Improvements in CAM4 :
Moist Turbulence, Shallow Convection, and Cloud Macrophysics

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DEFINITIONS

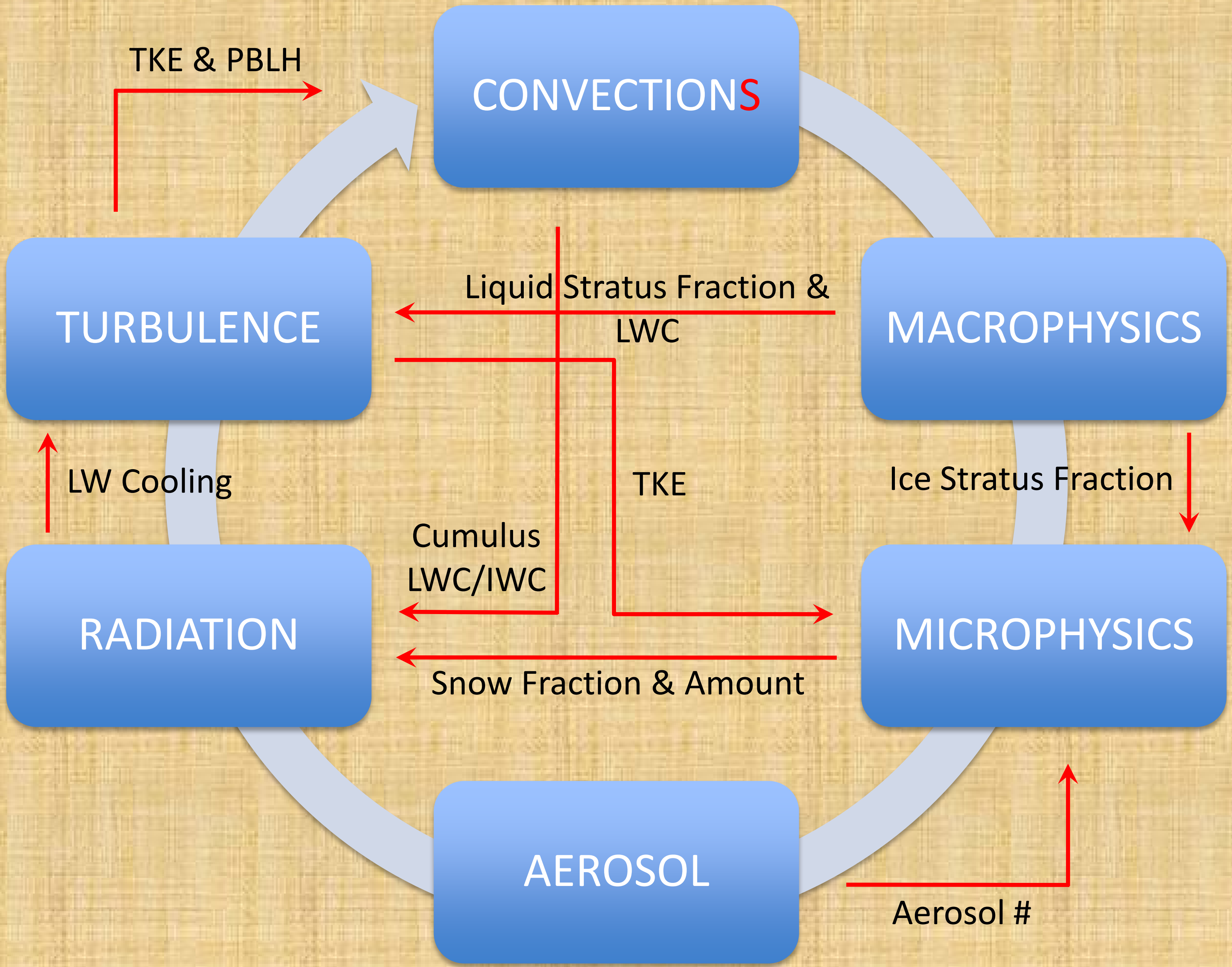
❑ Model Names

- *CAM3.5* : CAM3.0 + *Revised Deep Convection* + etc. (= Track I)
- *CAM4* : CAM3.5 + *All New Atmospheric Physics* (= Track V)

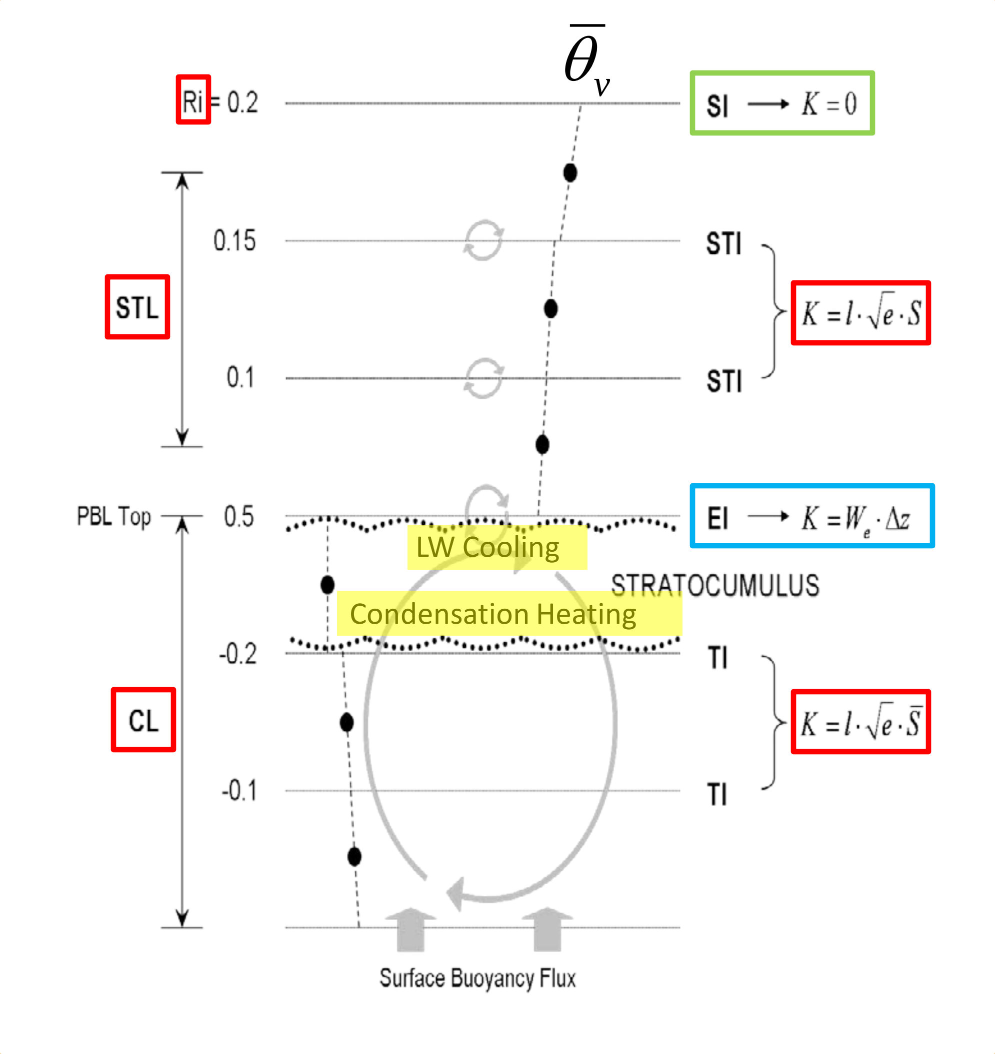
❑ Variables

- a : Cloud Fraction
- LCA : Low Cloud Amount
- TCA : Total Cloud Amount
- S : Lower-Tropospheric Stability, $S \equiv \theta_v(700) - \theta_v(1000)$

Physical Processes in CAM4



MOIST TURBULENCE SCHEME in CAM4



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

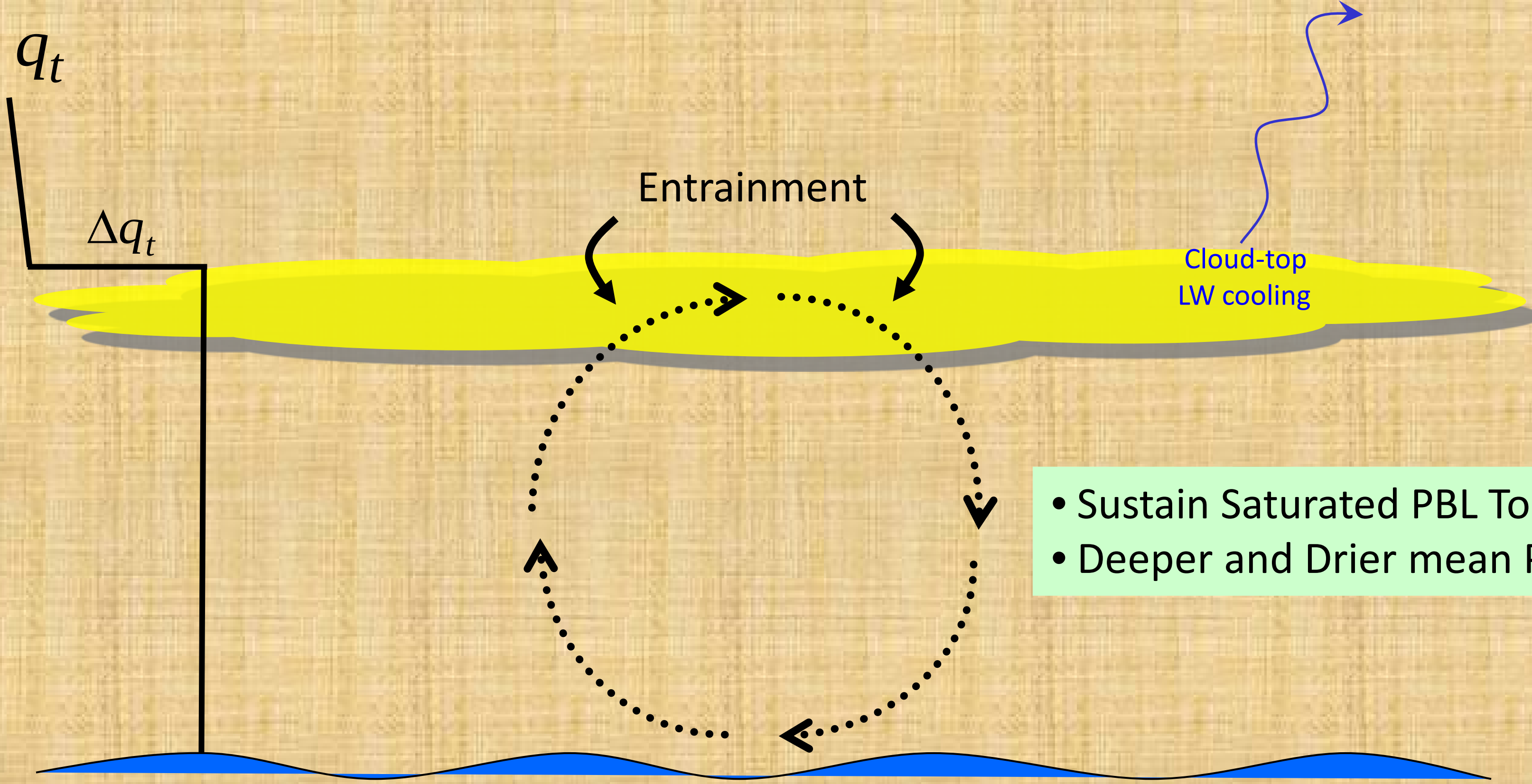
K : eddy diffusivity

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 CAM4

- 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 2nd aerosol indirect effect
  - Removal of the stability-based KH stratus fraction
- Activate in any layers above as well as within PBL
  - Simulate turbulences in the mid- and upper-level clouds
- Compared to CAM35 PBL scheme,
  - Much better performance in cloud-topped regime
  - Similar or superior performance in dry stable and convective regimes

Cloud-Radiation-Turbulence Interactions



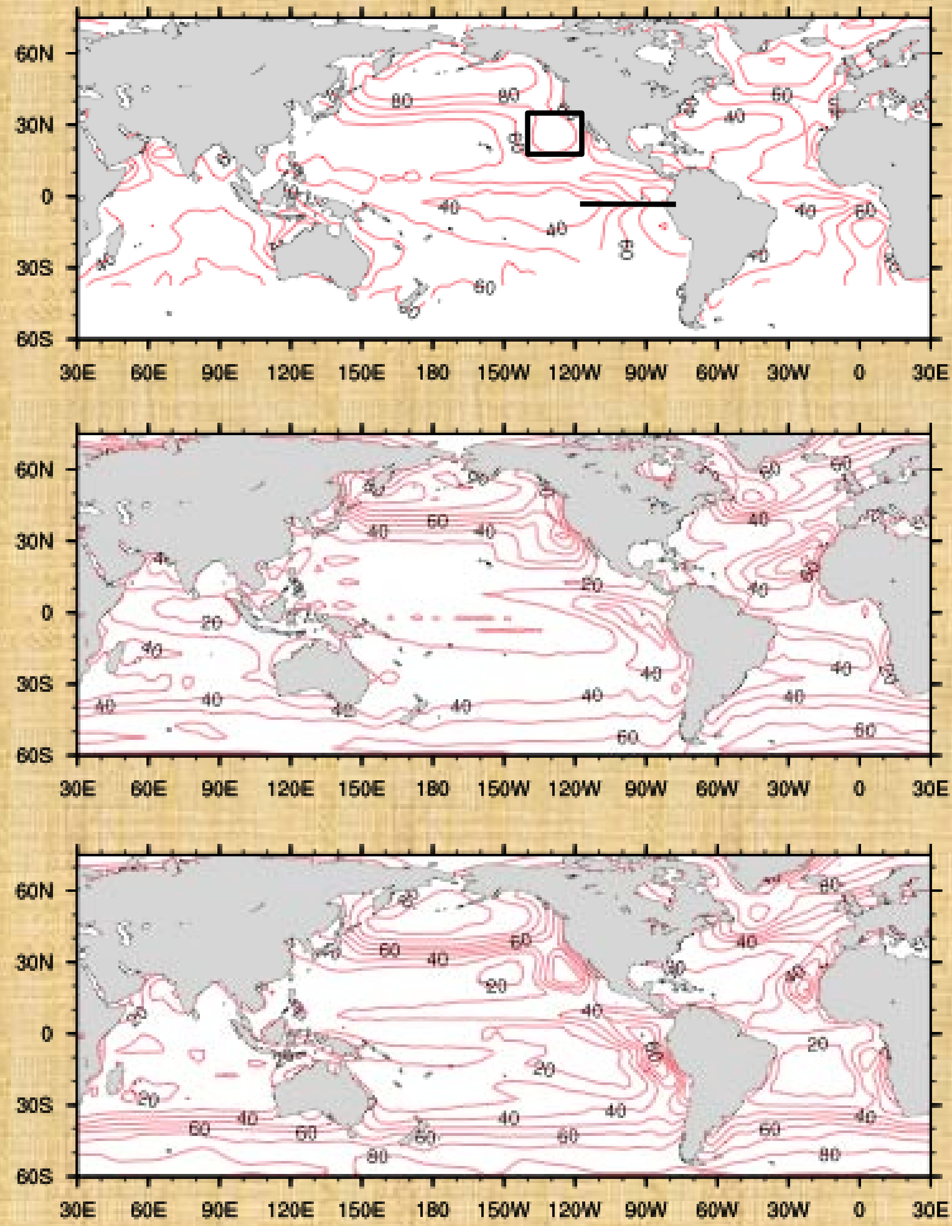
- Sustain Saturated PBL Top
- Deeper and Drier mean PBL

Low Cloud Amount. JJA.

Observation

CAM35

CAM4

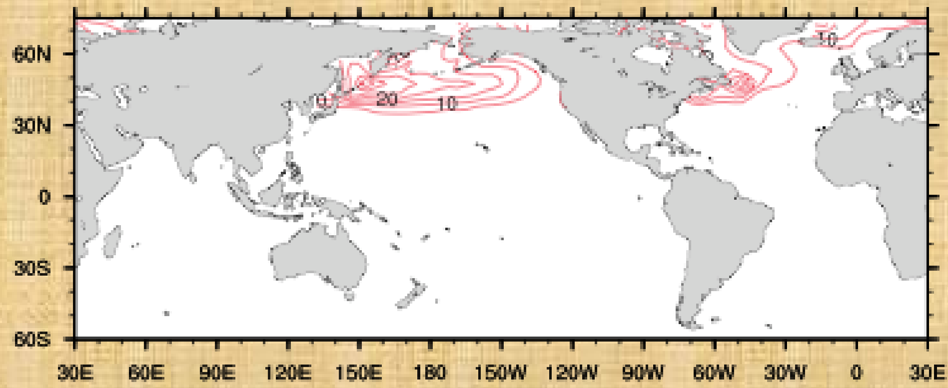


Use
KH's stratus fraction

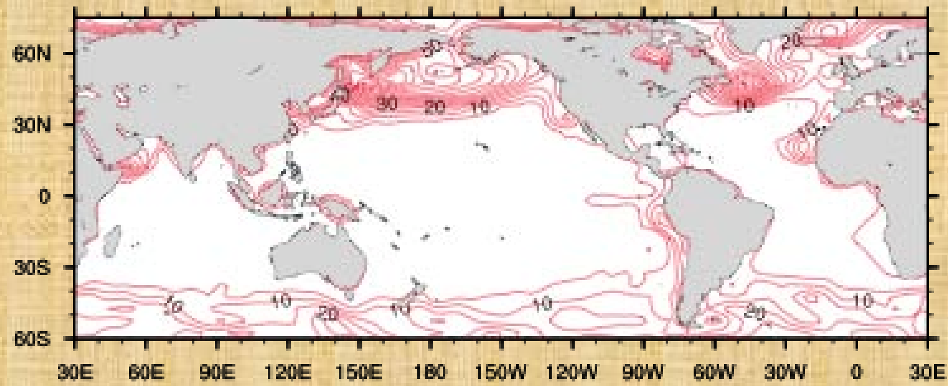
Do not use
KH's stratus fraction

Fog Amount. JJA.

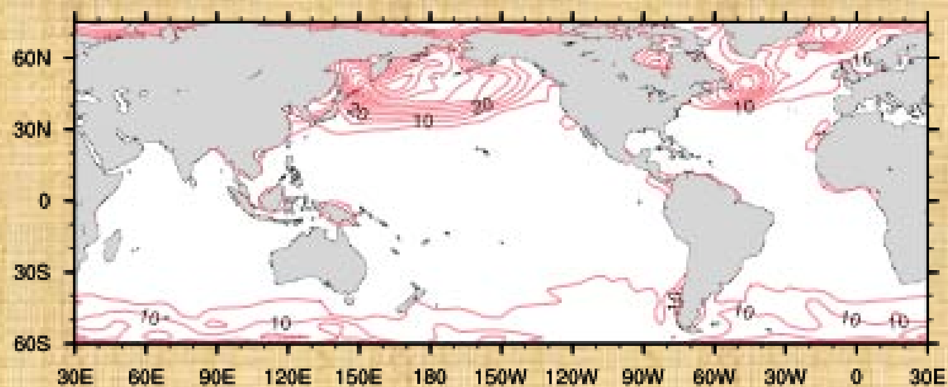
Observation



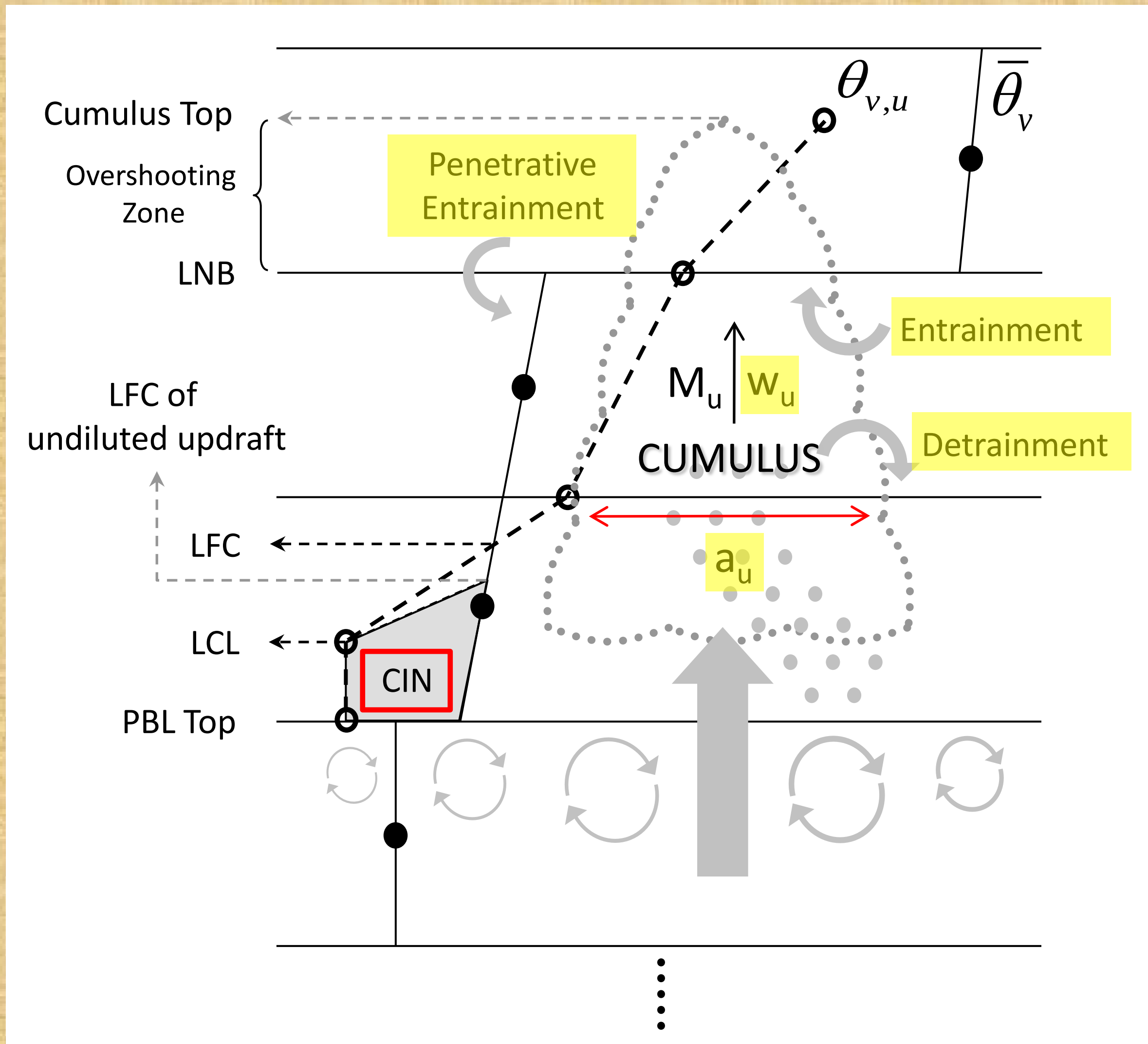
CAM35



CAM4



SHALLOW CONVECTION SCHEME in CAM4



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

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 CAM4

- 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 momentum and aerosols as well as thermodynamic conservative scalars
  - Computes cumulus fraction and LWC, vertical velocity, updraft mass flux
  - Direct influence on the global radiation budget

- Much less sensitive to vertical resolution than CAM35

- Can simulate deep as well as shallow convective activity

- Simulate the ‘*real*’ convective activity

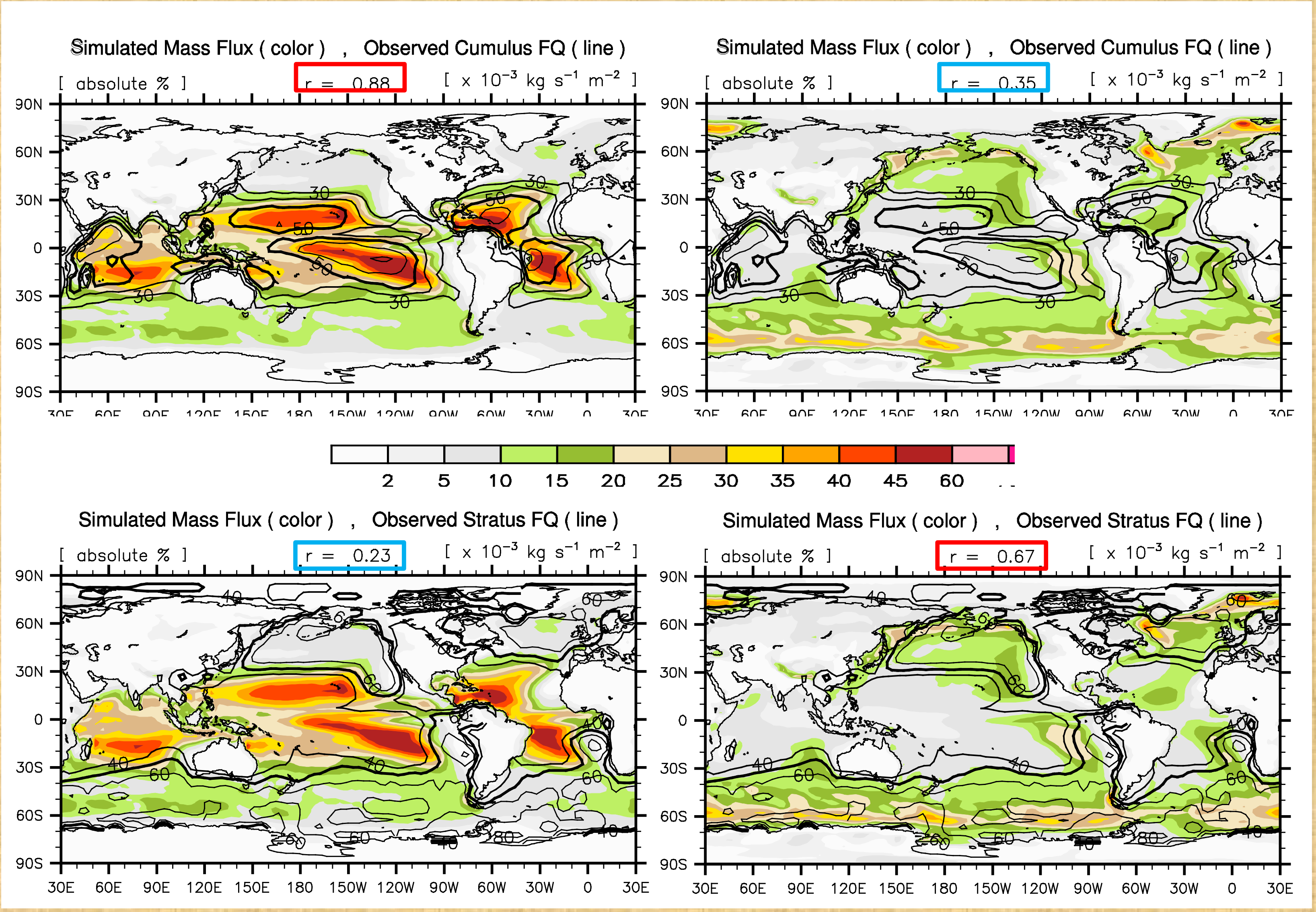
Shallow Convective Mass Flux at Cloud Base. Annual.

CAM4

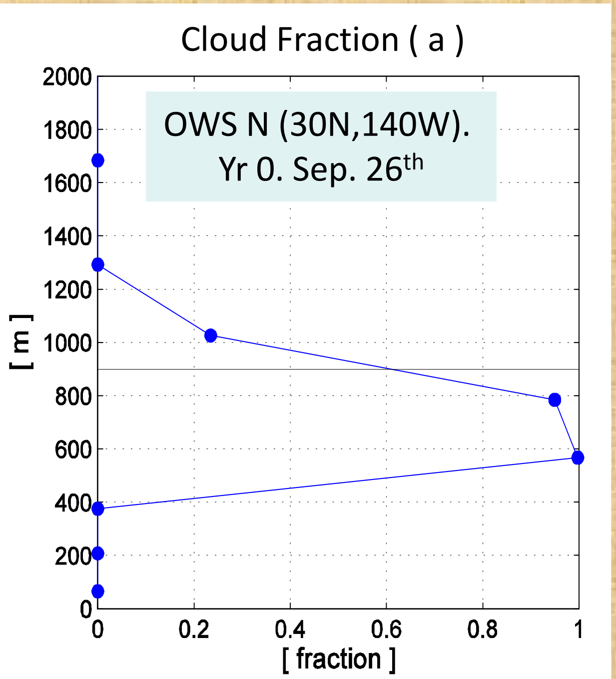
CAM35

Observed Cumulus

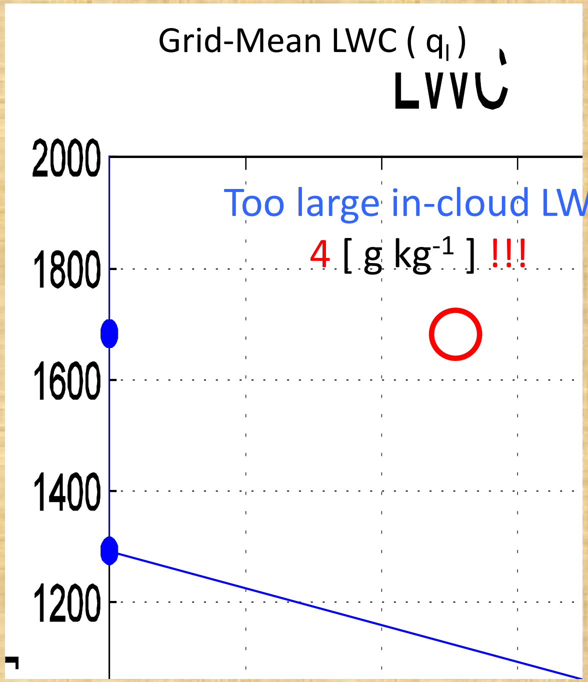
Observed Stratus



Inconsistency between 'Stratus Fraction' and 'In-Stratus LWC' in CAM35



PBL top



→ distorts LW cooling profile

→ too strong inversion at the PBL top

→ too weak entrainment rate

→ too shallow and moist PBL

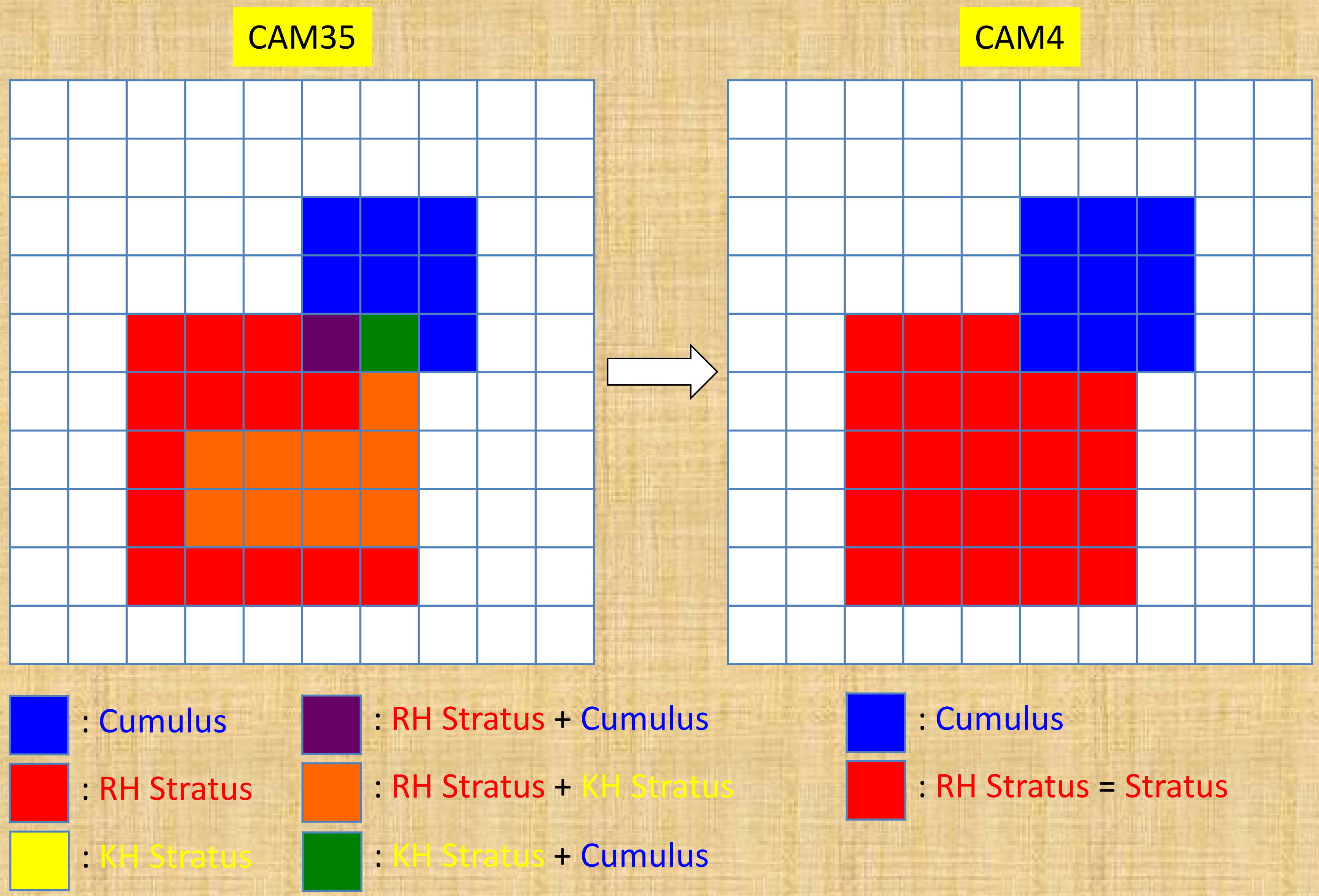
Macrophysics Scheme in CAM4

- 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



Improvements of Cloud Treatment in CAM4

- Removal of 'KH Stratus'

  ← New Moist Turbulence Scheme

- Realistic 'Cumulus Fraction' and 'Cumulus LWC'

  ← New Shallow Convection Scheme and Revised Deep Convection Scheme

- Enhanced Consistency between 'Stratus Fraction' and 'Stratus LWC'

  ← Revised Macrophysics

- Simulation of 'Interactive Cloud Droplet Number' as well as 'LWC/IWC'

  ← New 2-Moment Microphysics and Modal Aerosol Model

- More Realistic Radiative Properties of Clouds

  ← New Cloud Optics

Simulation Results:
Observation vs CAM35 vs CAM4

Observation : 42-yrs (1956-1997) EECRA ship-observations, NCEP/NCAR Reanalysis
17-yrs (1984-200) ISCCP satellite-derived radiation at surface

CAM35 : 92-yrs coupled simulation using pre-industrial GHG and aerosols

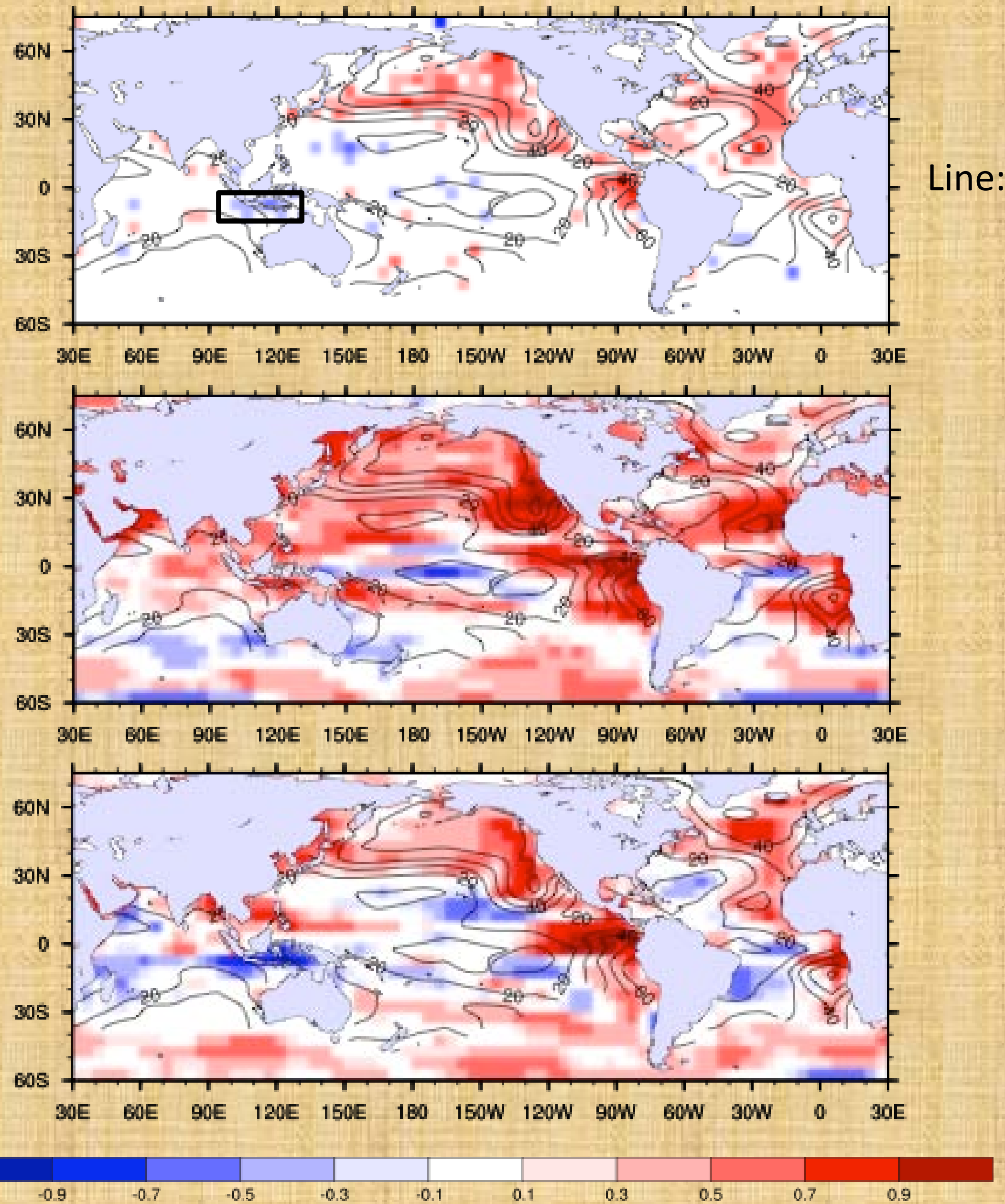
CAM4 : 87-yrs coupled simulation using pre-industrial GHG and aerosols

Interannual Correlation between $S \equiv \theta_v(700) - \theta_v(1000)$ and Low Cloud Amount. JJA.

Observation

CAM35

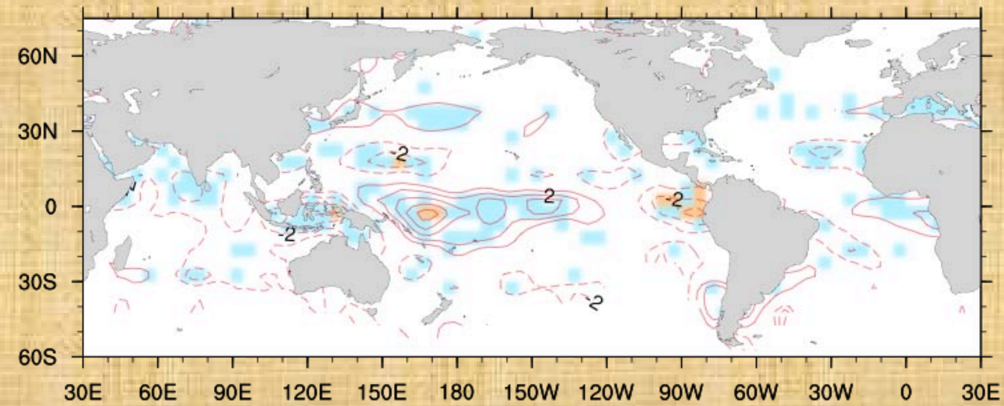
CAM4



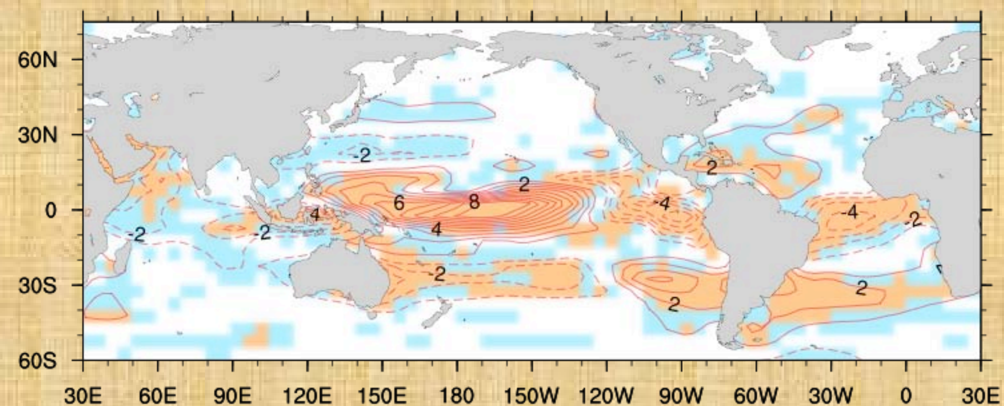
Line: Ship-observed LCA

ENSO Regression Anomalies of Total Cloud Amount [%]. JAS.

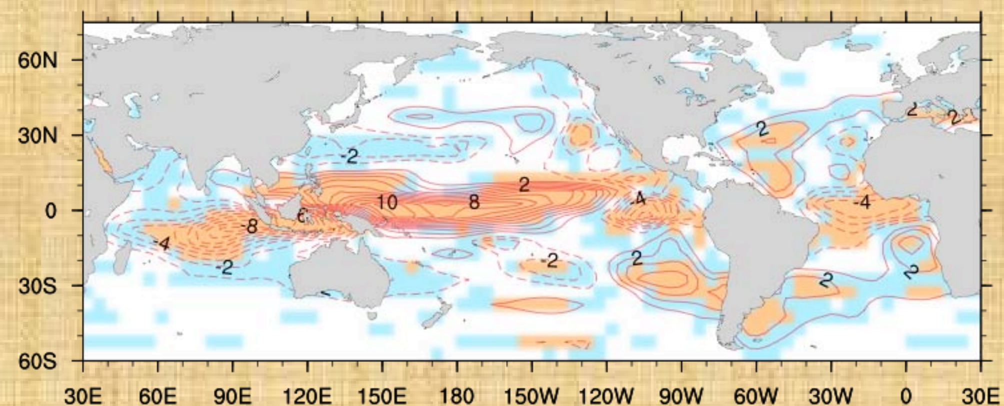
Observation



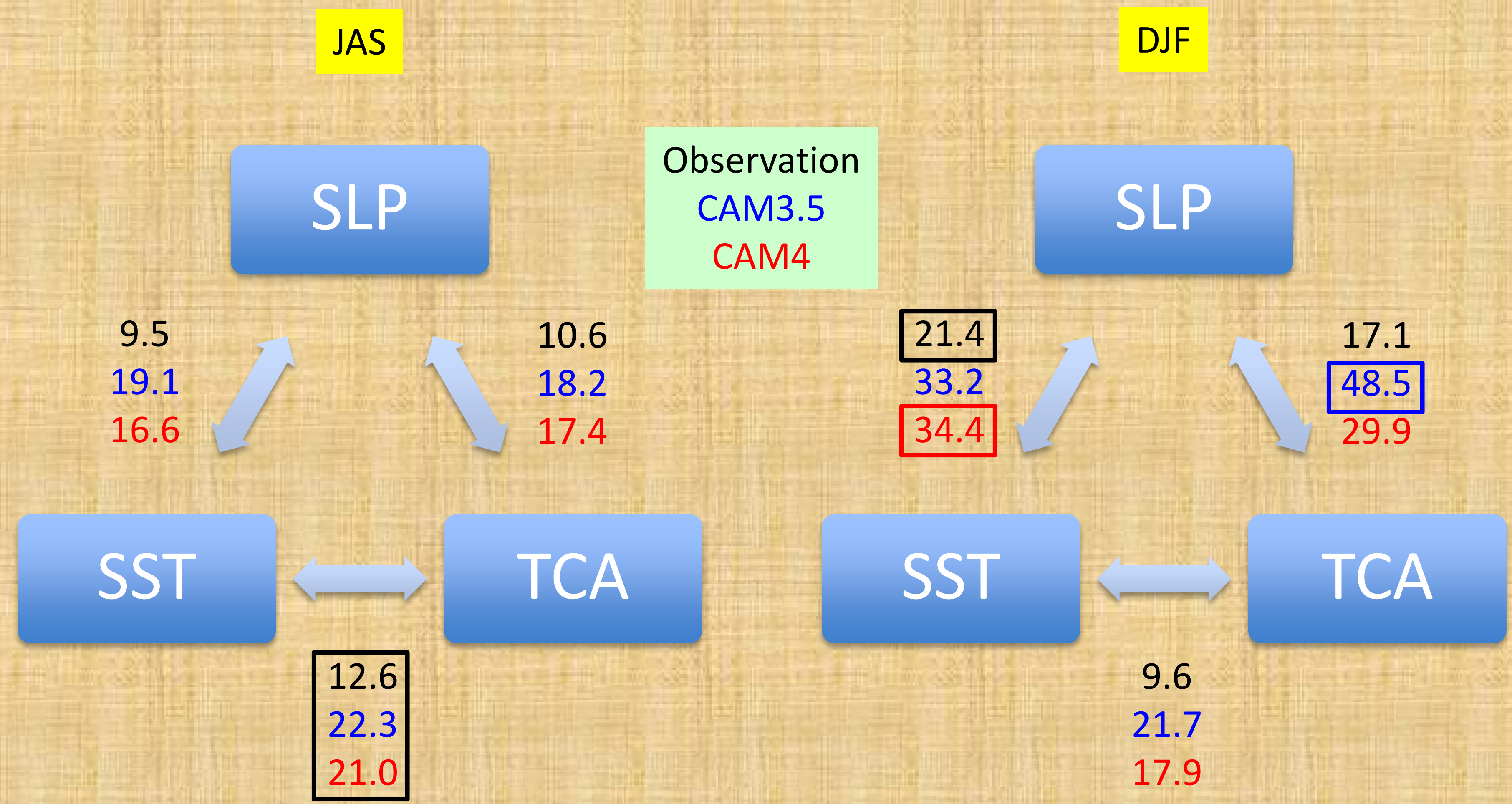
CAM35



CAM4



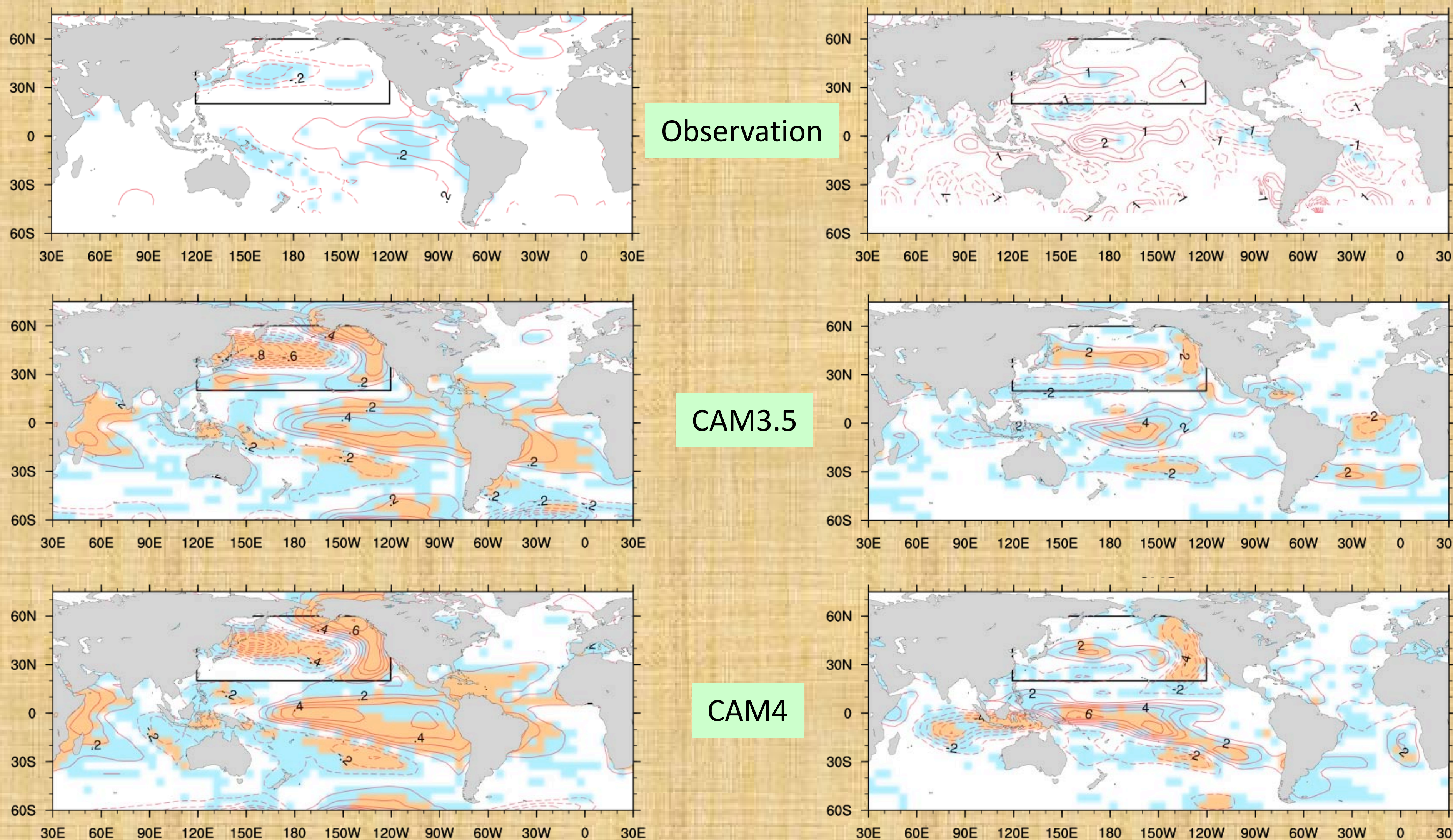
Normalized Covariance of the 1st Coupled Mode from the SVD Analysis over the North Pacific



SVD Heterogeneous Map. SST vs TCA. JAS.

SST

TCA

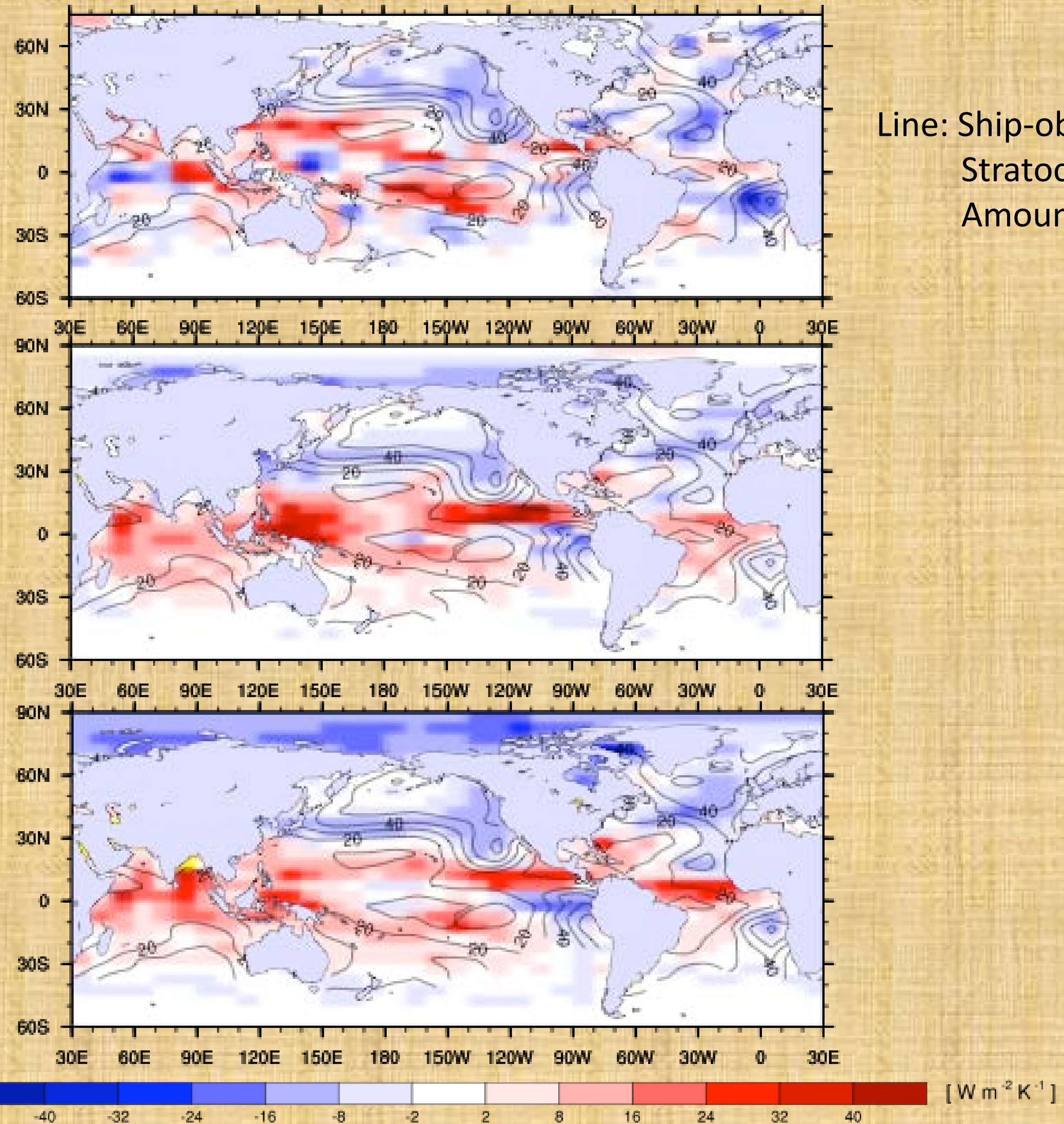


SW Surface Heat Flux Feedback $\lambda_{SW} \equiv -\partial Q^{\downarrow}_{SW} / \partial SST$. JJA.

Observation

CAM35

CAM4



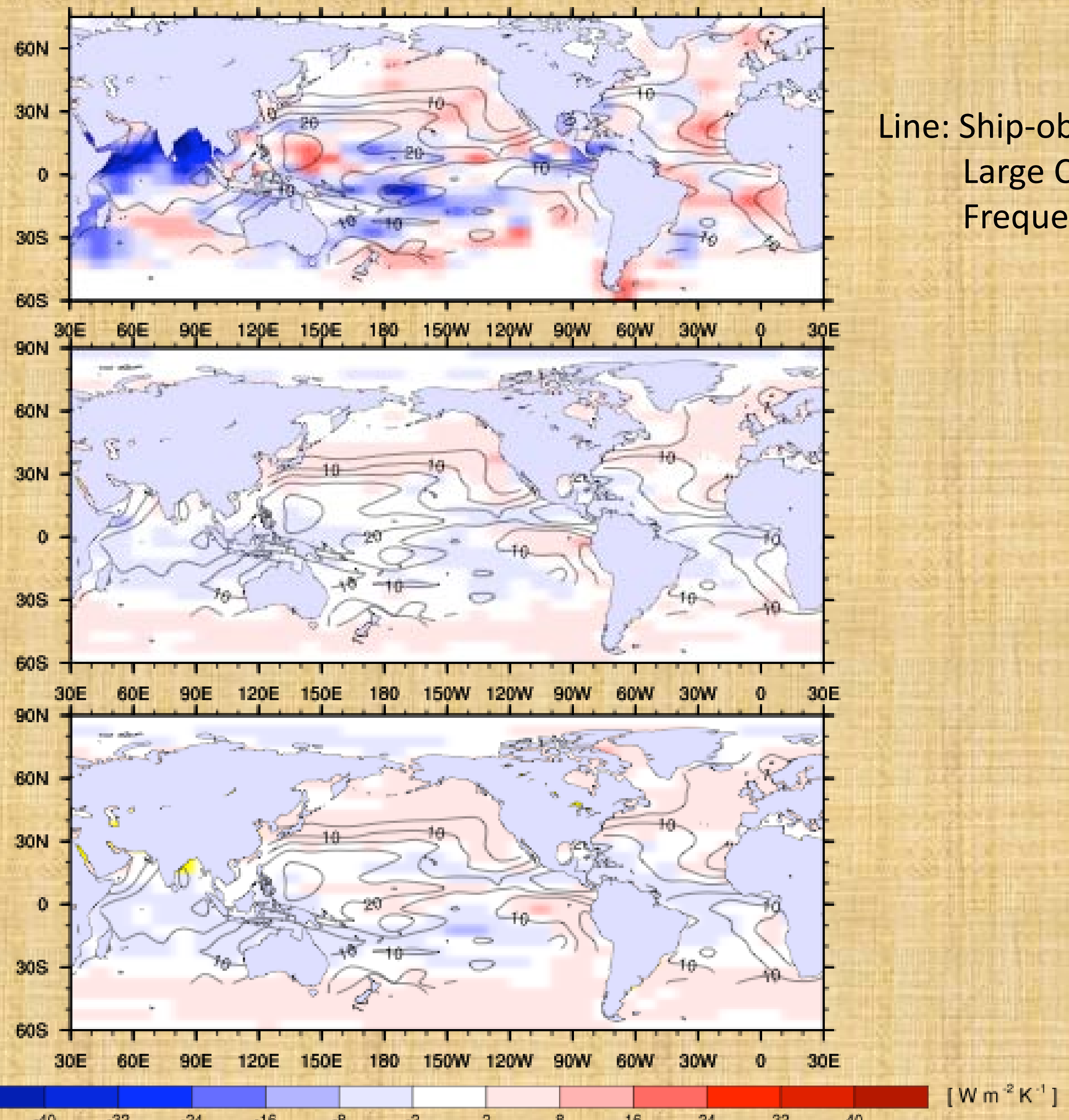
Line: Ship-observed Stratocumulus Amount

LW Surface Heat Flux Feedback $\lambda_{LW} \equiv -\partial Q_{LW}^{\downarrow} / \partial SST$. JJA.

Observation

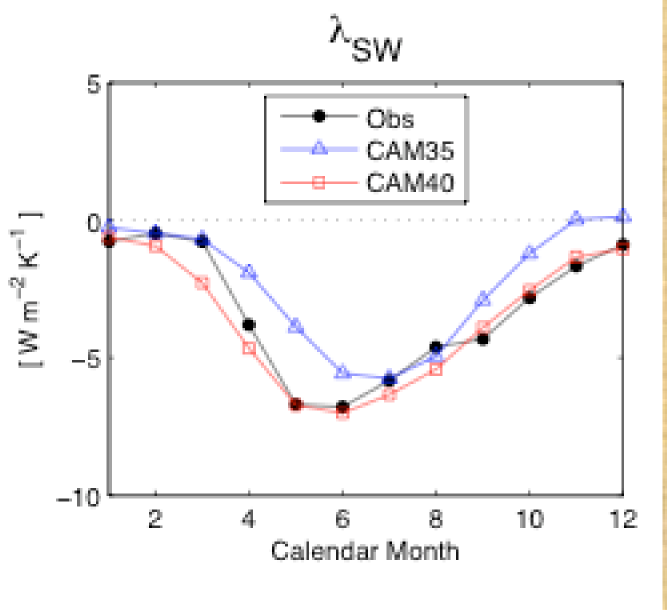
CAM35

CAM4



Line: Ship-observed
Large Cumulus
Frequency

Surface Heat Flux Feedback over the North Pacific Ocean



SUMMARY

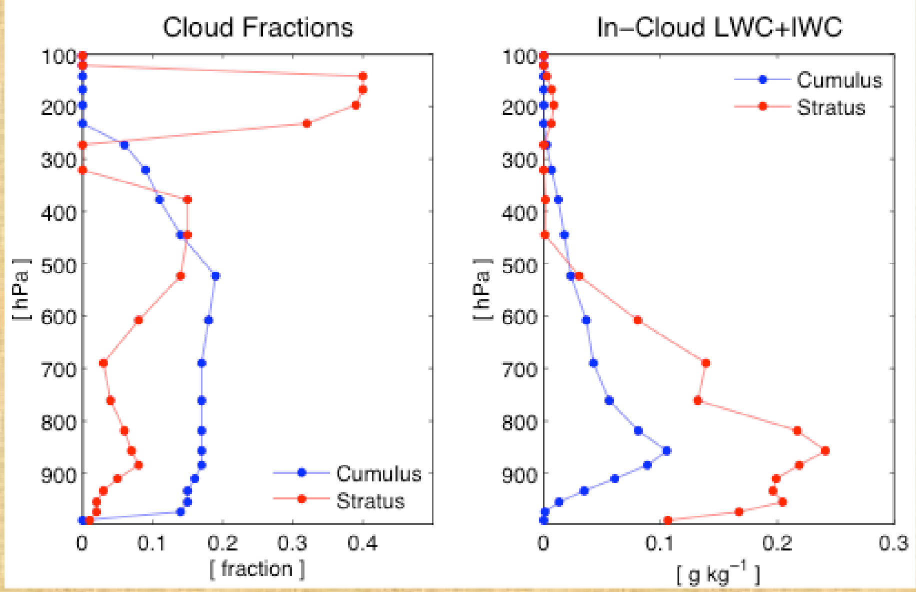
- CAM4 has much better physics and interactions among the physics than CAM35, without arbitrary kludges (e.g., stability based LCA etc.).

- Our analysis also showed that the overall practical performance of CAM4 is similar or better than CAM35.

- CAM4 can simulate many important features in a physically reasonable way, especially the ones associated with cloud processes themselves and cloud-climate interactions (e.g., marine stratocumulus clouds, cumulus, cloud-SST interaction, cloud-sea ice interaction, 1st and 2nd aerosol indirect effects, etc.).

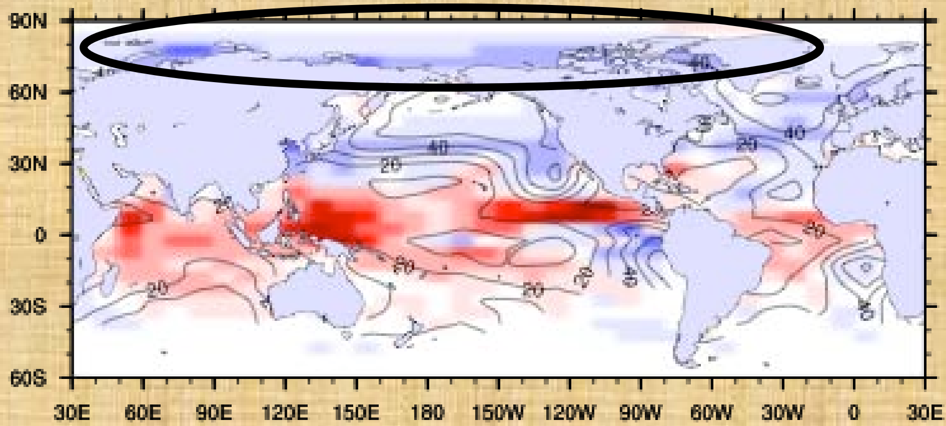
- Some important biases in CAM4:
  - Biases common both in CAM35 and CAM4 : moist atmosphere, weak LW CRF (?) and LW radiative feedback
  - Biases in CAM4 : small sea-ice fraction over the Arctic in summer

Sensitivity to Vertical Cloud-Overlapping Structure

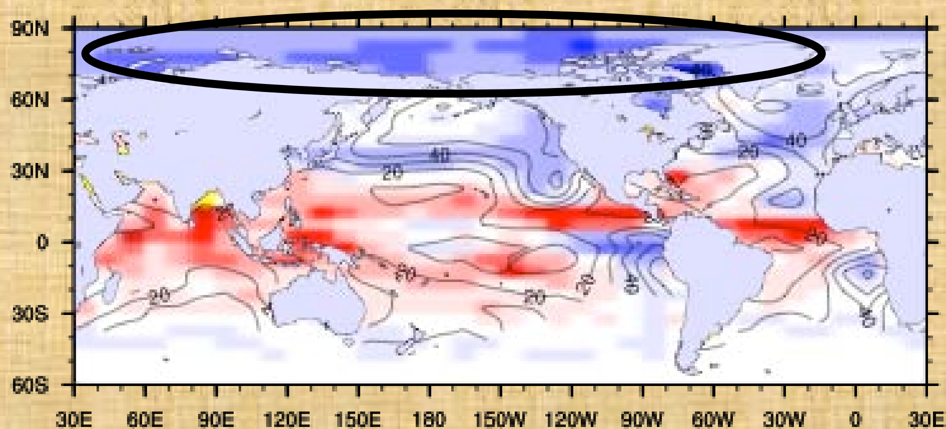


SW Surface Heat Flux Feedback $\lambda_{SW} \equiv -\partial Q^{\downarrow}_{SW} / \partial SST$. JJA.

CAM35

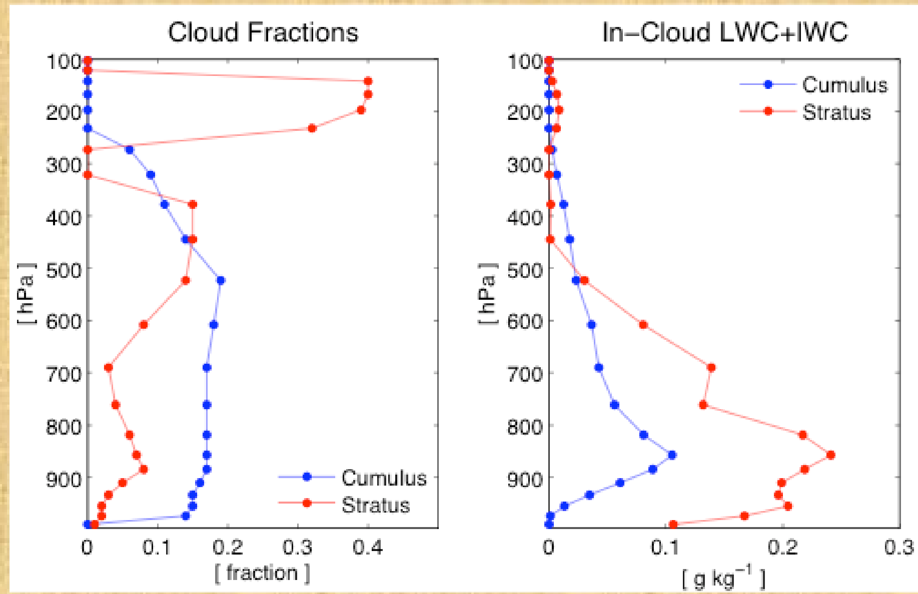


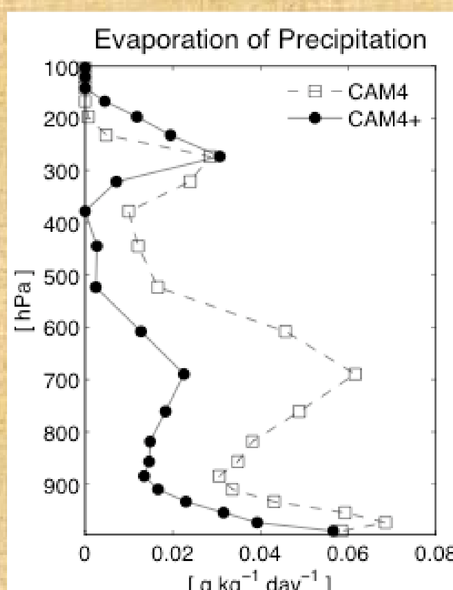
CAM4

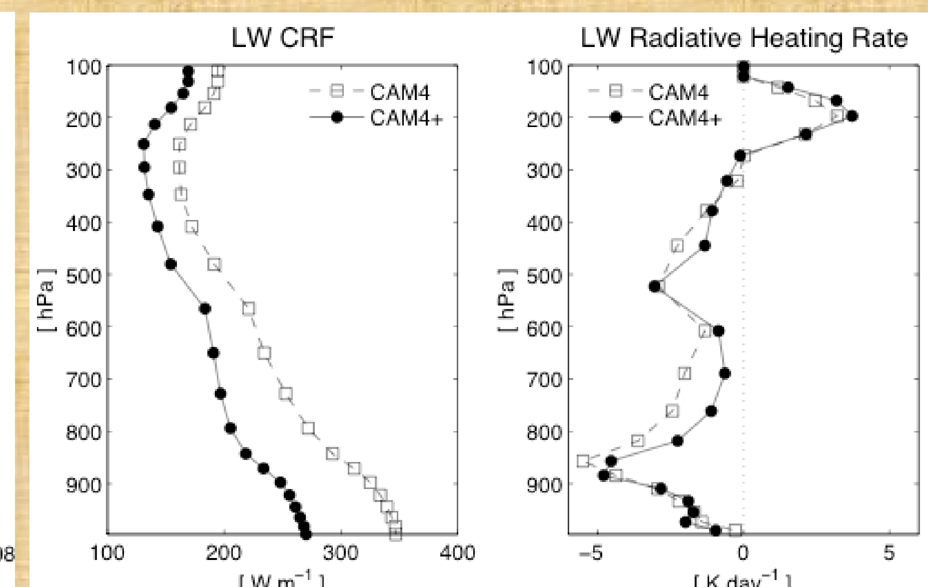


Weaker SW feedback in summer Arctic in CAM35, probably due to the built-in negative feedback between sea ice and stability-based stratus fraction,
may explain more sea ice extent in CAM35 than in CAM4.

The End of Presentation


Cloud Fractions
In−Cloud LWC+IWC
Cumulus
Stratus
[hPa]
[fraction]
[g kg⁻¹]

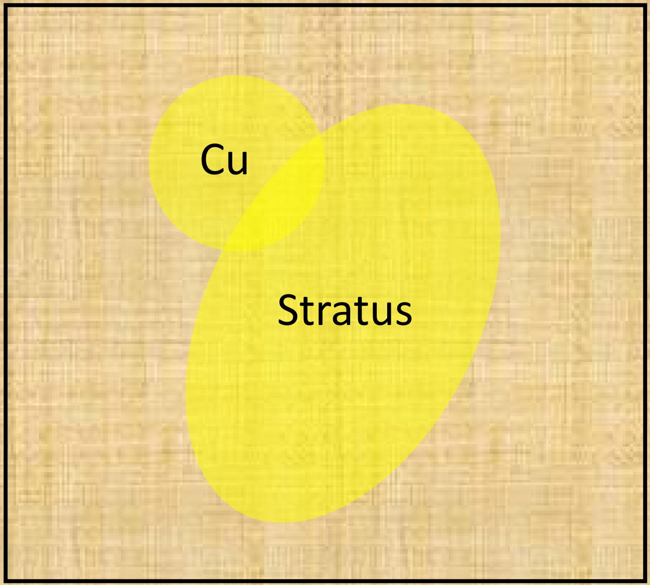

Evaporation of Precipitation
CAM4
CAM4+
[hPa]
[g kg⁻¹ day⁻¹]


LW CRF
LW Radiative Heating Rate
CAM4
CAM4+
[hPa]
[W m⁻¹]
[K day⁻¹]

Macrophysics Scheme in CAM4

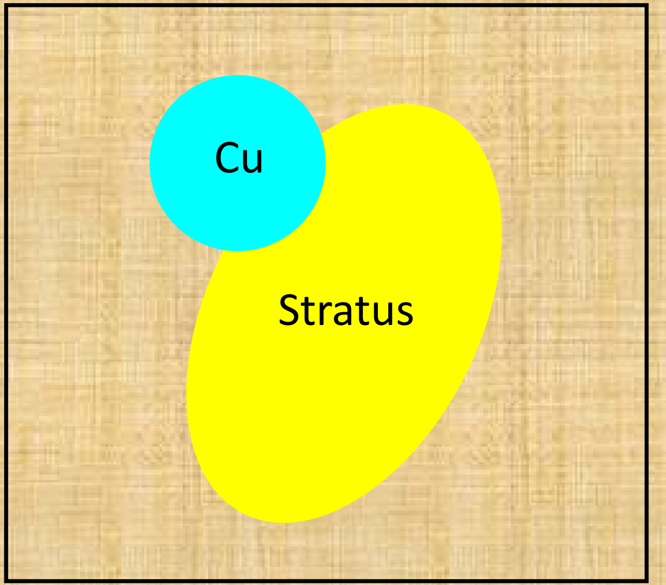
- Uses a single equilibrium cloud fraction at each time step.
- Condensation formulation based on conservative scalars
- Remove 'empty' ($a>0$, $q_{l,cloud}=0$) and 'dense'($a=0$, $q_{l,cloud}>0$) stratus
- Explicit treatment of in-cumulus LWC

CAM3 Macrophysics



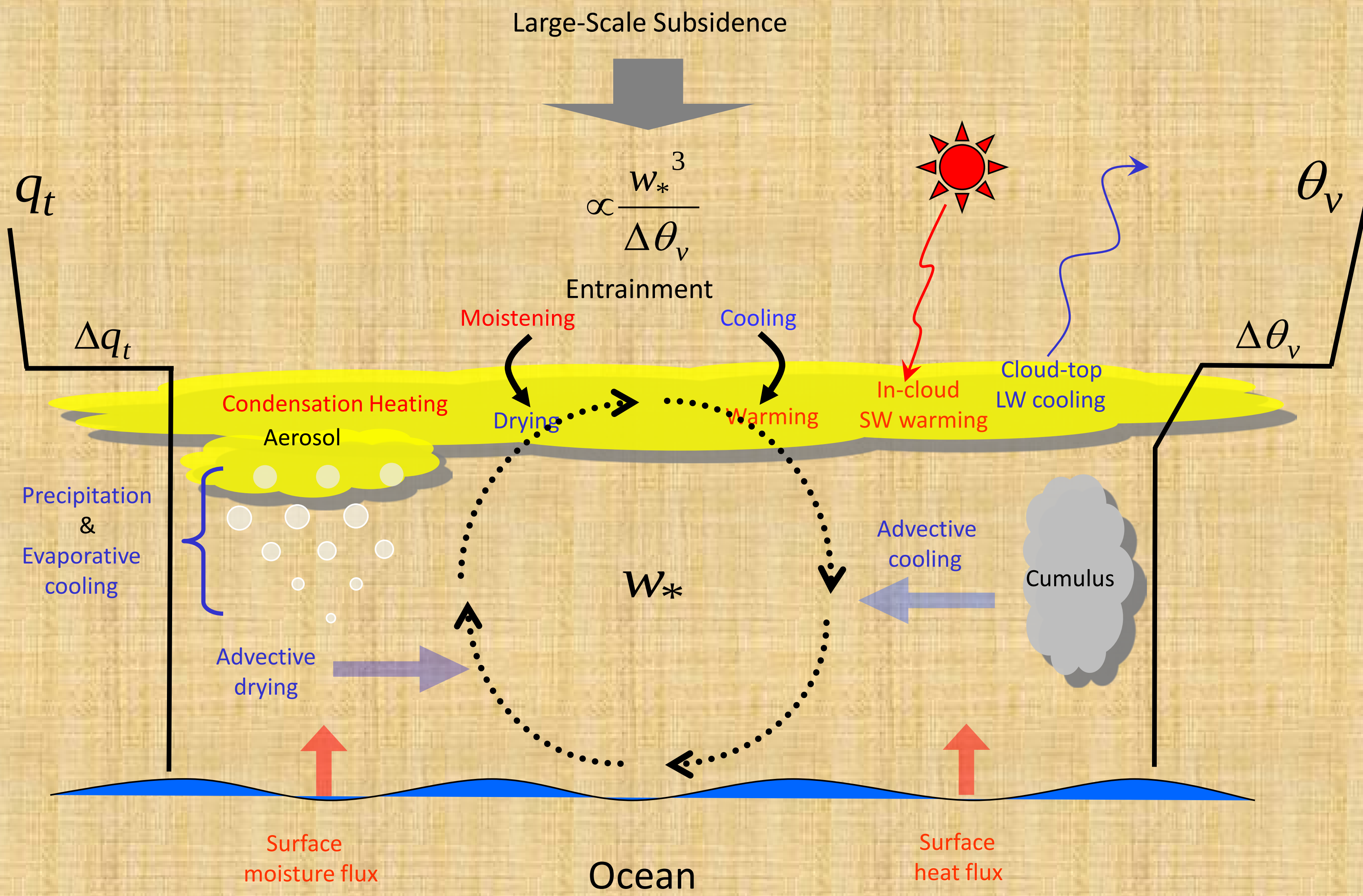
- Overlap
- In-cumulus LWC = In-stratus LWC

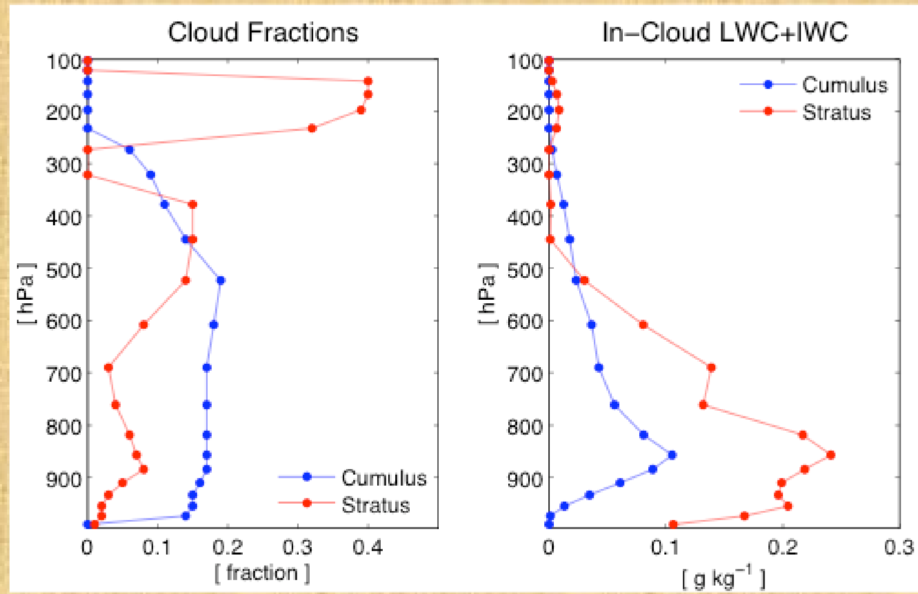
Revised Macrophysics

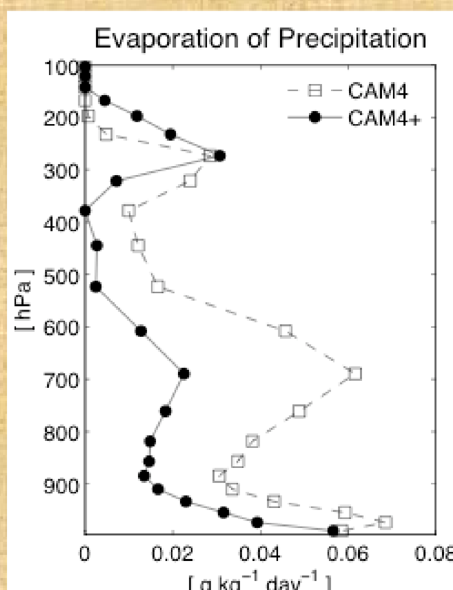


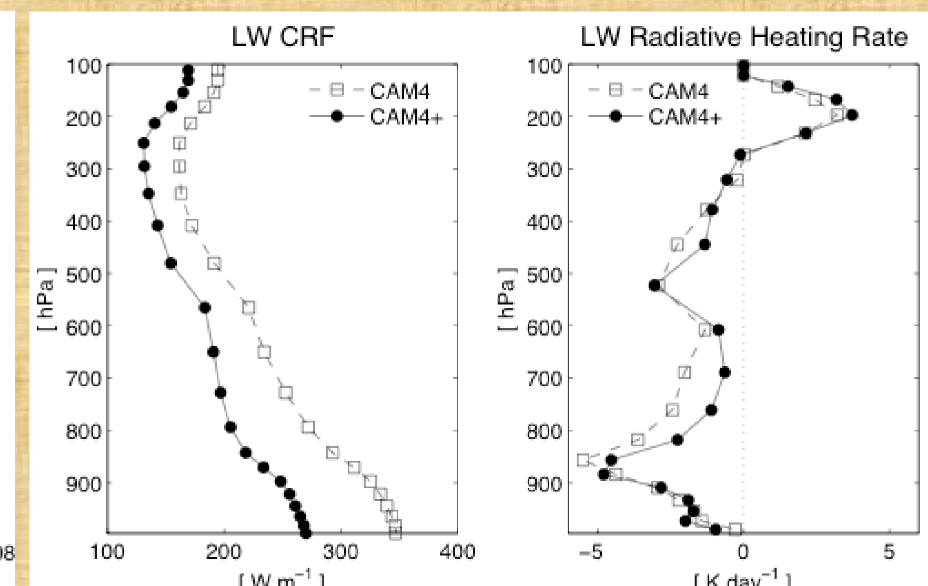
- Non-overlap
- In-cumulus LWC ≠ In-stratus LWC

Interplay among Various Processes in Stratocumulus

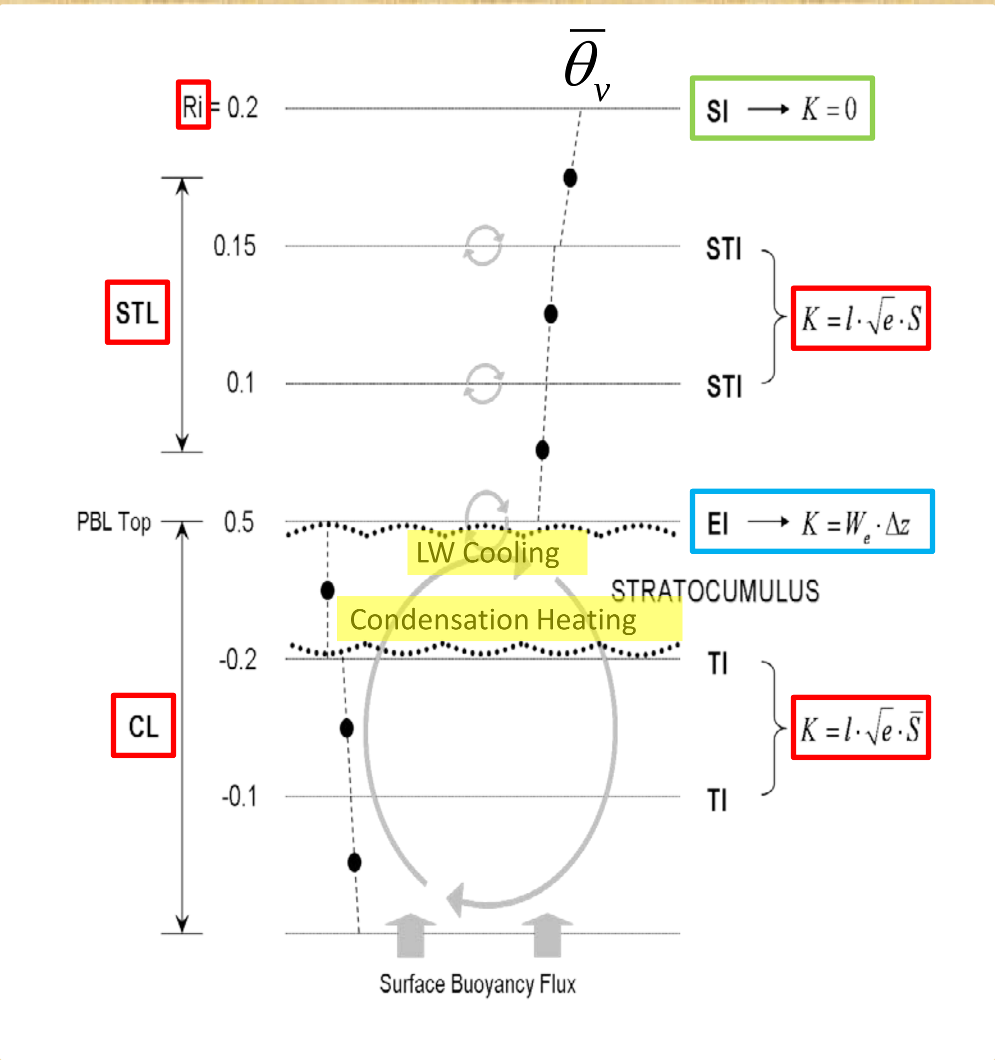



Cloud Fractions
[hPa]
100
200
300
400
500
600
700
800
900
0
0.1
0.2
0.3
0.4
[fraction]
Cumulus
Stratus
In−Cloud LWC+IWC
[hPa]
0
0.1
0.2
0.3
[g kg^{-1}]
Cumulus
Stratus


Evaporation of Precipitation
[hPa]
100
200
300
400
500
600
700
800
900
0
0.02
0.04
0.06
0.08
[g kg^{-1} day^{-1}]
CAM4
CAM4+


LW CRF
[hPa]
100
200
300
400
[W m^{-1}]
CAM4
CAM4+
LW Radiative Heating Rate
[hPa]
−5
0
5
[K day^{-1}]
CAM4
CAM4+

MOIST TURBULENCE SCHEME in CAM4



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K : eddy diffusivity

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S	: Stability function (fcn of Ri)
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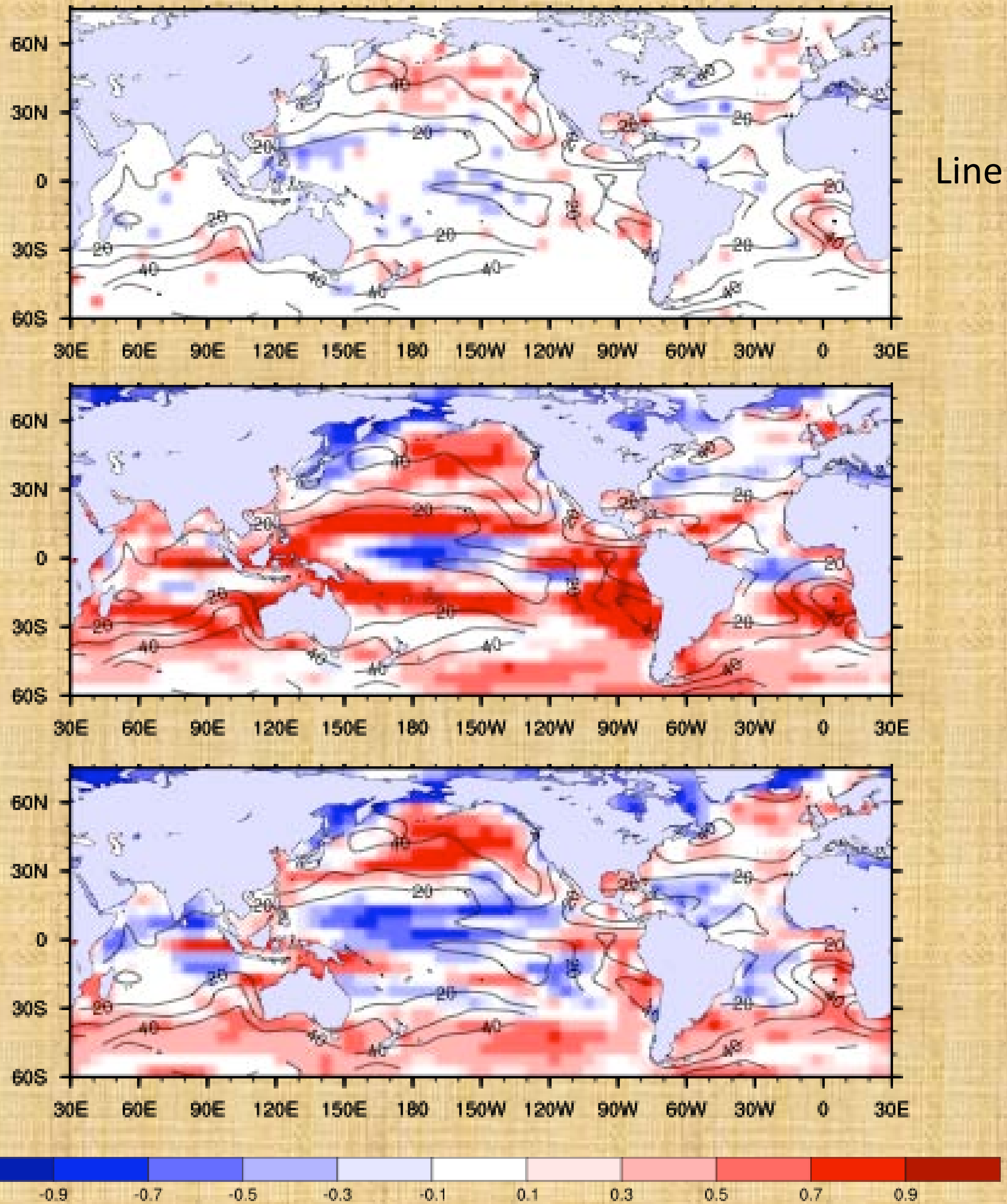
Interannual Correlation between $S \equiv \theta_v(700) - \theta_v(1000)$ and Low Cloud Amount. DJF.

Line: Ship-observed LCA

Observation

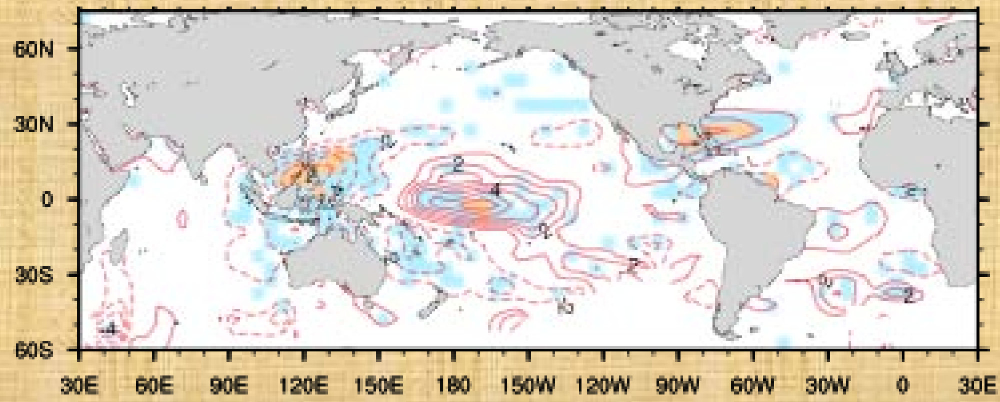
CAM35

CAM4

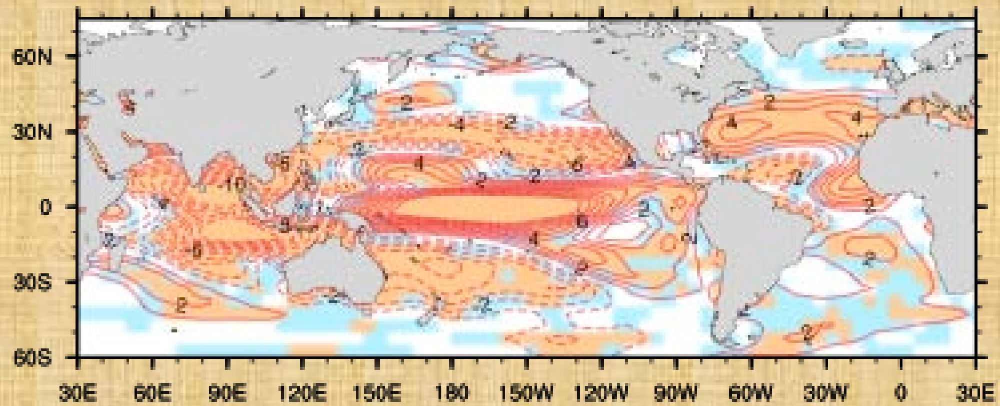


ENSO Regression Anomalies of Total Cloud Amount [%]. DJF.

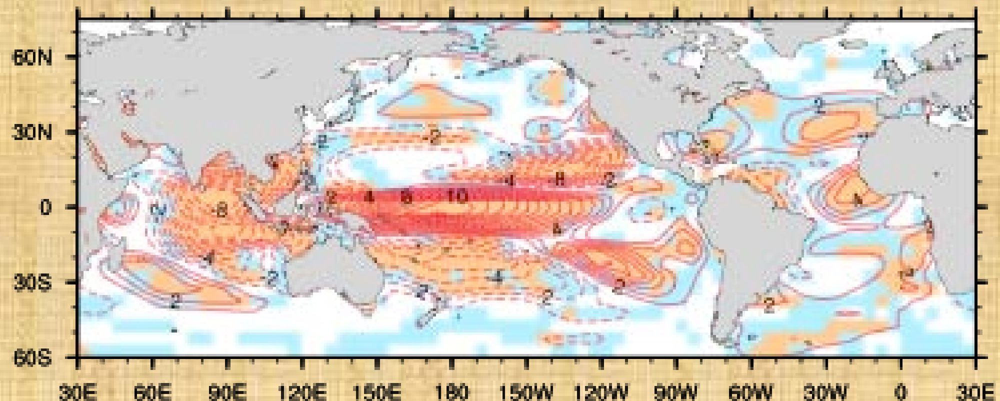
Observation



CAM35



CAM4



3 Cloud Types in CAM3.5

- Cumulus

$$a_c = f(M) \quad , \quad M:$$ Convective Updraft Mass Flux

- RH (Relative Humidity) Stratus

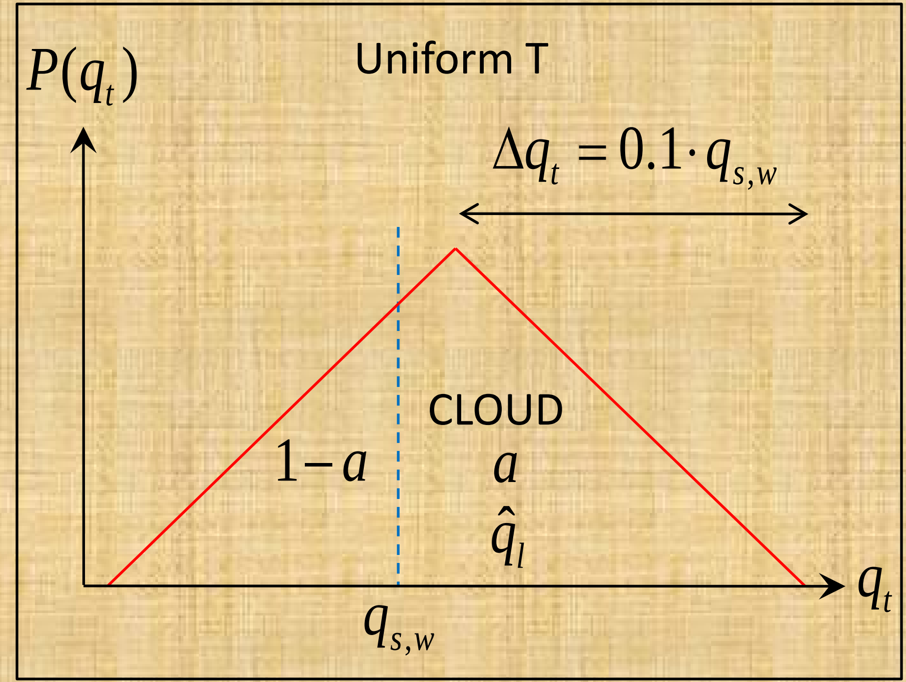
$$a_{s,RH} = f(\overline{RH}) \quad , \quad \overline{RH}:$$ Grid-Mean Relative Humidity

- KH (Klein-Hartmann) Stratus

$$a_{s,KH} = f(S) \quad , \quad S \equiv \theta_v(700) - \theta_v(1000)$$

Computation of Liquid Stratus Fraction

PDF of q_t for liquid cloud only



Stratus Fraction as a function of RH