Aerosol-Cloud-Climate Interactions using the NASA Global Modeling Initiative

Rafaella P. Sotiropoulou, Nicholas Meskhidze and Athanasios Nenes

Georgia Institute of Technology

GMI Science Meeting
October 11-13, 2006

Acknowledgements: NASA NIP, NASA IDS, DOE

GMI: Aerosol-Cloud-Climate Interactions

Currently Accomplished:

- Implementation of aerosol-cloud interaction modules:
  - Cloud-relevant parameters changes with meteo-fields used.
  - Meteo-fields currently used: DAO, GISS, GEOS-4.
  - Implementation of basic routines that diagnose large-scale relative humidity and cloud fraction from meteo-fields.
- Cloud properties are calculated from parameterizations.
- Implemented droplet formation parameterizations:
  - Boucher and Lohmann (1995) – empirical
  - Abdul-Razzak & Ghan (2000) - mechanistic
  - Nenes & Seinfeld (2003); Fountoukis & Nenes (2005) – mechanistic
- Assessments of indirect effect and autoconversion rate using various droplet formation parameterization and meteorology.

Modeling Framework (Cloud Radiative Properties)

- Aerosol module (Liu & Penner, 2002) coupled to GMI advection core
- Emissions: SO_2, DMS, BC, OC, mineral dust, and sea salt
- Chemical production of sulfate, gravitational sedimentation, dry deposition, wet scavenging in and below clouds, and hygroscopic growth
- In-cloud Liquid Water Content (Hack, 1998)
- Stratiform and Convective cloud fractions (Sundqvist et al., 1978; Xu and Krueger, 1991)

$$C_{LS} = 1 - \sqrt{1 - \frac{RH - RH_c}{1 - RH_c}}$$

$$C_C = \begin{cases} c_0 + c_1 \log(M_C) + c_2 (\log(M_C))^2 \\ \quad \text{if } M_C > 0.01\,\text{hPa h}^{-1} \\ 0, \text{otherwise} \end{cases}$$

$$C = 1\text{-}(1\text{-}C_{LS})\,(1\text{-}C_C)$$

Feng et al. [2004]

$$\tau = \tau_C C^{3/2}$$

Approximate random overlap (RAN) assumption

GMI Improvements:

✓ Effective radius

$$r_e = k\sqrt[3]{\frac{3}{4}\frac{\rho_a q_l}{\pi\rho_w b N_d}}$$

k=1.143 (Cont); k=1.077 (Mar)
(Martin et al., 1994)

✓ Cloud optical depth

$$\tau_C = \frac{3}{2}\frac{LWP}{\rho_w r_e}$$

(Seinfeld & Pandis, 1998)

✓ Cloud albedo

$$R_c = \frac{\tau}{\tau + 7.7}$$

✓ Radiative transfer module for shortwave (SW) radiative fluxes

✓ Solar radiation transmitted through each vertical layer:

$$I_i = I_i^{att}(1 - \alpha_i)$$

✓ Autoconversion rate (Khairoutdinov & Kogan, 2000; Rotstayn, 1997)

Cloud Droplet Number Calculation

Boucher & Lohmann (1995)

- Bypass complex physics of droplet formation

$N_d = 10^{2.21+0.41\log(mSO4)}$ (continental)

$N_d = 10^{2.06+0.48\log(mSO4)}$ (marine)

mSO_4 ($\mu g\ m^{-3}$) specified from GMI

Abdul-Razzak & Ghan (1998; 2000)

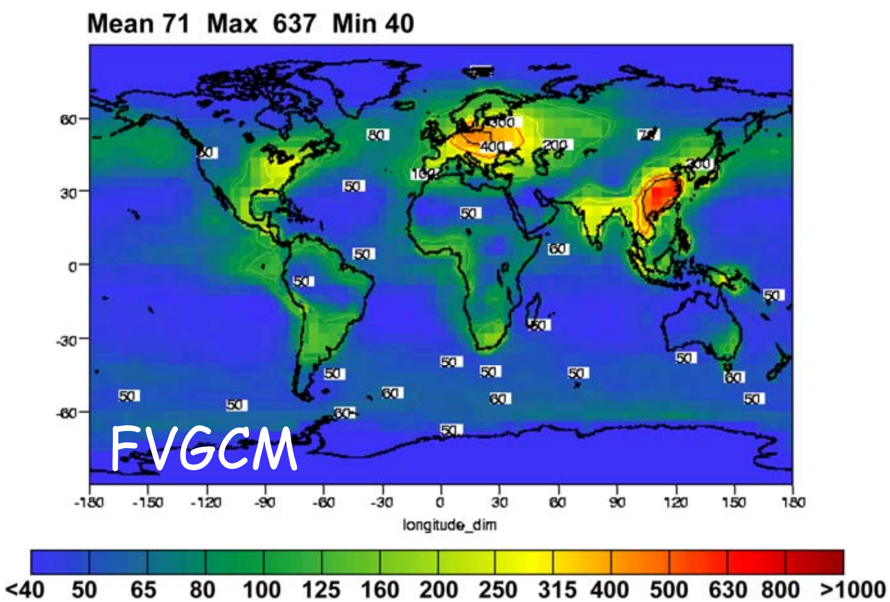
- For lognormal aerosol models
- Computationally efficient
- Kinetic limitations and the influence of surfactants on the activation process are neglected

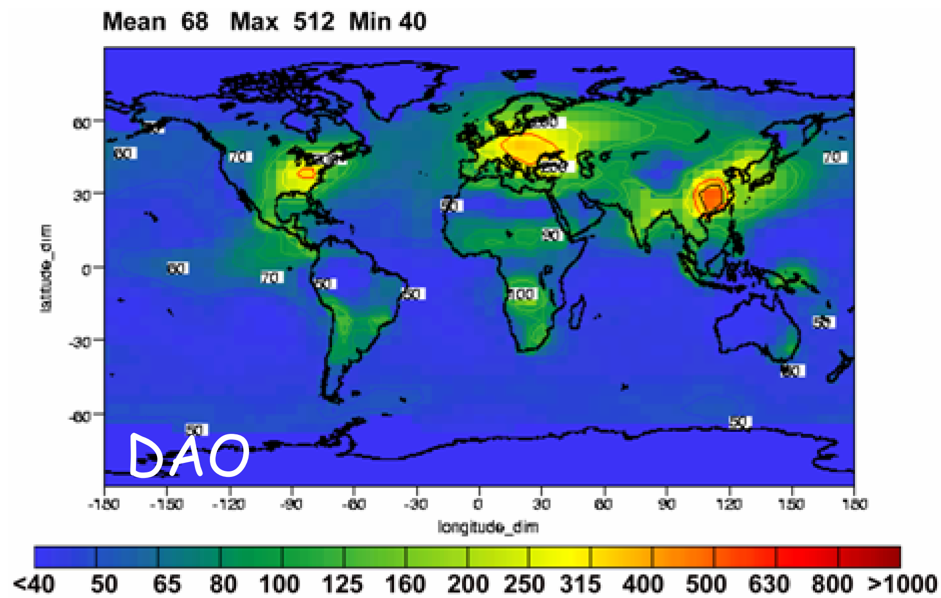
Cloud Droplet Number Calculation

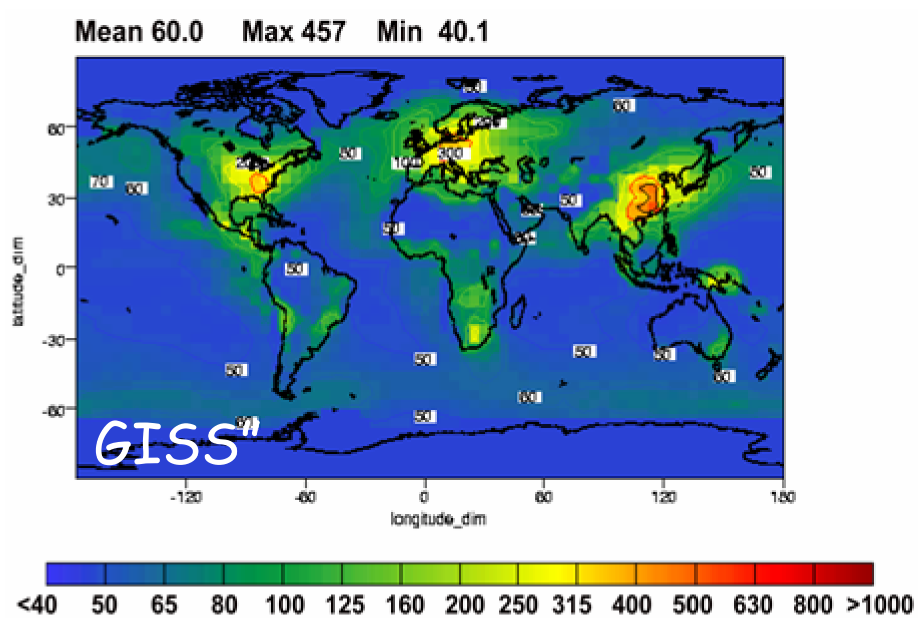
Nenes & Seinfeld, 2003; Fountoukis & Nenes, 2005 (Physically based)

- For lognormal and sectional aerosol models
- Computationally efficient (10^3-10^4 times faster than full numerical model)
- Can treat very complex internal/external aerosol, and effects of organic films on droplet growth kinetics.
- In-situ validation for a wide range of stratocumulus and cumulus clouds, clean and polluted (Meskhidze *et al.*, JGR, 2005; Fountoukis *et al.*, JGR, in review)
- Extensive intercomparison with other parameterizations show that it outperforms them for climatically relevant dataset (~ 1000 data points).

Cloud Droplet Number (cm^{-3}) (annual average)





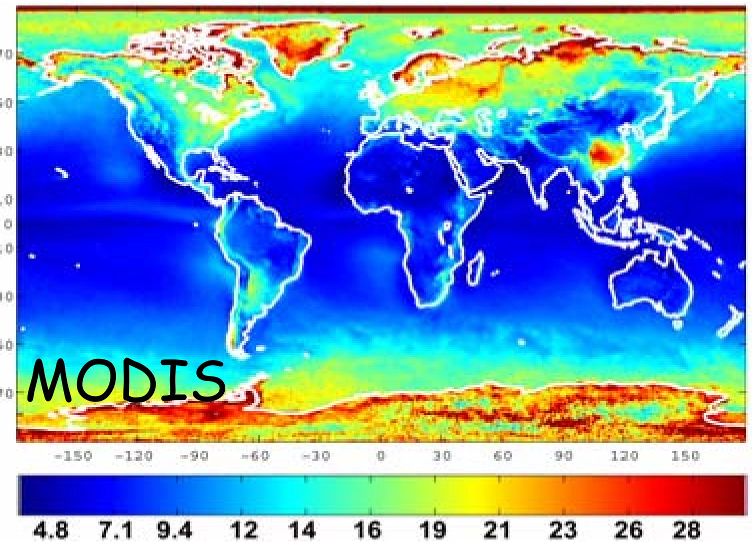


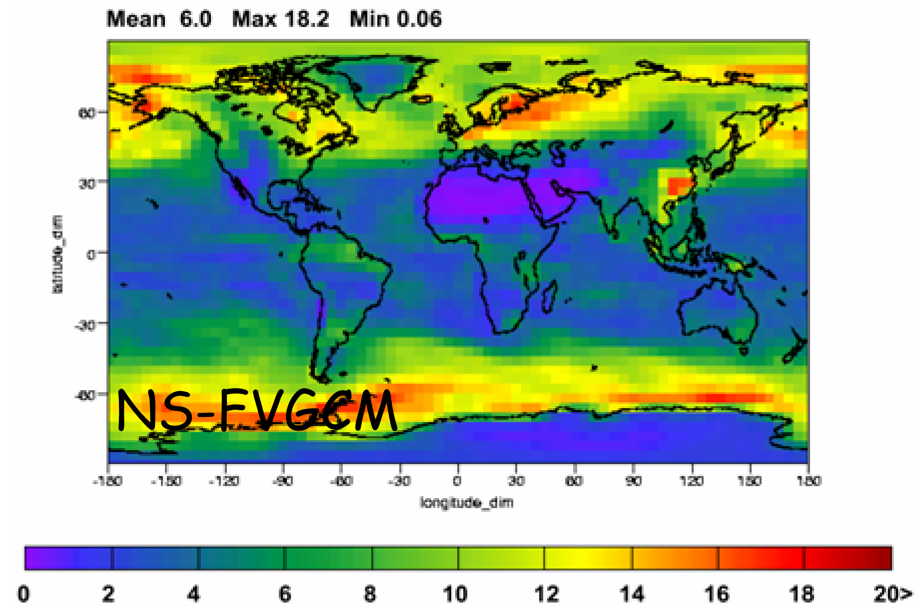
Conditions:

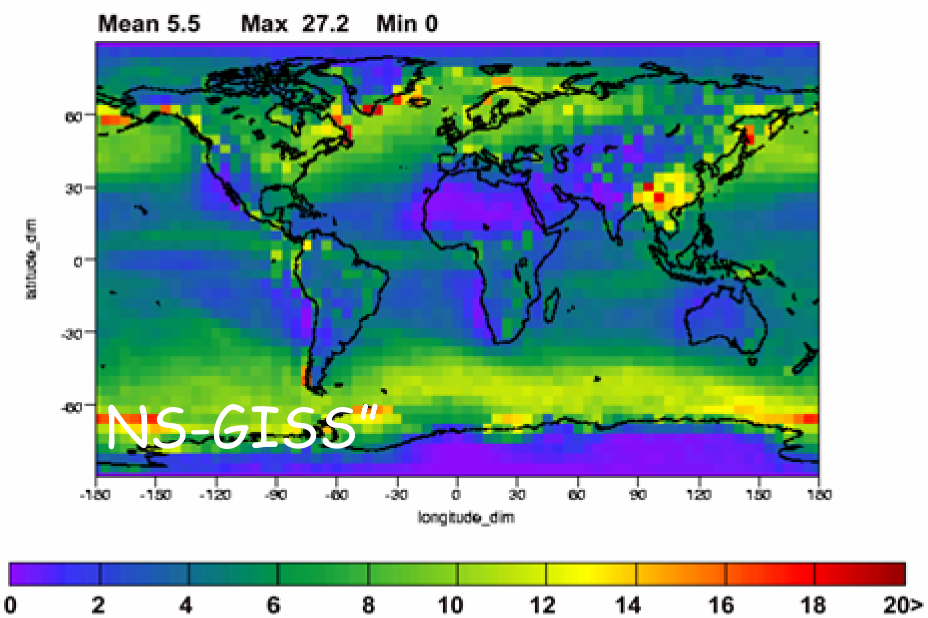
NS parameterization
Prescribed updrafts (marine: 0.35 ms^{-1}; continental: 1.0 ms^{-1})
Water vapor mass uptake coefficient, a_c, is set to 0.042

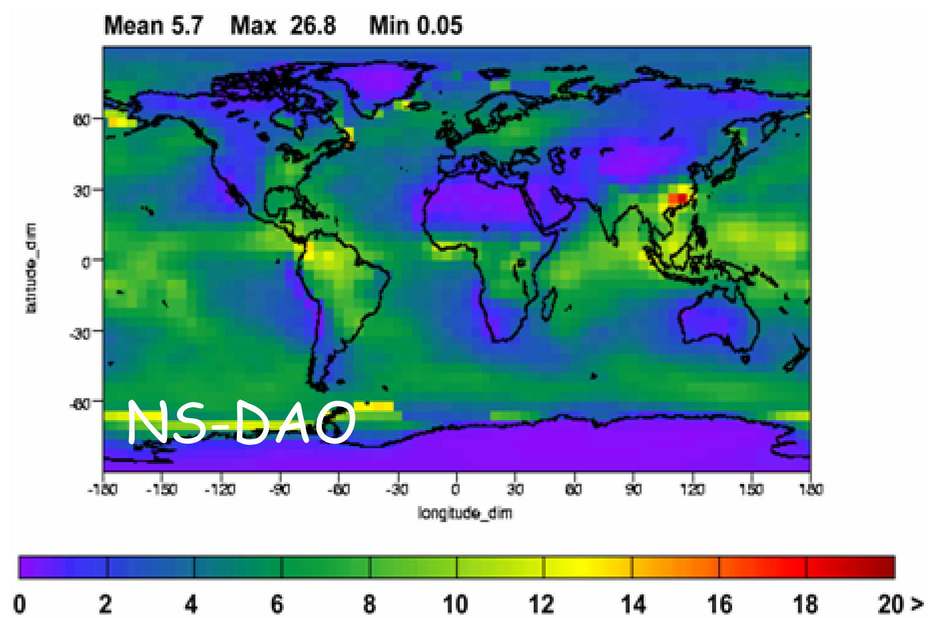
N_d(FVGCM)~N_d(DAO)>N_d(GISS")

Cloud Optical Thickness (τ)







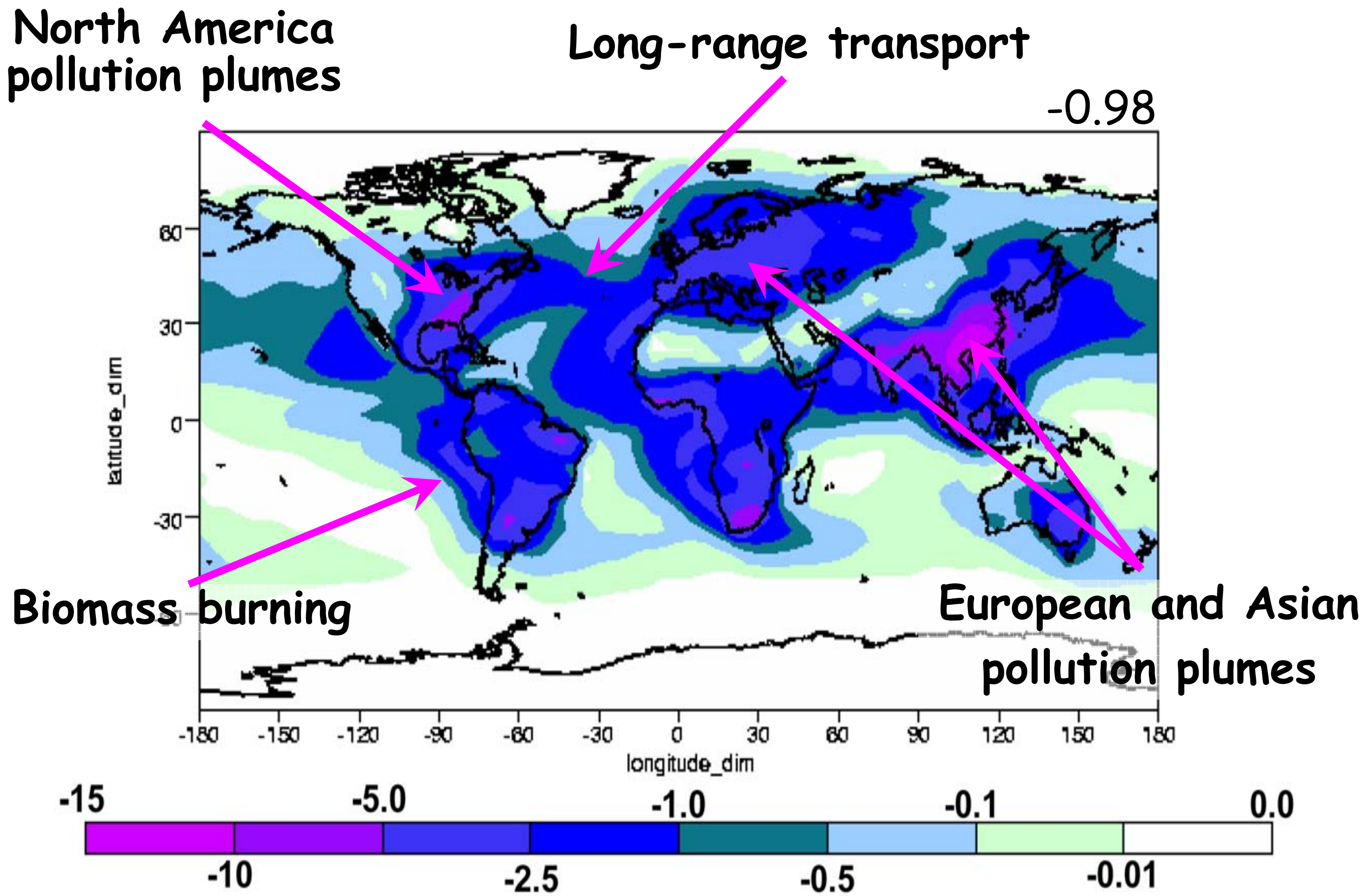


τ	FVGCM		DAO		GISS		ISCCP*
	NS	BL	NS	BL	NS	BL	
Ocean	5.82	5.97	5.78	5.91	5.74	5.85	6.9
NH Ocean	5.27	5.51	5.28	5.50	5.27	5.43	6.4
SH Ocean	6.21	6.30	6.11	6.22	6.01	6.07	7.4
Land	5.47	5.57	5.38	5.25	5.05	5.14	8.1
NH Land	6.11	6.22	5.65	5.78	5.32	5.41	7.8
SH Land	4.33	4.60	4.25	4.57	4.13	4.52	8.6

**Han et al.*, 1994

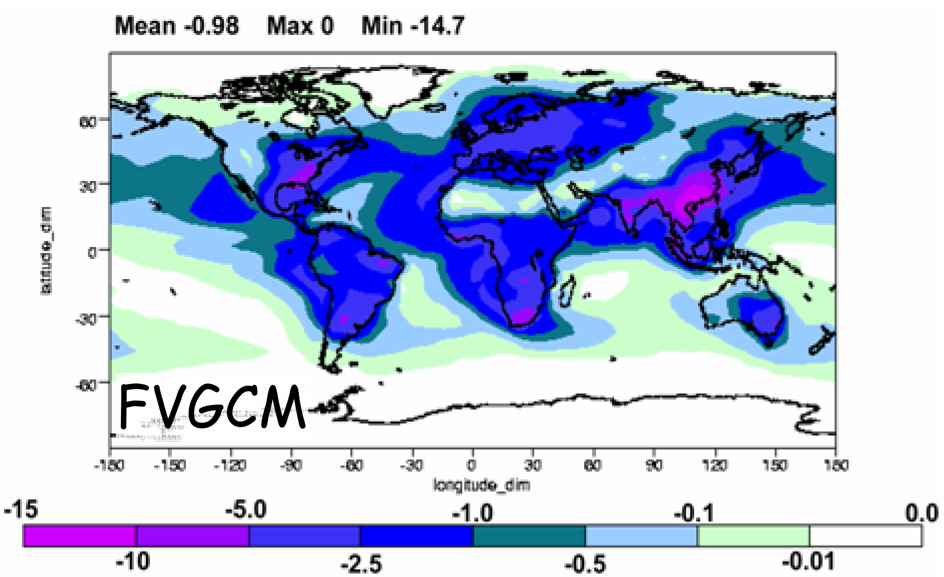
- Lower compared to the satellite particularly at high latitudes
- Small contribution to the indirect effect, but very important for local climate forcing.
- Captures high optical depths over China, eastern US, Europe

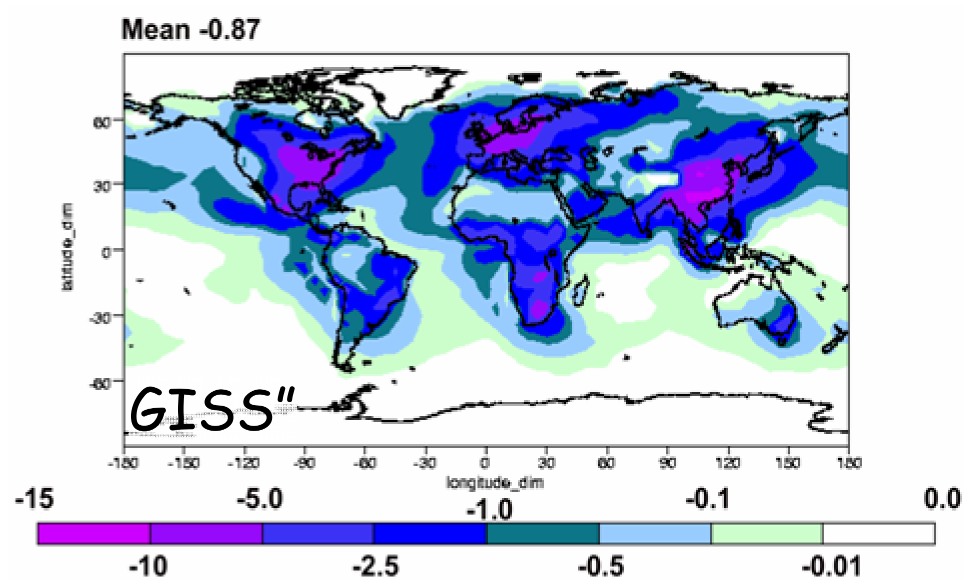
Annual Average Indirect Forcing (W m^{-2})

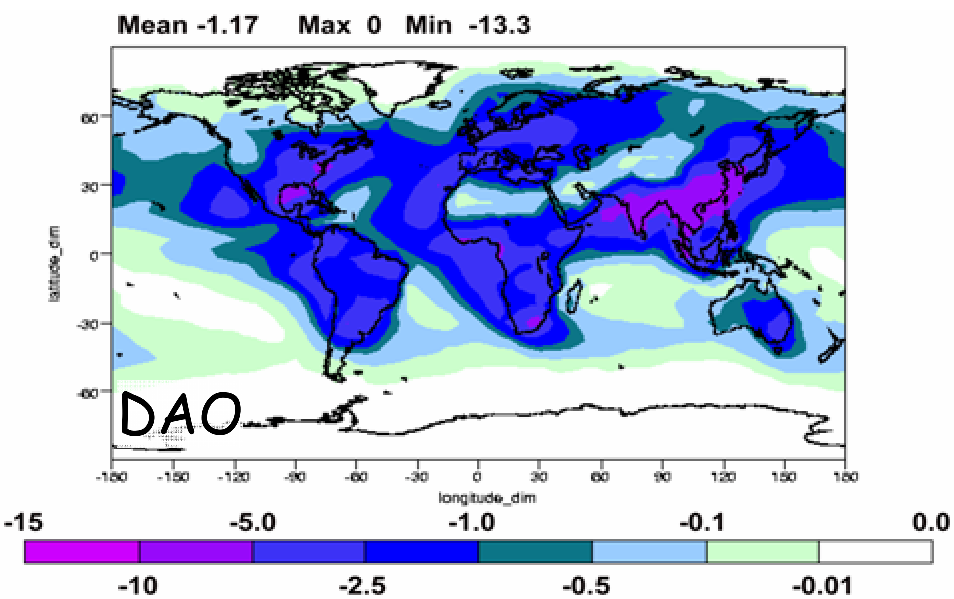


The spatial pattern of indirect forcing follows that of CDNC

Annual Mean First Indirect Effect (W m^{-2})







NS Parameterization

-0.98 W m^{-2} FVGCM

-1.17 W m^{-2} DAO

-0.87 W m^{-2} GISS"

Implications and Conclusions

- Depending on the droplet activation parameterization and the meteo-field used, global annual indirect forcing ranges:
  -0.87 W/m^2 to -1.17 W/m^2

- Different met fields lead up to **20%** (Global average) variability in indirect forcing calculations.

- Diagnostic and empirical parameterizations up to **20%** (Global average) difference. This small difference is primarily from the "fixed" aerosol size distribution assumed in the model. Interactive microphysics will certainly increase the sensitivity/differences (our experience with CACTUS and CACTUS/TOMAS support this).

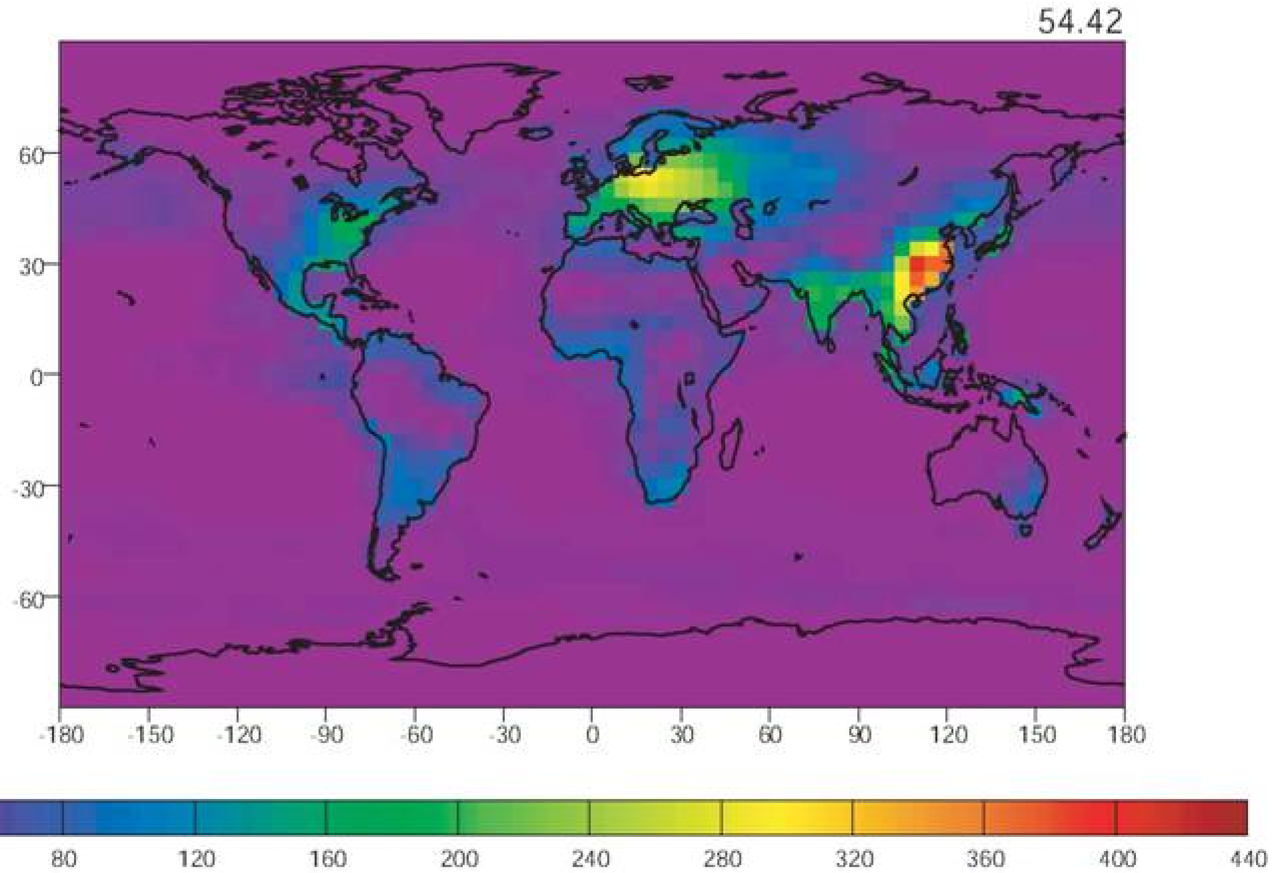
Work in Progress – Future Plans

- AEROCOM emissions for SO_2, DMS, black carbon, organic matter, mineral dust, and sea salt (Jose: we need to have that running well soon for DAO (current day) and pre-industrial)
- Incorporate other cloud droplet activation parameterizations (Feingold and Heymsfield [1992]; Segal and Khain [2006]).
- Run the indirect forcing /sensitivity test for interactive aerosol microphysics. (Jose, Joyce: when will we have that capability?).
- Introduce the entraining cloud droplet formation parameterization that we have developed in the group (Barahona and Nenes, *in prep.*)
- "Tie" autoconversion with cloud droplet formation even better.
- Cloud spectrum parameterization (Hsieh and Nenes, *in prep*) to link autoconversion with activation; this promises to eradicate "tuning" of autoconversion parameterizations.

Cloud Droplet Number (cm^{-3}) (annual average)

Conditions:

AG parameterization
Prescribed updrafts (marine: 0.35 ms^{-1}; continental: 1.0 ms^{-1})
FVGCM Meteo-fields



Parameterizing drizzle: how it's done now

Precipitation formation in GCMs is often *decoupled* from activation, and generation of rainwater is expressed in terms of a 'critical' liquid water content beyond which rainwater production becomes efficient:

conversion rate 'constants'

$$(\dot{q}_l)_P = -\left(c_T \left[1 - \exp\left\{ -\left(\frac{q_l / C}{c_w} \right)^2 \right\} \right] + c_A P \right) q_l$$

(Rotstayn, 1997)

critical LWC for rainwater

This is not how it happens in nature; rain is a collection process and must be treated as such, if possible.

Parameterizing drizzle: how it's done now

Improved precipitation parameterizations that consider microphysics exist, and are also used,

liquid water cloud fraction

average collection efficiency

$$\left(\dot{q}_l\right)_P = -C_1 \frac{0.104 g E \rho^{4/3}}{\mu\left(N_d \rho_w\right)^{1/3}} \left(\frac{q_l}{C_1}\right)^{7/3}$$

droplet number

(Rotstayn, 1997)

This is a step in the right direction, but the effects of spectral broadening (droplet size distribution) are not explicitly considered.

We seek an explicit link between aerosol, activation and subsequent coalescence at the "updraft" scale.

We are doing this now by predicting droplet size distribution in the updrafts that form clouds online in the GCM.

Autoconversion

3 schemes are used [Kharoutdinov & Kogan, 2000; Rotstayn, 1997]:

Cloud fraction LWMR Cloud droplet number

Autoconversion rate

$$(\dot{q}_l)_{AU} = 1350\; C_l q_c^{2.47} N_d^{-1.79} \qquad (1)$$

Mean volume radius

$$(\dot{q}_l)_{AU} = 4.1 \times 10^{15} C_l r_v^{5.67} \qquad (2)$$

Mean collection efficiency

$$(\dot{q}_l)_{AU} = -C_l \frac{0.104\, g E_{AU} \rho^{\frac{4}{3}}}{\mu\left(N_d \rho_w\right)^{\frac{1}{3}}} \left(\frac{q_l}{C_l}\right)^{\frac{7}{3}} H\left(\frac{q_l}{C_l} - q_{CR}\right) \qquad (3)$$

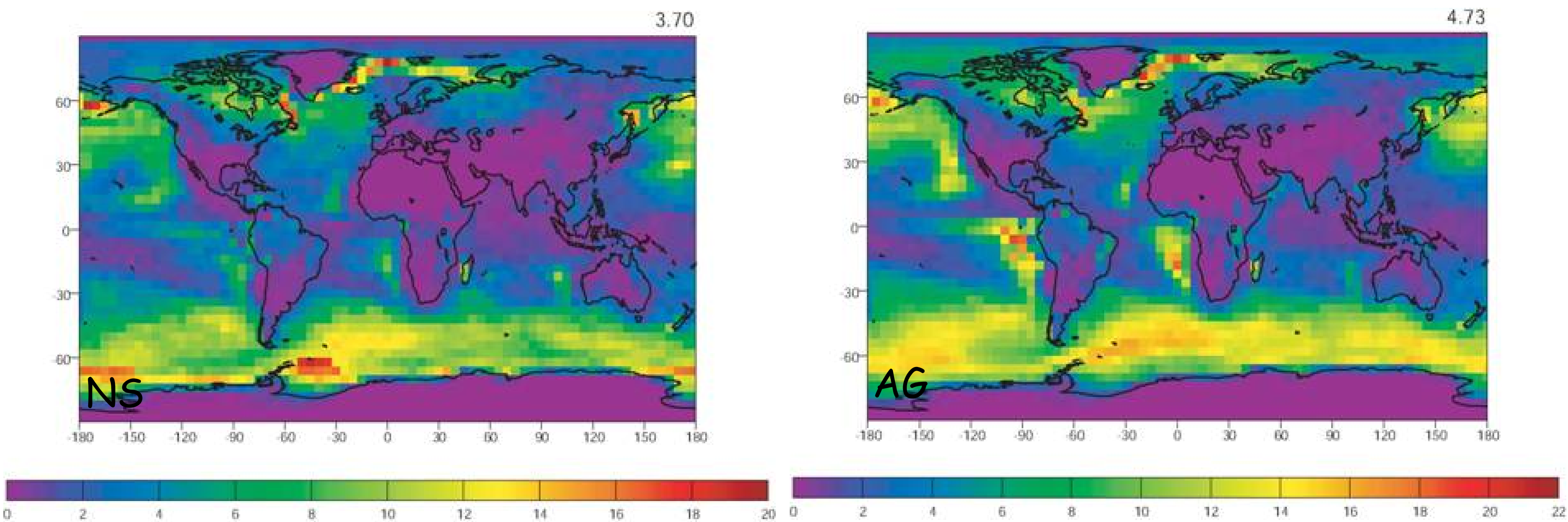
Dynamic viscosity of air Critical LWMR

Linking autoconversion with droplet formation: First steps

Autoconversion ($\times 10^{11}$ s^{-1}) (annual average)

Conditions:

Kharoutdinov & Kogan autoconversion parameterization (considers only N_d or r_{eff}).



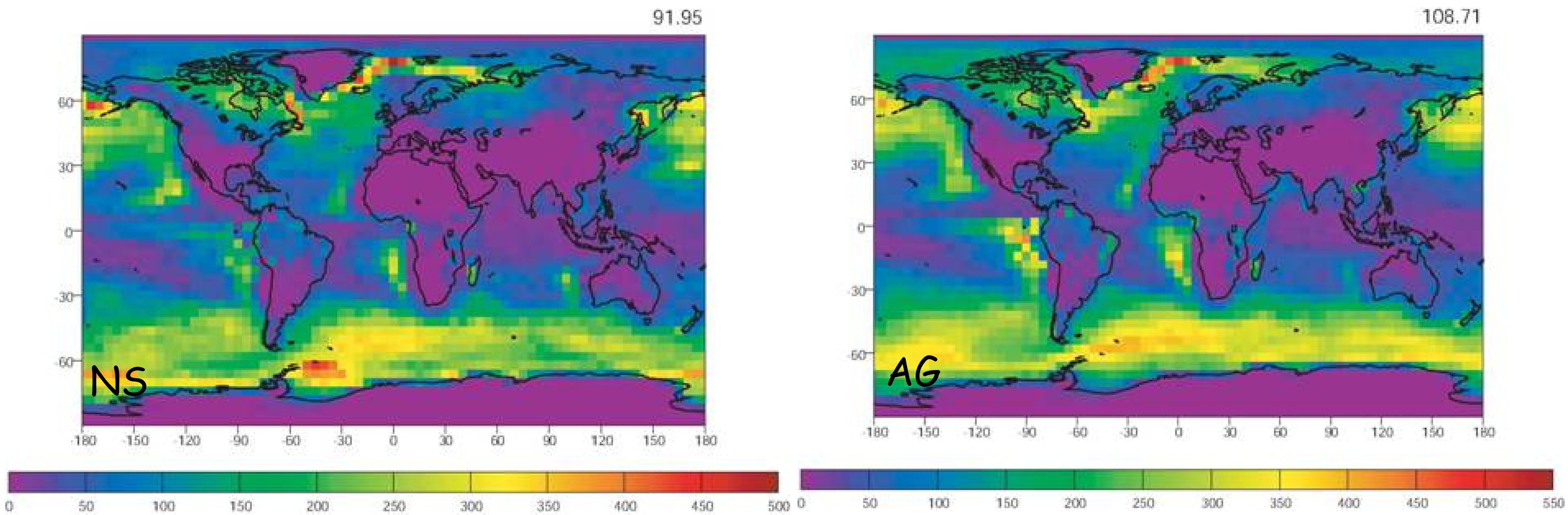
Spatial patterns are anticorrelated with the spatial patterns of CDNC

Linking autoconversion with droplet formation: First steps

Autoconversion ($\times 10^{11}$ s^{-1}) (annual average)

Conditions:

Rotstayn autoconversion parameterization (considers only N_d).



Spatial patterns are anticorrelated with the spatial patterns of CDNC

Parameterizing drizzle: what we will implement

Two-moment schemes developed for small-scale models can be used instead:

(e.g., Cohard and Pinty, 2000; there are more like R4 and R6 schemes of Liu & Daum)

spectral dispersion *average droplet size*

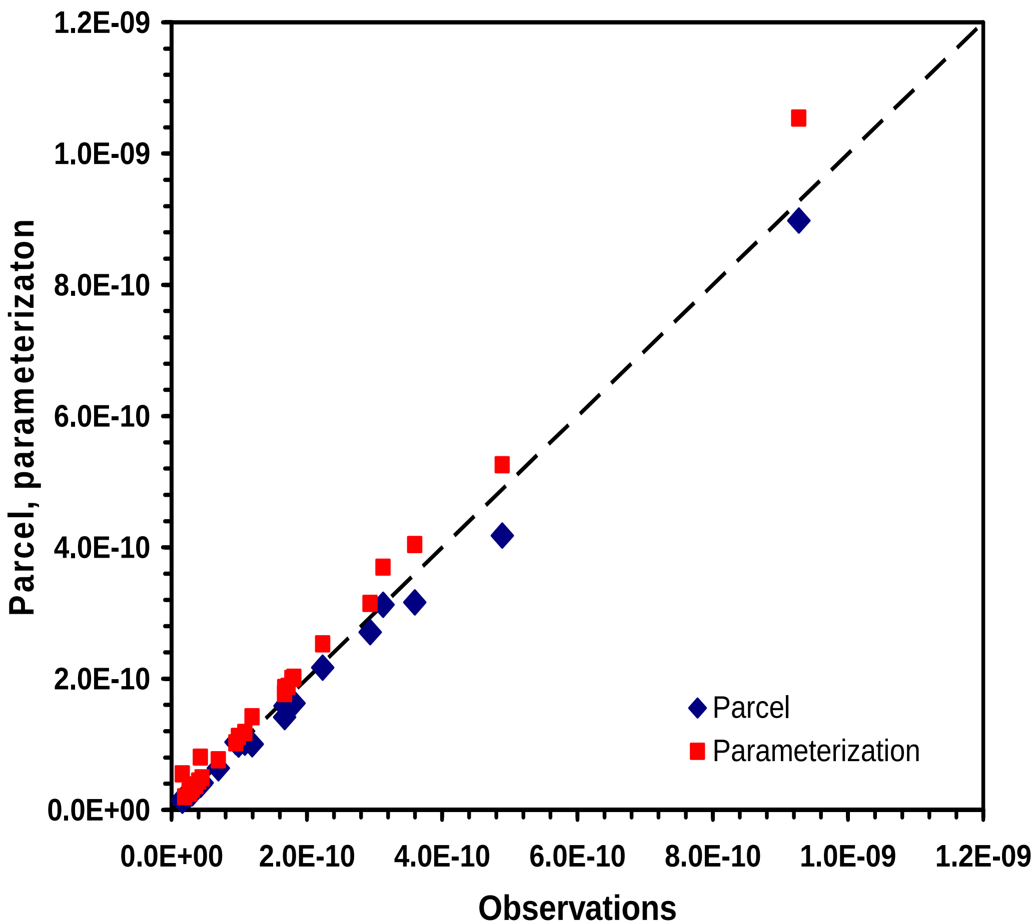
$$\left(\dot{q}_l\right)_P = -\frac{2.7\times10^{-2}\rho\,q_c\left(\dfrac{1}{16}\times10^{-20}\sigma^3 D_v - 0.4\right)}{\dfrac{3.7}{\rho\,q_c}\left(0.5\times10^{6}\sigma - 7.5\right)^{-1}}$$

We have all the elements we need (dispersion, droplet size) for a comprehensive treatment of precipitation. Why not include it in the GCM?

Challenge: How do we obtain these parameters in the global model?

Solution: From the *Nenes and Seinfeld Activation Parameterization*

Parameterizing drizzle: predicting droplet size in GCMs



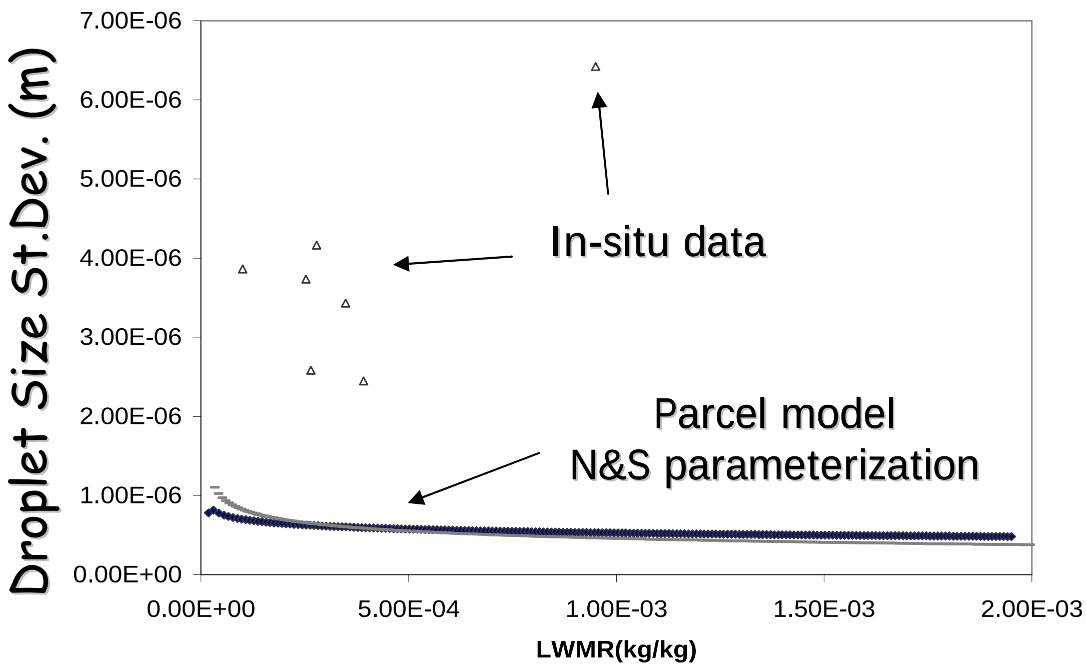
- Predict size distribution with Nenes and Seinfeld parameterization and cloud parcel model for **adiabatic cases** of CRYSTAL-FACE (cumulus) clouds.
- Use droplet number & size distribution to predict autoconversion rate.
- Use in-situ data to calculate autoconversion as well.
- The parameterization (and parcel model) capture the spectral width for adiabatic clouds well.
- Is it always like this? No.
- We need to address this problem.

Hsieh and Nenes, *in prep.*

New cloud droplet formation parameterization (Includes entrainment)

Why need a new parameterization?

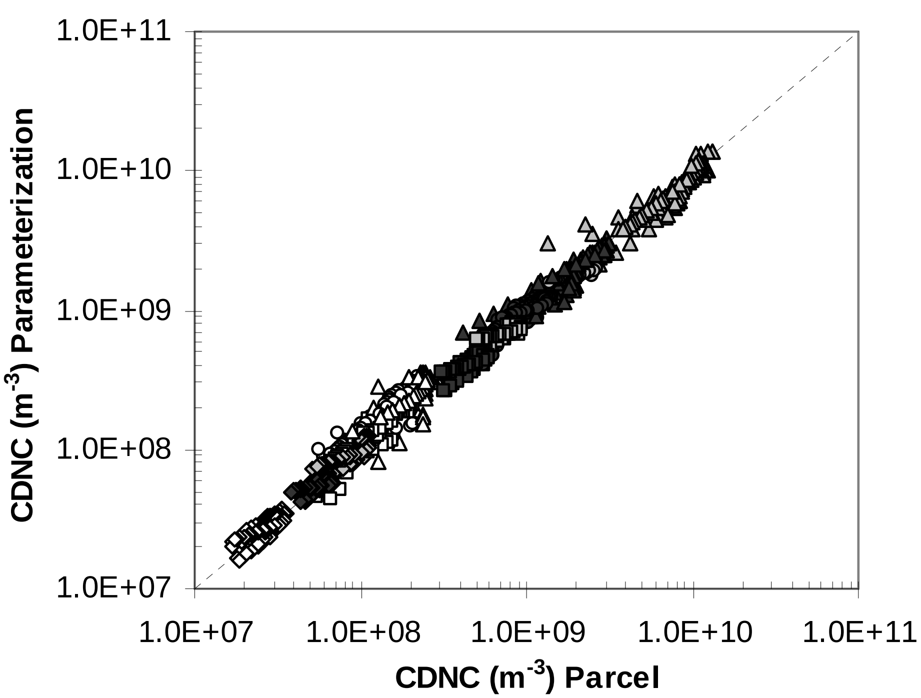
- **Current parameterizations are adiabatic**. Clouds are generally not.
- Droplet number predictions are good even for slightly diabatic conditions (although N_d can still be overestimated for strong entrainment).
- Nenes and Seinfeld can predict droplet size distribution, but they are too narrow (adiabatic), so autoconversion calculations would generally be "off".



- Comparison of predicted size distribution "width" vs. liquid water content for non-adiabatic CRYSTAL-FACE (cumulus) clouds.
- Parameterization and cloud parcel model agree great with each other, but not with the data (even though cloud droplet number is captured to within 5%!).
- An entraining parameterization would improve this because entrainment broadens the distribution.

New cloud droplet formation parameterization (Includes entrainment)

- The first parameterization of its kind (Barahona and Nenes, *in prep*).
- Complex organics can be treated, same conceptual framework ("population splitting") as the adiabatic parameterization.
- Mixing is parameterized in terms of an entrainment rate.
- Versions for lognormal and sectional aerosol developed.
- Same CPU requirements as the adiabatic "version".



We've looked at 4000 cases
Average error:10%

We plan to use CRYSTAL-FACE, CSTRIPE, ICARTT, MASE, TEXAS-AQS data to constrain the entrainment rate.

The predicted in-cloud droplet size distribution will be evaluated with the same dataset.

Upcoming Papers

- **Meskhidze, N., A. Nenes, J. Kouatchou, B. Das and J. Rodriguez, Aerosol Indirect Forcing from the NASA Global Modeling Initiative: Sensitivity to Meteorology, Emission Scenarios and Aerosol Microphysics, to be submitted in JGR (next 2 weeks).**

- **Sotiropoulou, R.E.P., N. Meshkhidze, A. Nenes, and J. Rodriguez, Sensitivity of aerosol indirect forcing and autoconversion to cloud droplet parameterization: An assessment with the NASA Global Modeling Initiative, in prep., to be submitted in JGR.**