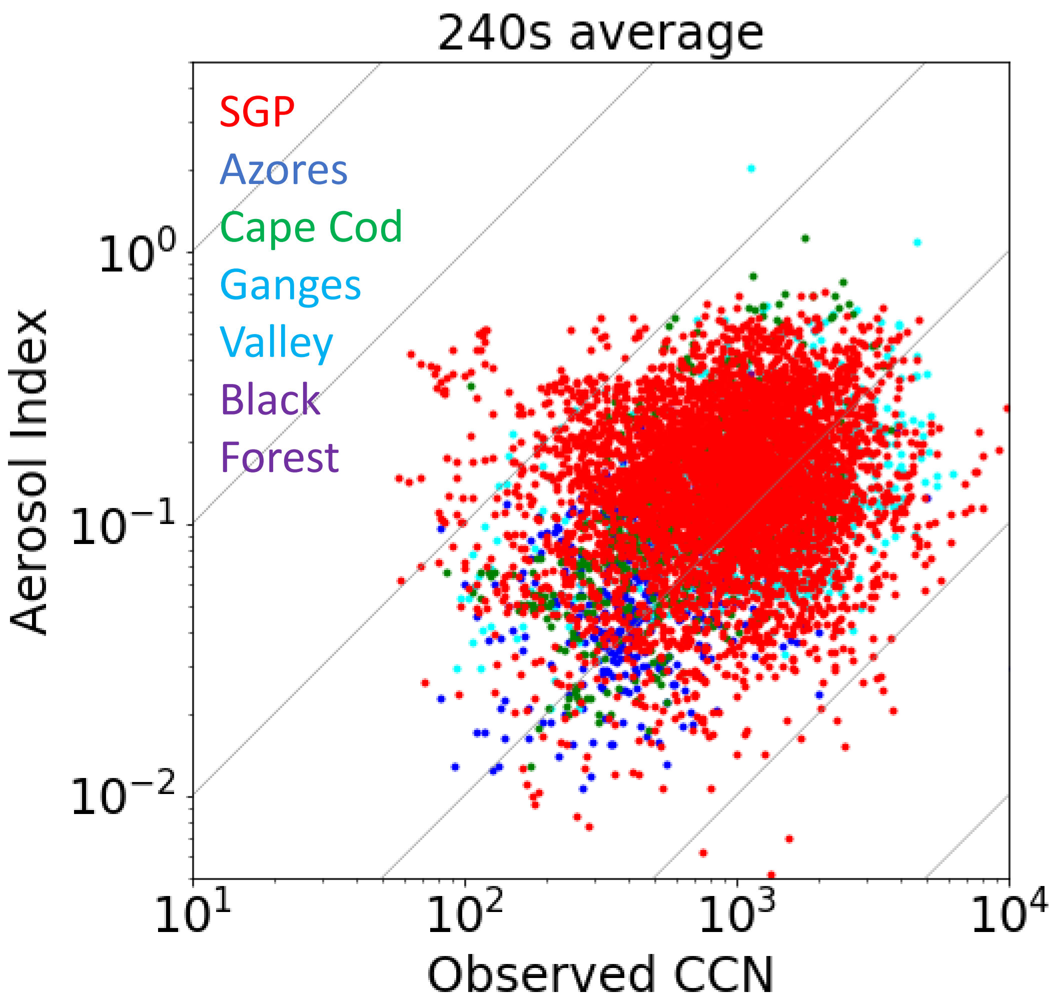
- Refine CCN approximation: retrieval uncertainty, vertical profile, humidification, fine-mode AOD
- Update ACI estimates: horizontal and temporal resolution, clouds over land, trends since 2002, radiative effects and forcing

Back-up slides

Coincident measurements of AOD and dry extinction at ARM/AERONET sites

- Positive correlation
- High variability
- A weak trend with Angstrom exp., possibly the effects on Azores marine aerosols of:
    - removal of **particles >10 um** upstream of in situ instruments
    - imperfect **cloud masking** of AERONET V2
    - high **humidification**
    - deeper **boundary layer height** (???)





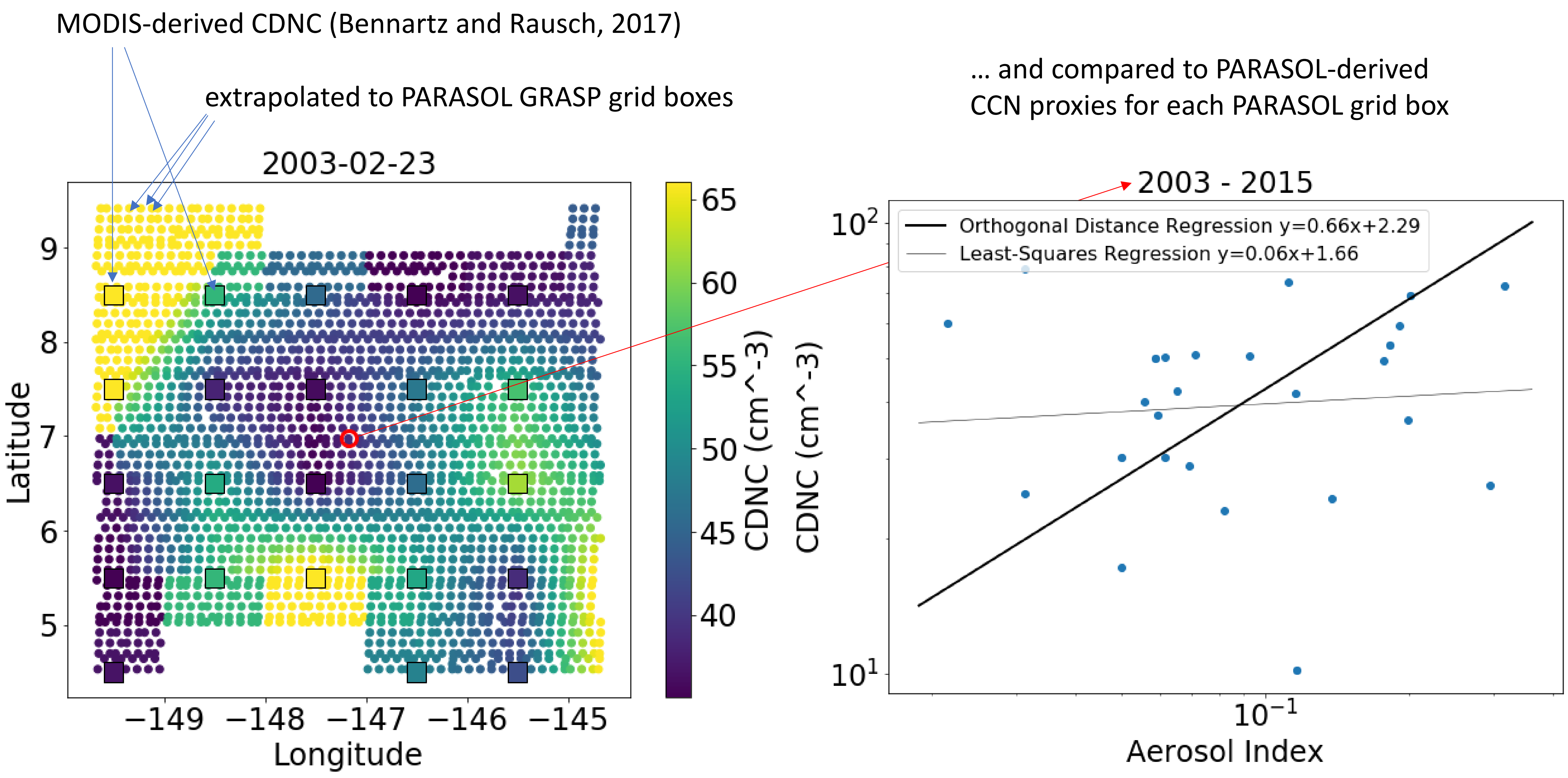
240s average
SGP
Azores
Cape Cod
Ganges
Valley
Black
Forest
Aerosol Index
Observed CCN
10^0
10^{-1}
10^{-2}
10^1
10^2
10^3
10^4

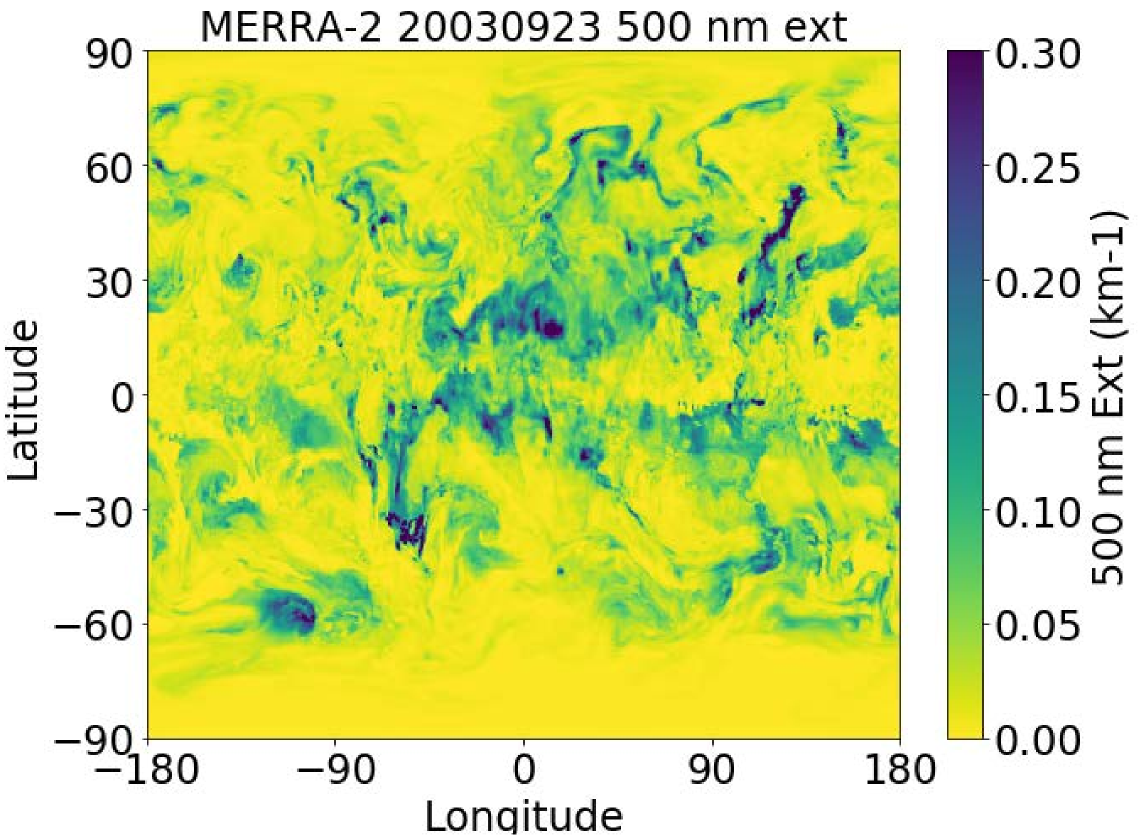
Relative variability (geometric standard deviation) of AI/CCN (coincident with in situ or not)

	Not sorted by site	Graciosa Island, Azores	Ganges Valley, India	Black Forest, Germany	Cape Cod, USA	Southern Great Plains, USA	Avg of Site GSTDs
Not sorted by season	2.4	2.2	2.1	1.5	2.0	2.5	2.1
DJF	2.2	2.3	1.9	-	-	2.2	2.2
MAM	2.1	-	1.9	-	1.7	2.2	2.1
JJA	1.9	-	-	-	-	1.9	1.9
SON	2.4	1.7	3.4	-	2.4	2.4	2.3
Avg of Seasonal GSTDs	2.2	1.9	2.4	-	2.1	2.2	

Relative variability (geometric standard deviation) of AI/CCN (for AERONET data coincident with in situ measurements)

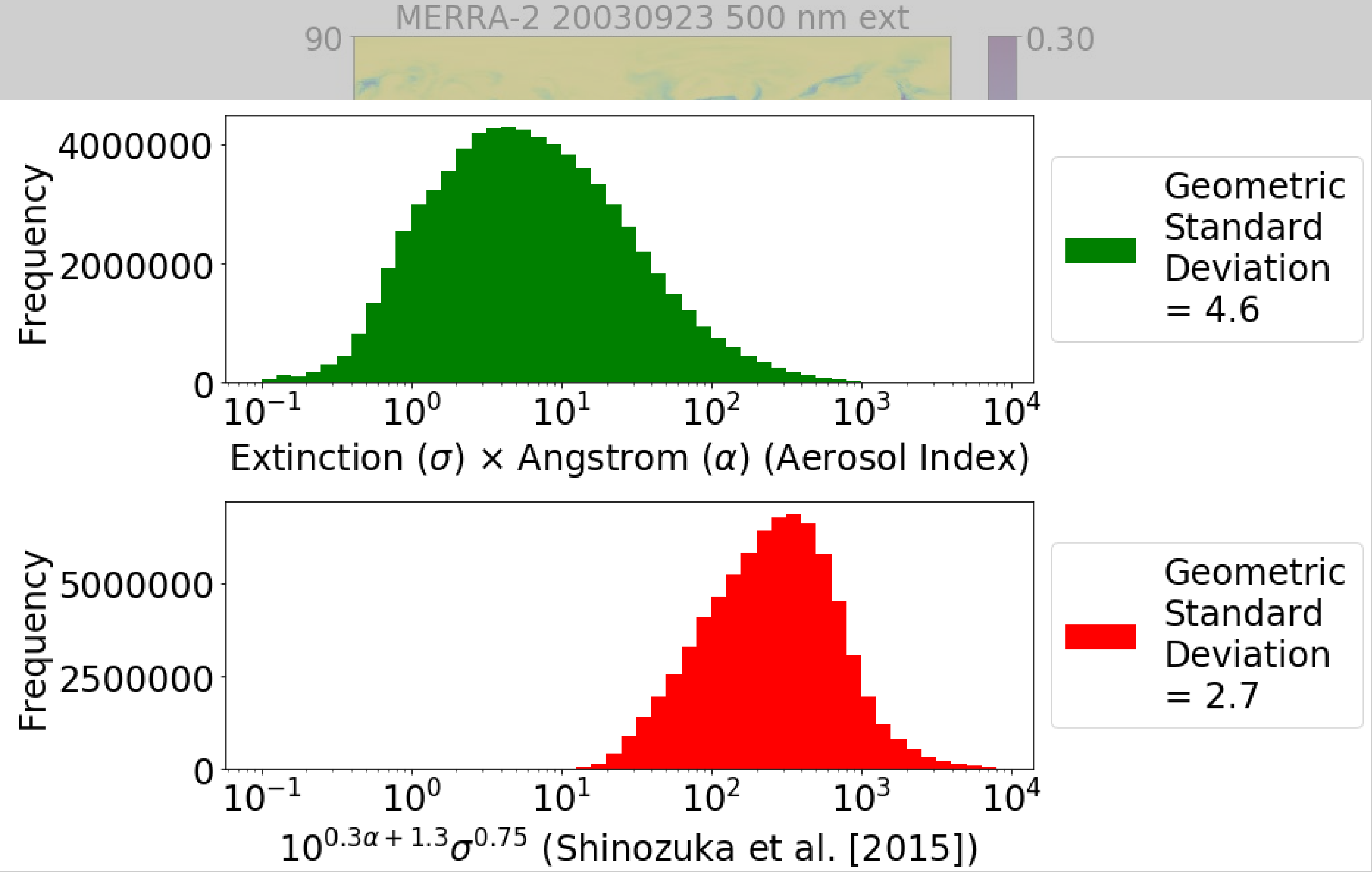
	Not sorted by site	Graciosa Island, Azores	Ganges Valley, India	Black Forest, Germany	Cape Cod, USA	Southern Great Plains, USA	Avg of Site GSTDs
Not sorted by season	2.4	2.1	1.9	1.4	2.0	2.4	2.0
DJF	2.1	-	1.9	-	-	2.2	2.1
MAM	2.1	-	1.9	-	1.7	2.2	2.1
JJA	1.9	-	-	-	-	1.9	1.9
SON	2.2	1.7	-	-	2.2	2.5	2.2
Avg of Seasonal GSTDs	2.1	1.7	1.9	-	2.0	2.2	

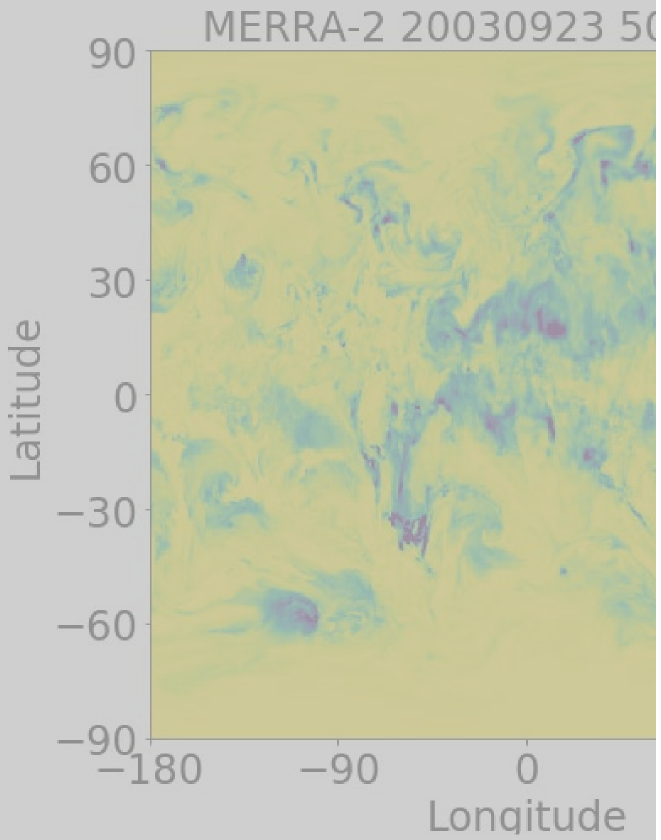

MODIS-derived CDNC (Bennartz and Rausch, 2017)
extrapolated to PARASOL GRASP grid boxes
... and compared to PARASOL-derived
CCN proxies for each PARASOL grid box
2003-02-23
Latitude
Longitude
CDNC (cm^-3)
2003 - 2015
Orthogonal Distance Regression y=0.66x+2.29
Least-Squares Regression y=0.06x+1.66
CDNC (cm^-3)
Aerosol Index

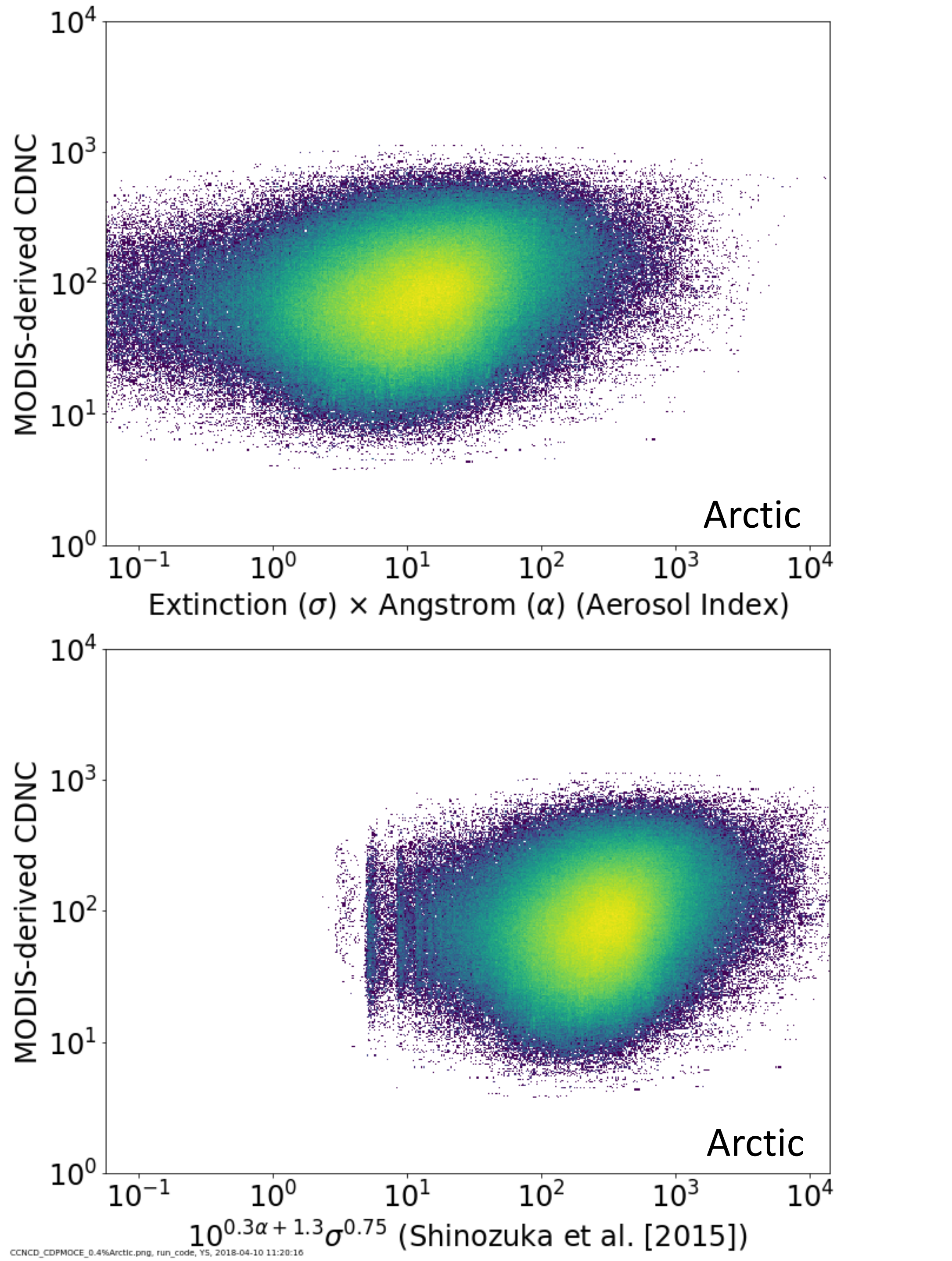


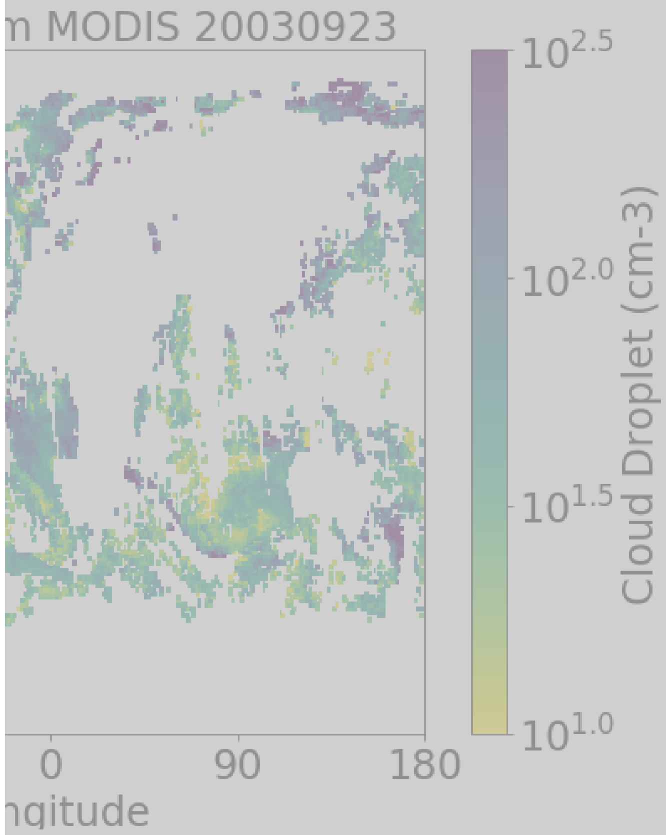
MERRA-II aerosol extinction from Arlindo M. da Silva, Ravi C. Govindaraju

• Aerosol Index varies more than cloud condensation nuclei (CCN).









Arlindo M. da Silva, Ravi … nd Rausch (2017)

Definitions of aerosol-cloud interactions (ACI)

The scale problem in quantifying aerosol indirect effects

A. McComiskey[1,2] and G. Feingold[2]

2012

ACI has been reported or derived later from measurements published in the literature for almost two decades. A variety of proxies has been used to represent the aerosol particles affecting the cloud, including aerosol number concentration N_a, τ_a, and aerosol index AI (the product of τ_a and the Ångström exponent), all of which will henceforth be denoted by α. Similarly, various proxies have been used to represent the cloud response to the change in aerosol, e.g., cloud optical depth τ_c, cloud drop number concentration N_d, and r_e. Using data for which the analysis scale closely matched the process scale, McComiskey et al. (2009) showed empirically that there is consistency amongst calculations of ACI using different microphysical proxies, provided the appropriate constraint on cloud liquid water path L is applied. Thus,

$$\mathrm{ACI}_\tau = \left.\frac{\partial \ln \tau_c}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_\tau < 0.33 \qquad (1a)$$

$$\mathrm{ACI}_r = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_r < 0.33 \qquad (1b)$$

$$\mathrm{ACI}_N = \frac{d \ln N_d}{d \ln \alpha} \qquad 0 < \mathrm{ACI}_N < 1 \qquad (1c)$$

$$\mathrm{ACI}_\tau = -\mathrm{ACI}_r = \frac{1}{3}\mathrm{ACI}_N. \qquad (1d)$$

Definitions of aerosol-cloud interactions (ACI)

The scale problem in quantifying aerosol indirect effects

A. McComiskey[1,2] and G. Feingold[2]

2012

ACI has been reported or derived later from measurements published in the literature for almost two decades. A variety of proxies has been used to represent the aerosol particles affecting the cloud, including aerosol number concentration N_a, τ_a, and aerosol index AI (the product of τ_a and the Ångström exponent), all of which will henceforth be denoted by α. Similarly, various proxies have been used to represent the cloud response to the change in aerosol, e.g., cloud optical depth τ_c, cloud drop number concentration N_d, and r_e. Using data for which the analysis scale closely matched the process scale, McComiskey et al. (2009) showed empirically that there is consistency amongst calculations of ACI using different microphysical proxies, provided the appropriate constraint on cloud liquid water path L is applied. Thus,

$$\mathrm{ACI}_\tau = \left.\frac{\partial \ln \tau_c}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_\tau < 0.33 \tag{1a}$$

$$\mathrm{ACI}_r = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_r < 0.33 \tag{1b}$$

$$\mathrm{ACI}_N = \frac{d \ln N_d}{d \ln \alpha} \qquad 0 < \mathrm{ACI}_N < 1 \tag{1c}$$

$$\mathrm{ACI}_\tau = -\mathrm{ACI}_r = \frac{1}{3}\mathrm{ACI}_N. \tag{1d}$$

Satellite-based estimate of the direct and indirect aerosol climate forcing

2008

Johannes Quaas,[1] Olivier Boucher,[2] Nicolas Bellouin,[2] and Stefan Kinne[1]

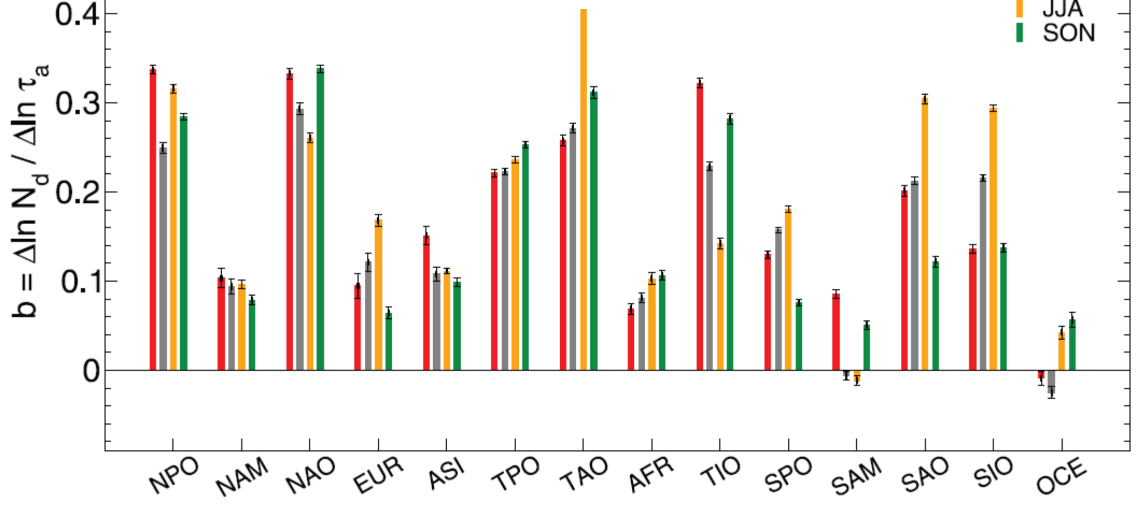


Figure 3. Slopes of the linear regression ln CDNC versus ln AOD for the different regions and seasons. Error bars show 10 times the standard deviation (a list of abbreviations is given in Table 1).

Definitions of aerosol-cloud interactions (ACI)

The scale problem in quantifying aerosol indirect effects

A. McComiskey[1,2] and G. Feingold[2]

2012

ACI has been reported or derived later from measurements published in the literature for almost two decades. A variety of proxies has been used to represent the aerosol particles affecting the cloud, including aerosol number concentration N_a, τ_a, and aerosol index AI (the product of τ_a and the Ångström exponent), all of which will henceforth be denoted by α. Similarly, various proxies have been used to represent the cloud response to the change in aerosol, e.g., cloud optical depth τ_c, cloud drop number concentration N_d, and r_e. Using data for which the analysis scale closely matched the process scale, McComiskey et al. (2009) showed empirically that there is consistency amongst calculations of ACI using different microphysical proxies, provided the appropriate constraint on cloud liquid water path L is applied. Thus,

$$\mathrm{ACI}_\tau = \left.\frac{\partial \ln \tau_c}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_\tau < 0.33 \tag{1a}$$

$$\mathrm{ACI}_r = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_r < 0.33 \tag{1b}$$

$$\mathrm{ACI}_N = \frac{d \ln N_d}{d \ln \alpha} \qquad 0 < \mathrm{ACI}_N < 1 \tag{1c}$$

$$\mathrm{ACI}_\tau = -\mathrm{ACI}_r = \frac{1}{3}\mathrm{ACI}_N. \tag{1d}$$

Satellite-based estimate of the direct and indirect aerosol climate forcing

2008

Johannes Quaas,[1] Olivier Boucher,[2] Nicolas Bellouin,[2] and Stefan Kinne[1]

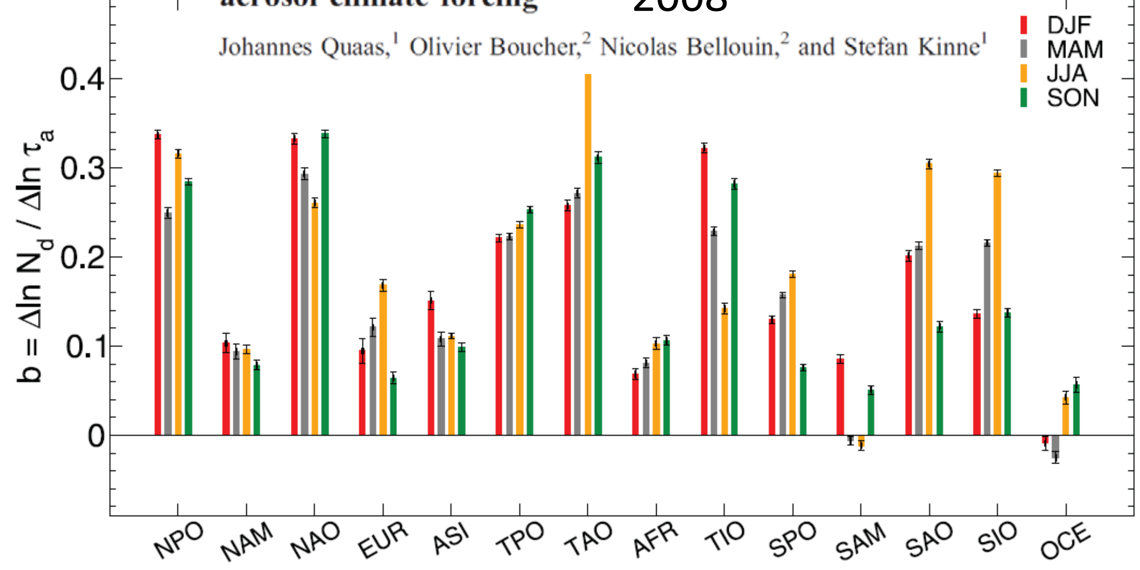
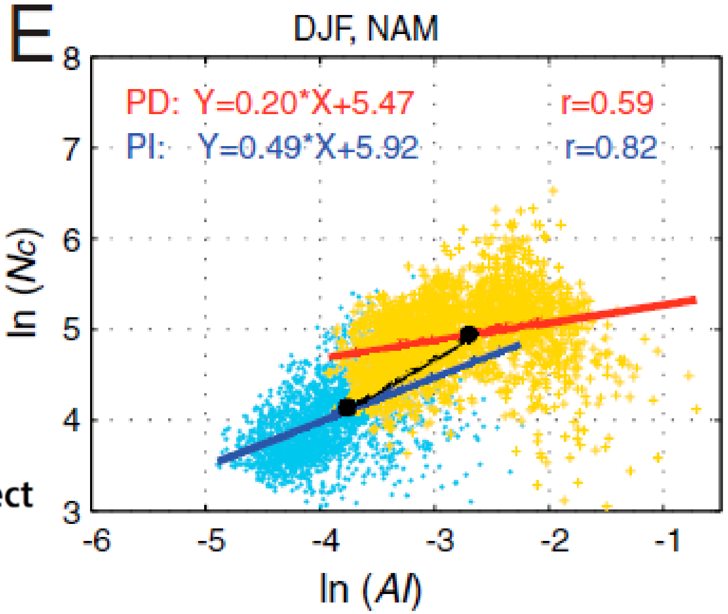


Figure 3. Slopes of the linear regression ln CDNC versus ln AOD for the different regions and seasons. Error bars show 10 times the standard deviation (a list of abbreviations is given in Table 1).

Satellite methods underestimate indirect climate forcing by aerosols

Joyce E. Penner[a,1], Li Xu[a], and Minghuai Wang[b]

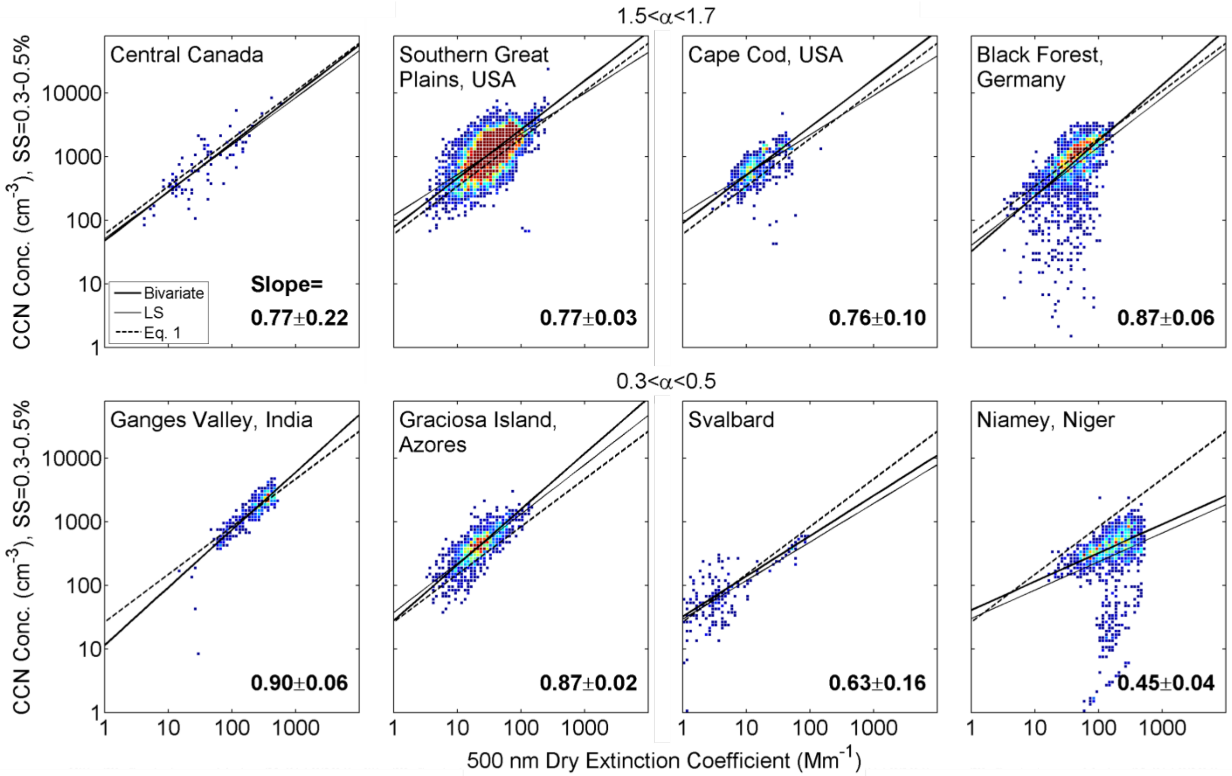
2011



Ground-based and airborne measurements

The relationship between CCN and dry extinction

- **The slope is less than unity**. Condensation increases extinction but not number.
- $CCN_{SS\sim0.4\%}(cm^{-3}) = \mathbf{10^{0.3\alpha+1.3}\sigma^{0.75}}$
  σ: dry ext. (Mm^{-1}),
  α: Angstrom exp.
  RMS deviation is a factor of 2.0.



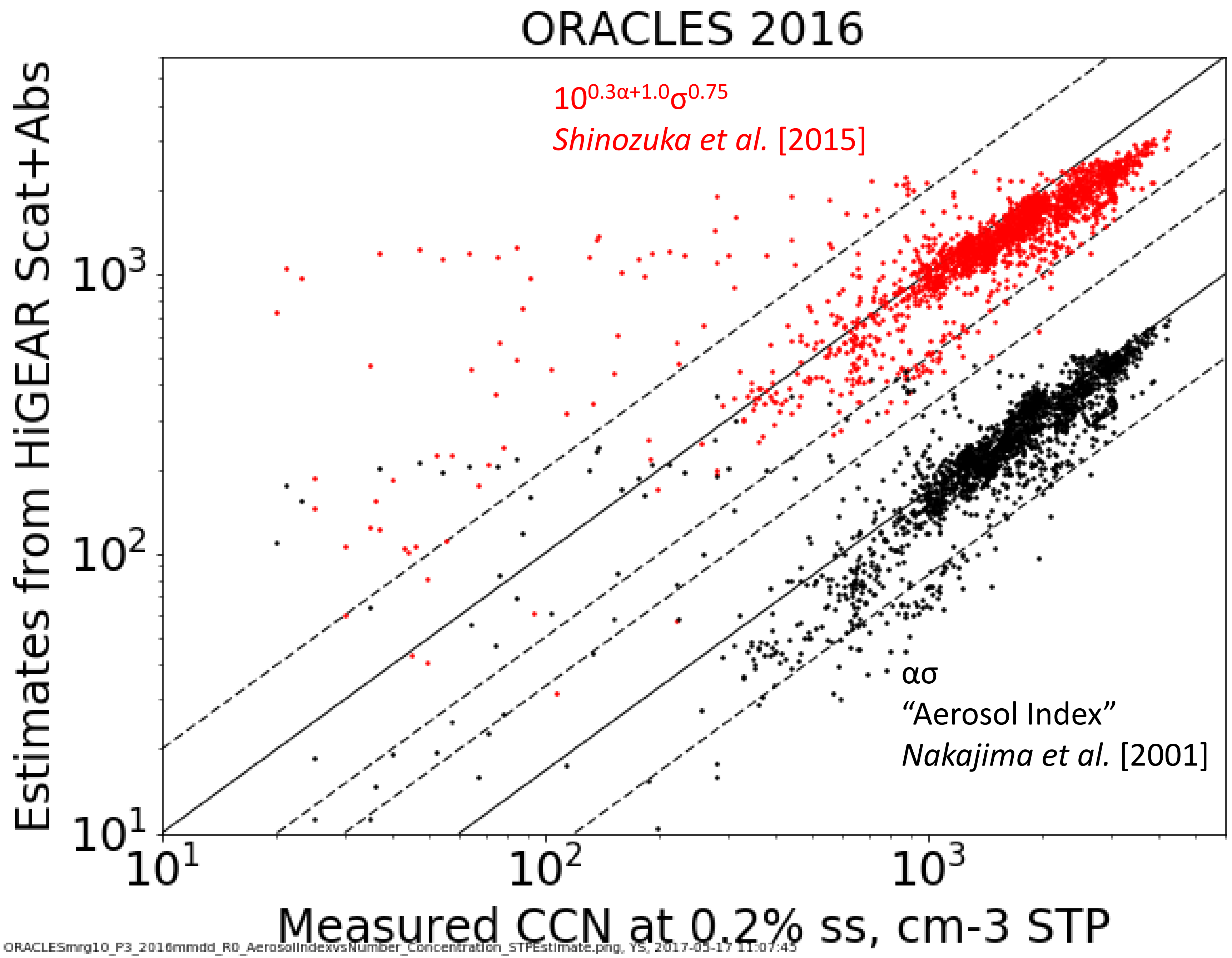
in situ observations

Shinozuka et al., ACP 2015

Preliminary data from GIT (Kacarab, Nenes), HiGEAR (Dobracki, Freitag, Howell, et al.)

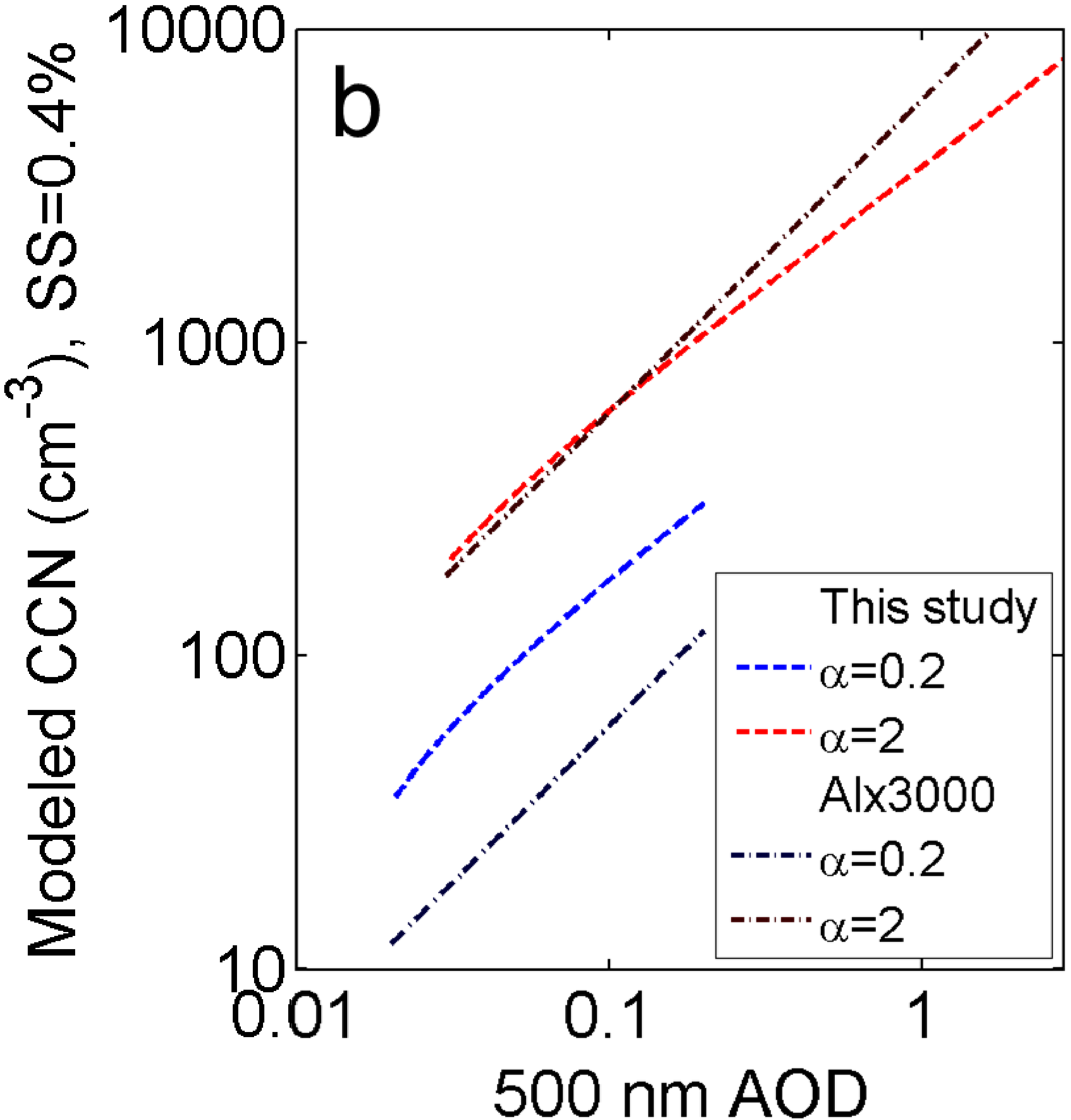
10s avg.

6 * AI ~= CCN

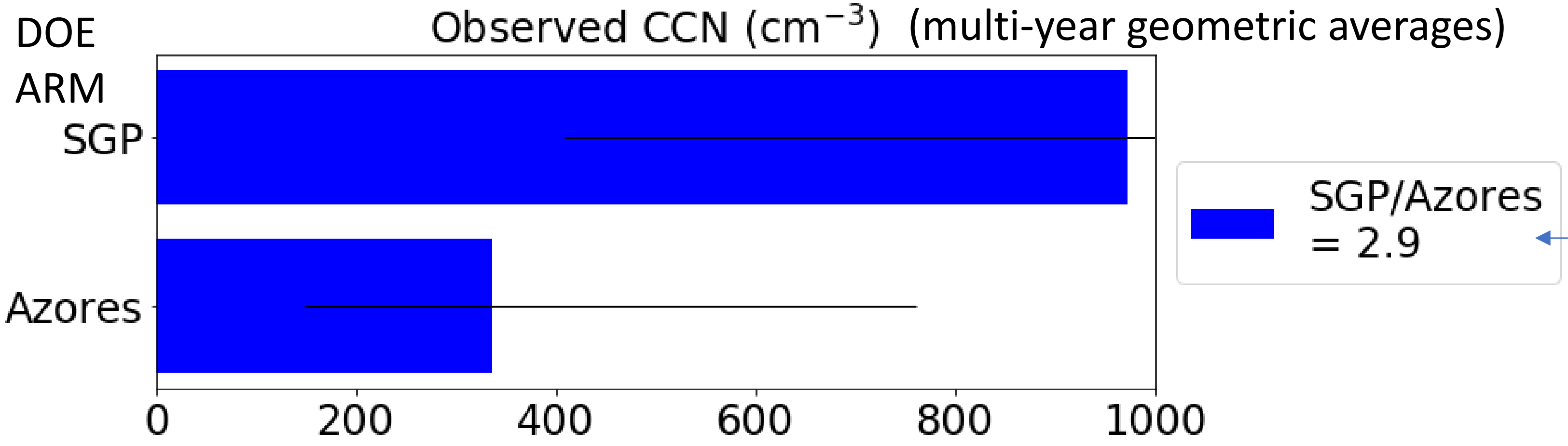


The relationship between CCN and dry extinction

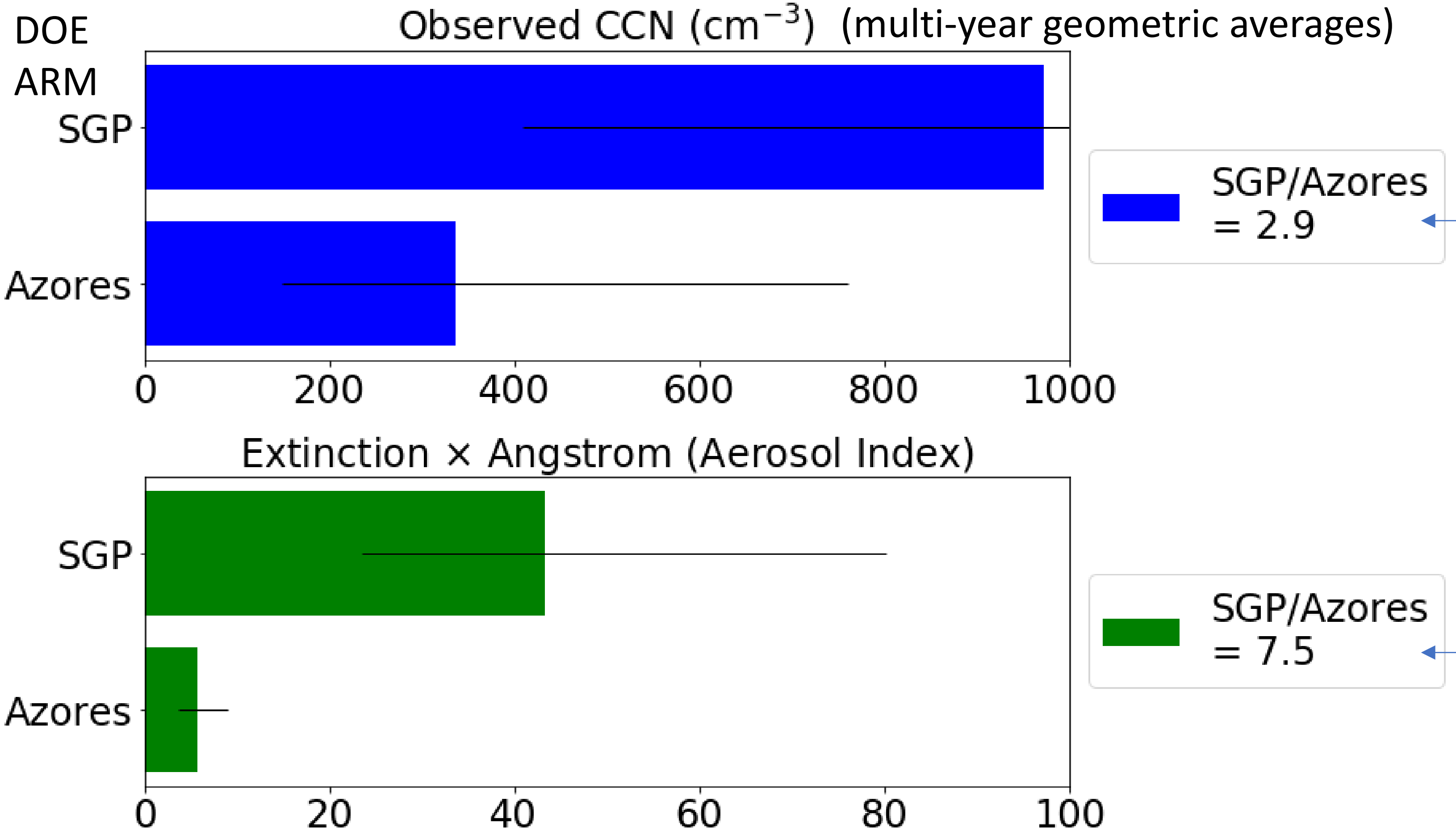
- CCN **varies less** than aerosol index (AI, AOD×α).
- A doubling of AOD is associated with less than a doubling of CCN.



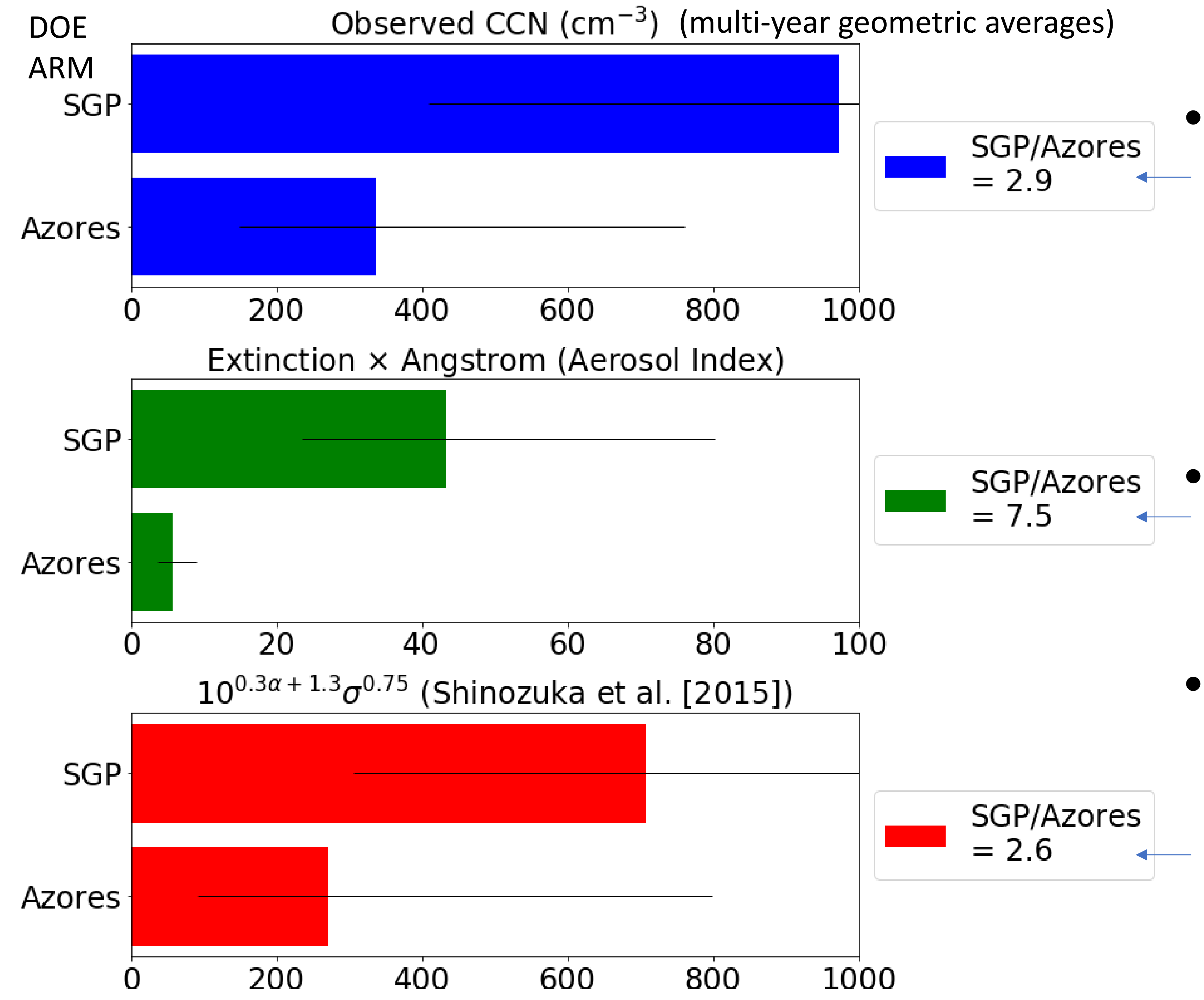
Shinozuka et al., ACP 2015



- Compared to the observed CCN…

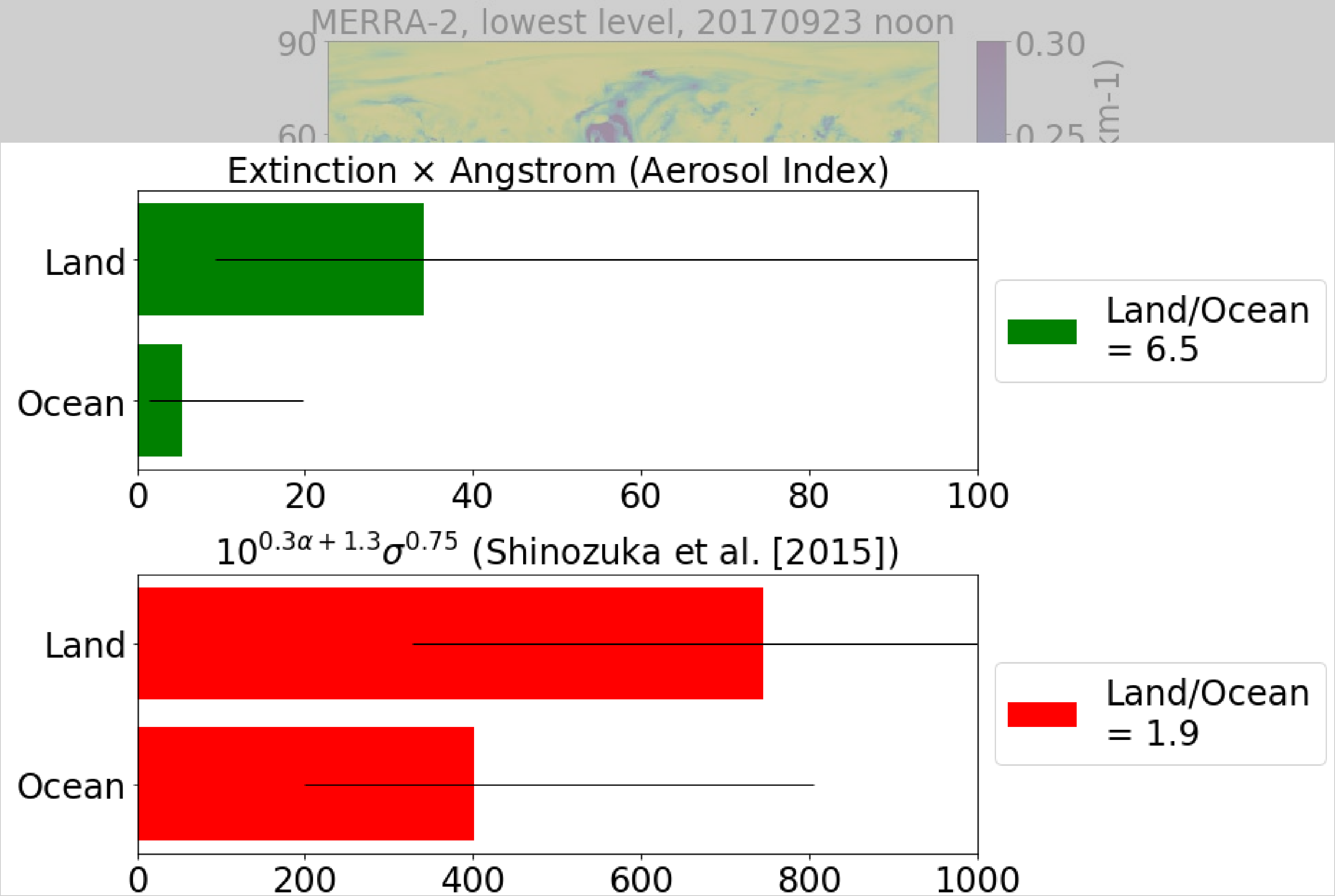


- Compared to the observed CCN…
- … Aerosol Index is more strongly site-dependent.



- Compared to the observed CCN…
- … Aerosol Index is more strongly site-dependent.
- Our microscale observation-based CCN-ext parameterization better captures the site dependence (and temporal variability).

- Aerosol Index varies more than cloud condensation nuclei (CCN).



Model and satellite-based estimates

Definitions of aerosol-cloud interactions (ACI)

ACI has been reported or derived later from measurements published in the literature for almost two decades. A variety of proxies has been used to represent the aerosol particles affecting the cloud, including aerosol number concentration N_a, τ_a, and aerosol index AI (the product of τ_a and the Ångström exponent), all of which will henceforth be denoted by α. Similarly, various proxies have been used to represent the cloud response to the change in aerosol, e.g., cloud optical depth τ_c, cloud drop number concentration N_d, and r_e. Using data for which the analysis scale closely matched the process scale, McComiskey et al. (2009) showed empirically that there is consistency amongst calculations of ACI using different microphysical proxies, provided the appropriate constraint on cloud liquid water path L is applied. Thus,

$$\mathrm{ACI}_\tau = \left.\frac{\partial \ln \tau_c}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_\tau < 0.33 \tag{1a}$$

$$\mathrm{ACI}_r = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_r < 0.33 \tag{1b}$$

$$\mathrm{ACI}_N = \frac{d \ln N_d}{d \ln \alpha} \qquad 0 < \mathrm{ACI}_N < 1 \tag{1c}$$

$$\mathrm{ACI}_\tau = -\mathrm{ACI}_r = \frac{1}{3}\mathrm{ACI}_N. \tag{1d}$$

The scale problem in quantifying aerosol indirect effects

A. McComiskey[1,2] and G. Feingold[2]

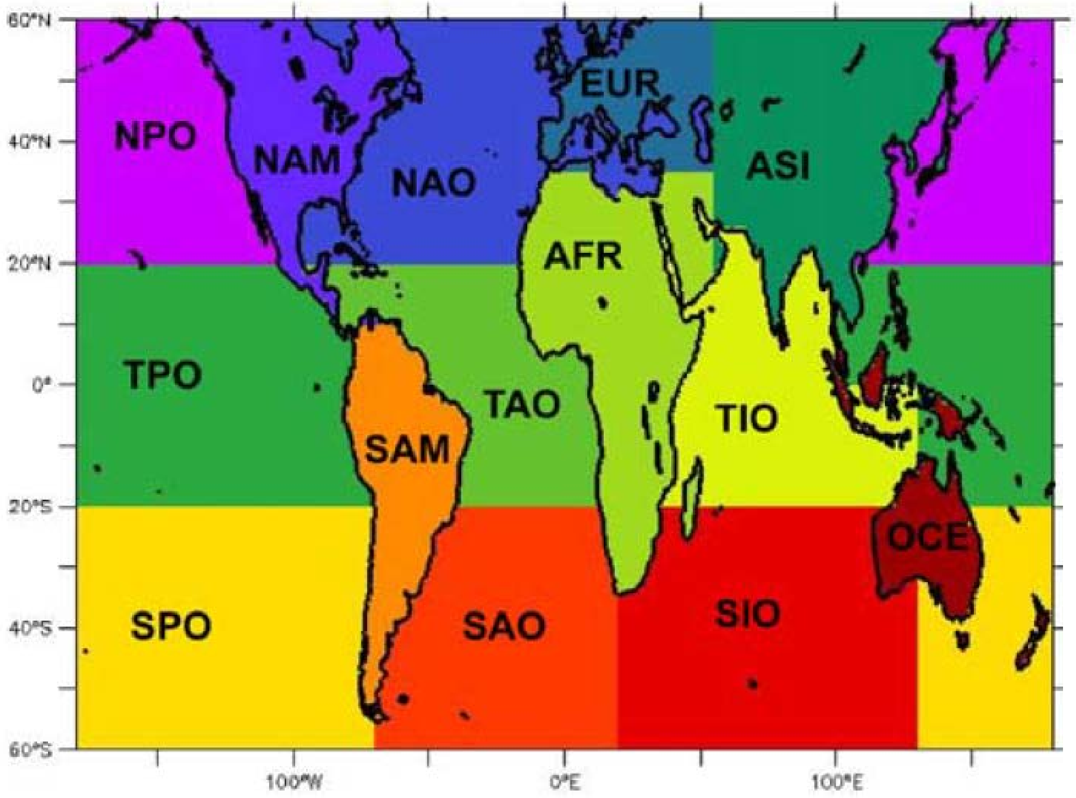


Figure 1. Choice of the fourteen different regions.

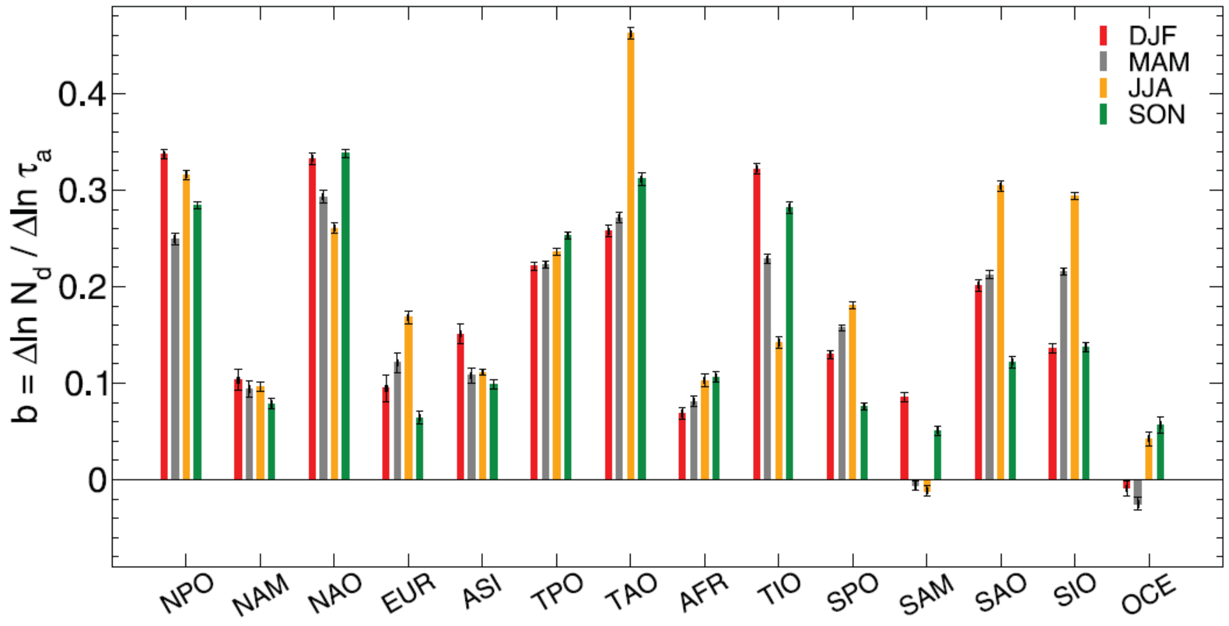
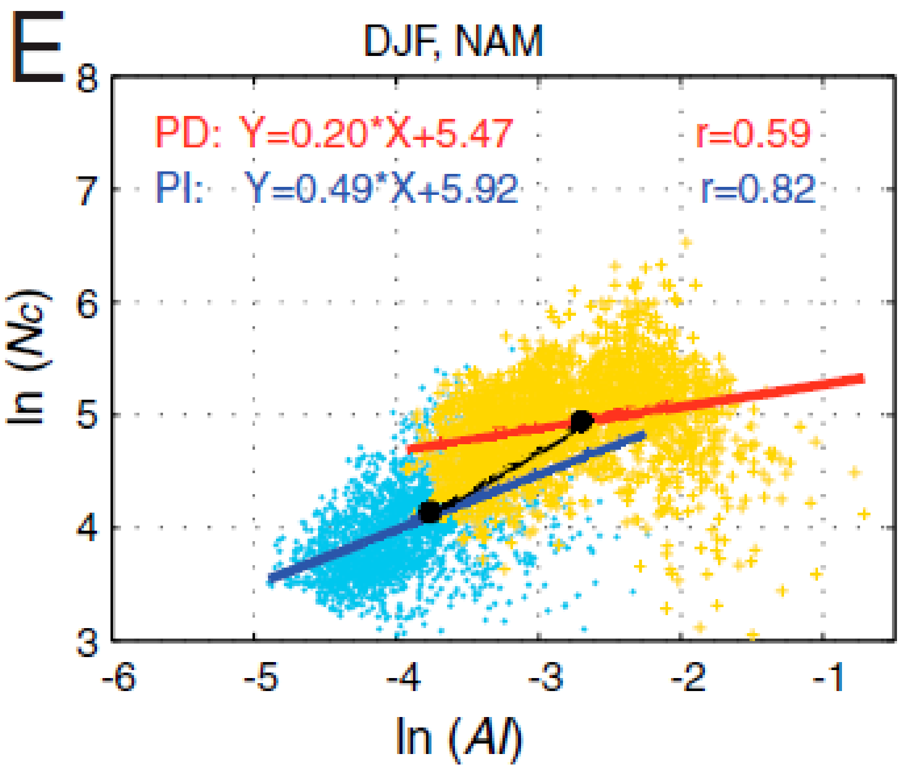


Figure 3. Slopes of the linear regression ln CDNC versus ln AOD for the different regions and seasons. Error bars show 10 times the standard deviation (a list of abbreviations is given in Table 1).

Satellite-based estimate of the direct and indirect aerosol climate forcing

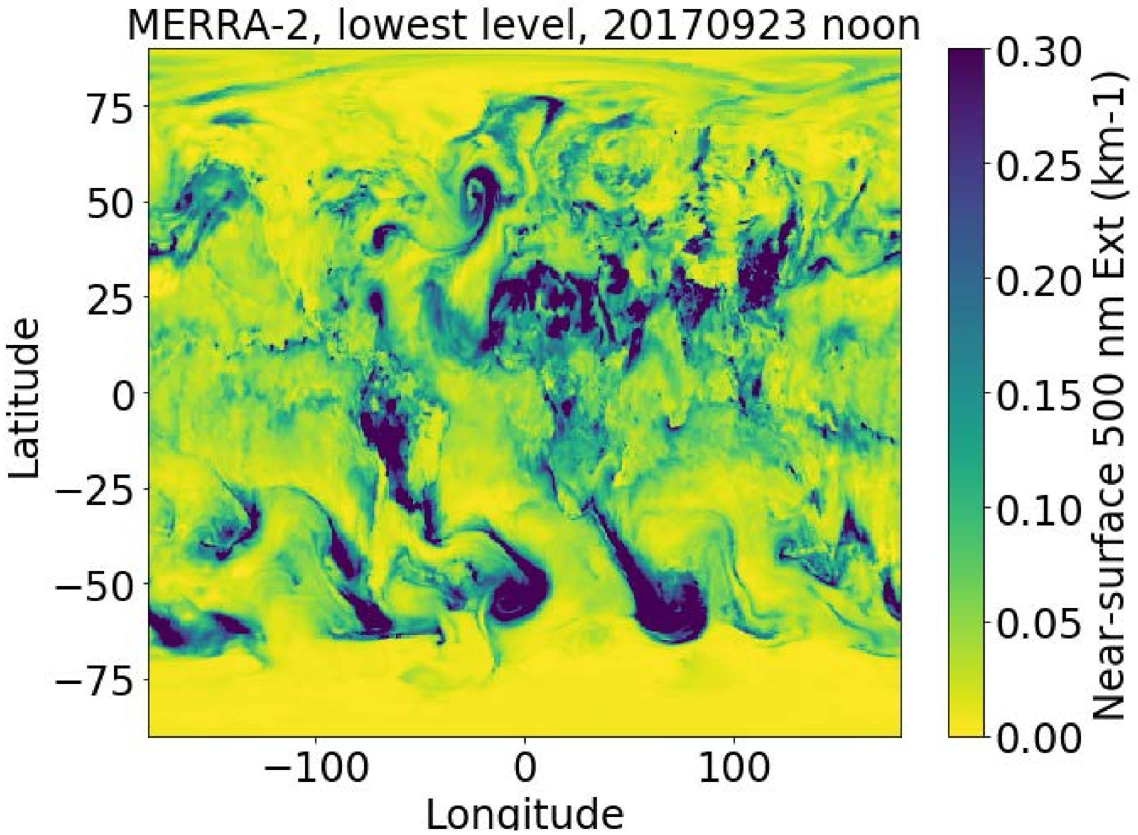
Johannes Quaas,[1] Olivier Boucher,[2] Nicolas Bellouin,[2] and Stefan Kinne[1]

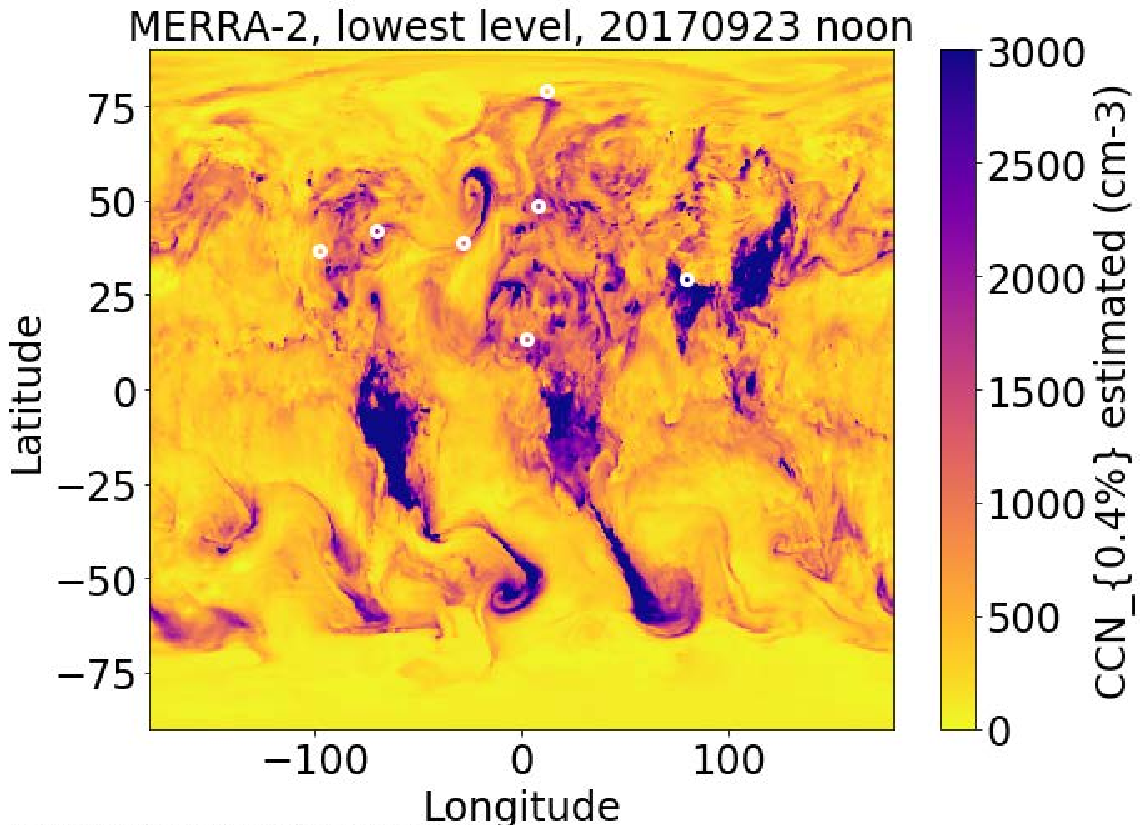


Satellite methods underestimate indirect climate forcing by aerosols

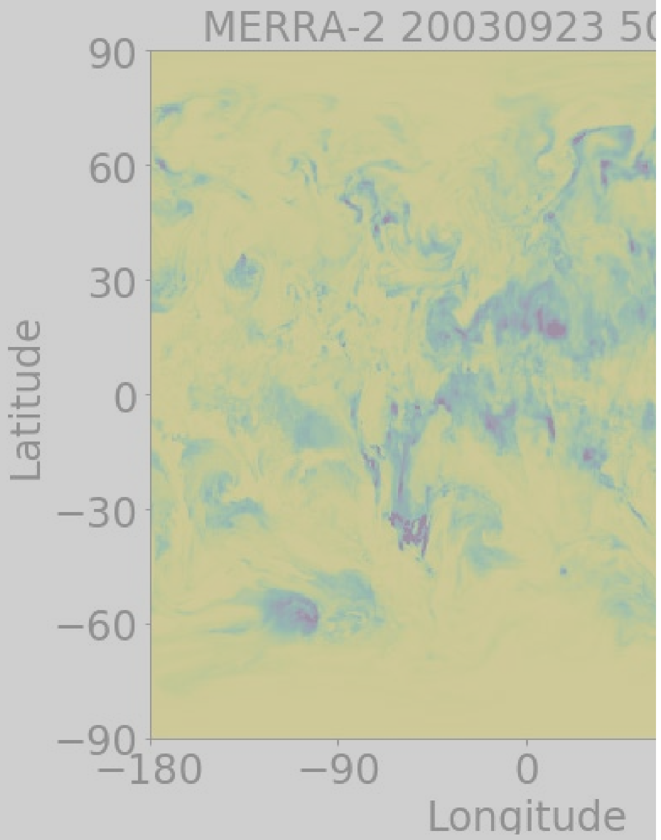
Joyce E. Penner[a,1], Li Xu[a], and Minghuai Wang[b]

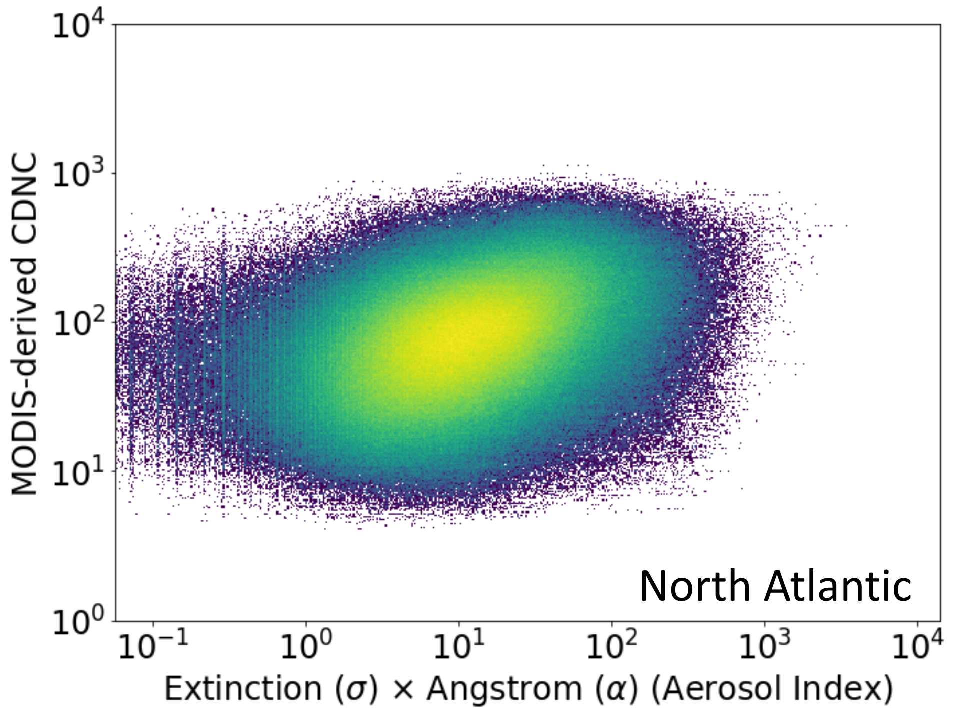
MERRA-II products from Arlindo M. da Silva, Ravi C. Govindaraju

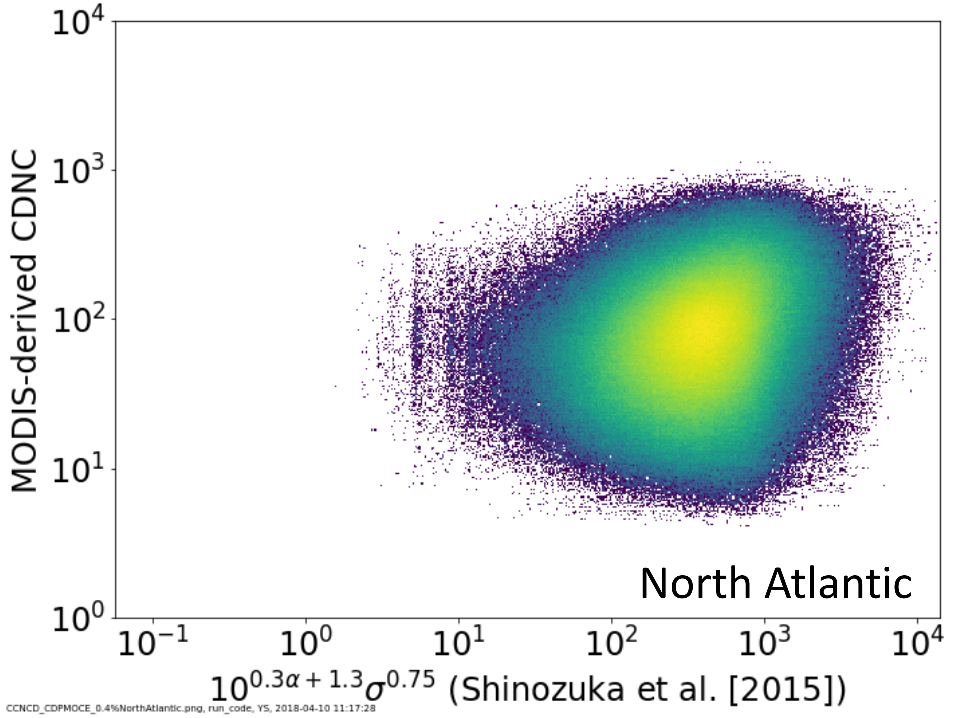


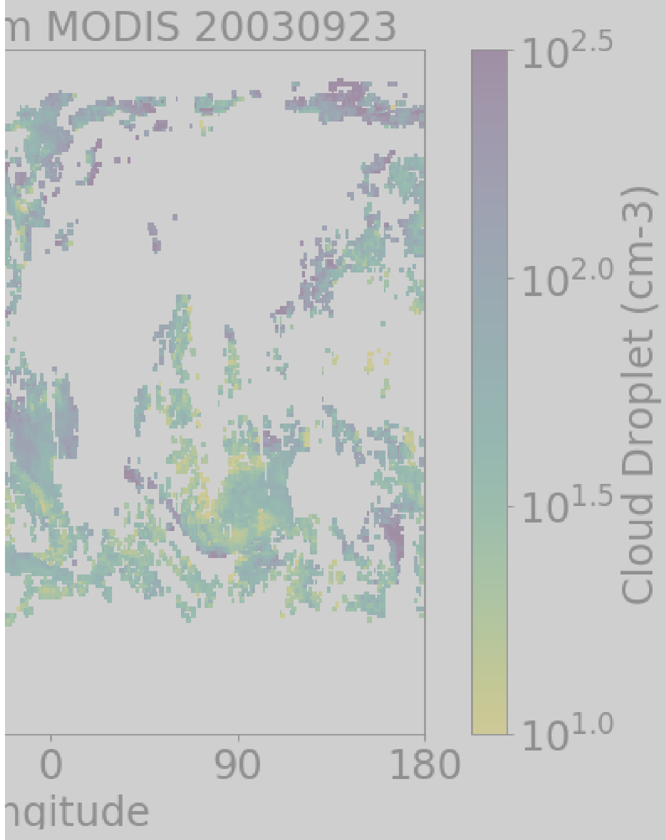


circles indicate long-term ground-based CCN measurements (e.g., DOE ARM sites)

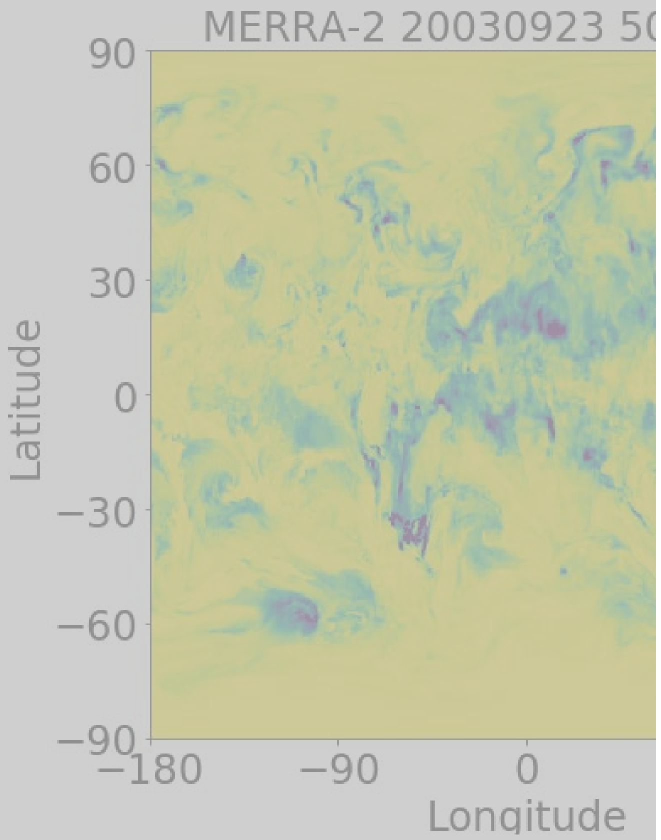


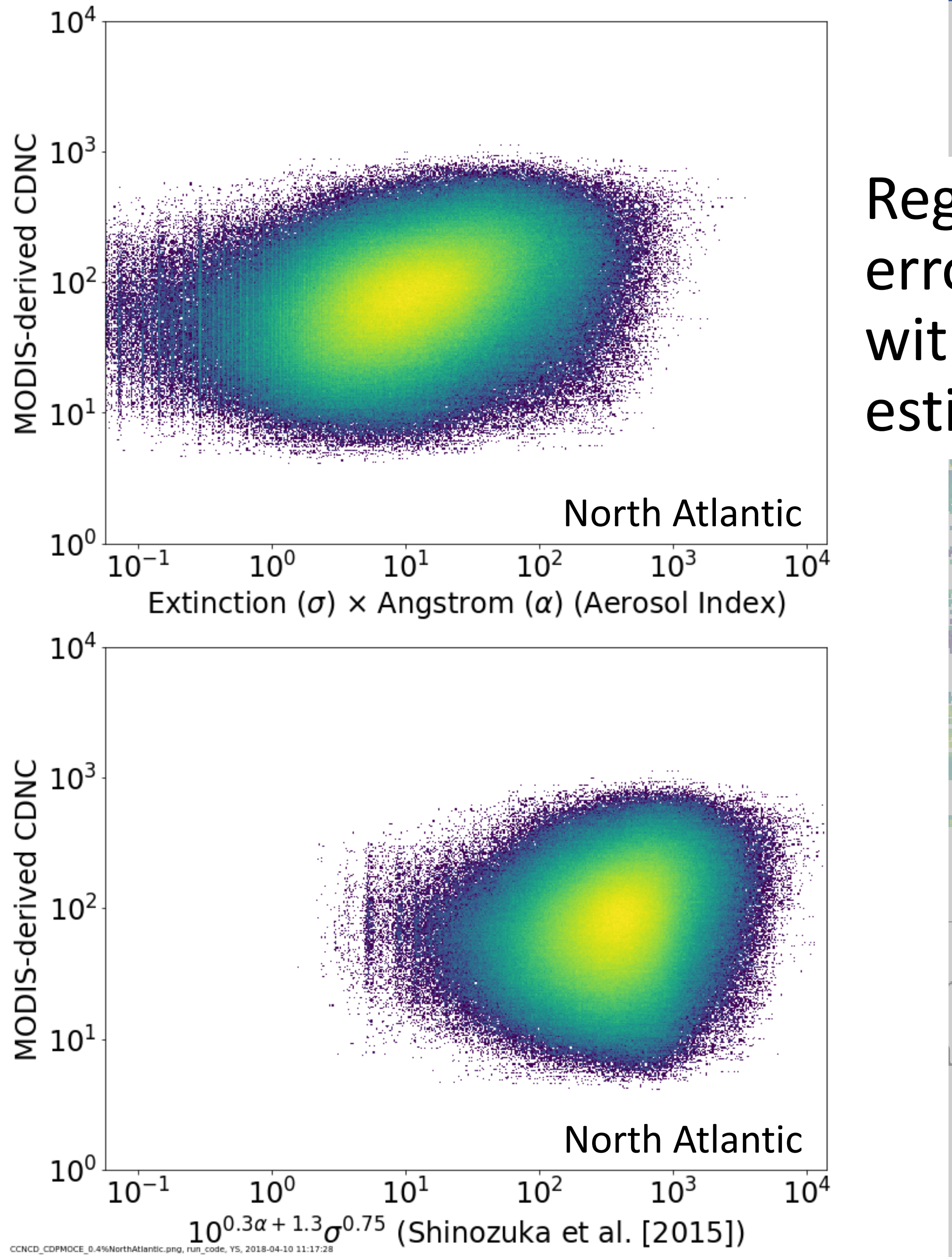


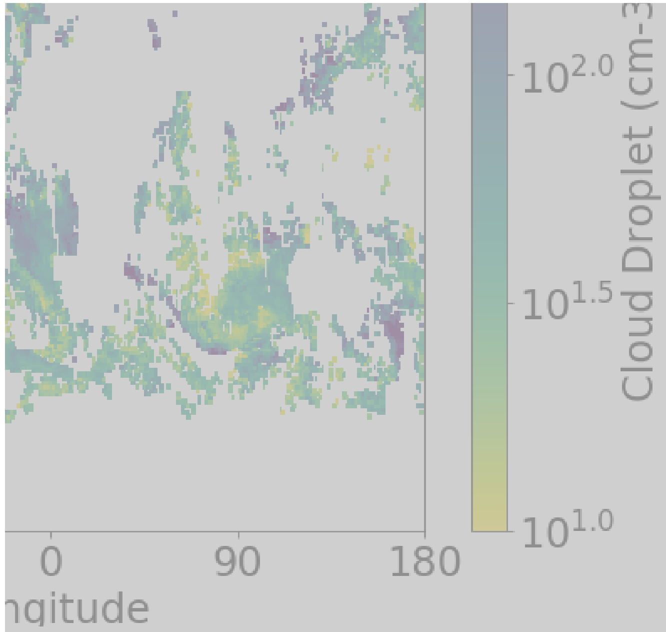




Arlindo M. da Silva, Ravi ... nd Rausch (2017)







Regression may be erroneous for the region with a narrow range of estimated CCN.

Arlindo M. da Silva, Ravi

nd Rausch (2017)