A Community Atmosphere Model: CAM5

CPT Presentation at NCEP. D.C.

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OUTLINE

I. Overview of CAM5 Physics
- Moist Turbulence
- Shallow Convection
- Cloud Macrophysics
- Cloud Microphysics
- Aerosol
- Radiation

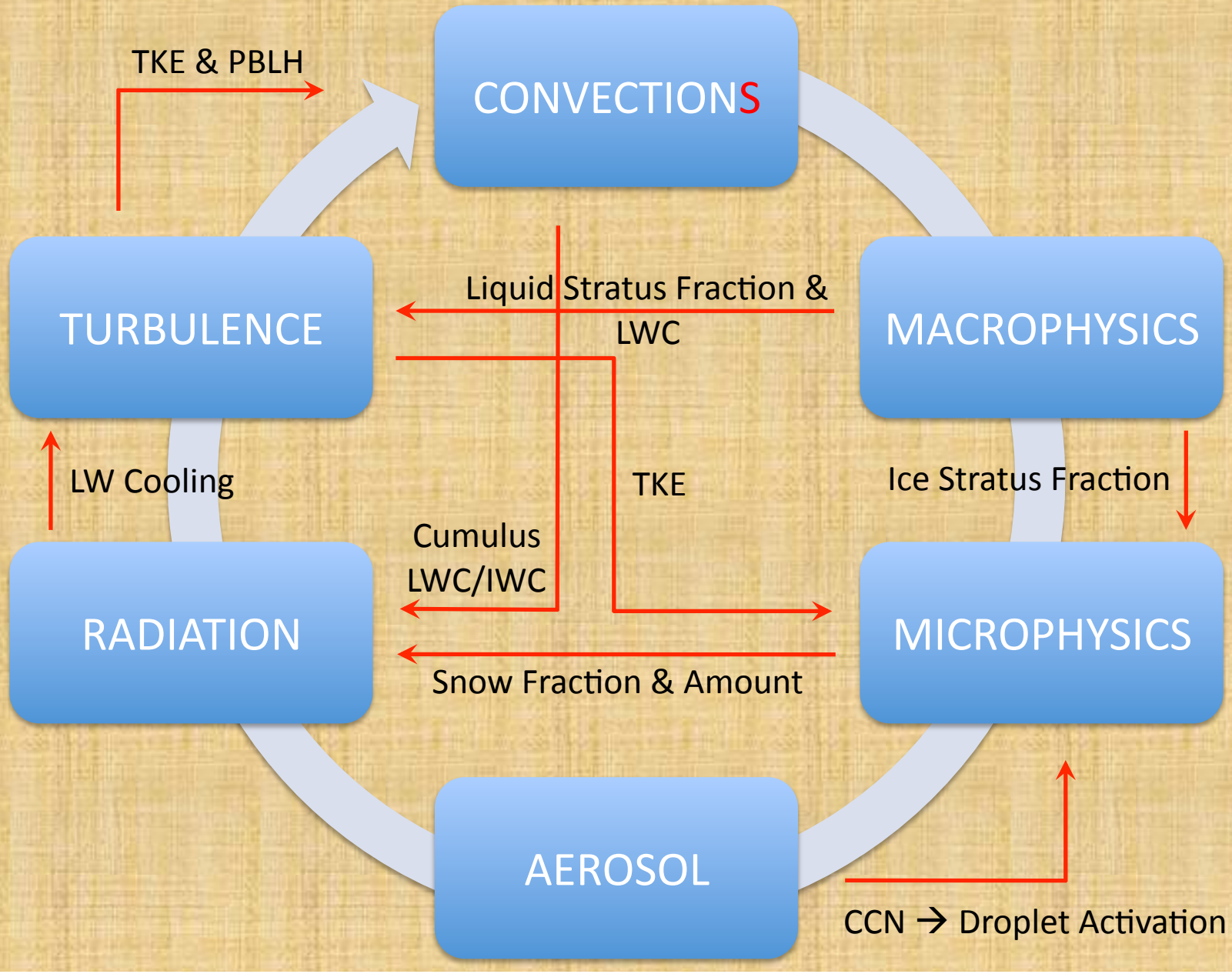
II. Climate Effects of 'Clouds' and 'Aerosols'
- Aerosol *Direct* and *Indirect* Effects
- The 20th Climate Change Simulation: Overall 'Clouds' + 'Aerosol' Feedbacks

III. SUMMARY

Evolutions of CAM

Model	CCSM3 (2004)	CCSM3.5 (2007)	CCSM4 (Apr 2010)	CESM1 (Jun 2010)
Atmosphere	CAM3 (L26)	CAM3.5 (L26)	CAM4 (L26)	CAM5 (L30)
Boundary Layer Turbulence	Holtslag-Boville (93) Dry Turbulence	Holtslag-Boville	Holtslag-Boville	Bretherton-Park (09) UW Moist Turbulence
Shallow Convection	Hack (94)	Hack	Hack	Park-Bretherton (09) UW Shallow Convection
Deep Convection	Zhang-McFarlane (95)	Zhang-McFarlane Neale et al.(08) Richter-Rasch (08)	Zhang-McFarlane Neale et al.(08) Richter-Rasch (08)	Zhang-McFarlane Neale et al.(08) Richter-Rasch (08)
Cloud Macrophysics	Zhang et al. (03)	Zhang et al. with Park & Vavrus' mods.	Zhang et al. with Park & Vavrus' mods.	Park-Bretherton-Rasch (10) UW Cloud Macrophysics
Stratiform Microphysics	Rasch-Kristjansson (98) *Single Moment*	Rasch-Kristian. *Single Moment*	Rasch-Kristian. *Single Moment*	Morrison and Gettelman (08) *Double Moment*
Radiation / Optics	CAMRT (01)	CAMRT	CAMRT	RRTMG Iacono et al.(08) / Mitchell (08)
Aerosols	Bulk Aerosol Model (BAM)	BAM	BAM	Modal Aerosol Model (MAM) Liu & Ghan (2009)
Dynamics	Spectral	Finite Volume (96,04)	Finite Volume	Finite Volume
Ocean	POP2 (L40)	POP2.1 (L60)	POP2.2 - *BGC*	POP2.2
Land	CLM3	CLM3.5	CLM4 - *CN*	CLM4
Sea Ice	CSIM4	CSIM4	CICE	CICE

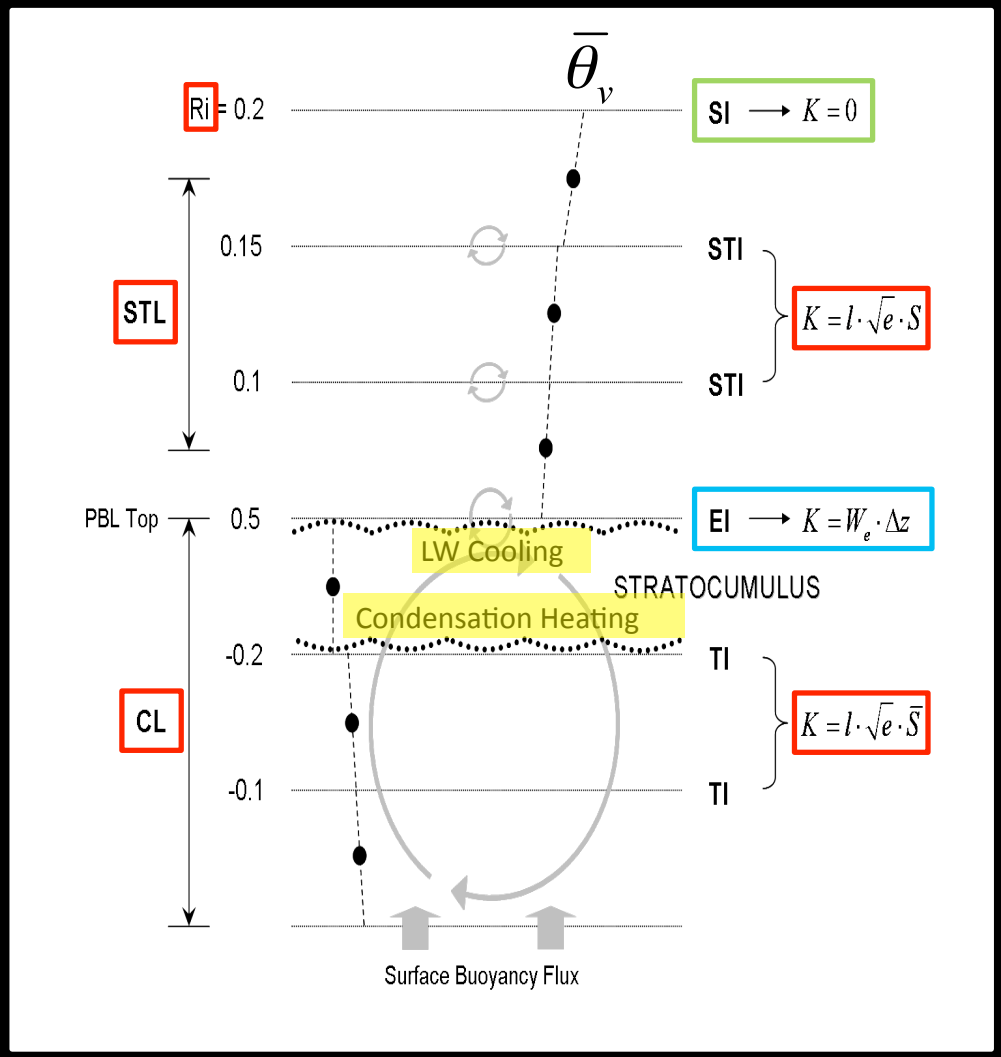
Physical Processes in CAM5



MOIST TURBULENCE SCHEME in CAM5

MOIST TURBULENCE SCHEME in CAM5

C. Bretherton and S. Park. 2009



$$\frac{\partial \overline{A}}{\partial t} = -\frac{\partial}{\partial z}\overline{w'A'} = \frac{\partial}{\partial z}\left(K\frac{\partial \overline{A}}{\partial z}\right)$$

K : eddy diffusivity

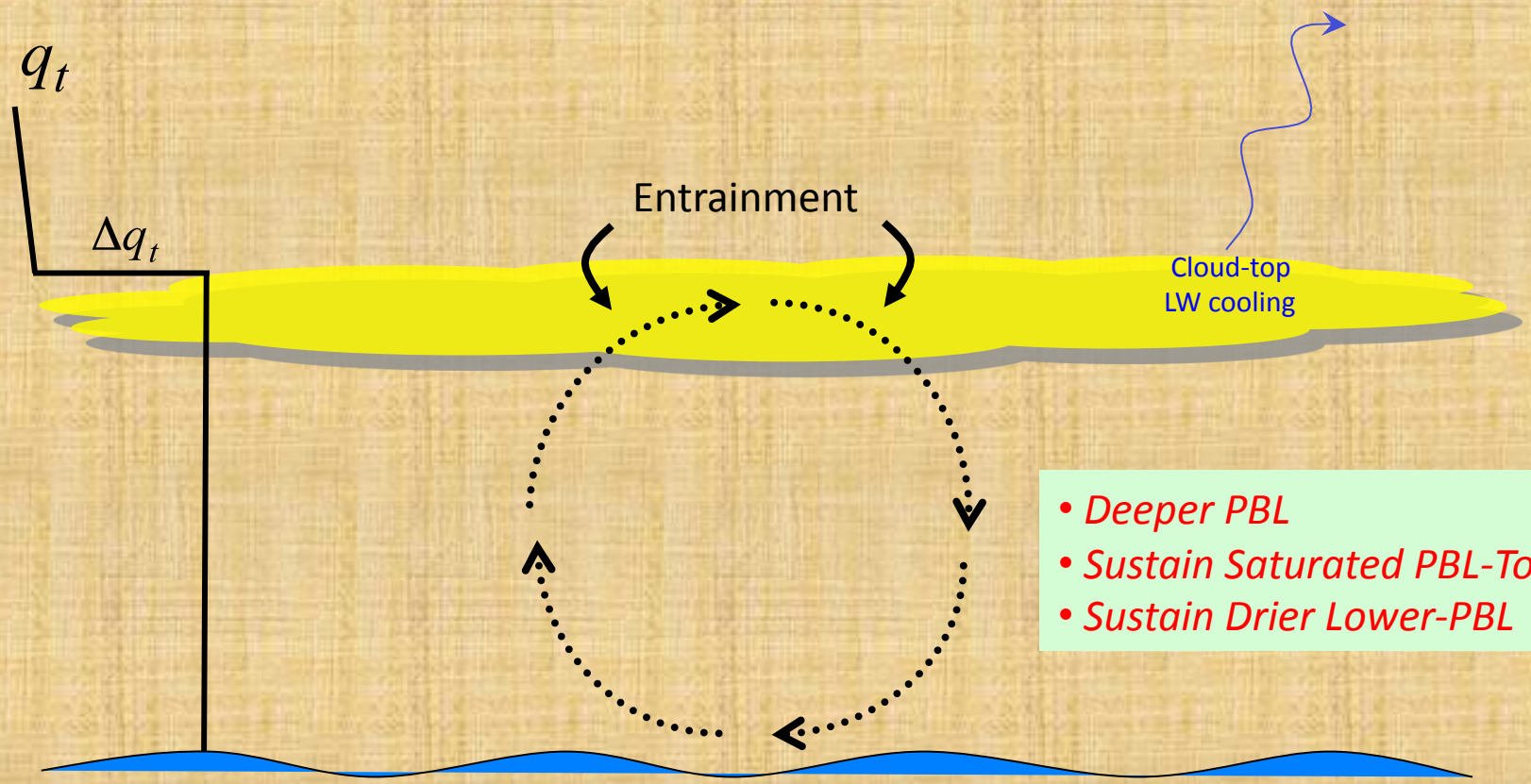
Ri	: Moist Richardson Number
SI	: Stable Interface
STI	: Stably Turbulent Interface
EI	: Entrainment Interface
TI	: Turbulent Interface
STL	: Stably Turbulent Layer
CL	: Convective Layer
l	: Turbulent length scale
S	: Stability function (fcn of Ri)
e	: TKE
W_e	: Entrainment rate

Moist Turbulence Scheme in CAM5

C. Bretherton and S. Park. 2009

- Diagnostic TKE-based 1st order K diffusion scheme with entrainment param.
  - Numerically stable, physically realistic, conceptually clear
  - TKE is fed into 'shallow convection' and 'cloud microphysics', and regulates the onset of cumulus updraft and cloud droplet activation
- Stratus-Top LW Cooling and In-Stratus Condensation Heating into TKE
  - Sensitive to 'cloud macro-microphysics' and 'radiation' schemes
  - Treatment of Stratus-Radiation-Turbulence Interactions
  - Now, stratus is a dynamic (as well as radiative) driver of the climate
  - Handling of the full 2nd aerosol indirect effects
  - Removal of the stability-based KH stratus fraction
- Activate in any layers above as well as within PBL
  - Simulate turbulences in the mid-level clouds
- Compared to CAM4 PBL scheme,
  - Much better performance in cloud-topped regime
  - Similar or superior performance in dry stable and convective regimes

Cloud-Radiation-Turbulence Interactions



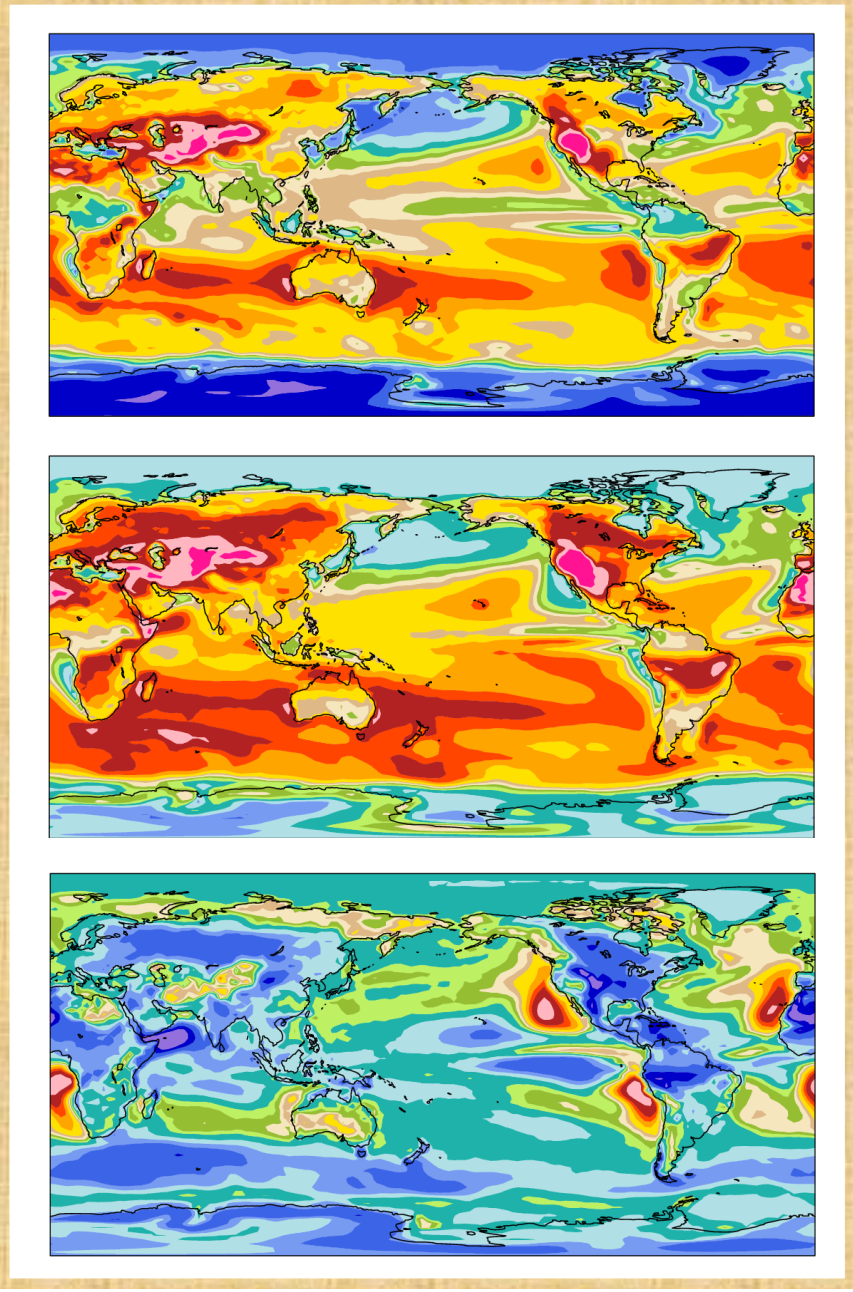
- *Deeper PBL*
- *Sustain Saturated PBL-Top*
- *Sustain Drier Lower-PBL*

PBLH. JJA

CAM5

CAM4

CAM5 – CAM4



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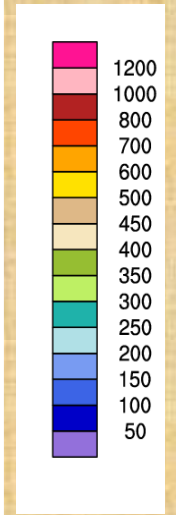
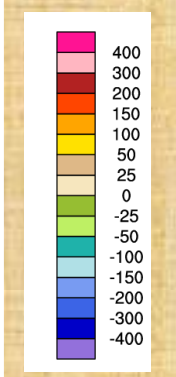
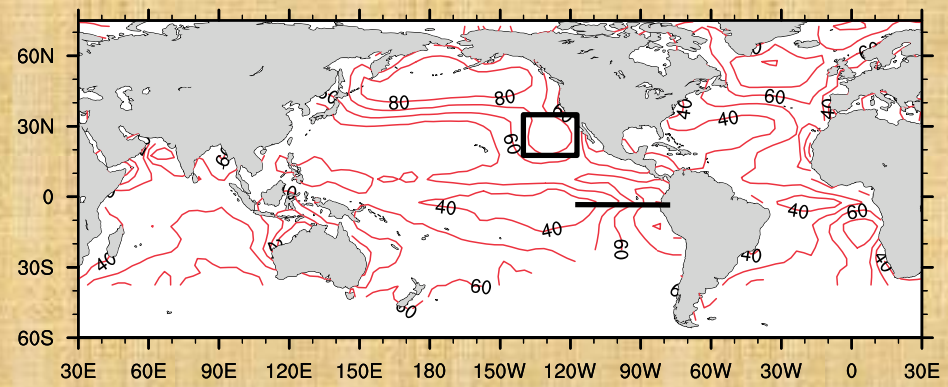




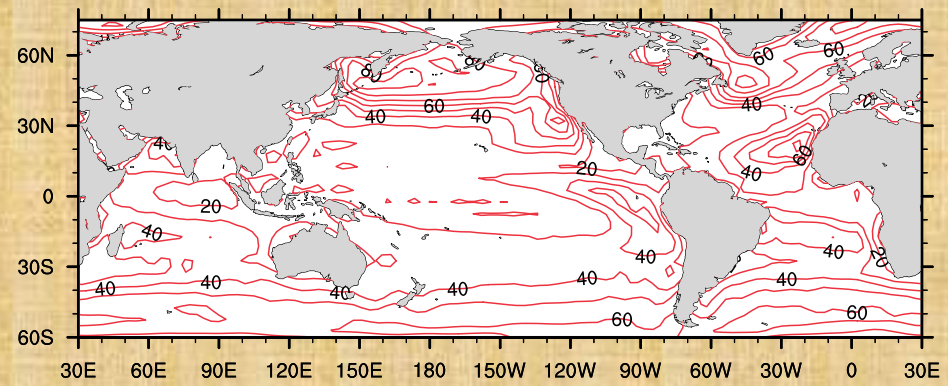
Deeper PBL in Sc-Regime

Low Cloud Amount. JJA.

Observation

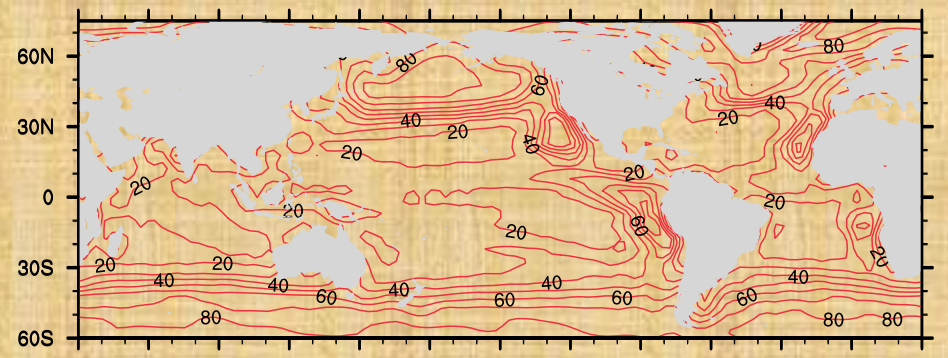


CAM4



Use
KH's stratus fraction

CAM5

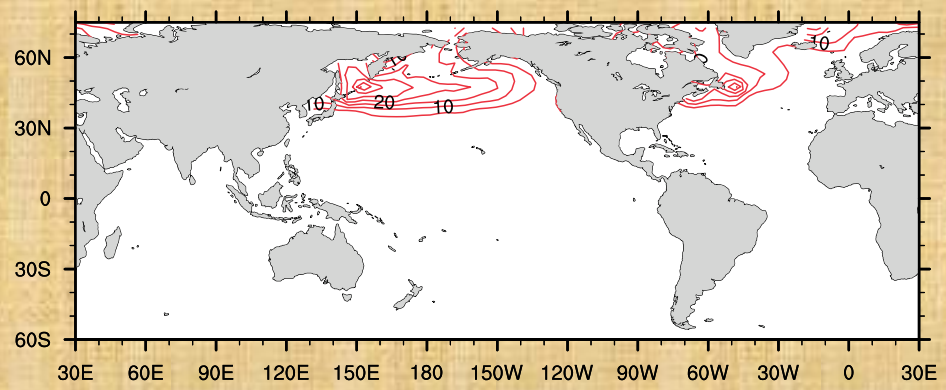


Do not use
KH's stratus fraction

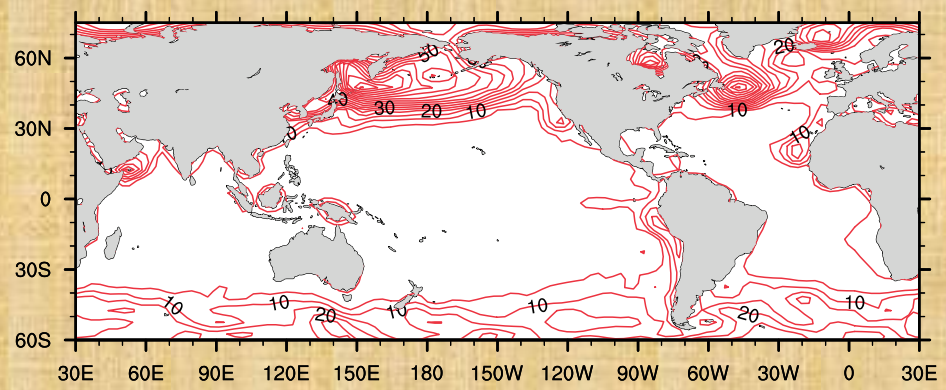
Sustain Saturated PBL Top

Fog Amount. JJA.

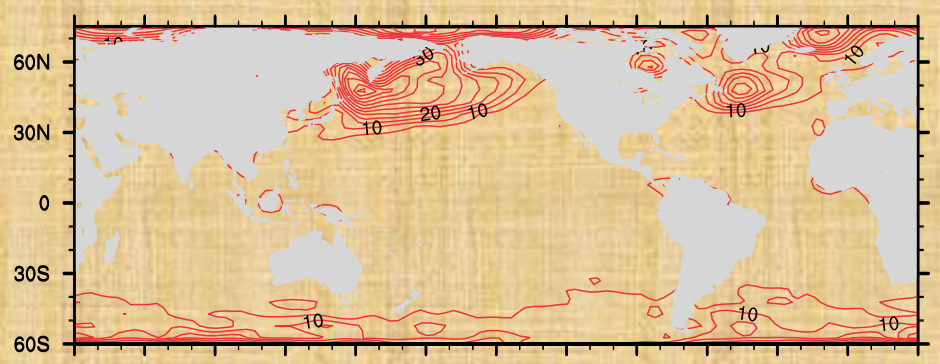
Observation



CAM4



CAM5

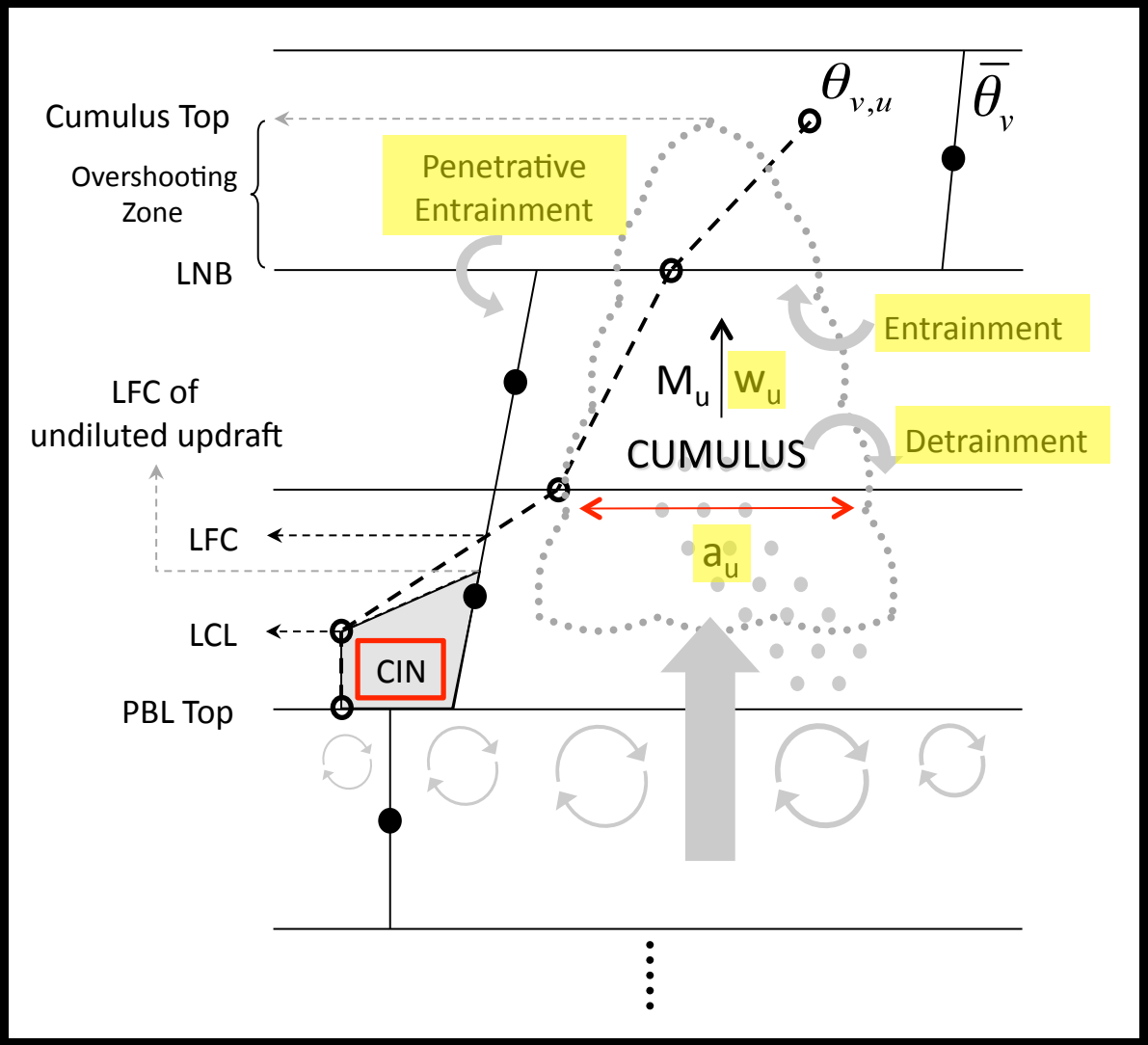


Sustain Drier Lower-PBL

SHALLOW CONVECTION SCHEME in CAM5

SHALLOW CONVECTION SCHEME in CAM5

S. Park and C. Bretherton. 2009



$$\overline{w'A'} = \rho \cdot M_u \cdot (A_u - \bar{A})$$

M_u : updraft mass flux

A_u : updraft scalar

CIN	: Convective INhibition
LCL	: Lifting Condensation Level
LFC	: Level of Free Convection
LNB	: Level of Neutral Buoyancy
w_u	: Updraft vertical velocity
a_u	: Updraft fractional area

Shallow Convection Scheme in CAM5

S. Park and C. Bretherton. 2009

- An entraining-detraining buoyancy-sorting updraft plume with a penetrative entrainment parameterization
  - Mass flux closure based on TKE and Convective Inhibition (CIN)
  - Close interactions with moist turbulence scheme
  - Transports aerosols and *cloud droplet number* similar to thermodynamic conservative scalars
  - Computes cumulus fraction and LWC, vertical velocity, updraft mass flux
  - Direct influence on the global radiation budget

- Less sensitive to vertical resolution than CAM4

- Simulate the '*real*' convective activity

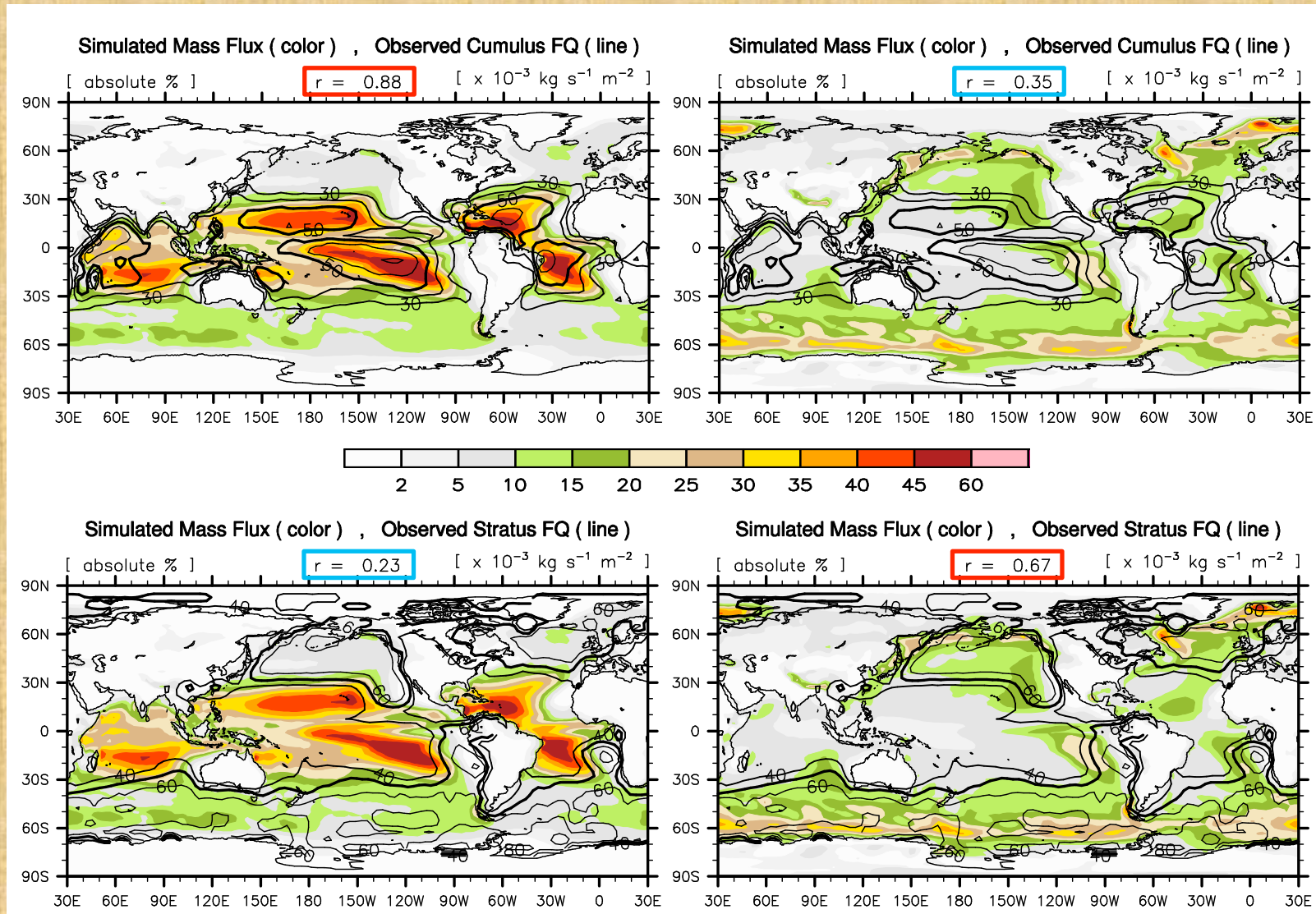
Shallow Convective Mass Flux at Cloud Base. Annual.

CAM5

CAM4

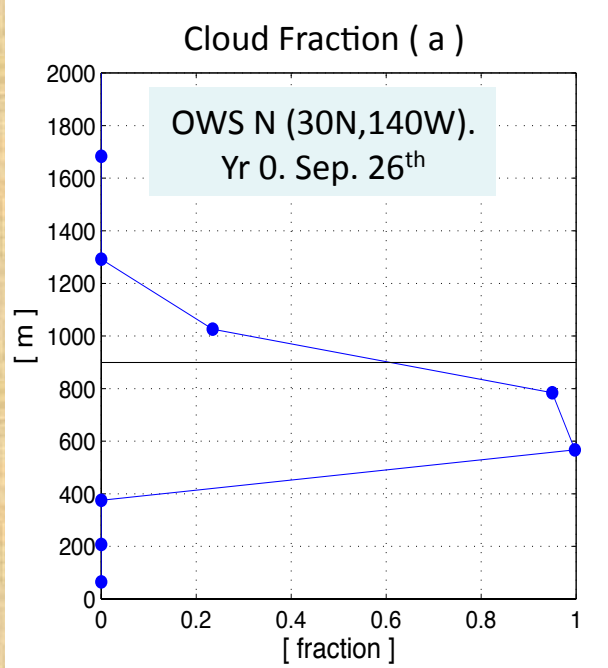
Observed Cumulus

Observed Stratus

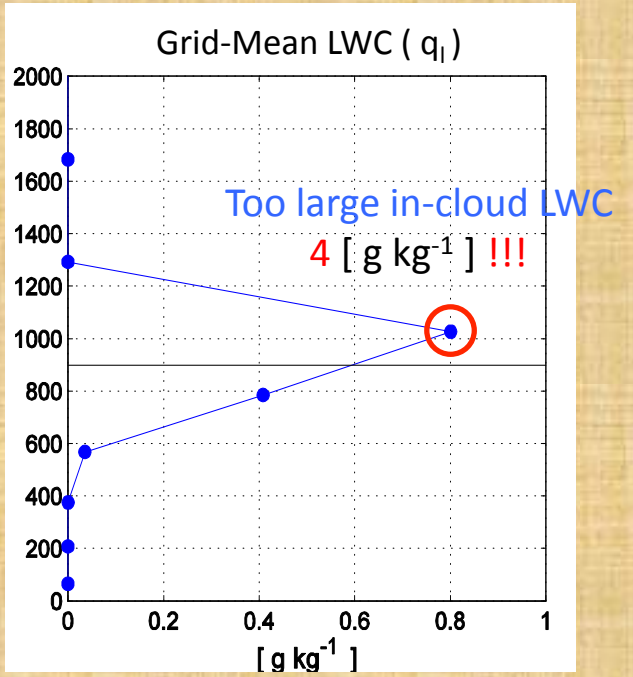


Cloud Macrophysics Scheme in CAM5

Inconsistency between 'Stratus Fraction' and 'In-Stratus LWC' in CAM3



PBL top



→ distorts LW cooling profile

→ too strong inversion at the PBL top

→ too weak entrainment rate

→ too shallow and moist PBL

Cloud Macrophysics Scheme in CAM5

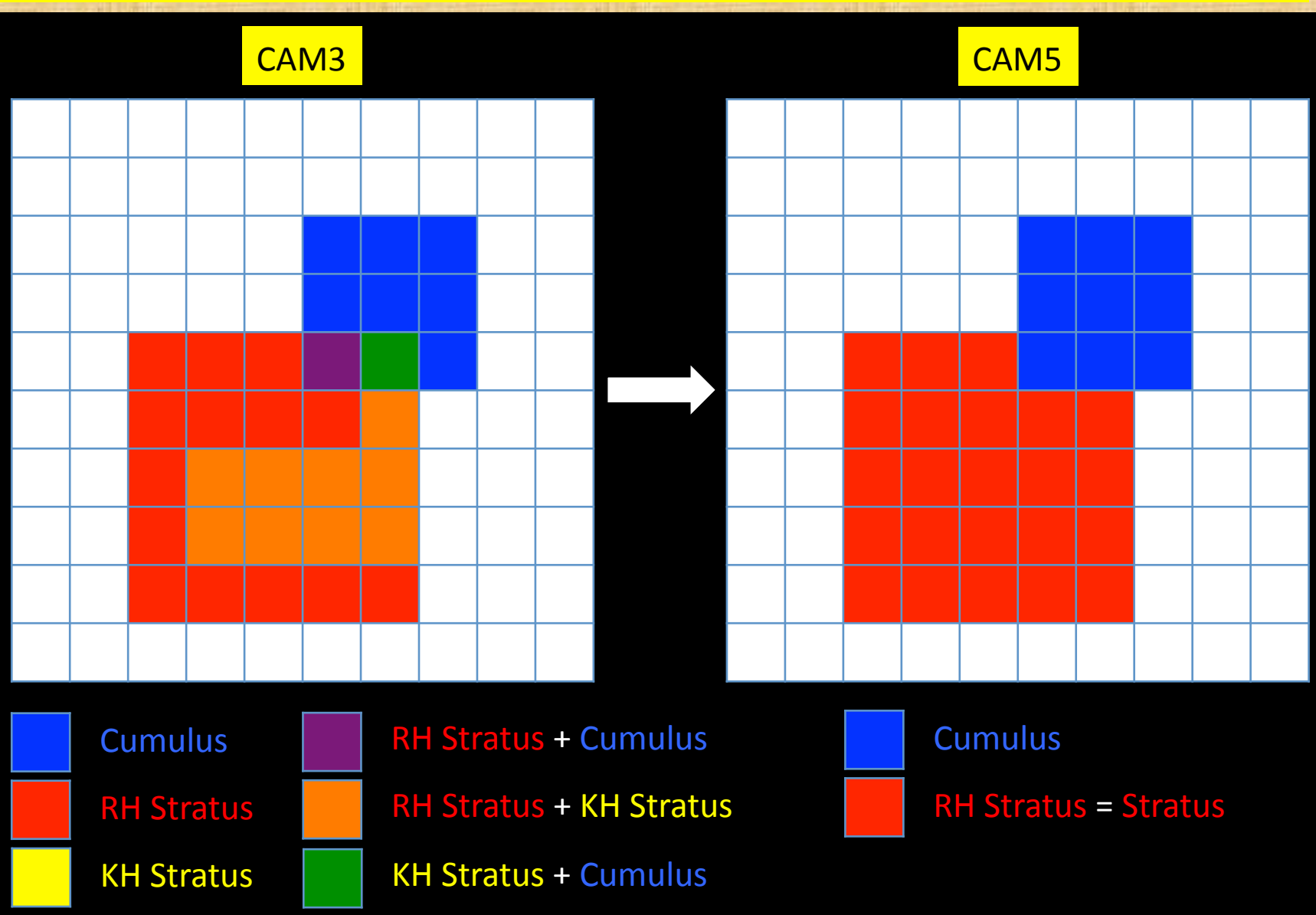
S. Park, C. Bretherton and P. Rasch. 2010

- Enhance consistency between stratus fraction and in-stratus LWC
- Remove 'empty' ($a>0$, $q_{l,cloud}=0$) and 'dense'($a=0$, $q_{l,cloud}>0$) stratus
- Uses a single equilibrium stratus fraction at each time step
- Liquid stratus fraction based on triangular PDF of q_t
- Removal of KH's stability based stratus fraction

- Separate treatment of liquid condensation and ice sublimation
- Separate diagnose of liquid and ice stratus fractions
- Liquid condensation formula based on conservative scalars

- Cumulus is non-overlapped with stratus in each layer.
- Cumulus has its own in-cumulus LWC.
- Cumulus is radiatively active.

Horizontal Geometry of Clouds in CAM



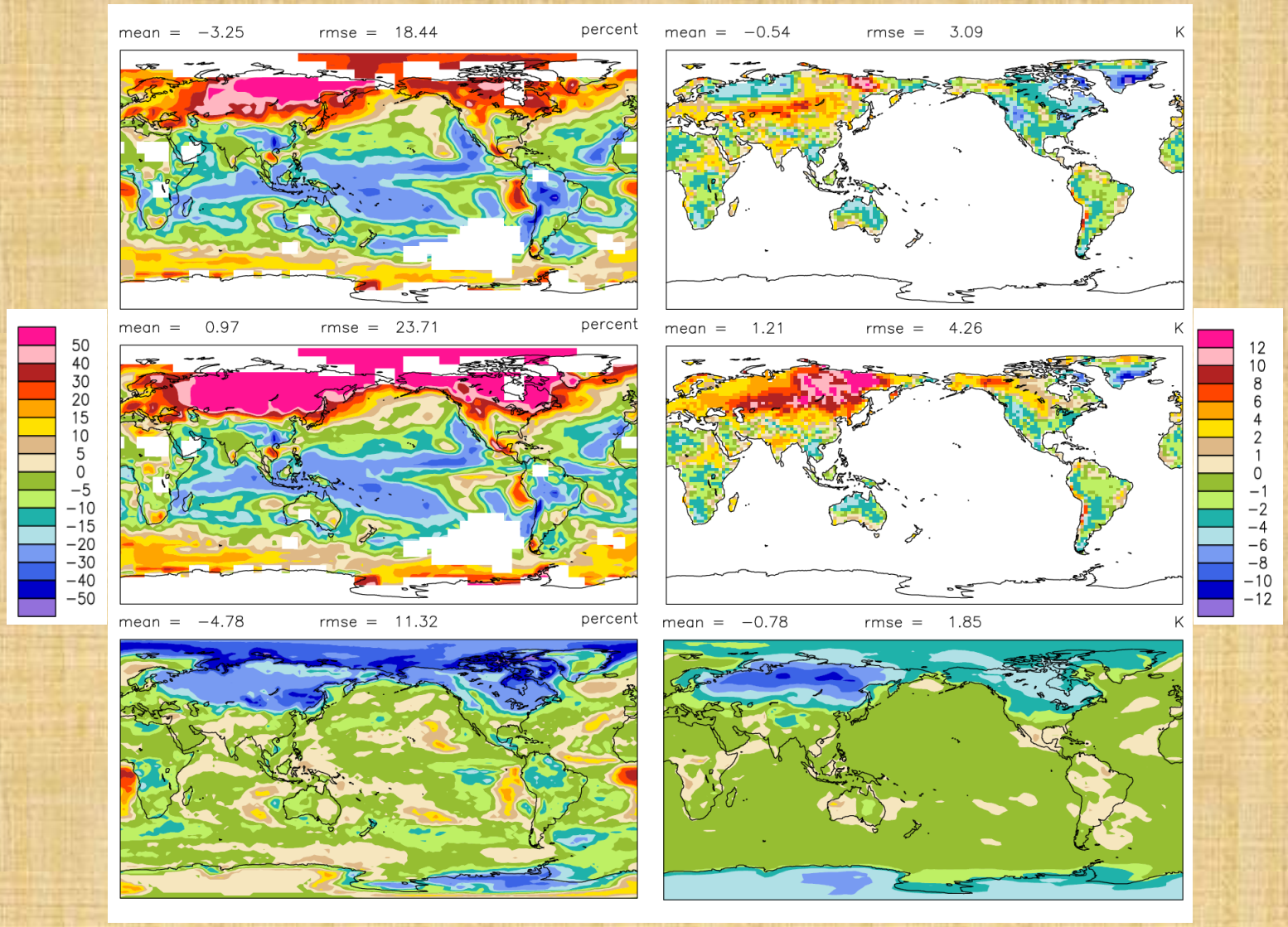
ΔLCA. DJF.

ΔT_{2m}. DJF.

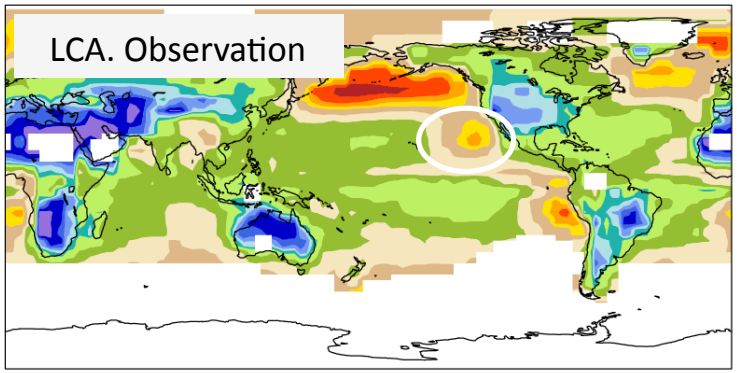
After Mod.
CAM5-OBS.

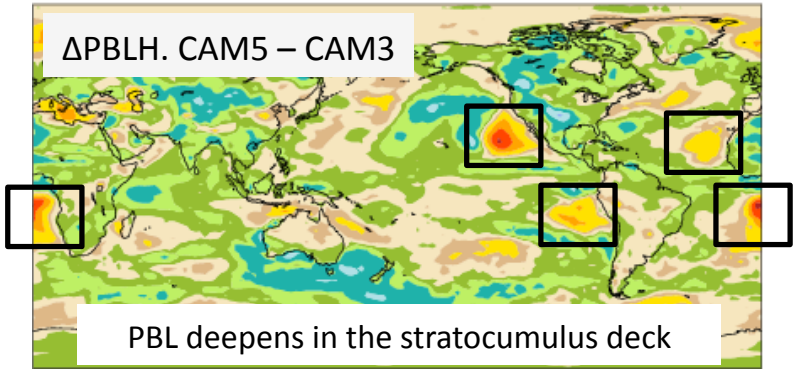
Before Mod.
CAM3-OBS.

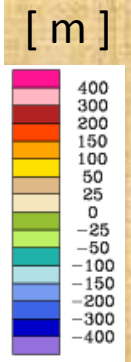
After Mod-
Before Mod

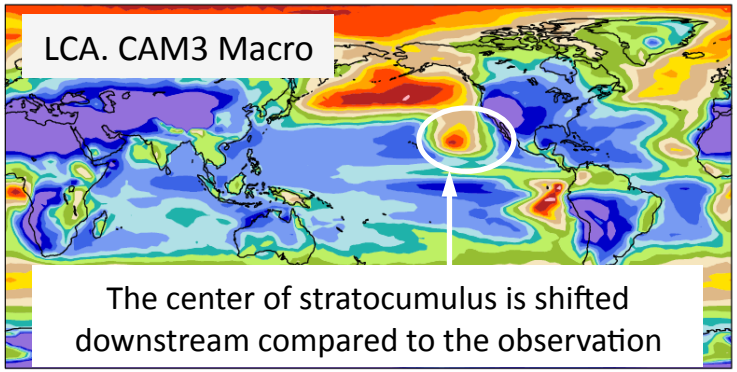


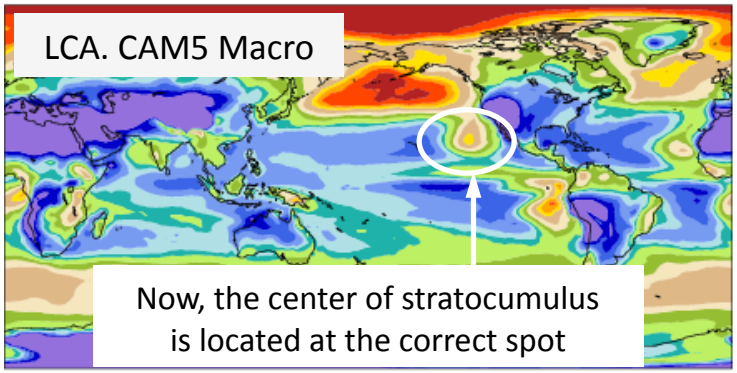
SENSITIVITY TO MACROPHYSICS. JJA.

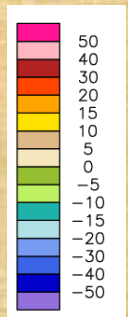


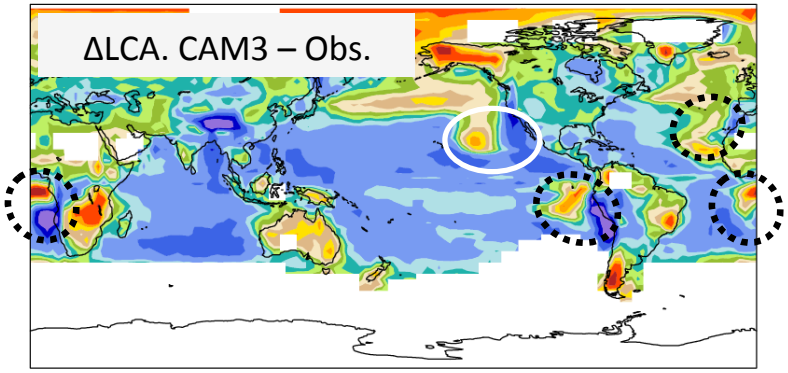


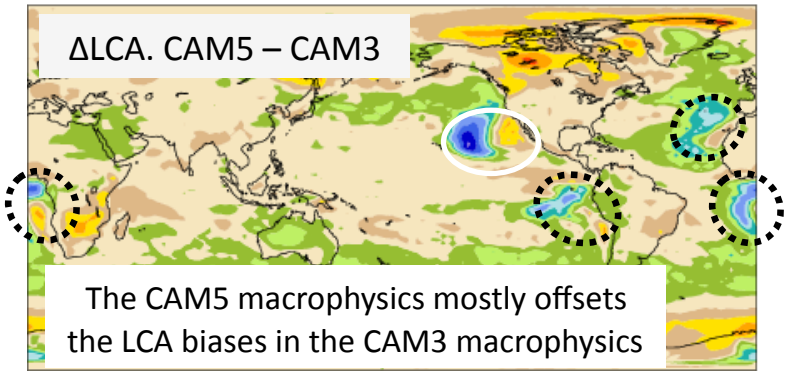




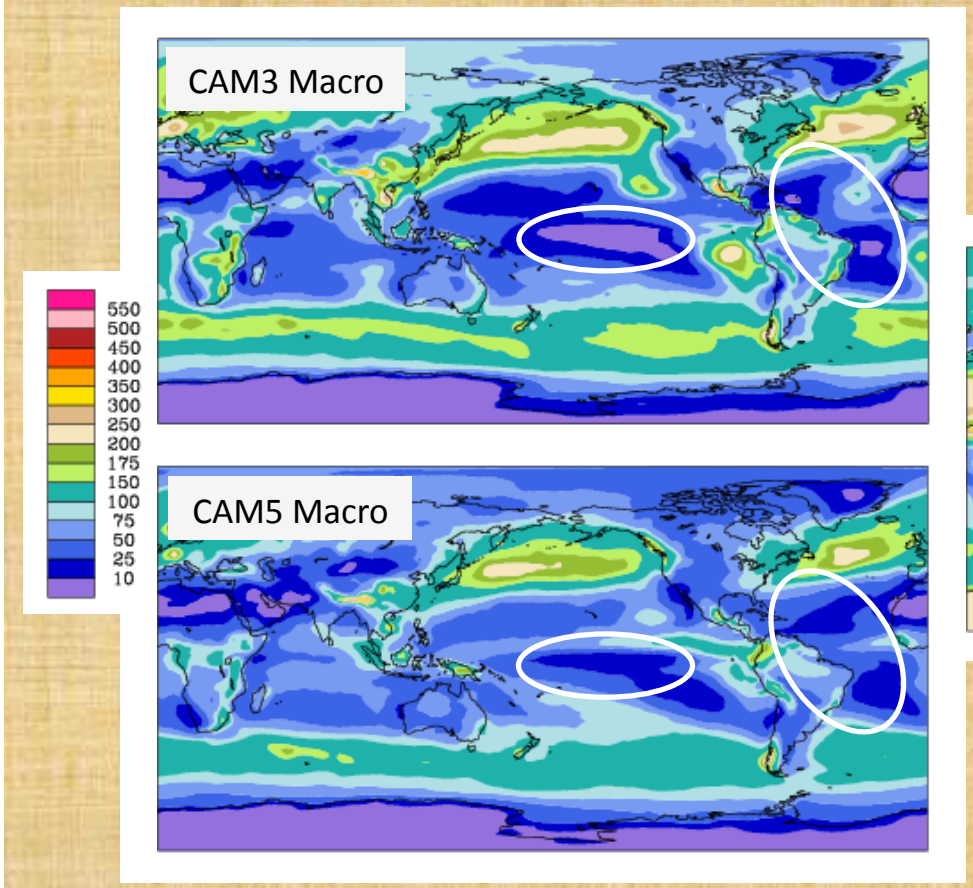


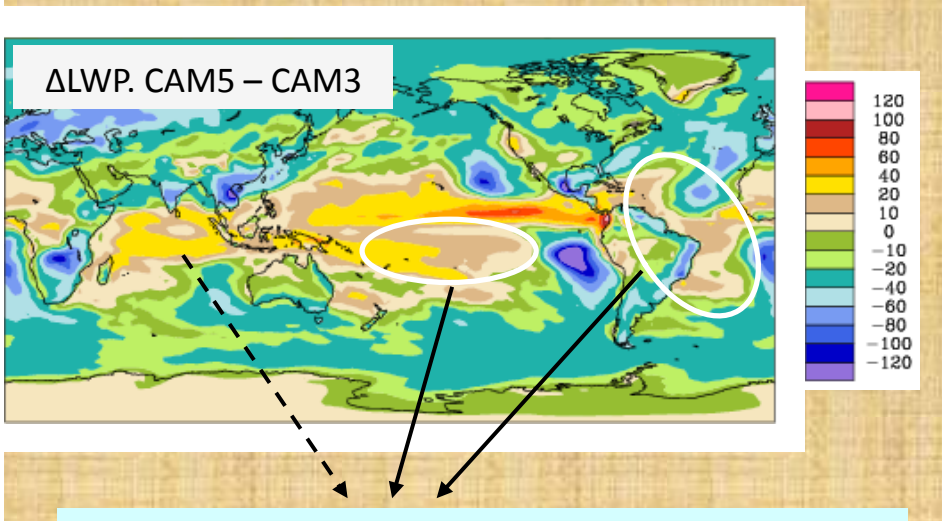






LWP. Annual Mean





LWP increase in the
trade cumulus & deep convective areas
due to explicit treatment of in-cumulus LWC

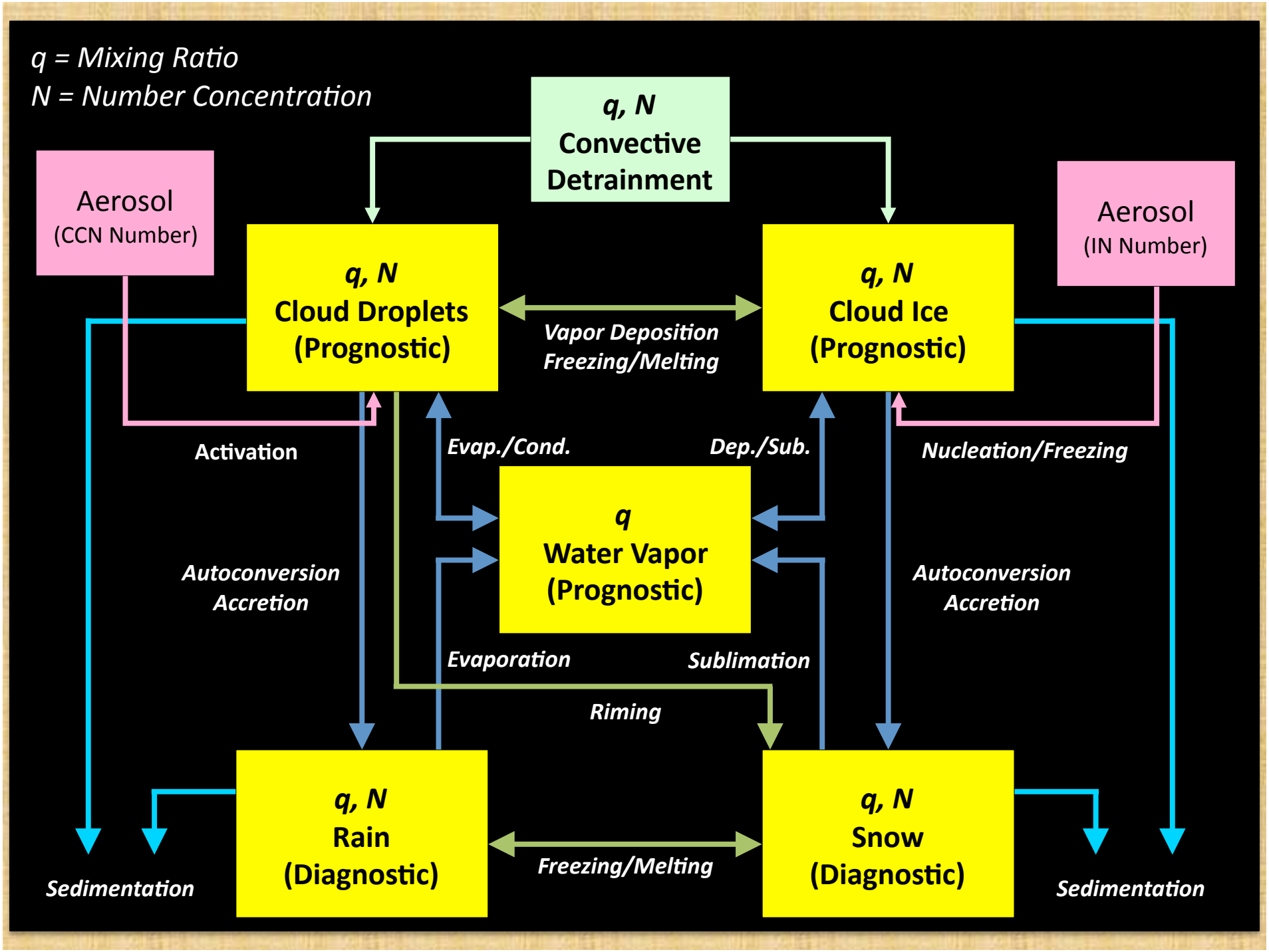
Cloud Microphysics Scheme in CAM5

Cloud Microphysics Scheme in CAM5

H. Morrison and A. Gettelman. 2008

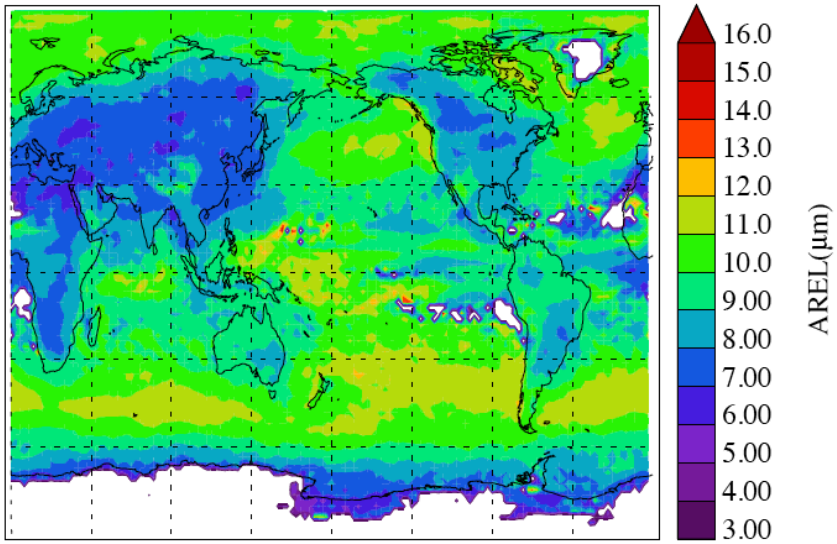
- 2-moment stratiform microphysics
  - Prognostic '*cloud mass*' and '*cloud droplet number*' (Γ-function size distributions)
  - Diagnostic 'precipitation mass' and 'precipitation droplet number'
- Cloud liquid droplet activation (Abdul-Razzak & Ghan 2002)
- Cloud ice crystal nucleation (Liu et al. 2007)
  - Homogeneous freezing on Sulfate
  - Heterogeneous nucleation on Dust
- Ice supersaturation and explicit vapor deposition
- Consistent treatment of clouds in radiation code
  - Parameters of Γ distribution describe cloud radiative properties
  - Snow is radiatively active.

Some slides in this section by the courtesy of Andrew Gettelman, NCAR

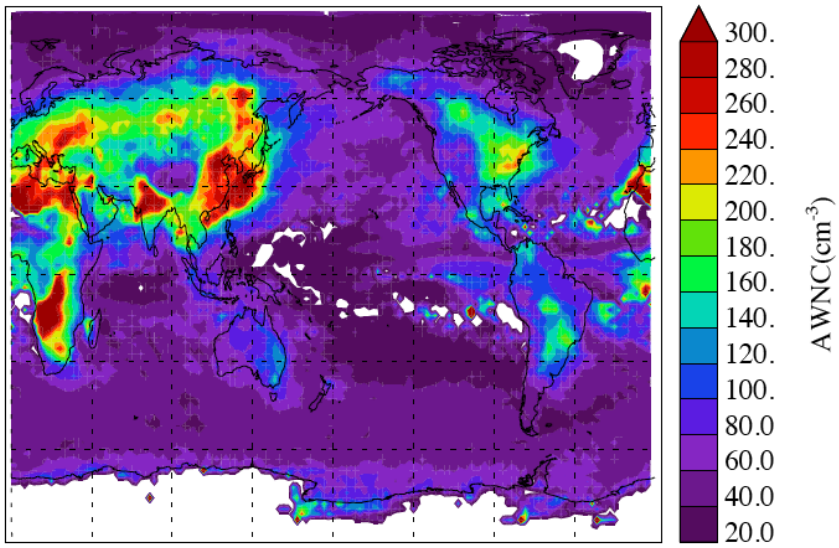

q = Mixing Ratio
N = Number Concentration
q, N
Convective
Detrainment
Aerosol
(CCN Number)
Aerosol
(IN Number)
q, N
Cloud Droplets
(Prognostic)
q, N
Cloud Ice
(Prognostic)
Vapor Deposition
Freezing/Melting
Activation
Evap./Cond.
Dep./Sub.
Nucleation/Freezing
q
Water Vapor
(Prognostic)
Autoconversion
Accretion
Autoconversion
Accretion
Evaporation
Sublimation
Riming
q, N
Rain
(Diagnostic)
q, N
Snow
(Diagnostic)
Freezing/Melting
Sedimentation
Sedimentation

Global Distribution (820hPa): Liquid

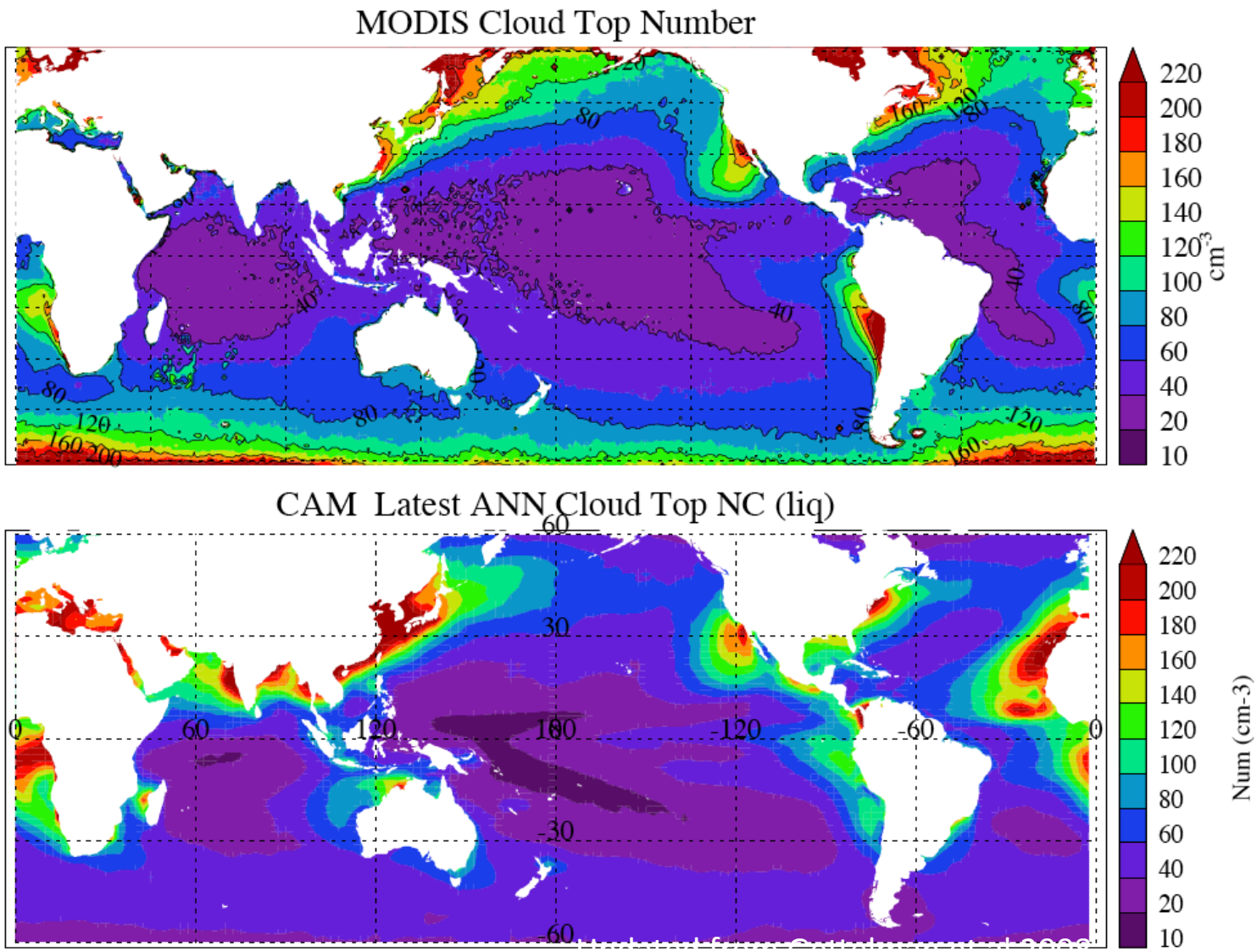
Drop Size (r_e)



Number Concentration



‘Cloud Top’ Drop Number



Aerosol Scheme in CAM5

Aerosol Scheme in CAM5 – Modal Aerosol Model

X. Liu and S. Ghan. 2007

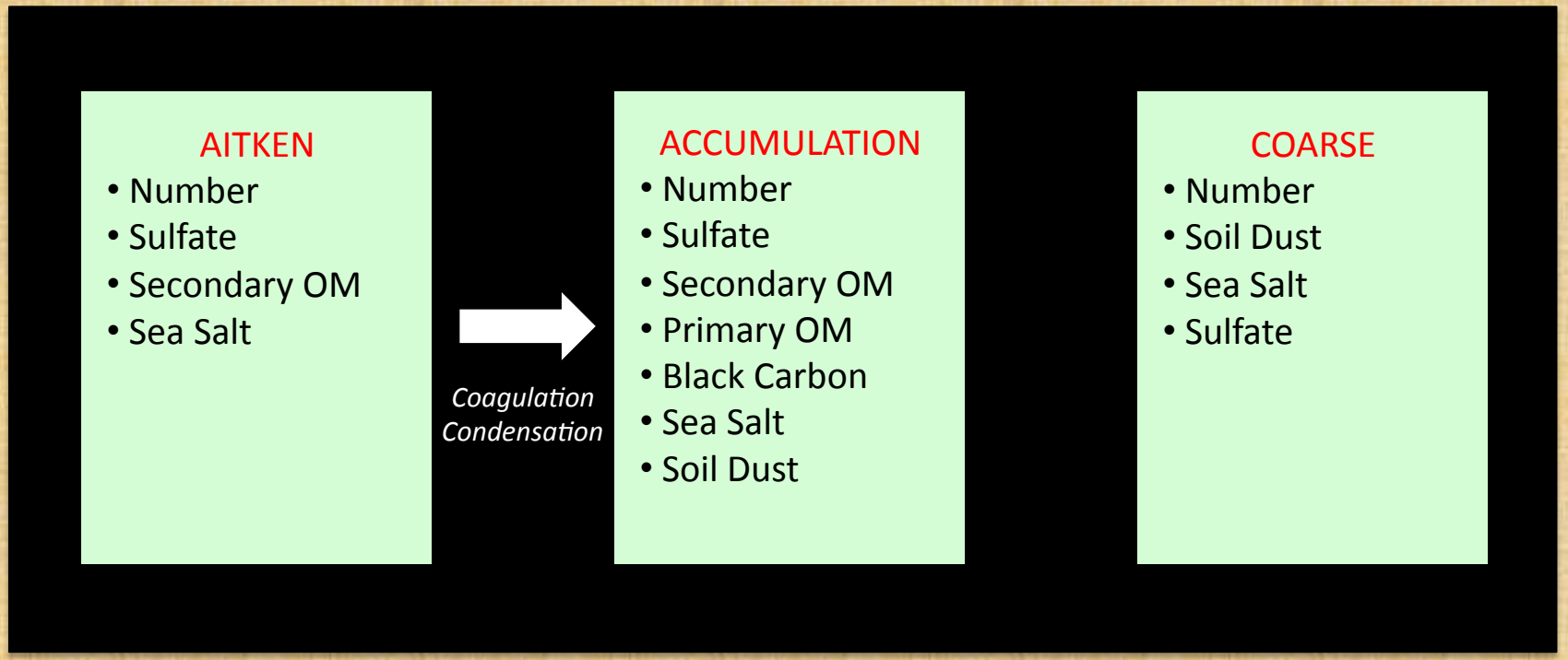
- 2-moment ('*mass*' and '*number*') aerosol scheme
- New particle formation in upper troposphere and boundary layer
- Coagulation within and between modes
- Dynamic condensation of trace gases (H_2S0_4, NH_3) on aerosols
- A new secondary organic aerosol (SOA) treatment: Reversible condensation of SOA
- Aerosol optics from Ghan and Zaveri (JGR, 2007)
- 3 Aerosol Modes : Aitken, Accumulation, Coarse
- 5 Main Species : Dust, Sea Salt, Sulfate, Organic Carbon, Black Carbon

Some slides in this section by the courtesy of Xiaohong Liu, PNNL

Simplified 3-Modes Modal Aerosol Model

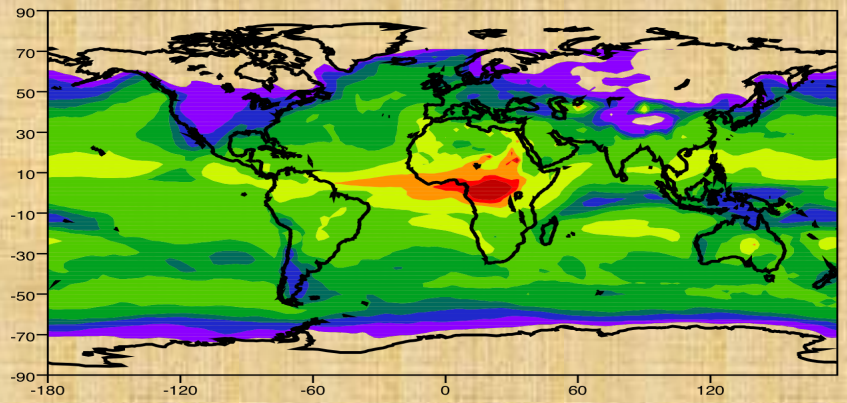
X. Liu and S. Ghan. 2007

- Primary carbon is internally mixed with secondary organic aerosols.
- Ammonium neutralizes sulfate.
- Aging of primary carbon to accumulation mode based on sulfate coating by condensation and coagulation.
- Sources of dust and sea salt are geographically separated.
- Total transported aerosol tracers : 15
- Computation time is 30% higher than Bulk Aerosol Model (BAM) of CAM3.

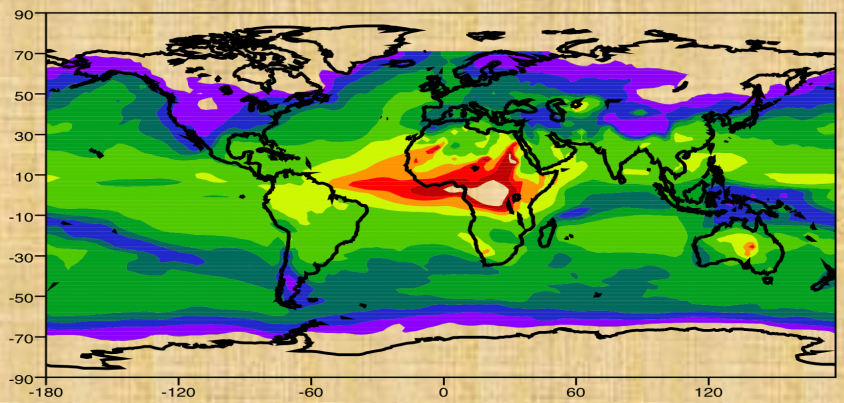


Aerosol Optical Depth - January

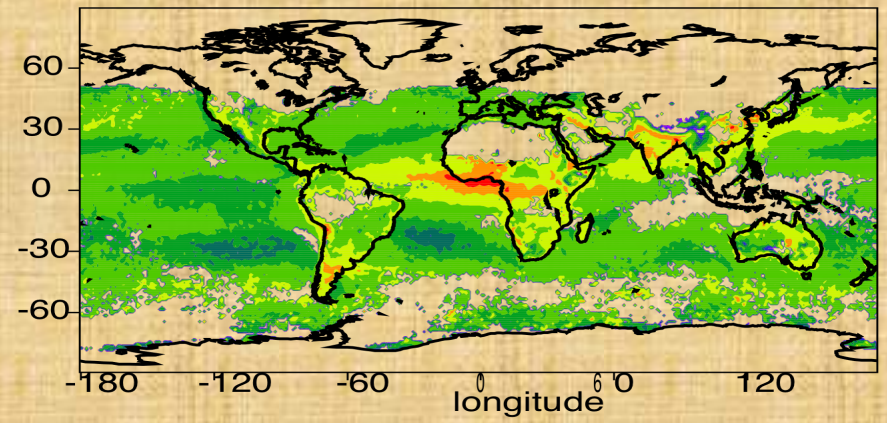
MAM3 AOD=0.12



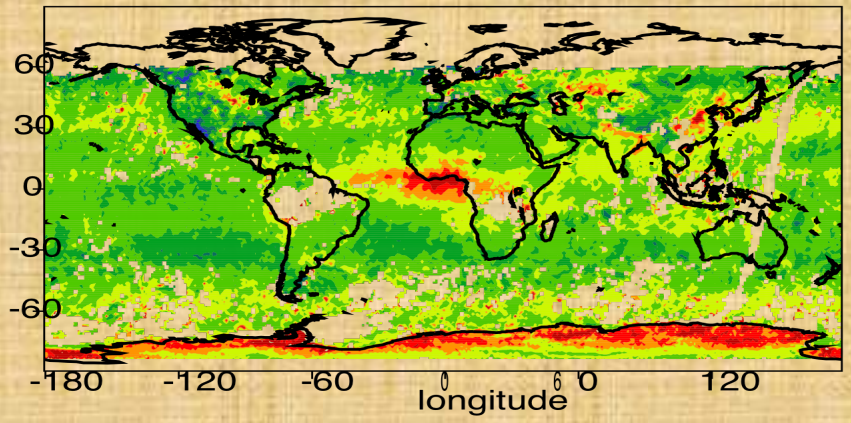
MAM7 AOD=0.12



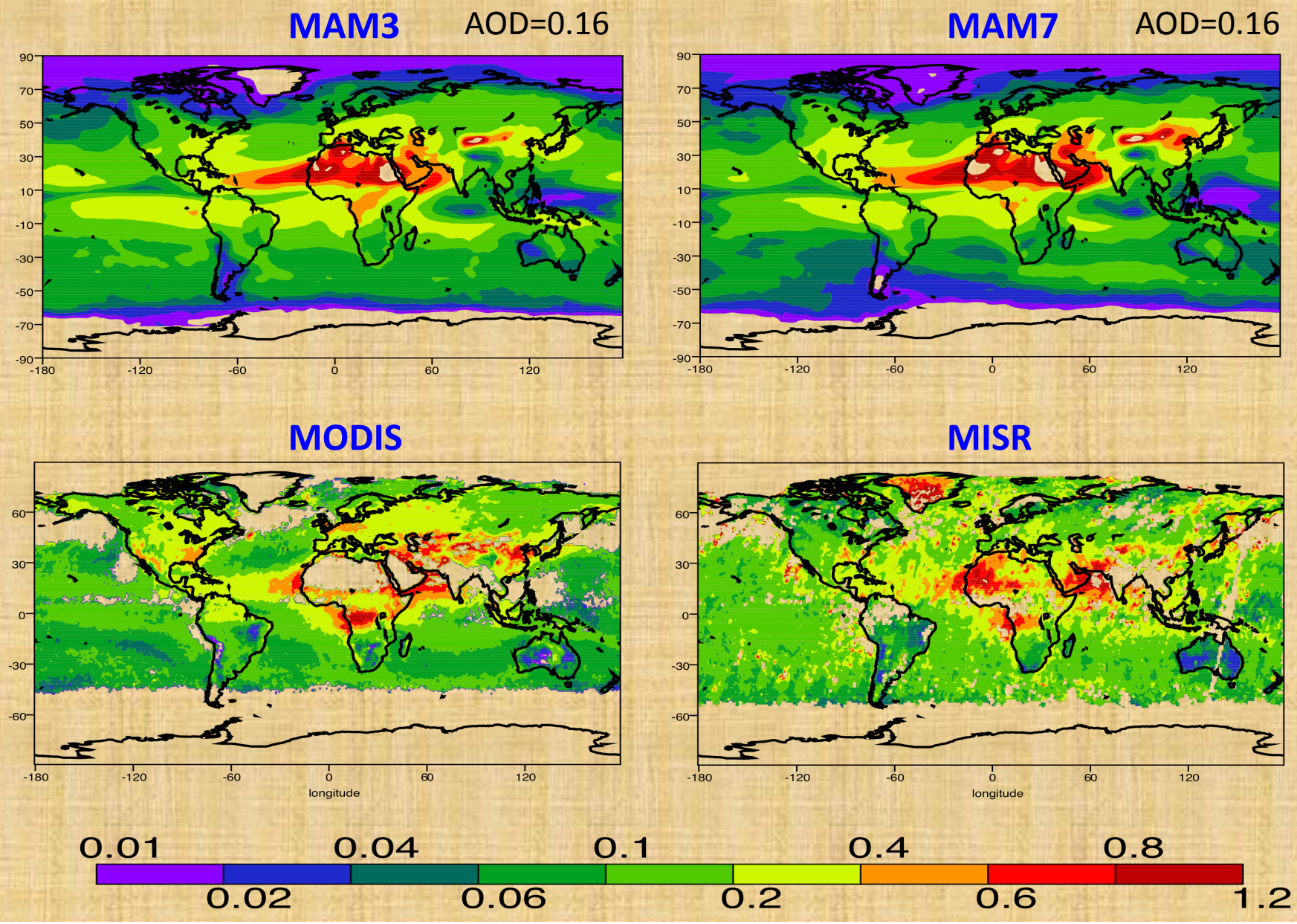
MODIS



MISR



Aerosol Optical Depth - July



Radiation Scheme in CAM5

Radiation Scheme in CAM5 – RRTMG

A. Conley, B. Collins, M. Iacono et al. 2004

- Correlated-*k* method for '*gases*' in LW and SW
- Comprehensive treatments of different optical properties of '*aerosols*' and '*cloud condensates*' by considering sub-grid scale size distributions.
- Sub-column generation assuming maximum-random overlap of a single cloud fraction in each layer.
- Monte Carlo Independent Column Approximation for clouds
- Much greater accuracy relative to LBL calculations.
- New treatment of cloud optics:
  - Liquid Optics : Slingo → Conley
  - Ice Optics : Ebert/Curry → Mitchell

Some slides in this section by the courtesy of Andrew Conley, NCAR

Radiation Scheme in CAM5 – RRTMG

A. Conley, B. Collins, M. Iacono et al. 2004

Stratus Macro.-Micro. & Convection Schemes

- Stratus Fraction (Liquid/Ice)
- Stratus Drop Size Parameters (Liquid/Ice)
- Shallow Cumulus Fraction
- Deep Cumulus Fraction
- Shallow Cumulus LWC/IWC
- Deep Cumulus LWC/IWC

Cloud Merger

- Cloud Fraction
- Cloud LWC/IWC
- Cloud Droplet Size Parameters (Liquid/Ice)

Sub-Column Generator

- Group to 'Low/Med/Hgh' Cloud
- Maximum-Random Ver. Overlap

For Individual Sub-Column

Gases

- Dry Air
- Water Vapor
- CO_2
- Ozone
- Others

Aerosols

- Sulfate
- Dust
- Sea Salt
- Organic Carbon
- Black Carbon

Cloud Condensates

- Cloud LWC/IWC
- Cloud Droplet Size Parameters

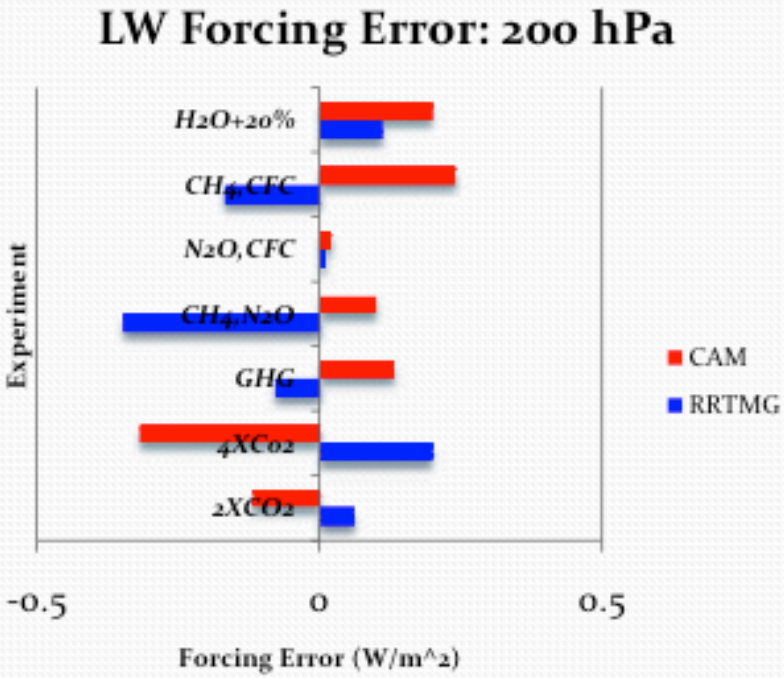
Optics for each Gases/Aerosols/Cloud-Condensates

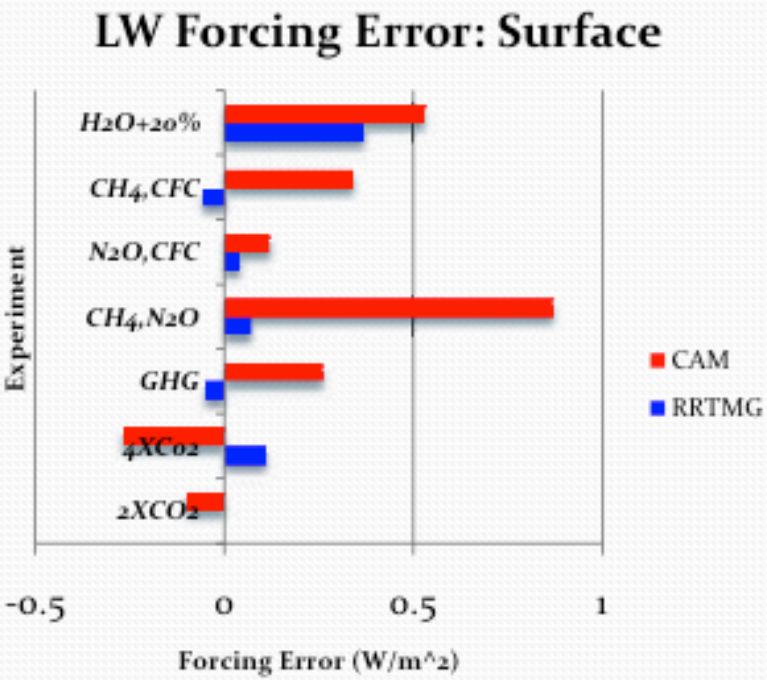
- Optical Depth / Single Scattering Albedo / Asymmetry Parameters

Monte-Carlo Independent Column Approximation Radiative Transfer Computation

Sub-Column Average to compute Grid-Mean Radiative Heating

Climate Forcing Accuracy (RTMIP)*





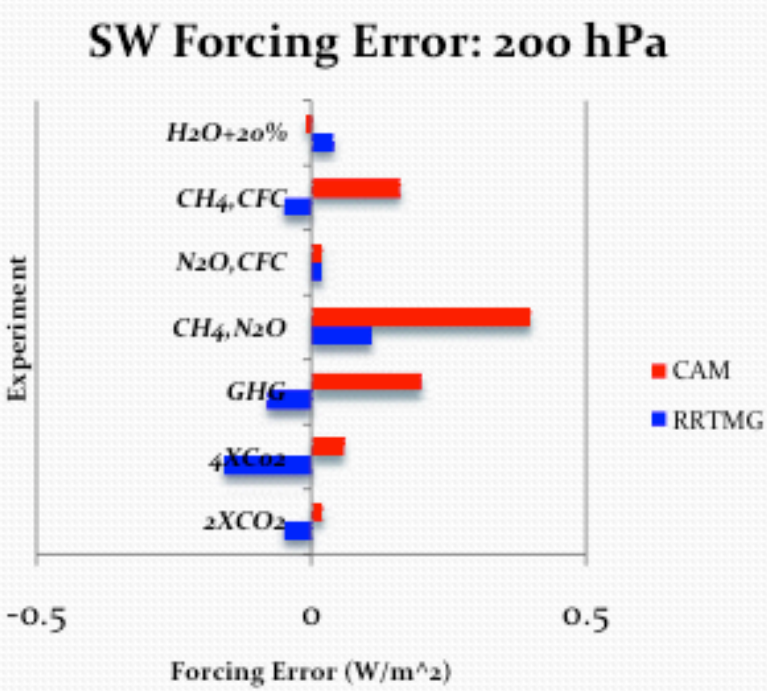
LW Benchmark code is LBLRTM.

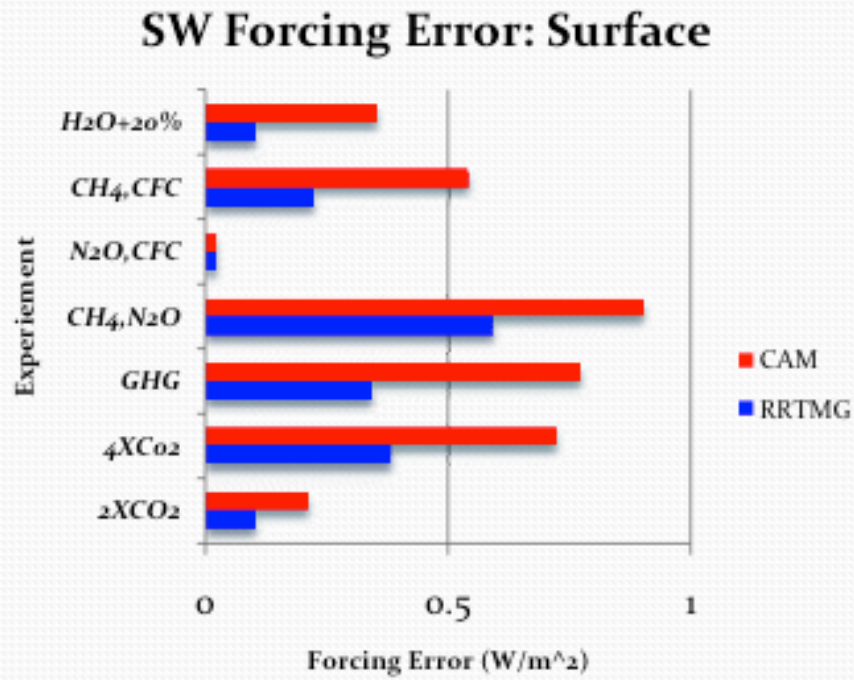
Experiments:

- *GHG ::* *1860->2000 (all species)*
- *CH_4,N_2O ::* *0 ppm -> 2000*
- *N_2O, CFC ::* *1860 -> 2000*
- *CH_4,CFC ::* *1860 -> 2000*

*Collins et al, 2006; Iacono et al 2008

Climate Forcing Accuracy (RTMIP)*





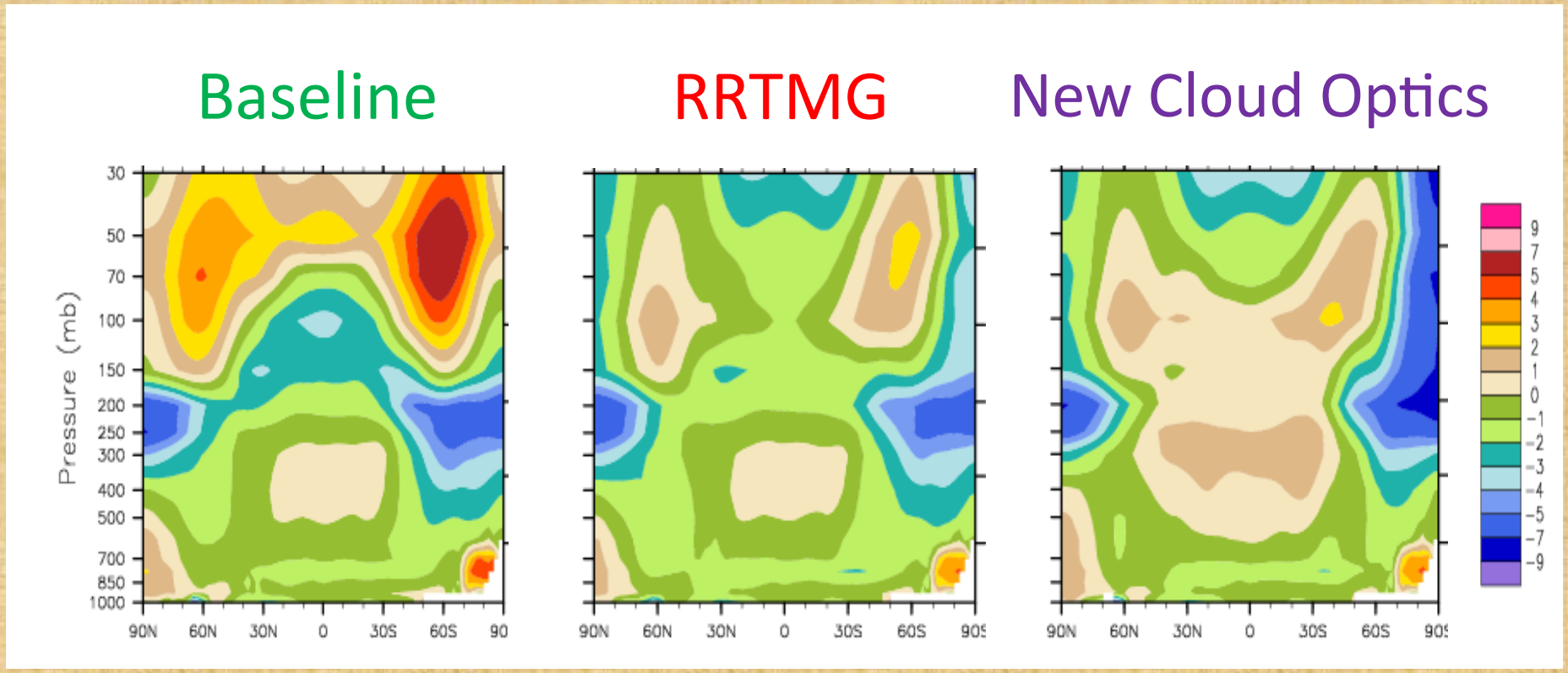
SW Benchmark code is CHARTS.

Experiments:

- *GHG ::* *1860->2000 (all species)*
- *CH4,N2O ::* *0 ppm -> 2000*
- *N2O, CFC ::* *1860 -> 2000*
- *CH4,CFC ::* *1860 -> 2000*

*Collins et al, 2006; Iacaono et al 2008

Temperature Errors



Difference from ERA40 Temperature

CAM5 Global Simulations

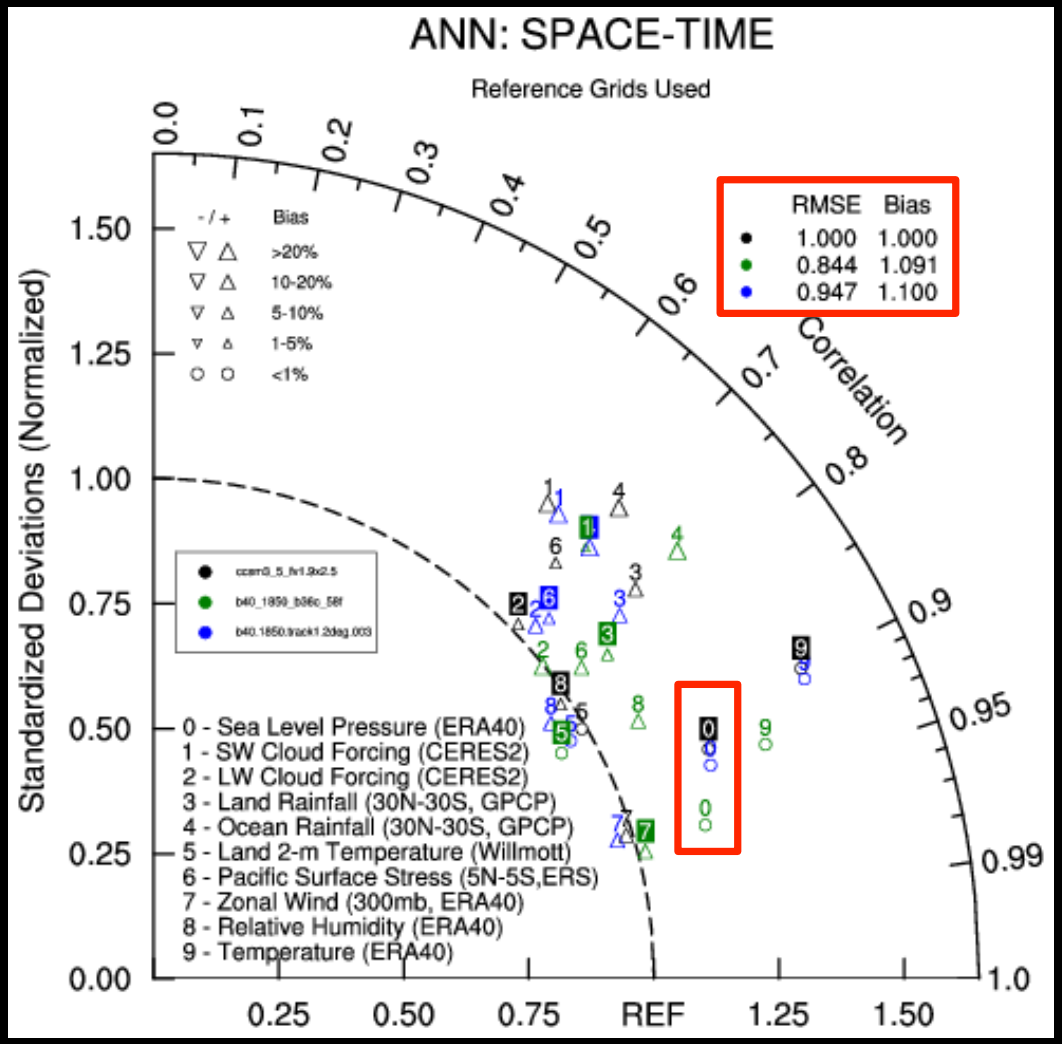
1850 Control Simulations

- Green House Gases (GHGs) and Aerosols in the year 1850 situation
- CESM1/CAM5 (Horizontal : 2^ox2^o, Vertical : 30 Layers)
  - 130+ year control (years 101-125)
  - Prescribe aerosol emissions & Predicted surface deposition
- CCSM4/CAM4 (Horizontal : 2^ox2^o, Vertical : 26 Layers)
  - 500+ year control
  - Prescribe aerosol burdens and Prescribed surface deposition

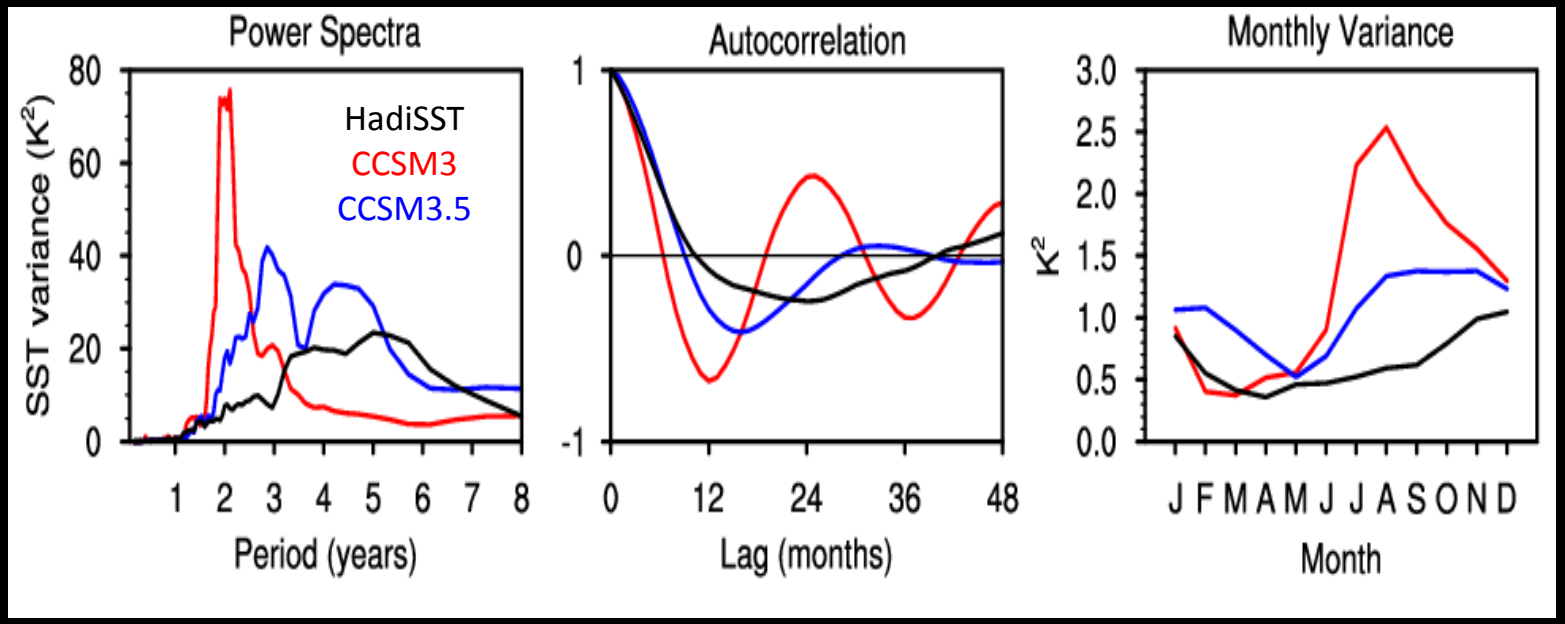
Some slides in this section by the courtesy of Richard Neale, NCAR

Taylor Metrics Summary

CCSM3.5
CCSM4
CESM1

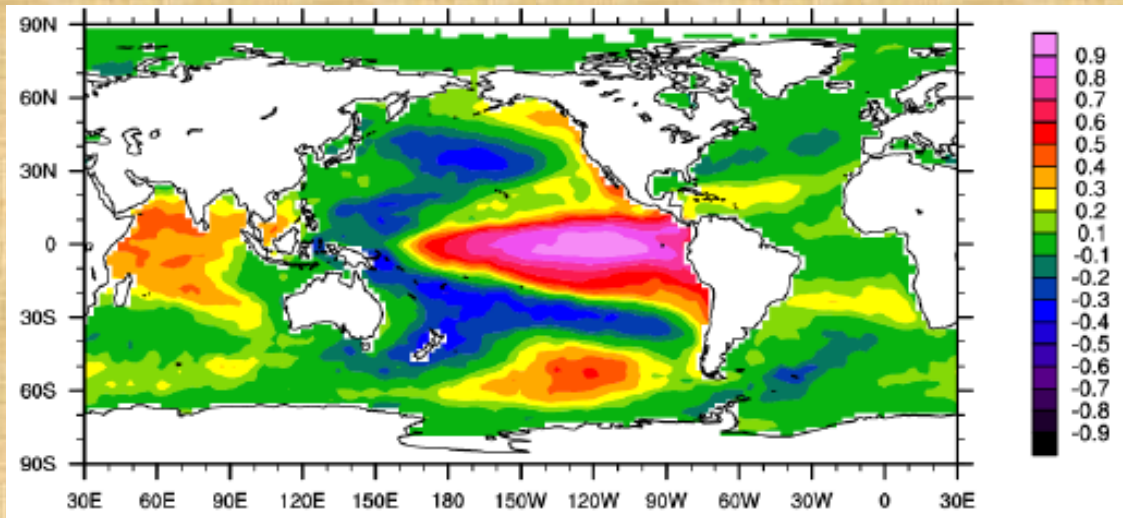


ENSO (Nino3 SST Anomaly)

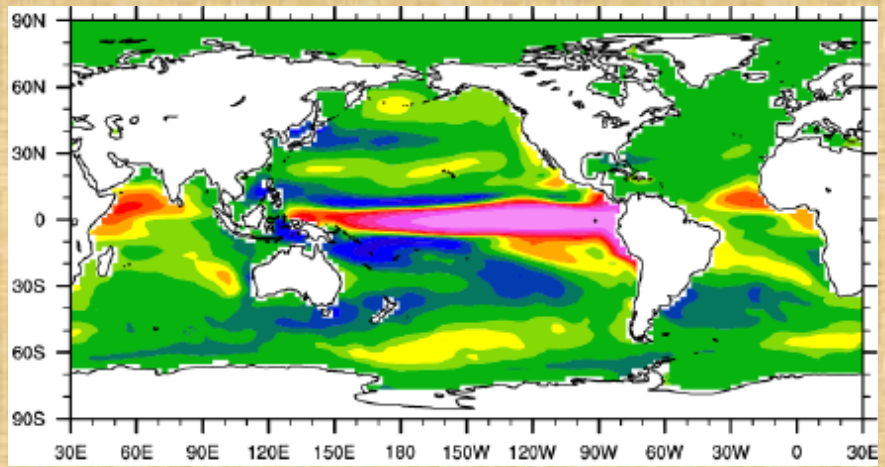


Lag 0 SST Correlation on Nino3 SST

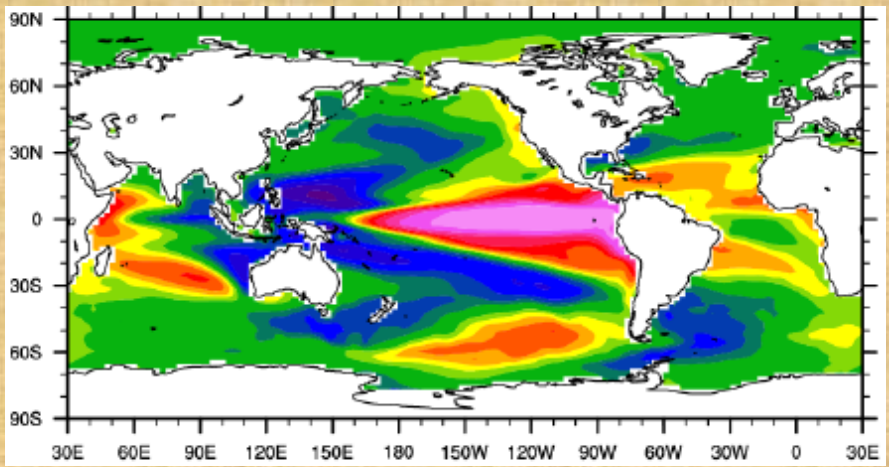
Observation



CCSM3



CCSM3.5

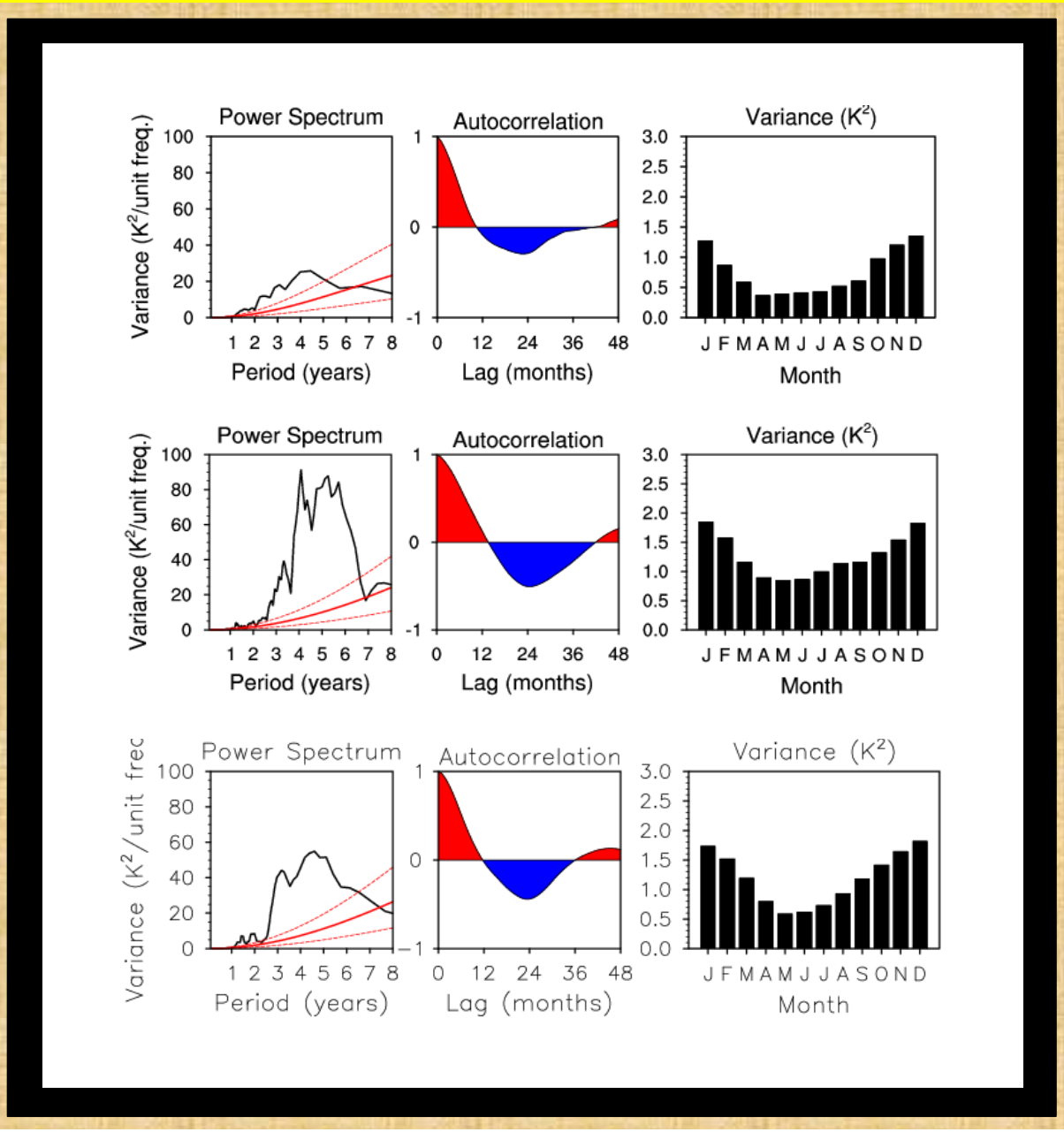


ENSO (Nino3.4 SST Anomaly)

Observation

CCSM4

CESM1

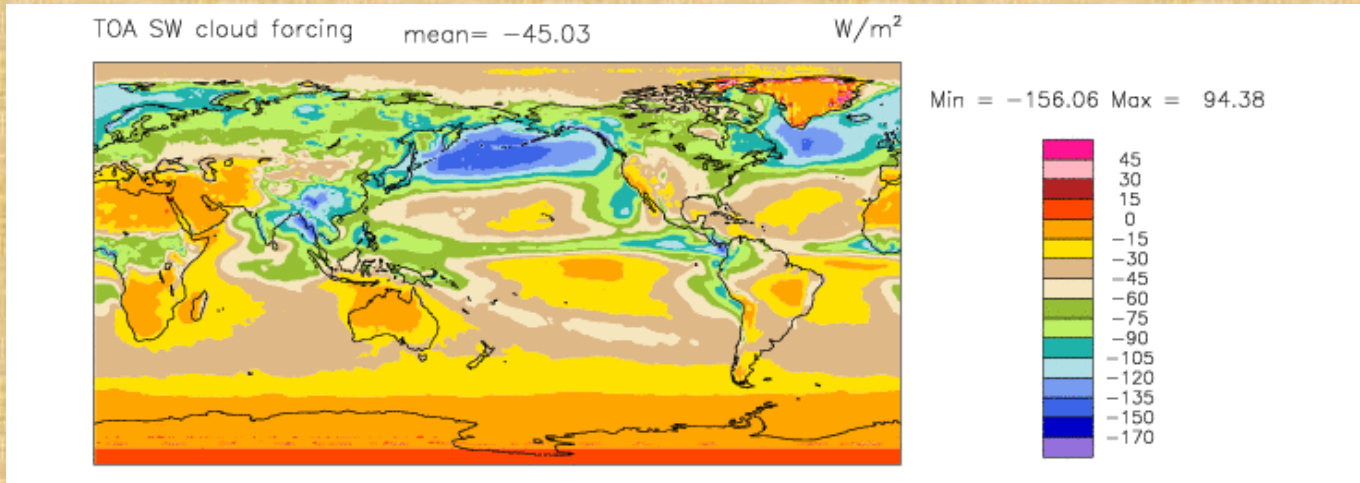


CLOUD RADIATIVE FORCING (CRF)

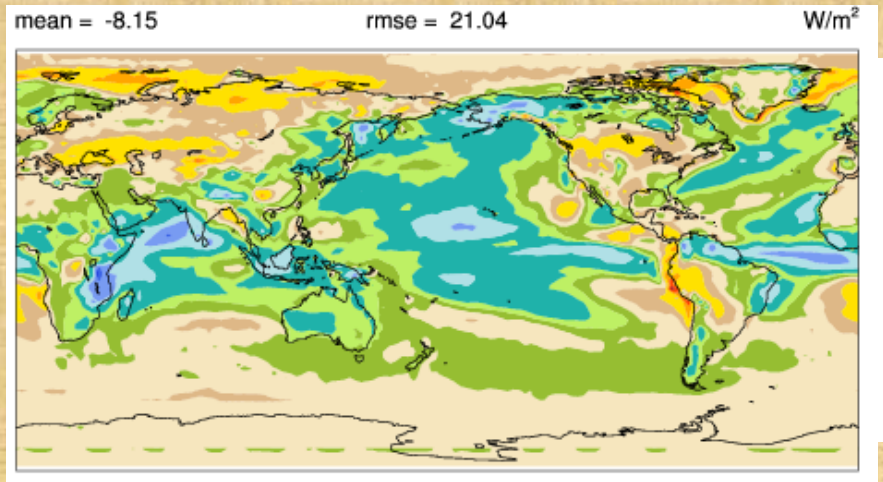
- CRF = net upward radiation of clear sky –
  net upward radiation of cloudy sky
- CRF > 0 (< 0) : Clouds warm (cool) the Earth-atmosphere
- CRF = a function of " cloud fraction, reflectivity, temperature, emissivity "

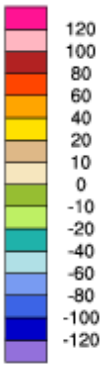
Short Wave Cloud Forcing (JJA)

Observation ('CERES-EBAF')

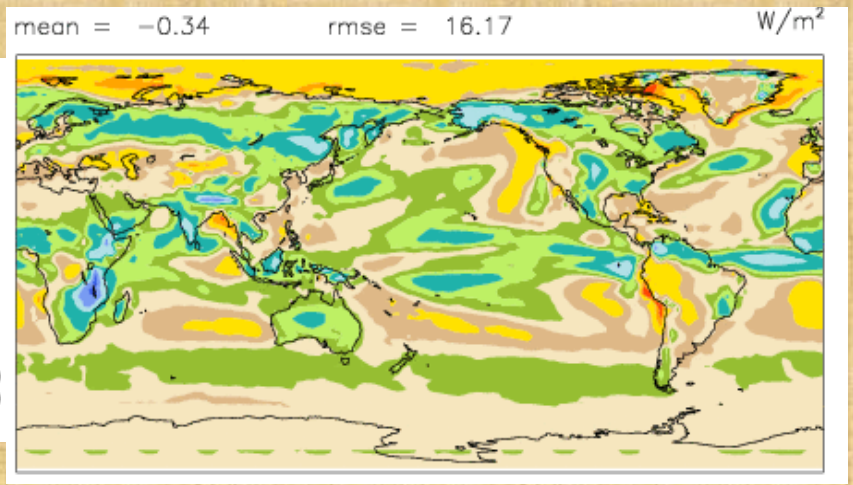


CAM4 - Observation



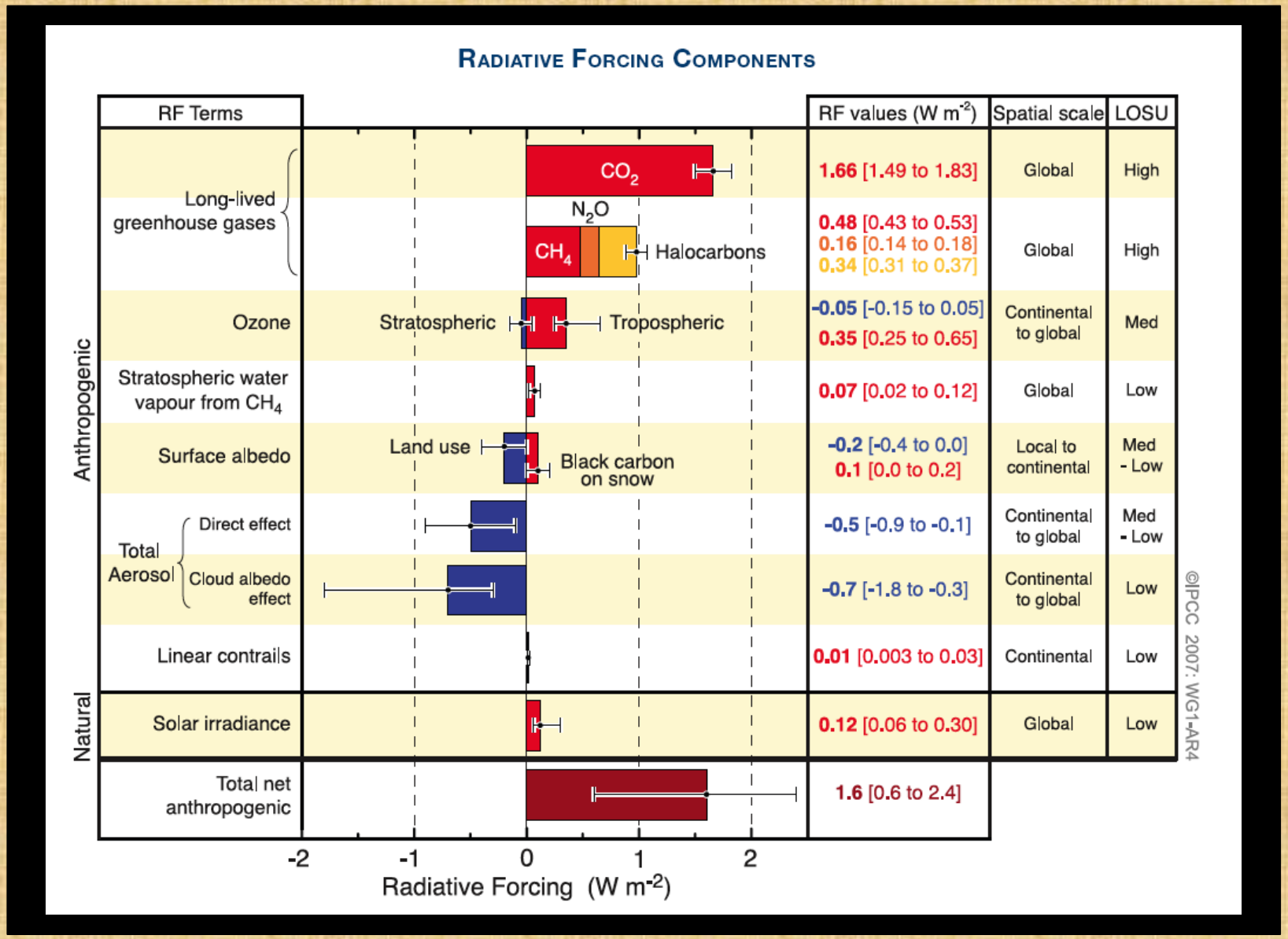


CAM5 - Observation



Cloud-Aerosol-Climate Interactions

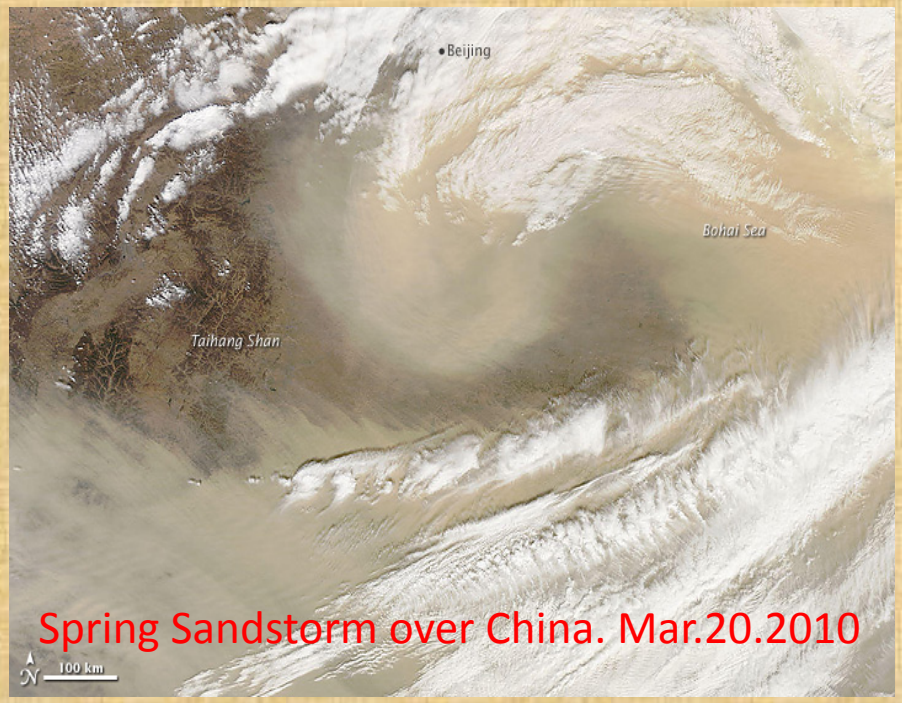
Why 'Cloud' and 'Aerosol' Processes are important ?



IPCC 2007 Policymakers Summary Figure 2

Aerosol Direct & Indirect Effects

Aerosol Direct Effect

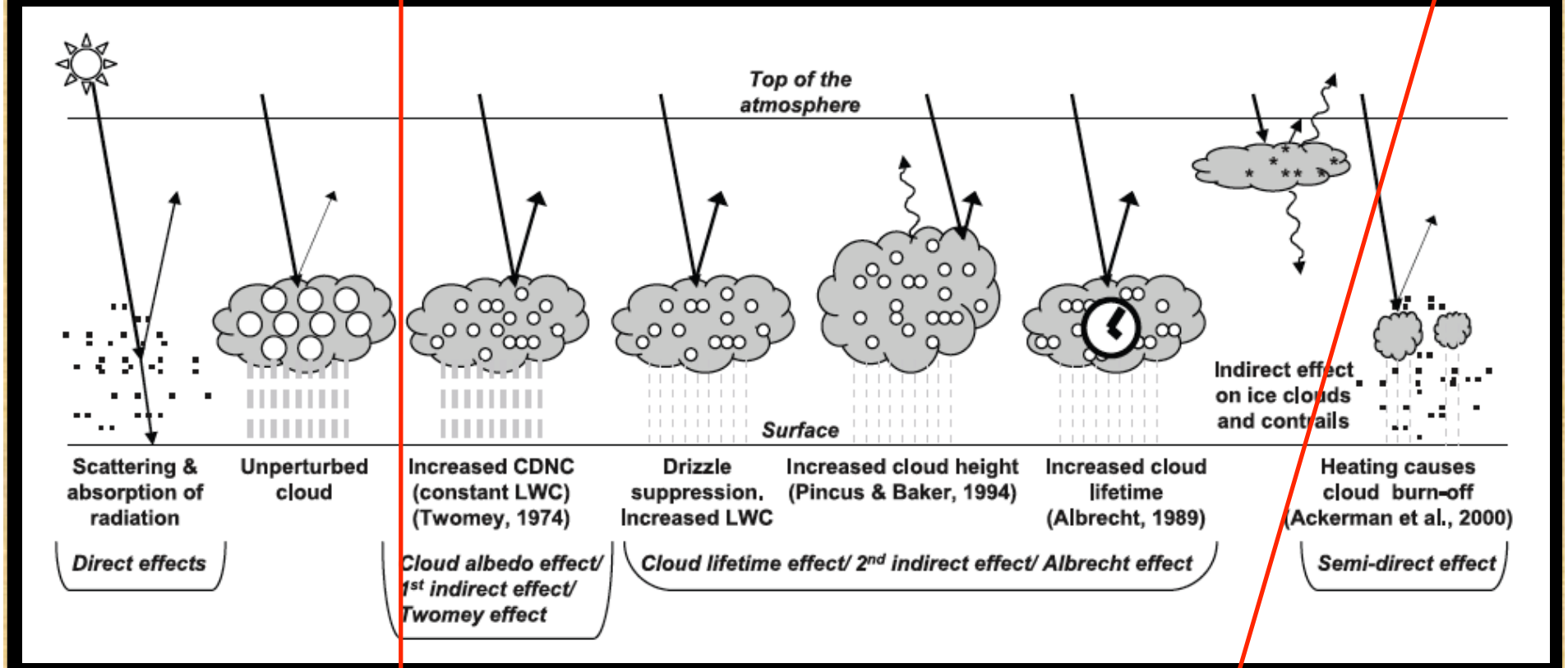


Spring Sandstorm over China. Mar.20.2010

Aerosol Indirect Effect

Ship Track Image. MODIS. 27.Jan.2003

‘Stratus-Aerosol’ Interactions

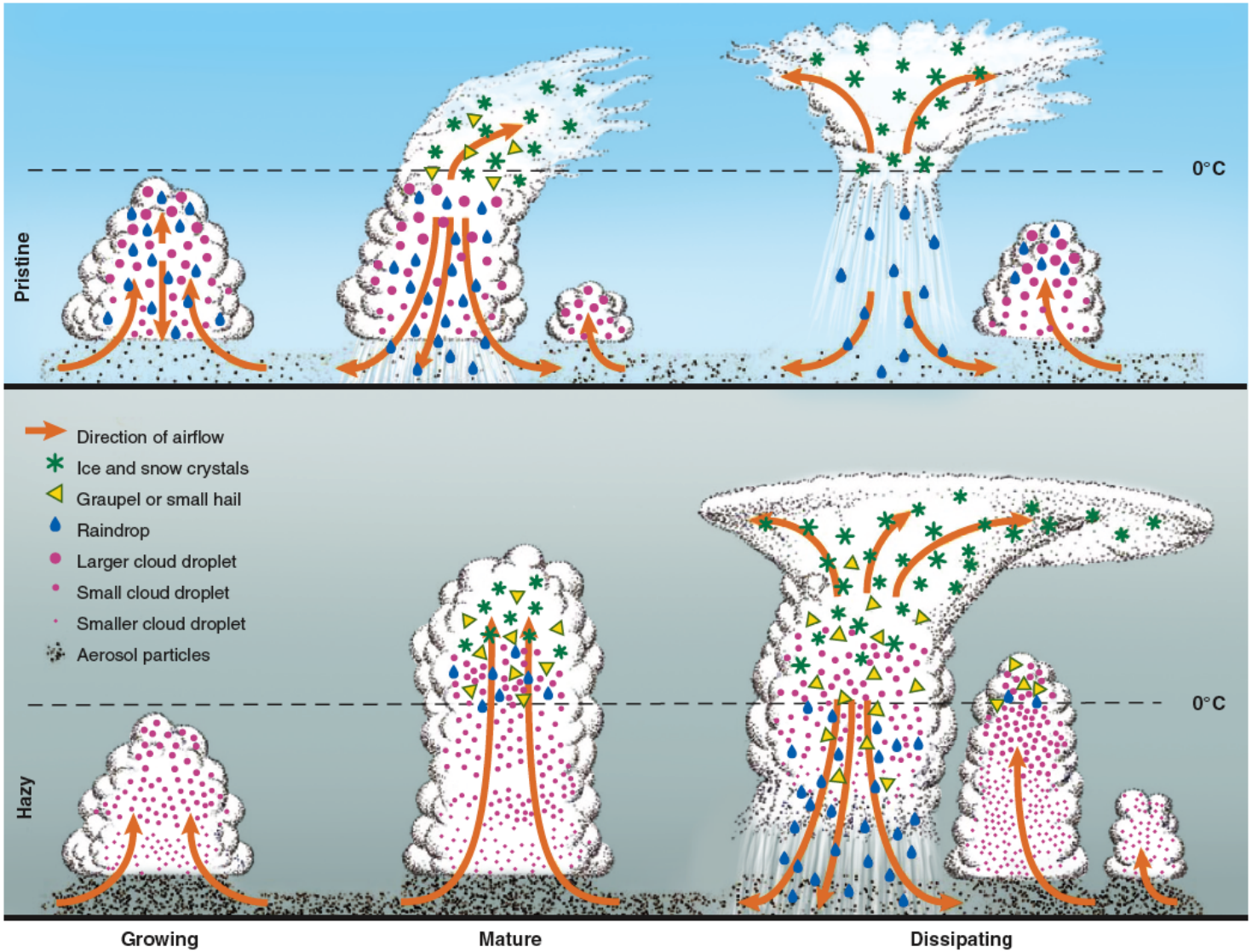


CAM3/CAM4/CAM5

Only CAM5 can simulate aerosol indirect effects associated with stratus thanks to the new ‘moist turbulence – microphysics – aerosol’ schemes.

CAM3/CAM4/CAM5

‘Cumulus–Aerosol’ Interactions



Rosenfeld et al, Science 2008

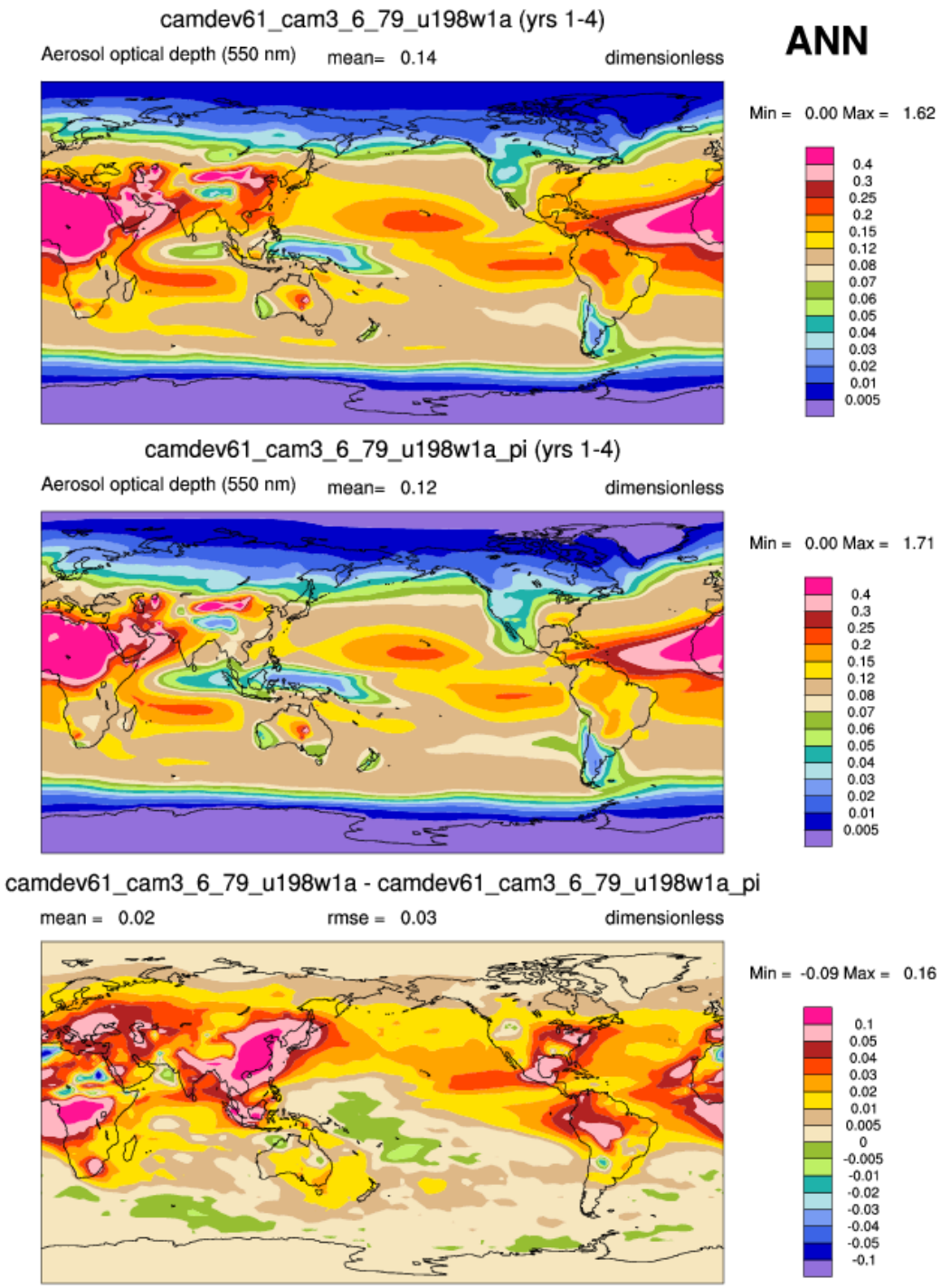
CAM5 cannot simulate complete ‘cumulus-aerosol’ interaction within convective updraft.

Simulations of Isolated Aerosol Effects in CAM5

- IPCC AR5 Emissions: Yr. 2000 & Yr. 1850
- Fixed (climatological) SST
- Fixed present day GHG's
- 5 years of simulation

Aerosol Emissions are Only Difference !

Aerosol Optical Depth

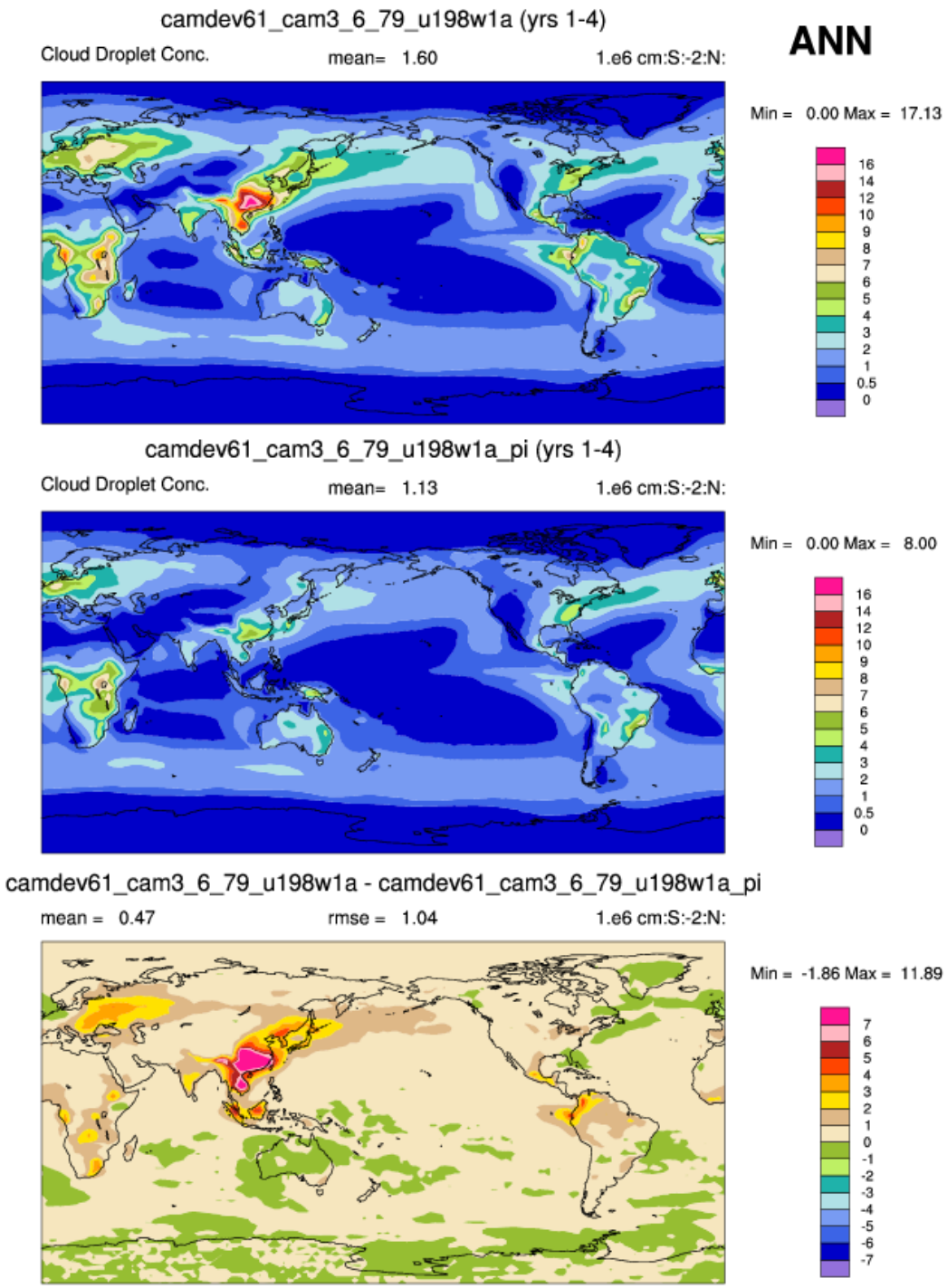


2000

1850

2000 - 1850

Vertically-Integrated Cloud Droplet #

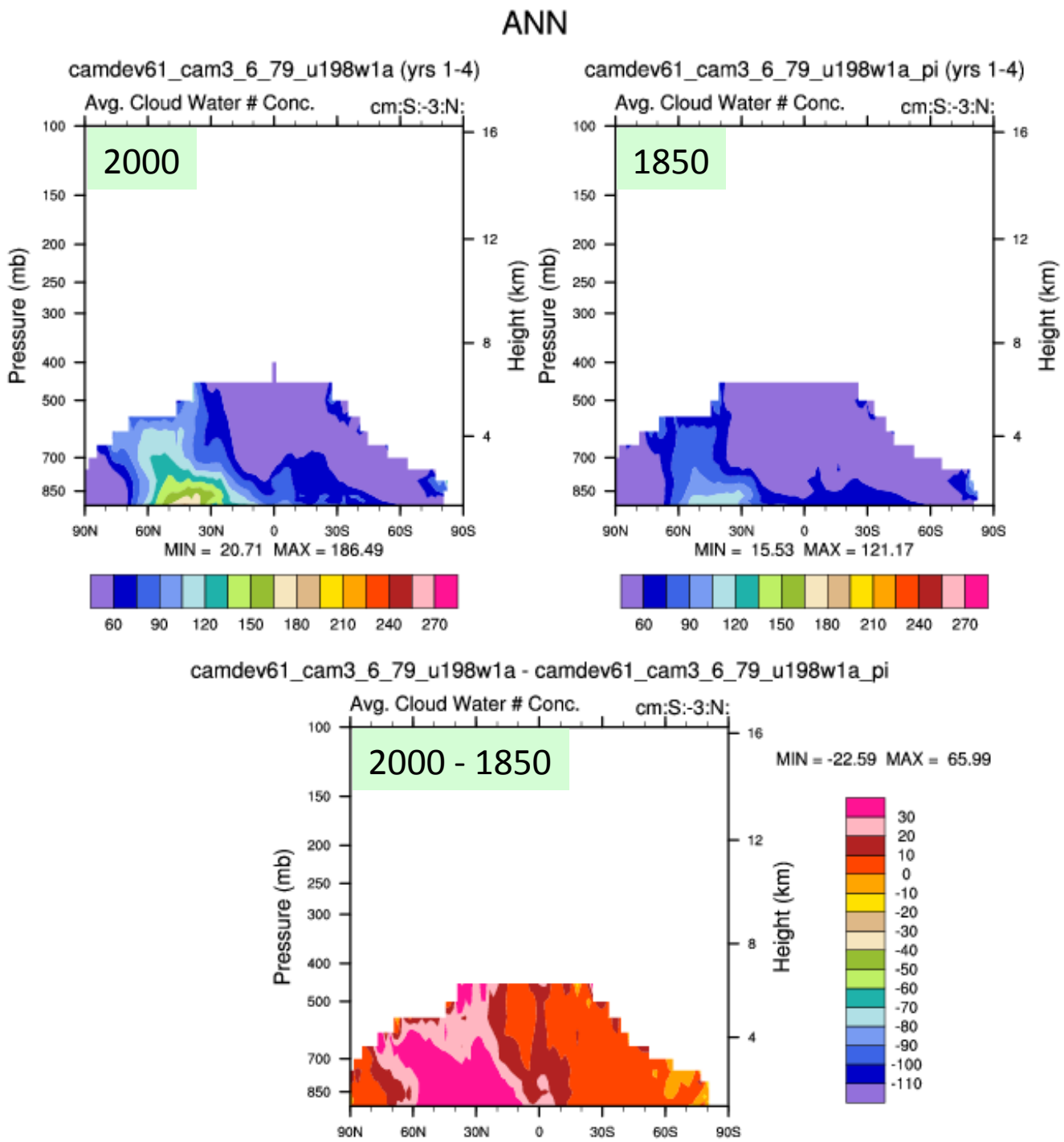


2000

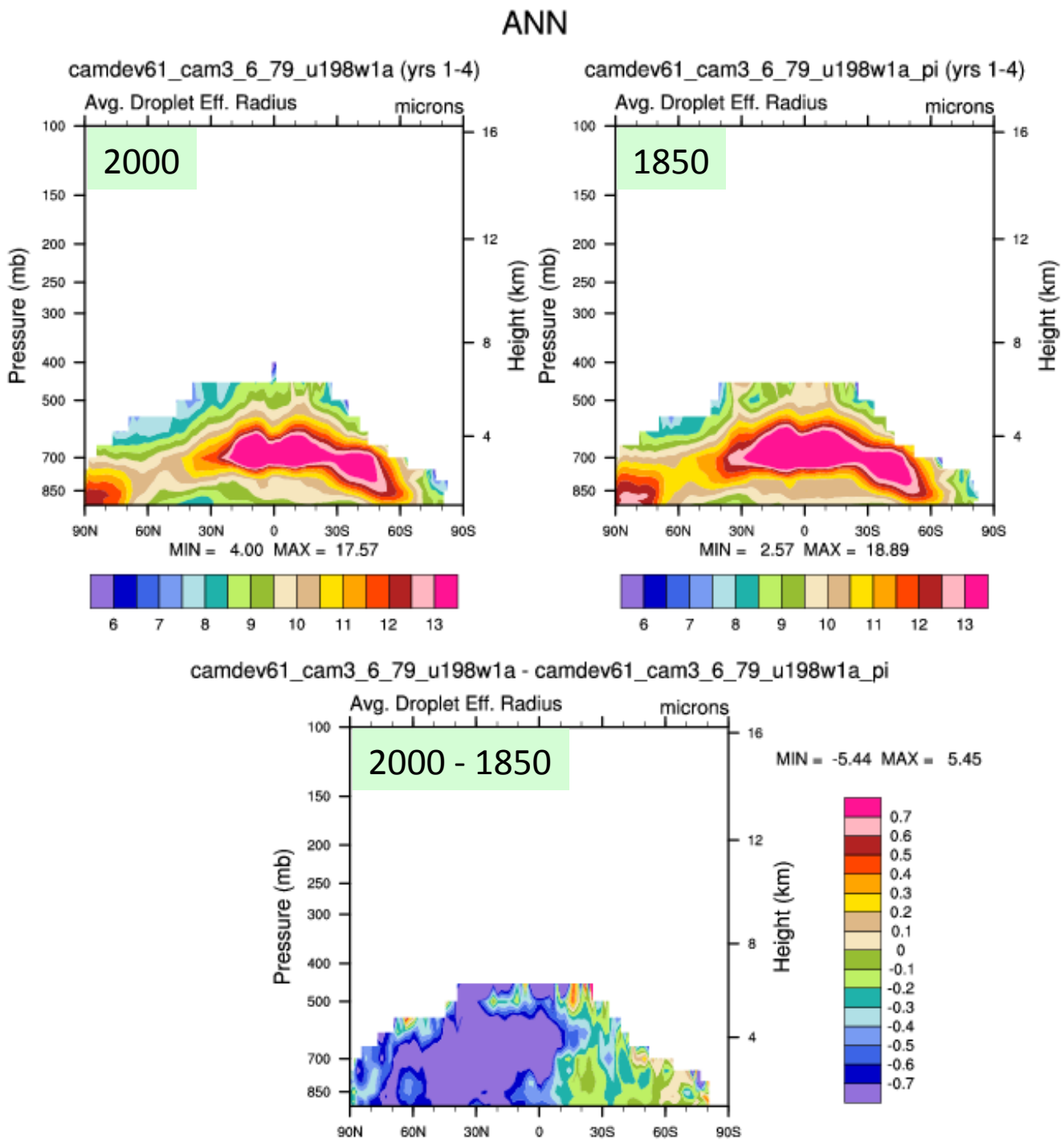
1850

2000 - 1850

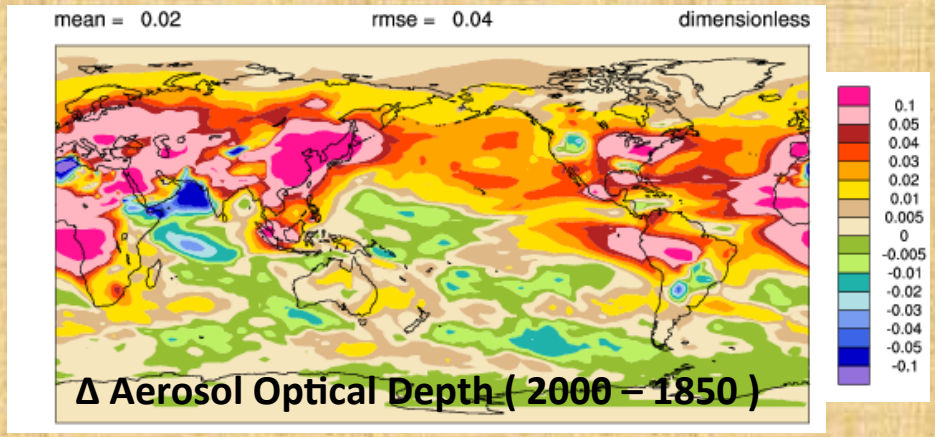
Liquid Cloud Droplet #

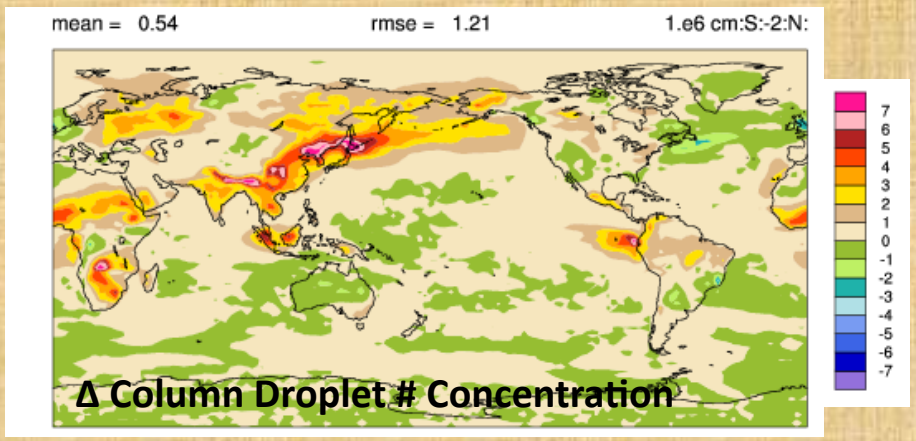


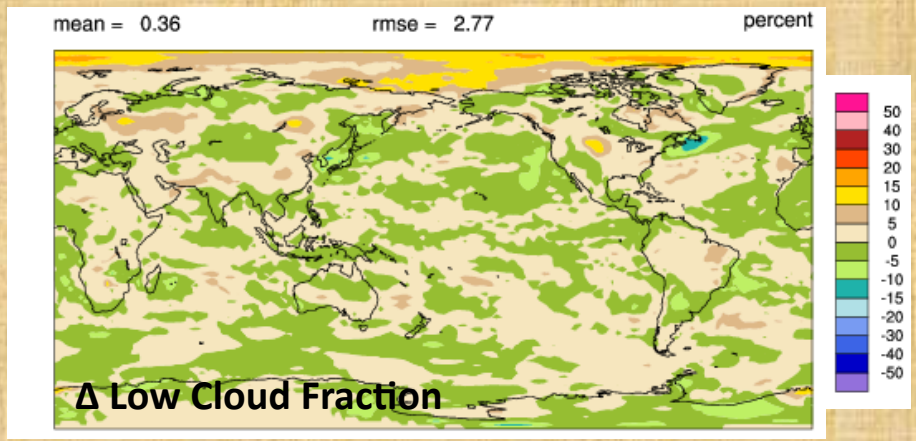
Effective Droplet Radius

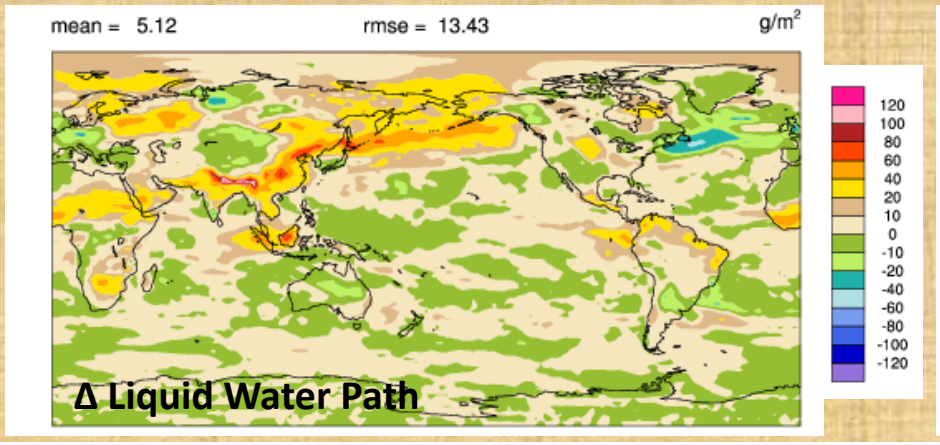


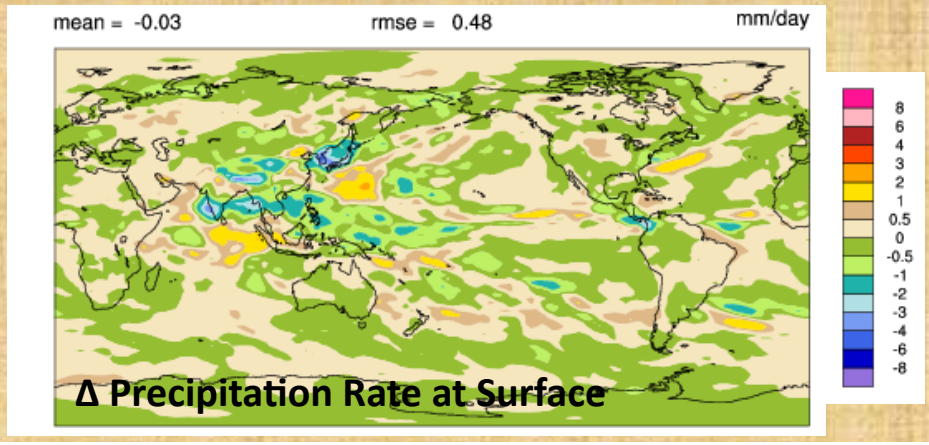
JJA


mean = 0.02
rmse = 0.04
dimensionless
0.1
0.05
0.04
0.03
0.02
0.01
0.005
0
-0.005
-0.01
-0.02
-0.03
-0.04
-0.05
-0.1
Δ Aerosol Optical Depth (2000 – 1850)


mean = 0.54
rmse = 1.21
1.e6 cm:S:-2:N:
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
Δ Column Droplet # Concentration

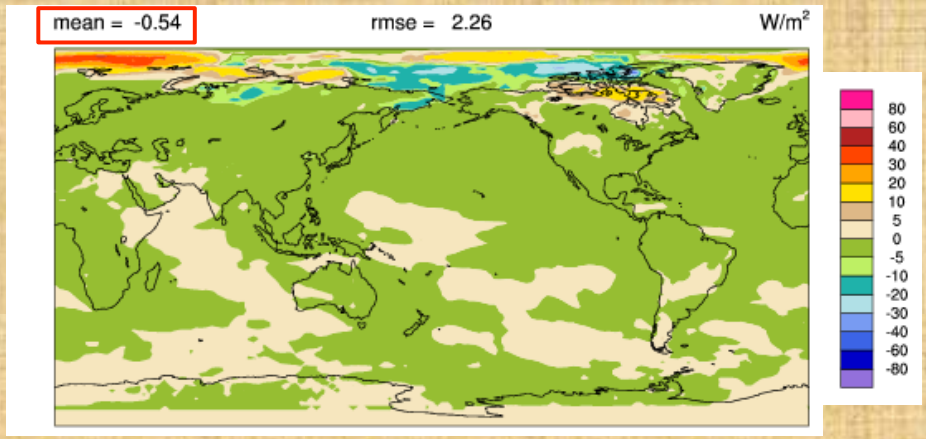

mean = 0.36
rmse = 2.77
percent
50
40
30
20
15
10
5
0
-5
-10
-15
-20
-30
-40
-50
Δ Low Cloud Fraction


mean = 5.12
rmse = 13.43
g/m2
120
100
80
60
40
20
10
0
-10
-20
-40
-60
-80
-100
-120
Δ Liquid Water Path

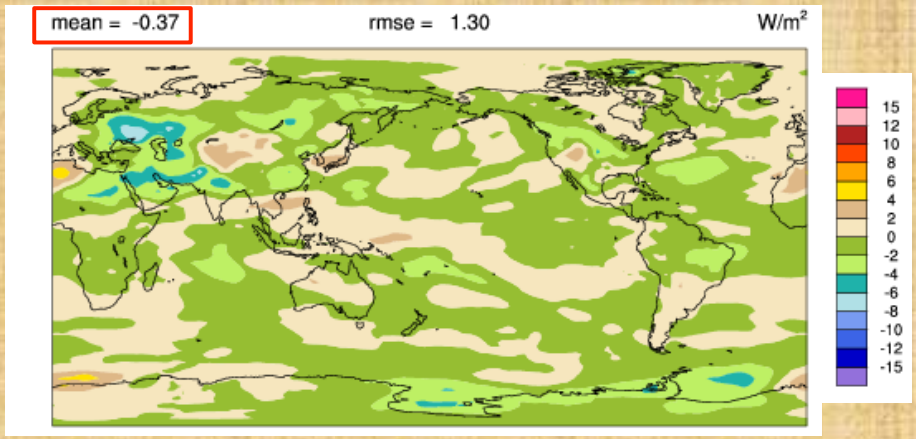

mean = -0.03
rmse = 0.48
mm/day
8
6
4
3
2
1
0.5
0
-0.5
-1
-2
-3
-4
-6
-8
Δ Precipitation Rate at Surface

Changes of Radiation Budgets at the Top of the Atmosphere. JJA

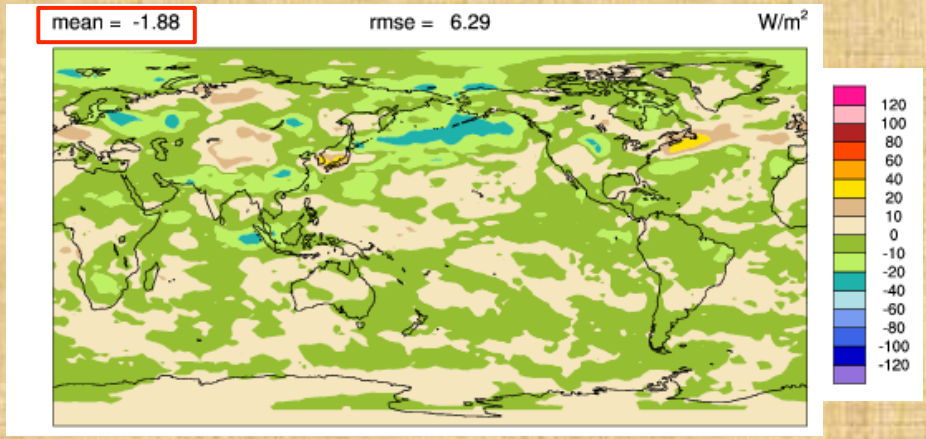
Δ Clear-Sky Net Downward SW



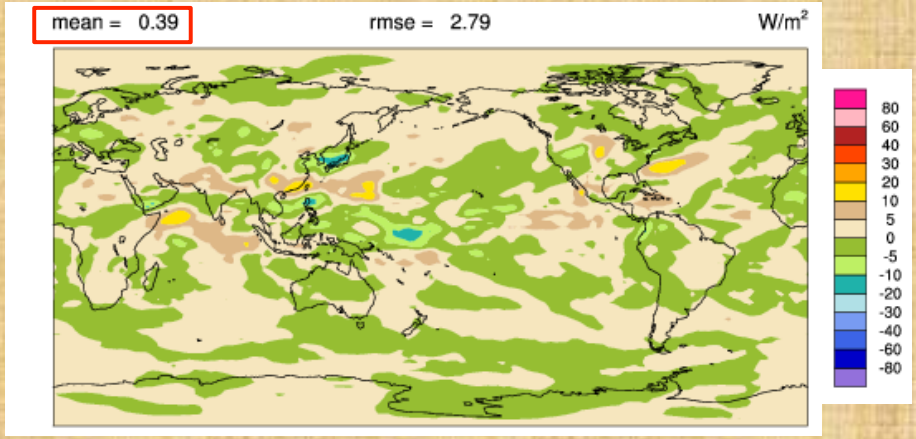
Δ Clear-Sky Net Upward LW



Δ SW Cloud Radiative Forcing



Δ LW Cloud Radiative Forcing



Aerosol Radiative Effects	[W m^{-2}]
SW A.I.E.	-1.55
LW A.I.E.	0.32
Net A.I.E.	-1.23
SW A.D.E.	-0.45
LW A.D.E.	0.22
Net A.D.E.	-0.23
Net A.E.	-1.46

Observed Net A.E. : -1.1 ± 0.8

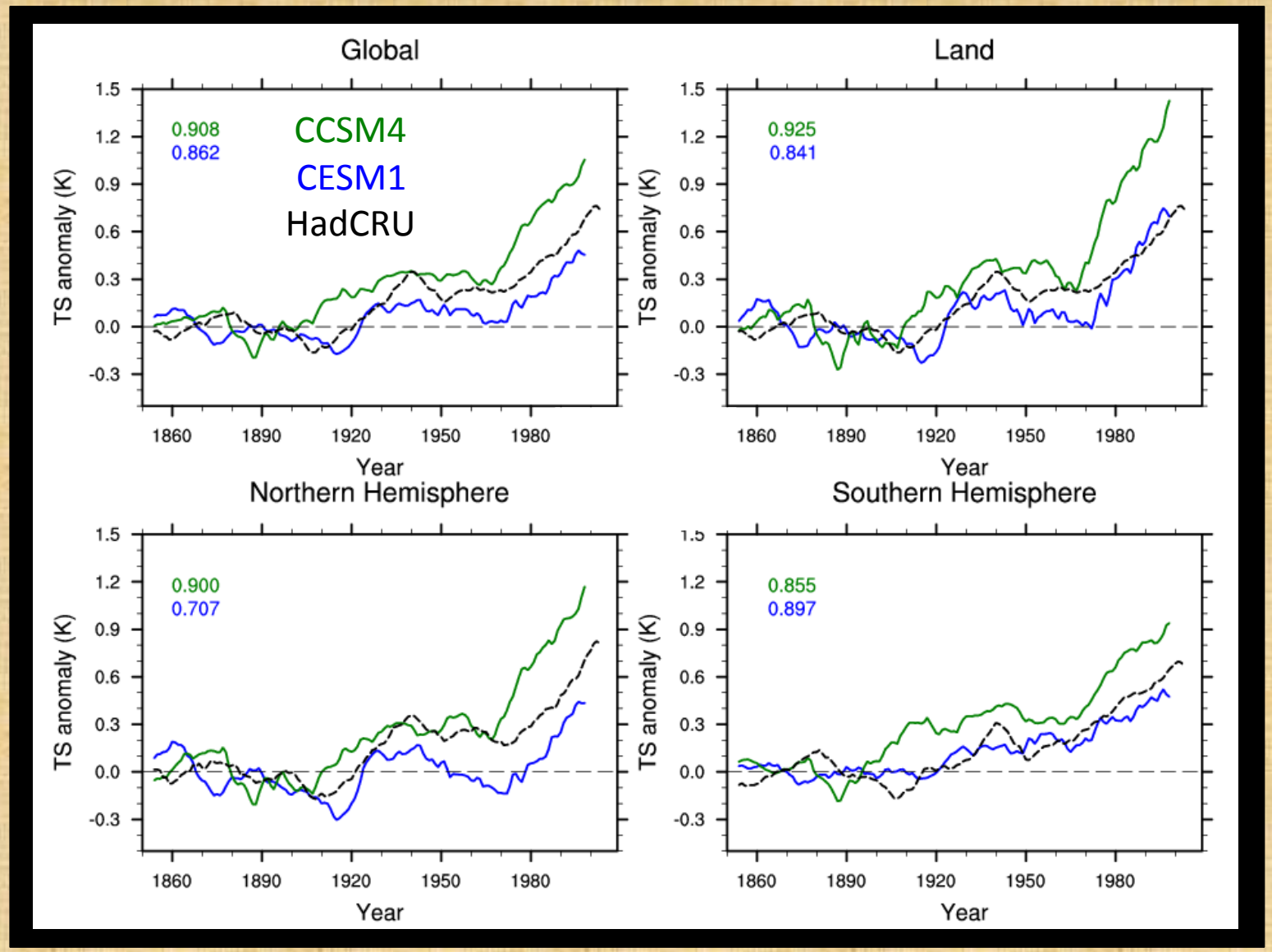
20th Century All Forcing Coupled Simulations

- 1850-2005 forcing fields
  - CCSM4/CAM4 (1 deg)
  - CESM1/CAM5 (2 deg)
  - GHGs, Solar, Large volcanoes burdens
  - *Prescribe aerosol burdens* and surface deposition (CCSM4)
  - *Prescribe aerosol emissions* and predicted surface deposition (CESM1)

In contrast to CCSM4,

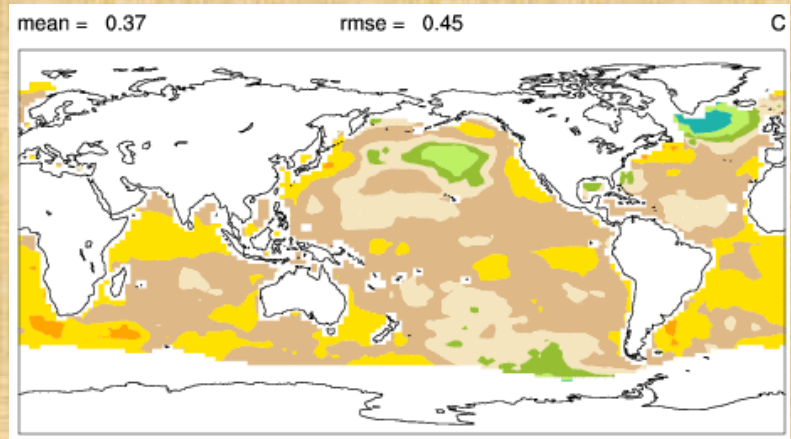
CESM1 can simulate aerosol indirect effect !

Surface Temperature Change

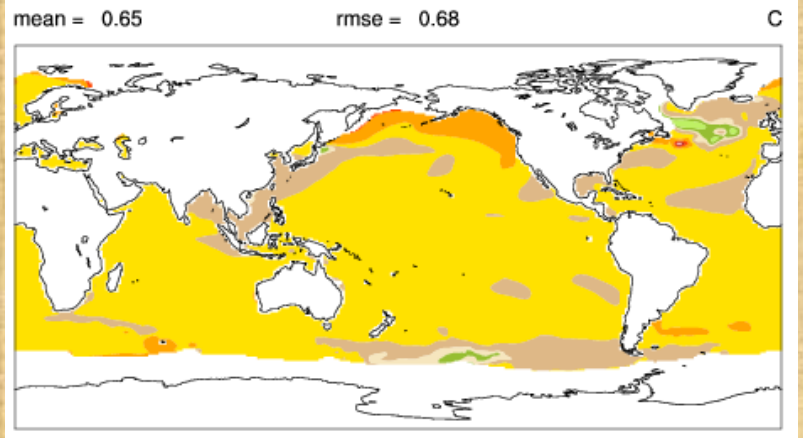


Sea Surface Temp Change ('1990-2004' – '1850')

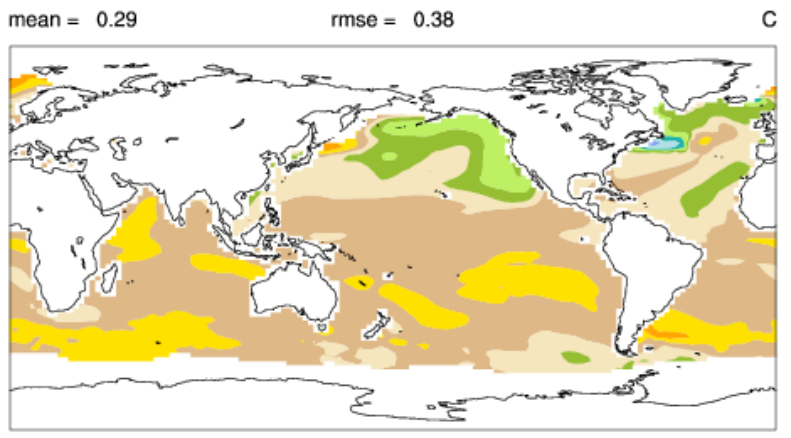
HadISST
1982-2001
minus
1870-1900



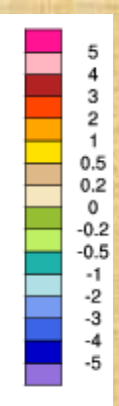
CCSM4



CESM1

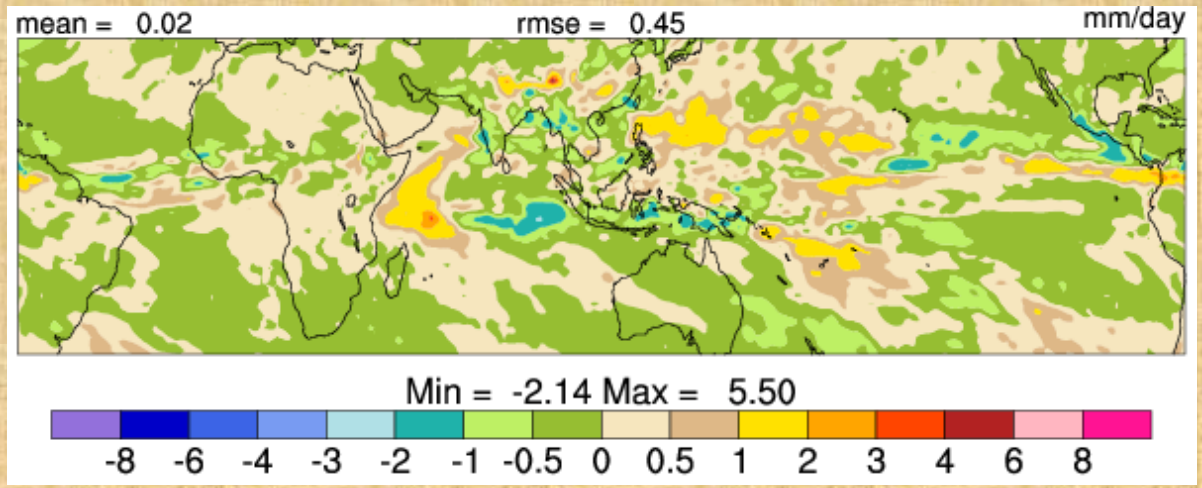


[K]

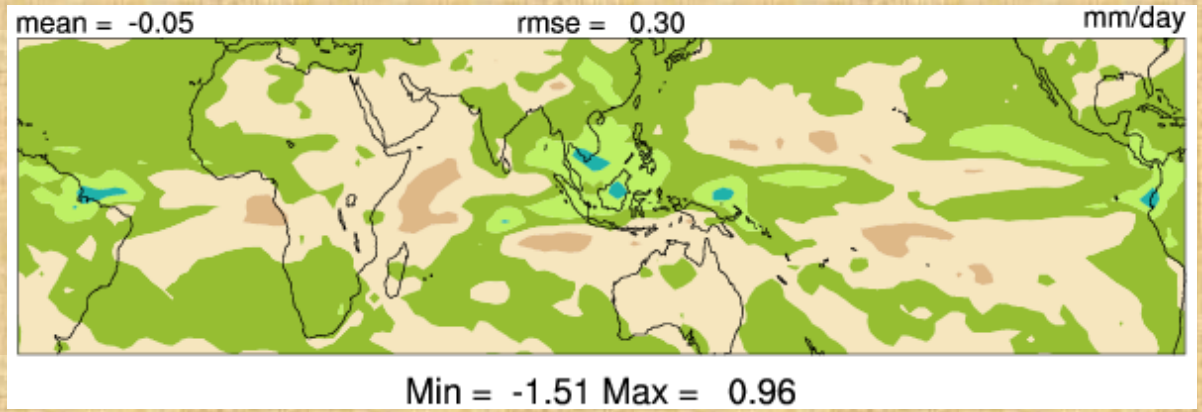


Precipitation Changes ('1990-2004' minus '1850' , ANN)

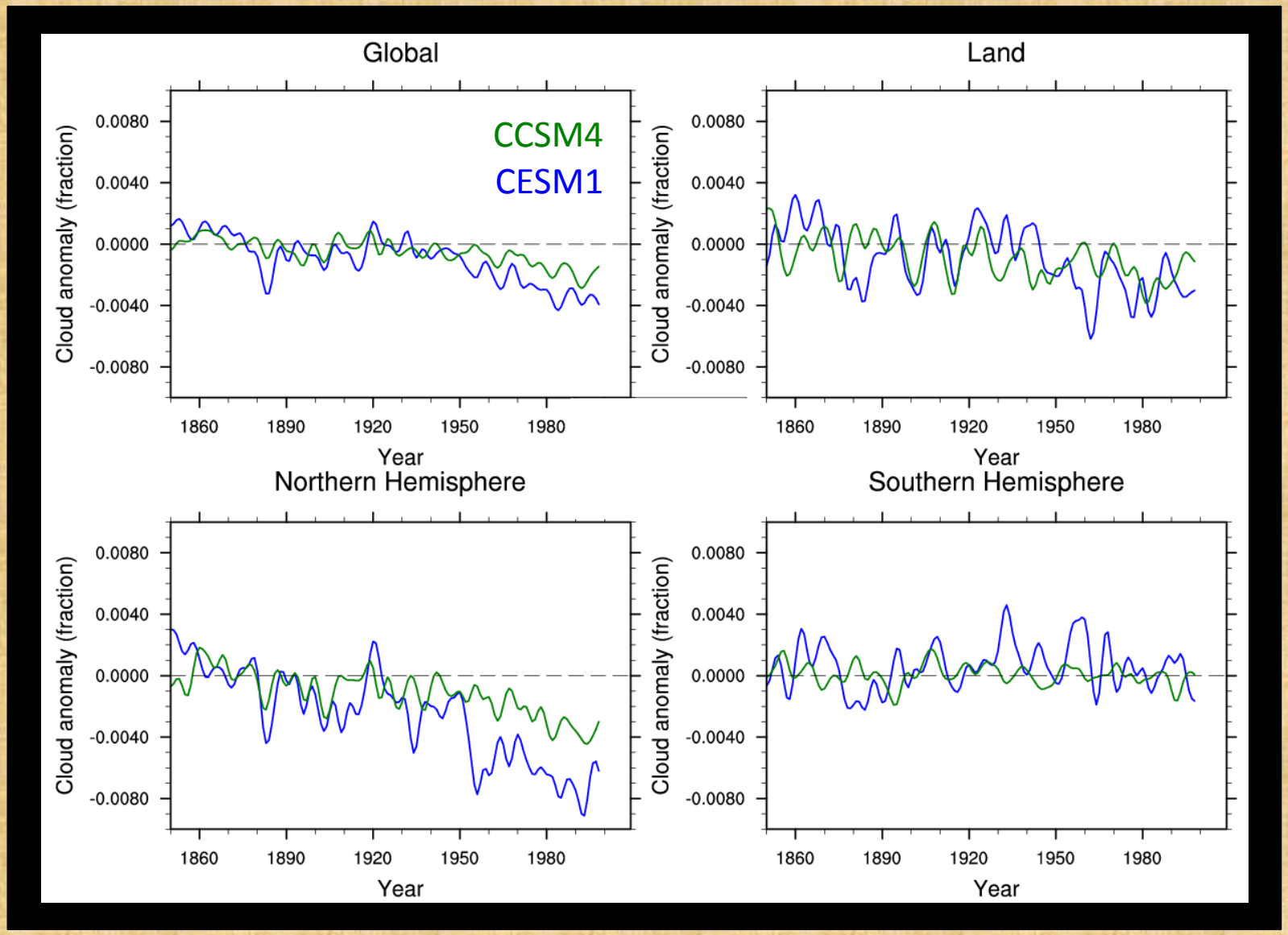
CCSM4



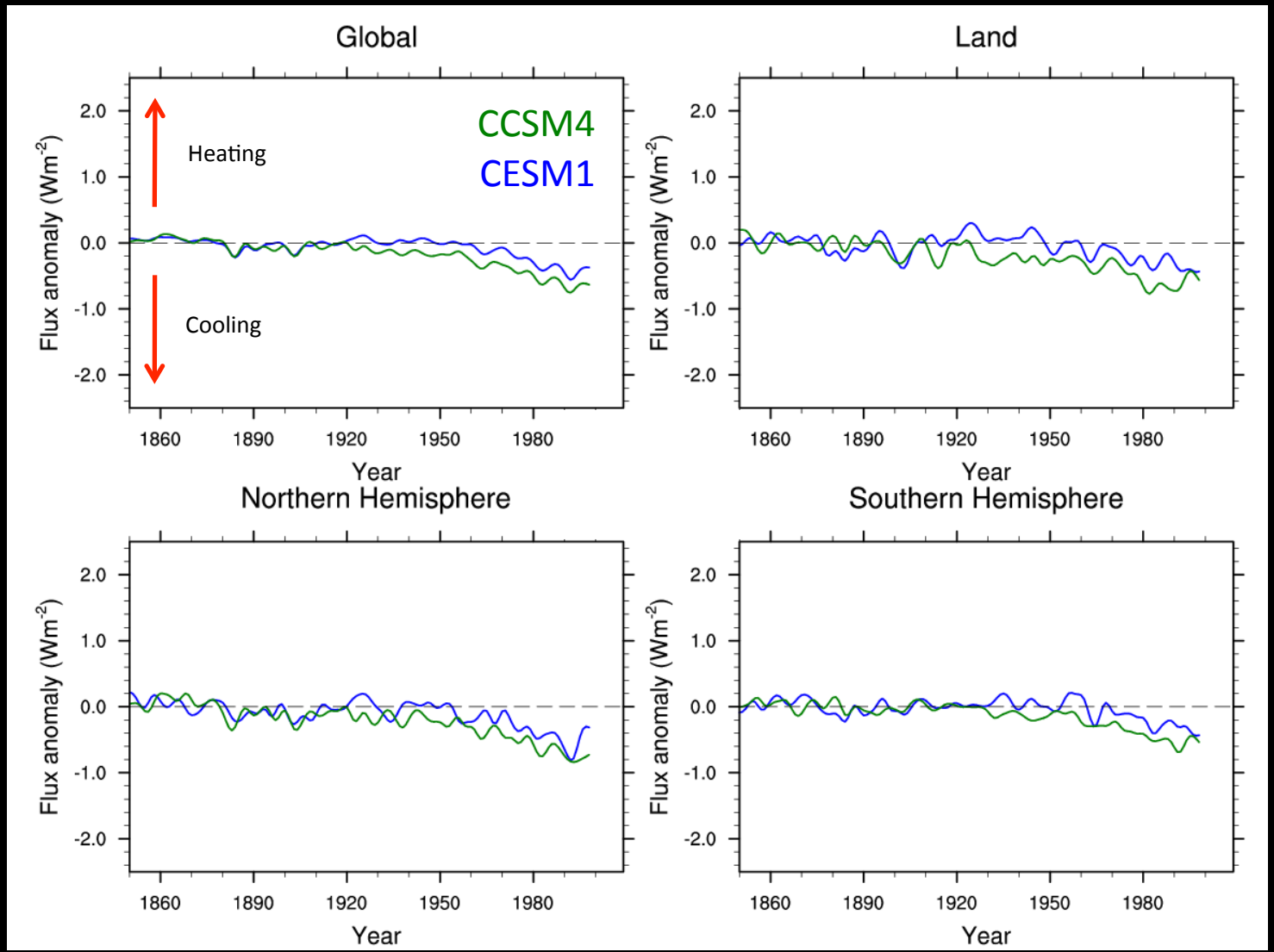
CESM1



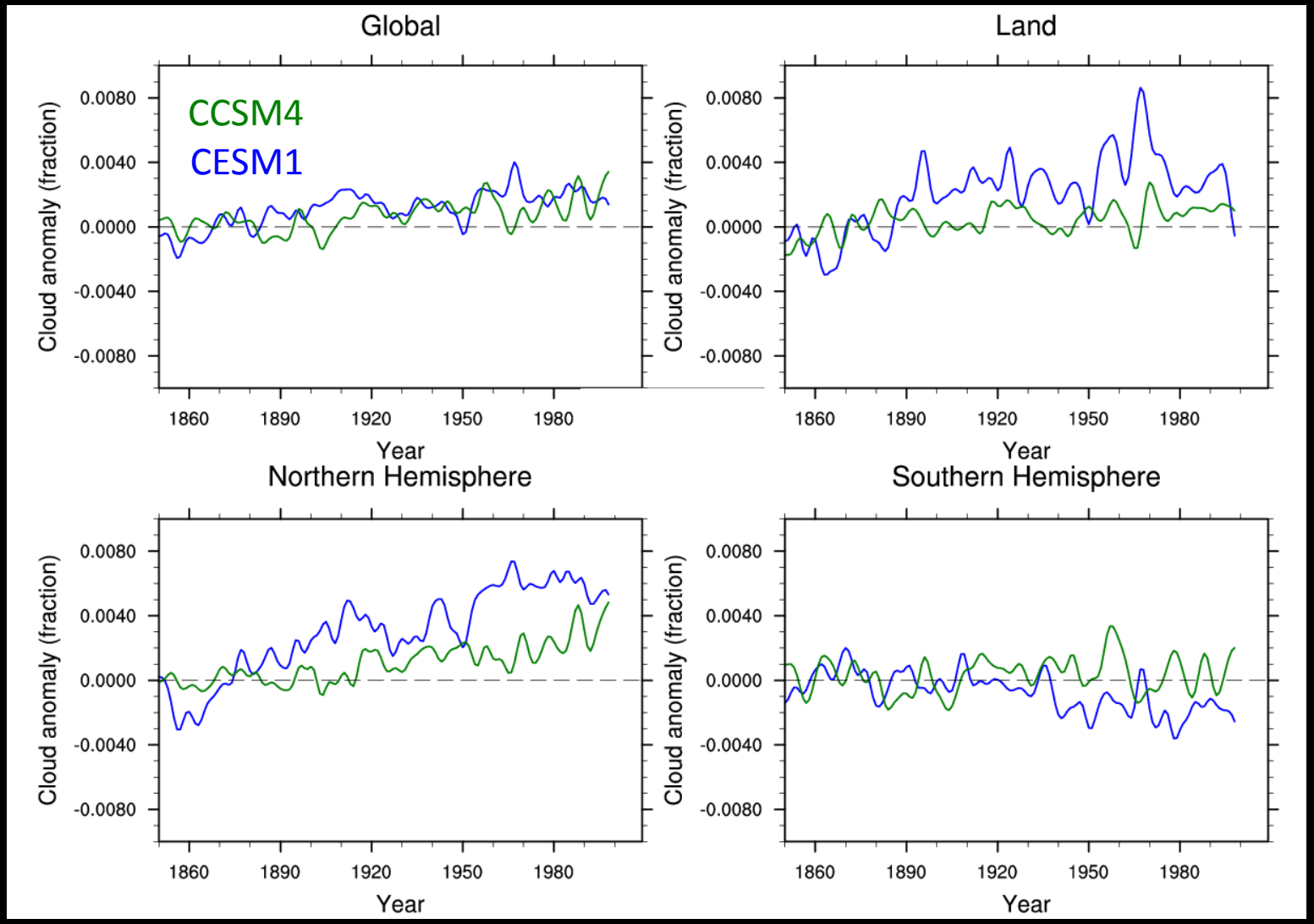
High Cloud Fraction



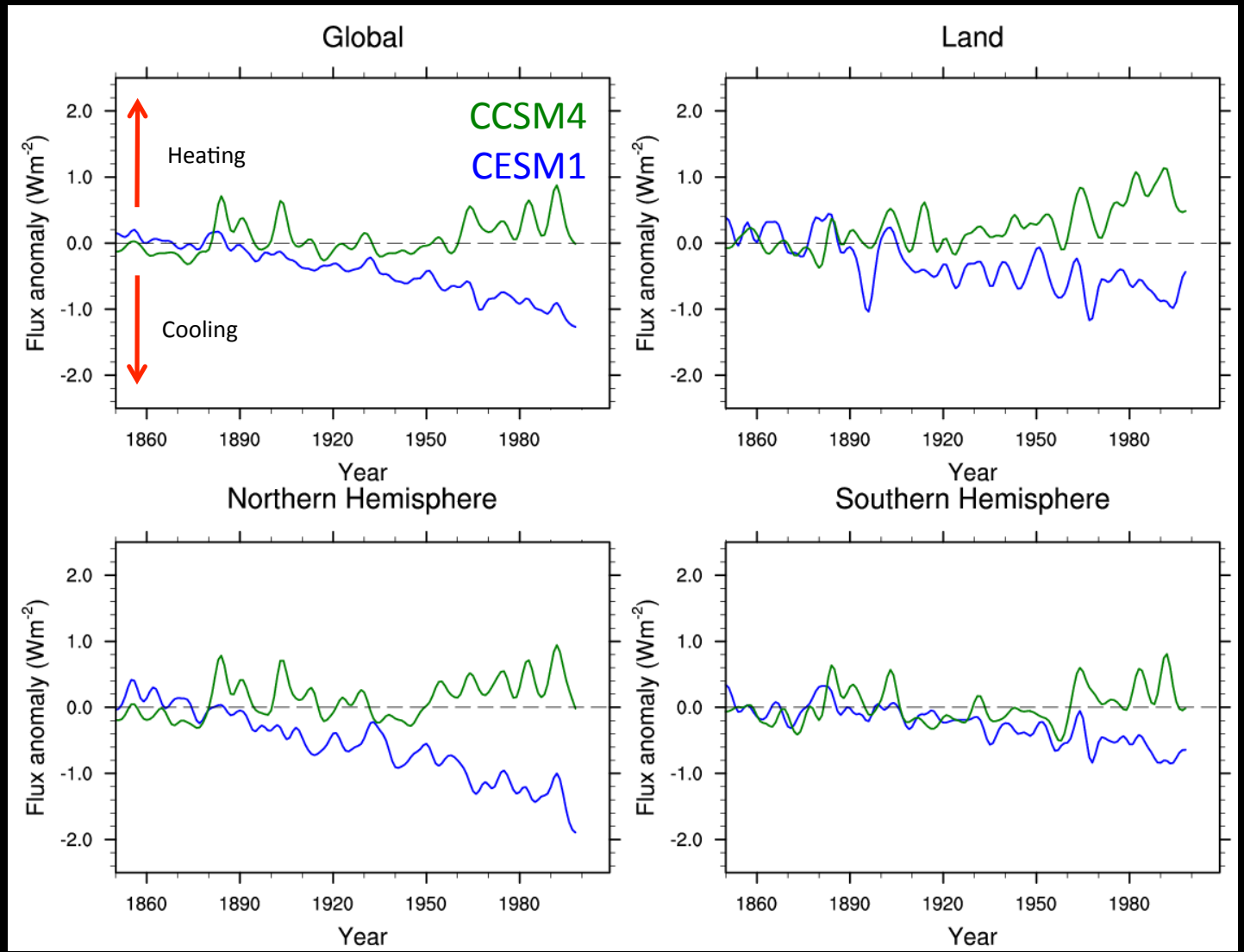
Long Wave Cloud Forcing



Low Cloud Fraction



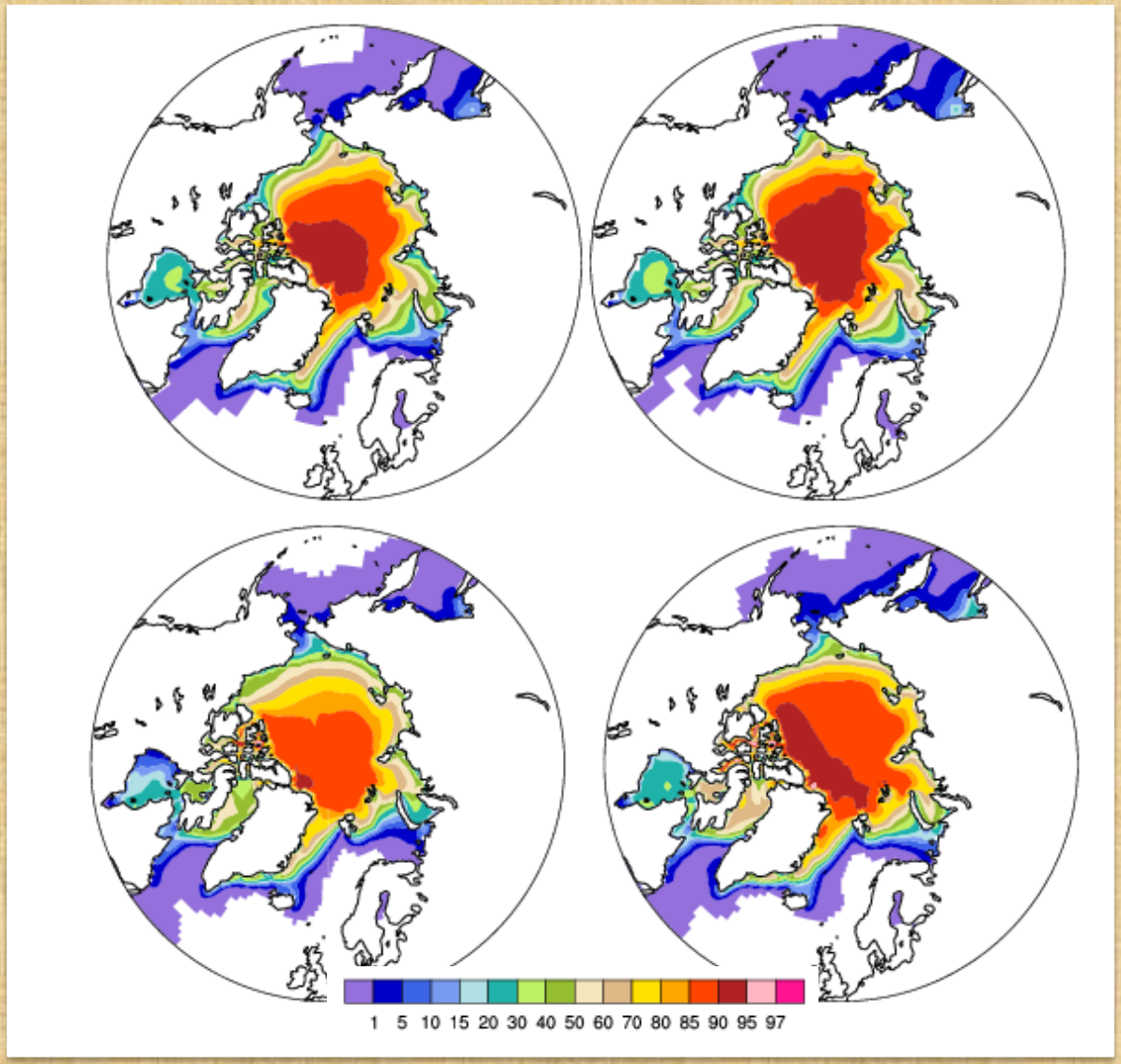
Short Wave Cloud Forcing



20th Century Arctic Sea Ice Fraction Change. JJA.

1990-2004

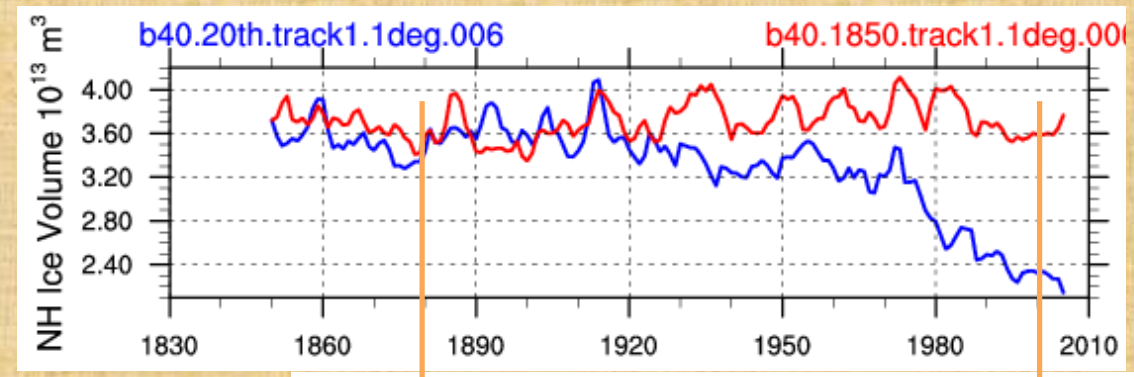
1850 control



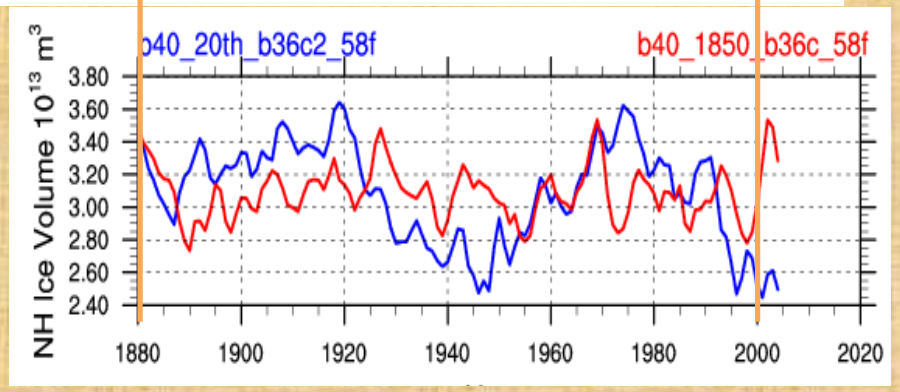
CCSM4

CESM1

20th Century Arctic Sea Ice Volume Change



CCSM4
Control
20thC



CESM1
Control
20thC

SUMMARY

- We have finished developing a new Community Atmosphere Model (CAM5) and Community Earth System Model (CESM1).

- The CAM5/CESM1 has much better physics and interactions among the physics than its precedents.

- CAM5/CESM1 can simulate many important features in a physically reasonable way, especially the ones associated with Cloud Processes themselves and Cloud-Seaice-Aerosol-Climate interactions (e.g., marine stratocumulus clouds, cumulus, cloud-SST interaction, cloud-sea ice interaction, 1st and 2nd aerosol indirect effects, etc.).

Benchmark 7-Modes Modal Aerosol Model

X. Liu and S. Ghan. 2007

- All modes log-normal distribution with a prescribed width.
- Total transported aerosol tracers : 31
- Cloud-borne aerosol and aerosol water predicted but not transported

AITKEN
- Number
- Sulfate
- Ammonium
- Secondary OM
- Sea Salt

ACCUMULATION
- Number
- Sulfate
- Ammonium
- Secondary OM
- Hydrophobic OM
- Black Carbon
- Sea Salt

FINE SOIL DUST
- Number
- Soil Dust
- Sulfate
- Ammonium

FINE SEA SALT
- Number
- Sea Salt
- Sulfate
- Ammonium

Coagulation / Condensation

PRIMARY CARBON
- Number
- Hydrophobic OM
- Black Carbon

COARSE SOIL DUST
- Number
- Soil Dust
- Sulfate
- Ammonium

COARSE SEA SALT
- Number
- Sea Salt
- Sulfate
- Ammonium

Computation time is 100% higher than BAM.