# GMI assessments of Aerosol–Cloud–Climate Interactions

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# GMI assessments of Aerosol-Cloud-Climate Interactions:

## Current Work

(Rafaella Sotiropoulou)

# GMI: Aerosol-Cloud-Climate Interactions

## Currently Accomplished:

- Implementation of aerosol-cloud interaction modules:
  - Cloud-relevant parameters change with meteo-fields used.
  - Meteo-fields currently used: DAO, GISS, GEOS-4.
- Cloud properties are calculated from parameterizations.
- Implemented droplet formation parameterizations:
  - Boucher and Lohmann, 1995 (**BL**) – empirical
  - Abdul-Razzak & Ghan, 2000 (**AG**) - mechanistic
  - Nenes & Seinfeld,2003; Fountoukis & Nenes,2005 (**FN**) – mechanistic
  - Segal & Khain, 2006 (**SK**) - empirical
- Assessments of indirect effect and autoconversion rate using various droplet formation parameterization and meteorology.
- U of Michigan, AEROCOM aerosol emission scenarios.

# New GMI Improvements (since last meeting):

Implementation of the CLIRAD-SW solar radiative transfer model (Chou et al., 1998; Chou and Suarez, 1999) online to calculate the cloud optical depth (COD) and shortwave (SW) cloud forcing from the surface layer to the top of the atmosphere (TOA).

Aerosol indirect forcing (IF) is computed offline as the difference in the TOA net whole-sky shortwave flux (downwelling minus upwelling) between simulations that use present-day (PD; natural plus anthropogenic) and pre-industrial (PI; natural only) emissions.

Repetition of all simulations

# Simulations completed (since last mtg.)

**Emission Scenarios**

- University of Michigan (Present day, Preindustrial)
- AEROCOM (Present day, Preindustrial)

**Base Case Simulations**

- Liquid Cloud Temperatures: 273 K and above
- Cloud droplet formation schemes: BL and FN

**Sensitivity examined**

- Cloud temperatures:
  263 K over land, 269 K over ocean (GISS GCM scheme)
- Cloud droplet formation schemes: BL, SK, AG, FN

## Total Number of Simulations (for now):

$$\overbrace{4 \times 3 \times 2 \times 2}^{\text{U of Michigan}} + \overbrace{4 \times 3 \times 2}^{\text{AEROCOM}} = 72$$

$N_d$ scheme, Met field, Threshold T, Emission Case, $N_d$ scheme, Met field, Emission Case

Results are presented for some of the sensitivity simulations

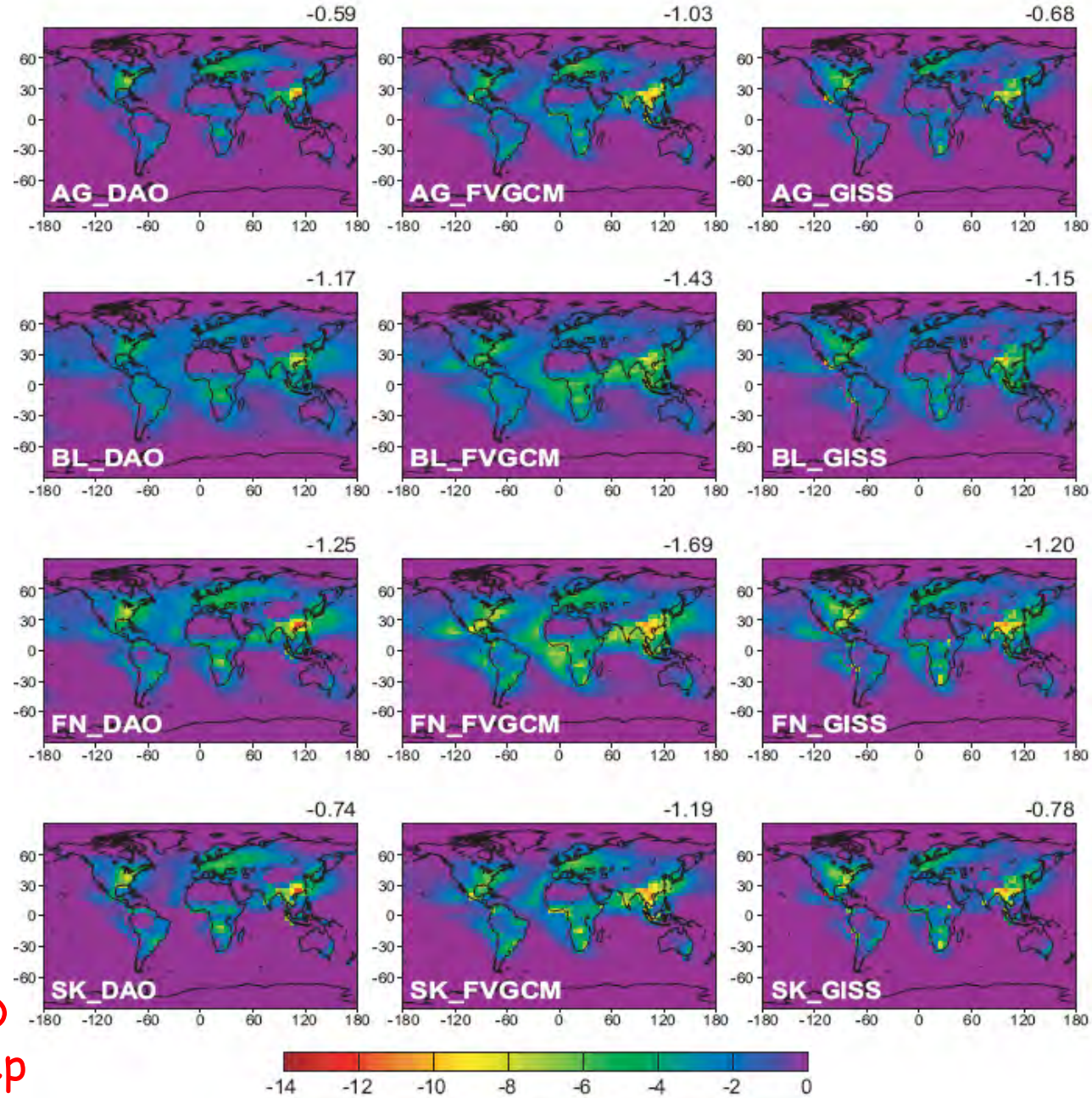
# Annual Mean First Indirect Forcing (W $m^{-2}$)

The spatial patterns of indirect forcing follow that of CDNC

Spatially, there are strong horizontal inhomogeneities with the largest values of IF predicted over SE Asia, Western Europe and Eastern US (i.e., areas with highest amount of anthropogenic sulfur emissions)

**Range:**
**-0.59 to -1.69 $Wm^{-2}$**

Sotiropoulou et al., ACPD
Sotiropoulou et al, in prep



# Annual Mean Autoconversion Forcing (%)

Presindustrial Autoconversion

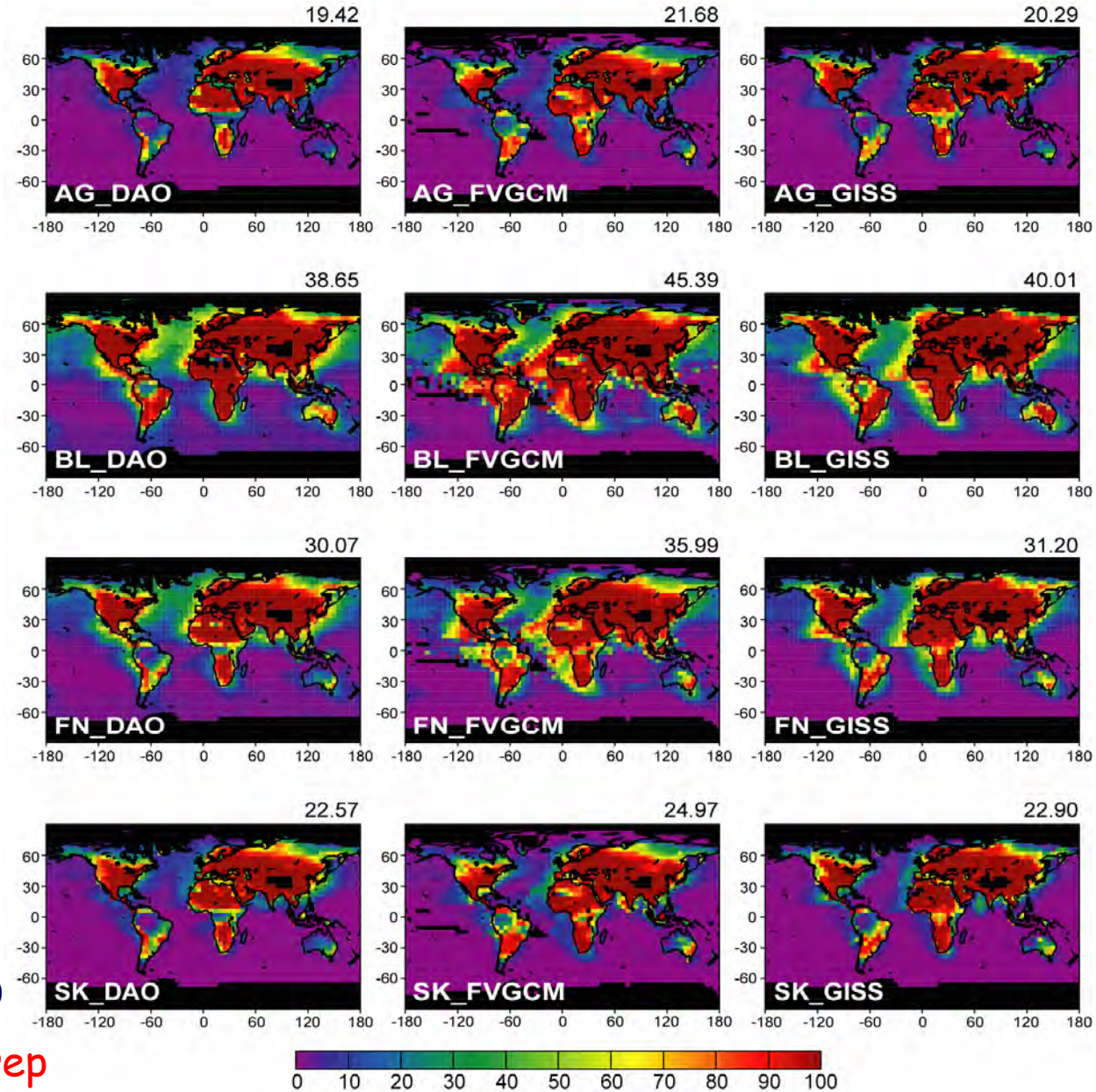
Present day Autoconversion

$$F_A = \frac{A^{PI} - A^{CD}}{A^{PI}}$$

Autoconversion Forcing

Large forcing over the continents and the ocean of the NH coinciding spatially with regions affected by pollution plumes or long range transport of pollution plumes.

Autoconversion with Khairoutdinov and Kogan, 2000




Sotiropoulou et al, in prep

# Implications and Conclusions

- GMI is able to correctly capture the land-ocean contrast in COD and $r_{eff}$ and the spatial variations in cloud properties between the SH and the NH regions observed in remotely sensed data.

- Depending on the droplet activation parameterization and the metfield used, global annual indirect forcing ranges from **-0.59 to -1.69 W m$^{-2}$** for all runs considered to date

- Different metfields lead up to **40%** (Global average) variability in indirect forcing calculations.

- Diagnostic and empirical parameterizations contribute up to **60%** (Global average) variability in indirect forcing. Although important it is a low estimate (it becomes larger if you use interactive microphysics - our experience with CACTUS and CACTUS/TOMAS support this).

# Implications and Conclusions

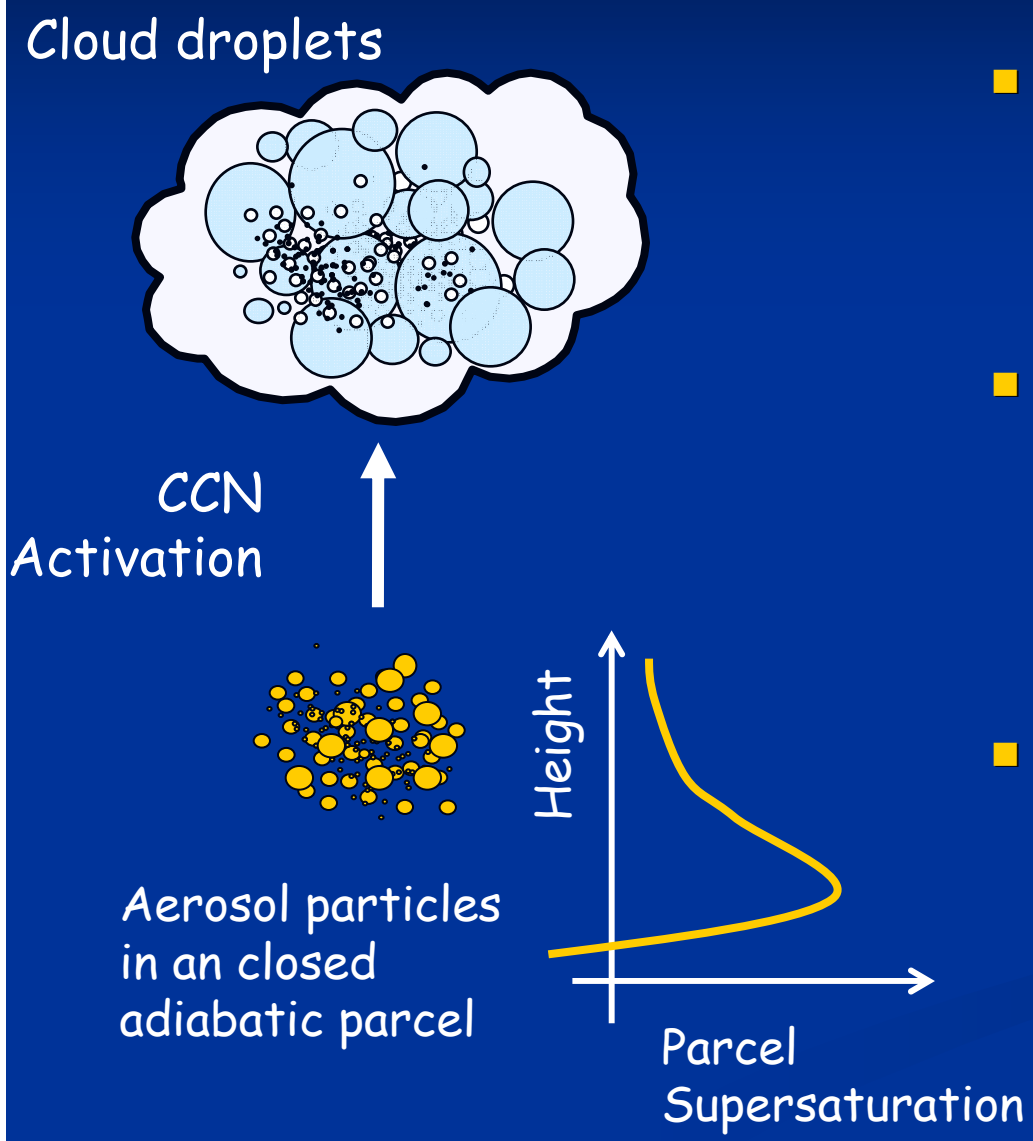
- For all droplet activation parameterizations and the metfields used the global annual autoconversion rate ranges from $1.10\times10^{-11}$ to $10.38\times10^{-11}$ $s^{-1}$ . The metfields contribute 70% variability and 30% is from the activation parameterization.
- The spatial patterns of autoconversion rate are similar for all metfields.
- Large differences in autoconversion rates over the oceans; this is one of the most important source of uncertainty from the droplet schemes.
- Larger autoconversion forcing (60-100%) is predicted over the anthropogenically perturbed regions of the globe

# GMI assessments of Aerosol-Cloud-Climate Interactions:

## Current Work

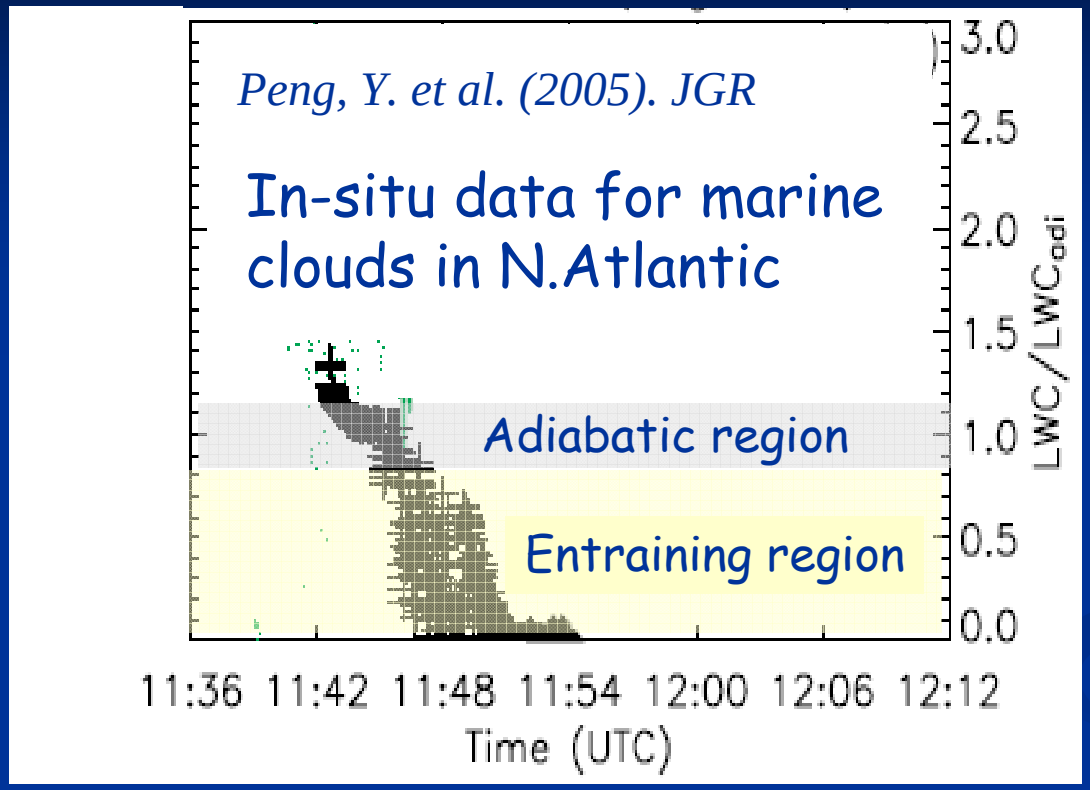
Donifan Barahona

# Cloud Droplet Formation in GCMs Current State-of-the-Art




- **State-of-the-art:** Physically-based prognostic representations of the activation physics.
- Cloud droplet formation is parameterized by applying conservation principles in an ascending adiabatic air parcel.
- All parameterizations developed to date rely on the assumption that the droplet formation is an adiabatic process.

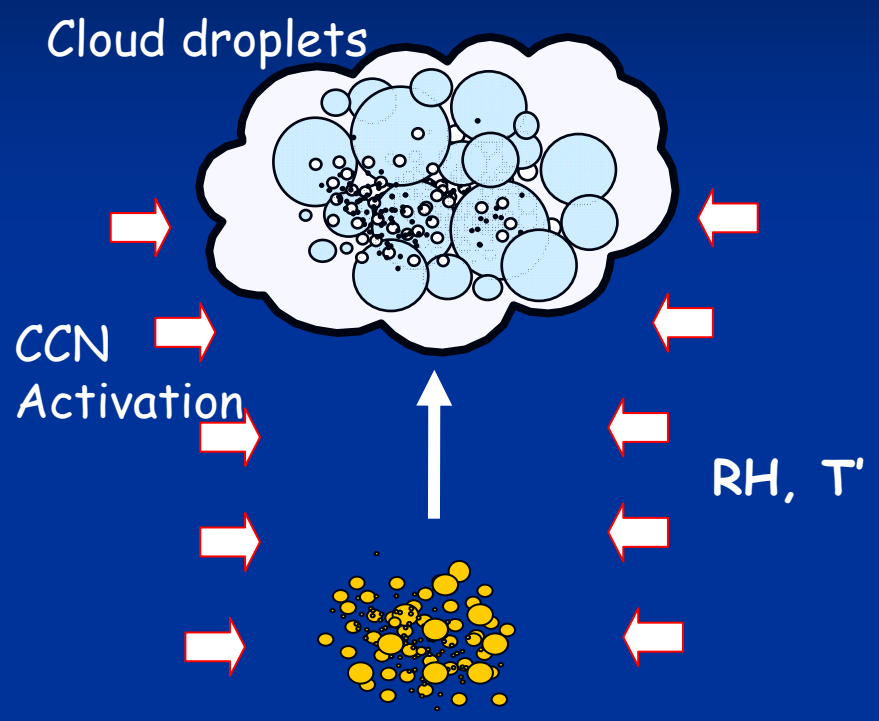
# But…Real Clouds are NOT Adiabatic




- Entrainment of air into cloudy parcels decreases droplet number relative to adiabatic conditions
- In-situ observations often show that the liquid water content measured is lower than expected by adiabaticity.

Neglecting entrainment may lead to an overestimation of in-cloud droplet number biasing indirect effect assessments

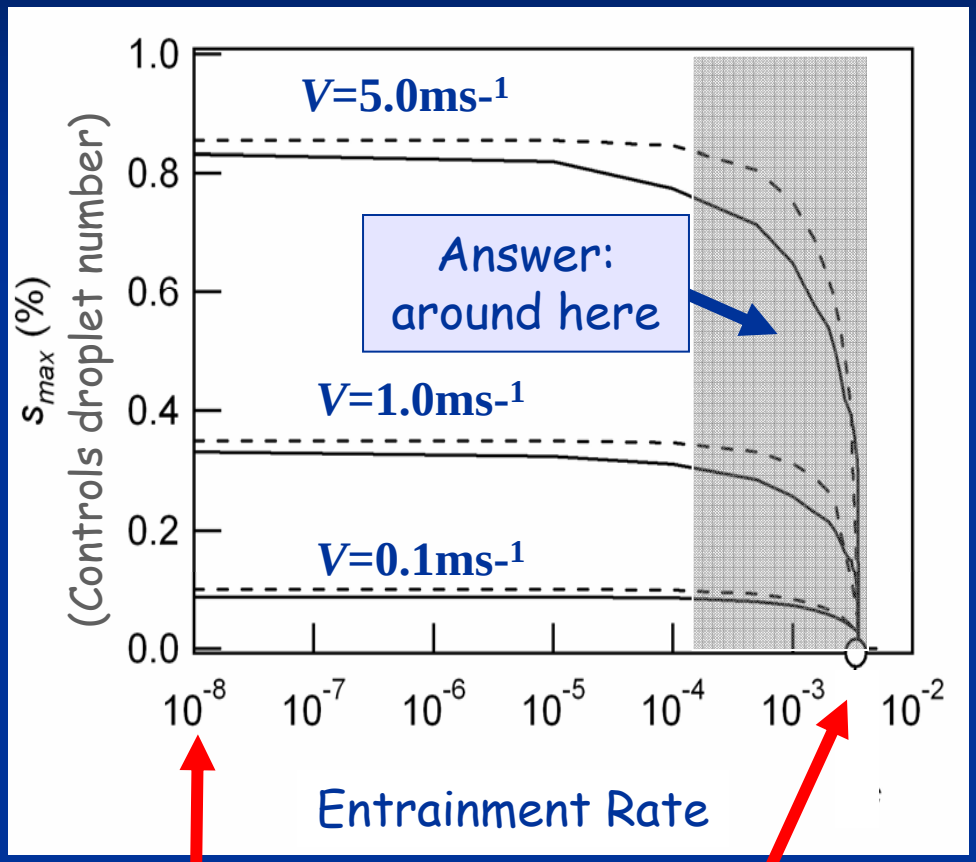
# Barahona and Nenes (JGR, 2007) Entraining Cloud Droplet Parameterization




- Analytical formulation based on entraining air parcel framework: mixing of outside air is allowed
- "Outside" air with (RH, T') is assumed to entrain at a rate of e (kg air)(kg parcel)$^{-1}$(m ascent)$^{-1}$
- Can treat all the chemical complexities of organics, for either lognormal, sectional aerosol. Equally fast as adiabatic formulation.

- Evaluated against detailed a numerical parcel model with average error below 3 ± 25 %
- Will be evaluated with in-situ data (CIRPAS TO datasets) soon

# When is Entrainment Important for Droplet Formation?



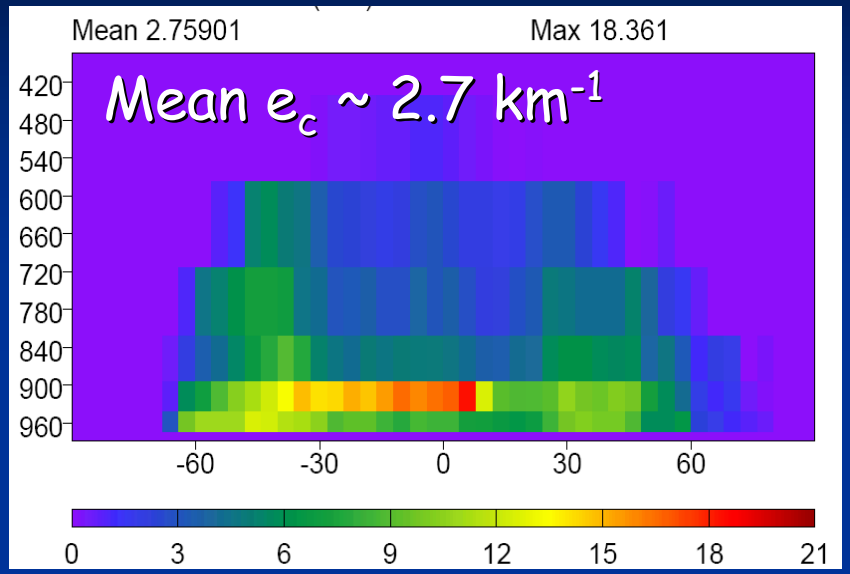

~ Adiabatic

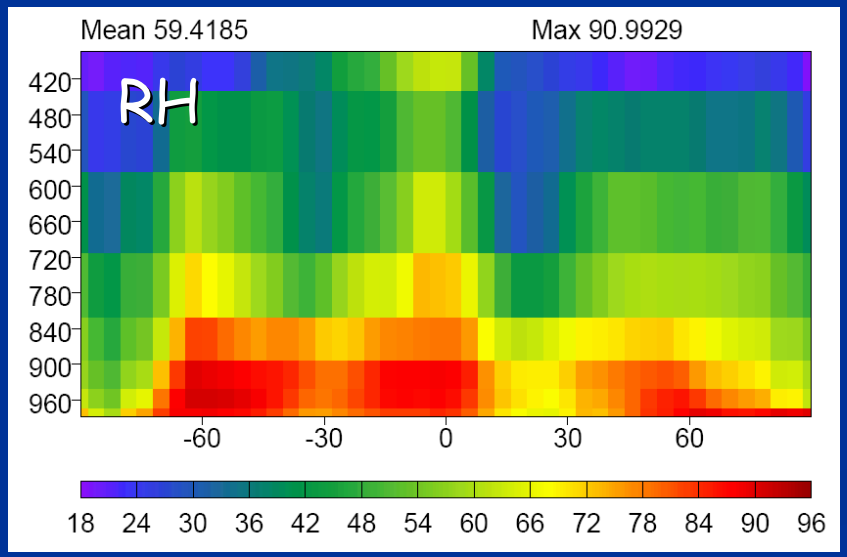
Critical
(cloud completely evaporates)

- A "critical entrainment rate", $e_c$, exists for which mixing of outside air completely evaporates the cloud.
- Entrainment becomes important if it is > 0.1 $e_c$
- Observation show that $e$ varies from 0.0 to 0.6$e_c$
- Average for marine stratocumulus during MASE is 0.4$e_c$ (*Wang et al. in review*)

*Barahona and Nenes, 2007, JGR*

# GMI Implementation: Global distributions of Critical Entrainment



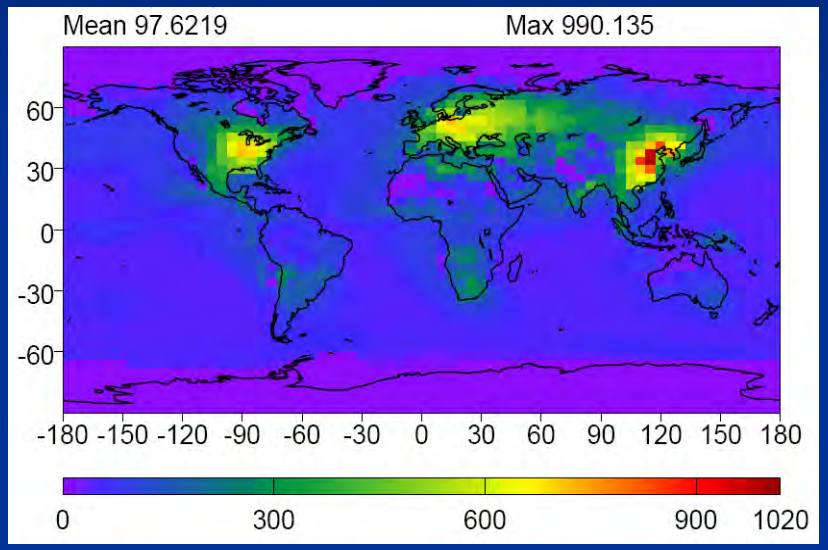




- Average $e_c$ is close but larger than reported values for e (~1-2 $km^{-1}$) (i.e., *Raga, et. al.; 1990*)
- $e_c$ is higher in regions of high relative humidity, i.e., effect of entrainment is more important in dry (climatically sensitive) areas.

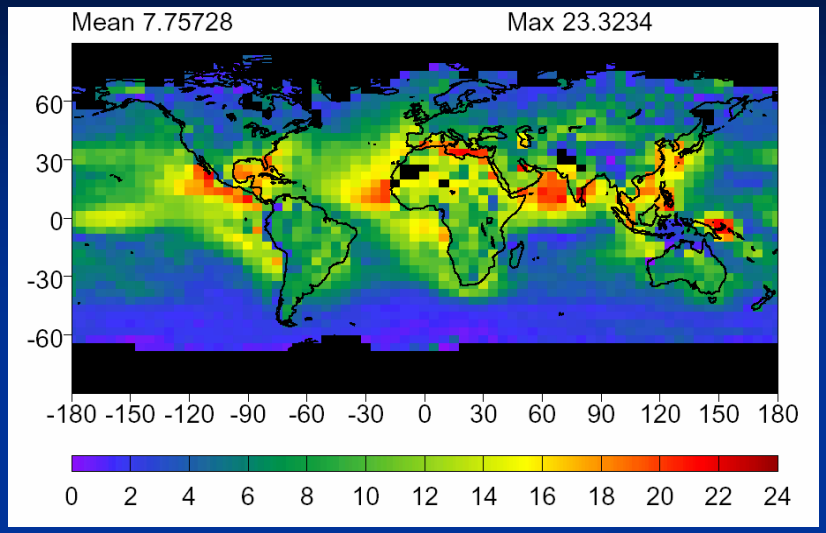
Present day simulations, GISS meteorology, annual averages

# Entrainment Effects on Cloud Droplet Number

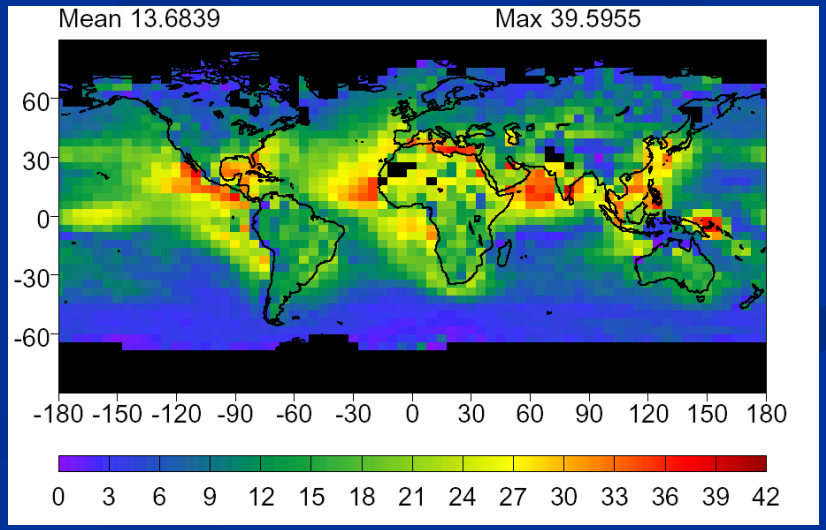
Adiabatic ~ 97 $cm^{-3}$




$e=0.4e_c$ – Adiab. ~ -8%




$e=0.6e_c$ – Adiab. ~ -14%

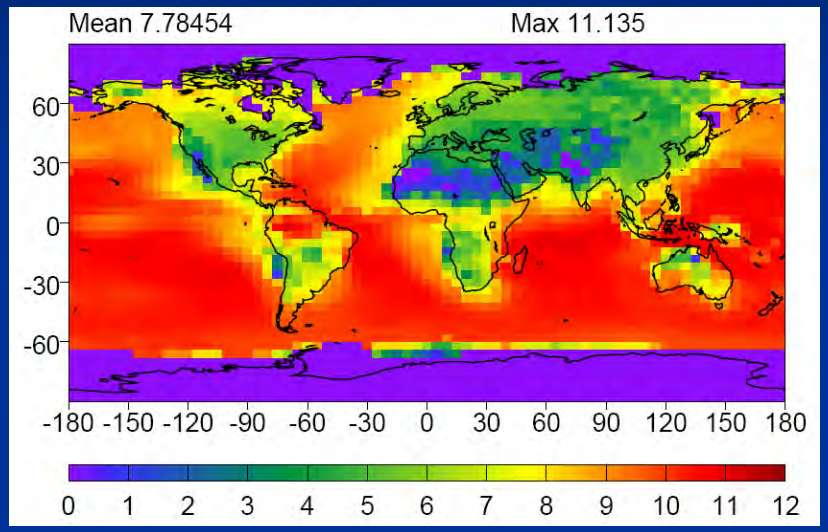



- Up to 40% CDNC reduction in the tropics (larger effect on clean environments)
- Linking e to TKE may produce even more variability in CDNC.

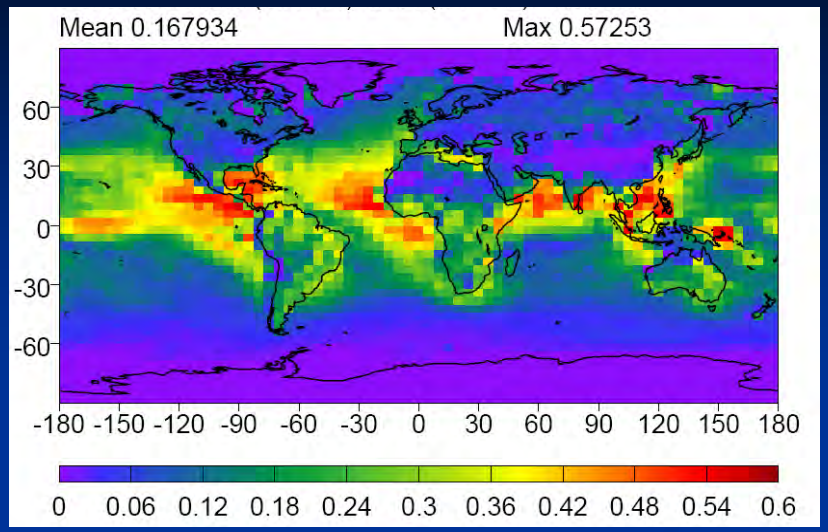
Present day, GISS meteorology, annual averages

# Entrainment Impacts on Effective Radius

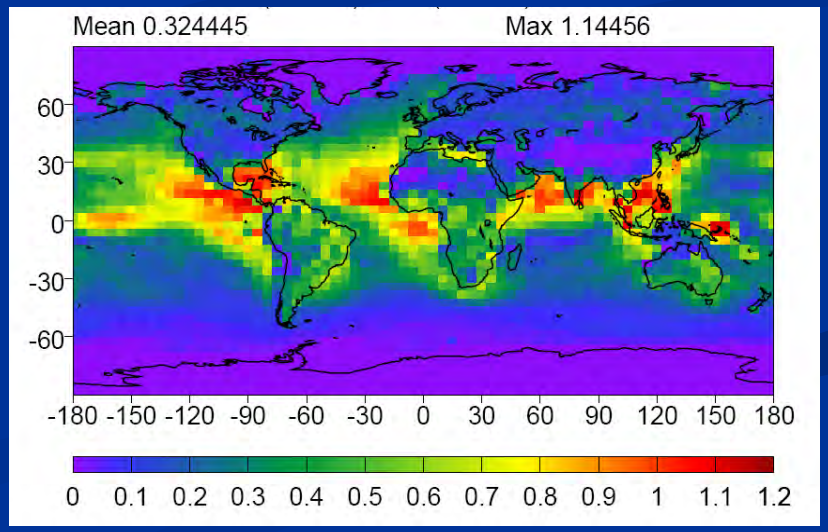
Adiabatic ~ 7.78 μm




$e=0.4e_c$ - Adiabatic = 0.16 μm




$e=0.6e_c$ - Adiabatic = 0.32 μm

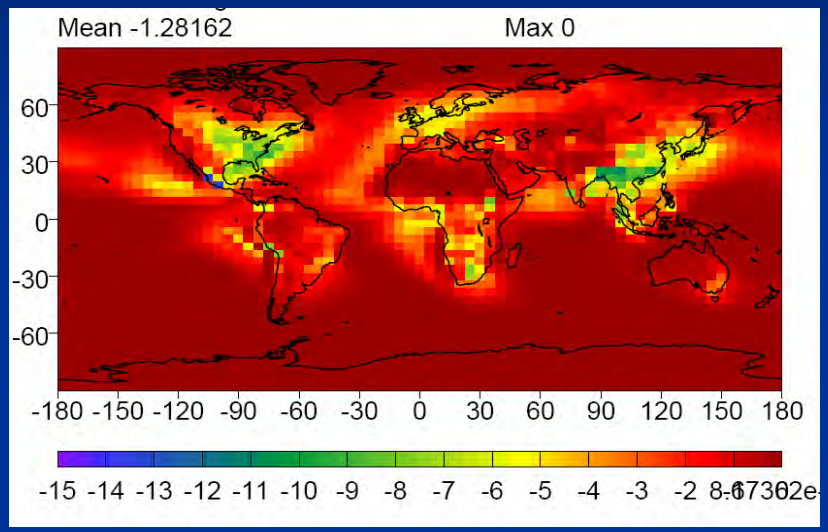



- Larger differences in the tropics (high LWC and $S_{max}$)
- ~ 1μm changes in large areas of the globe – important for IE
- Impacts on autoconversion rate are also important

Present day, GISS meteorology, annual averages

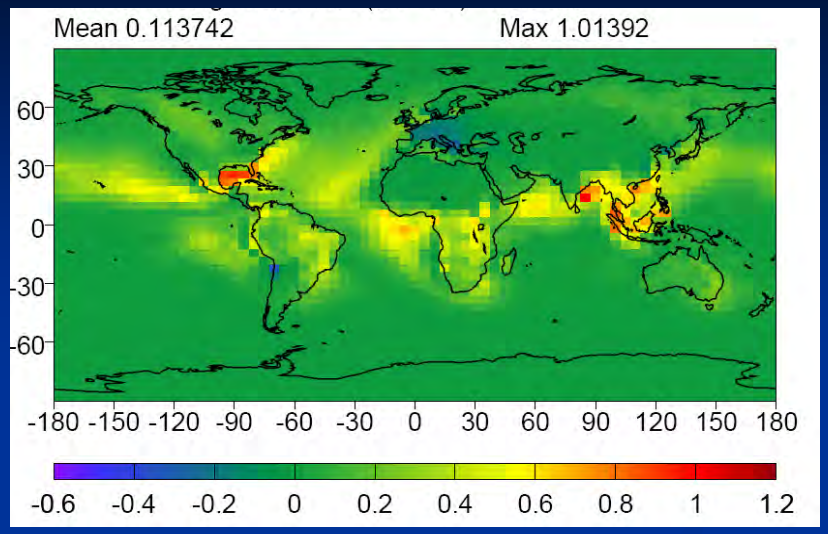
# Implications for Indirect Forcing

Adiabatic = -1.28 $Wm^{-2}$

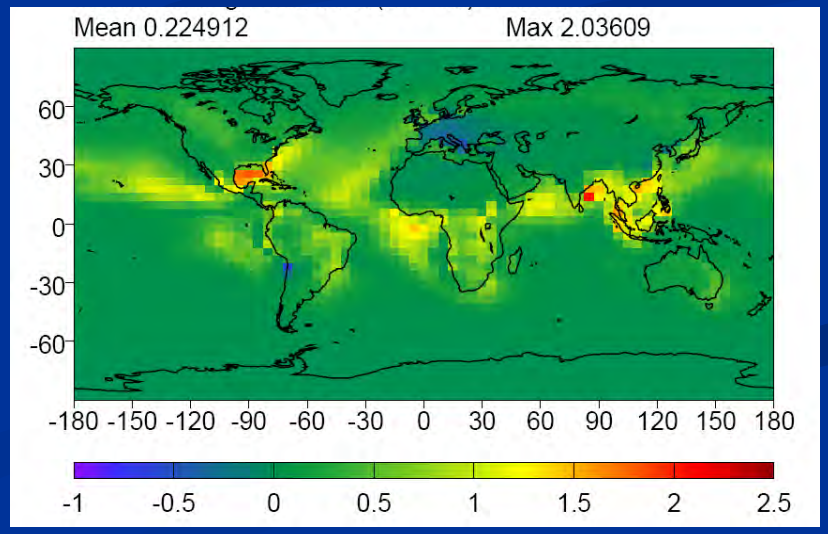



- Pattern follows $R_{eff}$ and LWC rather than droplet number
- Decreases indirect forcing by up to 20%
- Regional effects may be much larger (locally, up to 50%)

$e=0.4e_c$ - Adiabatic = 0.11 $Wm^{-2}$




$e=0.6e_c$ - Adiabatic = 0.22 $Wm^{-2}$




Present day, GISS meteorology, annual averages

# Ongoing Work

- Obtaining entrainment rate from LWC and TKE fields either from GMI fields – when available – or from GISS runs using the model in our group (find a "global" $e/e_c$).
- Entrainment effects on autoconversion and accretion (and the list goes on…)
- Sensitivity to all of the above with respect to GMI meteorological fields, aerosol microphysics, emission scenarios, etc.
- Once the entrainment work is "finalized", we will work with Jules to incorporate it in the "core" code at Goddard. Sorry Jules… (Thanos)

# GMI assessments of Aerosol-Cloud-Climate Interactions:

# Future Work

# Including Ice Microphysics

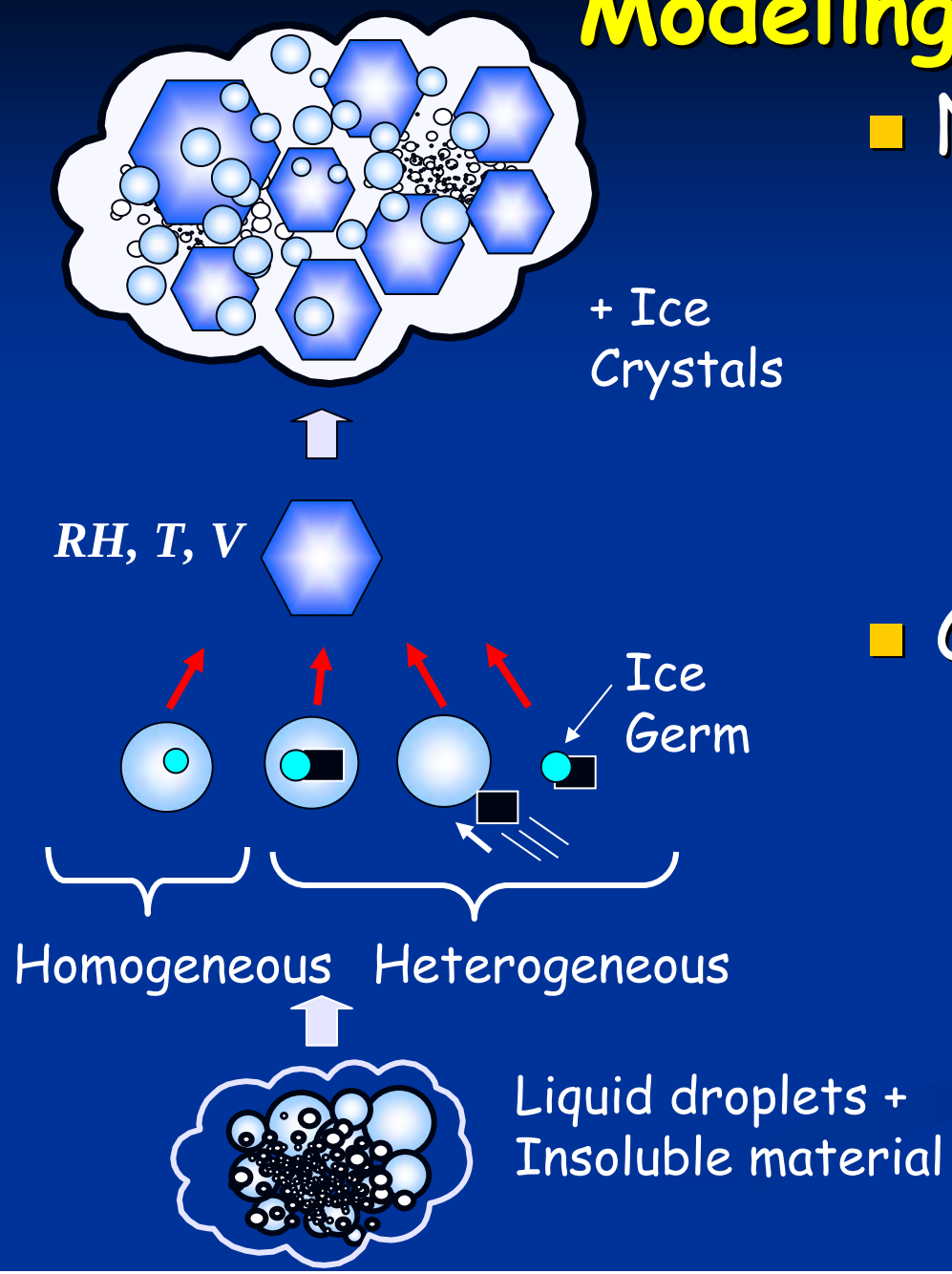
# The importance of Cirrus Clouds

- Cirrus are important for:
  - Radiative transfer: they tend to warm
  - Affecting stratospheric moisture
  - Regulation of the ocean temperature
  - Stratospheric circulation
  - Heterogeneous chemistry

Cirrus may be affected by aircraft emissions, transport of dust and pollution. One of the initial motivations for GMI ☺

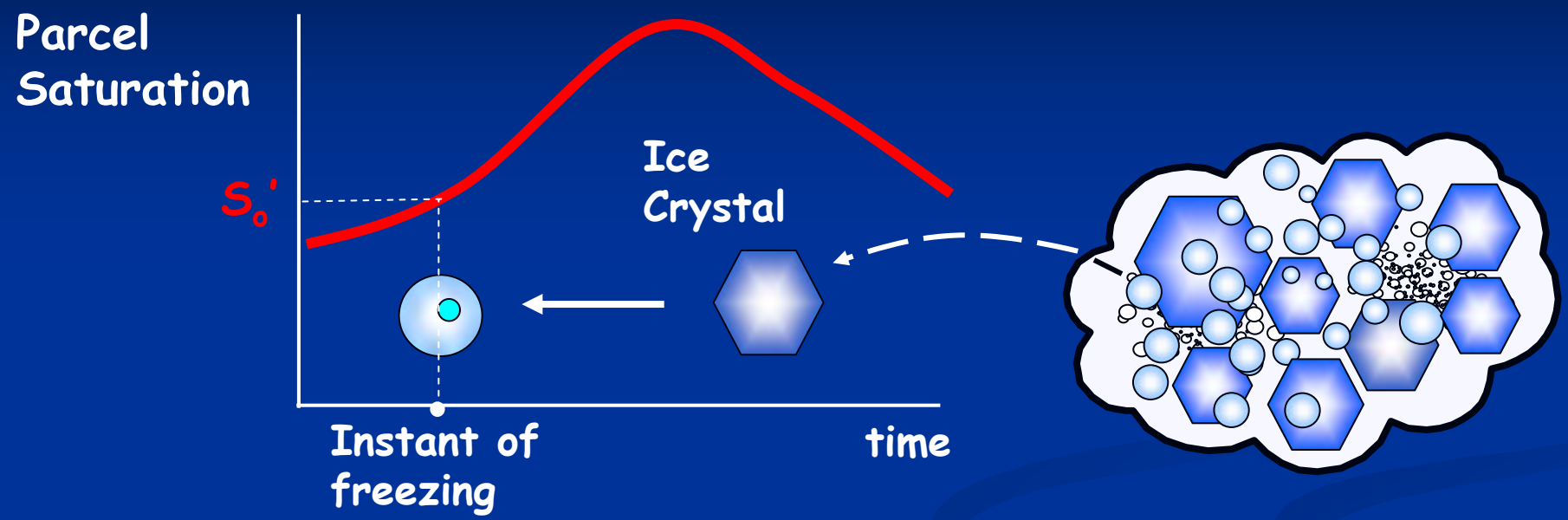
Aerosol effects on cirrus (and climate) are highly unknown!!

# Modeling Cirrus Formation




- Need to describe:
  - Onset of freezing
  - Ice crystal and droplet growth
  - Evolution of size distributions, *RH* and *T*
- Challenges:
  - Size and composition effects,
  - role of dynamic variability,
  - heterogeneous nucleation,
  - deposition coefficient

# Barahona and Nenes Ice Parameterization (JGR, in press)




- The probability of freezing changes with time (unlike with liquid cloud droplet formation!)
- Because of this, we need to trace back in time the growth of each ice crystal to find the conditions at which freezing occurred.

$$n_c(D_p) = -n_a(s_o') \frac{dP_f}{dD_p}(s_o')$$

# Analytical Development of the Parameterization

Find a Solution of:

$$\frac{\partial n_c(D_c, D_o)}{\partial t} = -\frac{\partial}{\partial D_c}\left( n_c(D_c, D_o)\frac{dD_c}{dt} \right)$$

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$$n_c(D_p) = -n_a(s_o^{'})\frac{dP_f}{dD_p}(s_o^{'})$$

Calculate freezing probability:

$$P_f(D_o, S_o^{'}) \approx \frac{1}{\alpha V S_{i,\max}} \int_{S_o}^{S_o^{'}} v_o J(S)\,dS = \frac{J(S_{i,\max})v_o}{\alpha V\, k(T) S_{i,\max}} \exp\left[-k(T)(S_{i,\max} - S_o^{'})\right]$$

# Analytical Development of the Parameterization

Find a Solution of:

$$\frac{\partial n_c(D_c, D_o)}{\partial t} = -\frac{\partial}{\partial D_c}\left( n_c(D_c, D_o)\frac{dD_c}{dt} \right)$$

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Calculate size distribution:

$$n_c(D_c)\Big|_{S_{i,\max}} = \frac{J(S_{i,\max})}{(S_{i,\max} - 1)} \left( \Gamma_1 D_c + \Gamma_2 \right) \exp\left[ -\mu \Gamma(D_c, \overline{D}_o) \right] \int \overline{n}_o(D_o) v_o dD_o$$

# Analytical Development of the Parameterization

Find a Solution of:

$$\frac{\partial n_c(D_c, D_o)}{\partial t} = -\frac{\partial}{\partial D_c}\left( n_c(D_c, D_o)\frac{dD_c}{dt} \right)$$

$$n_c(D_p) = -n_a(s_o^{'})\frac{dP_f}{dD_p}(s_o^{'})$$

Calculate freezing probability:

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**Integrate size distribution !**

$$\frac{dS_i}{dt} + \beta \frac{\rho_i}{\rho_a} \frac{\pi}{2} \int_{D_{o,\min}}^{D_{o,\max}} \int_{D_{c,\min}}^{D_{c,\max}} D_c^2 \frac{dD_c}{dt} n_c(D_c, D_o) dD_c dD_o = 0$$

# Analytical Development of the Parameterization

LOTS AND LOTS OF MATH…..

Cal
free
prol

Cal
dist

**Int**
**distribution !**

$$dt \quad \rho_a \; 2 \int_{D_{o,\min}} \int_{D_{c,\min}} D_c \quad dt \quad n_c(D_c, D_o) dD_c dD_o = 0$$

# Analytical Development of the Parameterization

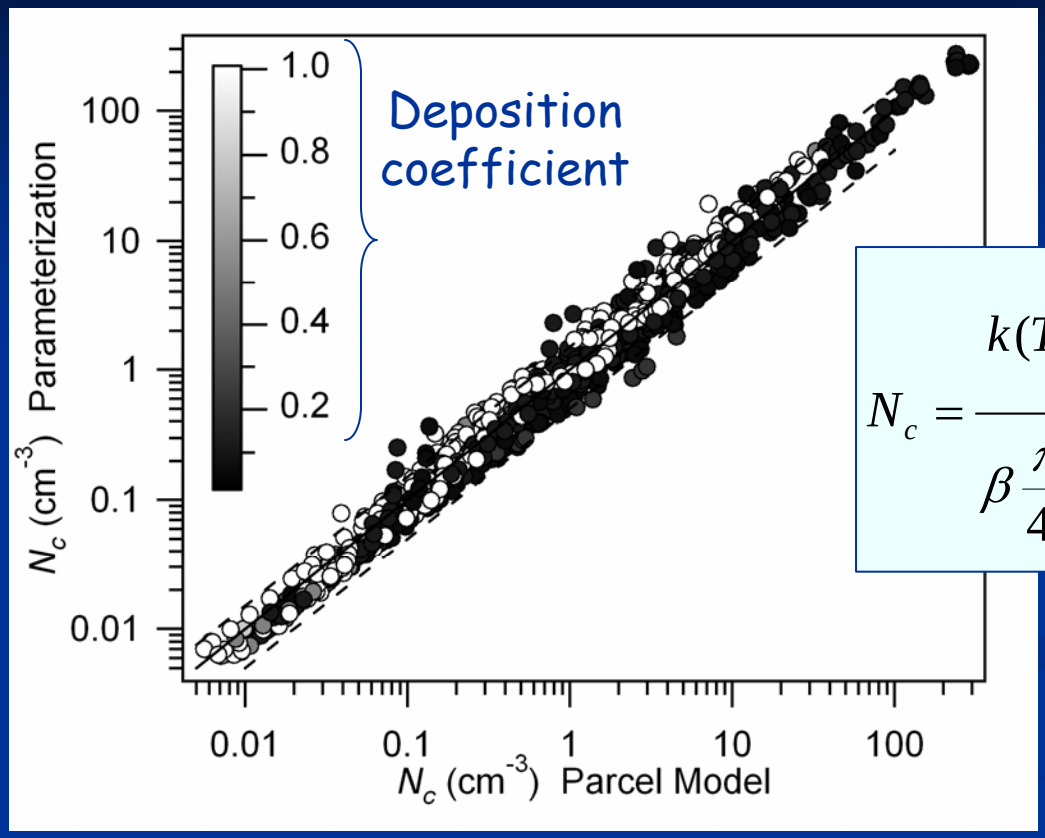
**After all this effort … the parameterization reduces to:**

$$N_c = \frac{k(T)^{1/2}\left(\dfrac{\pi k(T)\,\alpha\, w S_{\max}}{G(S_{\max}-1)}\right)^{3/2}}{\beta\dfrac{\pi\rho_i}{4\rho_a}\exp\left[\dfrac{k(T)\,\alpha\, w}{G(S_{\max}-1)}D_o^2\right]}$$

Ice Crystal Number Concentration

**1-2 lines of FORTRAN code … but it is *completely theoretical* (i.e. rigorous and robust) and captures the (complex) physics of ice nucleation. We can also calculate the size distribution… (not shown)**

# Parameterization vs. Parcel Model




$$N_c = \frac{k(T)^{1/2}\left(\frac{\pi k(T)\,\alpha\, w S_{max}}{G(S_{max}-1)}\right)^{3/2}}{\beta\,\frac{\pi\rho_i}{4\rho_a}\exp\left[\frac{k(T)\,\alpha\, w}{G(S_{max}-1)}D_o^2\right]}$$

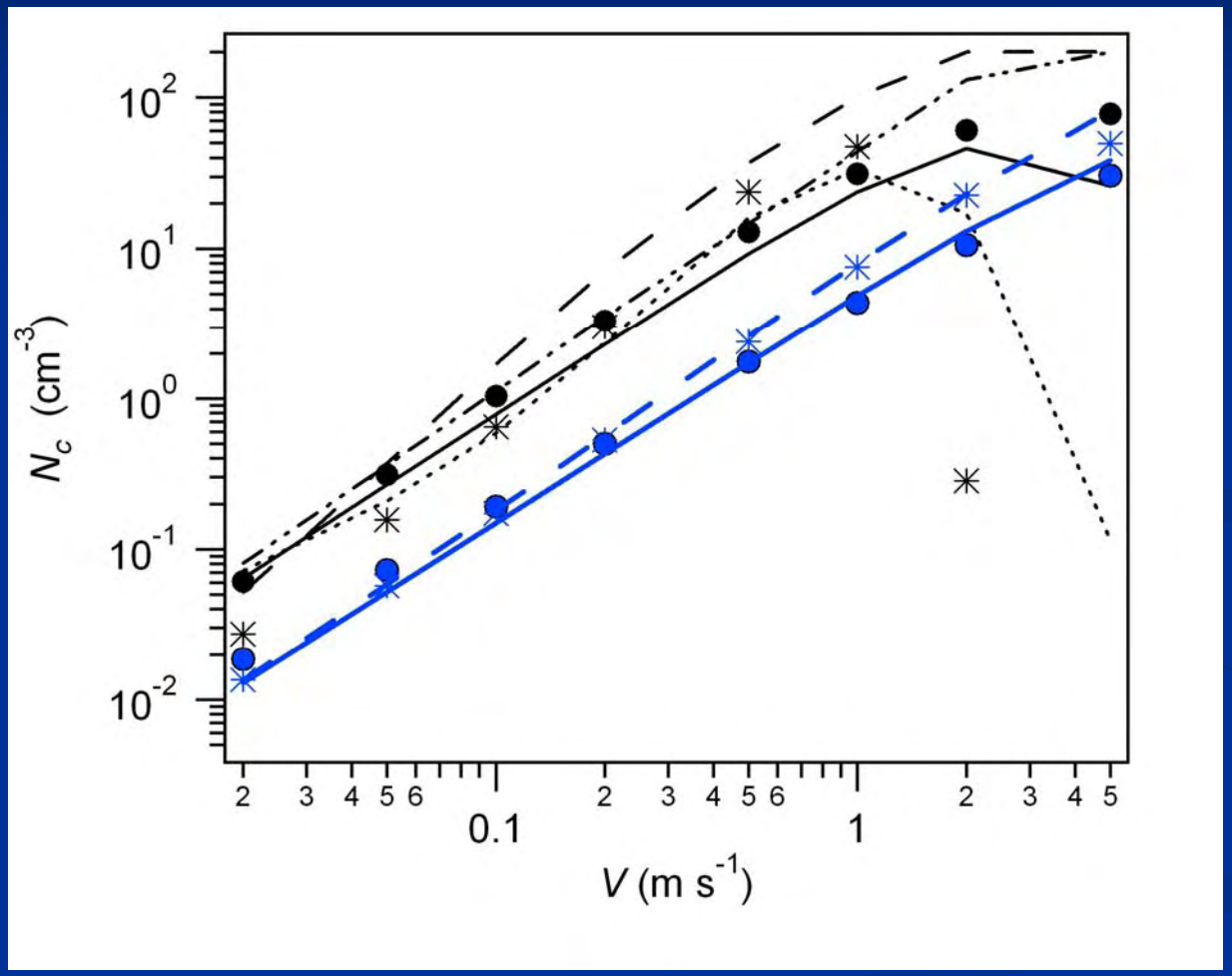
1200 runs.

*T*= 200-235 K,
*V*=0.02-5 ms-1.

- Explicity considers effect of aerosol size and number, deposition coefficient, T, P, and updraft velocity.
- Very robust: average error ~ 3 ± 28%
- MANY orders of mangitude faster than parcel model

*Barahona and Nenes, JGR, in press*

# Comparison with other parameterizations




Barahona

SB2000

KL2002

Parcel Model

LP2005

(only for a=1)

Deposition Coefficient:

Blue: 1.0

Black: 0.1

T=213K, $N_o$=200 cm$^{-3}$

$D_{dry}$=40 nm

*Barahona and Nenes, JGR, in press*

# Ongoing work: extension and GMI implementation

- Improving and extending the parameterization:
  - Heterogeneous freezing: Immersion and deposition freezing is being included.
  - External mixtures of liquid aerosol and heterogeneous IN, i.e, competition effects.
  - Compositional effects on nucleation (organics, etc.)
  - Entrainment effects, size distribution calculation, etc.

- **GMI implementation**: Need updraft, temperature, aerosol characteristics, deposition coefficient. Use the similar approach as to what's done for liquid clouds.

# GMI Manuscripts

- Sotiropoulou R.E.P., N. Meskhidze, et al., Aerosol - cloud interactions in the NASA GMI: Sensitivity of indirect effects to cloud formation parameterization and meteorological fields, *Atmos. Chem. Phys. Discuss.*, 7, 14295-14330, *in review* .
- Sotiropoulou, R.E.P., N. Meskhidze, et al.,: Aerosol – cloud interactions in the NASA GMI: Sensitivity of indirect effects to cloud formation parameterization and meteorological fields, *Atmos. Chem. Phys. Discuss.*, *in preparation.*
- Sotiropoulou, R.E.P., X. Liu, et al., : Aerosol – cloud interactions in the NASA GMI: Sensitivity of indirect effects to aerosol microphysics and emission scenario, *Atmos. Chem. Phys. Discuss.*, *in preparation.*

# Other Manuscripts (NIP support)

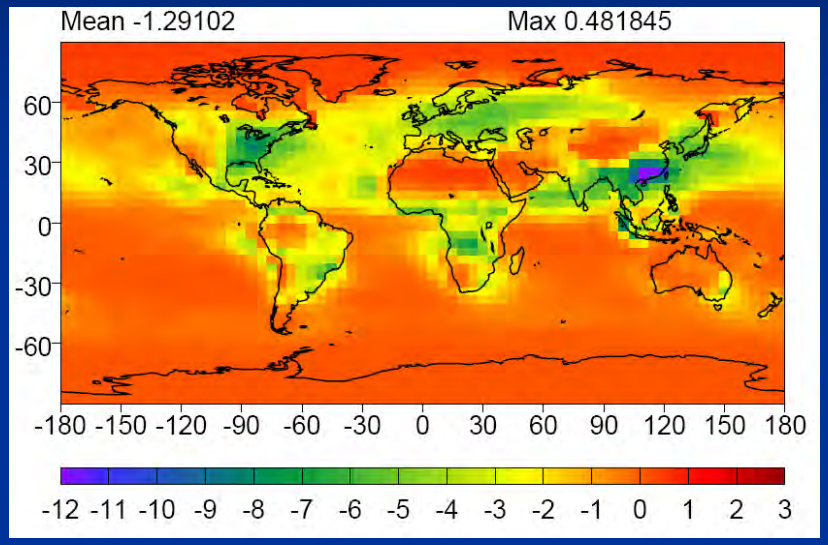
- Barahona D., A. Nenes (2007), Parameterization of cloud droplet formation in large-scale models: Including effects of entrainment, J. Geophys. Res., 112, D16206.
- Barahona, D., A. Nenes (2008), Parameterization of Cirrus Cloud Formation in Large Scale Models: Homogeneous Nucleation., *J. Geophys. Res.* in press.

# Thanks!

# Supporting Material (Donifan)

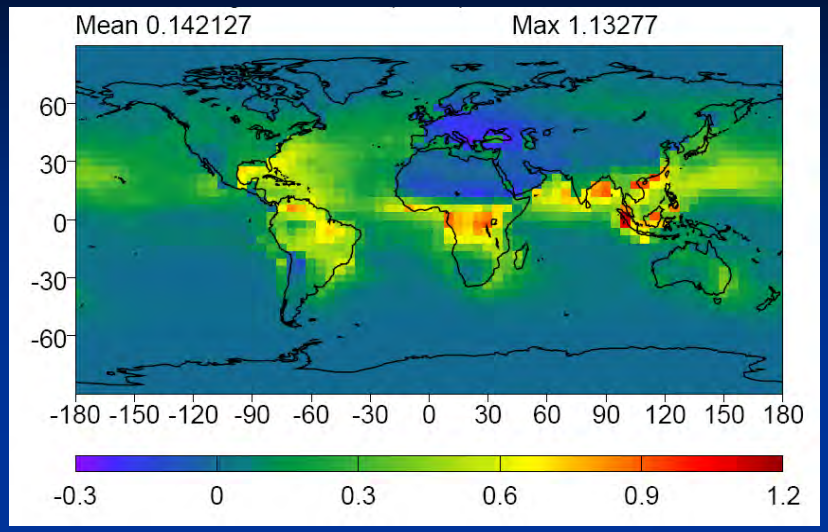
# Implications for Indirect Forcing (DAO)

Adiabatic = -1.29 $Wm^{-2}$

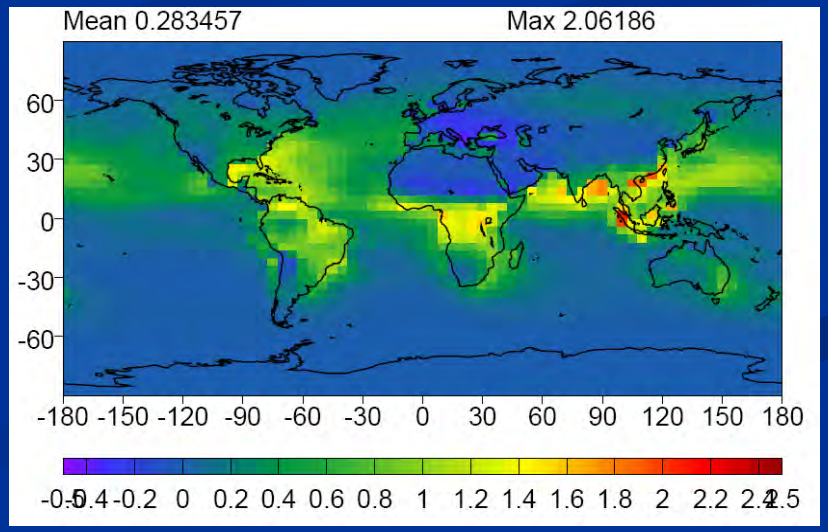



- Pattern follows $R_{eff}$ and LWC rather than droplet number
- Regional effects may be much larger

$e=0.4e_c$ - Adiabatic = 0.14 $Wm^{-2}$



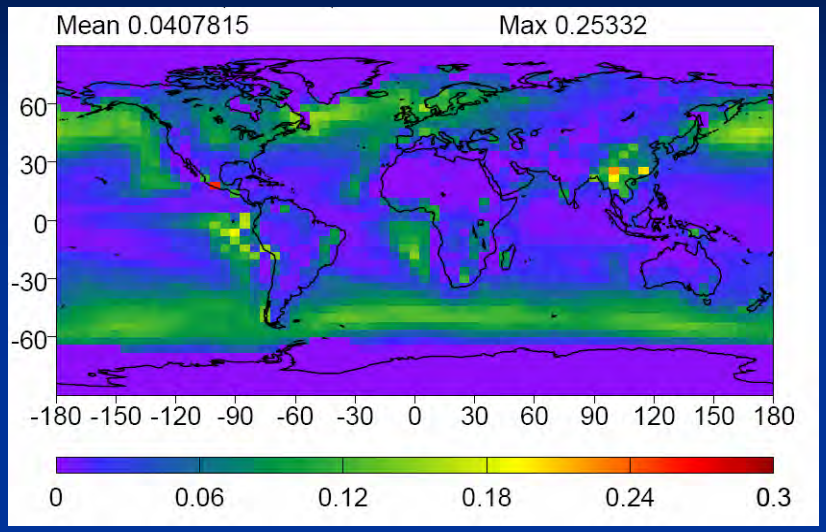

$e=0.6e_c$ - Adiabatic = 0.28 $Wm^{-2}$




Present day, GISS meteorology, annual averages

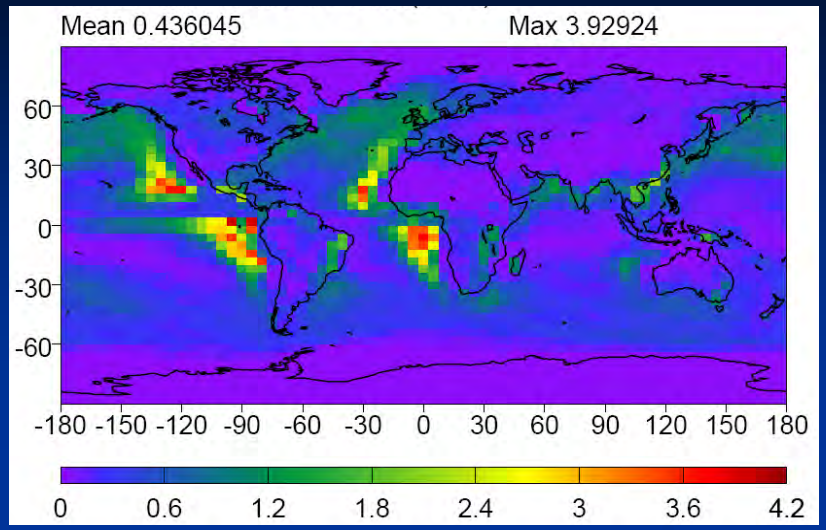
# Cloud Albedo

Adiabatic ~ 0.04

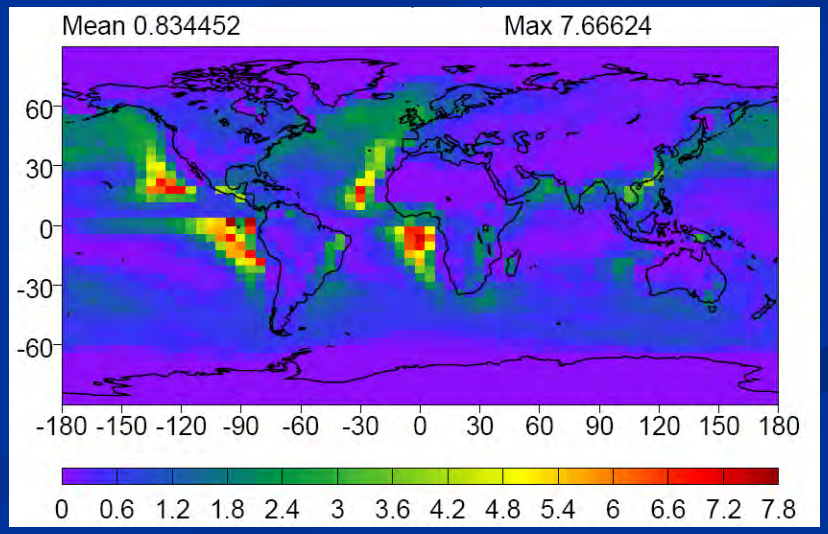



LWC ~ 0.04 g/m$^3$

Adiabatic - 0.4ec = $0.43*10^{-3}$

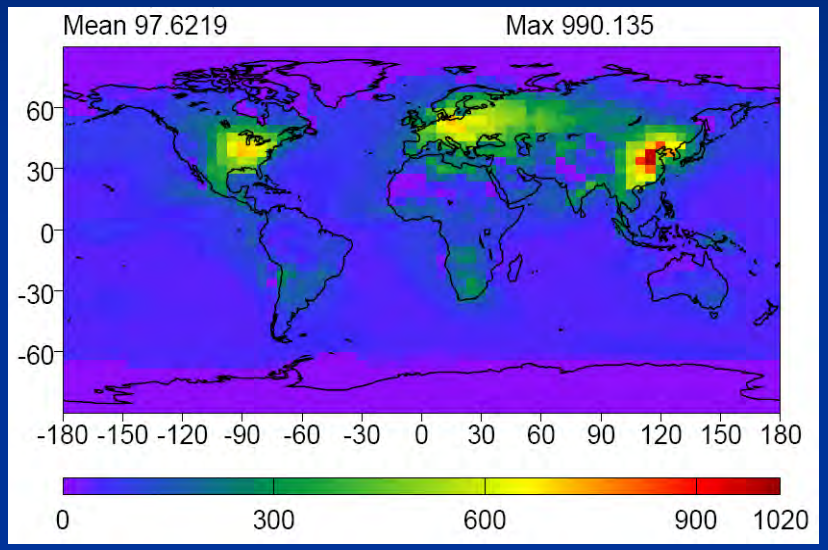



Adiabatic - 0.6ec = $0.83*10^{-3}$

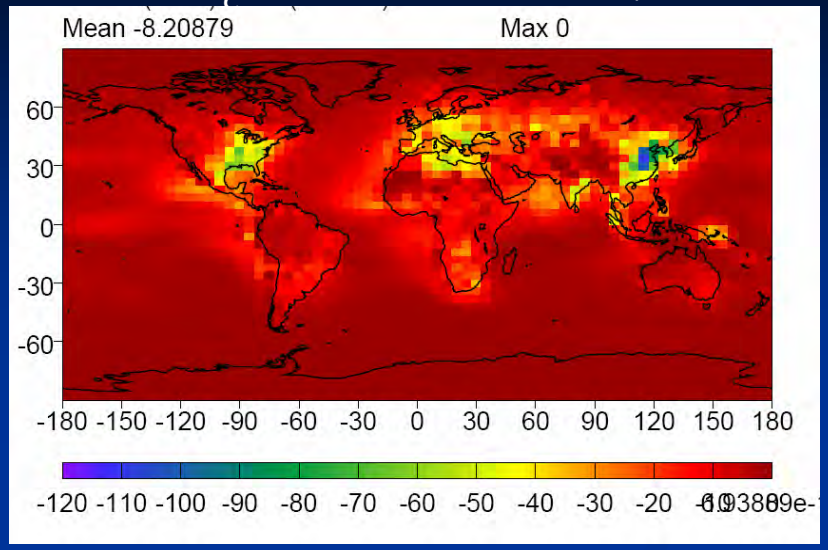


# Entrainment Effects on Cloud Droplet Number

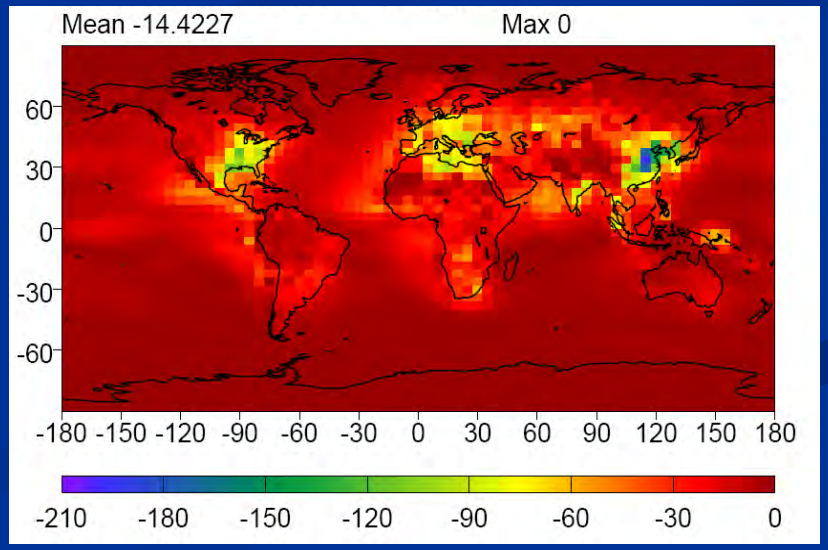
Adiabatic ~ 97 $cm^{-3}$




$e=0.4e_c$ – Adiab. ~ -8 $cm^{-3}$




$e=0.6e_c$ - Adiabatic ~ -15%

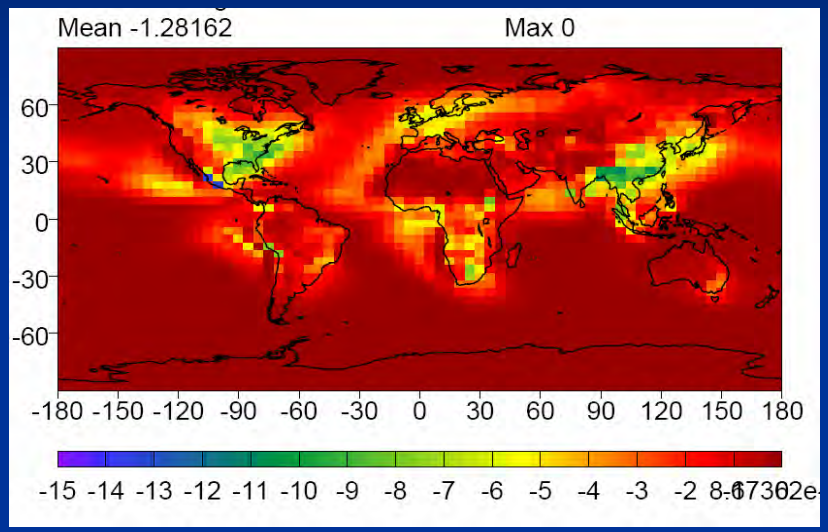



- Absolute Difference is proportional to droplet number (i.e., normalized by $e_c$)
- Linking e to TKE may produce even more variability in CDNC

Present day, GISS meteorology, annual averages

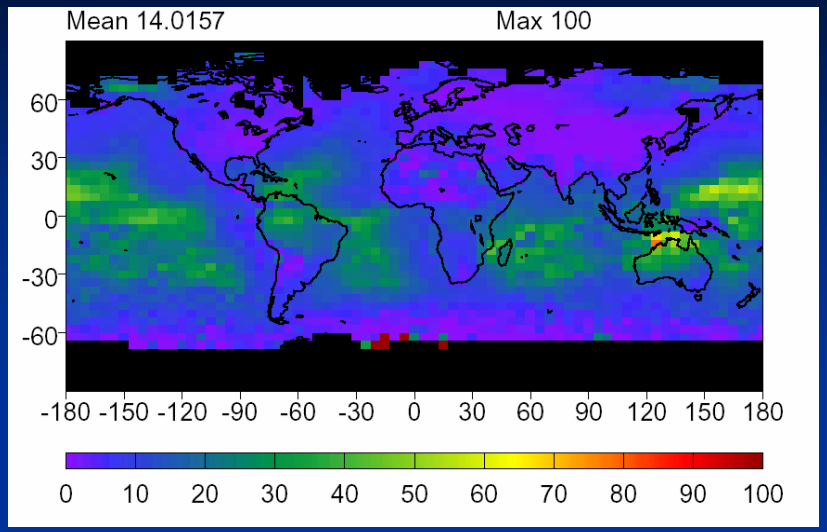
# Implications for Indirect Forcing

Adiabatic = -1.28 $Wm^{-2}$

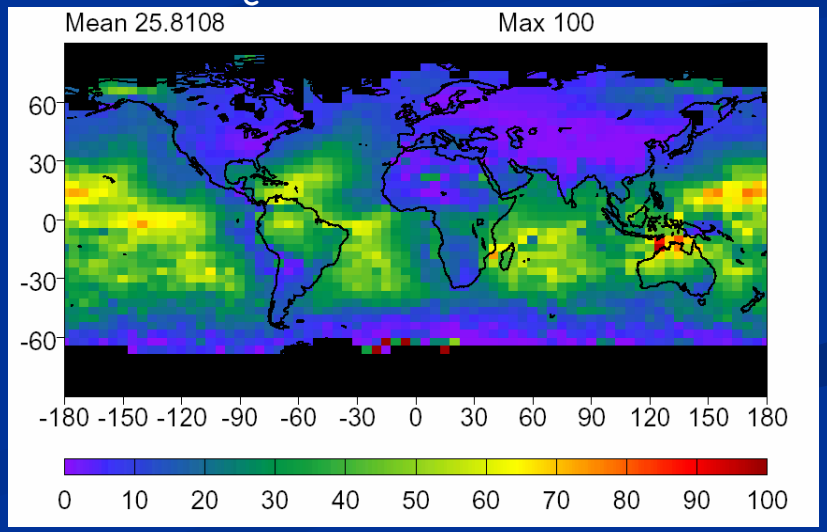



- Pattern follows $R_{eff}$ and LWC rather than droplet number
- Decreases indirect forcing by up to 20%
- Regional effects may be much larger (locally, up to 50%)

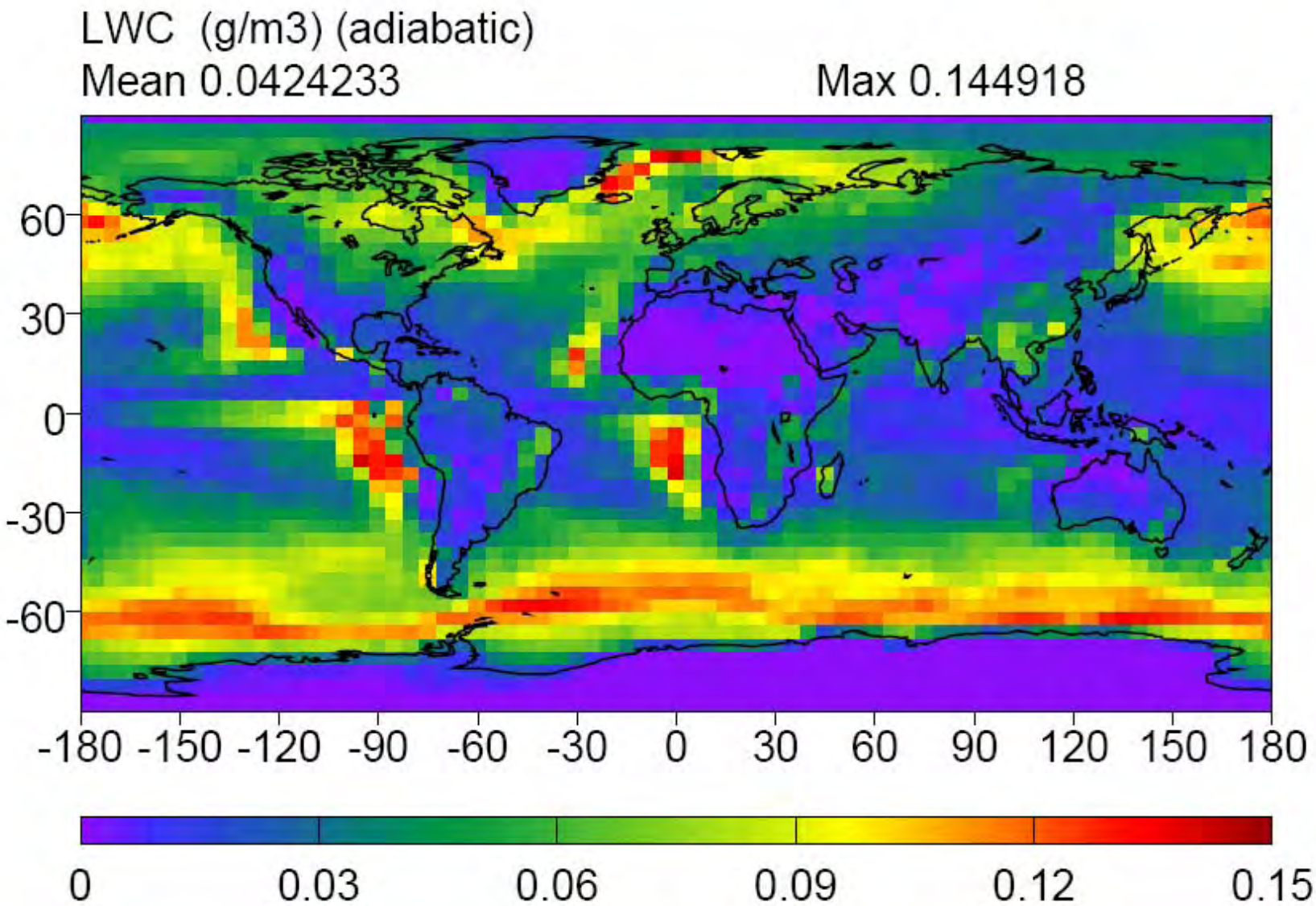
$e=0.4e_c$ - Adiabatic ~ 14%




$e=0.6e_c$ – Adiabatic ~ 25%




Present day, GISS meteorology, annual averages


LWC (g/m3) (adiabatic)
Mean 0.0424233
Max 0.144918
60
30
0
-30
-60
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
0
0.03
0.06
0.09
0.12
0.15

# Supporting Material (Rafaella)

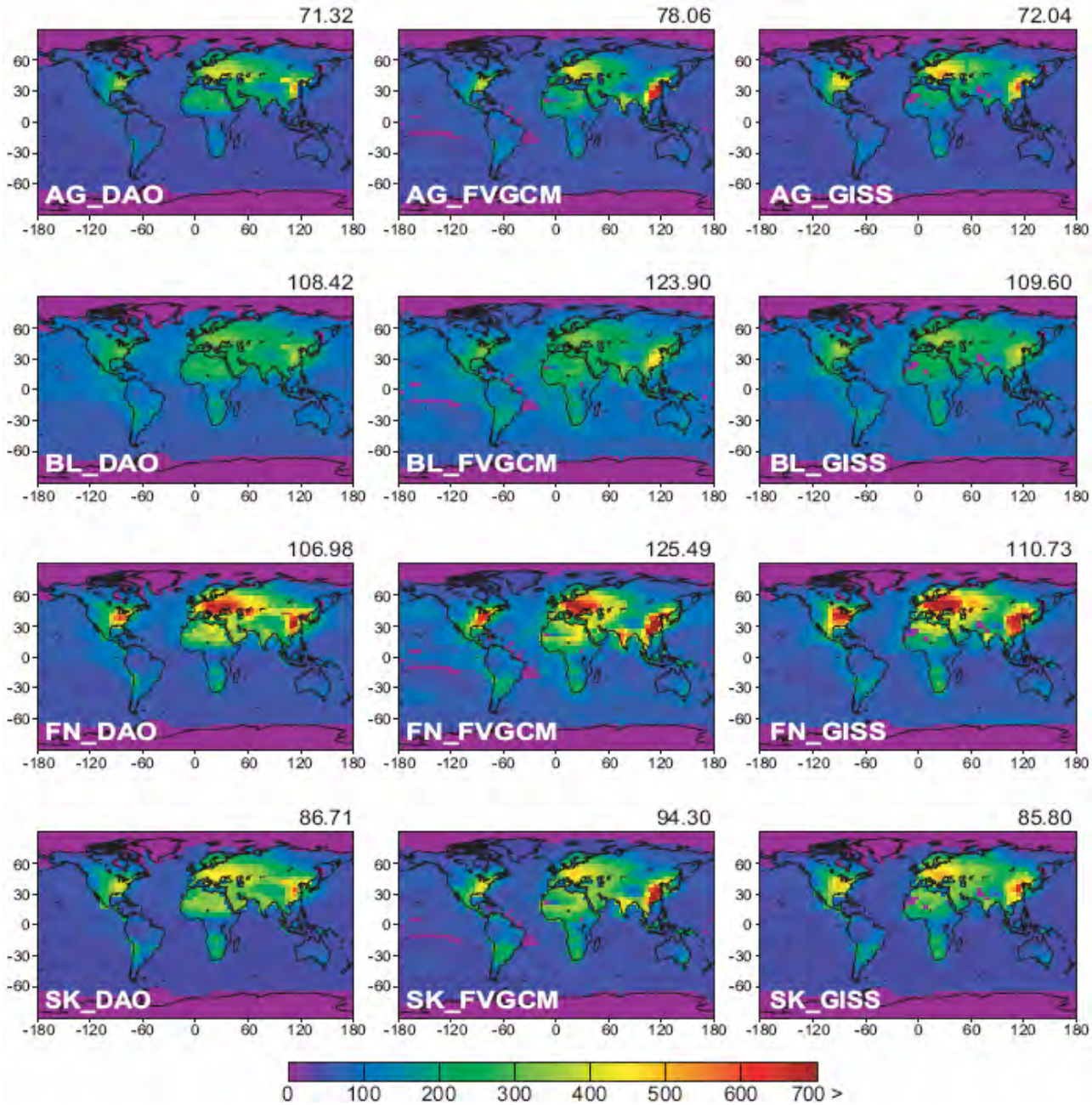
# Cloud Droplet Number ($cm^{-3}$) (annual average)

**Conditions:**

Prescribed updrafts (marine: 0.35 $ms^{-1}$; continental: 1 $ms^{-1}$)

Water vapor mass uptake coefficient, $a_c$ = 0.042 (FN)

Despite the general similarity in the spatial patterns, there are considerable differences introduced by different meteorological fields and droplet activation parameterizations



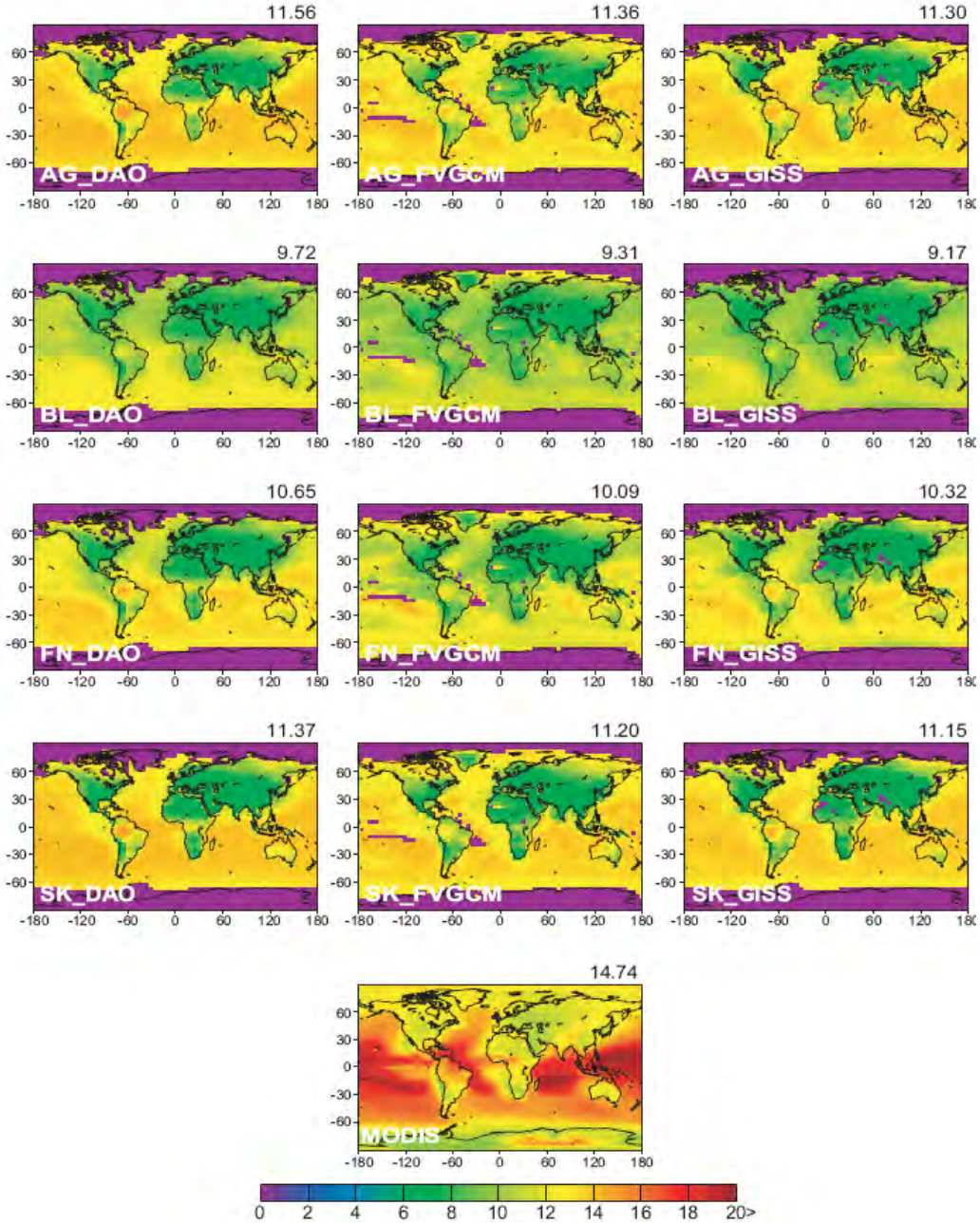
# Droplet Effective Radii (μm)

Differences in $r_{eff}$ between different droplet schemes are due to differences in predicted CDNC

Satellite and model values agree reasonably well in terms of land-ocean contrast and the differences between SH and NH.

Maximum droplet size is calculated over the western tropical Pacific warm pool region, where large evaporation associated with large sea surface temperature exists.

The smallest effective radius is calculated over continental regions with enhanced CCN concentration (i.e., eastern China, North America and Western Europe)

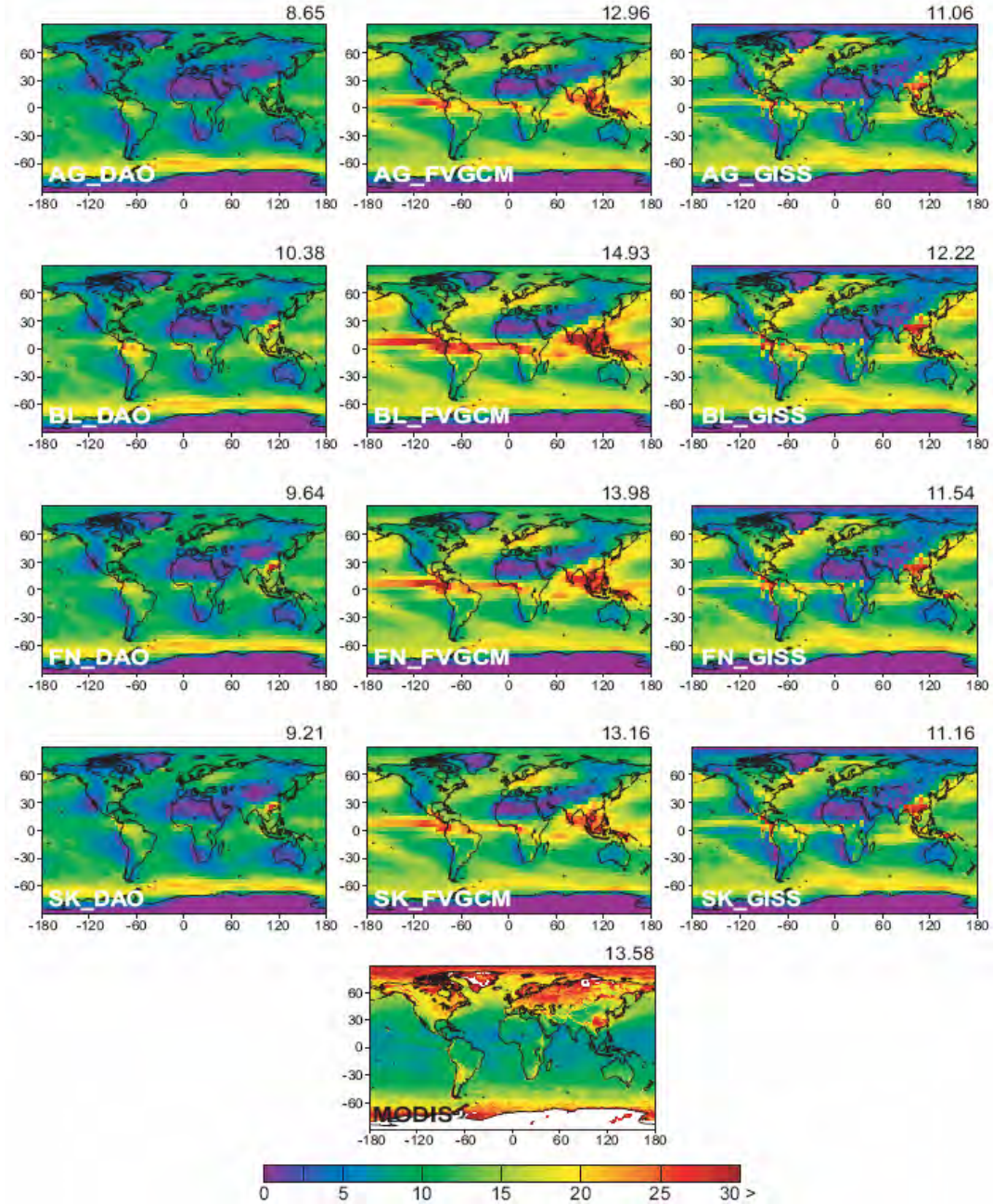


# Cloud Optical Thickness ($\tau$)

Similar general patterns of COD are predicted for different droplet activation schemes and meteorological fields used.

Higher COD is predicted for the clouds over anthropogenically influenced regions of eastern China, Europe, eastern US, and some biomass burning regions in South America and West Africa.

The modeling results are comparable with those retrieved from MODIS platform



# Model Evaluation with Satellite Observations

| $R_{eff}$ (μm) | DAO | | FVGCM | | GISS | | ISCCP[1] | MODIS[2] |
|---|---|---|---|---|---|---|---|---|
| | FN | BL | FN | BL | FN | BL | | |
| **Ocean** | 12.24 | 11.03 | 10.98 | 9.95 | 11.80 | 10.56 | 11.8 | **15.6** |
| **NH Ocean** | 11.36 | 10.11 | 10.25 | 9.35 | 11.19 | 9.92 | 11.6 | **15.4** |
| **SH Ocean** | 12.92 | 11.72 | 11.51 | 10.38 | 12.28 | 11.03 | 12.0 | **15.8** |
| **Land** | 8.93 | 8.44 | 8.65 | 8.39 | 8.53 | 8.16 | 8.5 | **12.5** |
| **NH Land** | 8.45 | 8.19 | 8.27 | 8.18 | 8.06 | 7.87 | 8.2 | **12.4** |
| **SH Land** | 10.96 | 9.62 | 10.02 | 9.14 | 10.47 | 9.40 | 9 .0 | **13.1** |

| COD | DAO | | FVGCM | | GISS | | ISCCP[1] | MODIS[2] |
|---|---|---|---|---|---|---|---|---|
| | FN | BL | FN | BL | FN | BL | | |
| **Ocean** | 10.78 | 11.58 | 16.14 | 17.19 | 12.91 | 13.63 | 6.9 | **7.99** |
| **NH Ocean** | 10.32 | 11.24 | 17.16 | 18.39 | 12.94 | 13.83 | 6.4 | **7.45** |
| **SH Ocean** | 11.17 | 11.94 | 15.69 | 16.69 | 12.97 | 13.62 | 7.4 | **8.17** |
| **Land** | 8.13 | 8.52 | 10.95 | 11.36 | 9.89 | 10.24 | 8.1 | **8.89** |
| **NH Land** | 7.88 | 8.05 | 11.22 | 11.39 | 9.60 | 9.75 | 7.8 | **9.88** |
| **SH Land** | 9.35 | 10.48 | 11.31 | 12.34 | 11.16 | 12.11 | 8.6 | **6.15** |

1) Values are taken from *Han et al.* [1994].
2) MODIS Terra Collection 005 (C5) Level-3 global gridded monthly averaged products at 1° by 1° resolution for April 2000 – December 2006 were used. To minimize data contamination by ice particles, data were averaged between 70°S to 70°N.

# Annual Mean Autoconversion Rate ($\times 10^{11}$ $s^{-1}$)

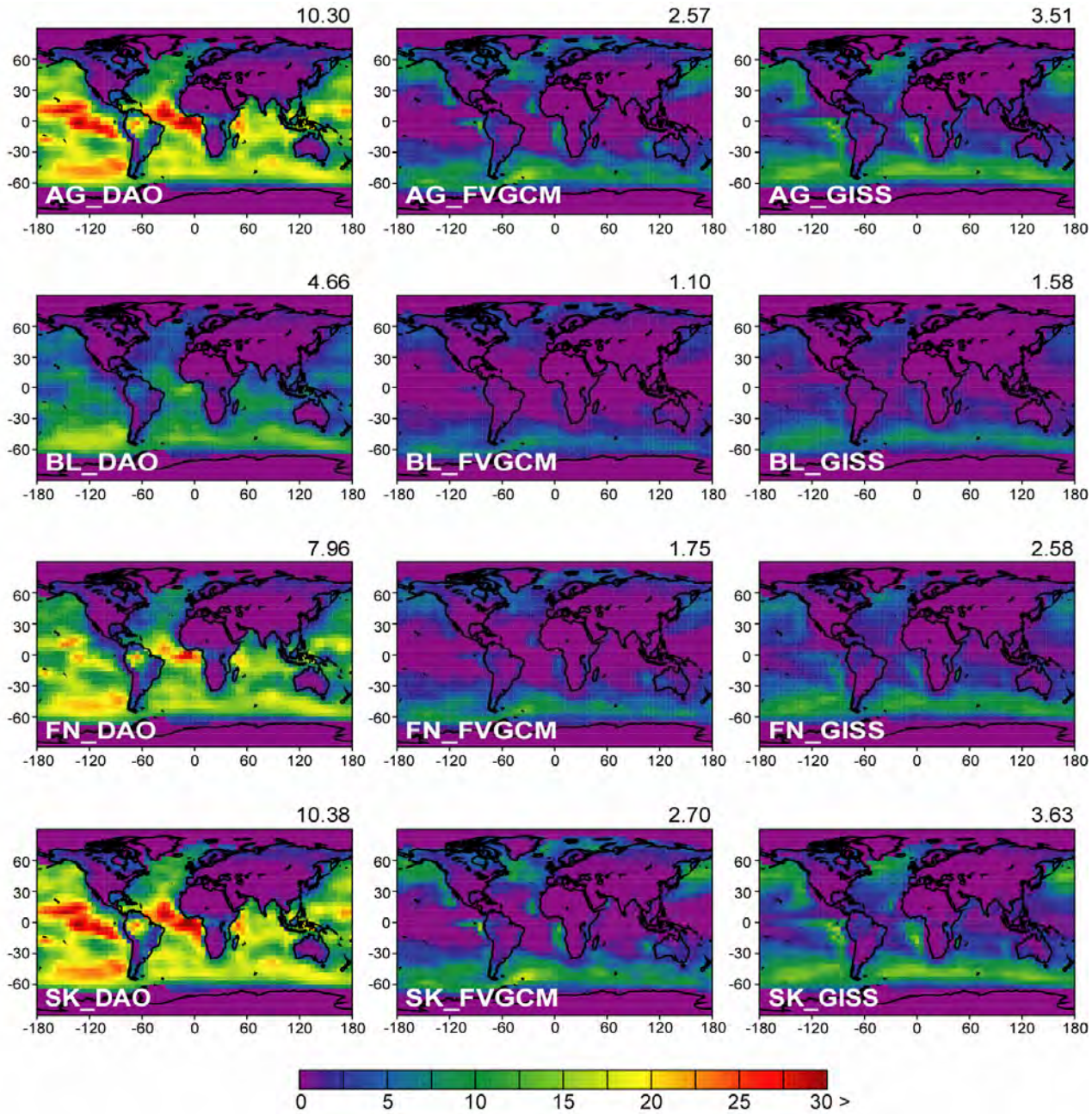
**Conditions:** Eq.1 of Kharoutdinov and Kogan, 2000

The contrast between land and ocean is large.

Large differences in autoconversion rates over the oceans.

Different meteorological fields contribute 70 % variability in calculations of autoconversion.

Cloud droplet formation schemes are of lesser importance for autoconversion rate calculations.



# Comparison of the calculated annual mean indirect forcing between the "old" and the "new" code (%)

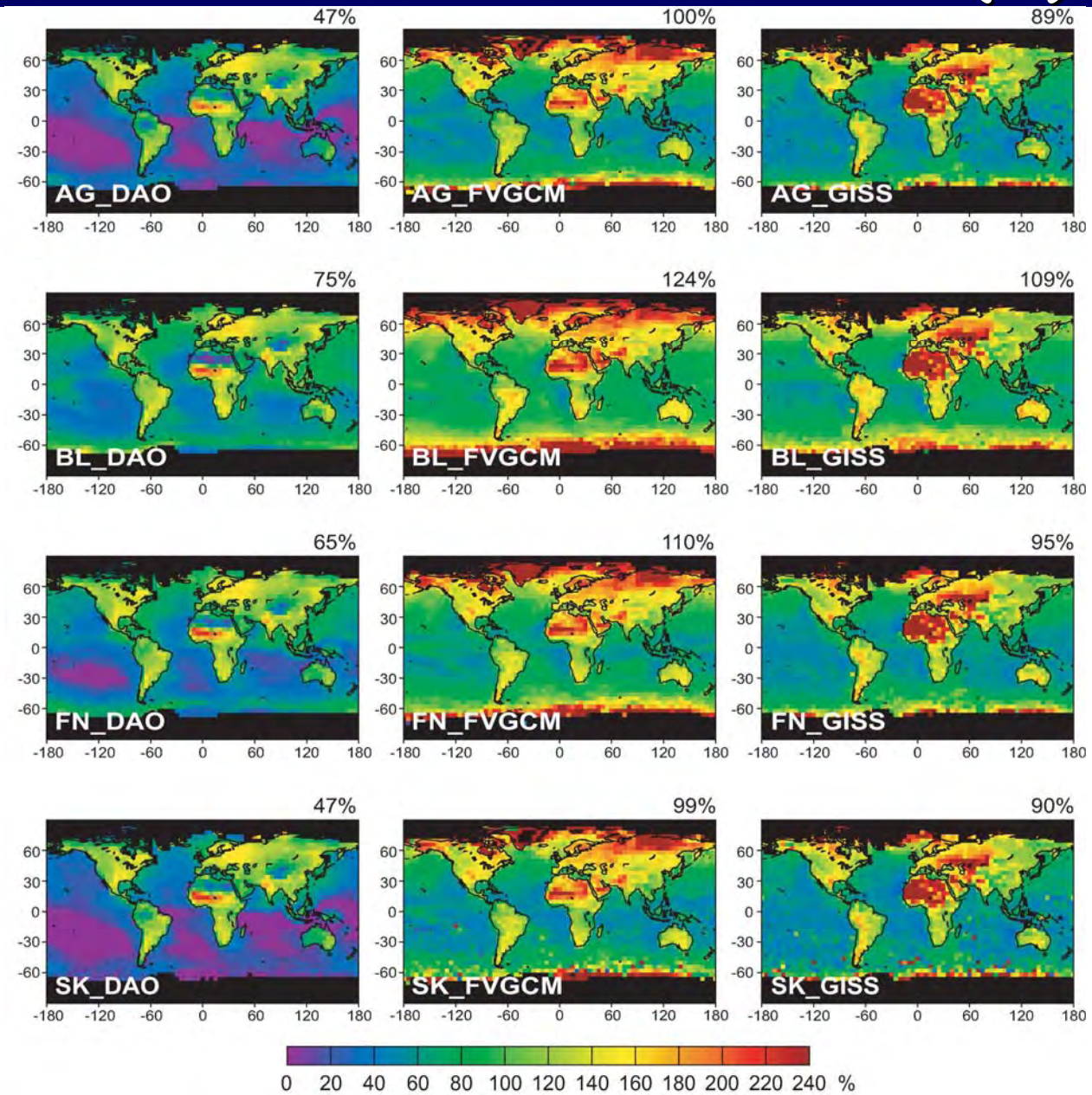
Results are presented for the surface layer.

$$R_IF = \frac{IF_{FAST-J}}{IF_{CLIRAD-SW}} \times 100$$

Difference ~ 25 % in IF.

Largest differences in calculated forcings over the continents.

These differences are mainly caused by the simplified treatment of COD and lack of aerosol direct effects in the old version of the code.



# GMI implementation

- 4′×5′ horizontal resolution.
- 23 vertical layers (27-959 mbar) (GISS meteorology), 1 year simulations.
- Entrainment rate is prescribed as a fraction of $e_c$.
- Updraft velocity: average values for clean, polluted and marine environments.
- Aerosol : standard distributions (*Whitby, 1978*) constrained by observations (*Lance et. al., 2004*). Number scaled using sulfate aerosol mass.