Representation of cloud-aerosol-precipitation interactions in global climate models

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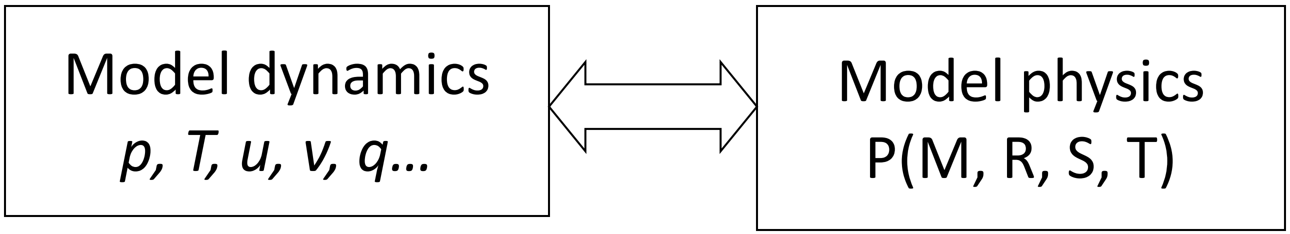
My task:

- To provide a broader context for the cloud-aerosol-precipitation interactions research that is conducted within ASR.
- To provide a perspective on the larger picture of how parameterizations have evolved over time,
- Aspects of parameterizations that are the real pressure points in predicting climate change
- How these activities relate to observational data.
- Perspectives on the way forward

How are aerosol/cloud interactions constructed in GCMs?

Components



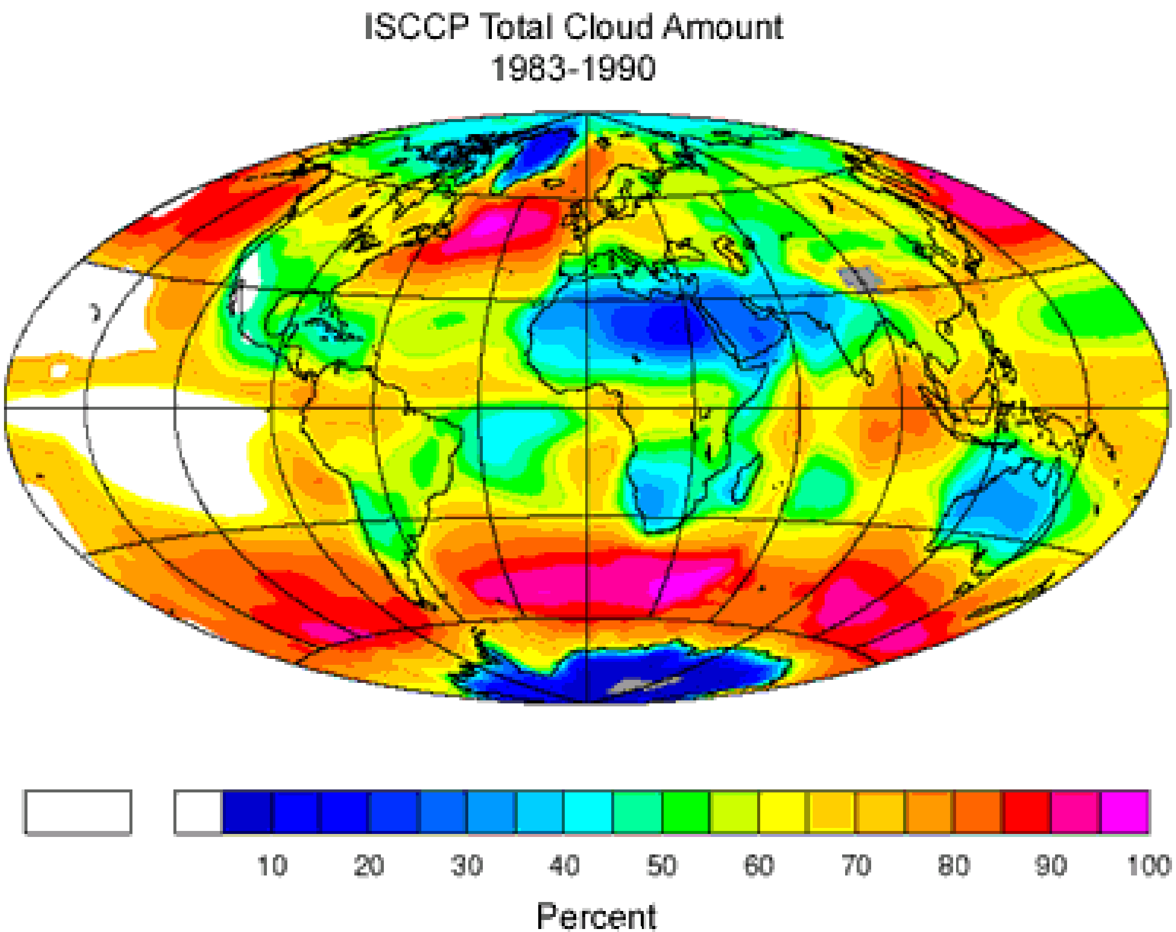
Parameterization: The method of replacing processes that are too small-scale or complex to be physically represented in the model by a simplified process.

Prognostic variables: A variable that a GCM predicts by integration of a physical equation, typically vorticity, divergence, temperature, surface pressure, and water vapor concentration.

Diagnostic variables: A variable that is derived after the prognostic variables have been calculated. Further quantities are then computed via parameterizations.

Probably the single most important aspect examined after changing parameterizations has been how clouds/aerosols affect the radiation budget

- Global cloud cover: 60%
- Cloud reflection of solar flux is about 60 W/m^2; absorption of longwave radiation about 30 W/m^2
- Aerosol reflection is about 2 W/m^2

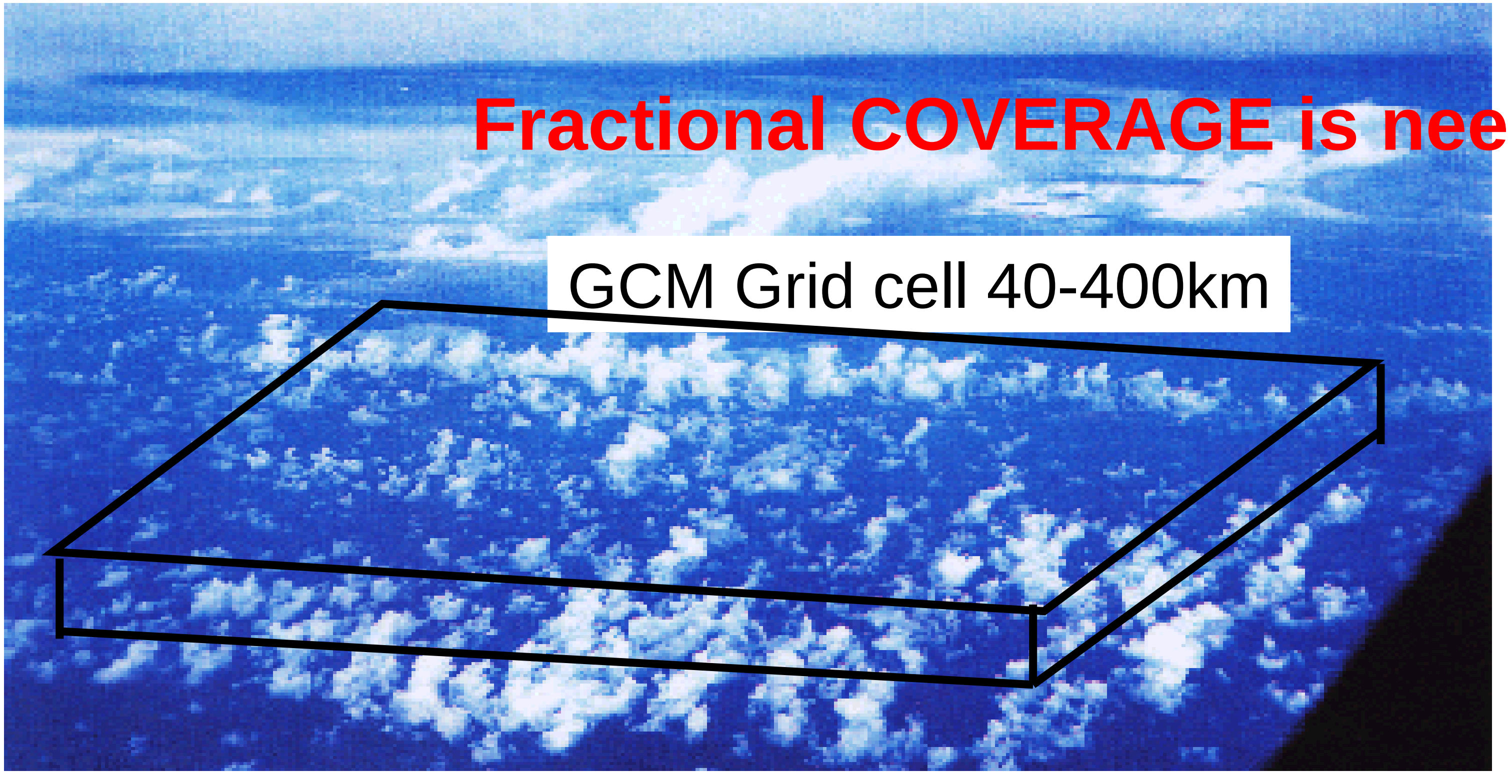


Precipitation effects of aerosols (CRM model results)

- Decreased precipitation in warm clouds
- Increased precipitation in convective clouds (Zhang et al., 2005, Lee et al., 2010)
- Decreased precipitation from shallow cumuli mixed phase clouds (Phillips et al., 2002, Khain et al., 2005)

Clouds in GCM - What are the problems ?

Many of the observed clouds and especially the processes within them are subgrid-scale processes (both horizontally and vertically)

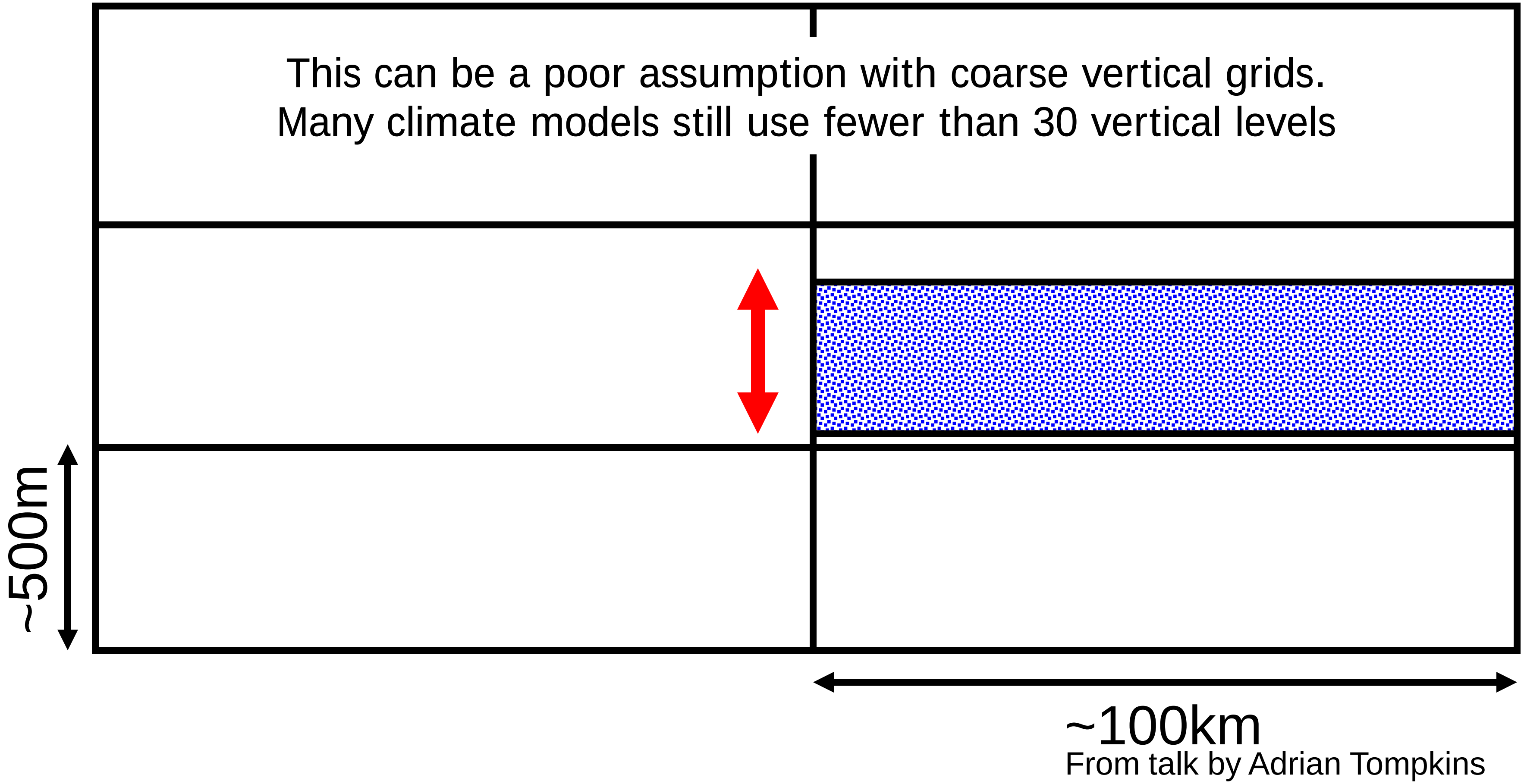


From talk by Adrian Tompkins

Issues of Parameterization

VERTICAL COVERAGE

Most models assume that this is 1



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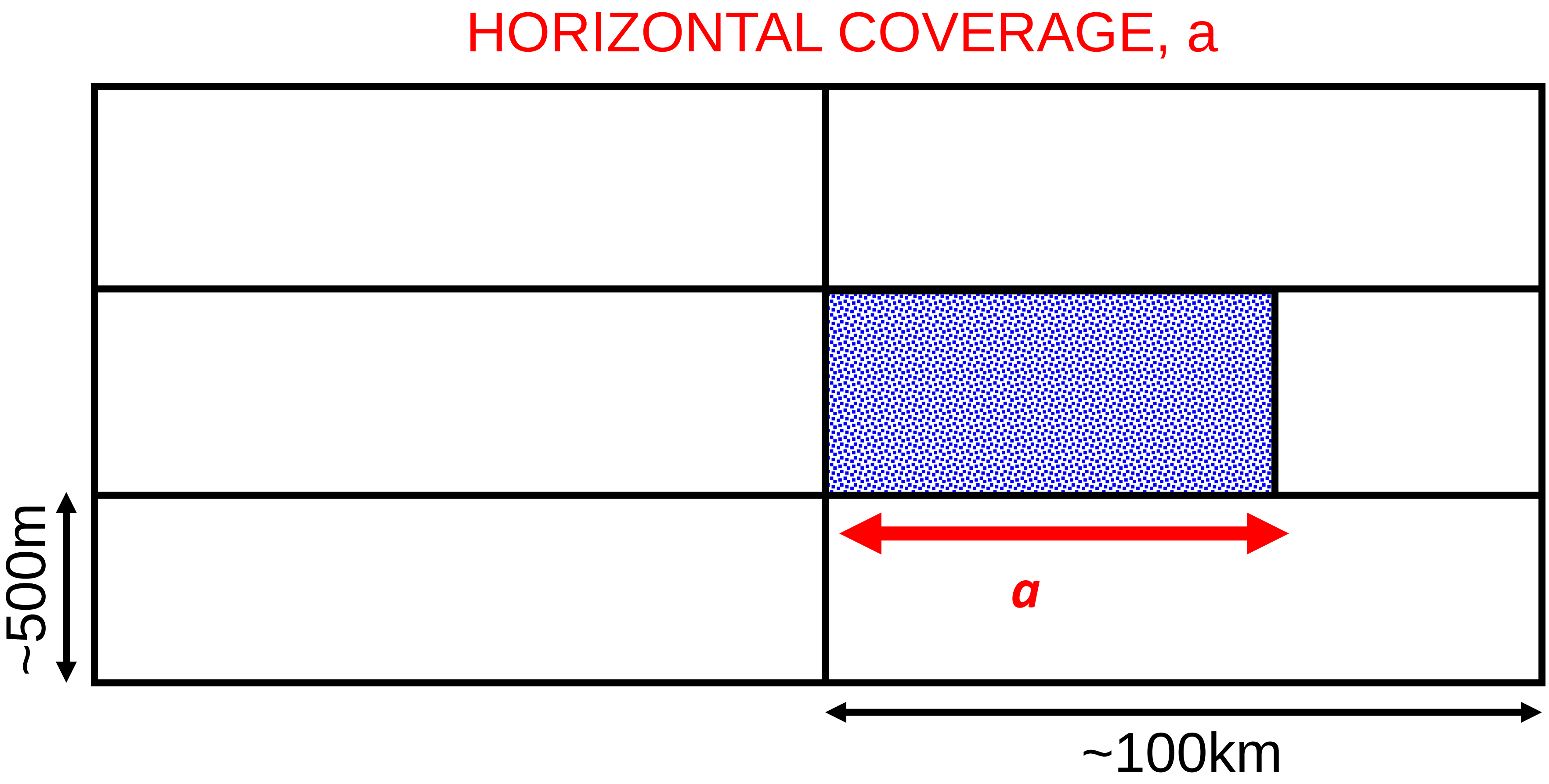
Issues of Parameterization

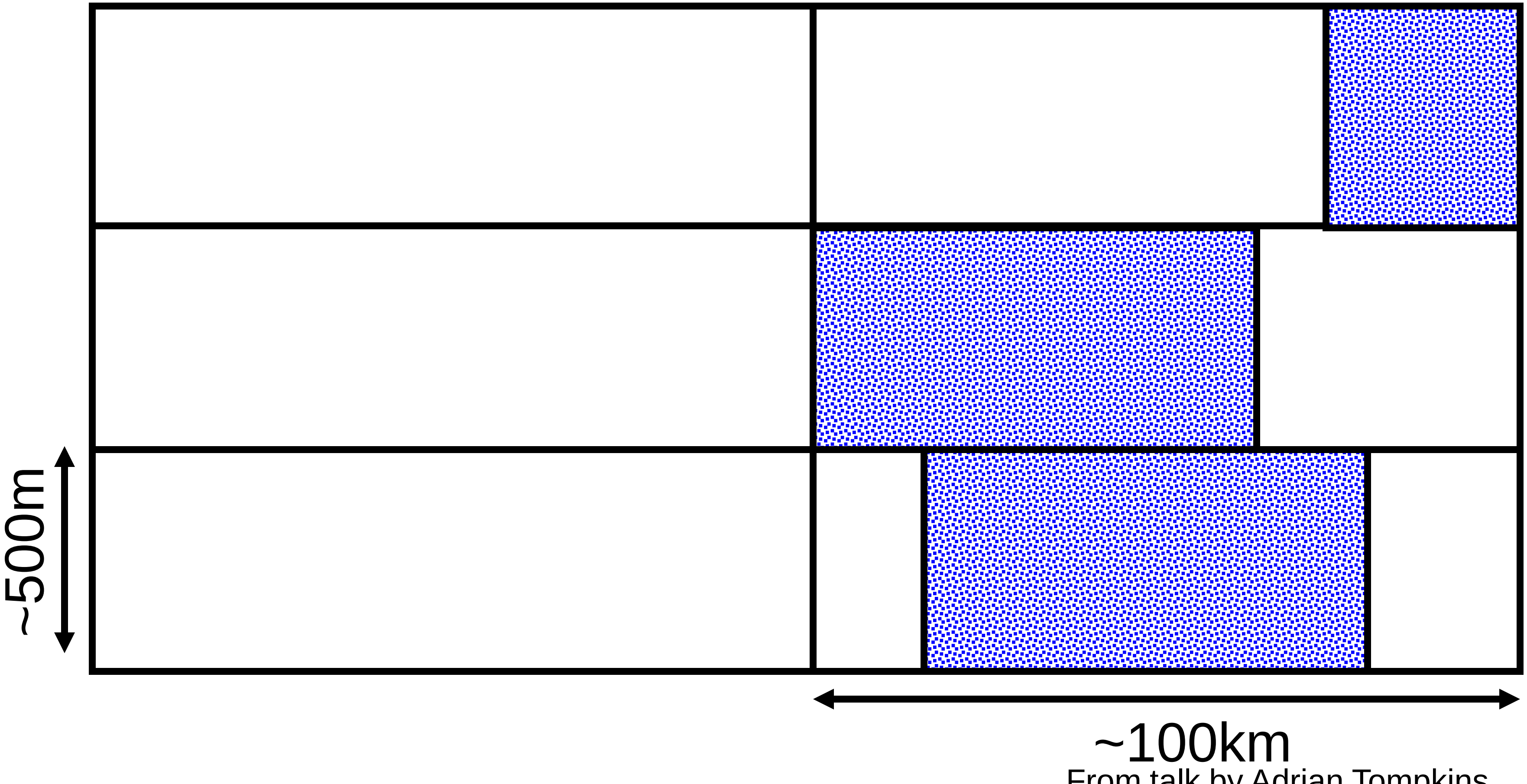


From talk by Adrian Tompkins

Issues of Parameterization

Vertical Overlap of clouds

Important for Radiation and Microphysics Interaction



From talk by Adrian Tompkins

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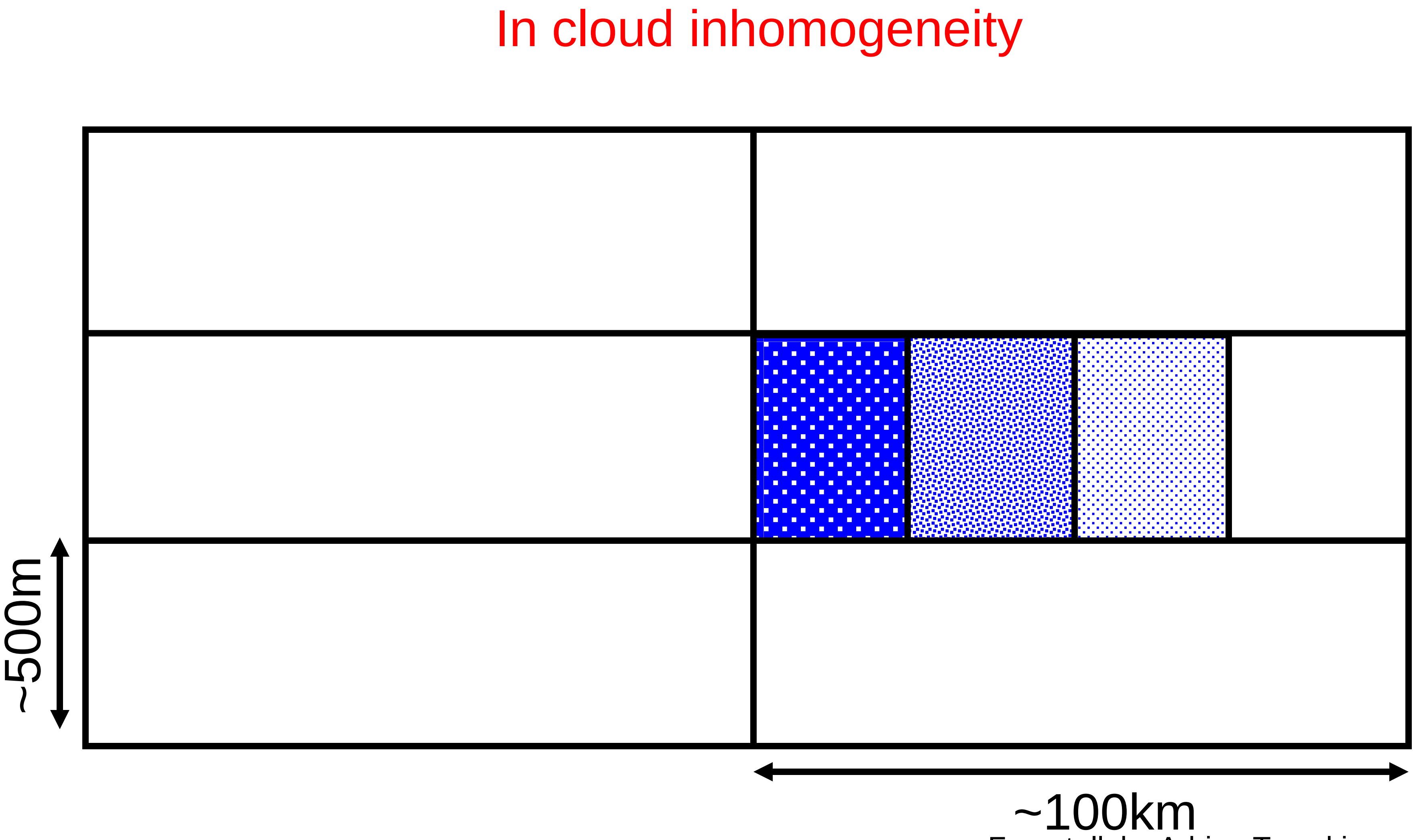

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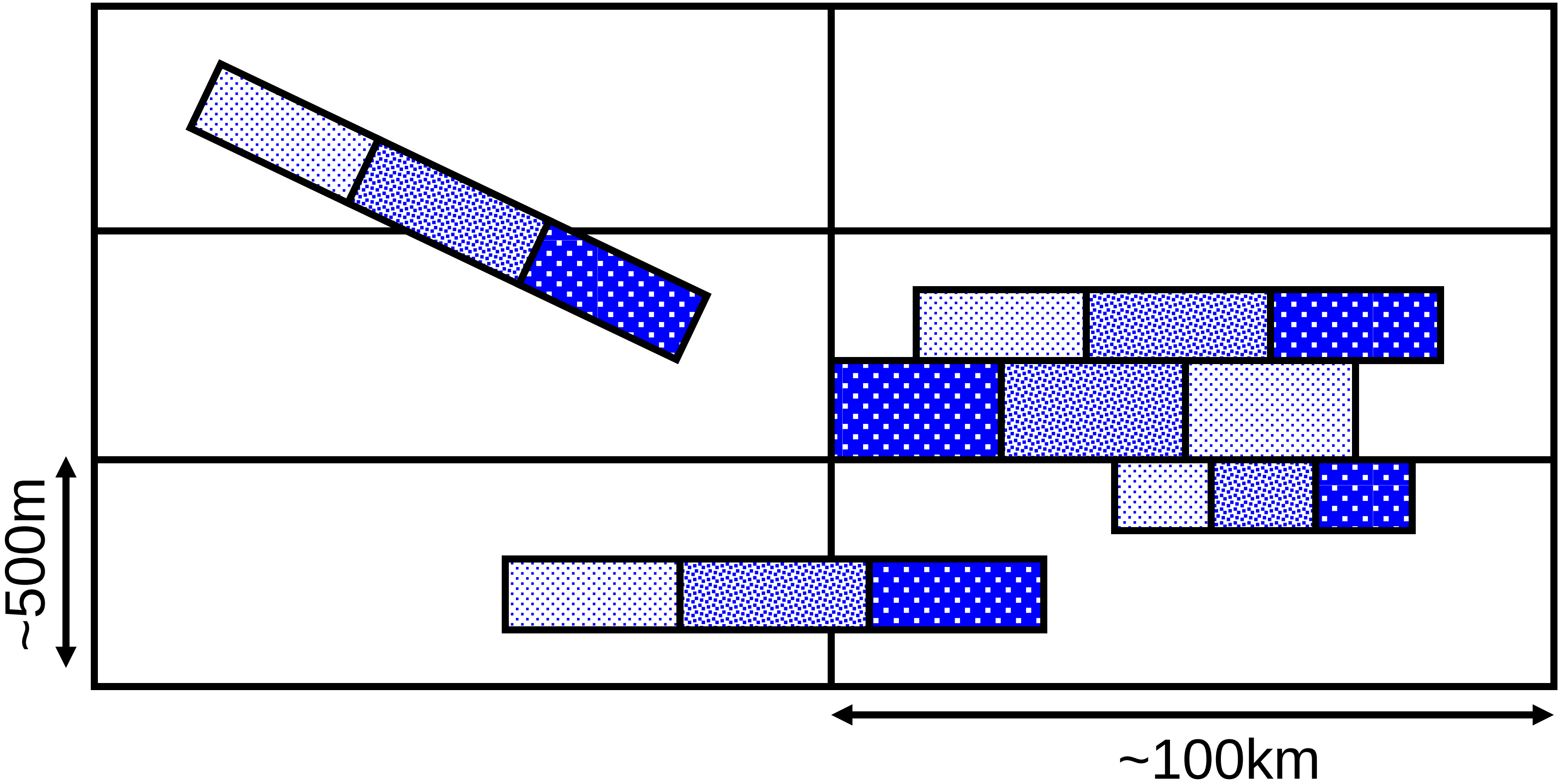
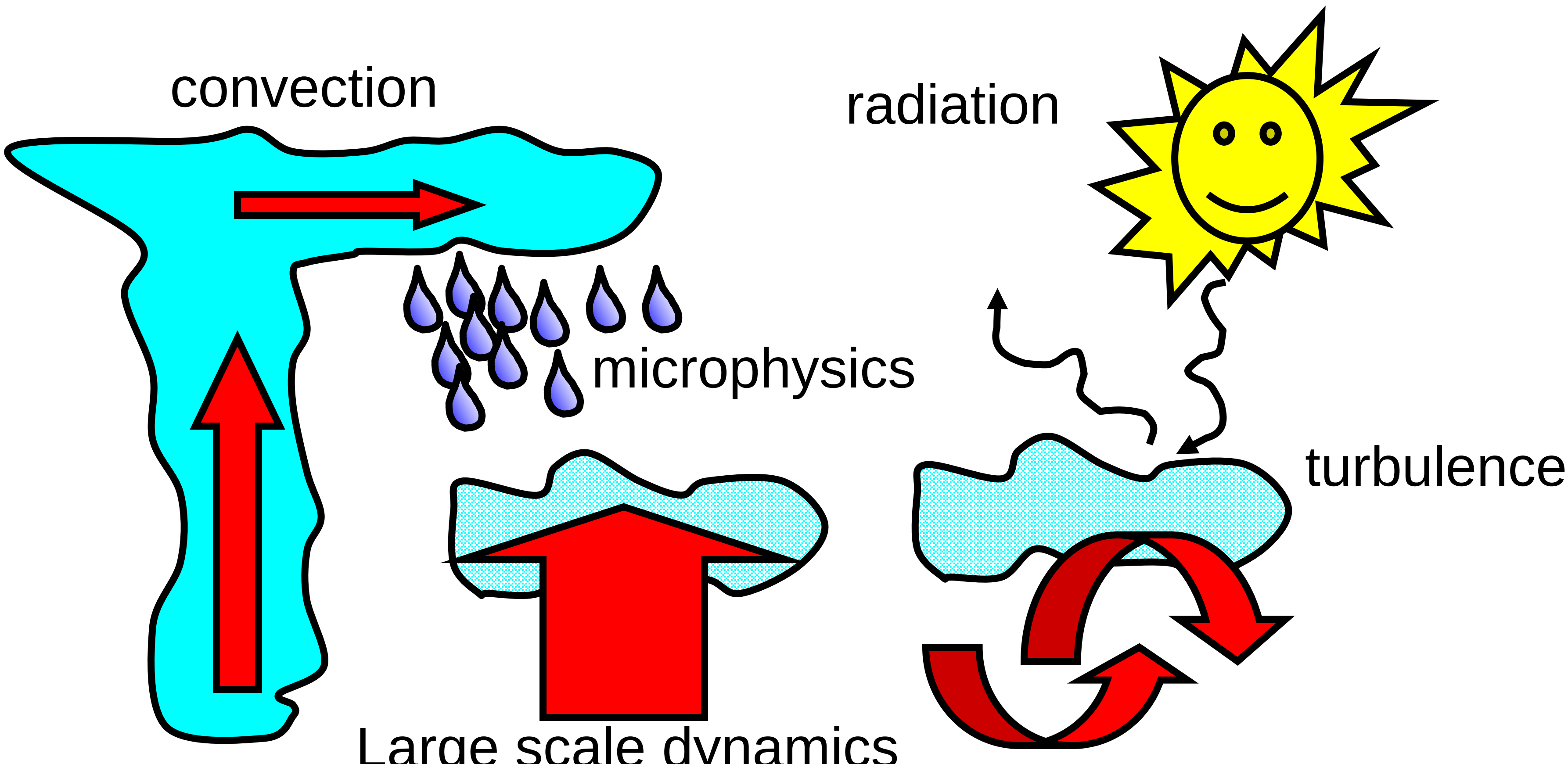
Issues of Parameterization

Just these issues can become very complex!!!



From talk by Adrian Tompkins

Clouds in GCM - What are the problems ?



Clouds are the result of complex interactions between a large number of processes

From talk by Adrian Tompkins

Clouds in GCM – what are problems?

- Cloud processes in GCM are subgrid-scale processes due to the coarse resolution of GCM. This problem will remain until resolutions of order 100 m are reached.

- In each grid, in addition to the condensate water mass, cloud fraction is needed to describe the cloud processes, and this raises additional issues in GCMs (overlap, heterogeneity, radiation interactions, turbulence interactions,…).

- Many other subgrid-scale processes, are also parameterized in GCMs and have strong interactions with cloud processes, which make the cloud parameterization more complicated.

How are clouds in GCMs treated?

Main variables:

Cloud fraction, a - refers to horizontal cover since cloud fills vertical
Cloud condensate mass (cloud water and/or ice), q_l, q_i.

Diagnostic approach

$$a = f_1\left(\Phi_1 \ldots \Phi_n, \frac{\partial \Phi_1}{\partial t} \ldots \frac{\partial \Phi_n}{\partial t}, \ldots\right) \qquad q_l = f_2\left(\Phi_1 \ldots \Phi_n, \frac{\partial \Phi_1}{\partial t} \ldots \frac{\partial \Phi_n}{\partial t}, \ldots\right)$$

Prognostic approach

$$\frac{\partial a}{\partial t} = A(a) + S(a) - D(a) \qquad \frac{\partial q_l}{\partial t} = A(q_l) + S(q_l) - D(q_l)$$

NOT DISTINCT - CAN HAVE MIXTURE OF APPROACHES

How are aerosols in GCMs treated?

Main variables:

Aerosol types: sulfate, organic, black carbon, nitrate, ammonium, sea salt, dust

Diagnostic approach:

Assumed aerosol size distribution, with some size representation for dust, sea salt (external mix); Assumed gas phase concentrations

Prognostic approach

Predict modes for sulfate, organic aerosol; Predict condensation on other aerosol types coagulation of aerosol types; Fully coupled with prediction of gas phase chemistry

Cloud/Aerosol Schemes - A Brief History

	60s →
Condensation (non-convective)	$q_v > q_s$
Radiation effects	Prescribed zonal mean albedo and emissivity
Microphysics	none
Aerosols	Simple fixed

Cloud/Aerosol Schemes - A Brief History

	60s	70s
Condensation (non-convective)	$q_v > q_s$	$q_v > q_s$
Radiation effects	Prescribed zonal mean albedo and emissivity	a diagnostic [usually f(RH)] q_l prescribed
Microphysics	none	none
Aerosols	Simple fixed	Simple fixed

Cloud/Aerosol Schemes - A Brief History

	60s	70s	80s
Condensation (non-convective)	$q_v > q_s$	$q_v > q_s$	q_l prognostic a diagnostic
Radiation effects	Prescribed zonal mean albedo and emissivity	a diagnostic [usually f(RH)] q_l prescribed	a = as cloud scheme
Microphysics	none	none	Simple bulk microphysics
Aerosols	Simple fixed	Simple fixed	Bulk for some types

Cloud/Aerosol Schemes - A Brief History

	60s	70s	80s	90s-
Condensation (non-convective)	$q_v > q_s$	$q_v > q_s$	q_l prognostic a diagnostic	q_l prognostic a prognostic (directly or indirectly)
Radiation effects	Prescribed zonal mean albedo and emissivity	a diagnostic [usually f(RH)] q_l prescribed	a = as cloud scheme	a = as cloud scheme
Microphysics	none	none	Simple bulk microphysics	Complex bulk microphysics (ice)
Aerosols	Simple fixed	Simple fixed	Bulk for some types	Bulk for all types

Cloud/Aerosol Schemes - A Brief History

	60s	70s	80s	90s-	00s-
Condensation (non-convective)	$q_v > q_s$	$q_v > q_s$	q_l prognostic a diagnostic	q_l prognostic a prognostic (directly or indirectly)	q_l prognostic a prognostic (directly)
Radiation effects	Prescribed zonal mean albedo and emissivity	a diagnostic [usually f(RH)] q_l prescribed	a = as cloud scheme	a = as cloud scheme	a, q_l = as cloud scheme
Microphysics	none	none	Simple bulk microphysics	Complex bulk microphysics (ice)	Double moment
Aerosols	Simple fixed	Simple fixed	Bulk for some types	Bulk for all types: simple chemistry	Modal with complete chemistry

Parameterization pressure points for predicting climate change

Some ‘parameterization pressure points’ for predicting climate change: Focus: Cloud/aerosol parameterization

- Treatment of turbulence/entrainment
- Treatment of supersaturation
- Treatment of cloud microphysics
- Treatment of aerosol/ice interactions

Cloud fraction:
CAM2

High thick clouds
High thin cirrus
Low thick clouds:
Too large

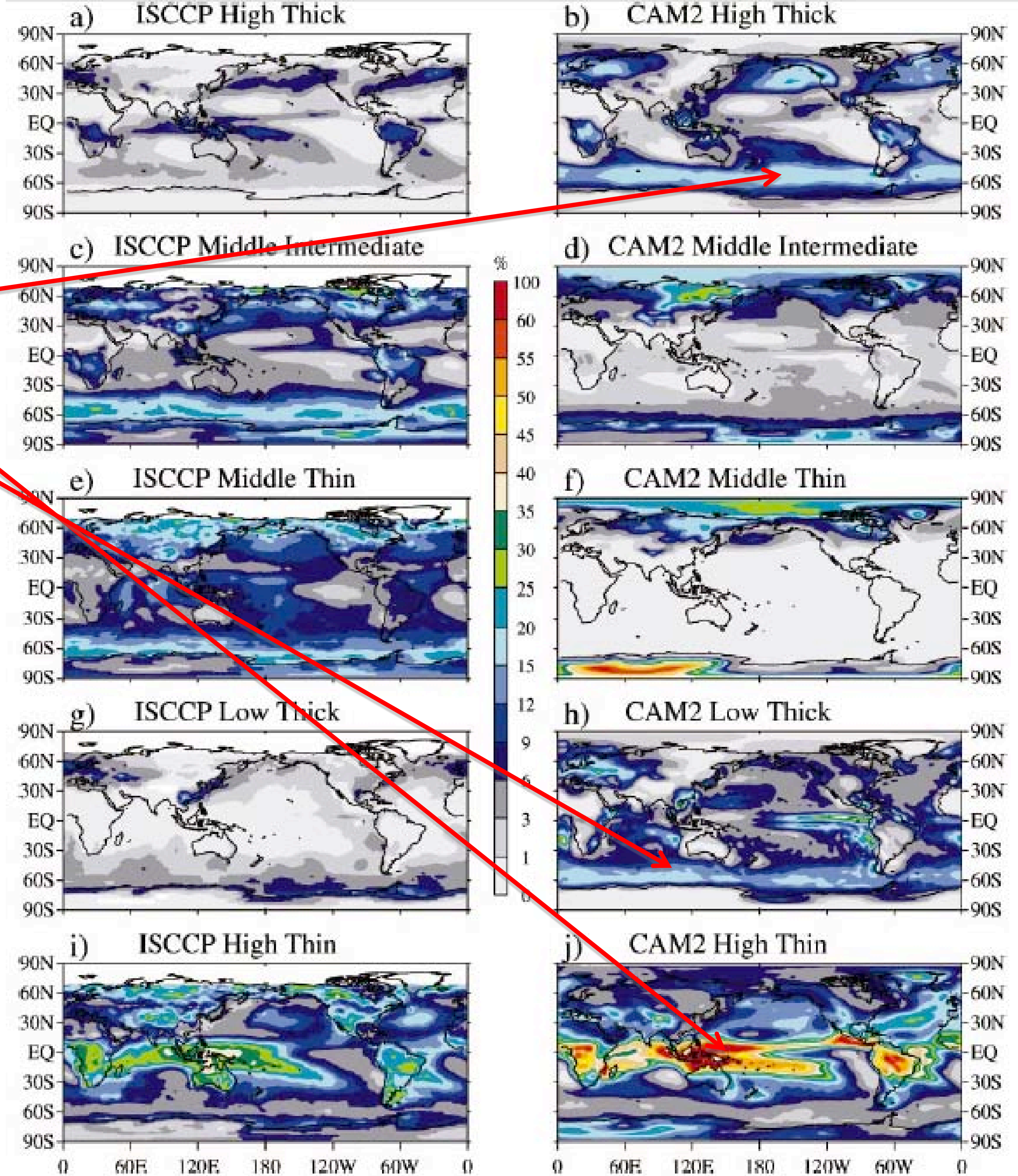
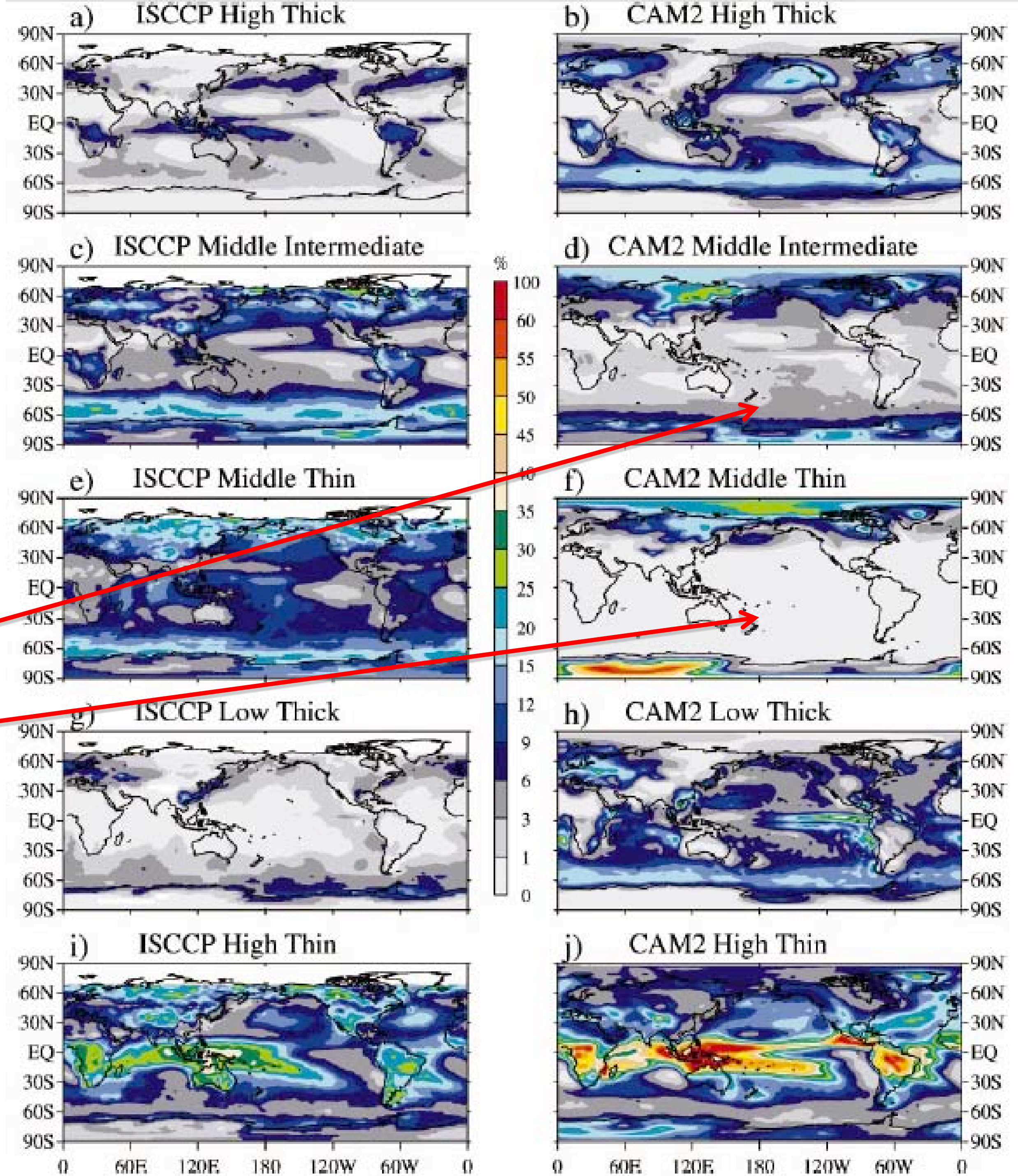


Fig 11 in Lin and Zhang 2004

Cloud fraction:
CAM2

High thick clouds
High thin cirrus
Low thick clouds:
Too large

Middle clouds with
intermediate
and thin optical
depth: Too small



Lin and Zhang, 2004

ISCCP | CAM3-Impact Diagnostic Aerosol No. | CAM3-Impact Modal

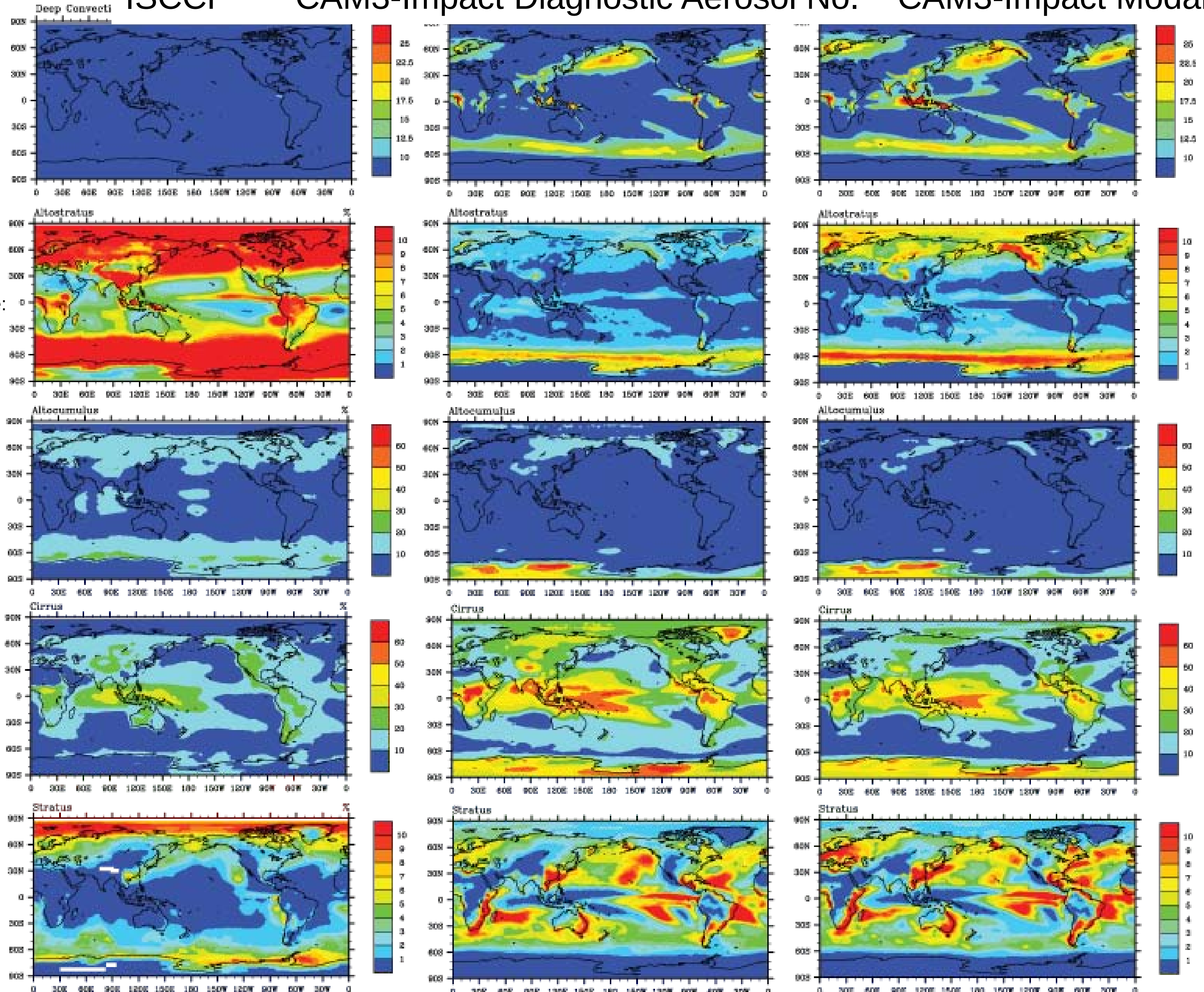
High thick: No better!

Middle Intermediate: Somewhat better

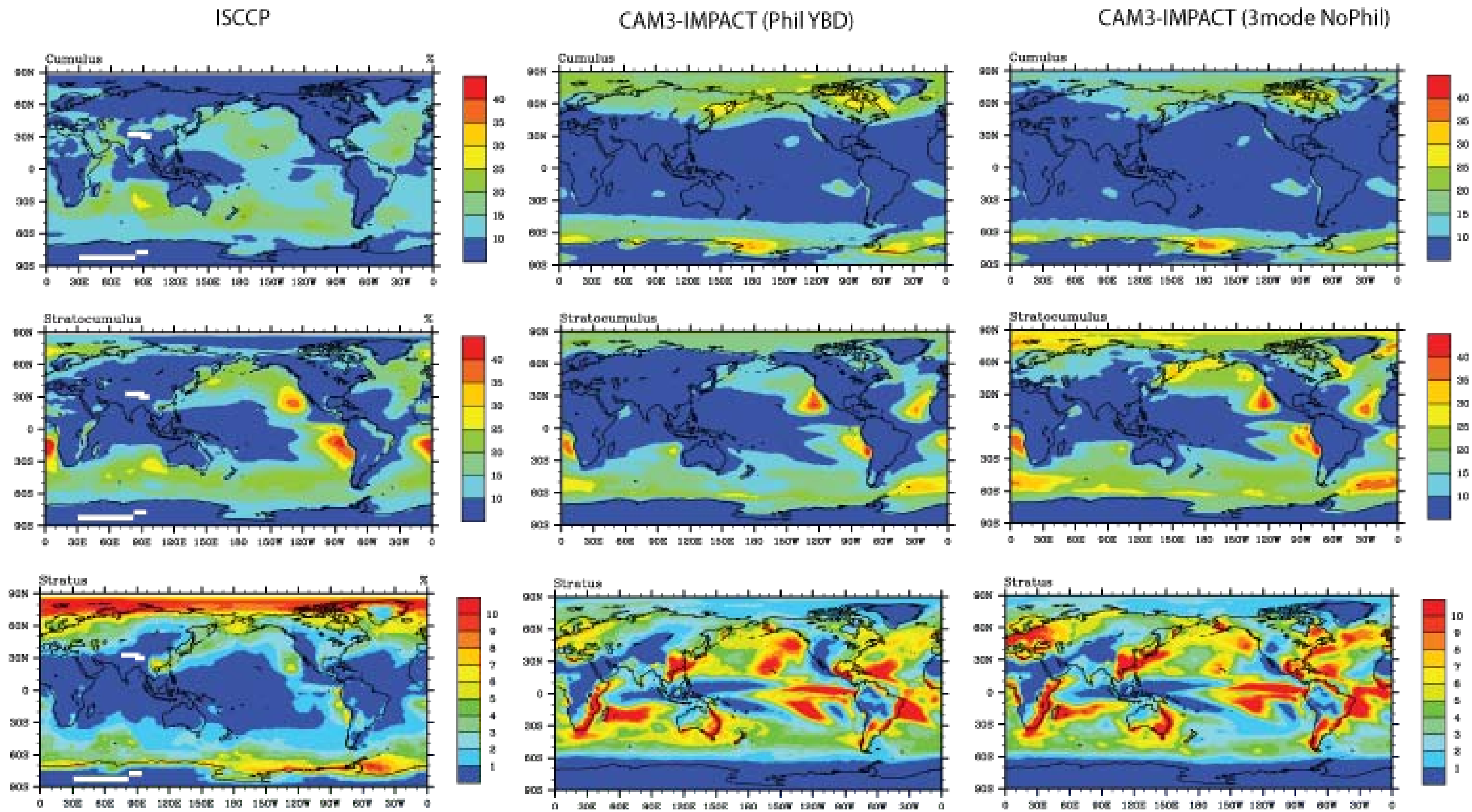
Middle thin: No better

High thin: Somewhat better

Low thick: No better



Low clouds: most aerosol/cloud development studies have focused on these cloud types

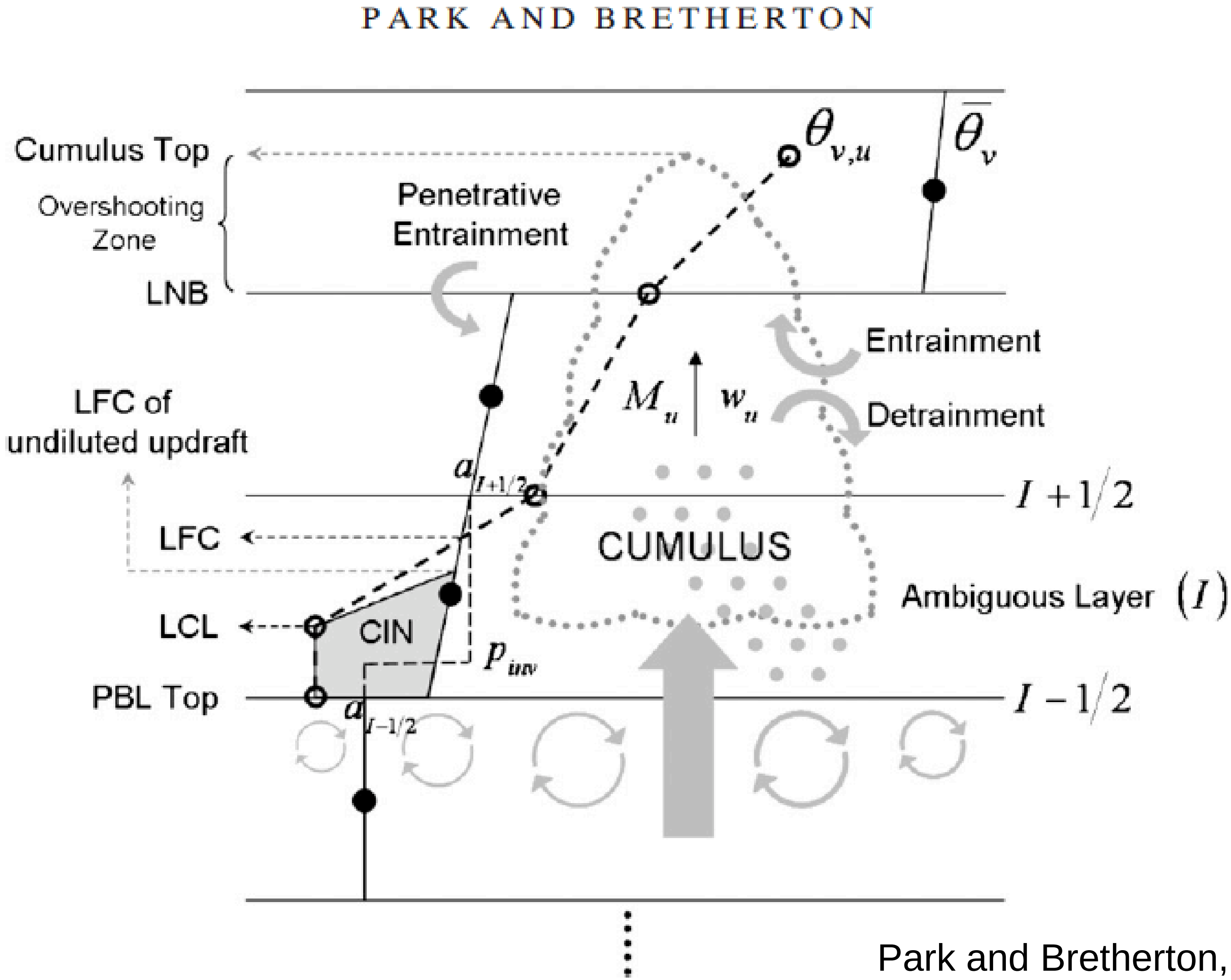


Low thin

Low intermediate: Somewhat better with modal

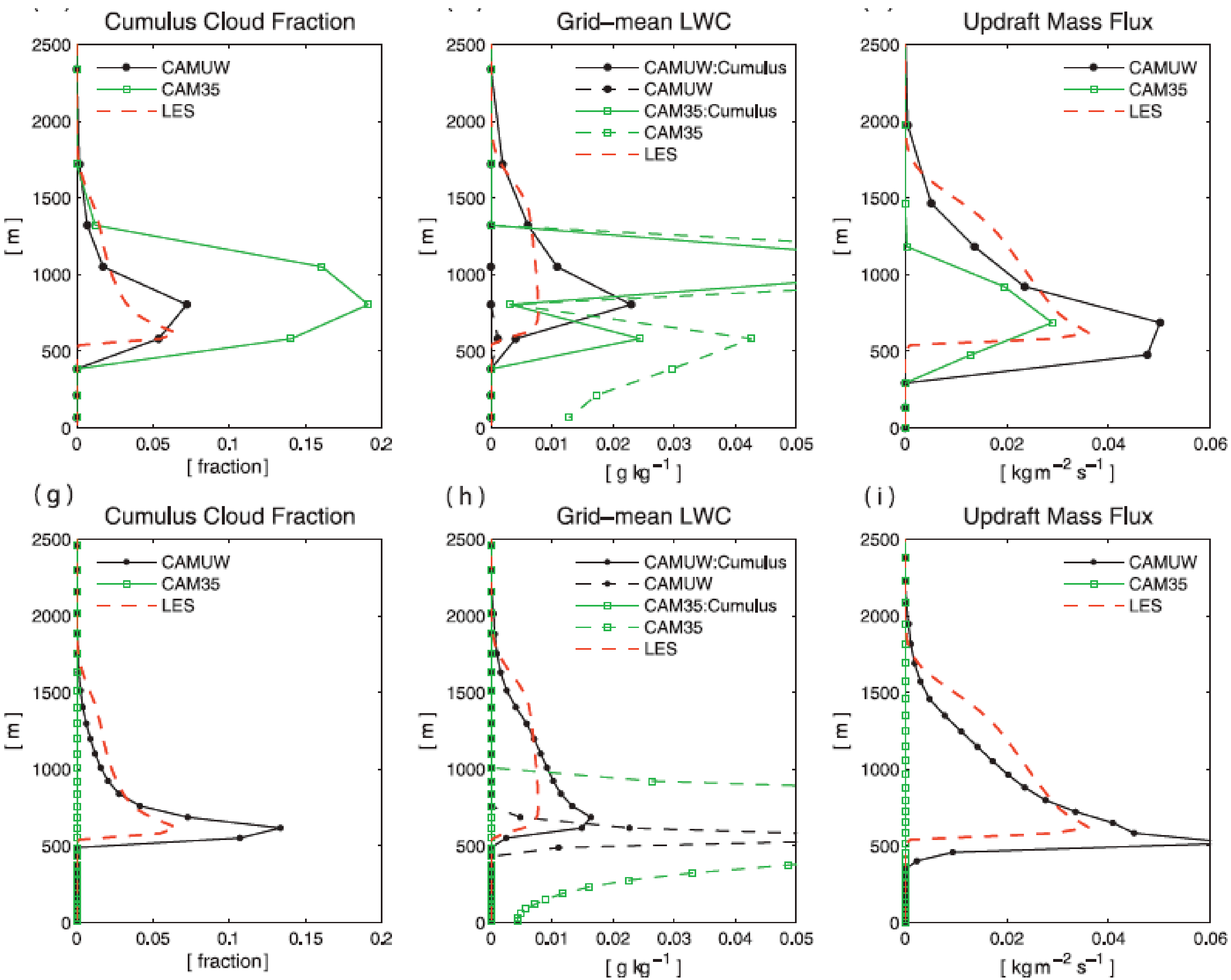
Low thick

Treatment of turbulence/entrainment: Shallow clouds



Park and Bretherton, 2009

Comparison of new/old parameterizations in process study: BOMEX

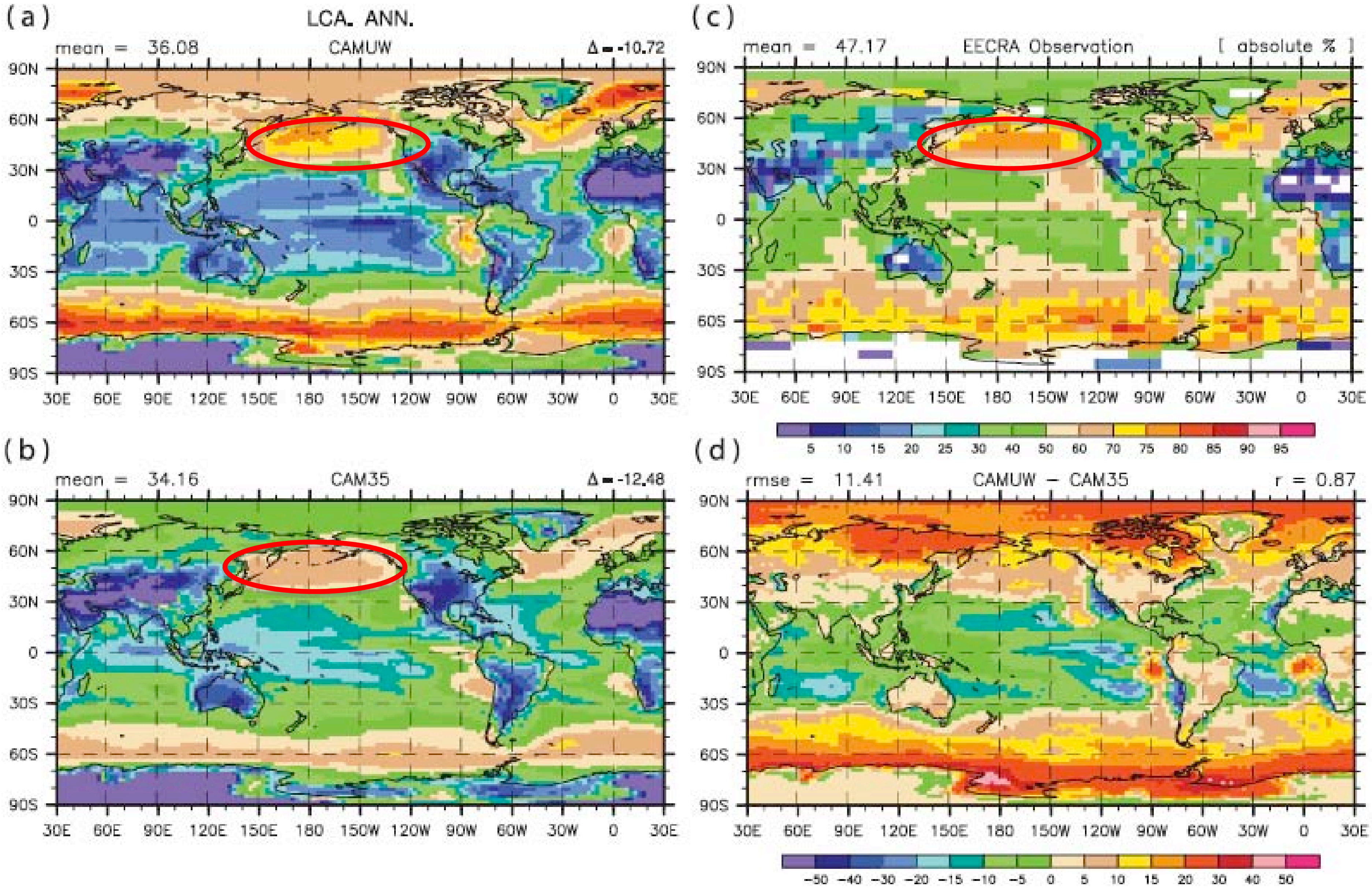


30 levels

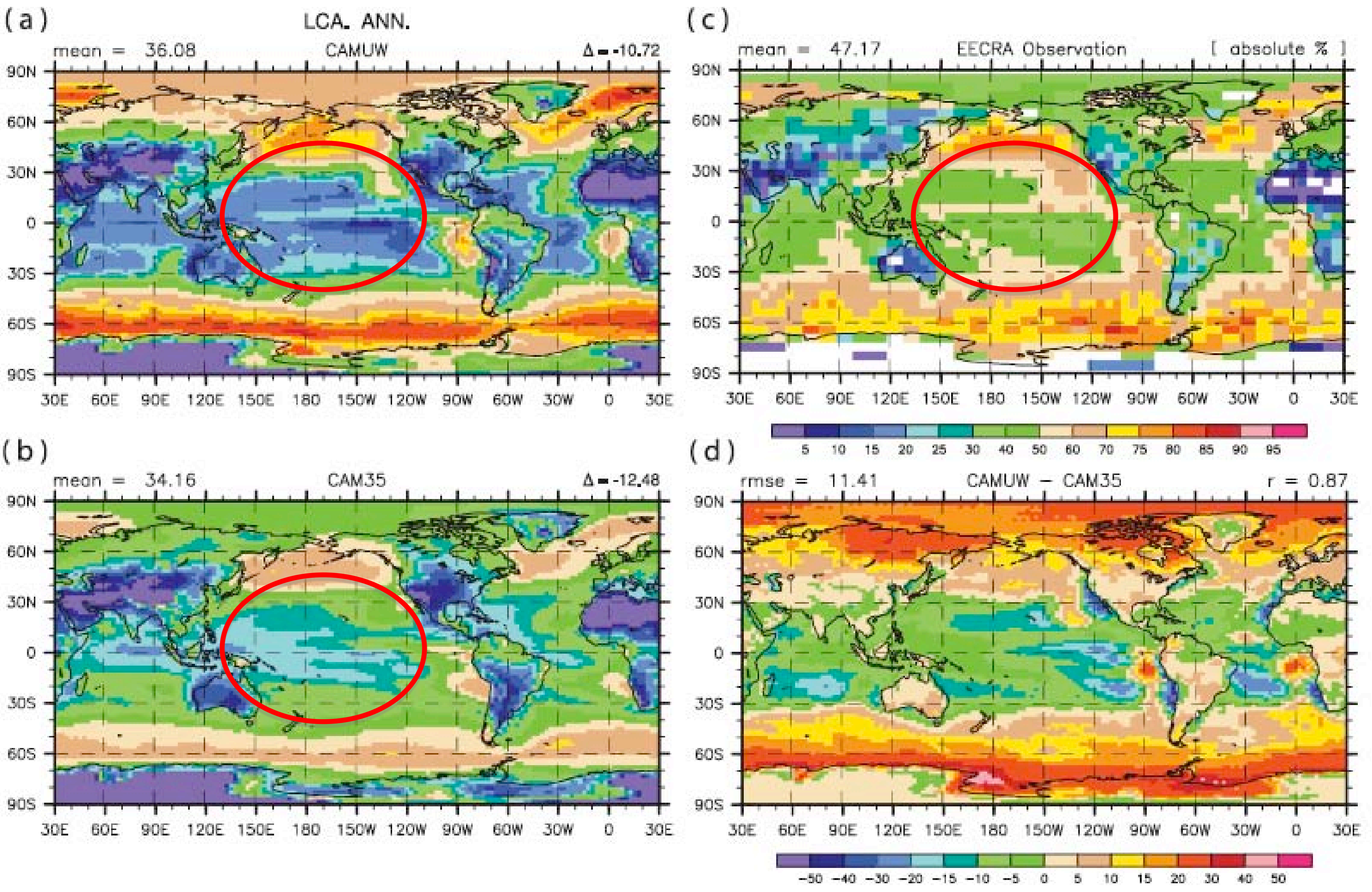
80 levels

Park and Bretherton, 2009

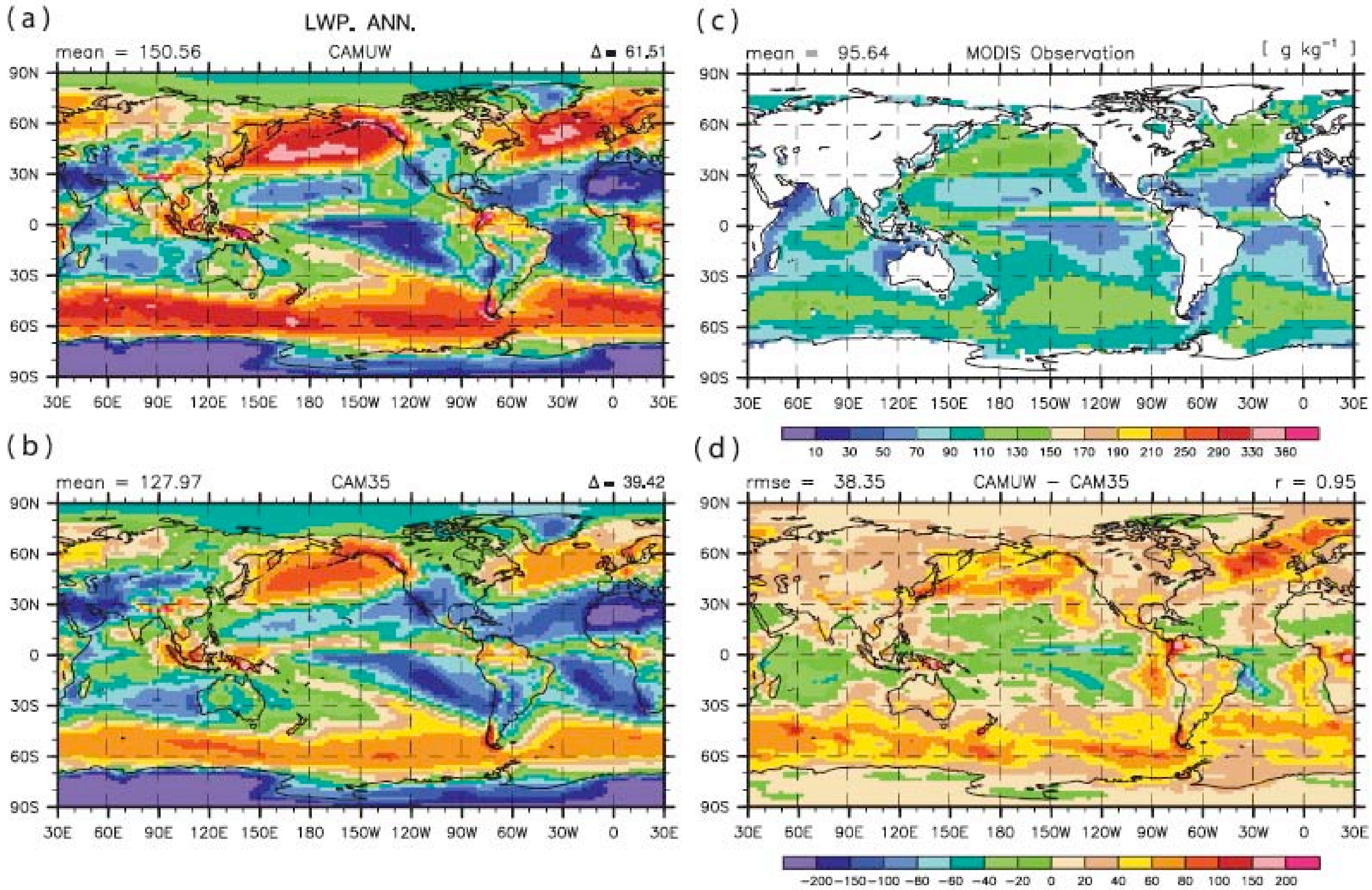
SW cloud forcing is improved, low cloud amout is better in NH storm tracks but worse in tropics, subtropics



SW cloud forcing is improved, and low cloud amout isbetter in NH storm tracks but worse in tropics, subtropics



LWP is also worse in mid latitude storm tracks (but improved with cloud microphysics included, see next study)



Effect of treating aerosol/cloud interactions in mixed phase clouds

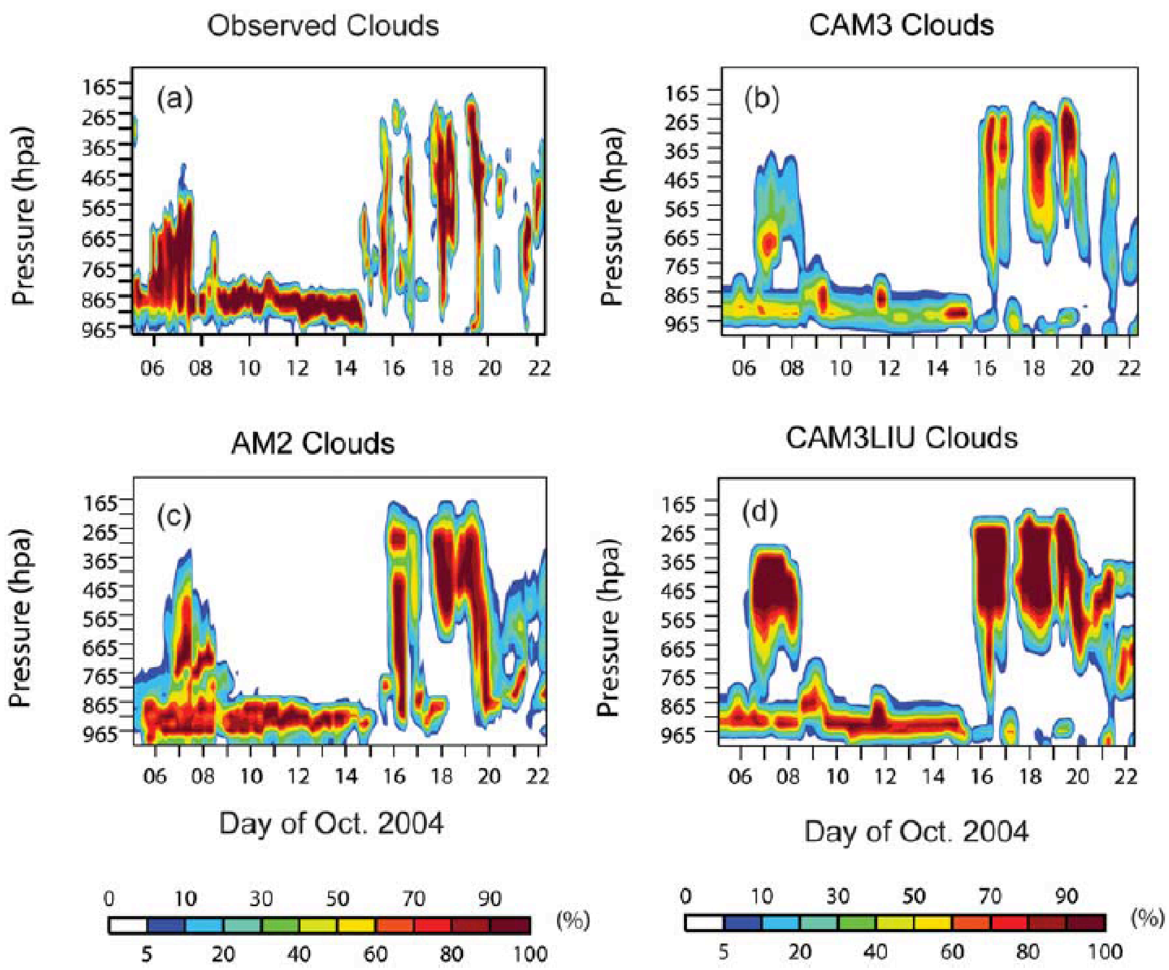
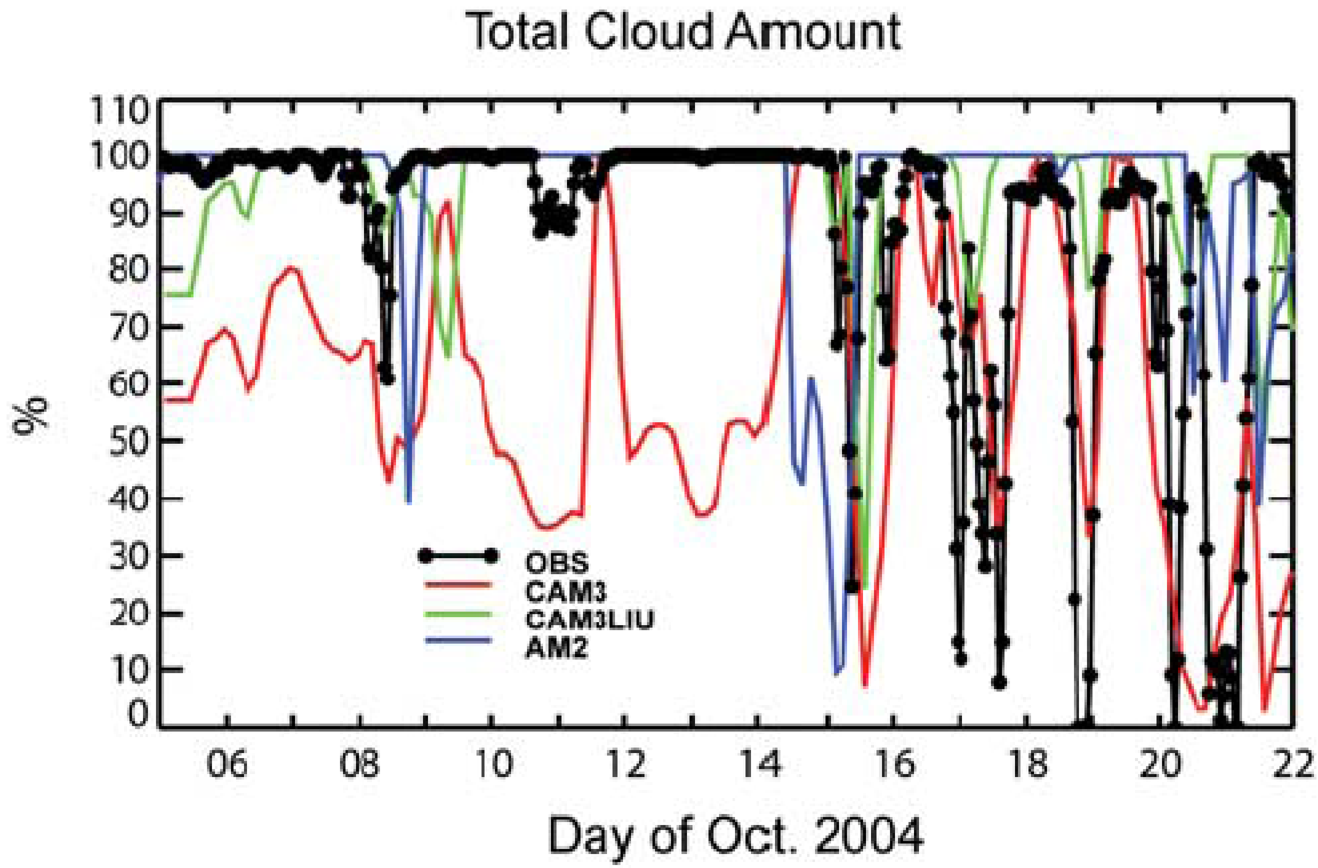


Figure 1. Time-height cross sections of (a) ARSCL cloud frequency and modeled cloud fraction (b) CAM3, (c) AM2, and (d) CAM3LIU at Barrow during M-PACE. The unit is %.

Xie et al., 2008

MPACE: Cloud amount is significantly improved when mixed phase microphysics is included



Xie et al., 2008

Side benefit of adding mixed phase treatment of aerosol/cloud interactions: Improvement of LWP

Table 2. Annual global mean cloud properties and their interannual variations (standard deviations).

	HOM	HMHT_0.01IN	HMHT_0.1IN	HMHT_1IN	HMHT_1.25T	HMHT_0.75T	LIU07	CAM3	Obs
LWP[a]	78.21±0.36	76.74±0.36	75.38±0.12	80.97±0.34	77.32±0.55	75.67±0.50	141	121	50–87
IWP[b]	20.94±0.05	21.02±0.04	21.07±0.09	21.46±0.04	21.06±0.06	20.91±0.11	21.8	15.6	26.7
N_d^c	2.31±0.020	2.26±0.015	2.22±0.013	2.41±0.014	2.28±0.015	2.22±0.012	#	#	4
N_i^c	0.088±0.006	0.062±0.004	0.023±0.002	0.050±0.003	0.094±0.009	0.041±0.004	0.027	#	#
r_{effl}^c	11.09±0.01	11.09±0.02	11.09±0.02	11.07±0.01	11.08±0.00	11.11±0.00	#	#	11.4–15.7
r_{effi}^d	47.54±0.45	55.10±0.26	48.21±0.25	41.51±0.30	52.88±0.73	57.05±0.37	#	#	25.21
N_{itop}^d	0.87±0.04	0.61±0.02	0.13±0.01	0.42±0.03	0.87±0.04	0.37±0.02	#	#	#
TCC[e]	66.07±0.15	66.83±0.09	67.92±0.13	68.18±0.11	66.59±0.11	67.31±0.17	77.90	58.6	65–67
TCCHGH[e]	35.41±0.14	38.30±0.12	39.94±0.11	39.67±0.13	37.61±0.17	39.39±0.17	56.80	32.2	21
TCCLOW[e]	44.59±0.13	44.22±0.09	43.83±0.14	45.22±0.12	44.40±0.16	44.05±0.13	#	#	#

Wang and Penner, 2010

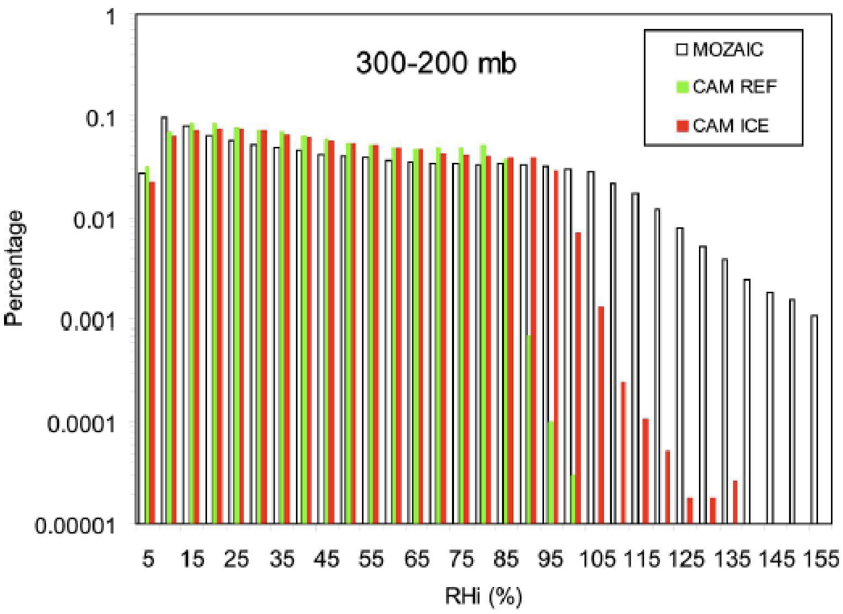
More recent observation-based aerosol/mixed phase cloud interactions nearly destroys agreement with LWP:

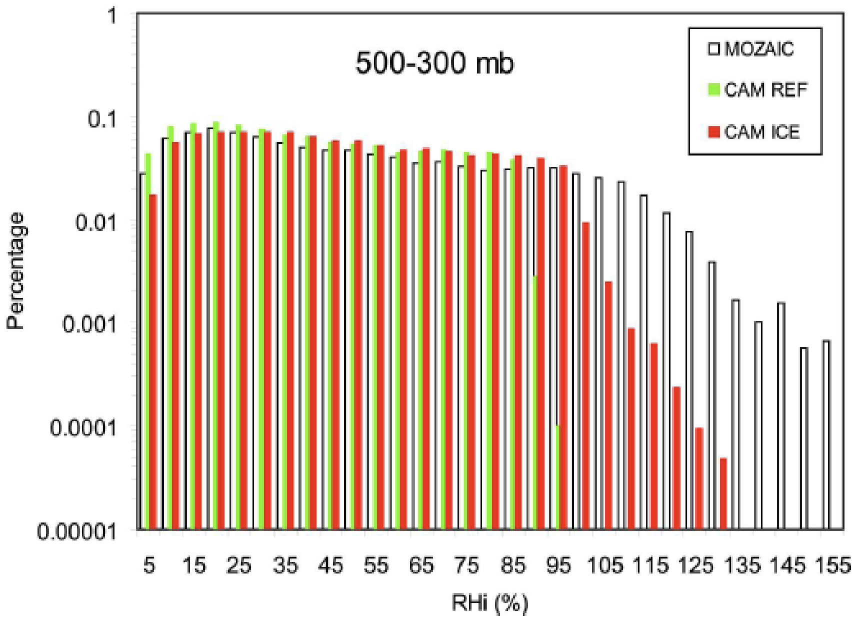
Table 2: Present-Day 5-year global mean cloud and aerosol properties and TOA energy budget.

	Mey_YD	Phi_YD	Mey_YDB	Phi_YDB	Mey_PDB	Phi_PDB	Obs
SWCF (W/m^2)	-50.76	-53.32	-44.96	-44.99	-52.15	-54.24	-47 to -54
LWCF (W/m^2)	26.42	28.32	24.99	25.09	26.95	28.71	29 to 30
NCF (W/m^2)	-24.34	-25.00	-19.97	-19.90	-25.20	-25.53	
LWP (g/m^2)	73.80	84.65	56.78	56.96	78.47	88.79	50-87
IWP (g/m^2)	21.10	18.52	26.37	26.11	19.96	17.55	26.7
Nd (10^{10}/m^2)	2.61	2.72	1.78	1.79	2.89	2.82	4
Ni (10^{10}/m^2)	0.0354	0.0371	0.0360	0.0369	0.0357	0.0367	
NI_DCI (10^{10}/m^2)	0.00312	0.00320	0.00304	0.00314	0.00314	0.00321	
NI_CON (10^{10}/m^2)	7.67	7.01	113.11	111.23	0.0053	0.0050	
Cloud Cover (%)	67.6	67.9	67.1	67.2	67.7	68.0	65-67
Ptot (mm/d)	2.915	2.903	2.902	2.906	2.917	2.903	2.61

Addition of more complete and observation-based mixed phase cloud increases liquid water content to the upper range of observed values

Comparison of Liu et al. 2009 Rhi with MOZAIC data:





New cirrus cloud scheme based on Kärcher and Burkhardt (2008)

At each time step, divide the q_v into clear and cloudy sky portions: q_{ve} and q_{vc}

Only grid mean $q_v = aq_{vc} + (1-a)q_{ve}$ is advected

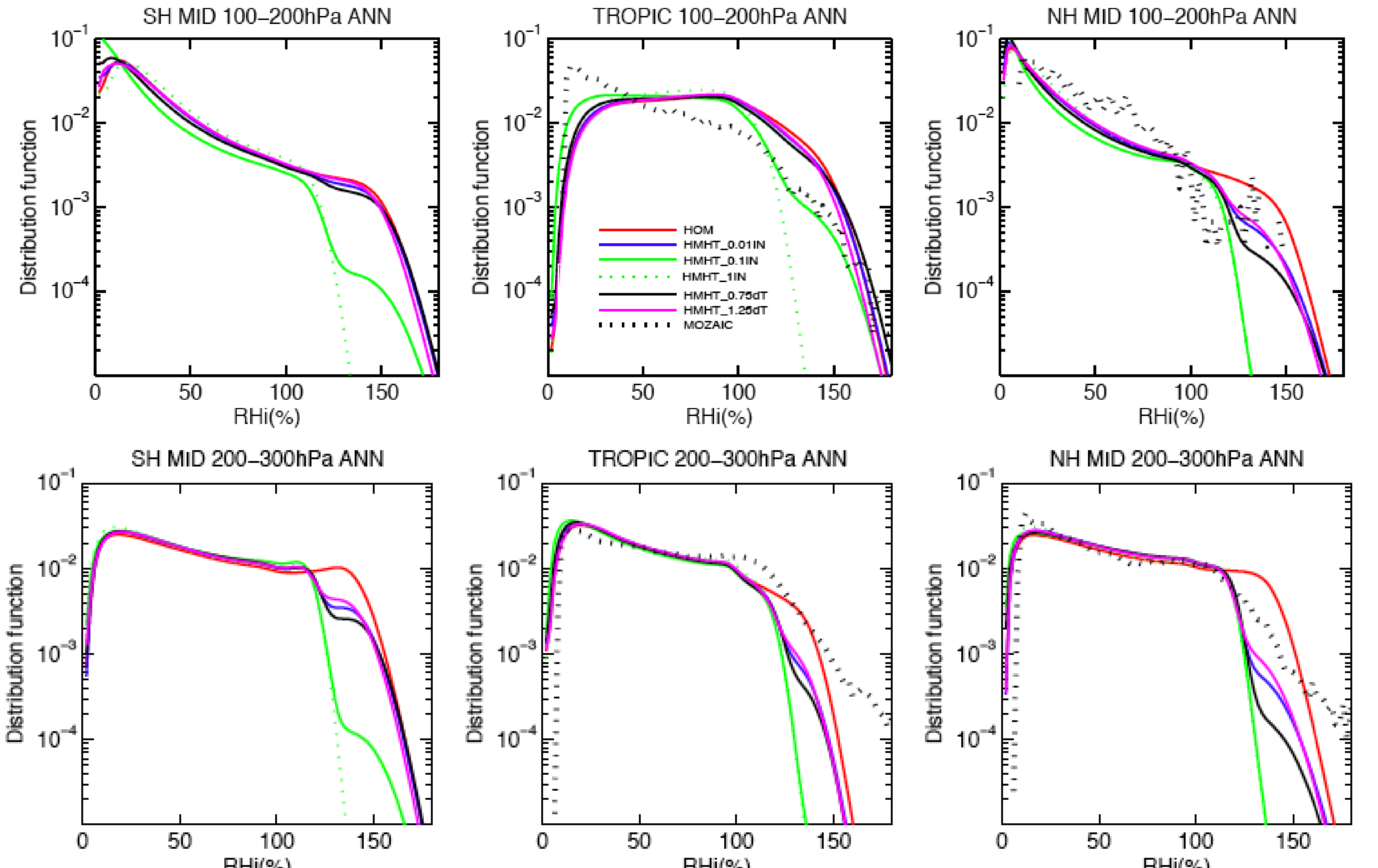
Cloud growth depends on q_{ve}; vapor deposition/ sublimation depend on q_{vc}

Introduces probability density function for temperature and saturation ratio to mimic sub-grid scale mesoscale variability:

$$dP_T/dT,\ dP_S/dS$$

Wang and Penner, 2010

Supersaturation agrees better with MOZAIC observations



New cloud cover scheme, however, worsens agreement with observations!

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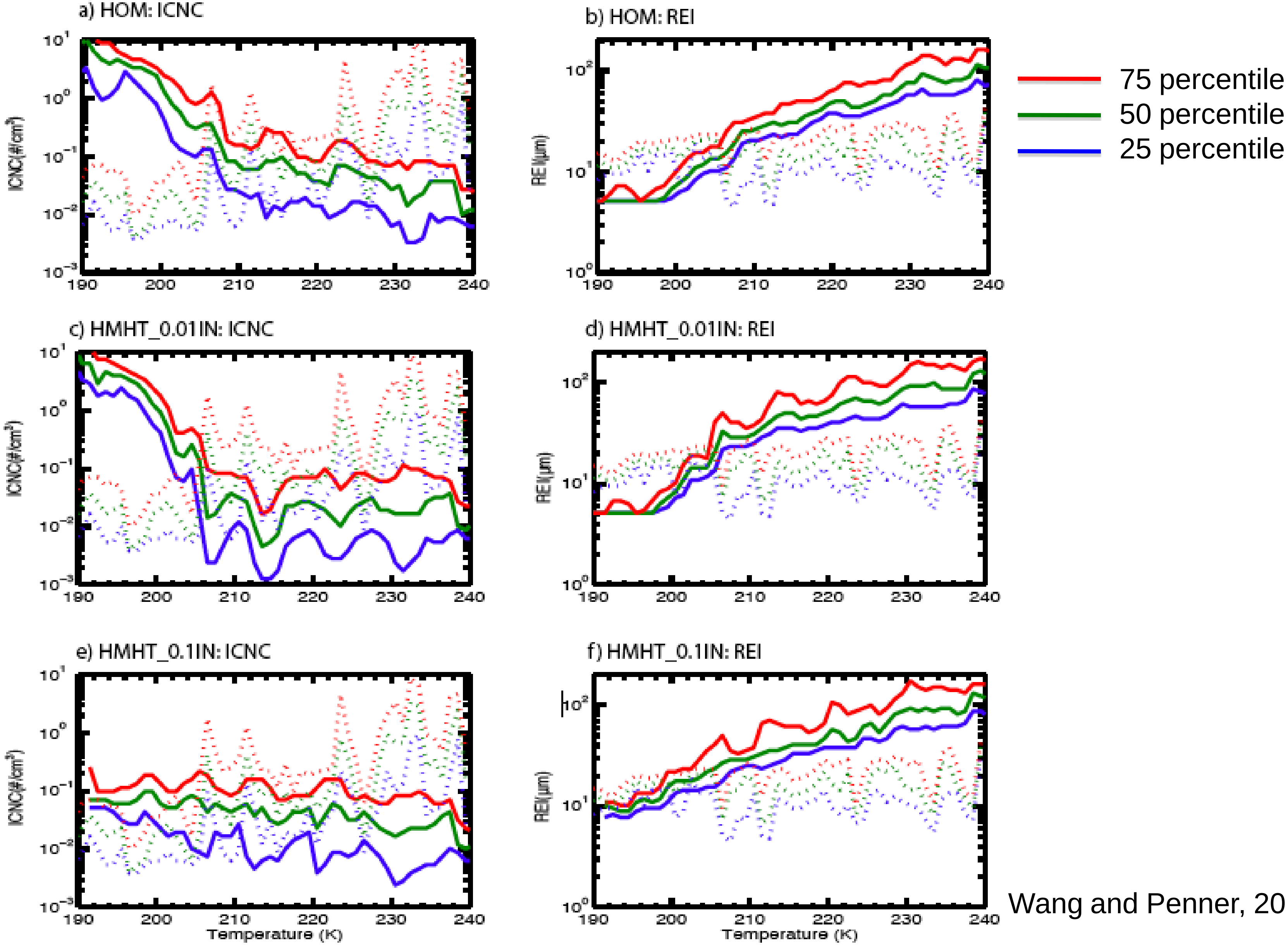
TCCLOW[e]	44.59±0.13	44.22±0.09	43.83±0.14	45.22±0.12	44.40±0.16	44.05±0.13	#	#	#

But high cloud fraction with prediction of cloud fraction based on aerosol/cloud interactions is not improved.

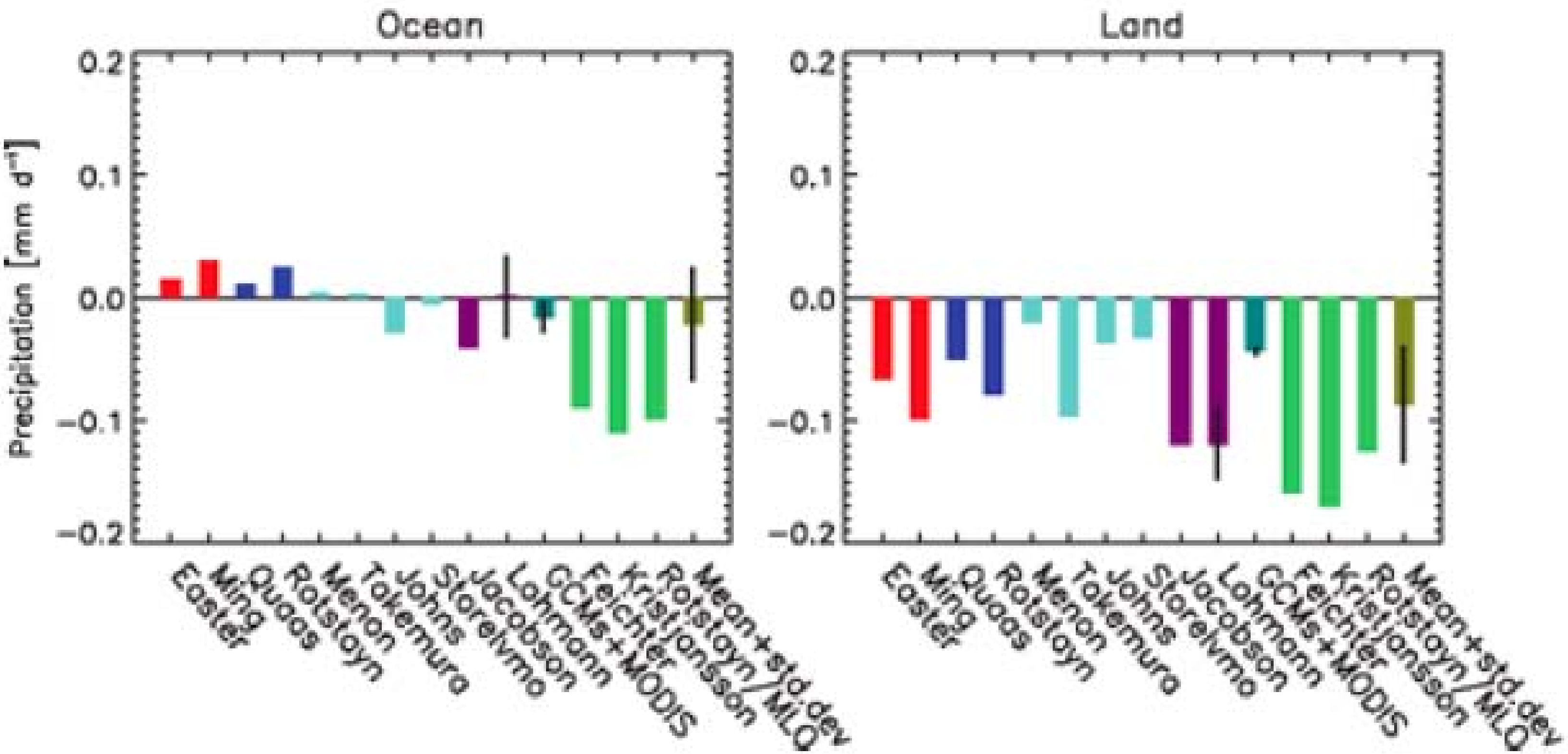
Wang and Penner, 2010

Prediction of ice number/effective radius needs improvement:



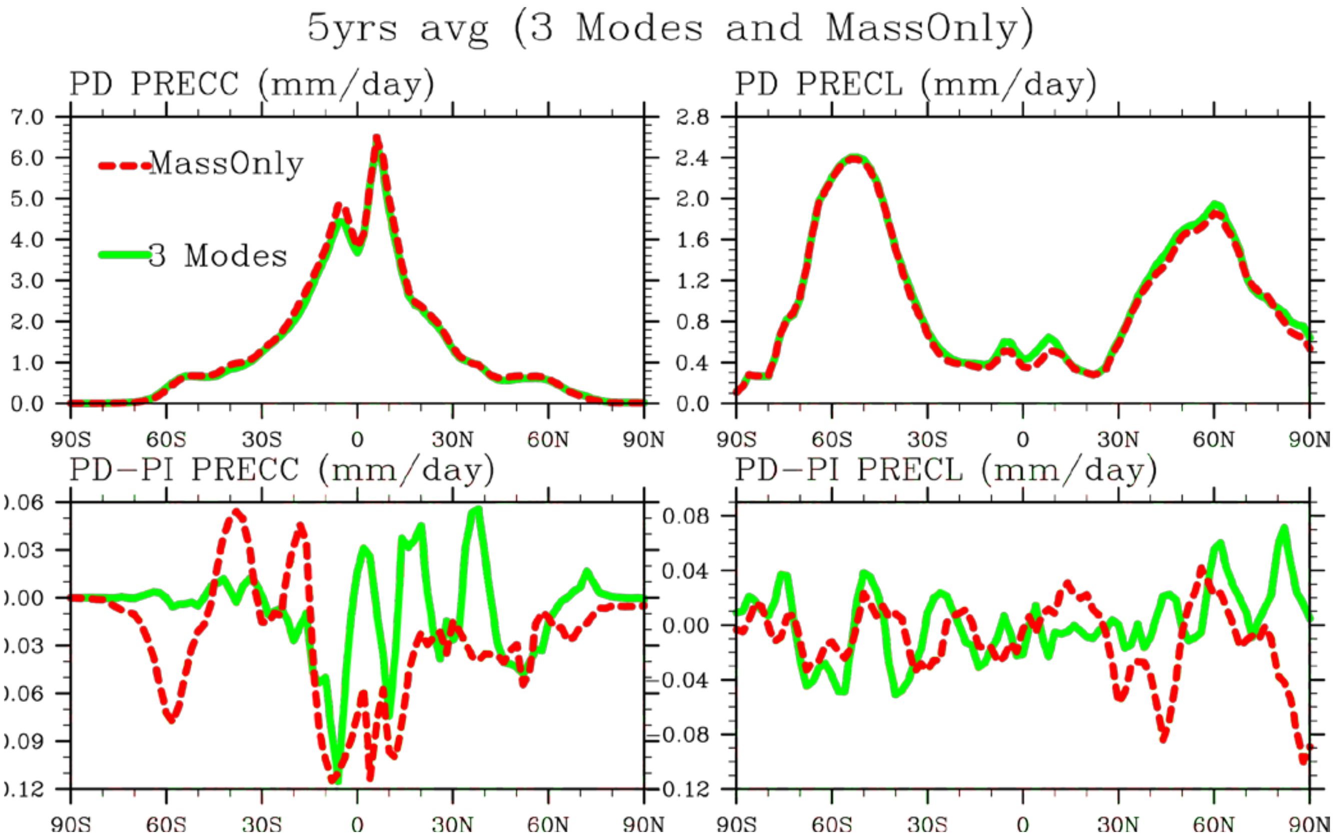
Wang and Penner, 2010

Precipitation changes in global models are mixed



Effect of aerosols on precipitation?

Large scale precipitation   Convective precipitation

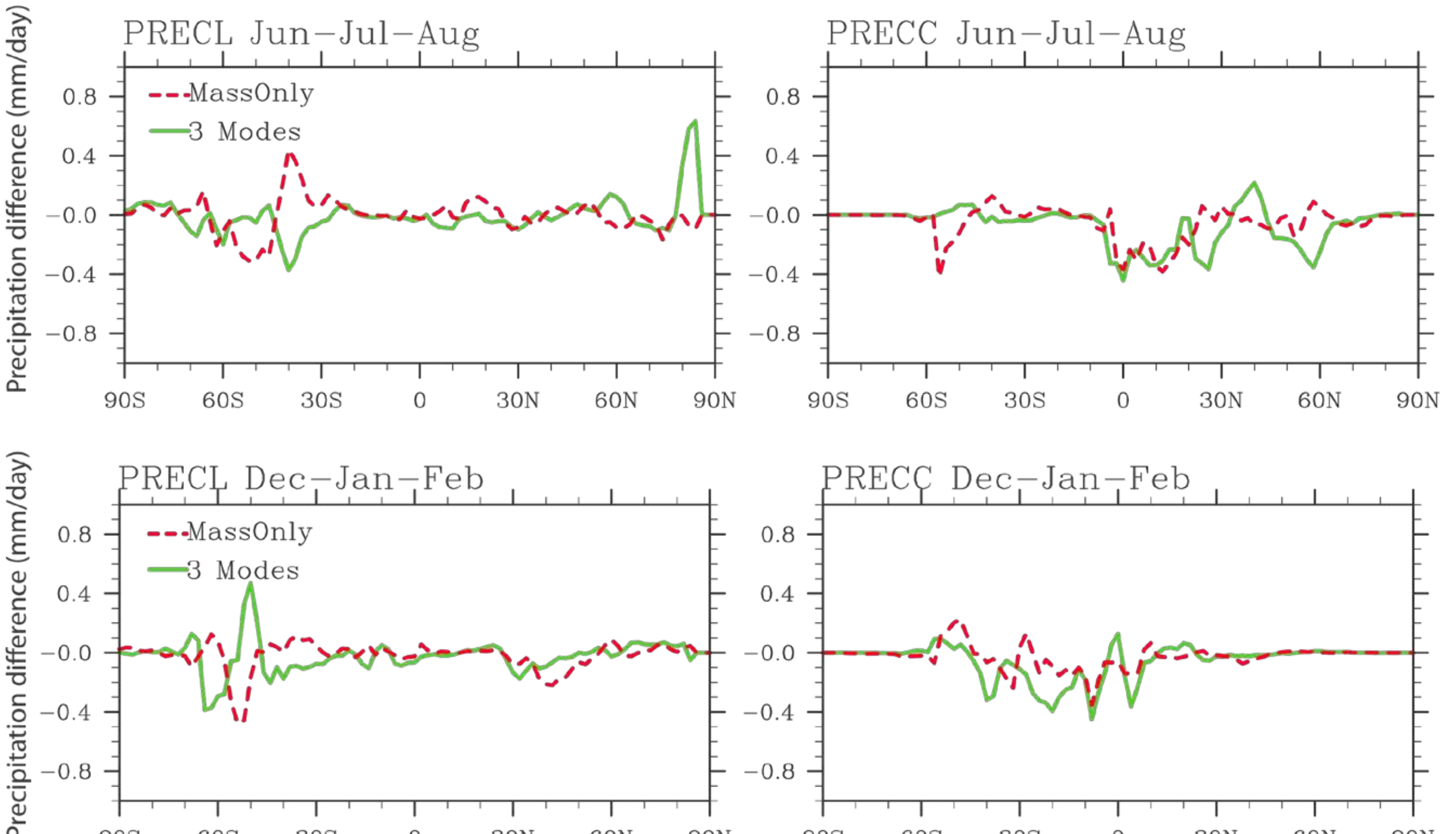


Difference between PD and PI small

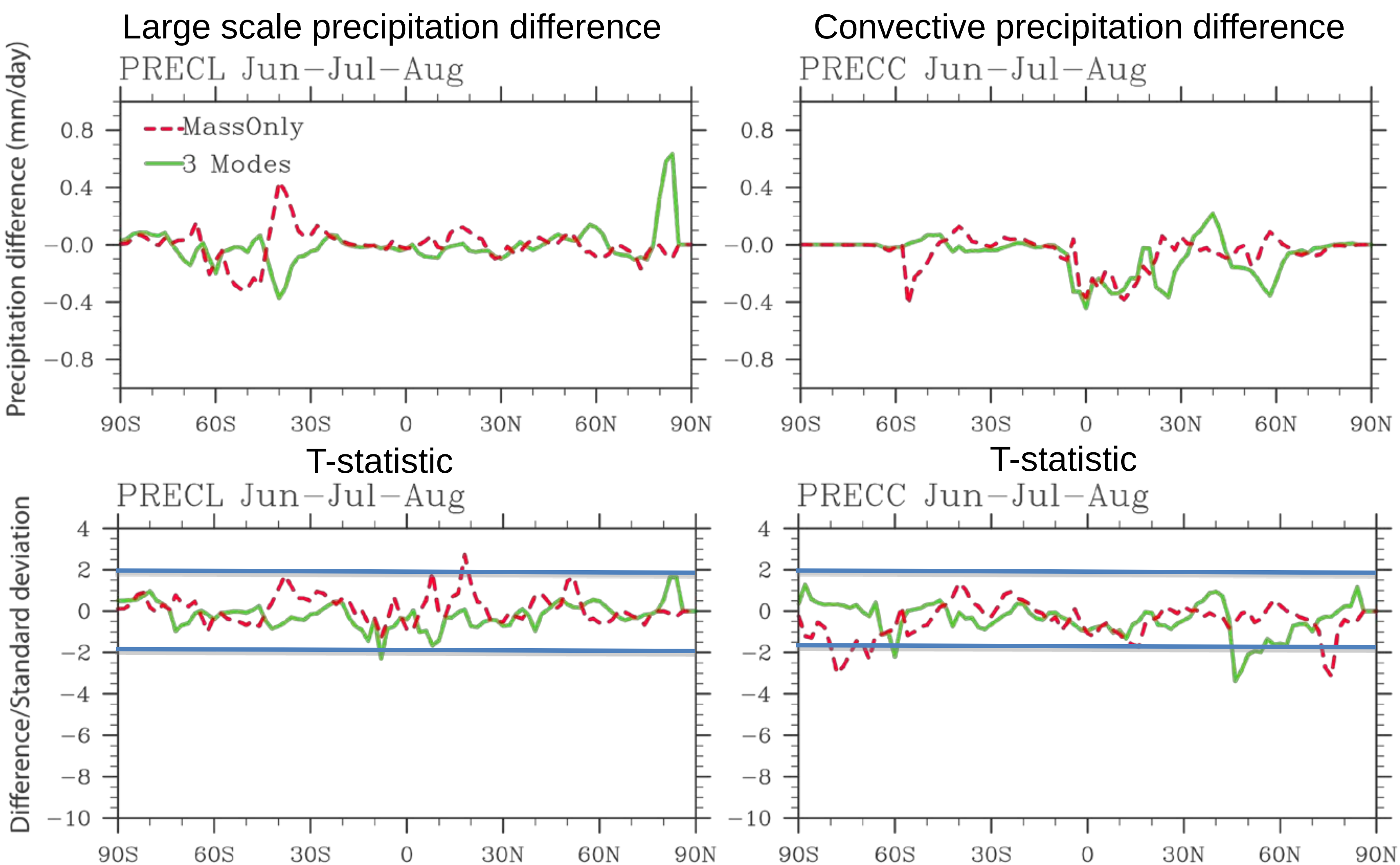
Calculate change over land by season

Large scale precipitation

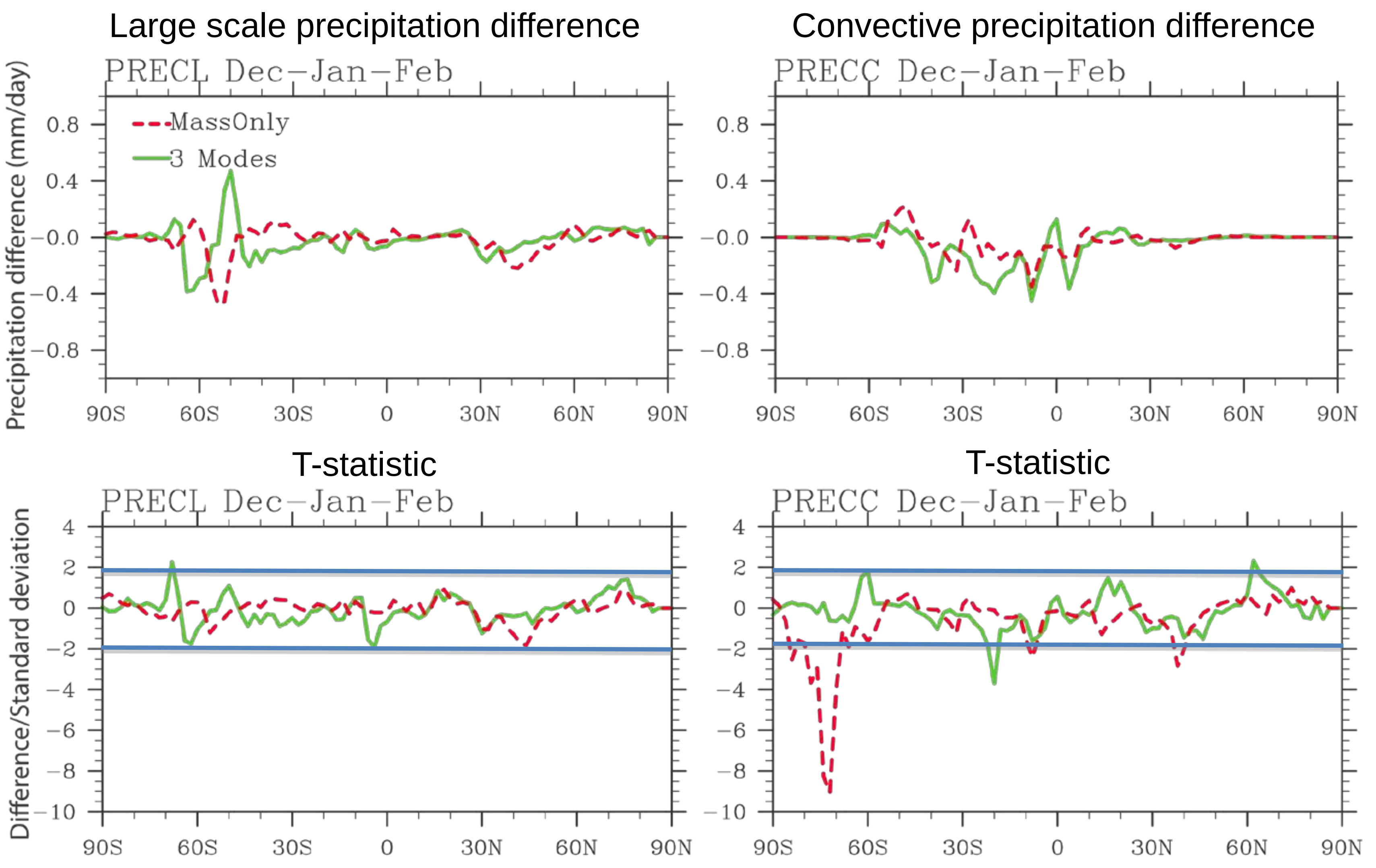
Convective precipitation



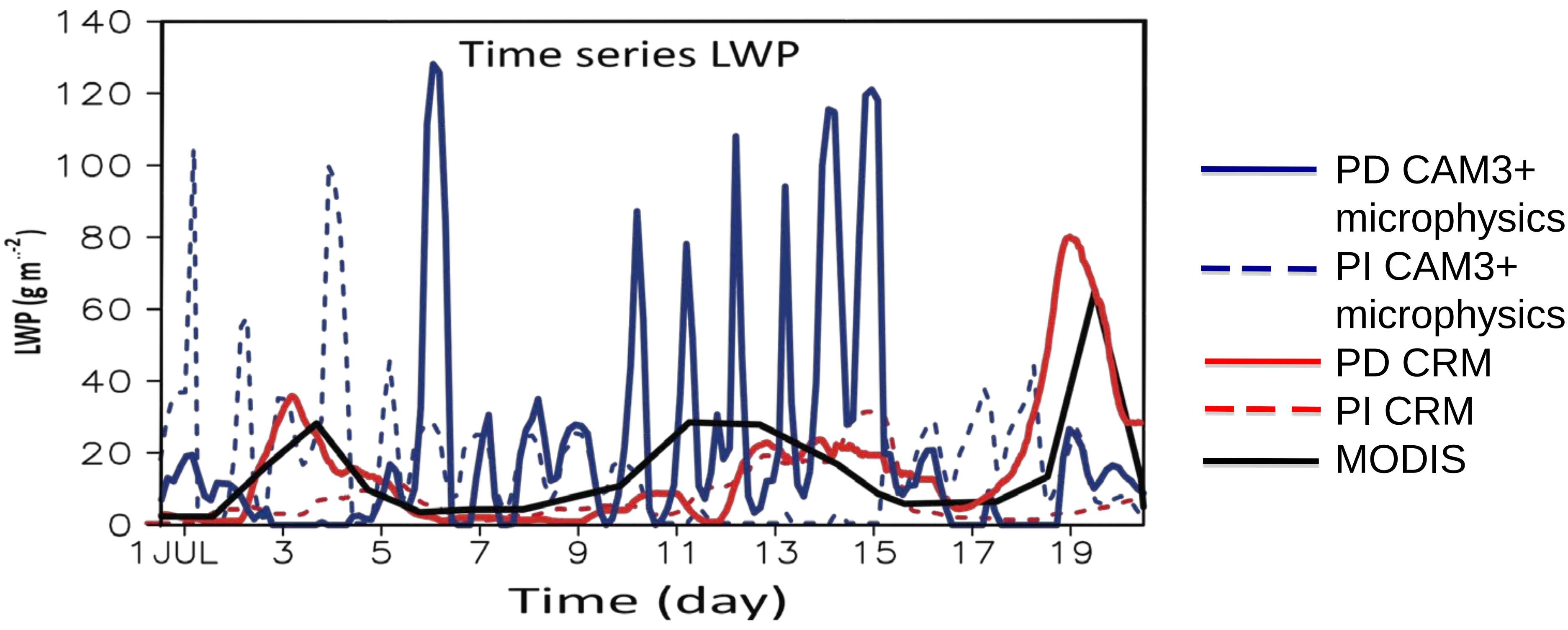
JJA land difference with T-statistic



DJF land difference with T-statistic



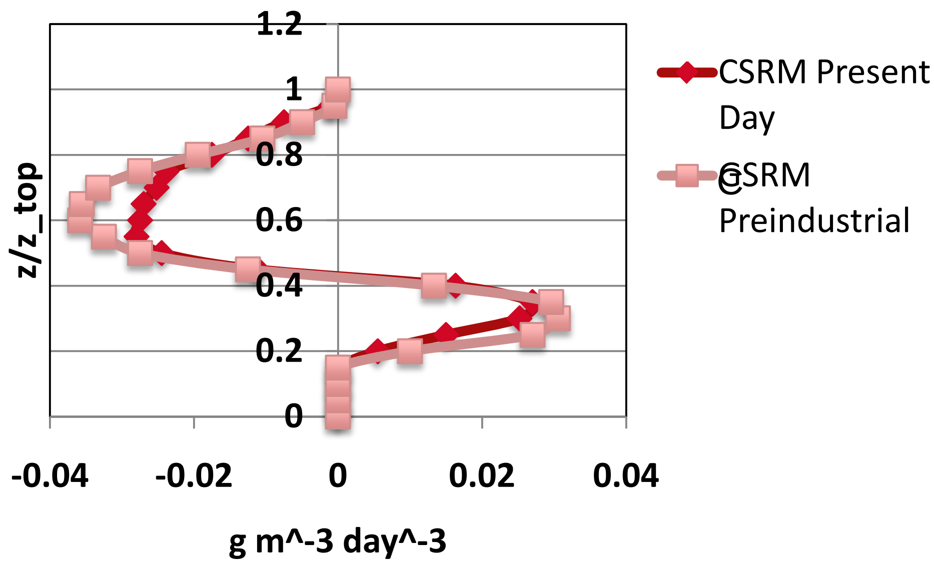
Examine difference between GCM and cloud resolving model:



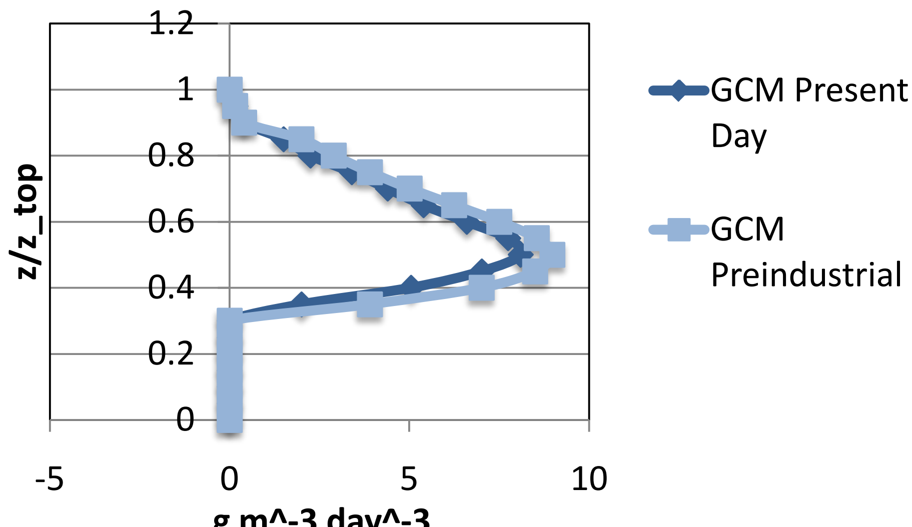
Lee and Penner, 2010

Role of representation of microphysics:

CSRM: change from sedimentation



GCM: loss of cloud liquid to rain



The CSRM includes a 2-bin representation of cloud size, allowing particles to fall below cloud base and evaporate. This promotes a decoupling between the surface and cloud layer, in part, allowing cumulus clouds to develop near the end of the simulation in the CSRM.

Lee and Penner, 2010

How these activities relate to observational data.

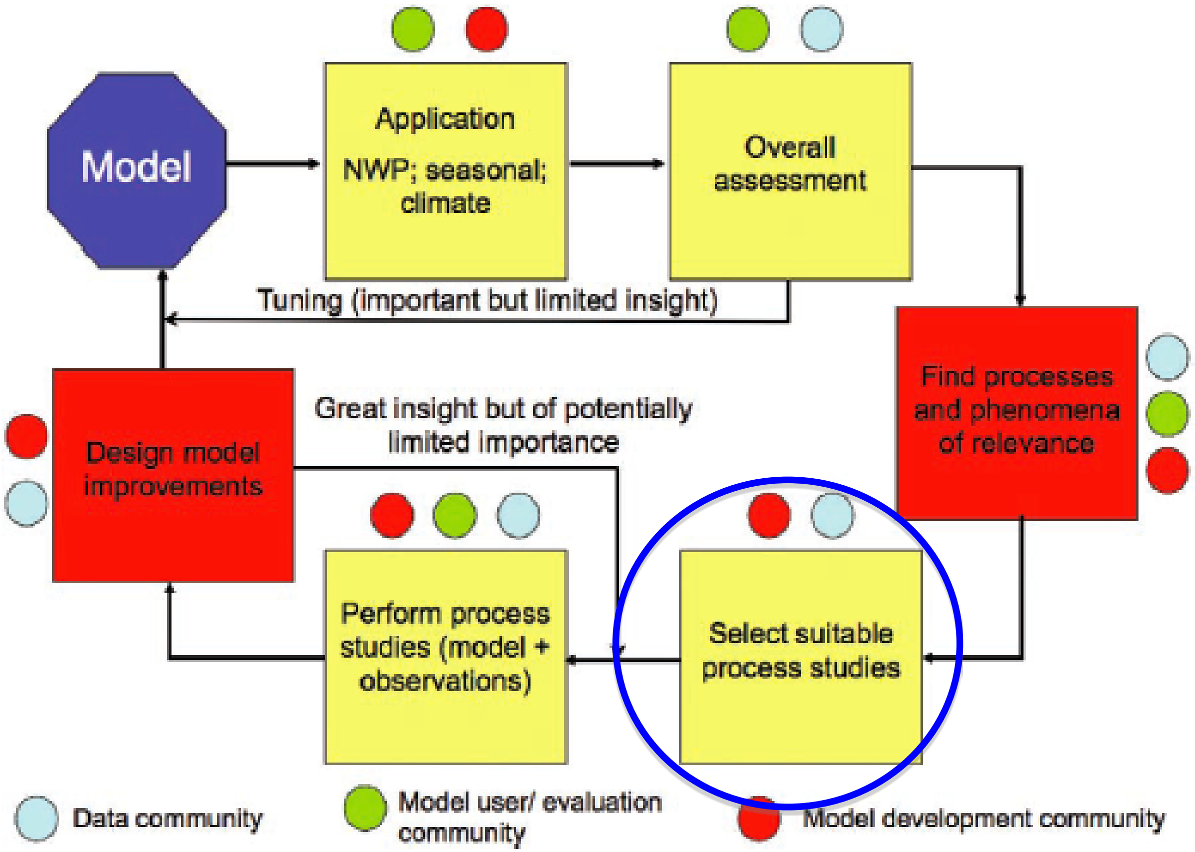


Fig. 1. A schematic of the model development process. See text for more details.

Jakob, 2010

Perspectives on the way forward

- GCM modelers need to include fully consistent parameterization in radiation/microphysics/cloud macrophysics and continue to improve basic representation
- GCM modelers need to examine the full set of available observations for clues about what might be improved
- Process modelers and observations need to explore the set of "unknowns" (i.e. what controls ice number concentration in mixed phase and cold cirrus clouds? Not just empirical relationships)
- GCM modelers need to carry through to an analysis of the consequences of process model studies to new parameterizations to observations in the full GCM