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Aerosol-Cloud-Climate Interactions in ModelE

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Aerosol-climate interactions

- Model: NASA Goddard Institute for Space Studies (GISS) climate-chemistry coupled model (atmosphere only), **ModelE**
- Time period:
  - Global:1750-2000

- Emissions: In general, **AEROCOM** emissions for global effects.

- Process updates: **Aerosol Direct, Indirect effects** (Bauer et al. 2008, ACP, Menon et al. 2009, Nat. Geosc.) and **Snow/ice albedo change from black carbon deposition over snow/ice** (Koch et al. 2009, J. Clim).

Aerosol-cloud interactions: Nucleation and Autoconversion

ModelE is coupled to either an **aerosol mass-based model** (Koch et al. 2009) or an **aerosol microphysical model (MATRIX)** (Bauer et al. 2008, ACP)

Cloud droplet nucleation follows prognostic treatment of Morrison et al. (2005, 2008)
(1) Cloud drop activation based on Lohmann et al. (2007) for aerosol mass model

$$CDNC = 0.1\left(\frac{N_a\omega}{\omega + \alpha N_a}\right)^{1.27}$$

$$\omega = \varpi + 1.33\sqrt{TKE}; \quad \alpha = 0.023 \text{ cm}^4 s^{-1}$$

$$N_a = Aerosol \text{ conc. (obtained from mass)}$$

(2) On Abdul-Razak and Ghan (2000) for aerosol microphysical model

Autoconversion scheme is based on **Beheng** (1994) or Seifert and Beheng (2001).

- Seifert and Beheng use analytical solutions to the stochastic collection equation and better predicts rain rate and timing than Beheng.
  Dependence on rain rate is a unique feature

(Menon et al. 2009)

MATRIX: Aerosol Microphysical model

Statistically-based alternative to modal and sectional methods.

- Key moments of the aerosol population: number, mass, and mixed moments.
- These enter the covariance matrix of a principal components analysis and are tracked in place of the distribution itself.
- Scheme uses only 2 moments (mass and number) and thus resembles a modal scheme; however the framework is in place to add more moments.

Matrix is implemented in the GISS climate model, using a flexible interface that allows choice of 8 different mechanisms. All mechanisms use the same emissions, but the transport and removal of the particles depend on their size, density and solubility, which depends on the aerosol mode the particle is assigned to.

Matrix includes primary modes, secondary modes (coagulation among primary modes), new particle formation, gas-particle mass transfer, aerosol phase chemistry, condensational growth and coagulation.

(Bauer et al. 2008)

MATRIX: Aerosol-cloud interaction representation

Species: Accumulation (*ACC*), Aitken (*AKK*), Sea-salt, soluble and insoluble mineral dust (*accumulation and coarse*), organic carbon, insoluble black carbon (*BC1,BC2,BC3) (3 different volume fractions of inorganic coating*), BCS (*coagulation of AKK or ACC with BC1/BC2/BC3*), mixed BC-OC, dust-BC and mixed.

Activated number is based on the Köhler theory (Abdul-Razaak and Ghan 2000, JGR) for multiple external lognormal modes, each composed of internally mixed soluble and insoluble material (AG scheme).

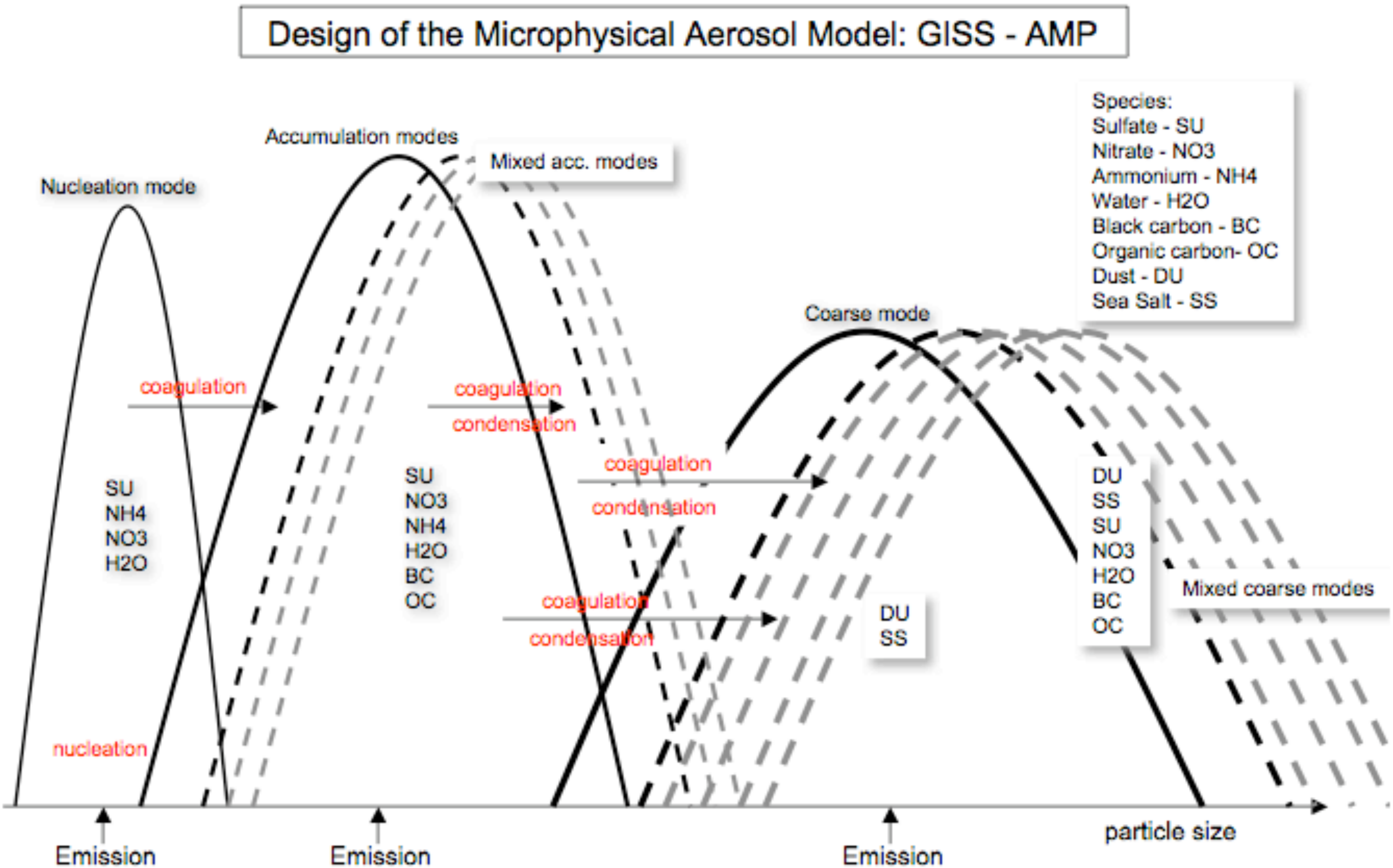
We then use the Morrison scheme to calculate CDNC

$$CDNC = \max\left(\frac{N - No}{\Delta t}, 0\right)$$

N and No are potential and existing droplets
(Morrison et al., JAS 2005).

(Menon et al. 2009)

Different modes in MATRIX

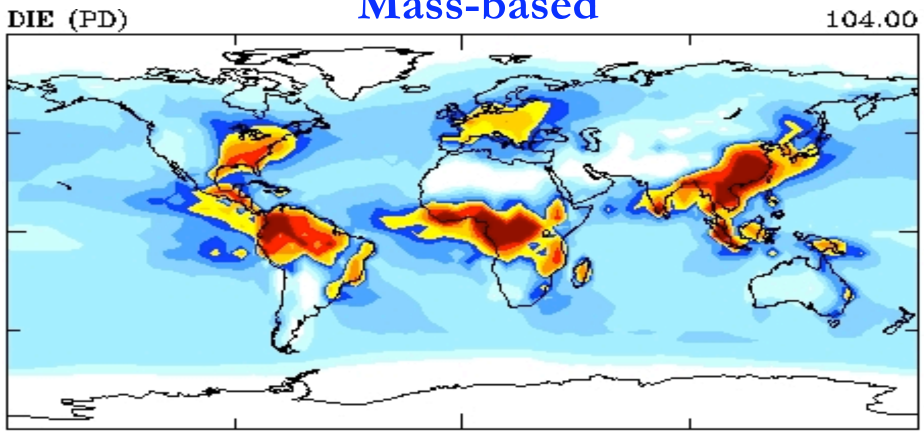


(Bauer et al. 2008)

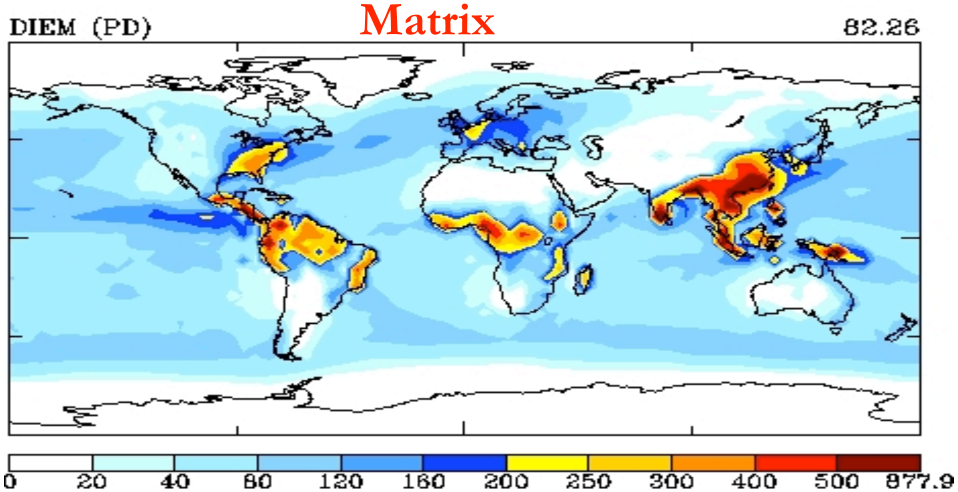
Cloud droplet number

Cloud droplet number (cm^{-3}) for the Lohmann et al. (2007) scheme versus the Abdul-Razak and Ghan (2000) scheme for present-day emissions.

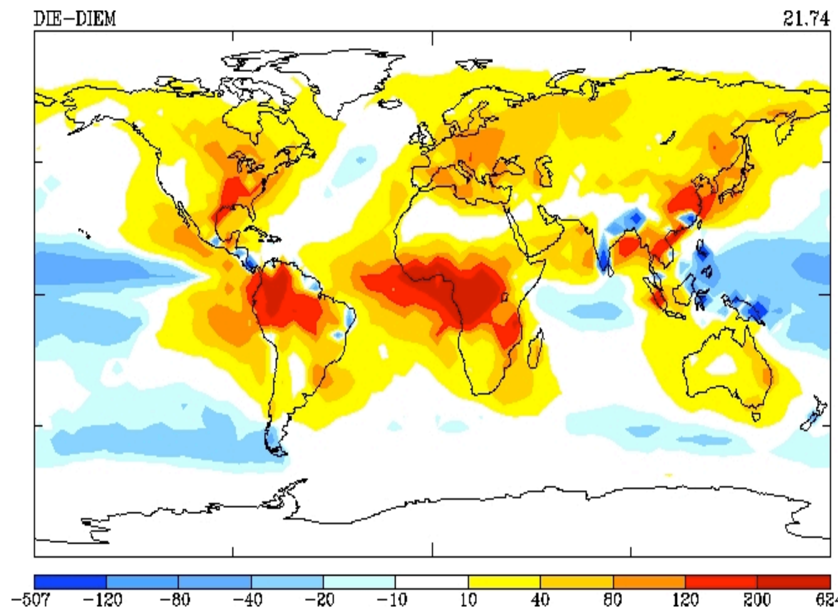
Mass-based



Matrix



Diff. bet. Mass-based and MATRIX



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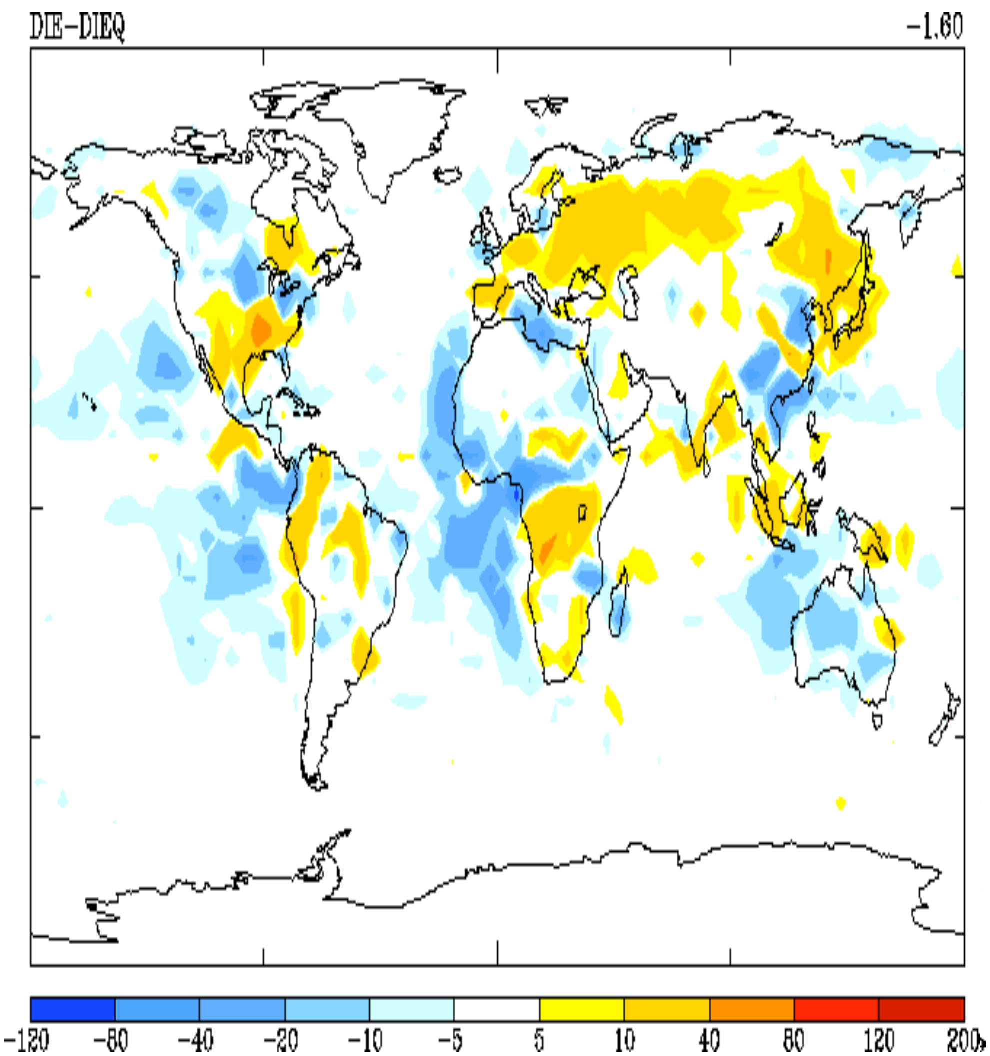
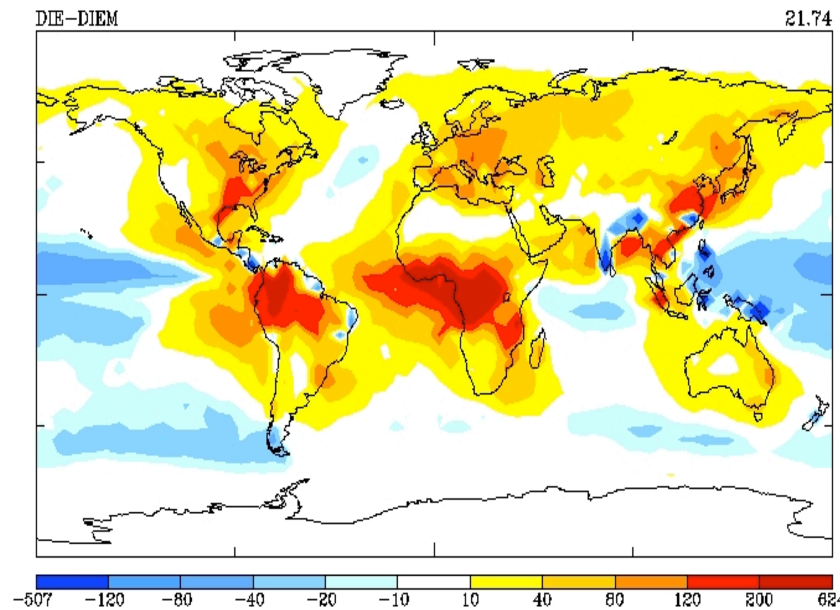


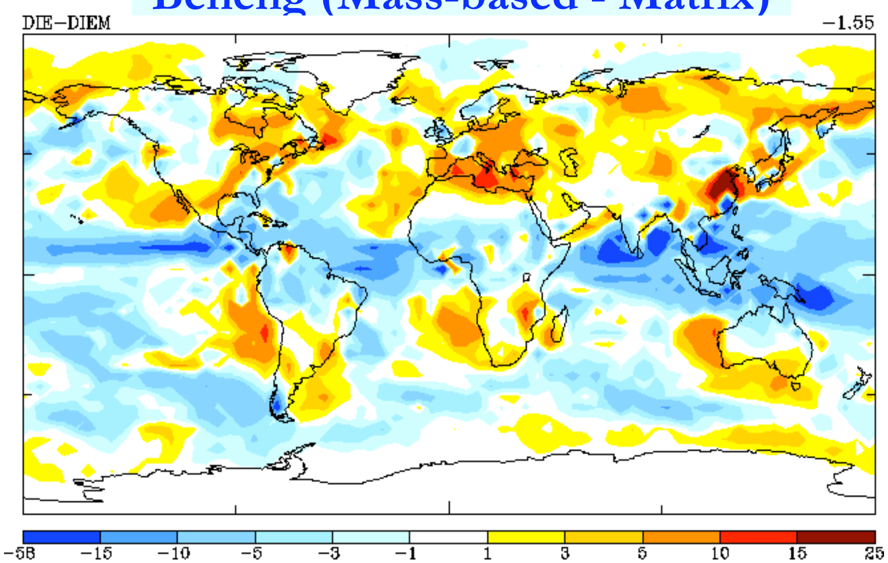
Diff. bet. Mass-based and MATRIX



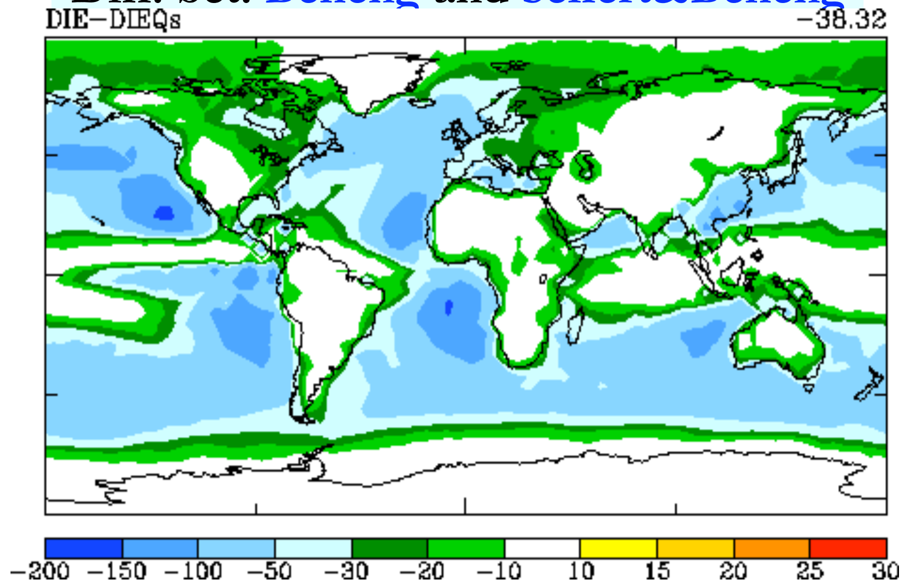
Liquid Water Path

For indirect effect: Liquid water path (gm^{-2}) changes are important

Beheng (Mass-based - Matrix)



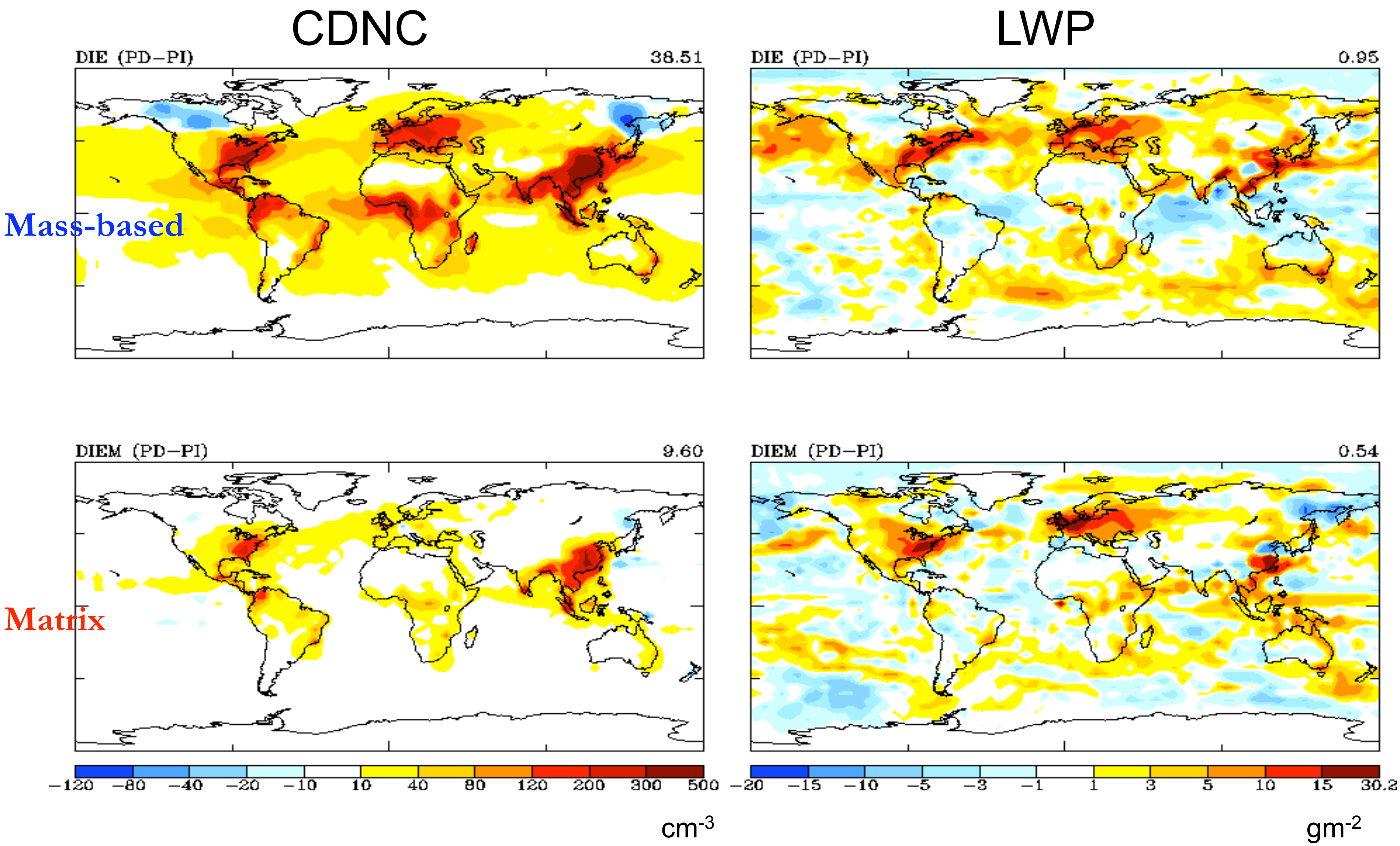
Diff. bet. Beheng and Seifert&Beheng



With Seifert and Beheng scheme, differences in LWP is too large.

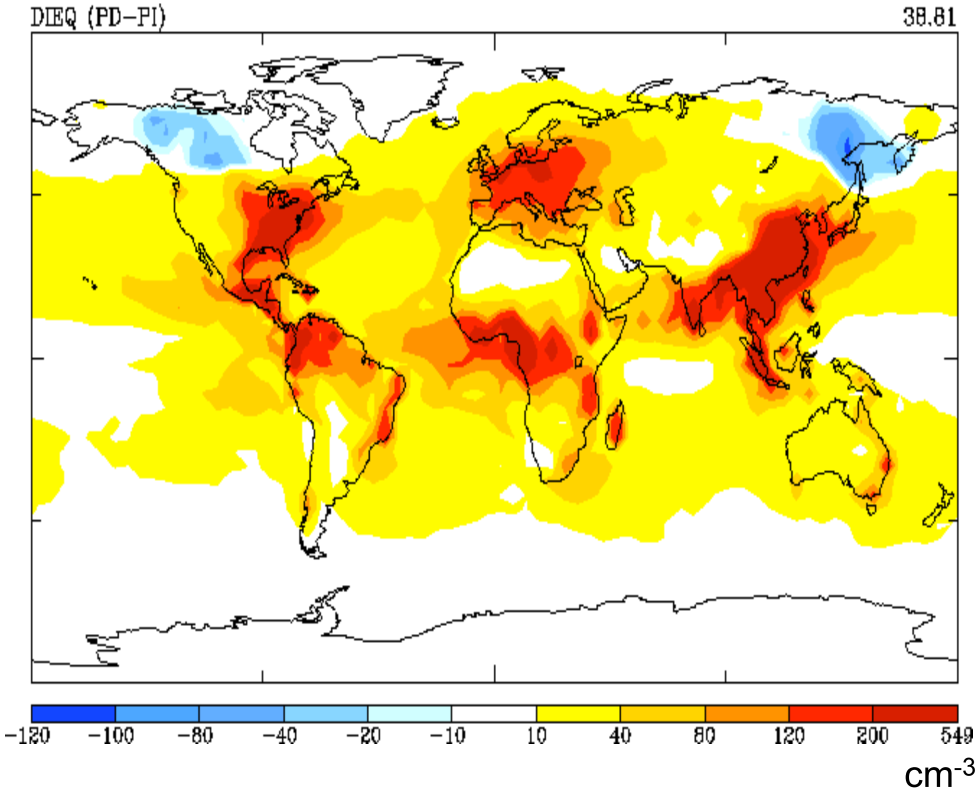
Nucl. Scheme: Cloud droplet number and LWP

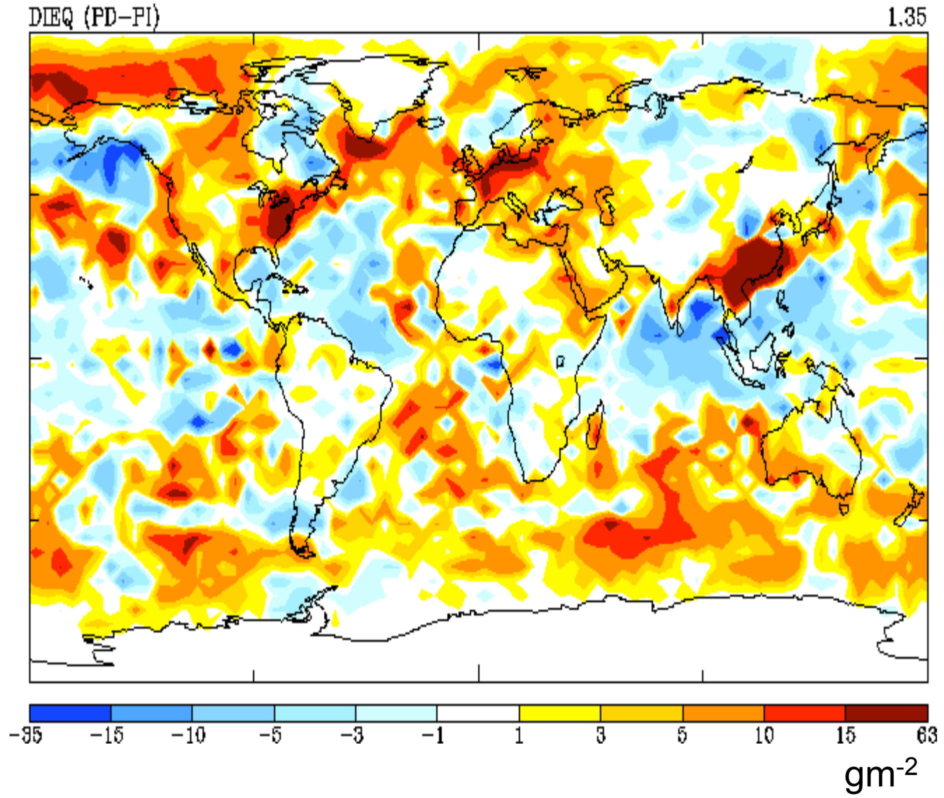
Diff. between present-day and pre-industrial emissions



Qaut scheme: Cloud droplet number and LWP

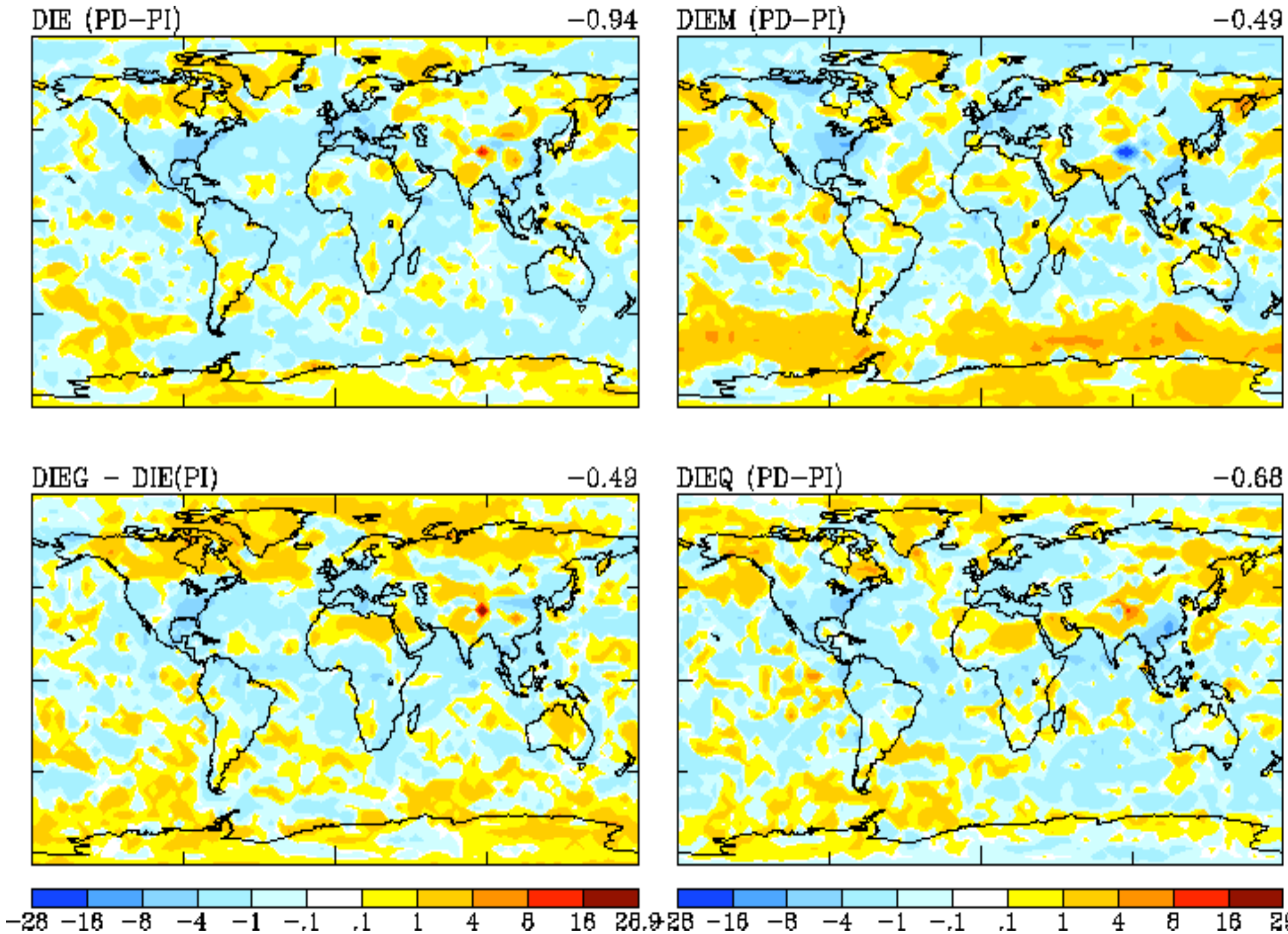
Diff. between present-day and pre-industrial emissions





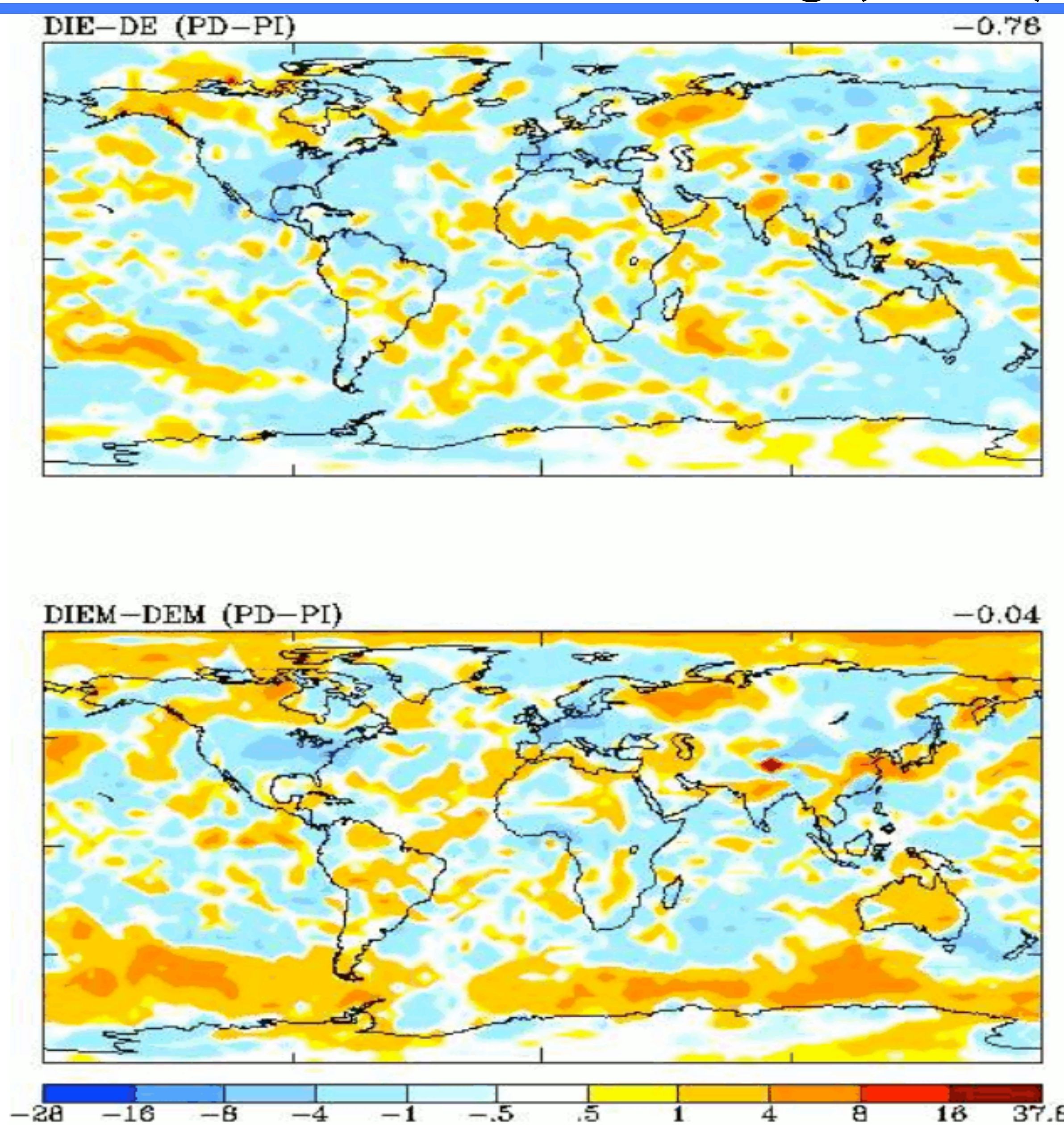
1750 to 2000: Net Radiation at TOA

We examine differences between PD and PI simulations for:
(1) Indirect + Direct effects (DIE)
(2) when the model is coupled to MATRIX (DIEM)
(3) For diff GHG levels (DIG-DIE(PI))
(4) when Seifert&Beheng Qaut scheme is used (DIEQ)



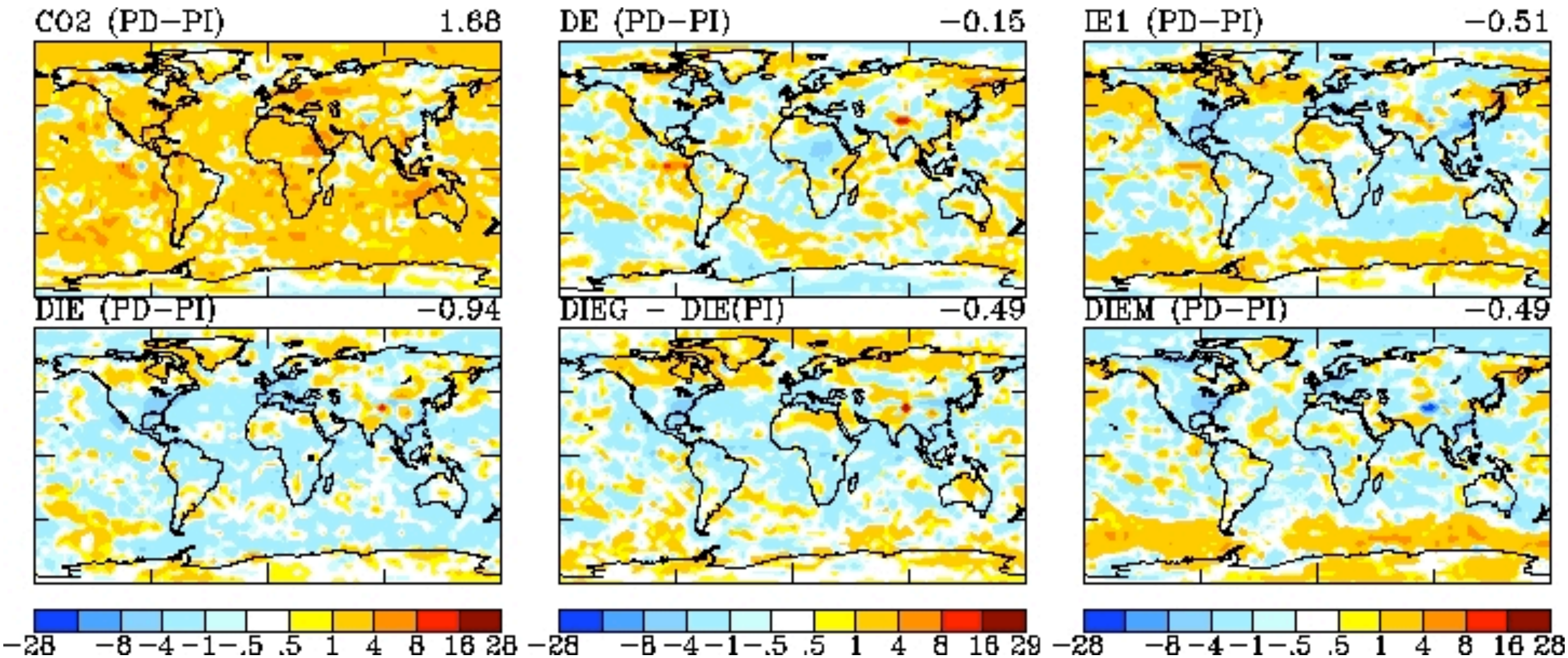
Indirect effect: Net cloud rad. Forcing (Wm^{-2})

We examine differences between PD and PI simulations for:
(1) Indirect - Direct effects (DIE-DE)
(2) when the model is coupled to MATRIX (DIEM-DEM)



1750 to 2000: Net Radiation at TOA

We examine differences between PD and PI simulations for CO2, and aerosol processes: DE: Direct effect; 1st indirect effect (IE), Indirect + Direct effects (DIE) at two GHG levels **--1990 and 2000** (DIEG) and when the model is coupled to MATRIX (DIEM).



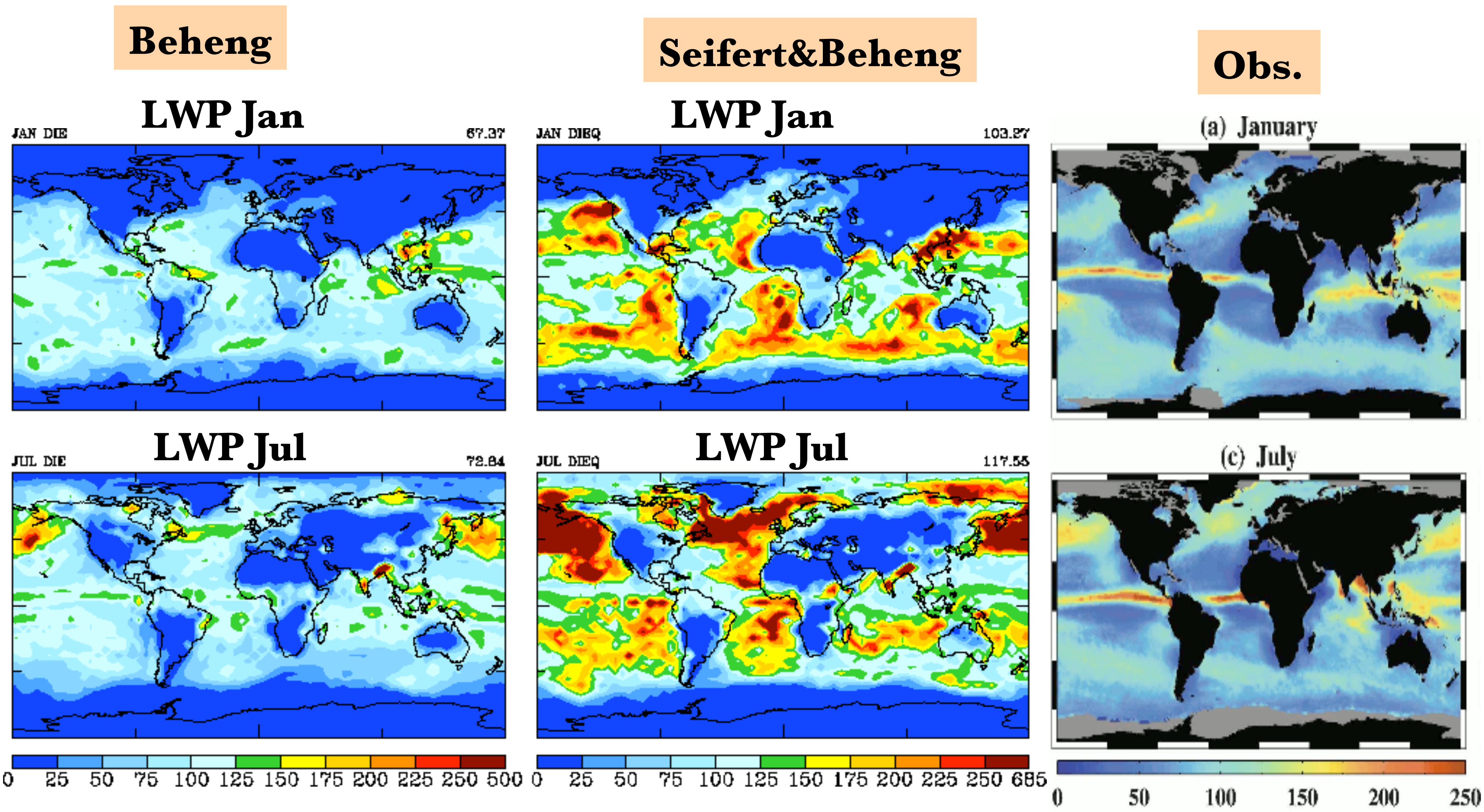
1750 to 2000: Aerosol-cloud-climate interactions

Various version of aerosol direct+indirect effects give a wide range of forcings (net TOA radiation); all between -0.5 to -1 Wm^{-2}:

Std.	MATRIX	Diff. Qaut	GHG_change
DIE	DIEM	DIEQ	DIE_{GHG00}
-0.94	-0.49	-0.68	-0.49

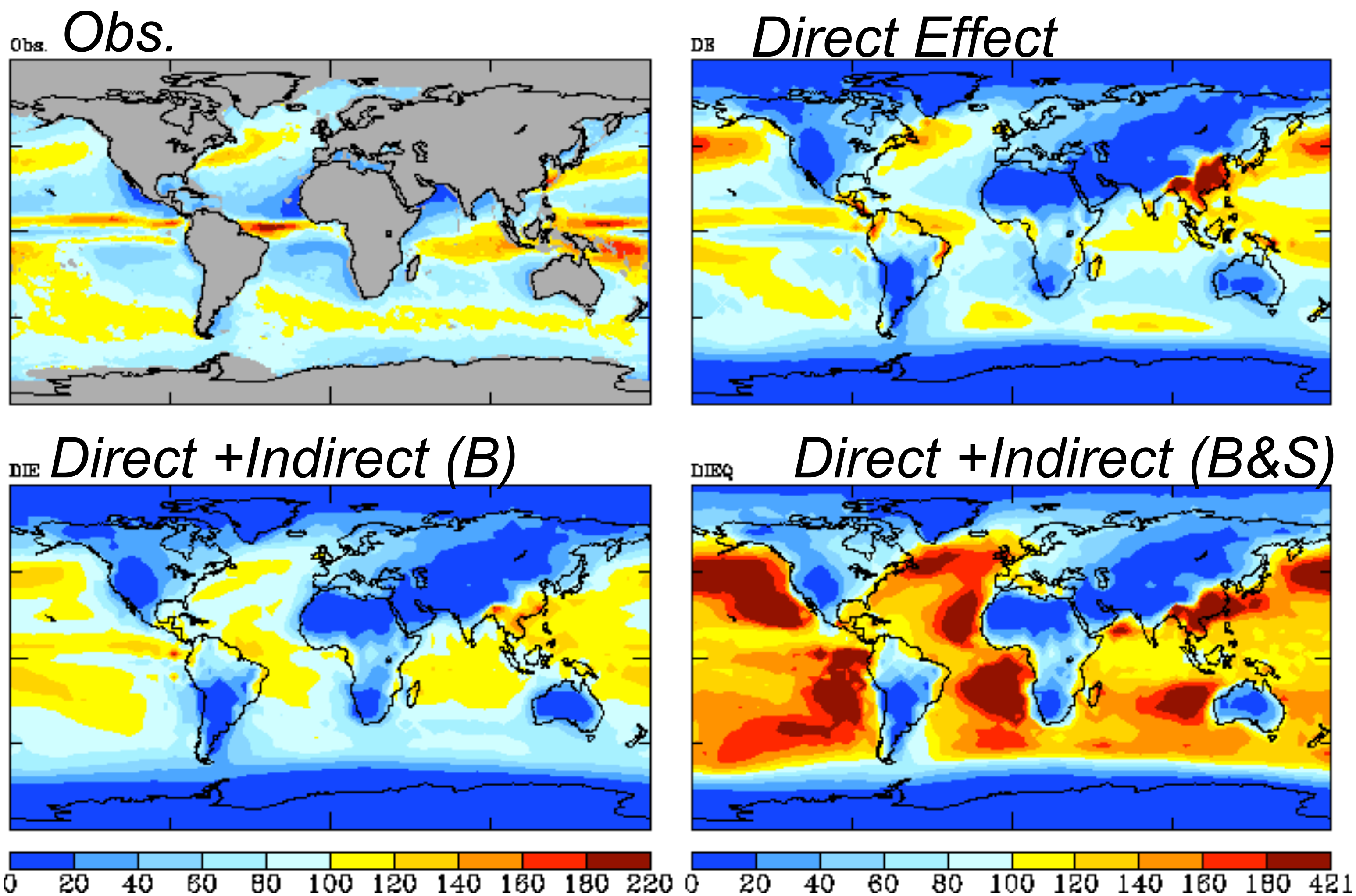
- 50% increase with MATRIX (and diff. nucleation scheme)
- ~30% decrease for diff. autoconversion scheme
- Direct+Indirect effects offset 44% of warming from CO_2
- An increase in CO_2 and CH_4 of 4% (1990 to 2000) offsets 48% of the impacts from aerosol direct and indirect effects.

Cloud Liquid Water Path (gm^{-2})

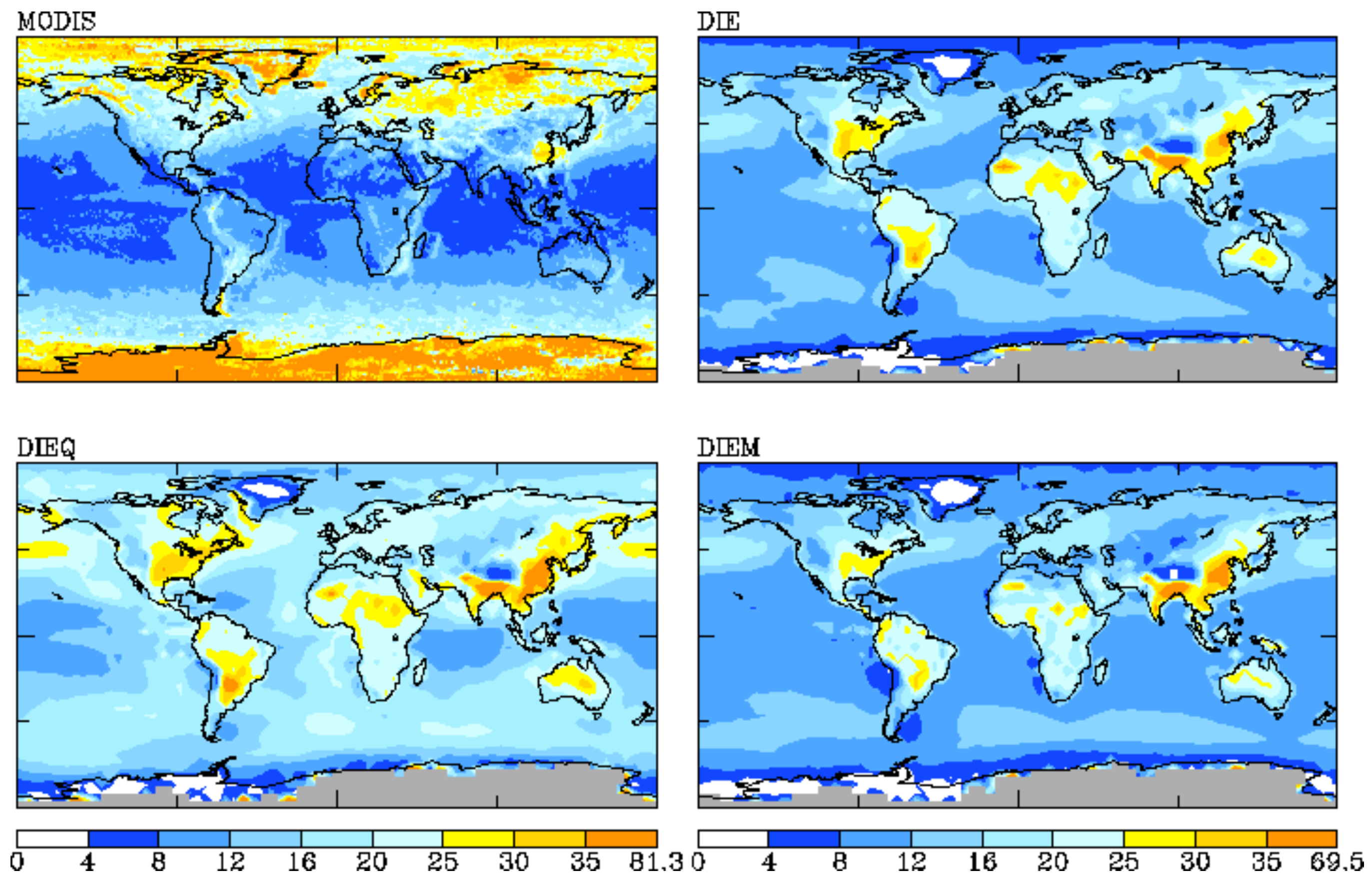


(O'Dell et al. 2008)

Annual Cloud liquid water path (gm^{-2})



Cloud optical depth



Global averages: Obs. vs Model

		Std.	MATRIX	Diff. Qaut
Variable	Obs	DIE	DIEM	DIEQ
Ocn LWP (gm^{-2})	**50-84**	**68.3**	**67.8**	**114**
CC (%)	**62-67**	**60.5**	**60.3**	**61.8**
SW Cloud Forcing (Wm^{-2})	**-50.0**	**-48.3**	**-48.3**	**-53.0**

Favourite Question: Data need of modelers

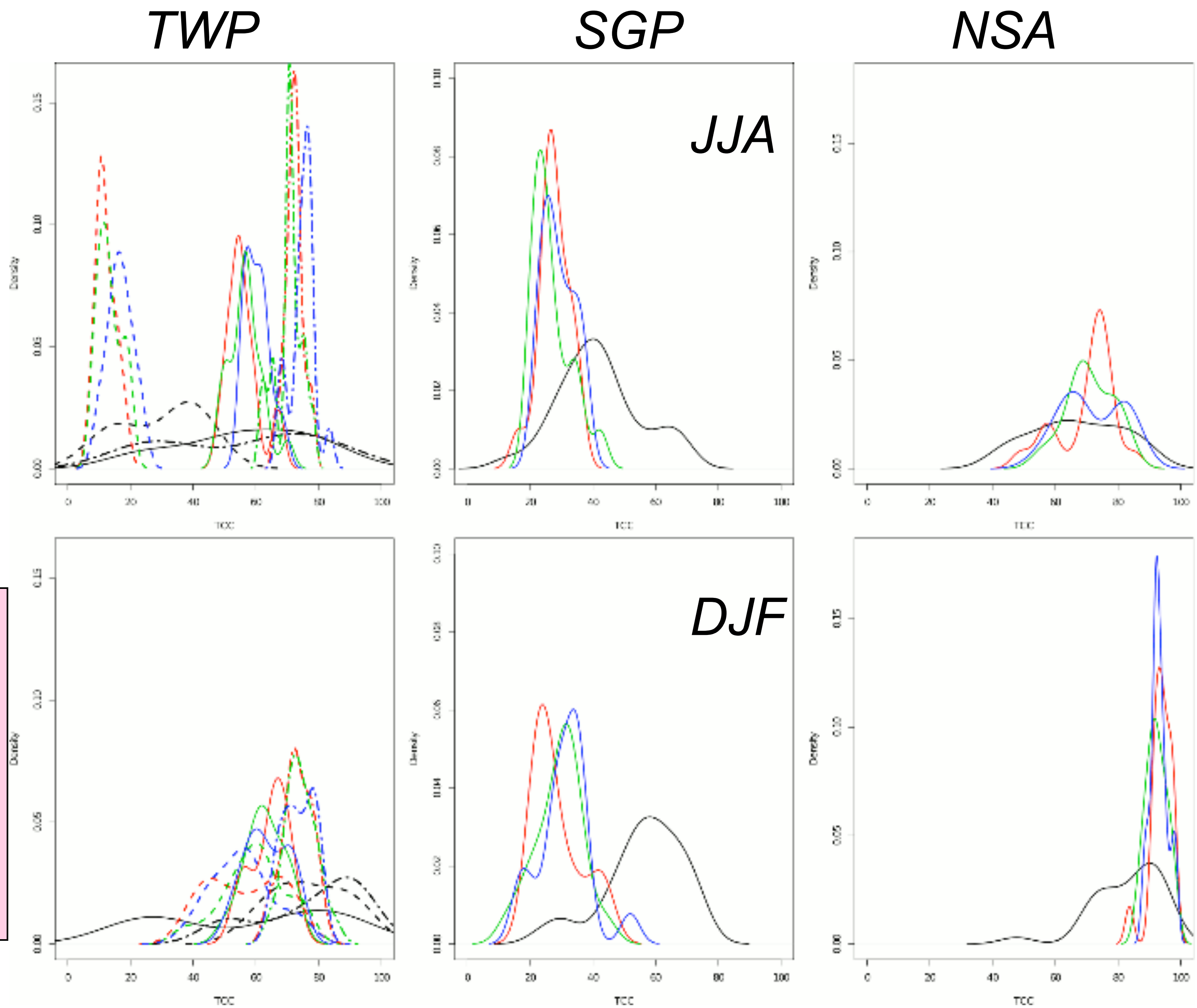
What particular data needs do you see the opportunity for past/present/future ARM ground and/or aircraft-based observations to address?
If ARM/ACRF meets such needs, additional input on any issues with the properties of available data sets (spatiotemporal resolution, averaging times, conditions/locations for which data are available, limitations you might have encountered, suggestions for improvement, etc.)

CMBE type products are useful. These are for 3 ARM sites only. For evaluating a climate model, **how can we integrate several datasets to increase the spatial coverage of products that are common**. Especially useful for continental locations.

With CMBE data products can we also have associated satellite data and other data sets put together to evaluate the range in observed products when comparing with the model?

Will we have an ACMBE product? Again, very useful for continental locations.

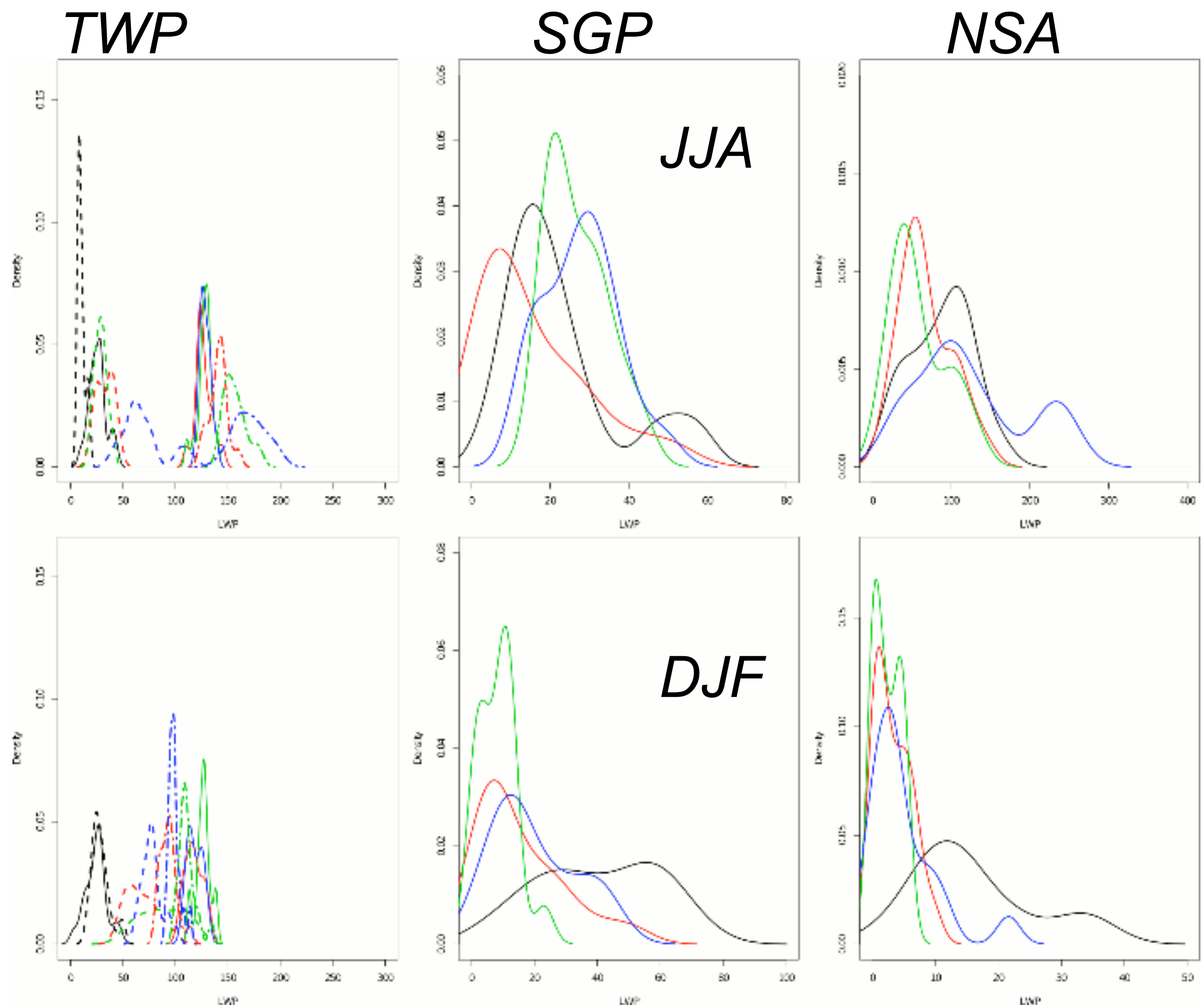
CMBE: Total cloud cover



Black: Obs
DIE: Std
DIEM: Green
DIEQ: Blue

TWP C1: 2-dash
TWP C2: solid
TWP C3: dashed

CMBE: Liquid Water Path (g/m2)



Black: Obs
DIE: Ref
DIEM: Green
DIEQ: Blue

TWP C1: 2-dash
TWP C2: solid
TWP C3: dashed

CMBE versus ModelE

	Obs	DIE	DIEM	DIEQ
LWP JJA/DJF				
NSA	**87.5/16.0**	**67.9/2.90**	**95.4/4.22**	**175/7.32**
SGP	**22.5/40.4**	**7.53/14.8**	**5.28/7.67**	**7.54/23.4**
TWP	**18.3/26.6**	**99.8/93.5**	**109/105**	**128/100**
CC JJA/DJF				
NSA	**66.8/83.0**	**70.2/93.5**	**73.7/93.8**	**77.6/92.5**
SGP	**42.0/56.3**	**9.14/28.7**	**8.23/27.8**	**8.36/32.6**
TWP	**47.2/70.9**	**46.8/64.7**	**47.5/64.8**	**49.1/65.2**

Single-layer Arctic stratus clouds

OBS: DOE ARM's site at the North Slope of Alaska for 2000 to 2003 for single- layer clouds with bases below 4 km, cloud optical depth ≤ 8 and cloud droplet size ≤ 25 μm. (*Zhao and Garrett, 2007, JGR*)

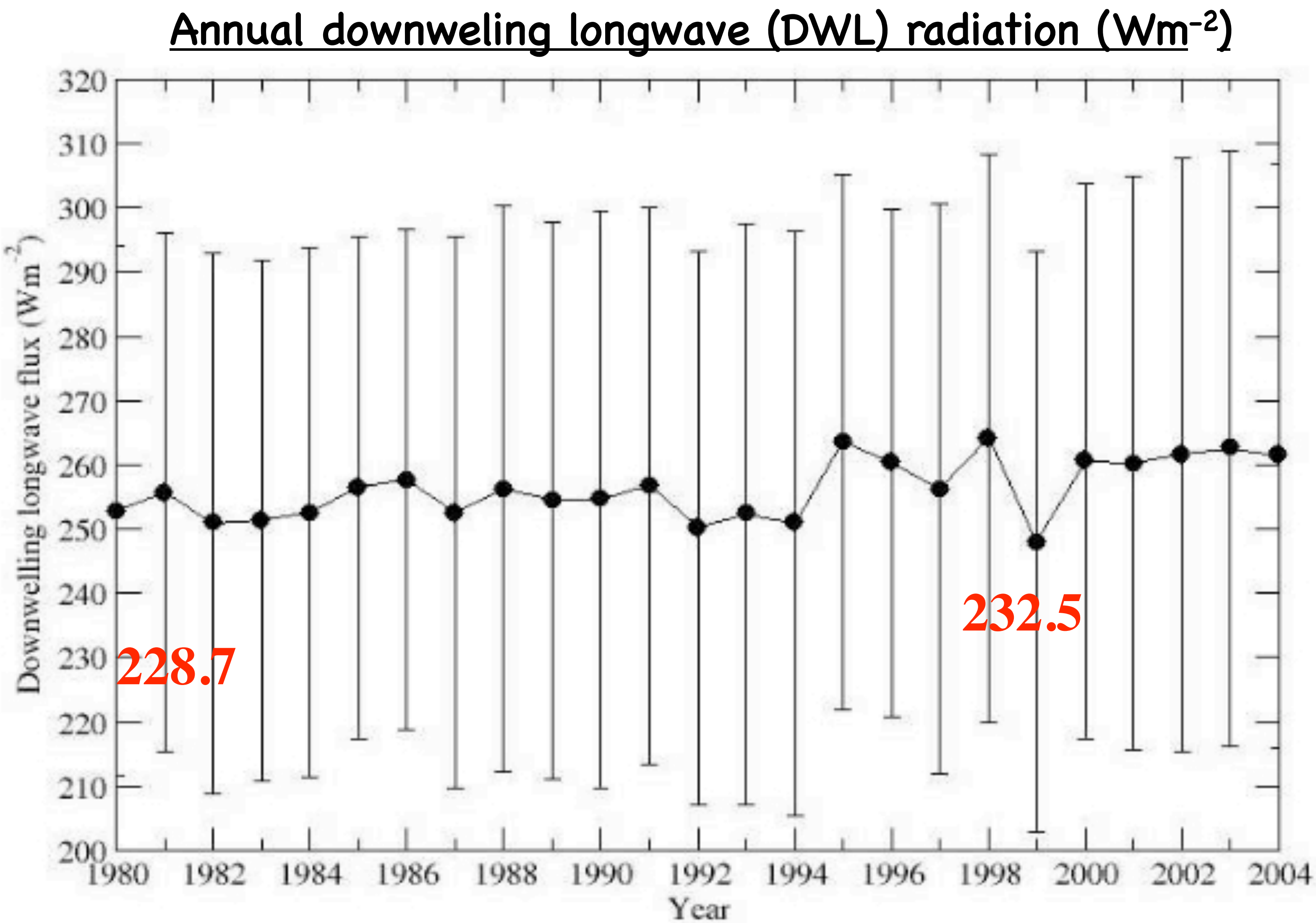
Climatological ranges for June to August

	OBS	ModelE
Cloud thickness	300-1200 m	**100-900 m**
CDNC	20-40 cm^{-3}	**60 cm^{-3}**
Reff	10-12 μm	**9.2 μm**
Cloud optical depth	4.5-5.5	**3.8**
LWP	30 gm^{-2}	**18 gm^{-2}**

DLW (Wm^{-2}): 60-70N,145-165W (*Francis et al. 2003*)

	1980		2000		2030
	Obs	**ModelE**	**Obs**	**ModelE**	**ModelE**
DLW:	320.3	**303.0**	331.3	**303.0**	**309.9**

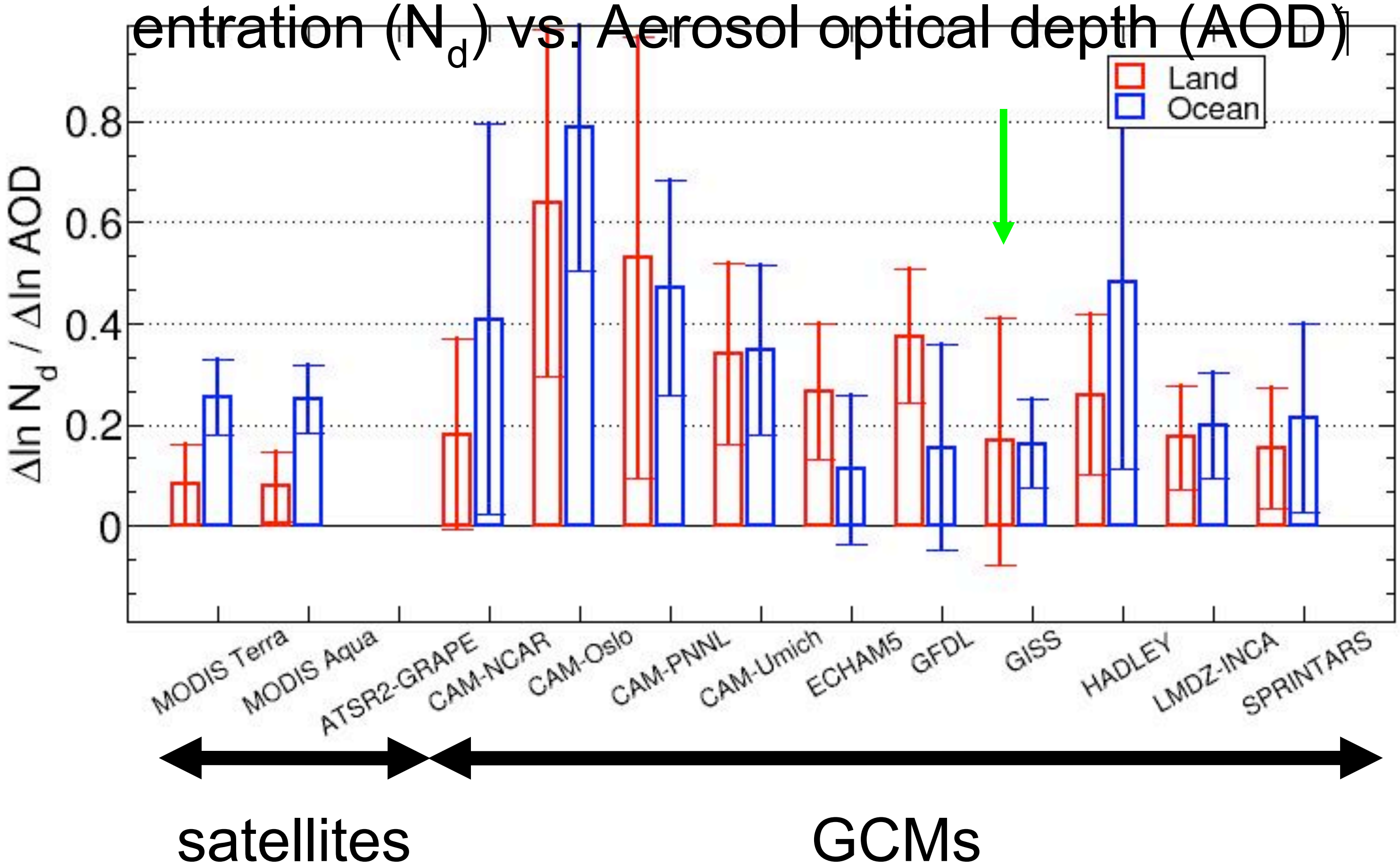
Observed Climate 60-90N (1980-2004)



(From Francis et al. 2003)

AEROCOM: Cloud droplet vs. AOD

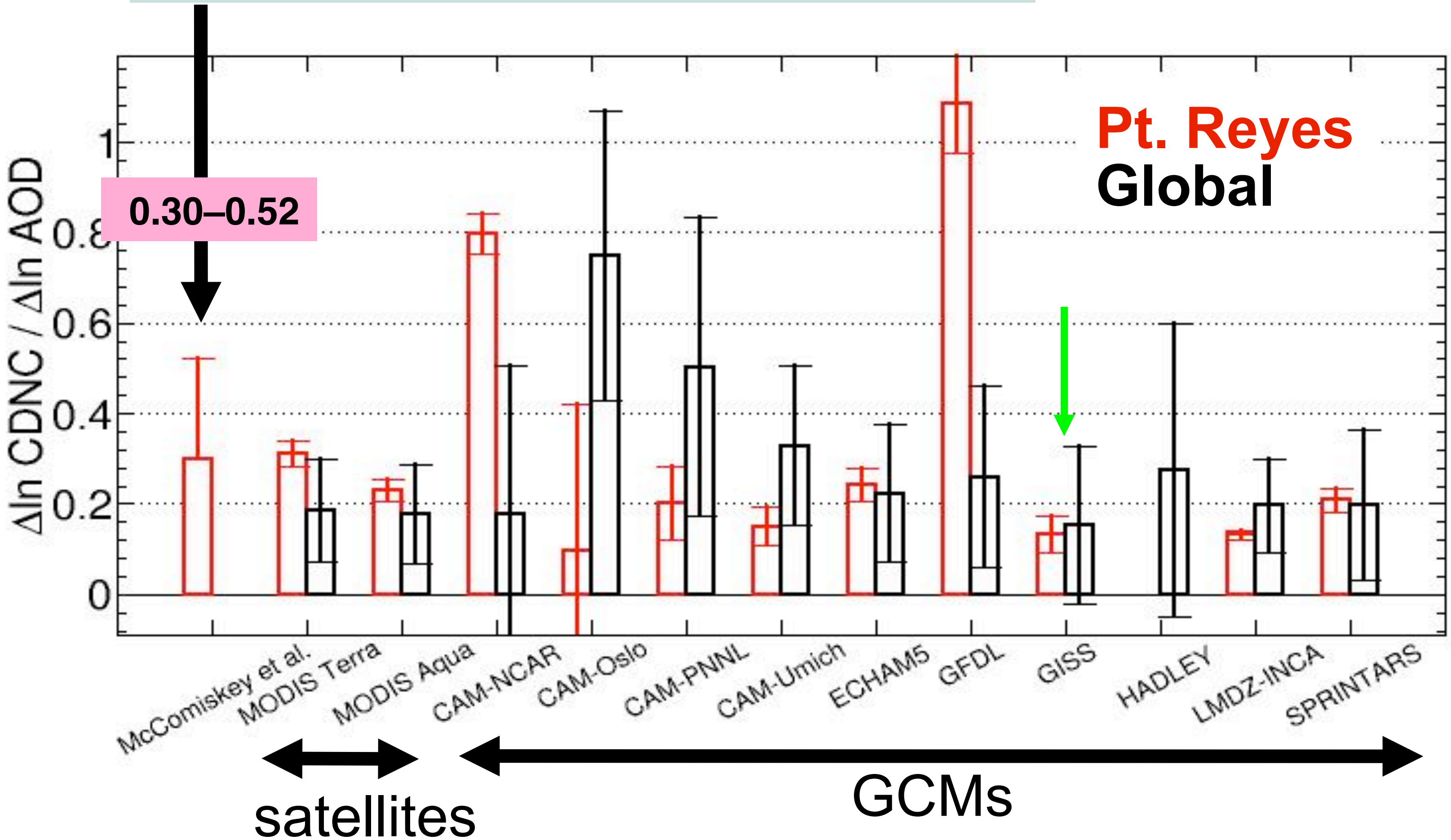
Cloud droplet number conc
entration (N_d) vs. Aerosol optical depth (AOD)



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

Use of ARM data to evaluate indirect effect

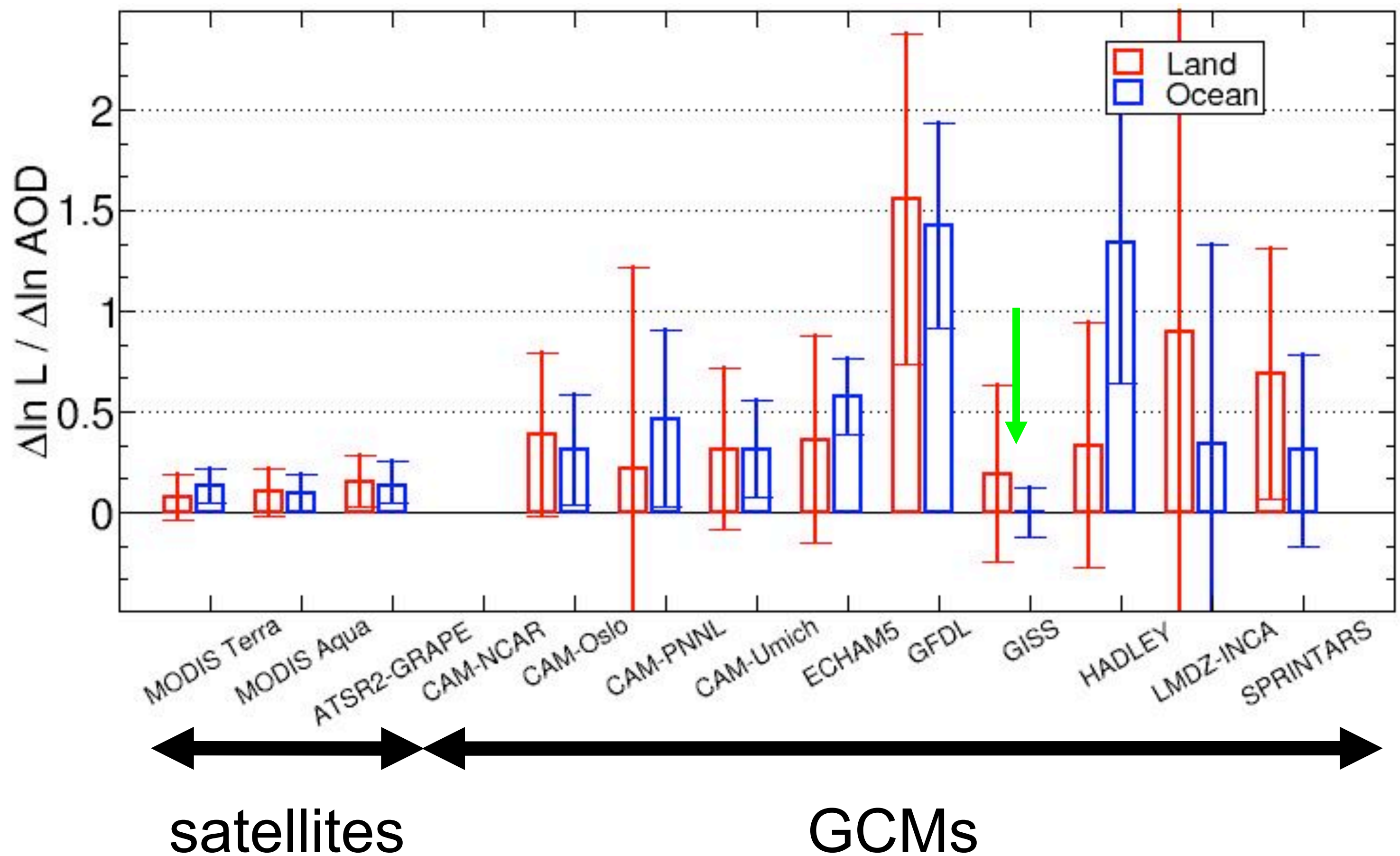
- one season (JJA) of ground-based data
- coastal site in California (stratocumulus)



McComiskey et al., J. Geophys. Res., 2009

Liquid water path vs AOD

Satellites (3) and models (9)



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

Observations to constrain models

Combination of models and observations suggest that the total aerosol forcing in the shortwave is **-1.5 ±0.5 Wm^{-2}**

The cloud-sky estimate (cloud radiative forcing) for the indirect effect is **-0.7 ± 0.4 Wm^{-2}**

ModelE estimates for total aerosol forcing is **-0.94 Wm^{-2}** and the indirect effect from the cloudy-sky estimate is **-0.76 Wm^{-2}.**

However, although LWP-AOT relationship is comparable to satellite over land, we **underestimate** over ocean, as with CDNC-AOT slopes and to some extent cloud cover-AOT slopes.

Need: (1) Ground-based estimates of LWP and Cloud cover change with AOT from ARM sites and AMF sites.