Precipitation as a driver of cloud droplet concentration variability along 20°S

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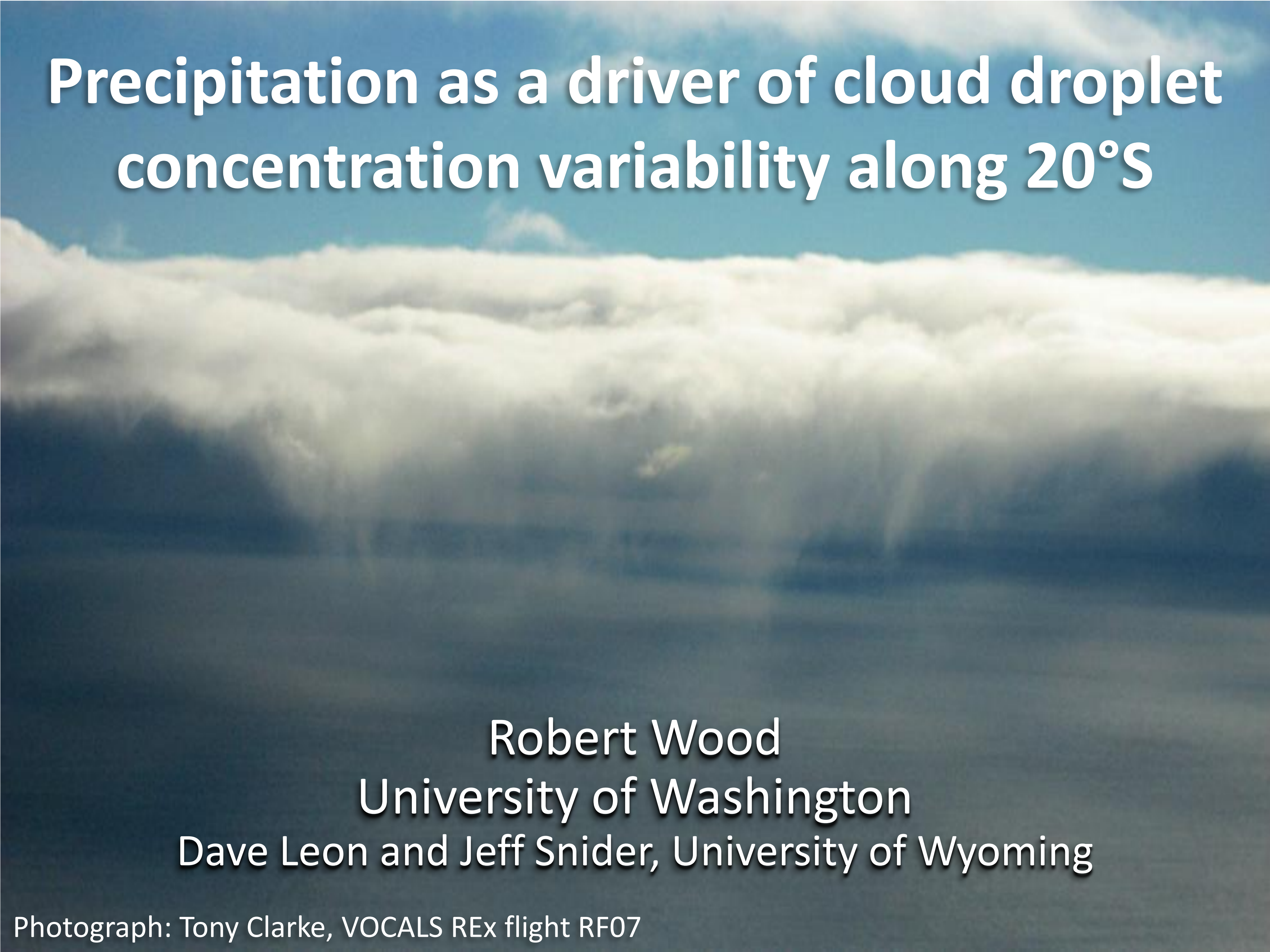
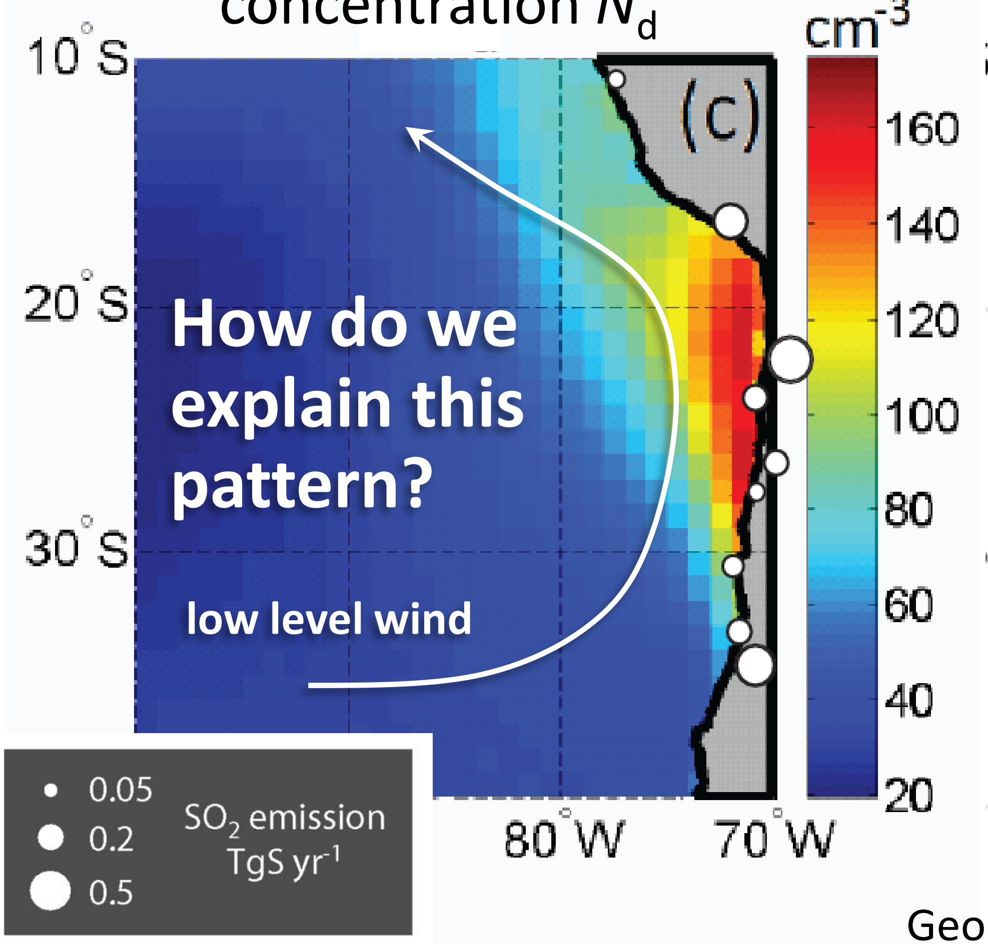


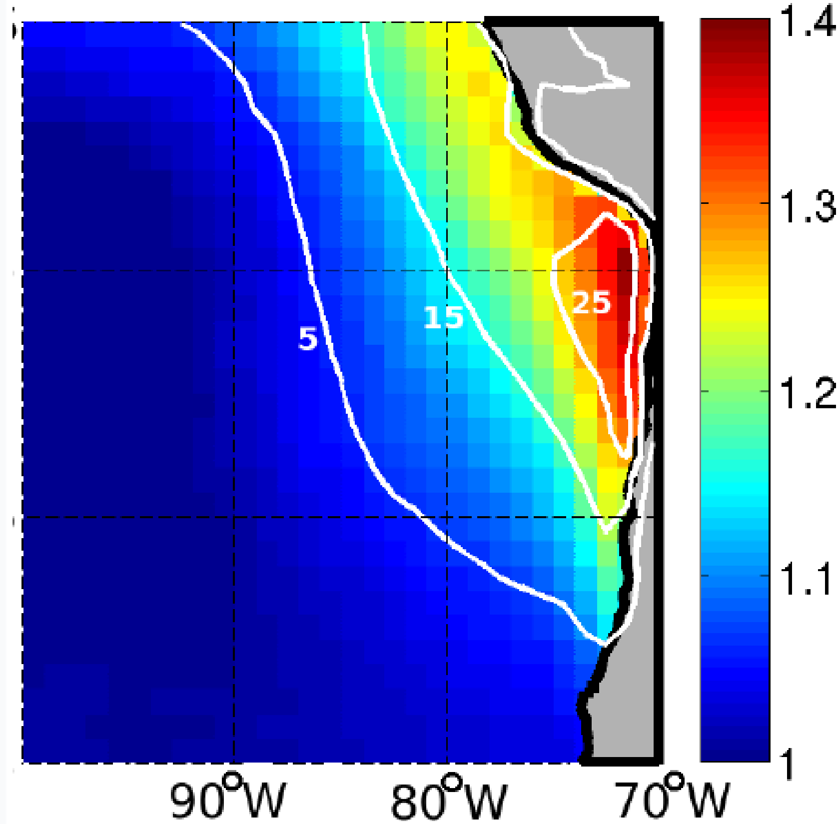
Photograph: Tony Clarke, VOCALS REx flight RF07

Radiative impact of cloud droplet concentration variations

Satellite-derived cloud droplet concentration N_d

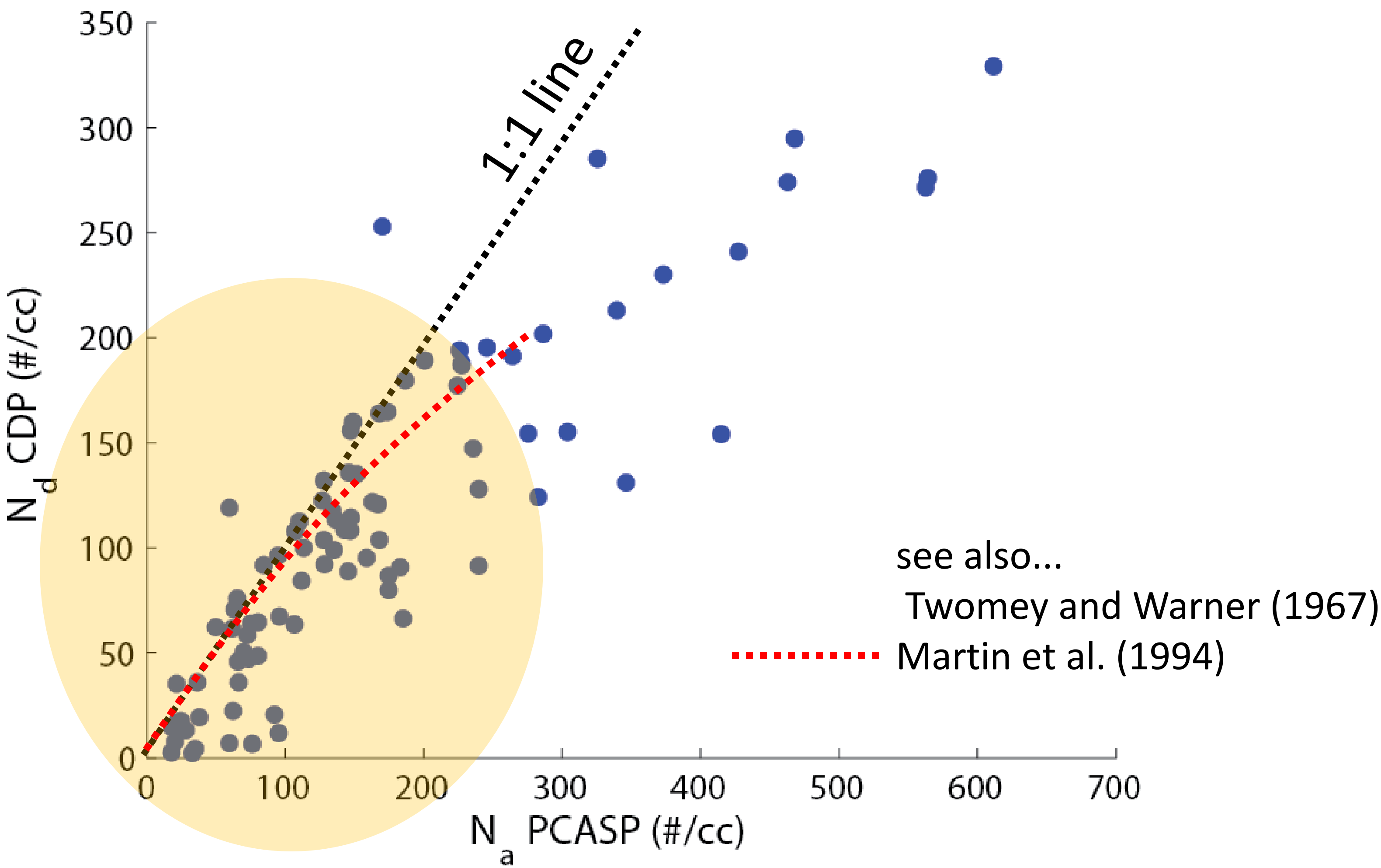


albedo enhancement (fractional)

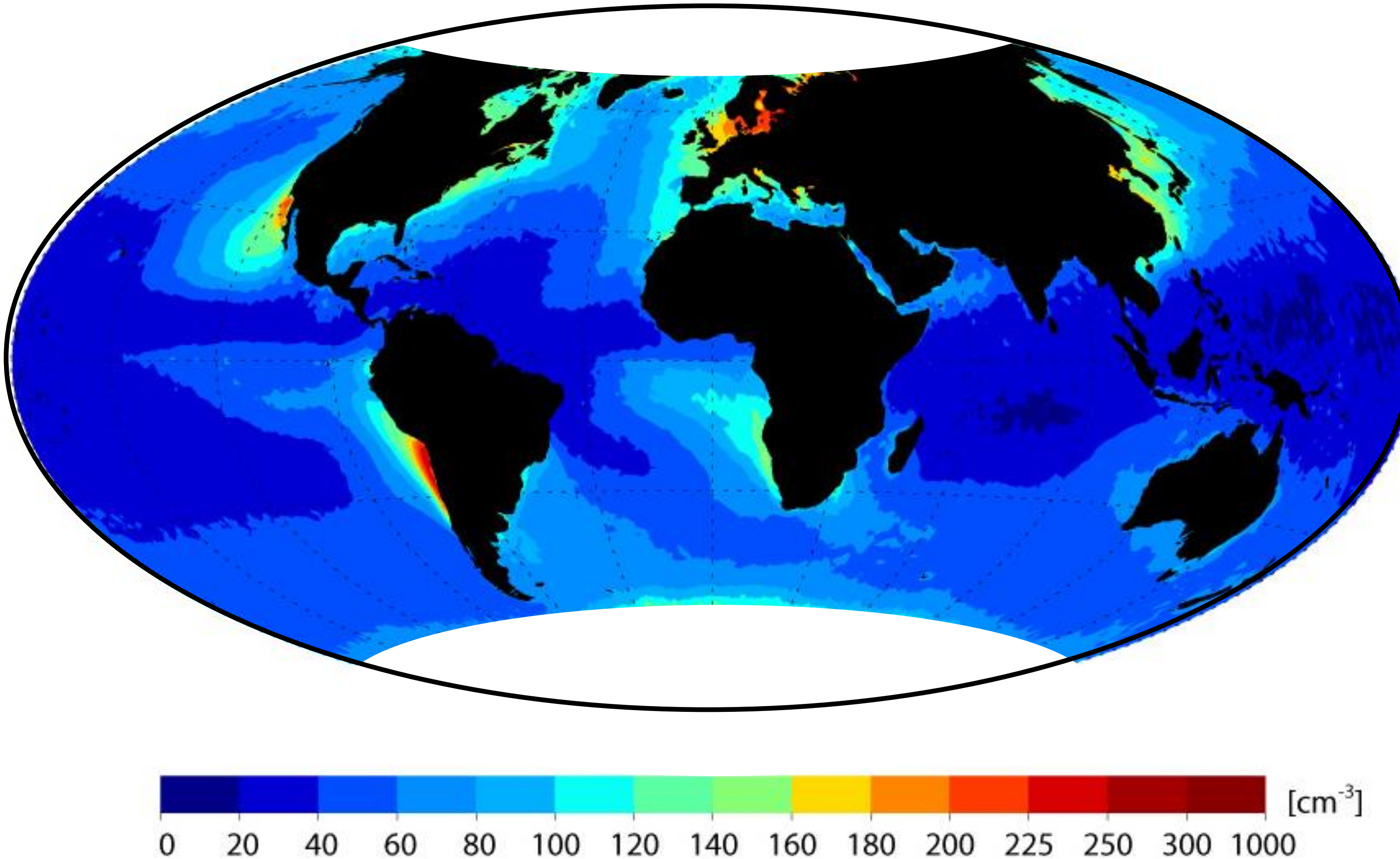


George and Wood, *Atmos. Chem. Phys.*, 2010

Aerosol (D>0.1 μm) *vs* cloud droplet concentration (VOCALS, SE Pacific)

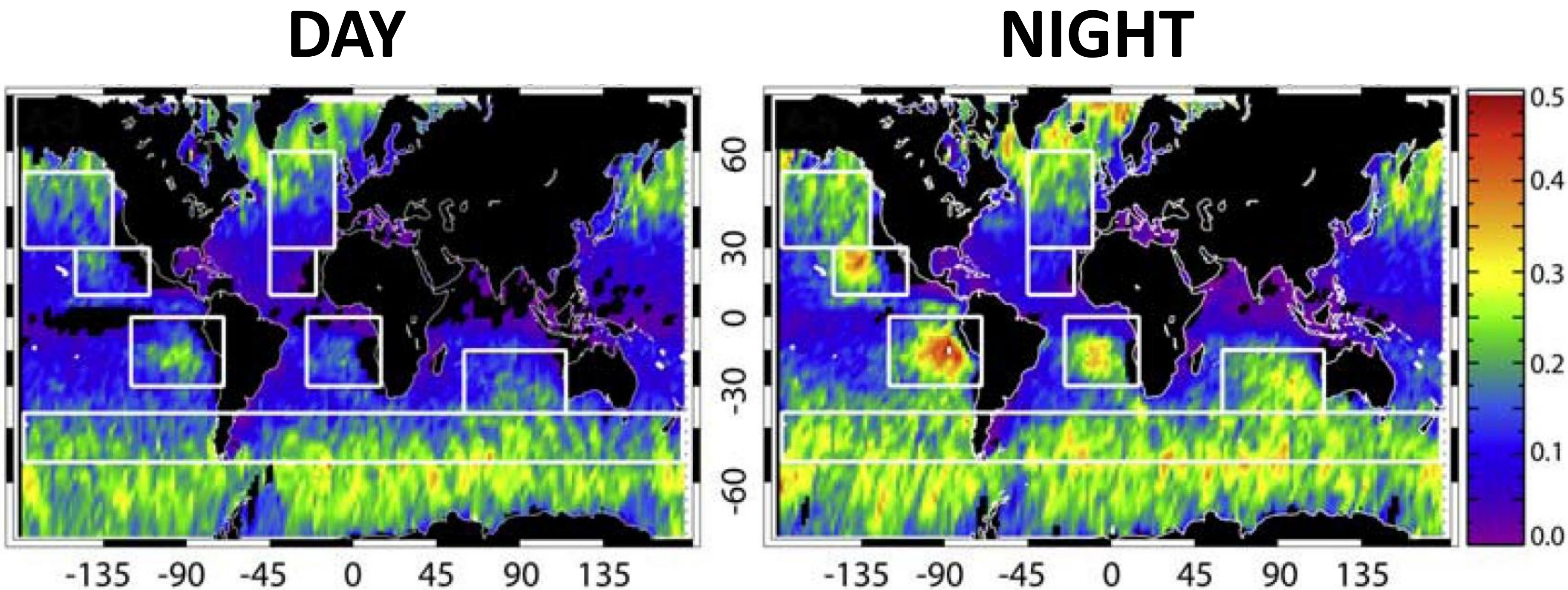


MODIS-estimated mean cloud droplet concentration N_d



- Use method of Boers and Mitchell (1996), applied by Bennartz (2007)
- Screen to remove heterogeneous clouds by insisting on CF_{liq}>0.6 in daily L3

Prevalence of drizzle from low clouds



Drizzle occurrence = fraction of low clouds (1-4 km tops) for which Z_{max}> -15 dBZ

Leon et al., *J. Geophys. Res.* (2008)

Simple CCN budget in the MBL

$$\dot{N} = [\dot{N}]_{ent} + [\dot{N}]_{sfc} + [\dot{N}]_{coal} + \cancel{[\dot{N}]_{dry\ dep}}$$

≈ 0

Model accounts for:

- Entrainment
- Surface production (sea-salt)
- Coalescence scavenging
- Dry deposition

Model does not account for:

- New particle formation – significance still too uncertain to include
- Advection – more later

Production terms in CCN budget

Entrainment rate

FT Aerosol concentration

$$[\dot{N}]_{ent} = \frac{w_e(N_{FT} - N)}{z_i}$$

MBL depth

Sea-salt parameterization-dependent constant

Wind speed at 10 m

$$[\dot{N}]_{sfc} = \frac{\beta U_{10}^{3.41}}{z_i}$$

We use Clarke et al. (*J. Geophys. Res.*, 2007) at 0.4% supersaturation to represent an upper limit

Loss terms in CCN budget: (1) Coalescence scavenging

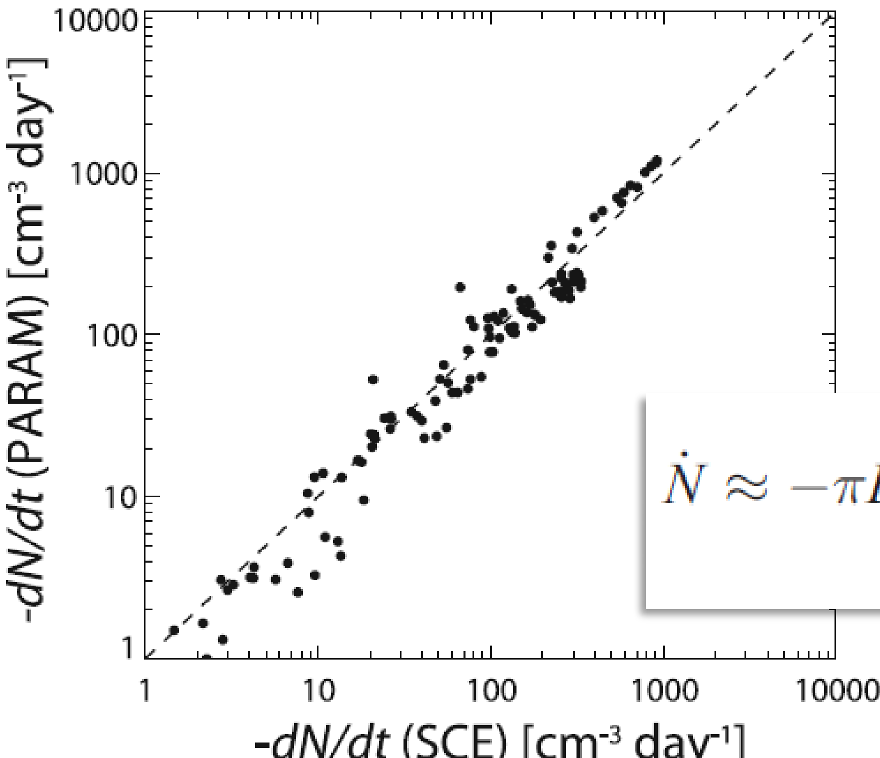
Constant

Precip. rate at cloud base

$$[\dot{N}]_{coal} = -KNP_{CB}\frac{h}{z_i}$$

cloud thickness

MBL depth



Comparison against results from stochastic collection equation (SCE) applied to observed size distribution

$$\dot{N} \approx -\pi E_0 N \int_0^\infty r^3 w_T n(r)\,dr = -\frac{3}{4\rho_w} E_0 N P$$

Wood, *J. Geophys. Res.*, 2006

Steady state (equilibrium) CCN concentration

$$N_{eq} = \frac{\left(N_{FT} + \frac{\beta U_{10}^{3.41}}{Dz_i}\right)}{\left(1 + \frac{hkP_{CB}}{Dz_i}\right)}$$

$w_e/z_i = D =$ surface divergence

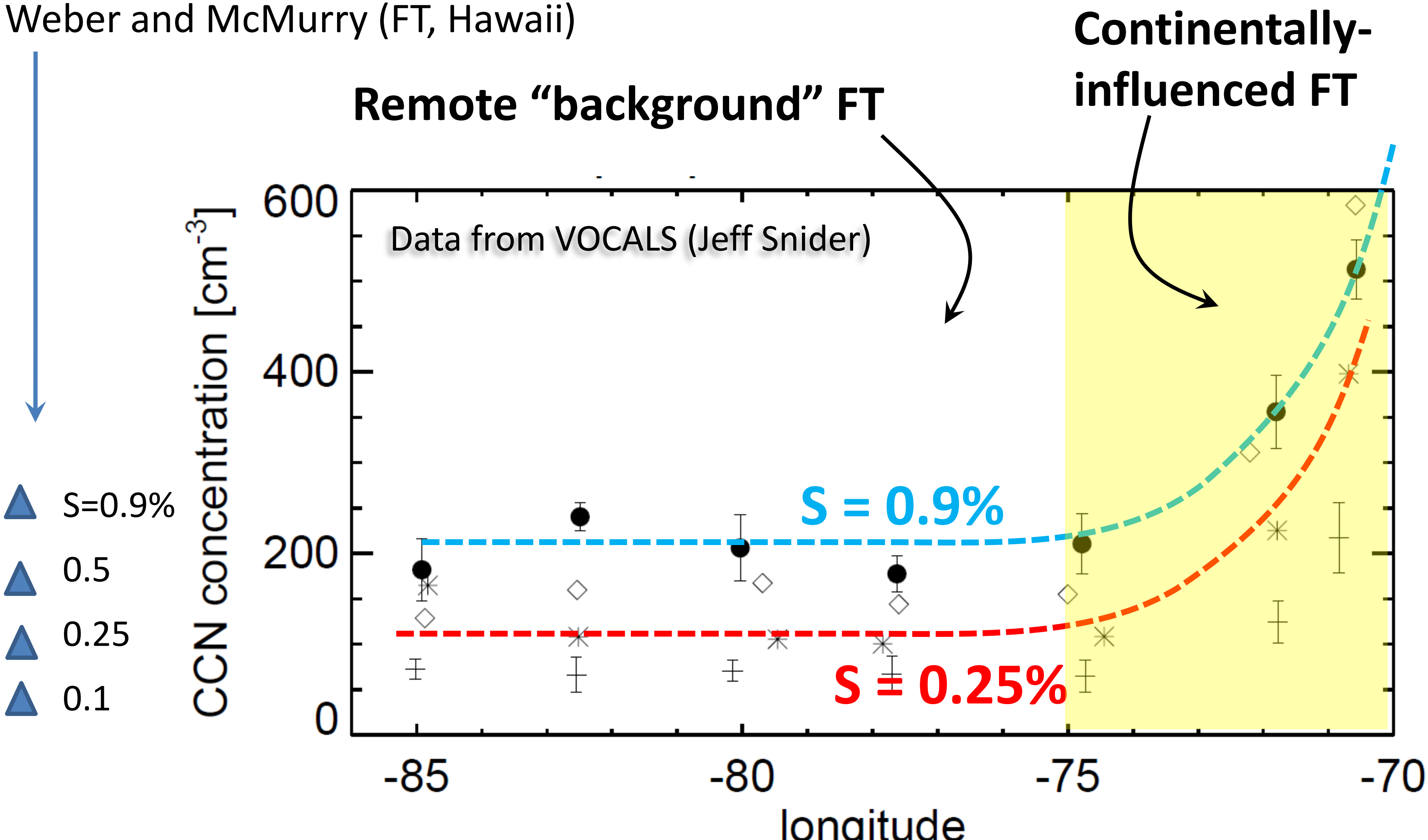
Observable constraints from VOCALS and A-Train

$$N_{eq} = \frac{\left(N_{FT} + \frac{\beta U_{10}^{3.41}}{D z_i}\right)}{\left(1 + \frac{h k P_{CB}}{D z_i}\right)}$$

Variable	Source	Details
N_{FT}	Weber and McMurry (1996) & **VOCALS** in-situ observations (next slide)	150-200 cm^{-3} active at 0.4% SS in remote FT
D	ERA-40 Reanalysis	divergent regions in monthly mean
U_{10}	Quikscat/Reanalysis	-
P_{CB}	CloudSat **VOCALS** (WCR and in-situ)	PRECIP-2C-COLUMN, Haynes et al. (2009) & Z-based retrieval
h	MODIS	LWP, adiabatic assumption
z_i	CALIPSO or MODIS or COSMIC	MODIS T_{top}, CALIPSO z_{top}, COSMIC hydrolapse

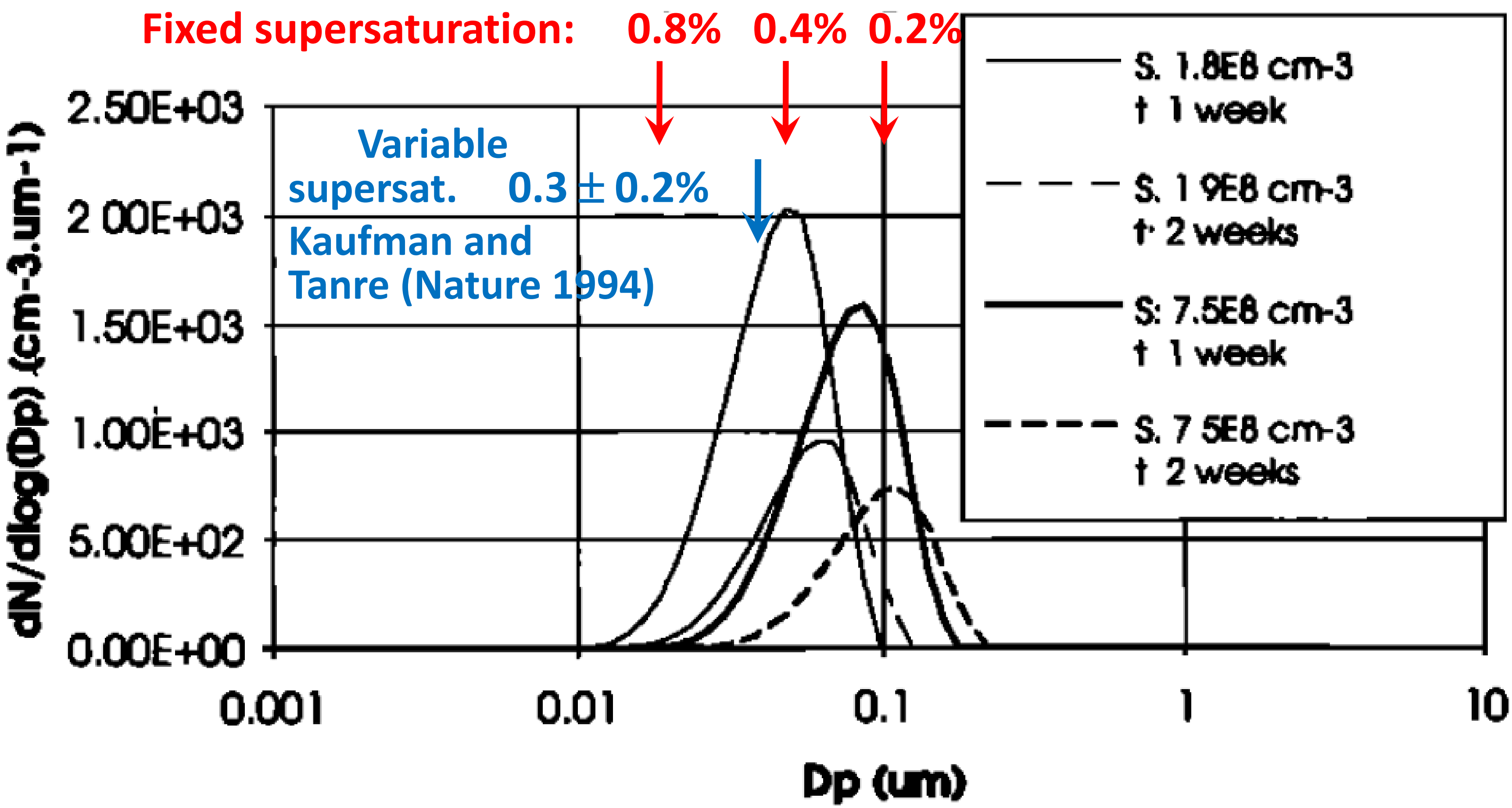
Free tropospheric CCN source

Weber and McMurry (FT, Hawaii)



Self-preserving aerosol size distributions

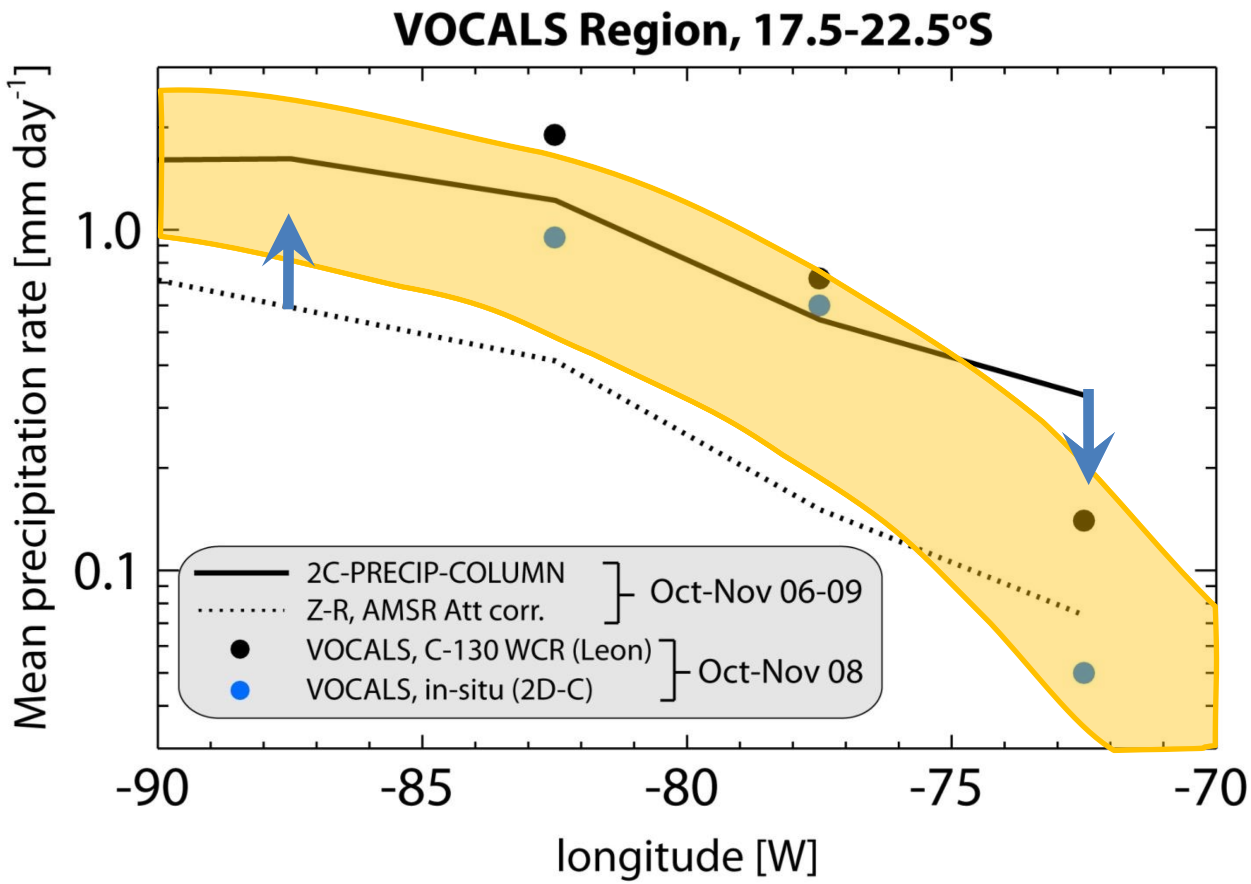
- after Friedlander, explored by Raes:



Raes et al., *J. Geophys. Res.* (1995)

Precipitation over the VOCALS region

- **CloudSat**
  Attenuation and Z-R methods
- **VOCALS**
  Wyoming Cloud Radar and in-situ cloud probes



Significant drizzle at 85°W

Very little drizzle near coast

WCR data courtesy Dave Leon

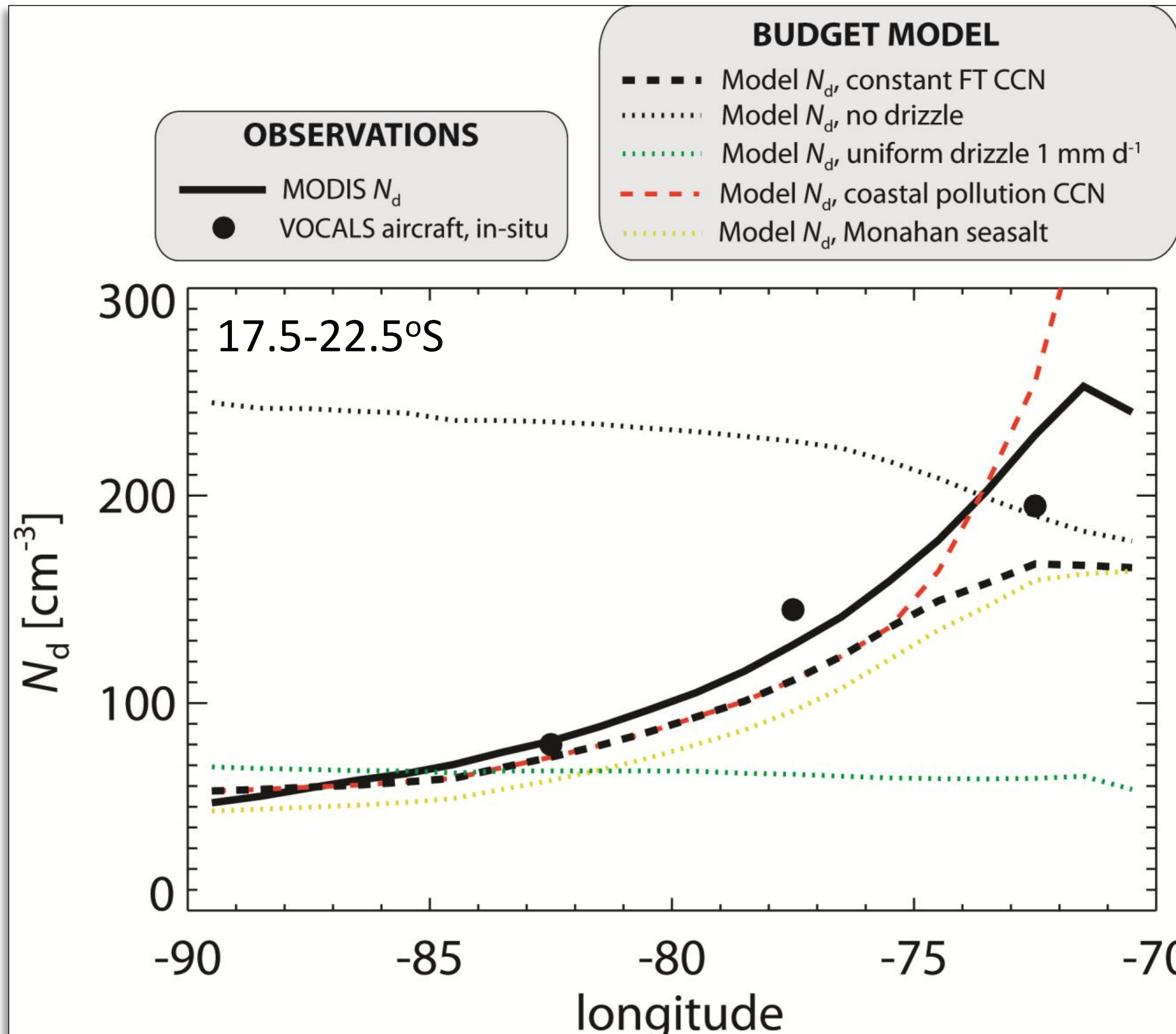
Predicted and observed N_d, VOCALS

- Model increase in N_d toward coast is related to **reduced drizzle** and explains the majority of the observed increase

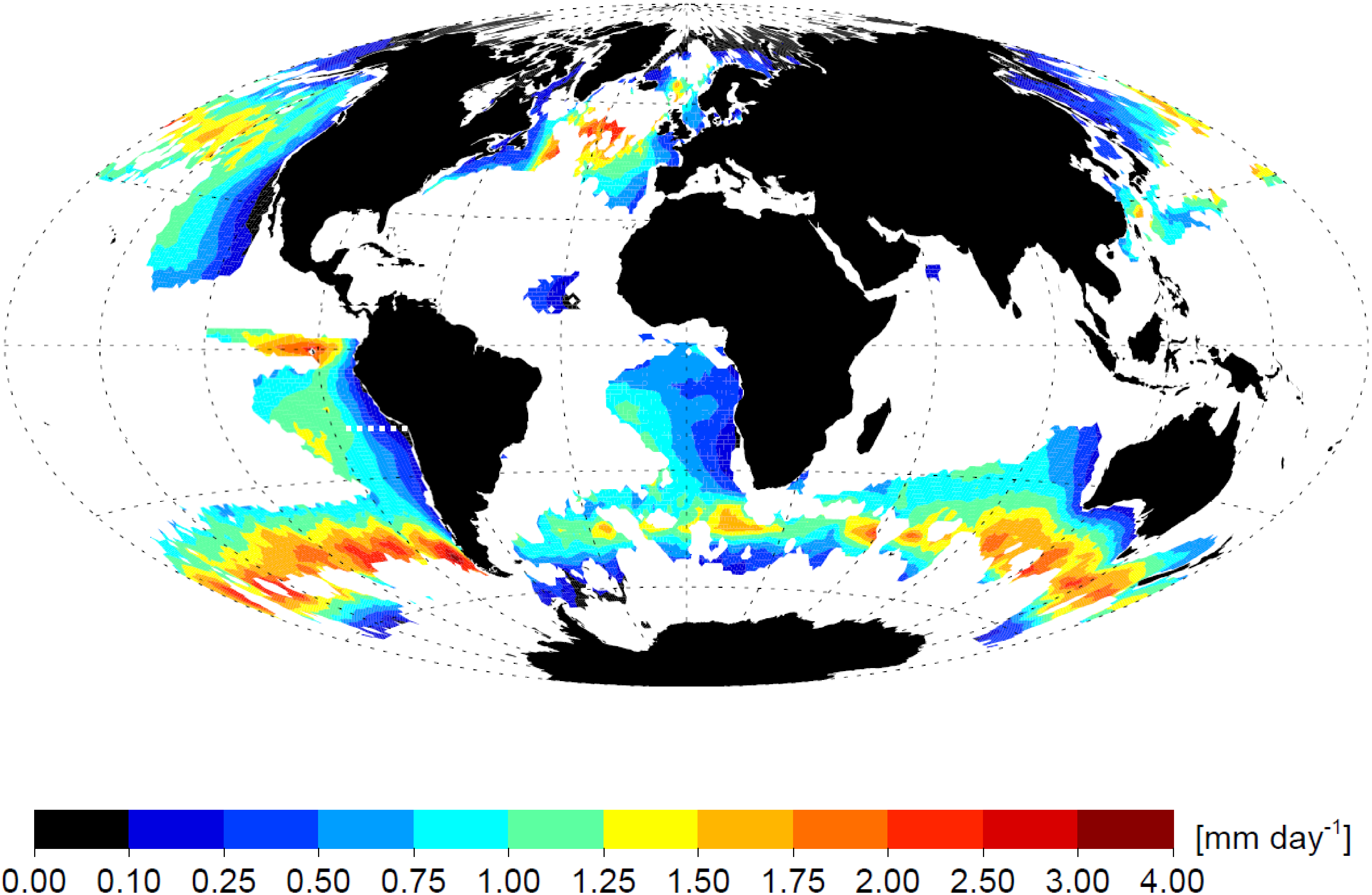
- Very close to the coast (<5°) an additional CCN source is required

- Even at the heart of the Sc sheet (80°W) coalescence scavenging halves the N_d

- Results insensitive to sea-salt flux parameterization



Mean precipitation rate (CloudSat, 2C-PRECIP-COLUMN, Stratocumulus regions)



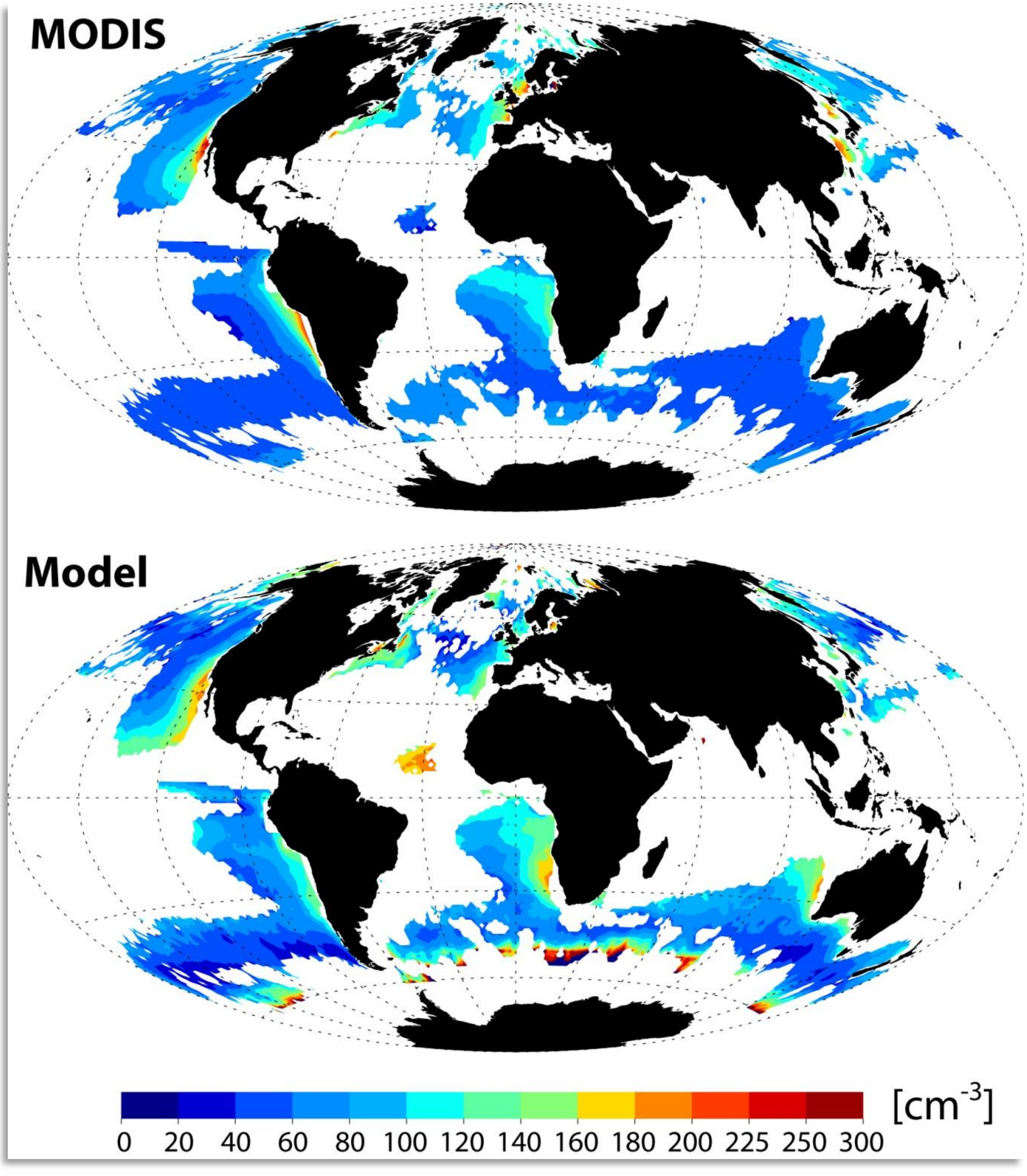
Predicted and observed N_d

- **Monthly climatological means** (2000-2009 for MODIS, 2006-2009 for CloudSat)

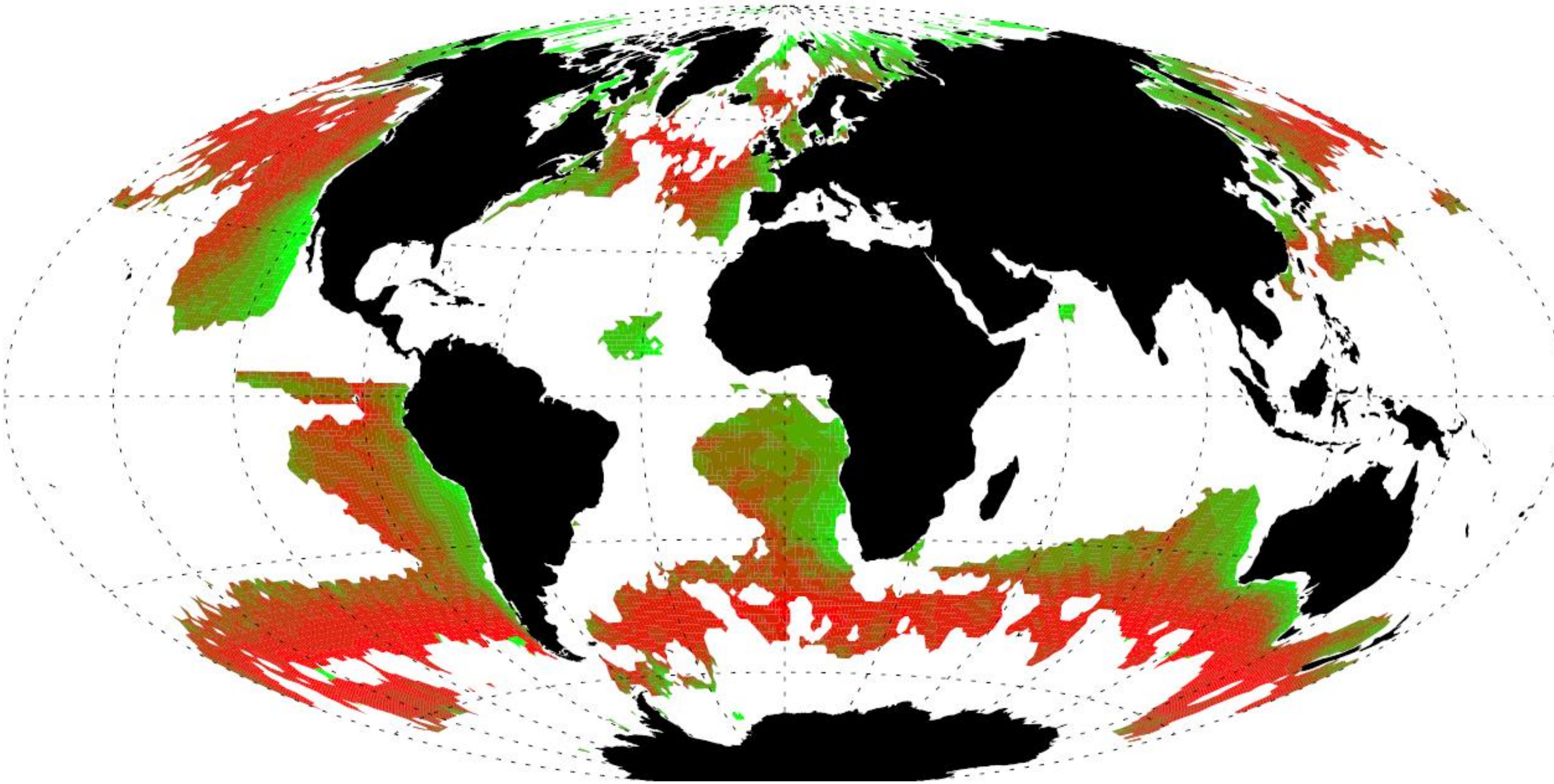
- **Derive mean for locations** where there are >3 months for which there is:

(1) positive large scale div.
(2) mean cloud top height <4 km
(3) MODIS liquid cloud fraction > 0.4

- Use 2C-PRECIP-COLUMN and Z-R where 2C-PRECIP-COLUMN missing



Reduction of N_d from precipitation sink



- Precipitation from midlatitude low clouds reduces N_d by a factor of 5
- In coastal subtropical Sc regions, precip sink is weak

But what controls precipitation?

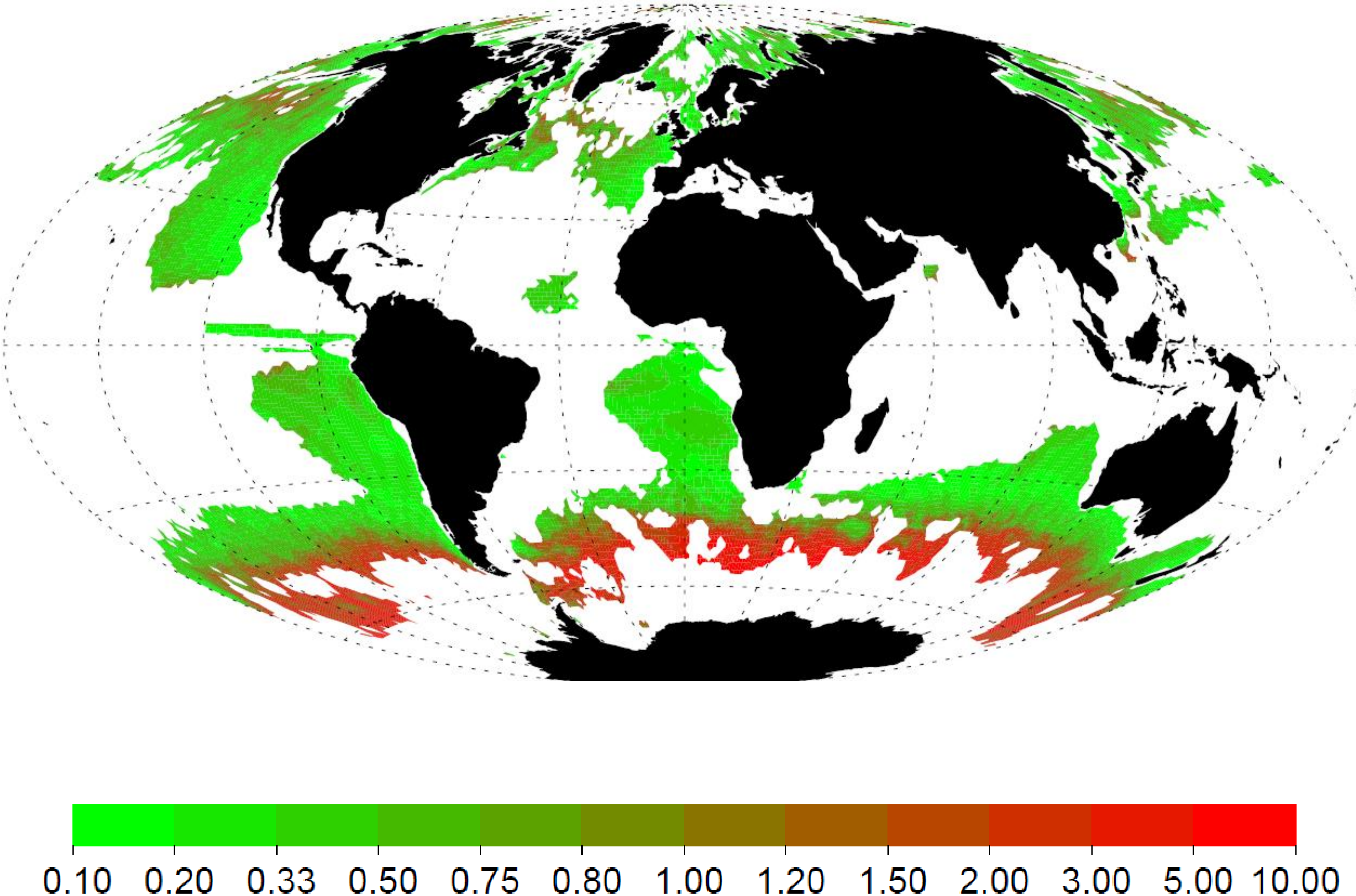
- Precipitation rates P_{CB} scale approximately with $LWP^{1.5}$ and N_d^{-1} (e.g. Pawlowska and Brenguier 2003, Comstock et al. 2004, VanZanten et al. 2005)
- $LWP^{1.5}$ *increases* by a factor of **~2.2** from 72.5°W to 82.5°W, while N_d *decreases* by a factor of **2.5** (Bretherton et al. 2010)
  - ⇒ *LWP* and N_d influence the zonal gradient in precipitation rate along 20°S in approximately equal measure
  - ⇒ significant positive feedback on N_d through aerosol-driven precipitation suppression; $N_d\uparrow \Rightarrow P_{CB}\downarrow \Rightarrow N_d\uparrow$

- But see Chris Terai's poster on precipitation susceptibility

Conclusions

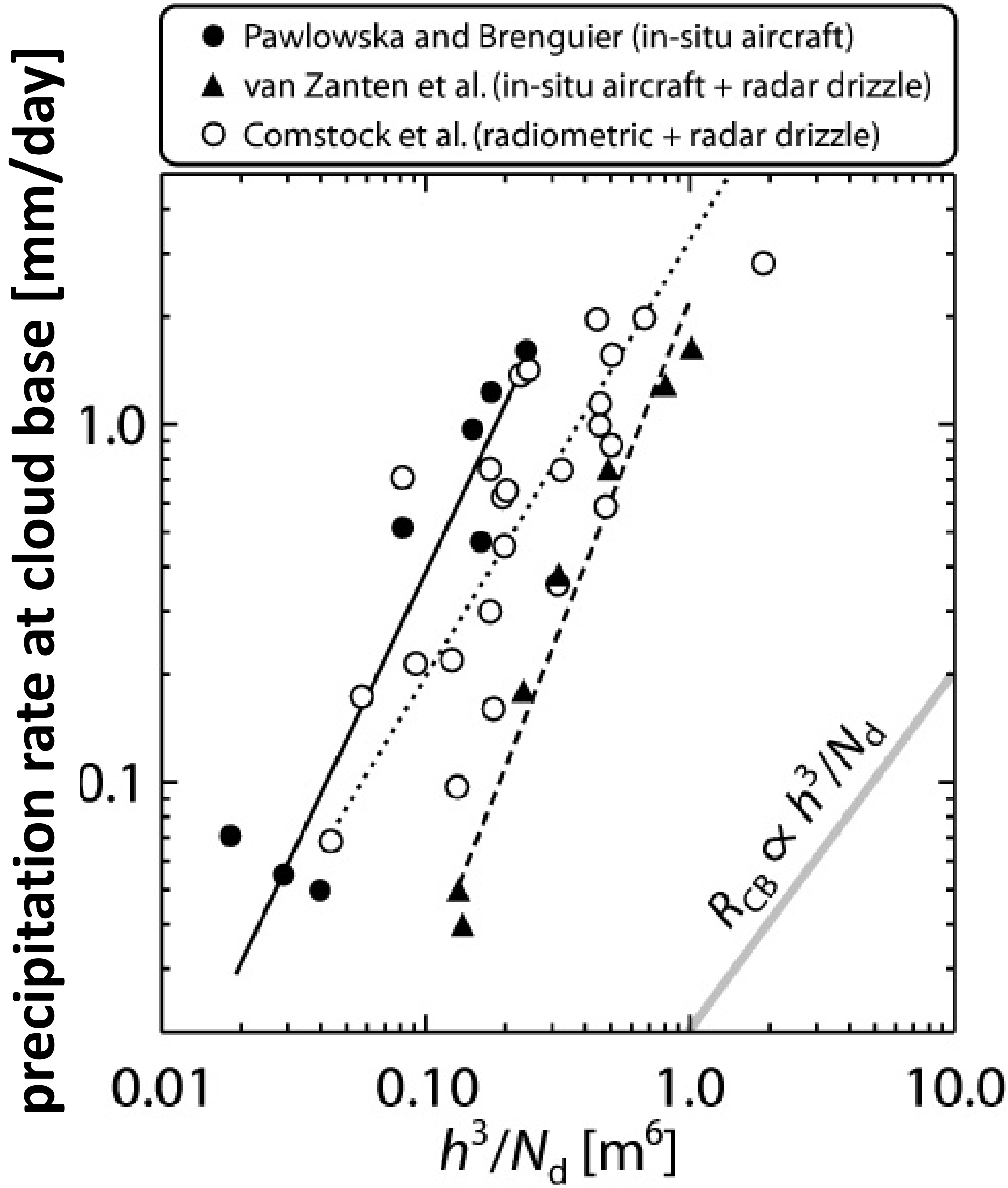
- Simple CCN budget model, constrained with VOCALS observations predicts observed gradients in cloud droplet concentrations with some skill. **FT aerosol significant possible source west of 75°W.**
- Significant fraction of the variability in N_d across regions of extensive low clouds (from remote to coastal regions) is likely related to precipitation sinks rather than source variability. **Implications for VOCALS Hypothesis H1c** :
  - The small effective radii measured from space over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN)
- It may be difficult to separate the chicken from the egg in correlative studies suggesting inverse dependence of precipitation rate on cloud droplet concentration. **Implications for Hypothesis H1a**:
  - Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.

Sea-salt source strength compared with entrainment from FT



Precipitation closure

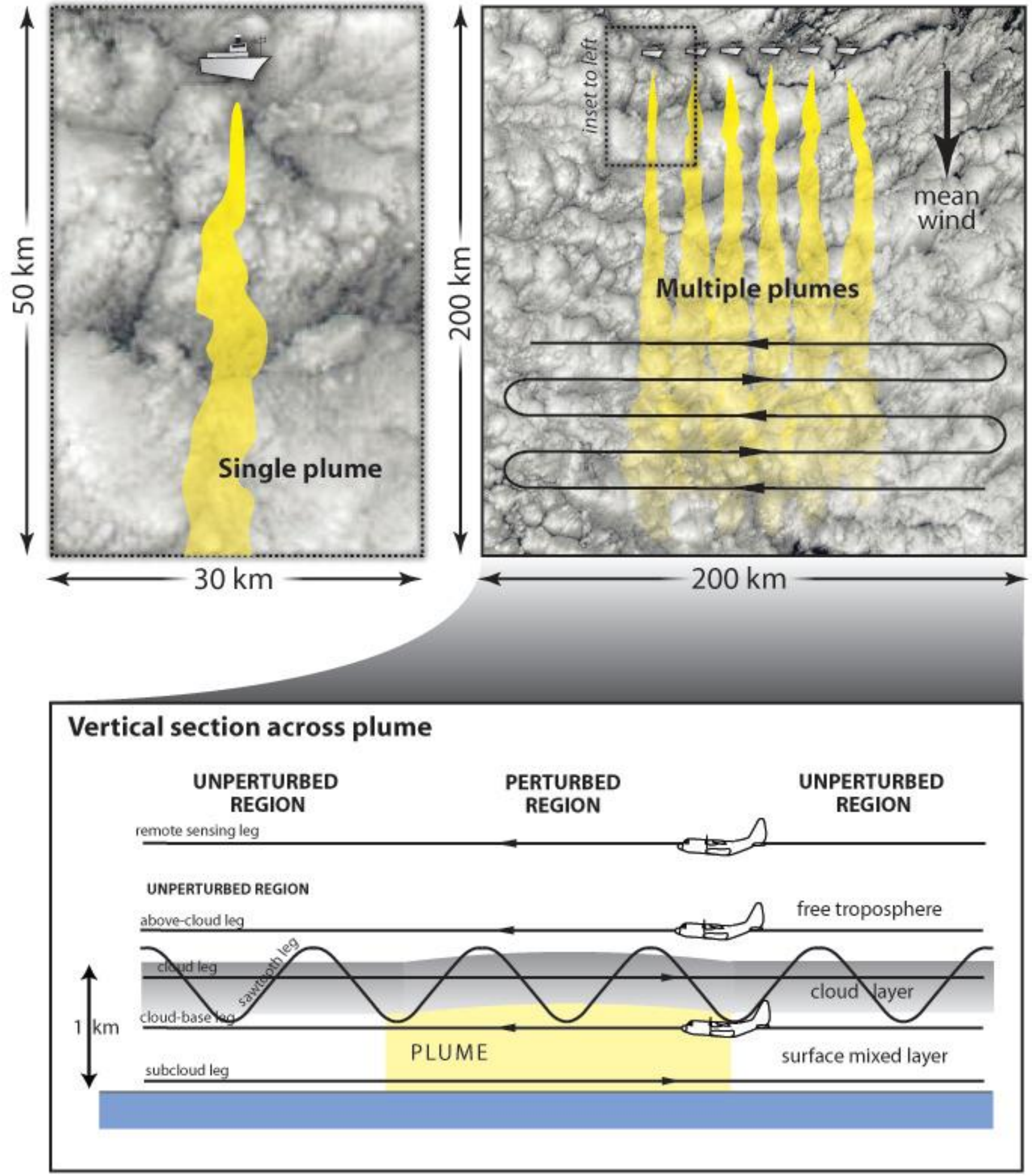
- Precipitation rate dependent upon:
  - cloud **macrophysical** properties (e.g. thickness, LWP);
  - **microphysical** properties (e.g. droplet conc., CCN)



from Brenguier and Wood (2009)

A proposal

- A limited area perturbation experiment to critically test hypotheses related to aerosol indirect effects
- Cost ~$30M

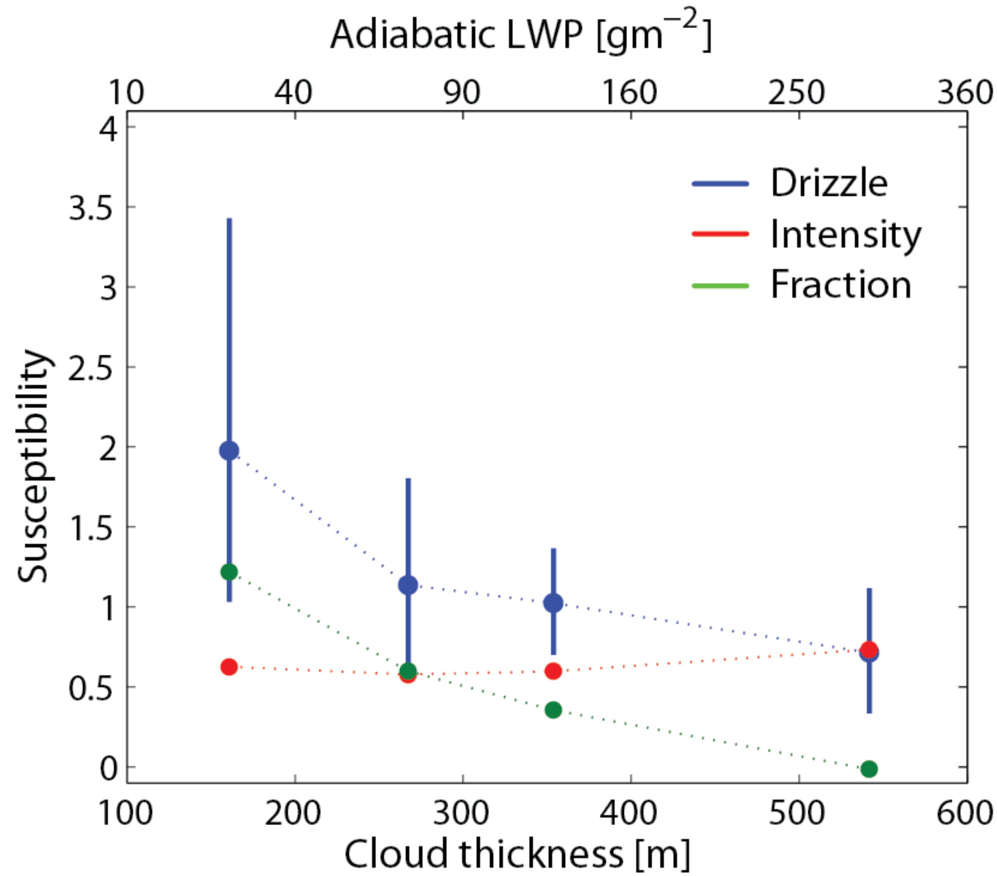


Precipitation susceptibility

- Construct from Feingold and Siebert (2009) can be used to examine aerosol influences on precipitation in both models and observations

$\boldsymbol{S} = -(\mathrm{dln}R_{\mathrm{CB}}/\mathrm{dln}N_{\mathrm{a}})_{LWP,h}$

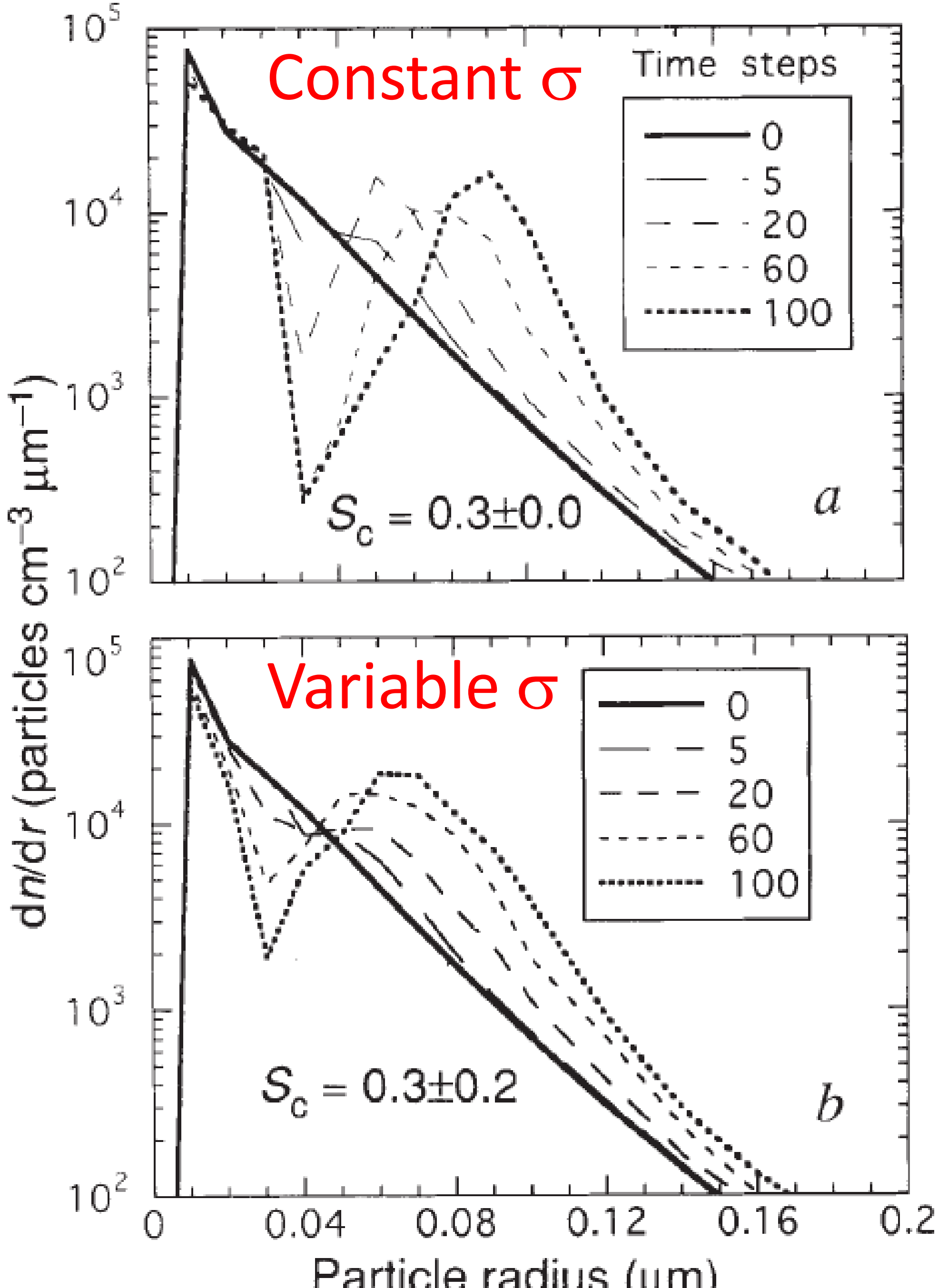
- *S* decreases strongly with cloud thickness
- Consistent with increasing importance of accretion in thicker clouds
- Consistent with results from A-Train (Kubar et al. 2009, Wood et al. 2009)



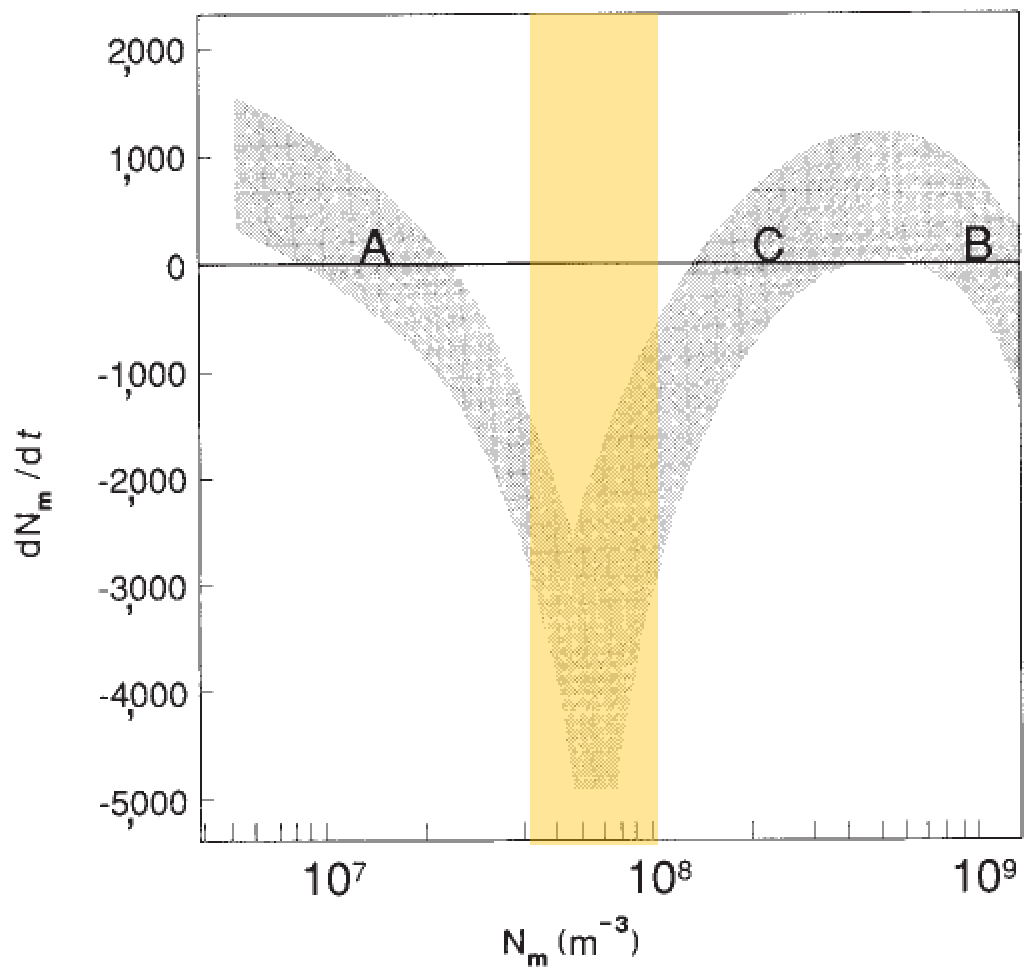
Data from stratocumulus over the SE Pacific, Terai and Wood (*Geophys. Res. Lett.*, 2011)

Effect of variable supersaturation

- Kaufman and Tanre 1994



- Range of observed and modeled CCN/droplet concentration in Baker and Charlson "drizzlepause" region where loss rates from drizzle are maximal
- Baker and Charlson source rates



Baker and Charlson, *Nature* (1990)

- Timescales to relax for N

Entrainment:

Surface: $\tau_{sfc} \sim \; N z_i / \beta U_{10}^{3.4}$

Precip: $z_i/(hKP_{CB})$ = 8x10^5/(3*2.25) = 1 day for P_{CB}=1 mm day^{-1}

$\tau_{dep} \sim z_i/w_{dep}$ - typically 30 days

Can dry deposition compete with coalescence scavenging?

$$\frac{[\dot{N}]_{coal}}{[\dot{N}]_{dry\ dep.}} = \frac{K P_{CB} h}{w_{dep}}$$

w_{dep} = 0.002 to 0.03 cm s^{-1} (Georgi 1988)
K = 2.25 m^2 kg^{-1} (Wood 2006)

For P_{CB} = > 0.1 mm day^{-1} and h = 300 m

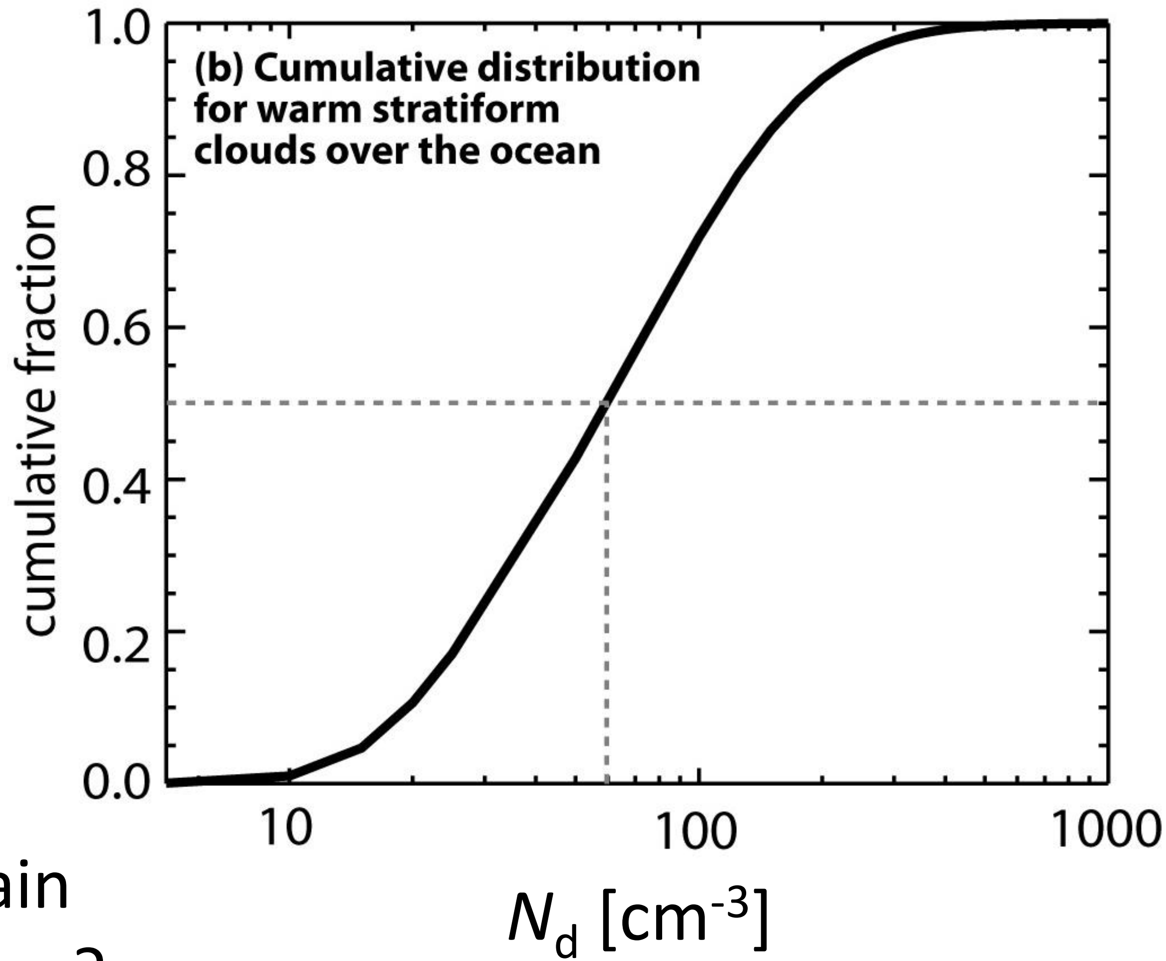
$$\frac{[\dot{N}]_{coal}}{[\dot{N}]_{dry\ dep.}} = 3 \text{ to } 30$$

For precip rates > 0.1 mm day^{-1},
coalescence scavenging dominates

- Examine MODIS Nd imagery – fingerprinting of entrainment sources vs MBL sources.

Cloud droplet concentrations in marine stratiform low cloud over ocean

The view from MODIS

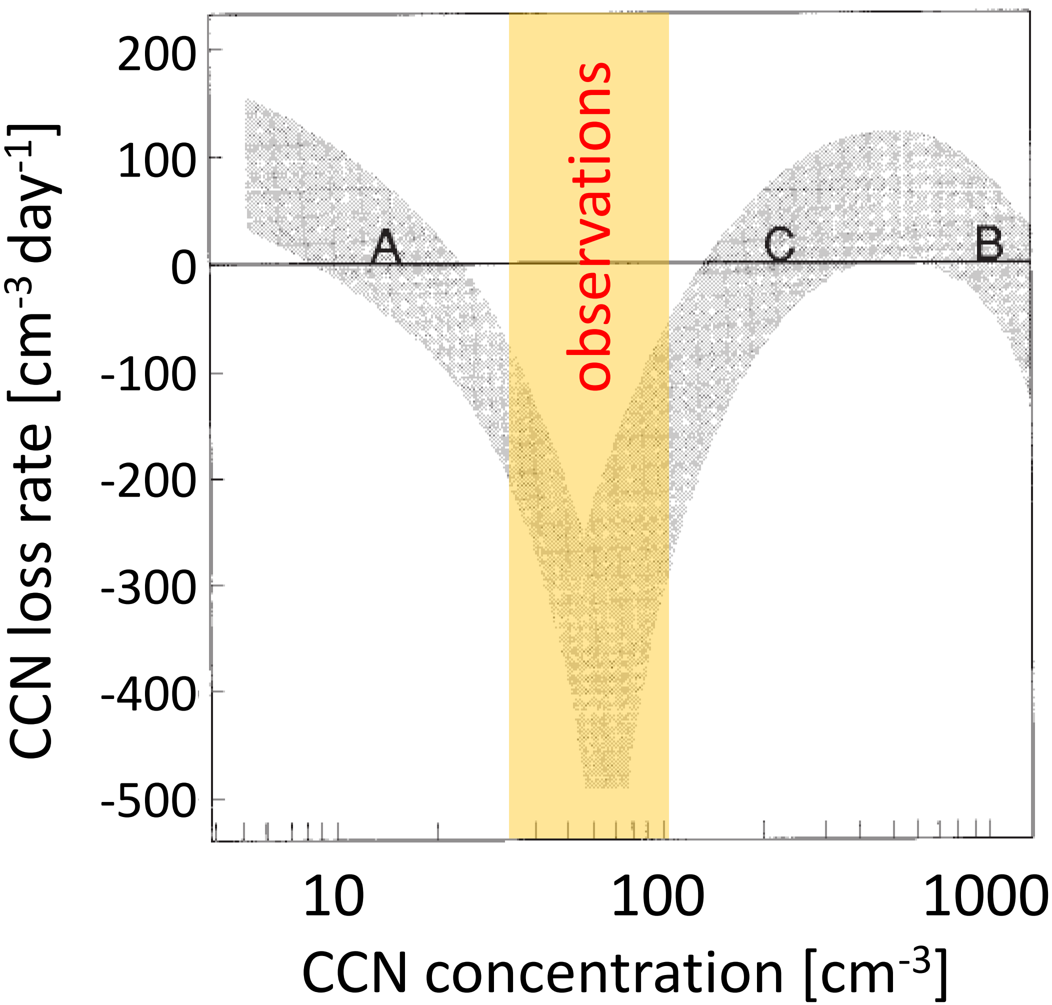


....how can we explain this distribution?

Latham et al., *Phil. Trans. Roy. Soc.* (2011)

Baker and Charlson model

- CCN/cloud droplet concentration budget with sources (specified) and sinks due to drizzle (for weak source, i.e. low CCN conc.) and aerosol coagulation (strong source, i.e. high CCN conc.)
- Stable regimes generated at point A (drizzle) and B (coagulation)
- Observed marine CCN/N_d values actually fall in unstable regime!

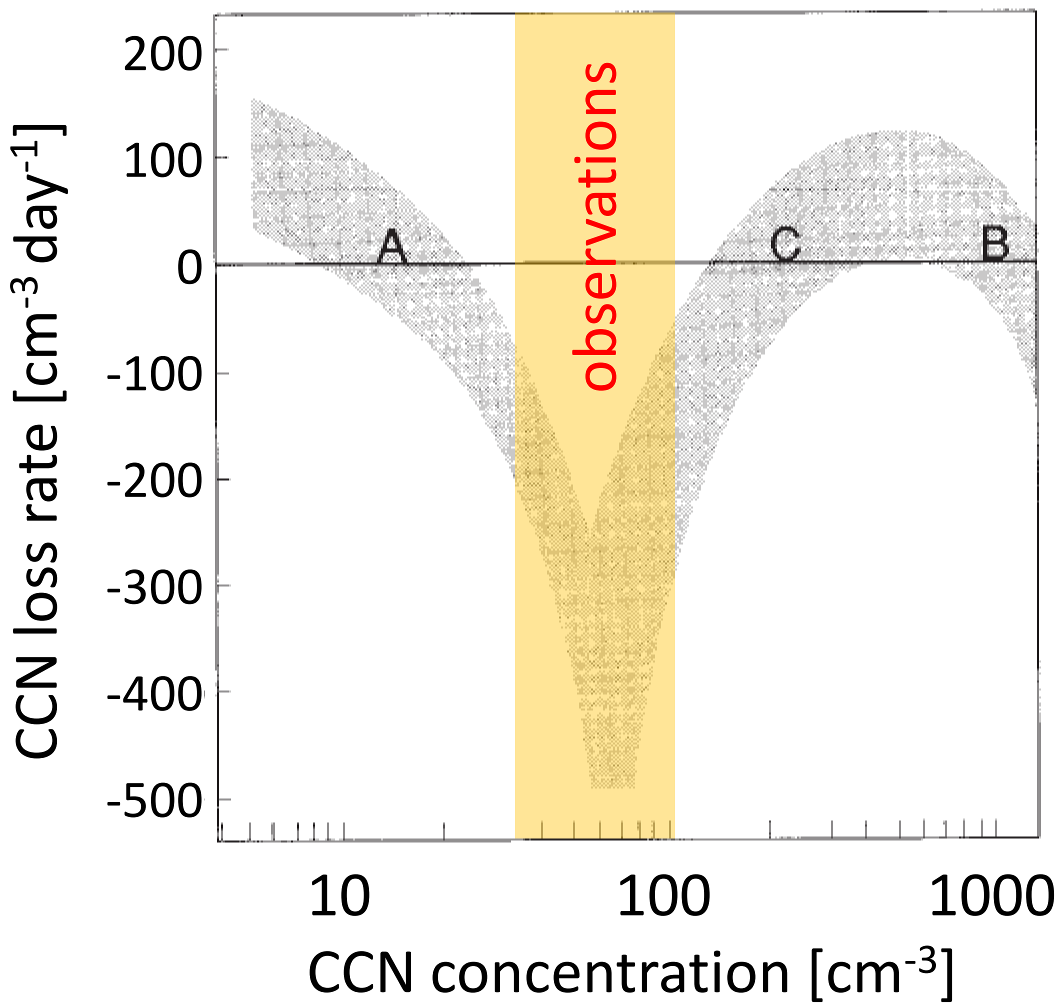


Baker and Charlson, *Nature* (1990)

Baker and Charlson model

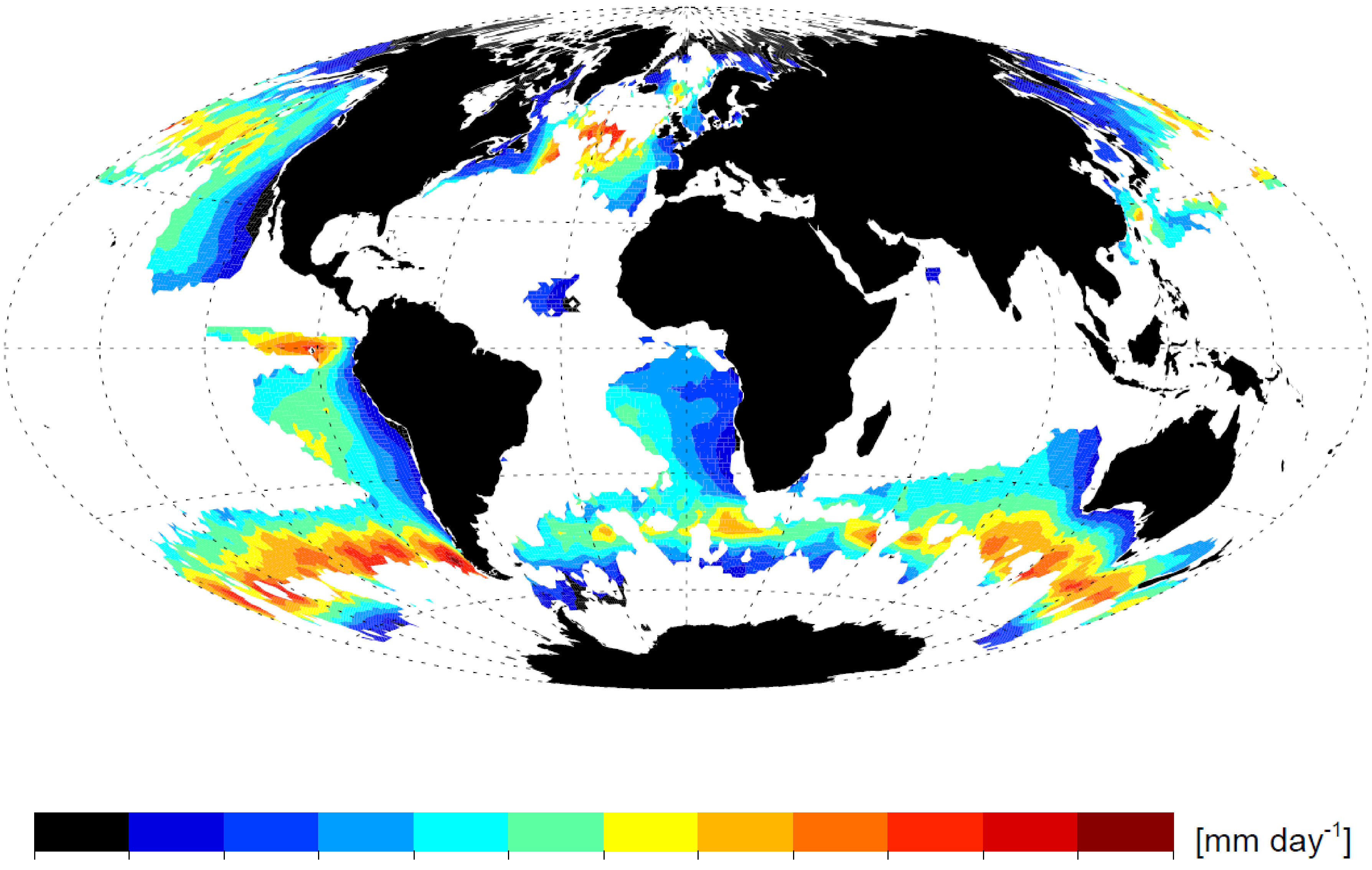
- Stable region A exists because CCN loss rates due to drizzle increase strongly with CCN concentration
  - In the real world this is probably not the case, and loss rates are ~constant with CCN conc.

- However, the idea of a **simple** CCN budget model is alluring

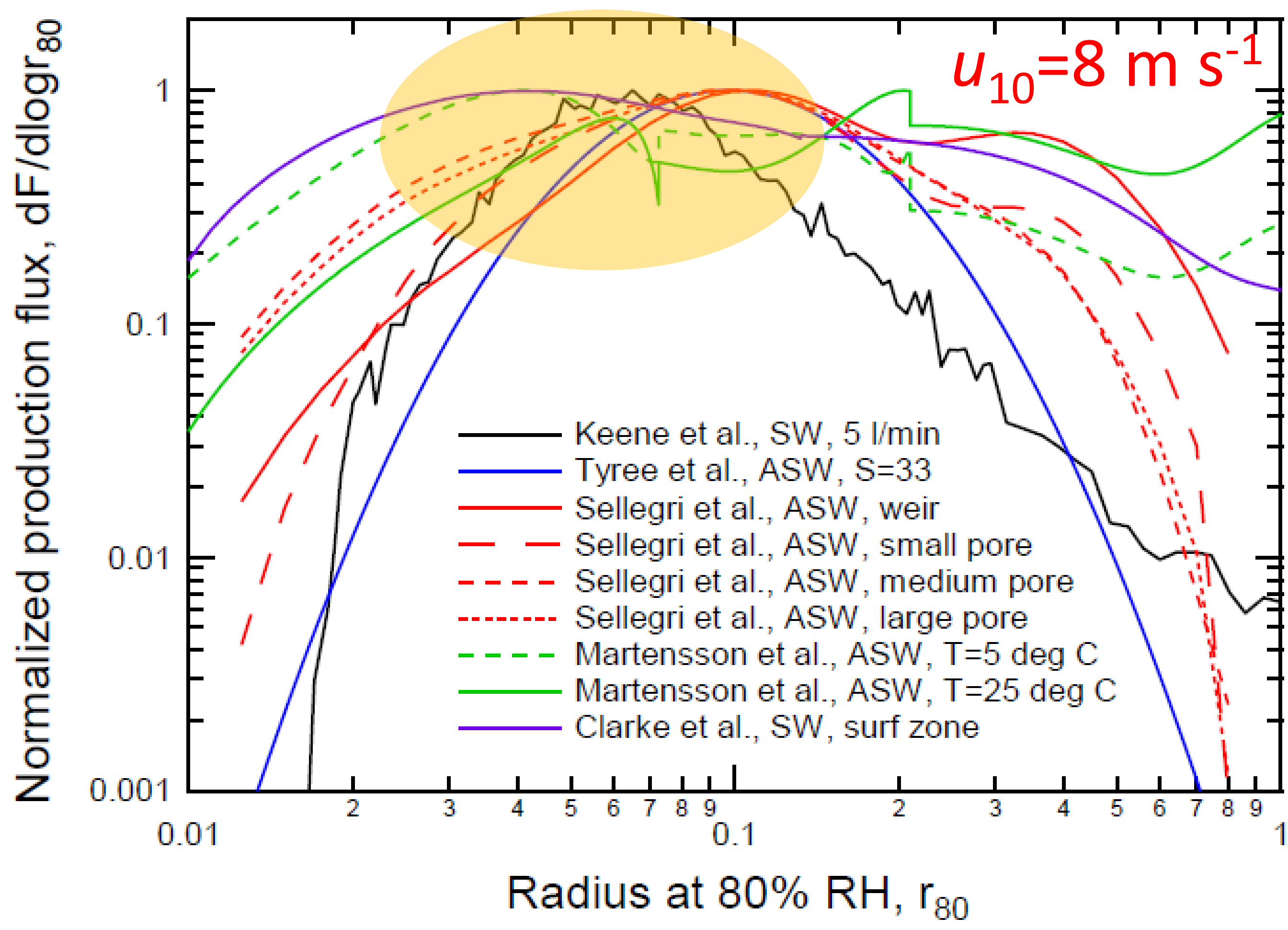


Baker and Charlson, *Nature* (1990)

Mean precipitation rate (2C-PRECIP-COLUMN)



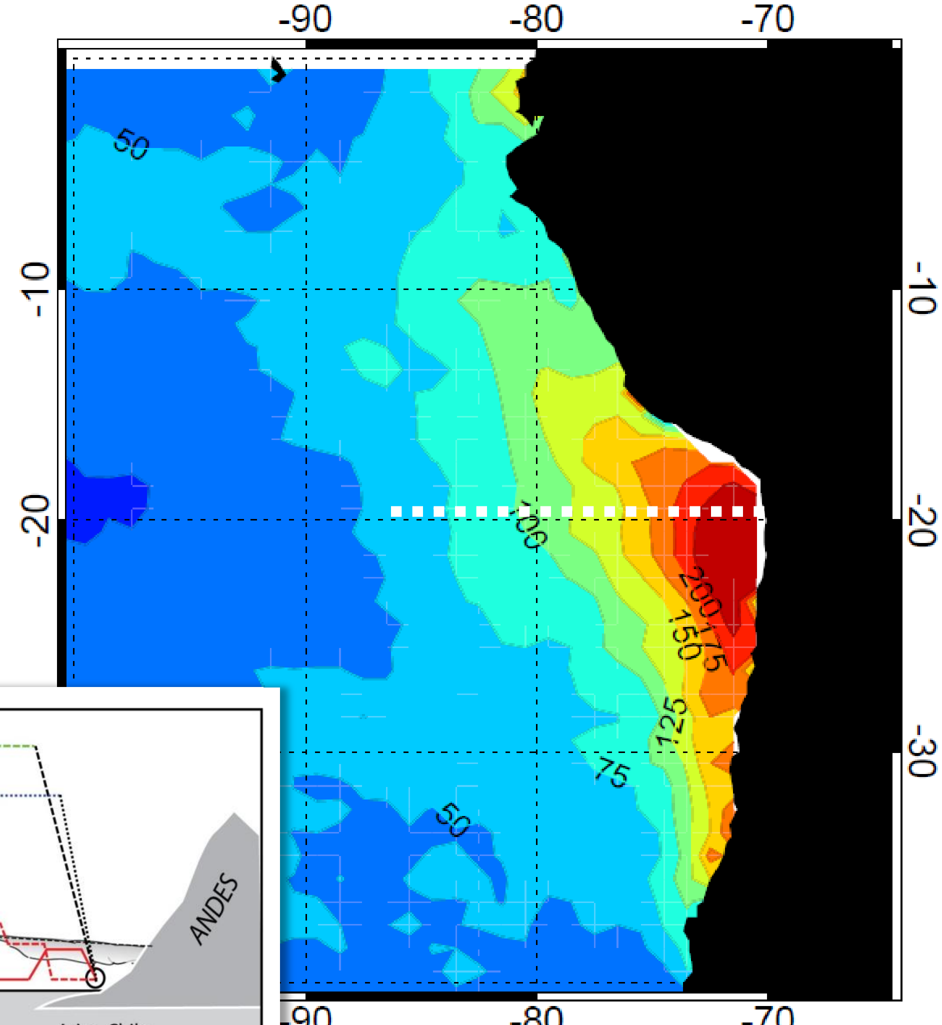
Sea-spray flux parameterizations

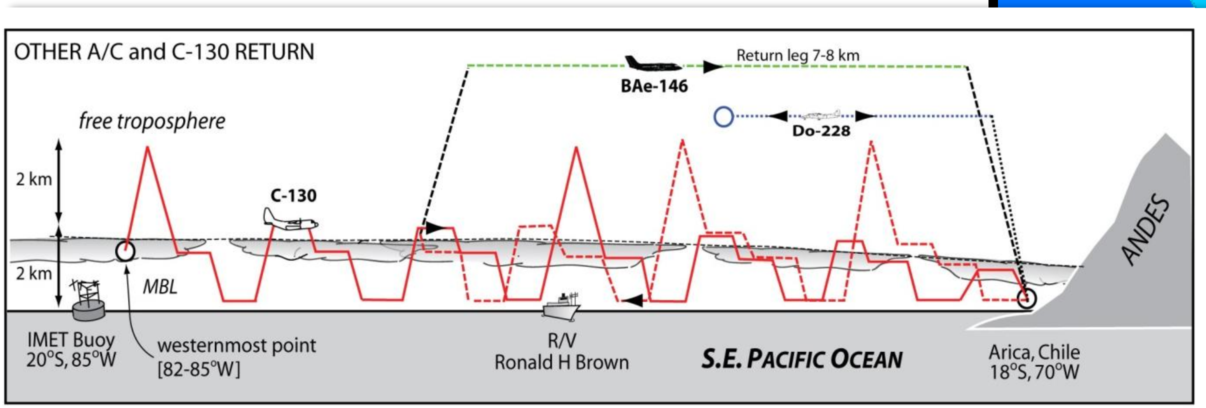


Courtesy of Ernie Lewis, Brookhaven National Laboratory

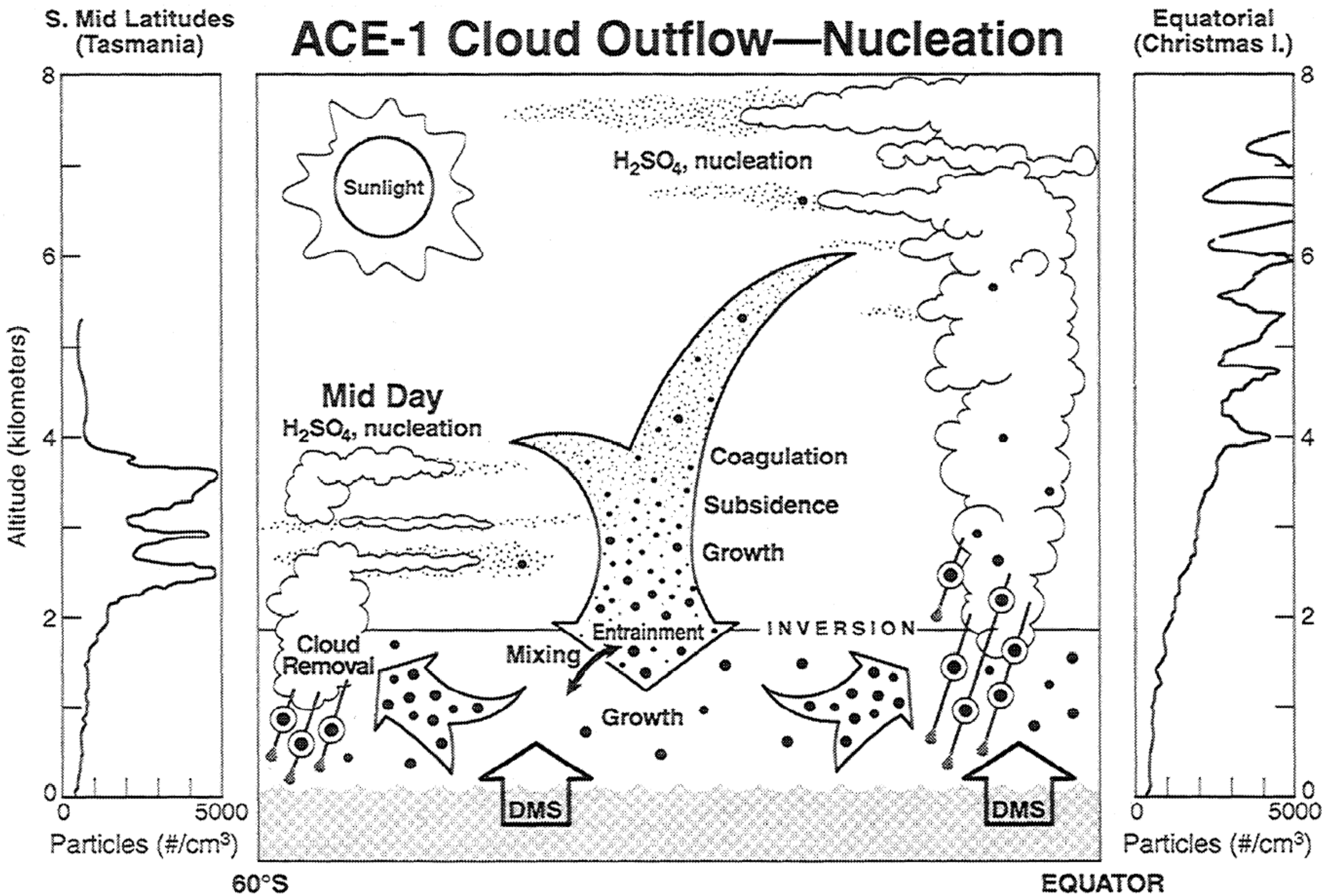
MODIS-estimated cloud droplet concentration N_d, VOCALS Regional Experiment

- Data from Oct-Nov 2008
- Sampling along 20ºS across strong microphysical gradient



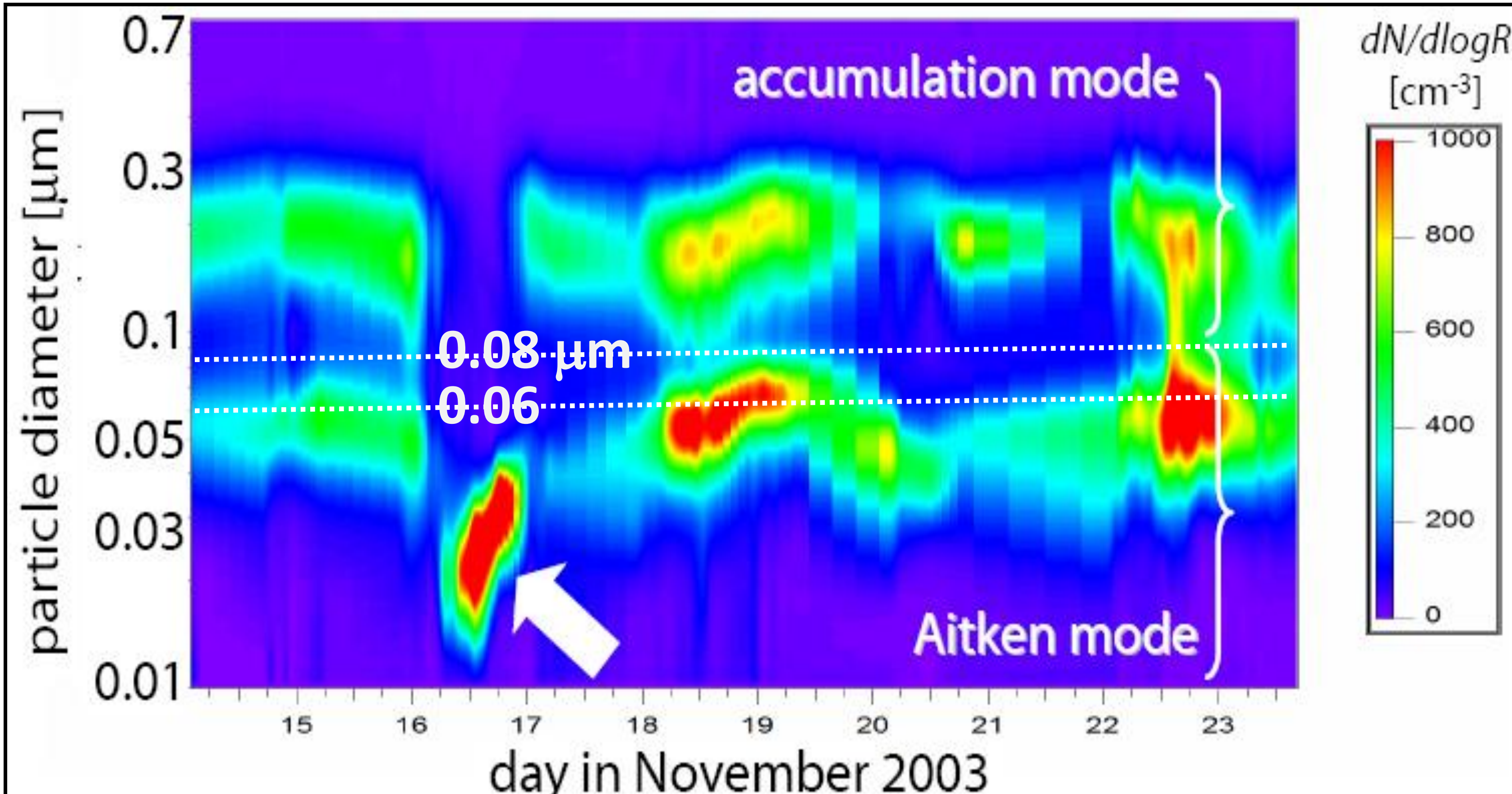


Conceptual model of background FT aerosol



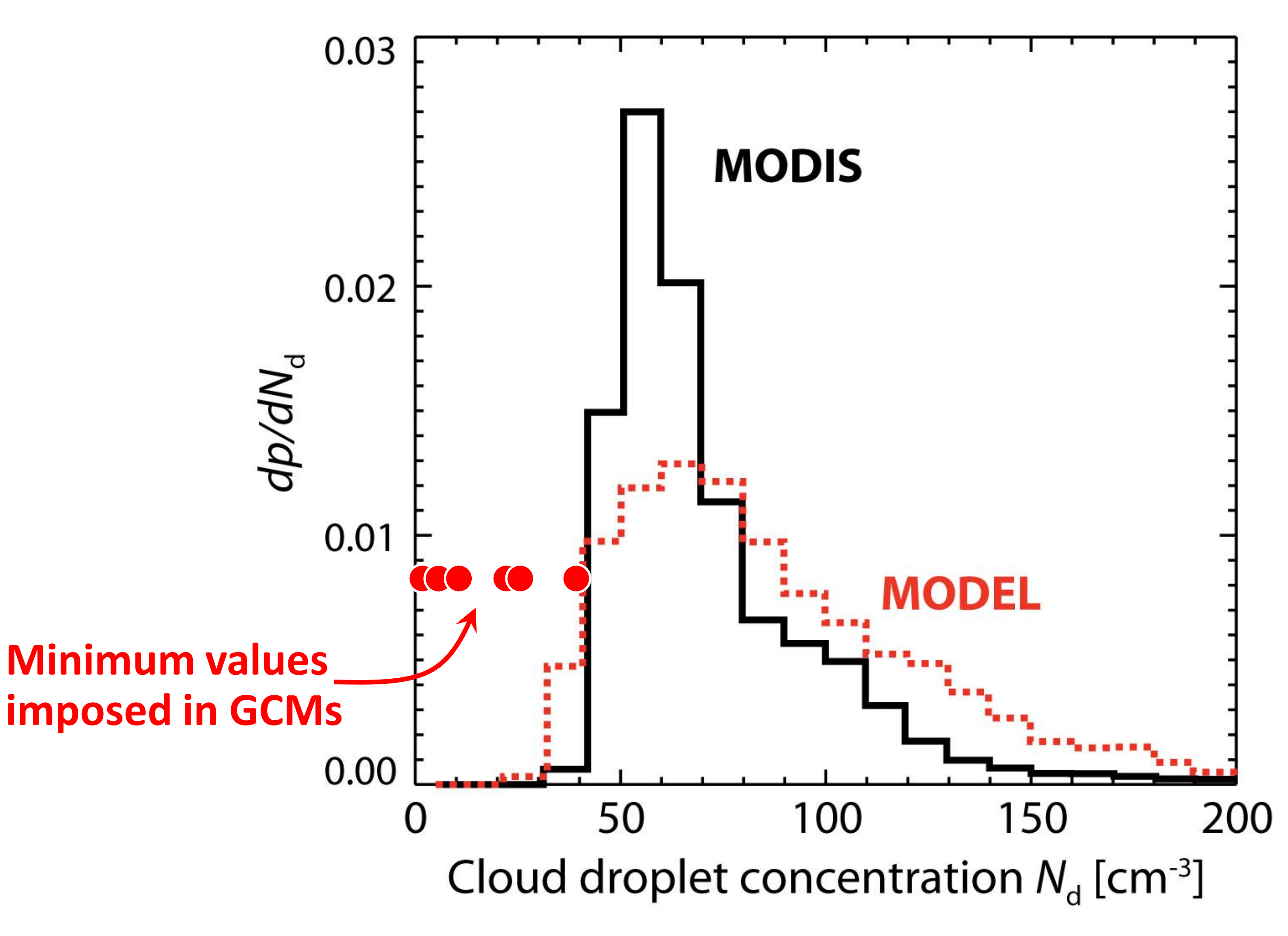
Clarke et al. (*J. Geophys. Res*. 1998)

Observed MBL aerosol dry size distributions (SE Pacific)



Tomlinson et al., *J. Geophys. Res.* (2007)

Predicted and observed N_d - histograms



Loss terms in CCN budget: (2) Dry deposition

$$[\dot{N}]_{dry\ dep.} = -N\frac{w_{dep}}{z_i}$$

Deposition velocity

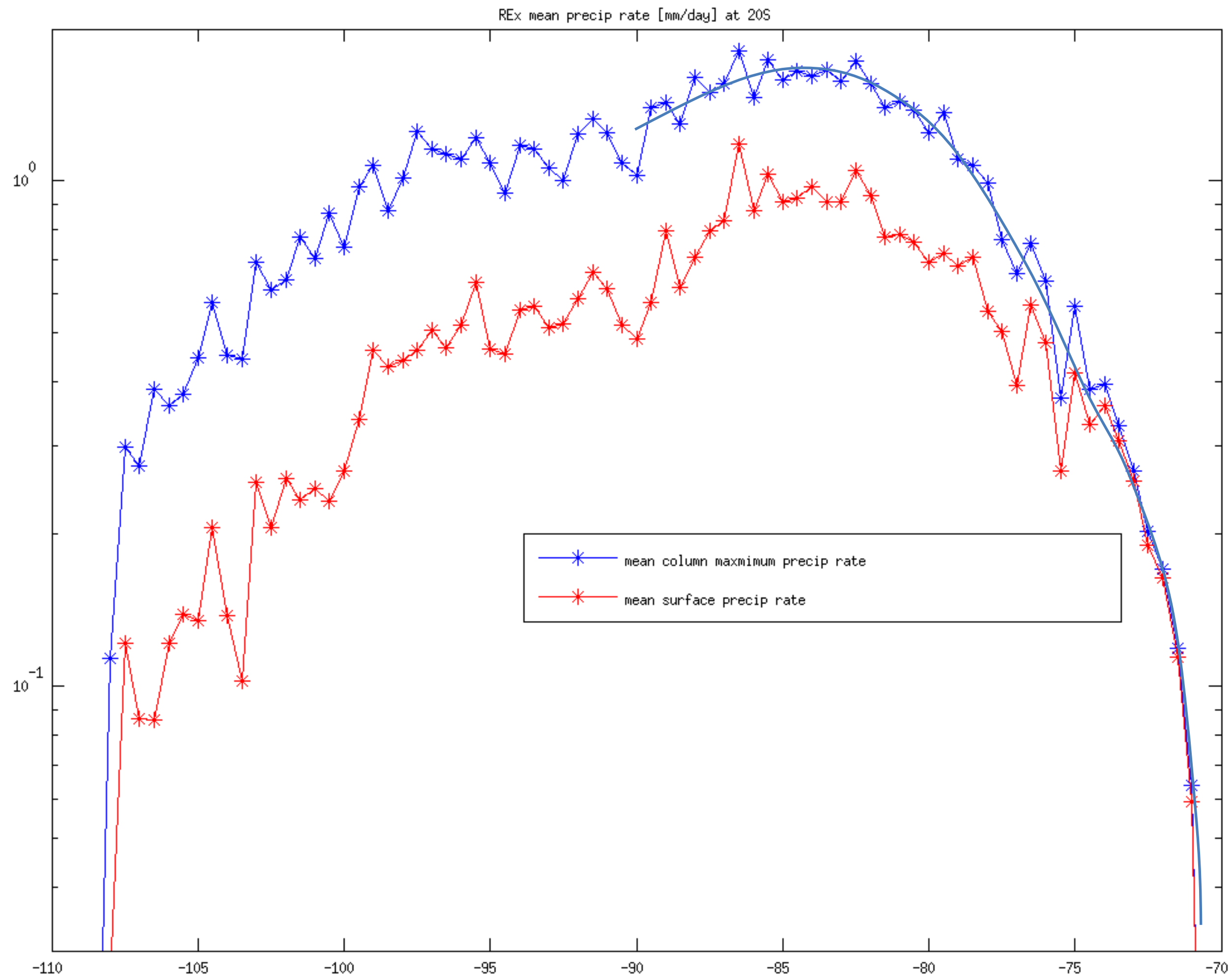
$$\frac{[\dot{N}]_{coal}}{[\dot{N}]_{dry\ dep.}} = \frac{KP_{CB}h}{w_{dep}}$$

w_{dep} = 0.002 to 0.03 cm s^{-1} (Georgi 1988)
K = 2.25 m^2 kg^{-1} (Wood 2006)

For P_{CB} = > 0.1 mm day^{-1} and h = 300 m

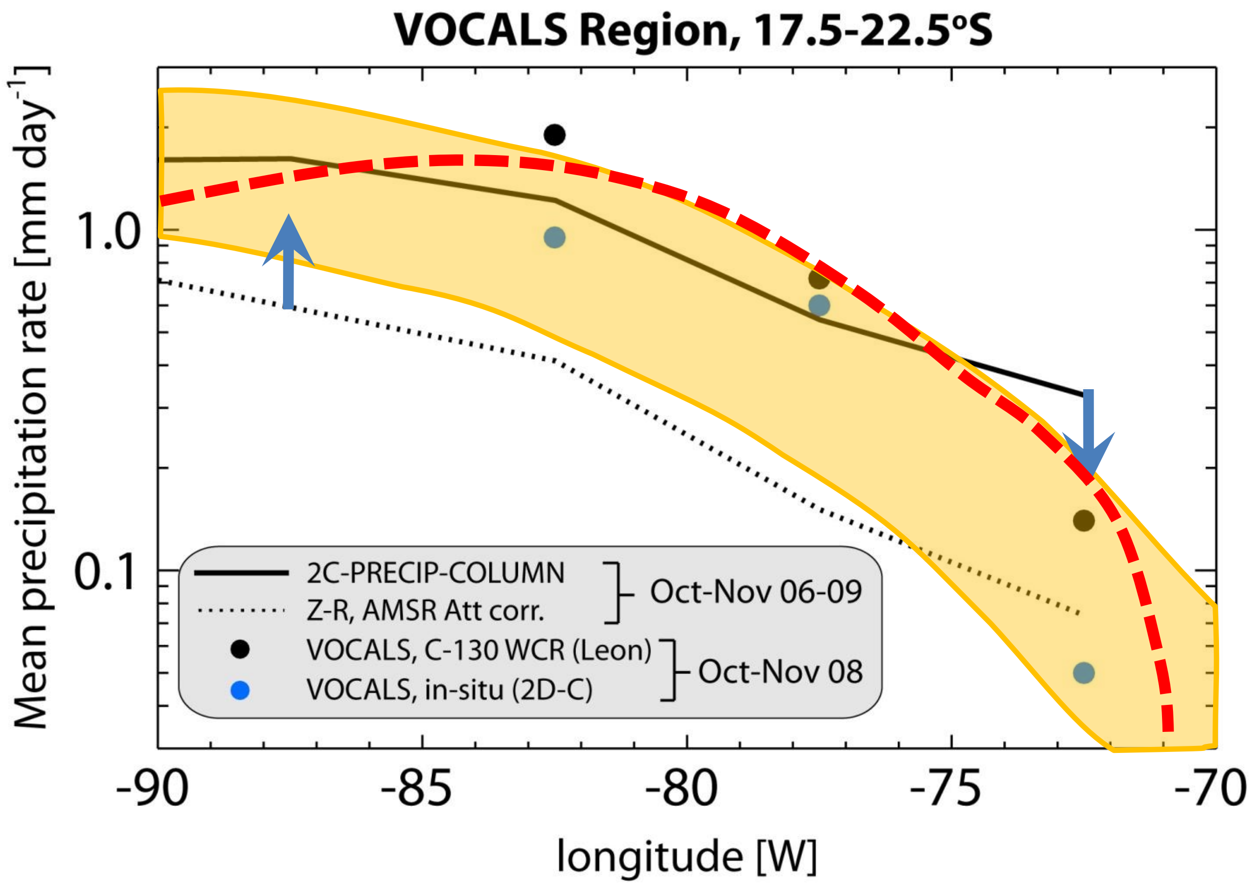
$$\frac{[\dot{N}]_{coal}}{[\dot{N}]_{dry\ dep.}} = 3 \text{ to } 30$$

For precip rates > 0.1 mm day^{-1}, coalescence scavenging dominates


REx mean precip rate [mm/day] at 20S
10^0
10^{-1}
-110
-105
-100
-95
-90
-85
-80
-75
-70
mean column maxmimum precip rate
mean surface precip rate

Precipitation over the VOCALS region

- **CloudSat**
  Attenuation and Z-R methods
- **VOCALS**
  Wyoming Cloud Radar and in-situ cloud probes



Significant drizzle at 85°W

Very little drizzle near coast

WCR data courtesy Dave Leon