PBL and Cloud Macrophysics in CAM

CAM Tutorial

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OUTLINE

I. Parameterization of Symmetric Turbulence (i.e., PBL Scheme)

- Dry Turbulence Scheme (CAM3 PBL)
- Moist Turbulence Scheme (CAM4 PBL)

II. Cloud Macrophysics

- Net Condensation Rate of Water Vapor into Cloud Liquid (Q)
- Cloud Fraction (a)
- Vertical Overlap of Cloud Fraction

DEFINITIONS

☐ Model Names

- *CAM3.5* : CAM3.0 + *Revised Deep Convection* + etc.
- *CAM4* : CAM3.5 + *All New Atmospheric Physics* (~ *CAMUW*)

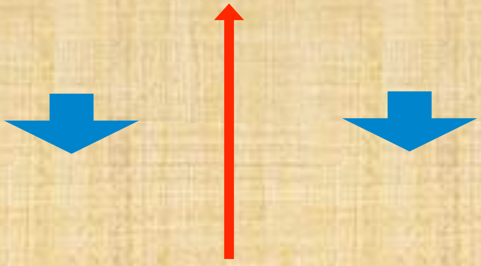
I.
Parameterization of Symmetric Turbulence in CAM

$$\frac{\partial \overline{A}}{\partial t} = -\vec{V}\cdot\nabla\overline{A} + \overline{Q}_A \boxed{-\frac{\partial}{\partial z}\overline{w'A'}}$$

Adiabatic Mixing by Turbulences

Symmetric Turbulence

(PBL Scheme ~ Symmetric Turbulence Scheme)

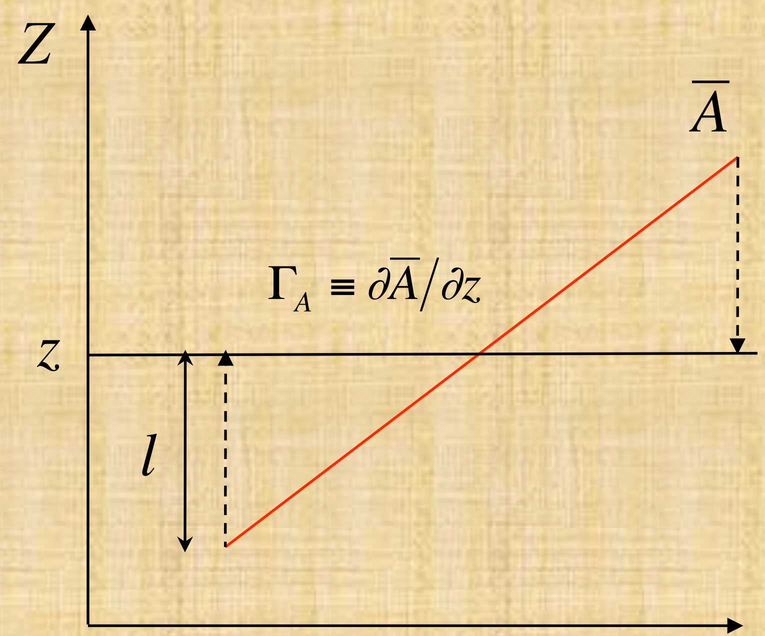


Asymmetric Turbulence

(Convection Scheme ~ Asymmetric Turbulence Scheme)

Single Small-Scale Turbulence

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



$$A_u - \overline{A} = -\Gamma_A \cdot l$$

$$w_u - \overline{w} \approx \left|u_u - \overline{u}\right|\cdot S = l\cdot\left|\frac{\partial\overline{u}}{\partial z}\right|\cdot S$$

$$\overline{w'A'} = -l\cdot\underbrace{l\cdot\left|\frac{\partial\overline{u}}{\partial z}\right|\cdot S}_{K_A}\cdot\Gamma_A$$

$$\boxed{\overline{w'A'} = -K_A\cdot\left(\Gamma_A - \underbrace{\gamma_A}_{\text{Non-Local Term}}\right)}$$

$$\overline{w'A'} = -l\cdot \boxed{l\cdot\left|\frac{\partial|\vec{u}|}{\partial z}\right|}\cdot S\cdot\Gamma_A$$

CAM3 Dry Turbulence Scheme with Non-Local Term

CAM4 Moist Turbulence Scheme

$$\overline{w'A'} = l\cdot V\left(\boxed{(\overline{w'\theta_v'})_o,(\overline{w'u'})_o};\boxed{\sqrt{e}}\right)\cdot S\cdot\Gamma_A \quad , \quad e\equiv 0.5\cdot(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})$$

$$\frac{\partial}{\partial t}\overline{w'A'} = -\frac{\partial}{\partial z}\overline{w'w'A'} + \ldots \quad , \quad \overline{w'w'A'} = -l\cdot V(\sqrt{e})\cdot S\cdot\frac{\partial}{\partial z}\overline{w'A'}$$

$$\frac{\partial}{\partial t}\overline{w'w'A'} = -\frac{\partial}{\partial z}\overline{w'w'w'A'} + \ldots \quad , \quad \overline{w'w'w'A'} = -l\cdot V(\sqrt{e})\cdot S\cdot\frac{\partial}{\partial z}\overline{w'w'A'}$$

Higher Order Closure

$$\begin{bmatrix} \overline{A}(t+\Delta t, z=1) \\ \overline{A}(t+\Delta t, z=2) \\ \overline{A}(t+\Delta t, z=3) \\ \overline{A}(t+\Delta t, z=4) \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix} \cdot \begin{bmatrix} \overline{A}(t, z=1) \\ \overline{A}(t, z=2) \\ \overline{A}(t, z=3) \\ \overline{A}(t, z=4) \end{bmatrix}$$

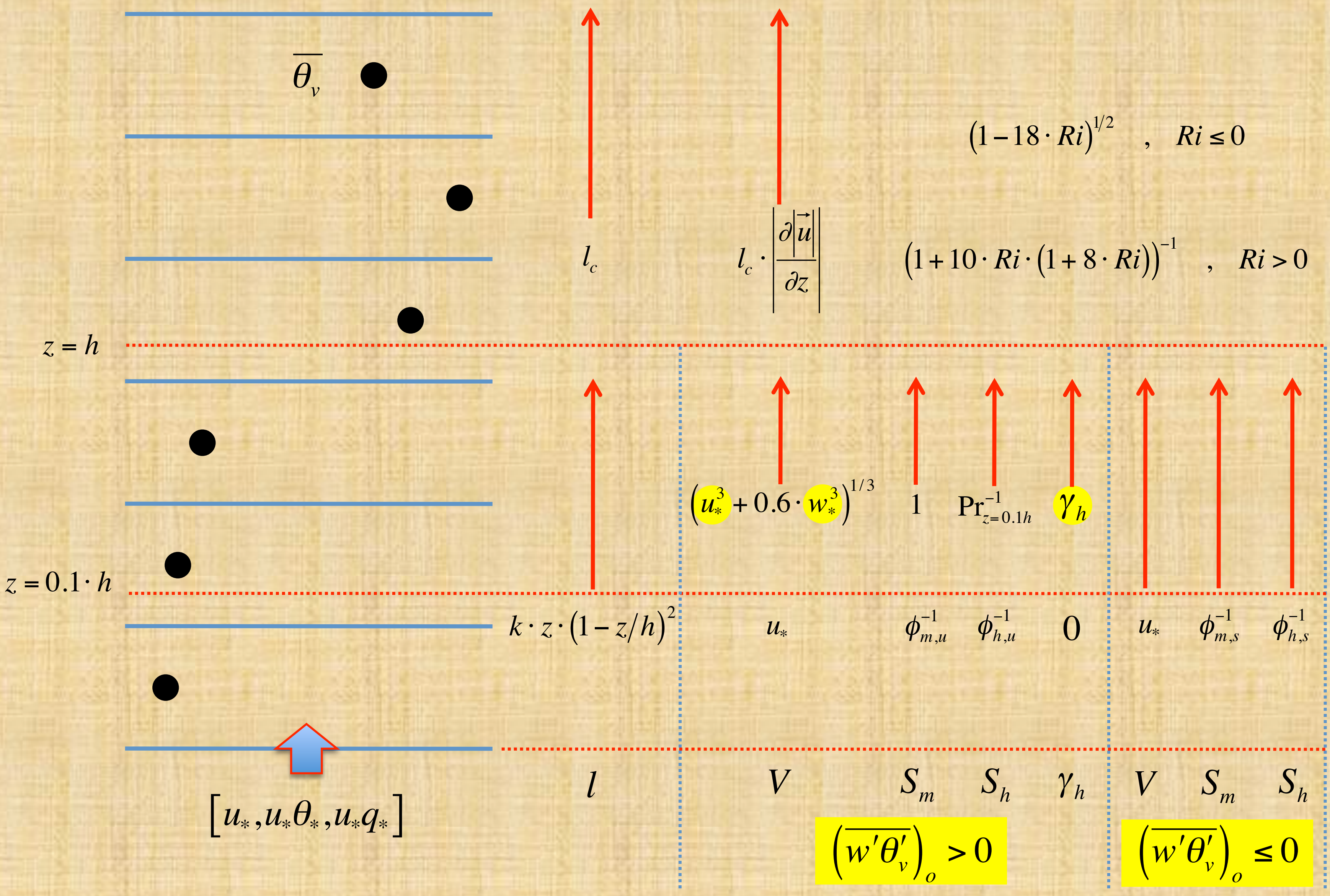
Transilient Theory

$$\overline{w'A'} = -K_A \cdot \left(\frac{\partial \overline{A}}{\partial z} - \gamma_A \right)$$

$$K_A = l \cdot V \cdot S_A$$

$$\gamma_A$$

1^{st} Order Non-Local Closure for Dry Turbulence : CAM3



$\overline{\theta}_v$

l_c

$l_c \cdot \left| \frac{\partial |\vec{u}|}{\partial z} \right|$

$(1-18 \cdot Ri)^{1/2} \quad , \quad Ri \le 0$

$(1+10 \cdot Ri \cdot (1+8 \cdot Ri))^{-1} \quad , \quad Ri > 0$

$z = h$

$(u_*^3 + 0.6 \cdot w_*^3)^{1/3}$ $\quad 1 \quad$ $\mathrm{Pr}_{z=0.1h}^{-1}$ $\quad \gamma_h$

$z = 0.1 \cdot h$

$k \cdot z \cdot (1 - z/h)^2$ $\quad u_*$ $\quad \phi_{m,u}^{-1}$ $\quad \phi_{h,u}^{-1}$ $\quad 0$ $\quad u_*$ $\quad \phi_{m,s}^{-1}$ $\quad \phi_{h,s}^{-1}$

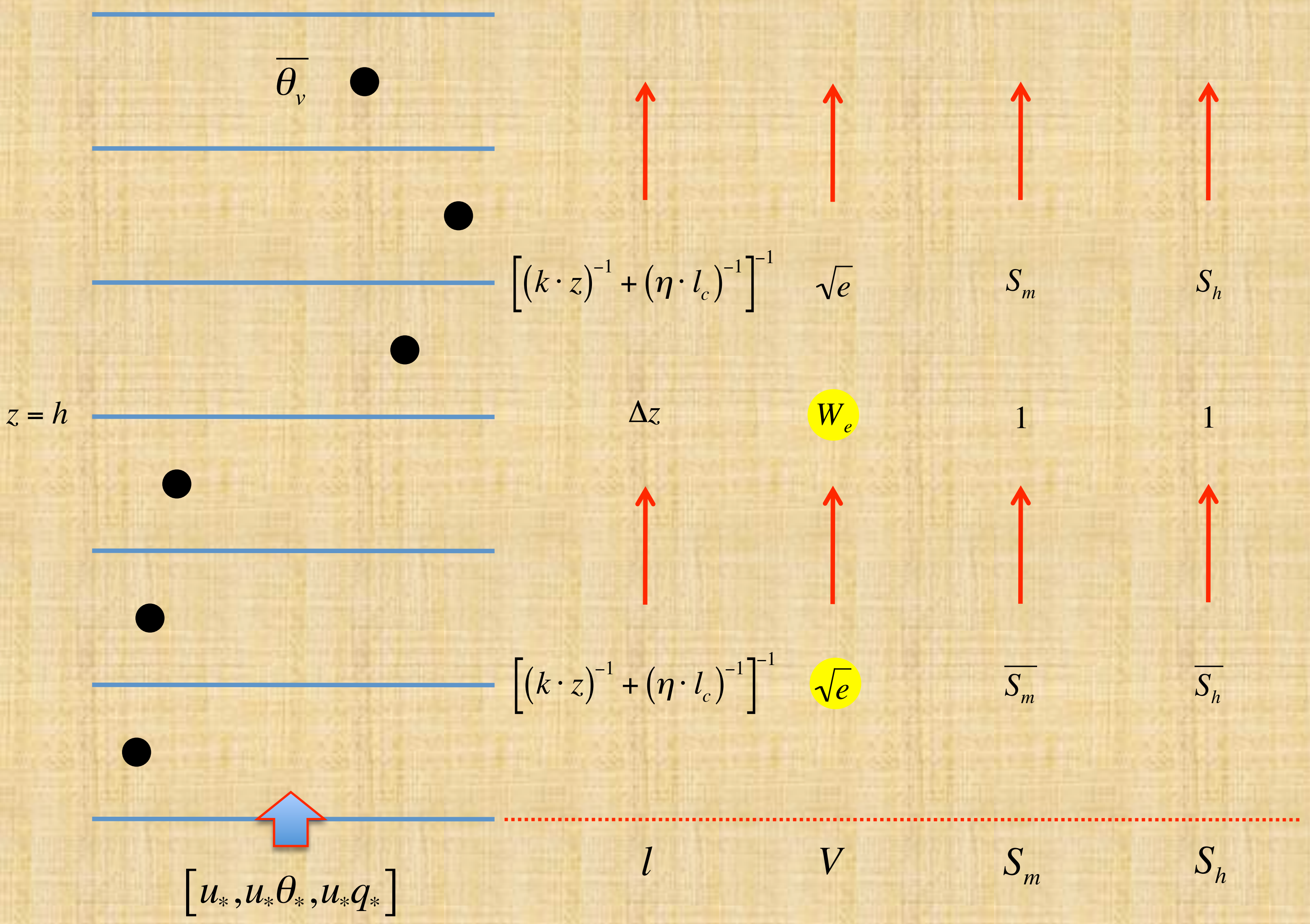
$[u_*, u_*\theta_*, u_*q_*]$

l $\quad V$ $\quad S_m$ $\quad S_h$ $\quad \gamma_h$ $\quad V$ $\quad S_m$ $\quad S_h$

$\left(\overline{w'\theta_v'}\right)_o > 0$

$\left(\overline{w'\theta_v'}\right)_o \le 0$

1.5 Order Local Closure for Moist Turbulence : CAM4



$\overline{\theta}_v$

$\left[(k\cdot z)^{-1}+(\eta\cdot l_c)^{-1}\right]^{-1}$ $\sqrt{e}$ S_m S_h

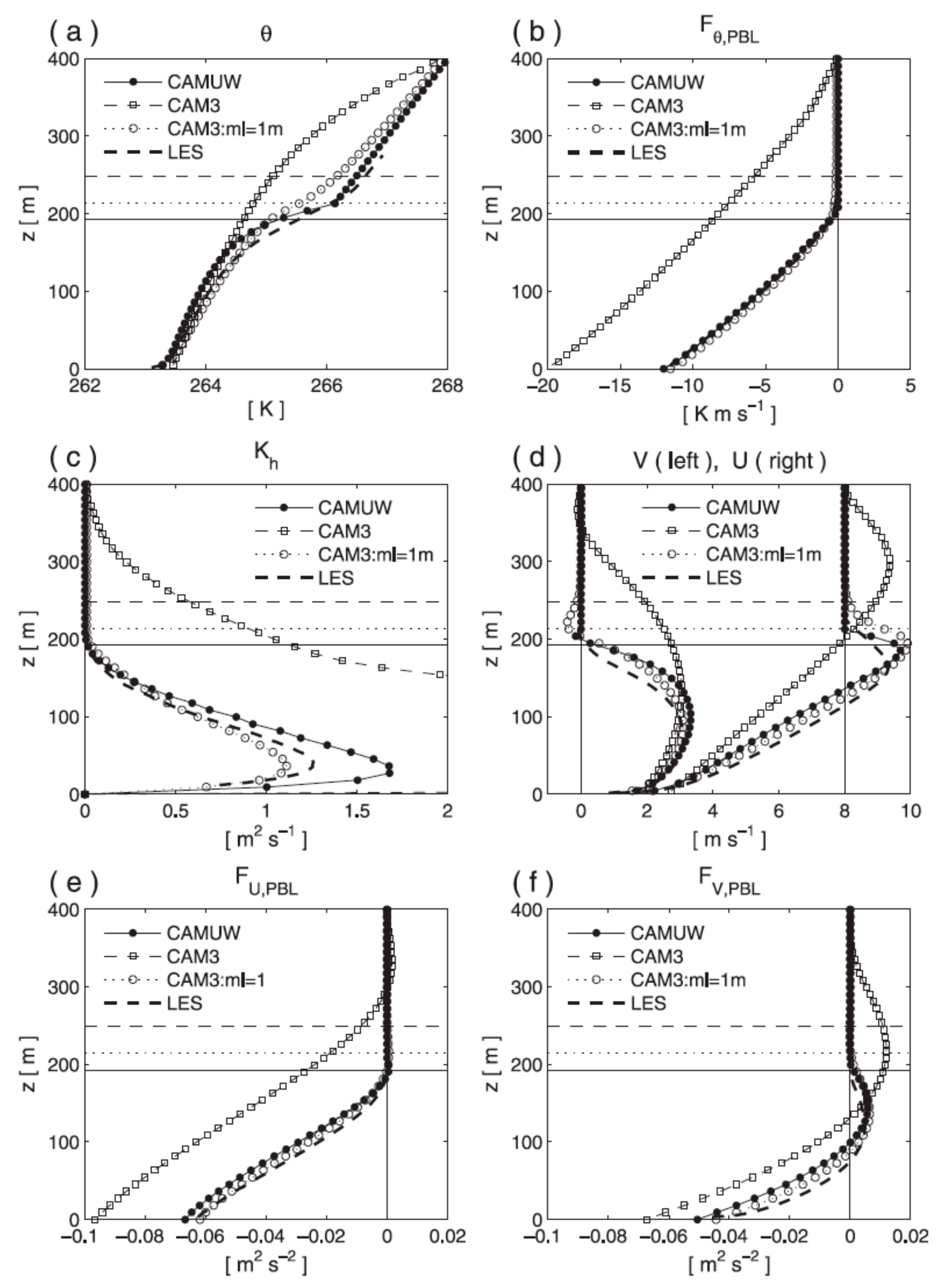
$z=h$ Δz W_e 1 1

$\left[(k\cdot z)^{-1}+(\eta\cdot l_c)^{-1}\right]^{-1}$ $\sqrt{e}$ $\overline{S}_m$ $\overline{S}_h$

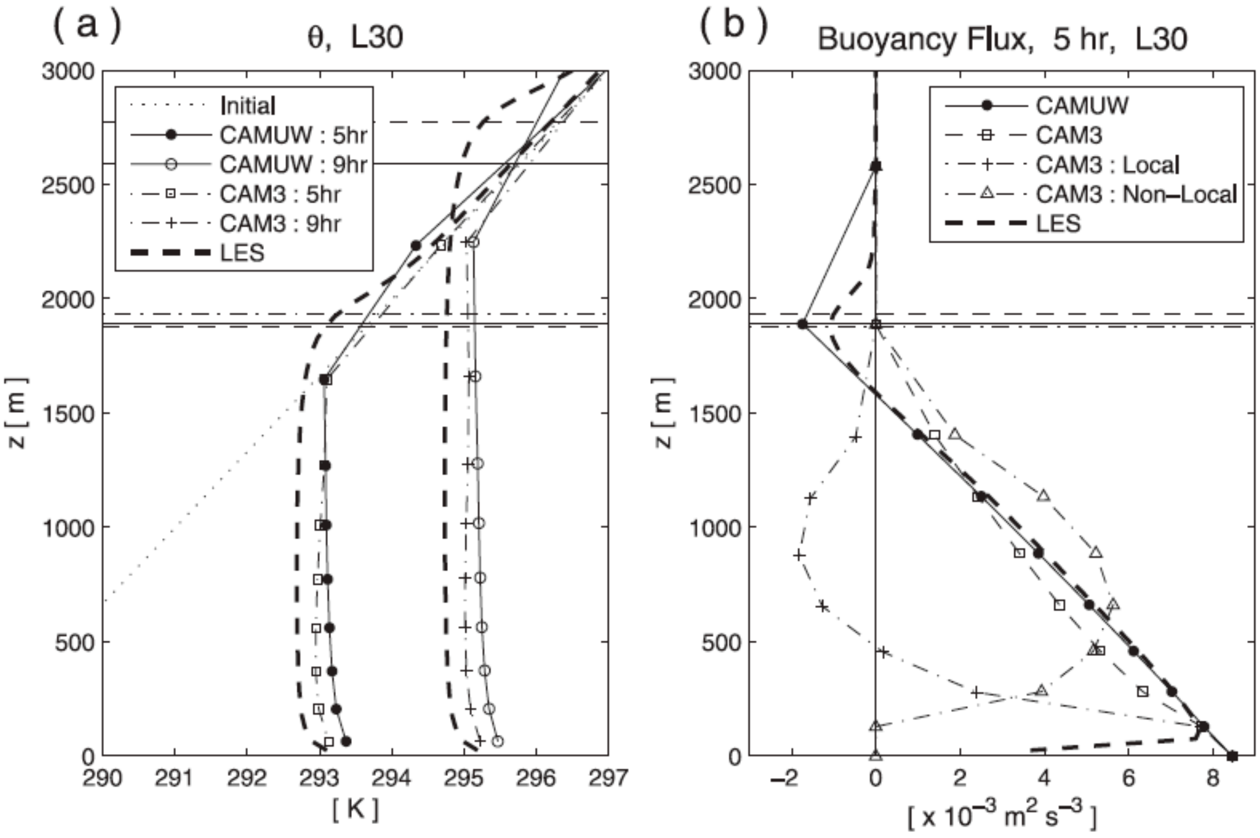
l V S_m S_h

$\left[u_*, u_*\theta_*, u_*q_*\right]$

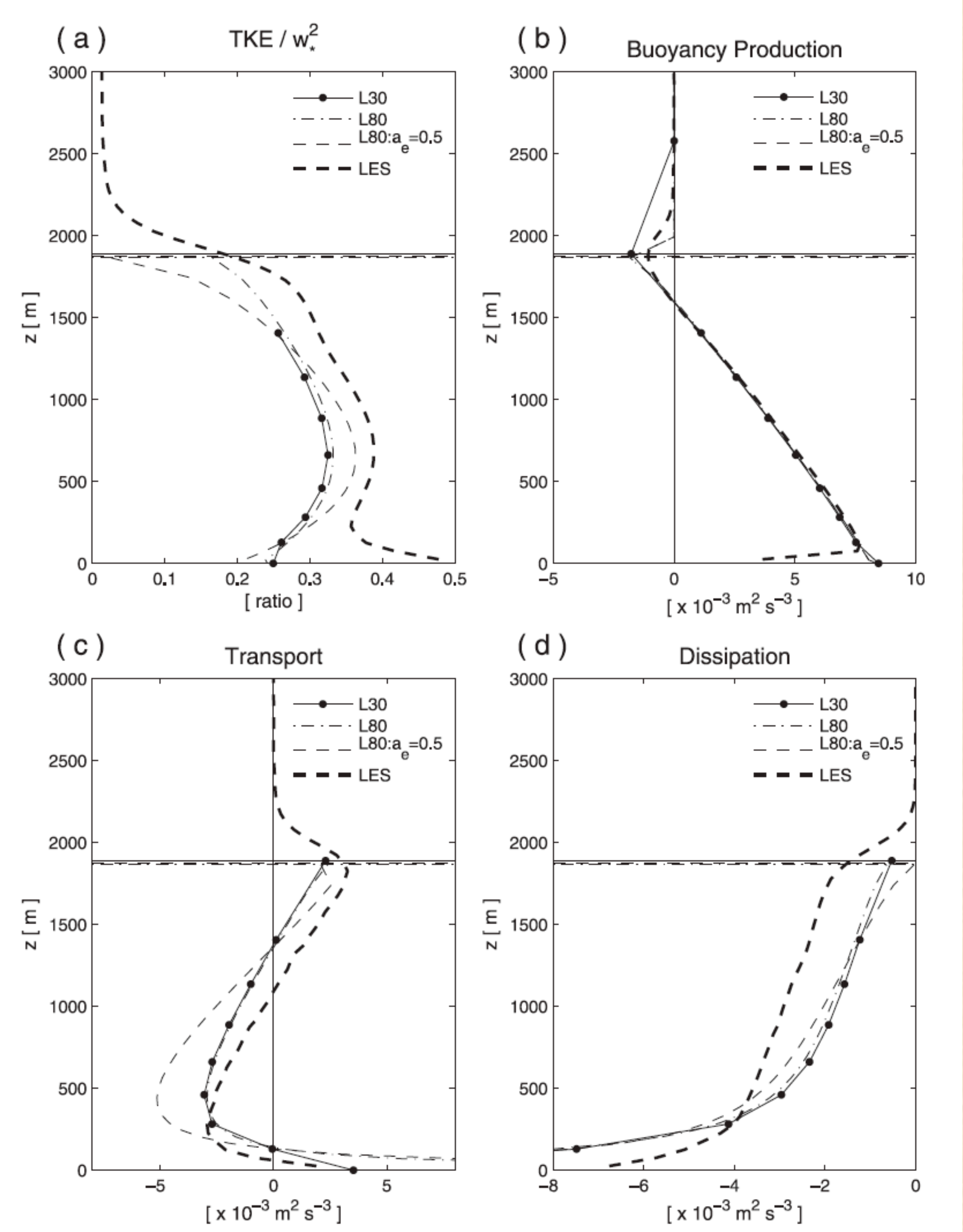
Dry Stable PBL
: GABLS



Dry Convective PBL



Dry Convective PBL



Comparison of Turbulence Velocity

CAM3
Dry Turbulence

$$u_* = \left| \left(\overline{w'u'} \right)_o^2 \right|$$

$$w_* = \left[(g/\theta_v) \cdot \left(\overline{w'\theta'_v} \right)_o \cdot h \right]^{1/3}$$

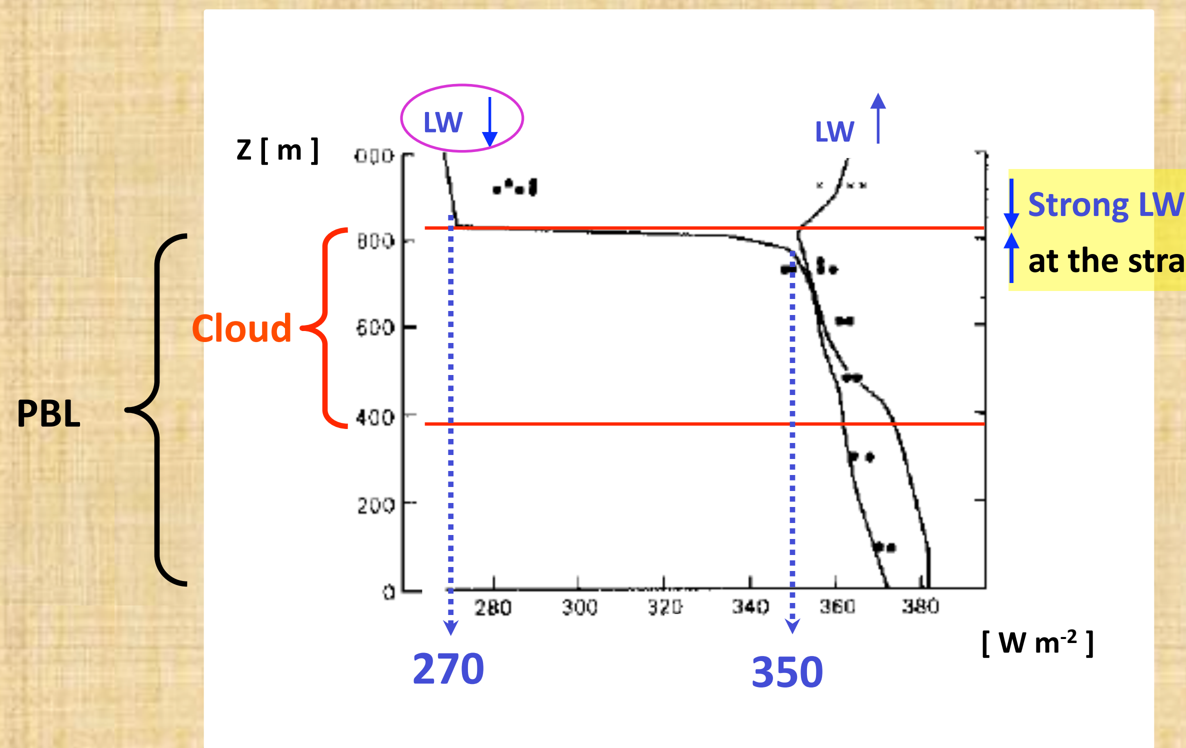
CAM4
Moist Turbulence

$$e = 6 \cdot \frac{l}{\sqrt{e}} \cdot \left((g/\theta_v) \cdot \overline{w'\theta'_v} - \overline{w'u'} \cdot \frac{\partial \bar{u}}{\partial z} \right) + 24 \cdot \frac{l}{h} \cdot \left(\langle e \rangle - e \right)$$

$$w_* = \left[2.5 \cdot (g/\theta_v) \cdot \int_0^h \left(\overline{w'\theta'_v} \right)(z) \cdot dz \right]^{1/3}$$

CAM4 handles elevated sources of turbulent energy.
→ Critical for simulating moist turbulence associated with clouds.

LW Radiative Flux at the top of Cloud

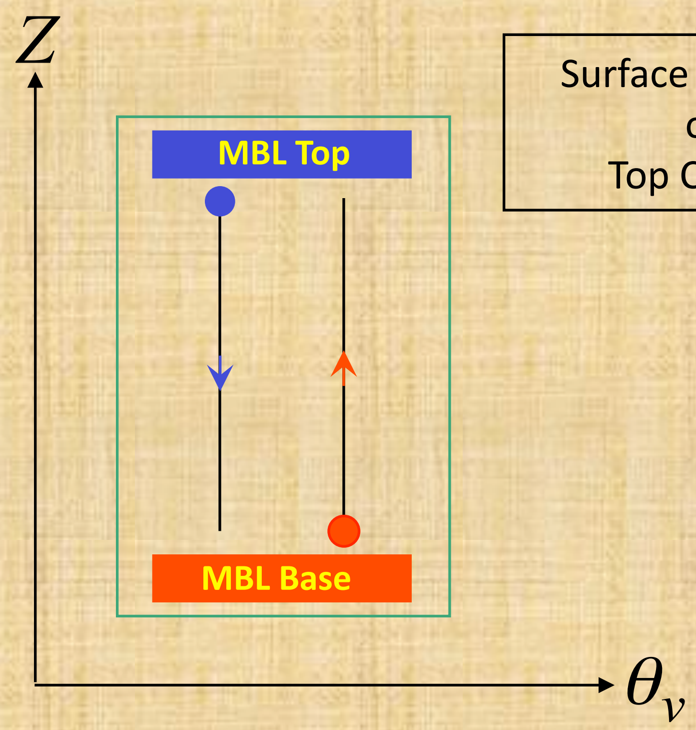


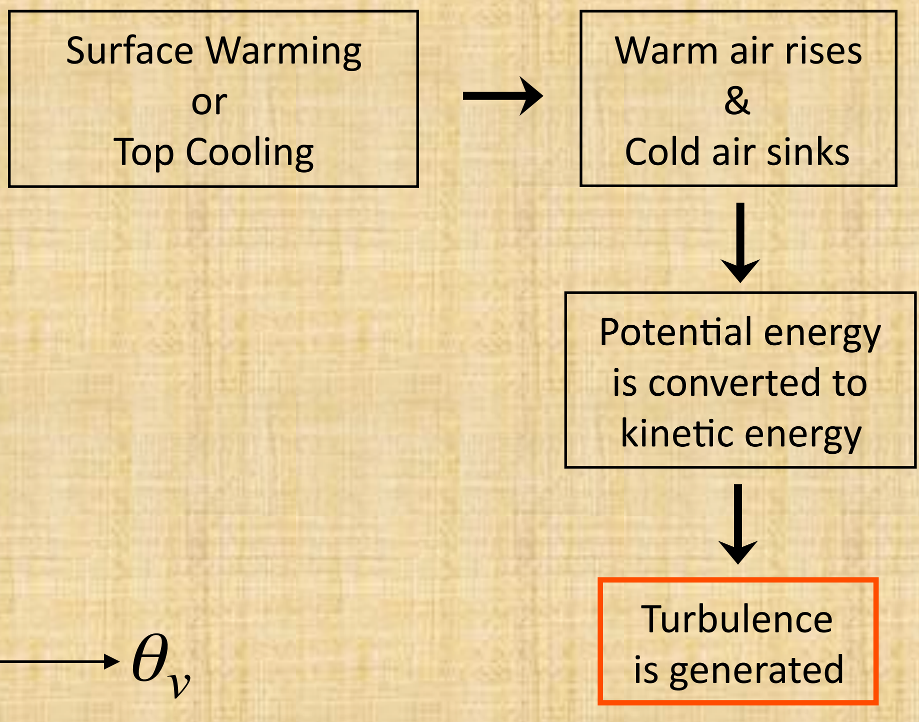
↓ **Strong LW cooling is confined**
↑ **at the stratocumulus top.**

[Nicholls 1984, *Quart. J. R. Met. Soc.*]

TURBULENCE GENERATED BY BOUNDARY HEATING

$$\frac{\partial TKE}{\partial t} \propto B(a) \equiv (g/\theta_v)\cdot\overline{w'\theta'_v}$$





Surface Warming
or
Top Cooling

→

Warm air rises
&
Cold air sinks

↓

Potential energy
is converted to
kinetic energy

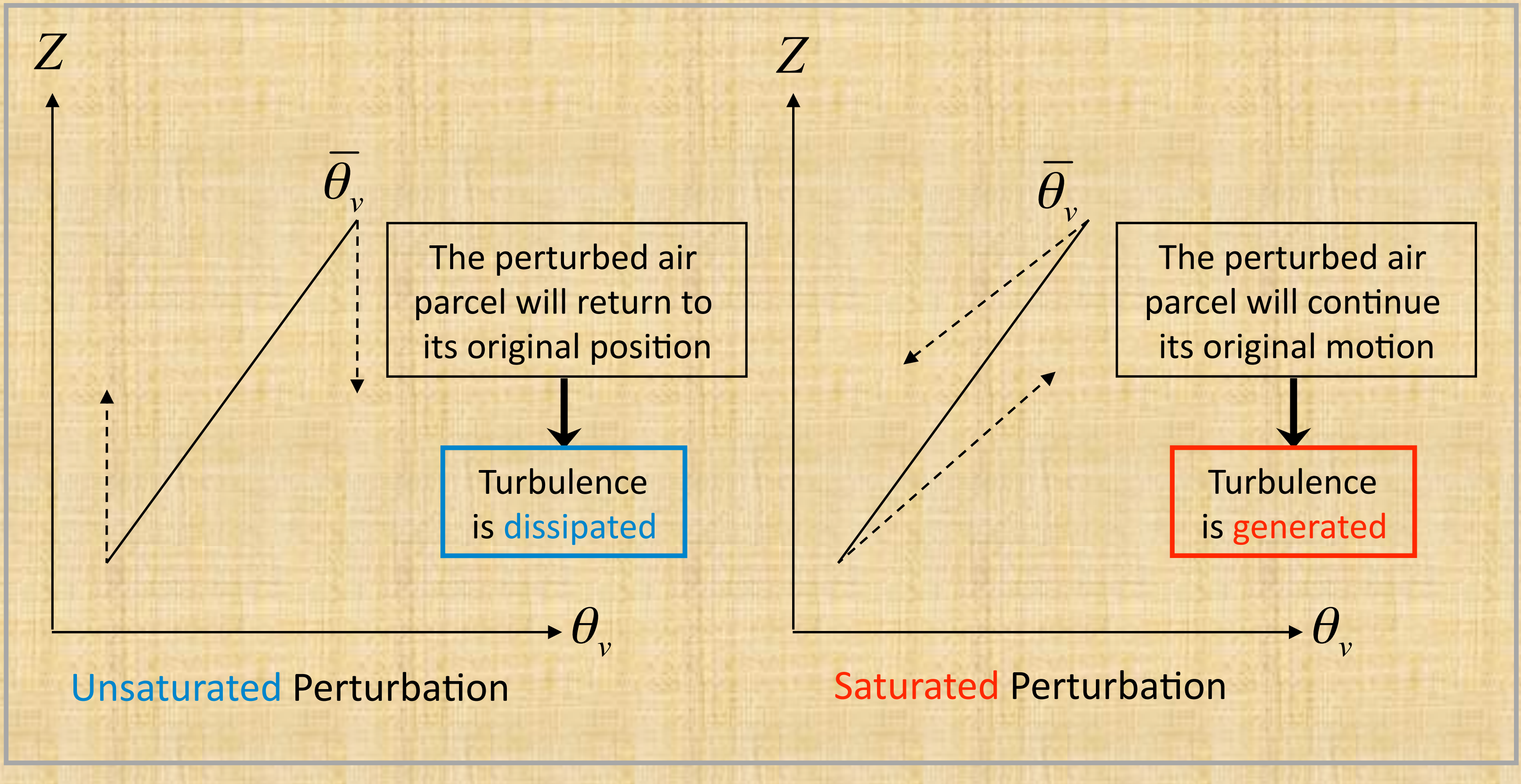
↓

Turbulence
is generated

Turbulence is generated by MBL top LW cooling driven by stratocumulus

TURBULENCE GENERATED BY CONDENSATION HEATING

$$\frac{\partial TKE}{\partial t} \propto B(a) \equiv (g/\theta_v)\cdot\overline{w'\theta_v'}$$



The perturbed air parcel will return to its original position

Turbulence is dissipated

Unsaturated Perturbation

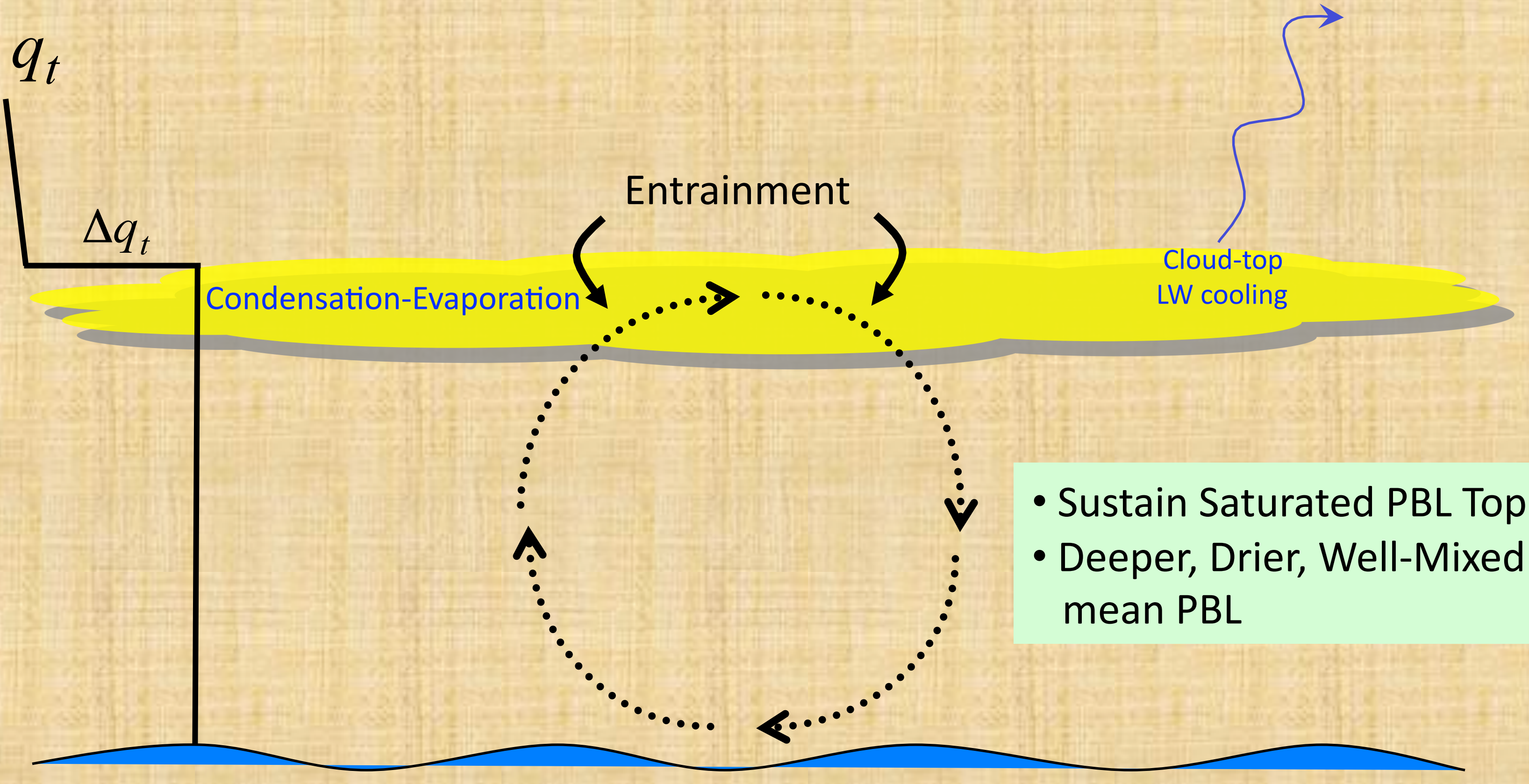
The perturbed air parcel will continue its original motion

Turbulence is generated

Saturated Perturbation

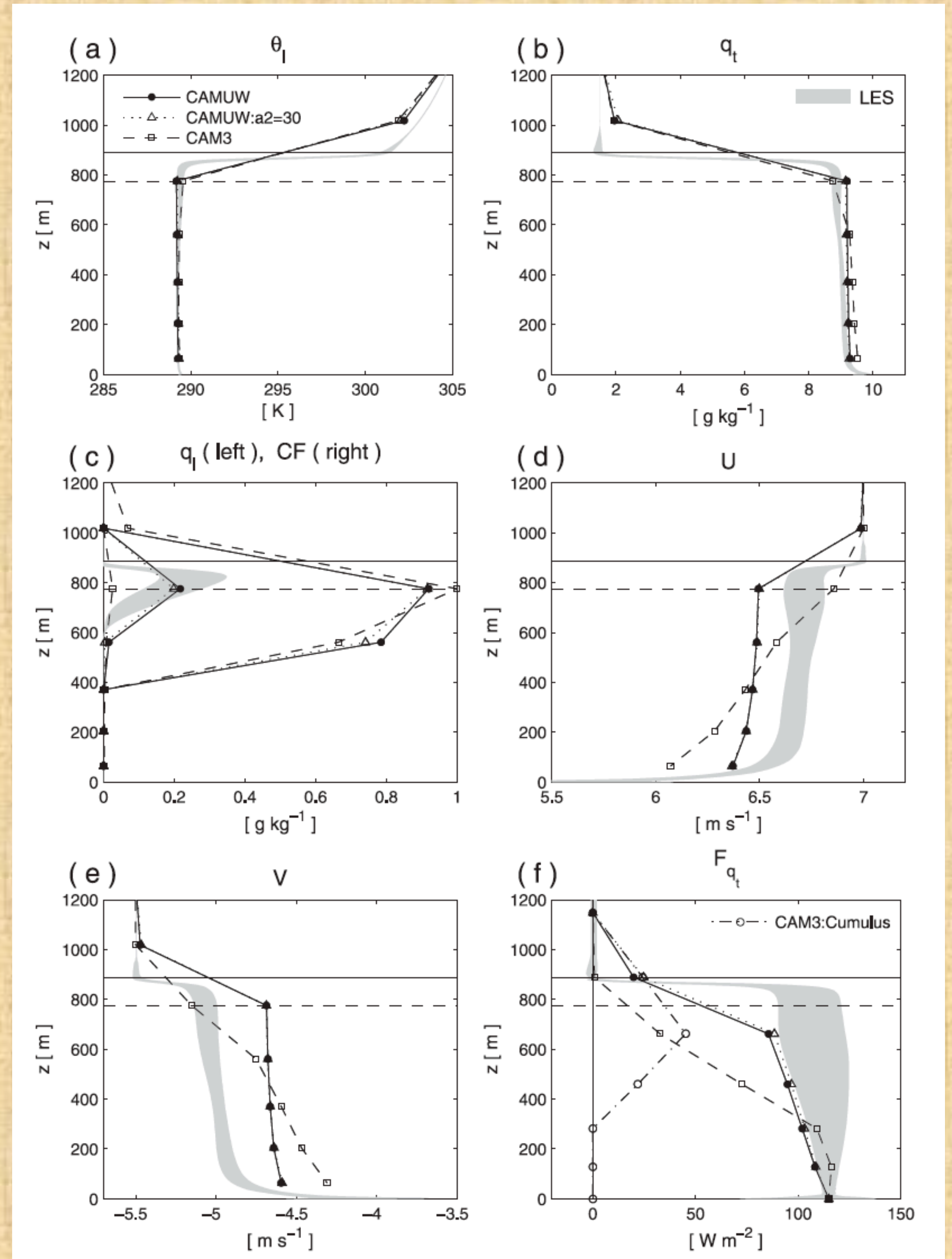
Turbulence is generated by condensation-evaporation heating, which is in turn controlled by cloud fraction within the grid.

Cloud-Radiation-Turbulence Interactions



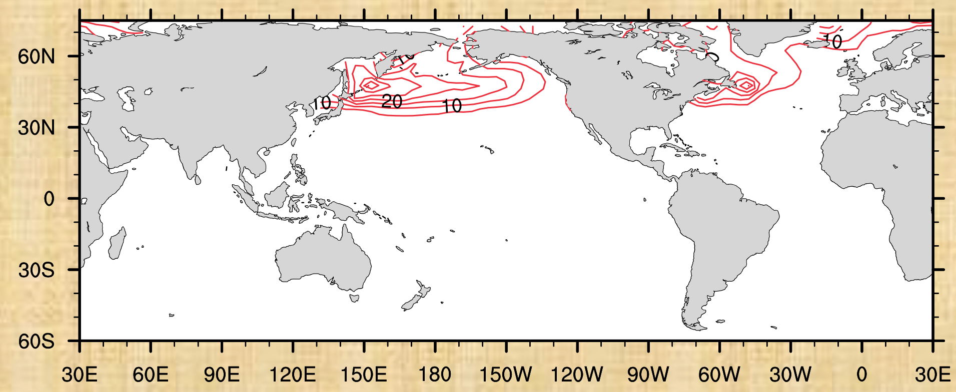
- Sustain Saturated PBL Top
- Deeper, Drier, Well-Mixed mean PBL

Cloud-Topped PBL
: DYCOMS

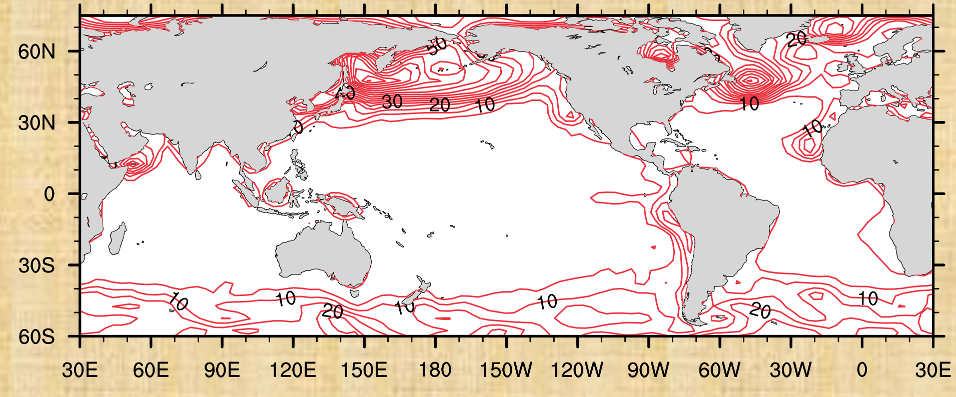


Fog Amount. JJA.

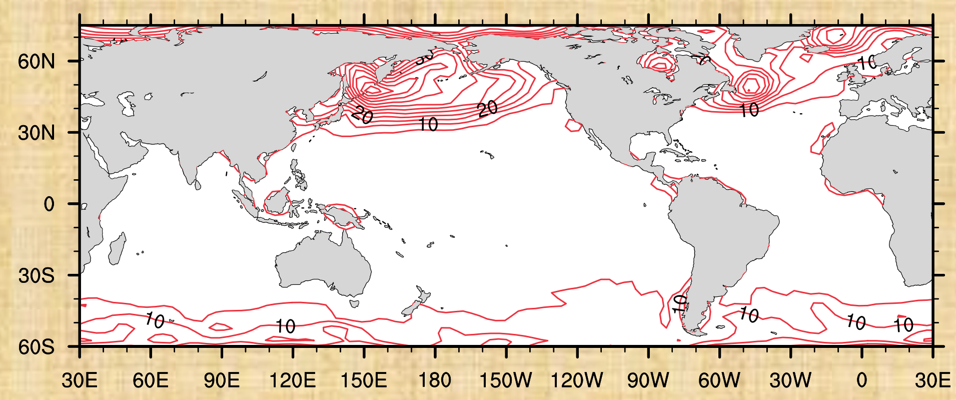
Observation



CAM35



CAM4



SUMMARY

In contrast to the dry turbulence scheme in CAM3,
the moist turbulence scheme in CAM4 takes into account of
elevated sources of TKE associated with clouds.

→ CAM4 successfully simulates cloud-topped PBL as well as dry PBL.

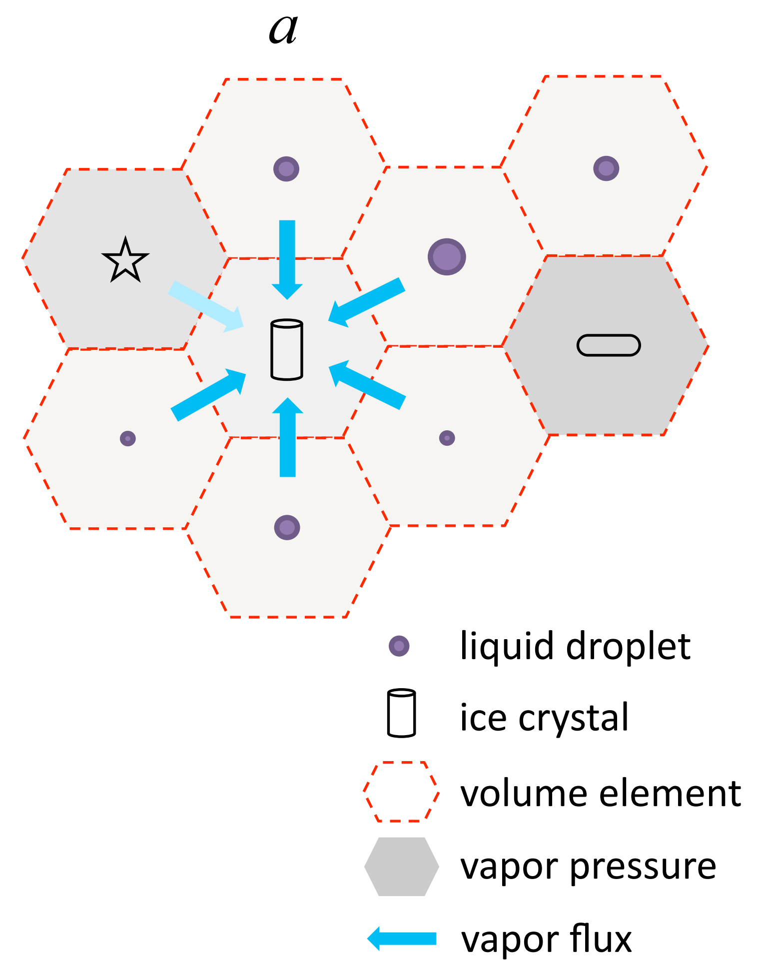
II.

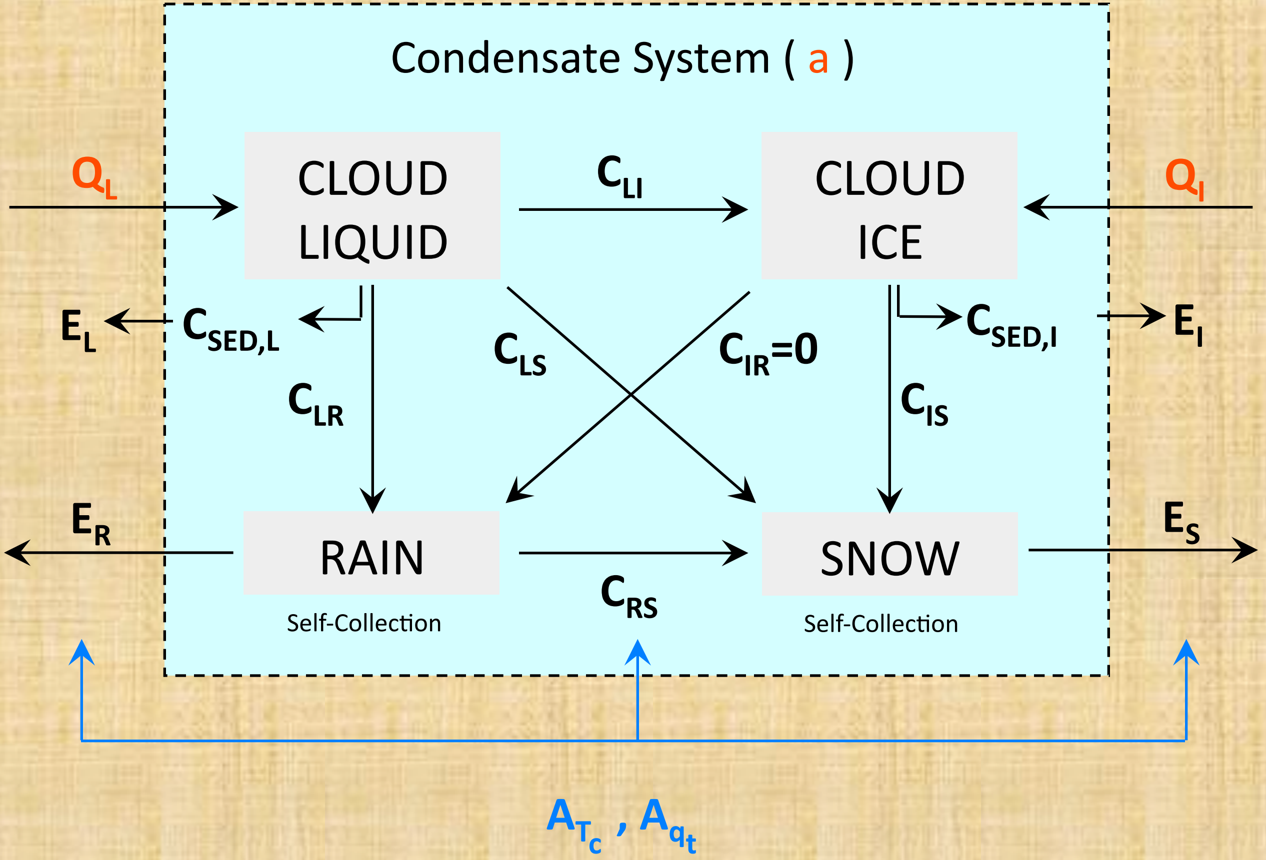
Cloud Macrophysics in CAM

WHAT IS CLOUD ?

CLOUD : The sum of volume elements containing condensates.

5 key properties : a, LWC, IWC, $N(r_l)$, $N(r_i)$





C_{LI} : Heterogeneous (Immersion) freezing
Bergeron-Findeisen deposition freezing
C_{LS} : Accretion of cloud liquid by snow
Bergeron-Findeisen conversion
C_{LR} : Autoconversion of cloud liquid into rain
Accretion of cloud liquid by rain
C_{IS} : Autoconversion of cloud ice into snow
Accretion of cloud ice by snow
C_{RS} : Accretion of rain by snow
Heterogeneous freezing
Homogeneous freezing

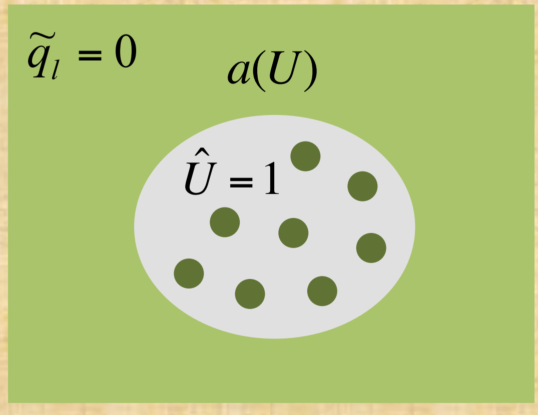
$C_{SED,L}$: Sedimentation of cloud liquid
$C_{SED,I}$: Sedimentation of cloud ice
E_L : Evaporation of sedimented cloud liquid
E_I : Evaporation of sedimented cloud ice
E_R : Evaporation of rain
E_S : Evaporation of snow
Q_L : Net condensation into cloud liquid
Q_I : Net condensation into cloud ice

What does Cloud Macrophysics do?

- Condensation rate of water vapor into cloud liquid (Q)
- Cloud fraction (a)
- Vertical overlap of cloud fraction

I. BULK SATURATION ADJUSTMENT

$$Q = a\cdot\underbrace{\hat{Q}_{cloud}}_{\text{in-cloud condensation}} + \underbrace{(1-a)\cdot\tilde{Q}_{clear}}_{\text{clear sky evaporation}} + \underbrace{\hat{q}_l\cdot\frac{\partial a}{\partial t}}_{\text{change of cloud fraction}}$$



$A_T > 0$

$$\longrightarrow \quad \hat{Q}_{cloud} < 0 \quad , \quad \tilde{Q}_{clear} = 0 \quad , \quad \frac{\partial a}{\partial t} < 0$$

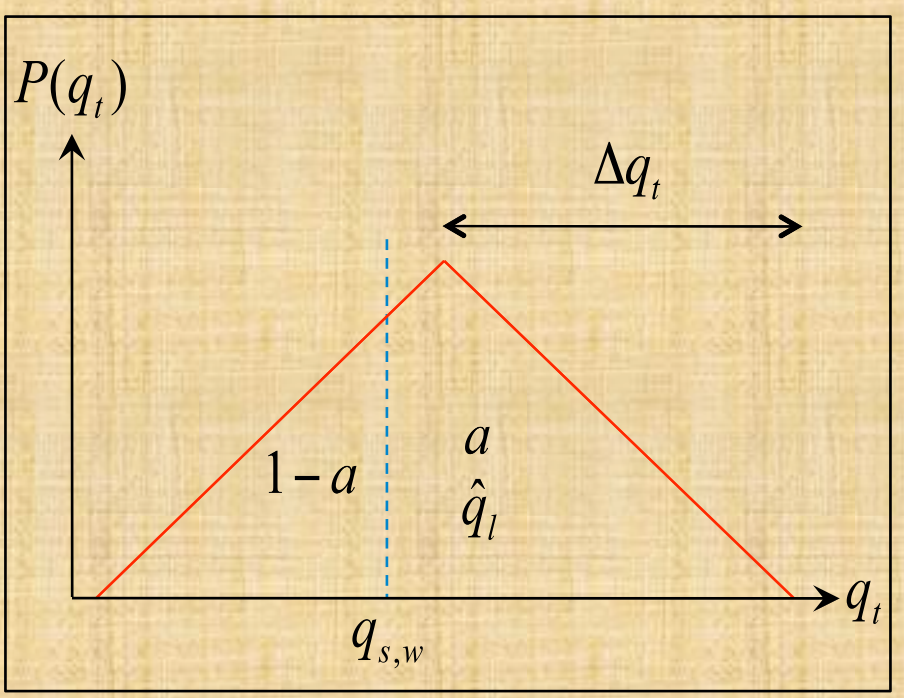
$A_{qv} > 0$

$$\longrightarrow \quad \hat{Q}_{cloud} > 0 \quad , \quad \tilde{Q}_{clear} \geq 0 \quad , \quad \frac{\partial a}{\partial t} > 0$$

$A_{ql} > 0$

$$\longrightarrow \quad \hat{Q}_{cloud} = 0 \quad , \quad \tilde{Q}_{clear} < 0 \quad , \quad \frac{\partial a}{\partial t} = 0$$

II. PDF-based SATURATION ADJUSTMENT



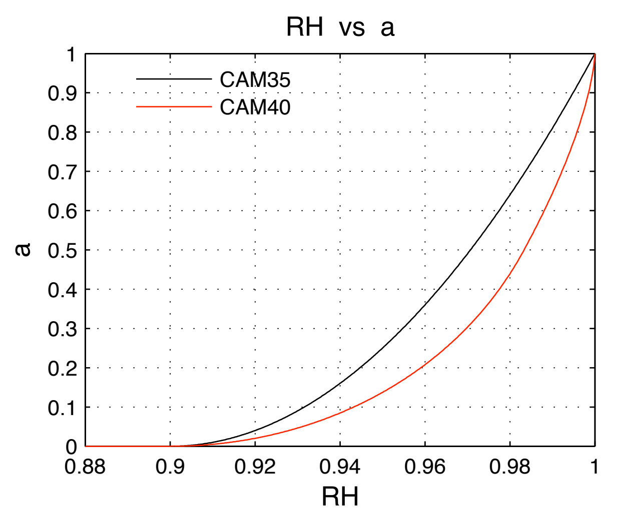
$A_T > 0$ $\Rightarrow$ $Q < 0 \quad , \quad \frac{\partial a}{\partial t} < 0$

$A_{qt} > 0$ $\Rightarrow$ $Q > 0 \quad , \quad \frac{\partial a}{\partial t} > 0$

BULK vs PDF-based Approach

$$a(U) = \left[\frac{U - U_c}{1 - U_c}\right]^2$$

$$\left[\frac{\Delta q_t}{q_{s,w}}\right] = 1 - U_c \quad \Rightarrow \quad a(U) = \ldots$$



$$U_{clr} = \frac{U - a}{1 - a} = \frac{(1 - U_c)\sqrt{a} + U_c - a}{1 - a}$$

$$U_{clr} = \frac{U - a}{1 - a} = \ldots\ldots$$

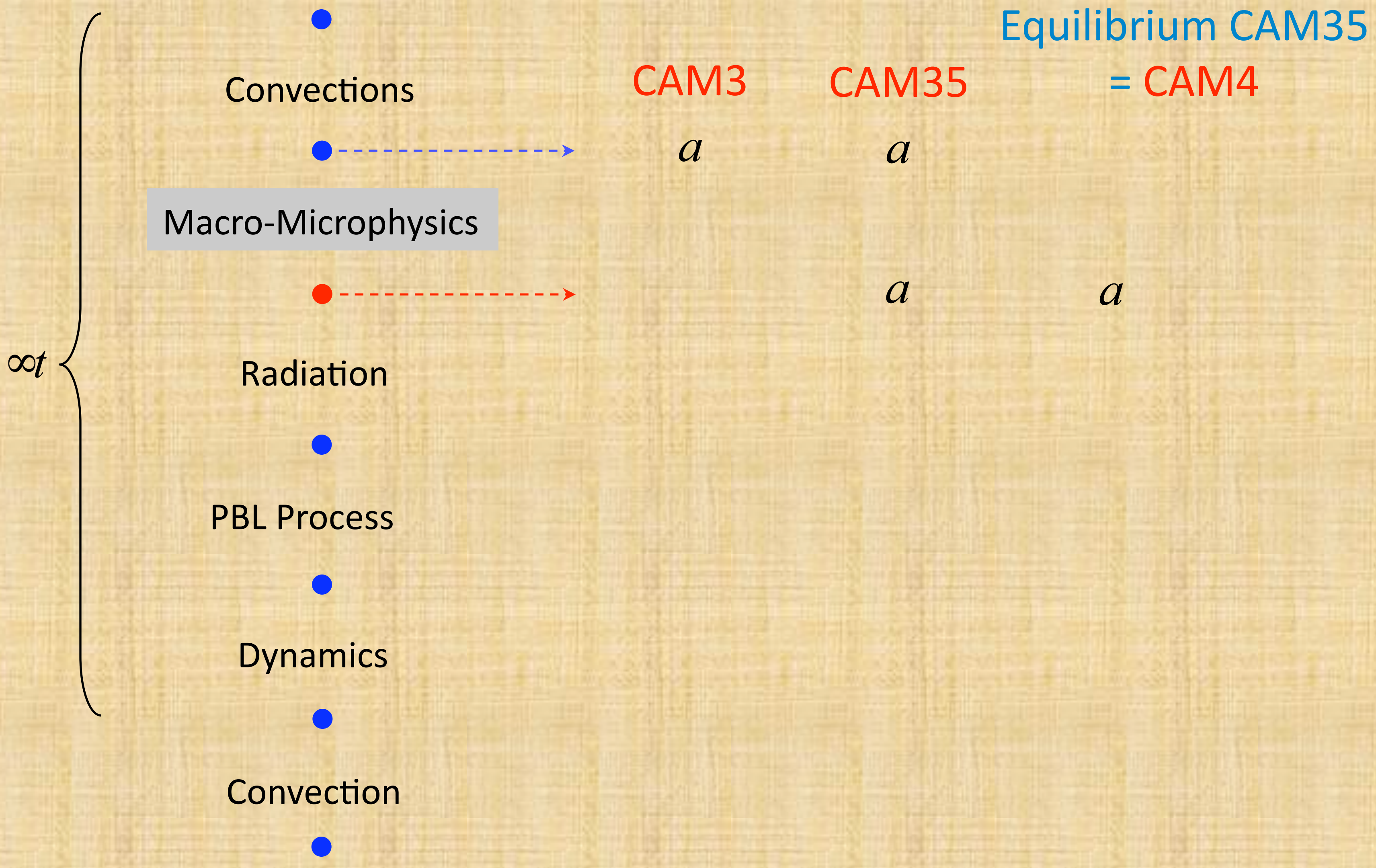
$$U_{clr}(a \to 1) = \left[\frac{1 + U_c}{2}\right]$$

$$U_{clr}(a \to 1) = 1$$

Consistency between Cloud Fraction and In-Cloud LWC

- Force the layer at p = 900 [hPa], T = 280 [K], q_v = 6.84 [g kg^{-1}], q_l = 0.16 [g kg^{-1}], a = 0.6, Δp = 20 [hPa] with various external forcings of temperature (A_T) and water vapor (A_{qv})
- Examine ‘Q’ and ‘Δa vs $\Delta q_{l,cloud}$’.
- Test for Bulk and PDF-based approach with a half width of total specific humidity = 0.1*q_s(T,p) corresponding to U_c= 0.9.

3 Different Configurations of Bulk Saturation Adjustments



Equilibrium CAM35

CAM3 CAM35 = CAM4

Convections

a a

Macro-Microphysics

a a

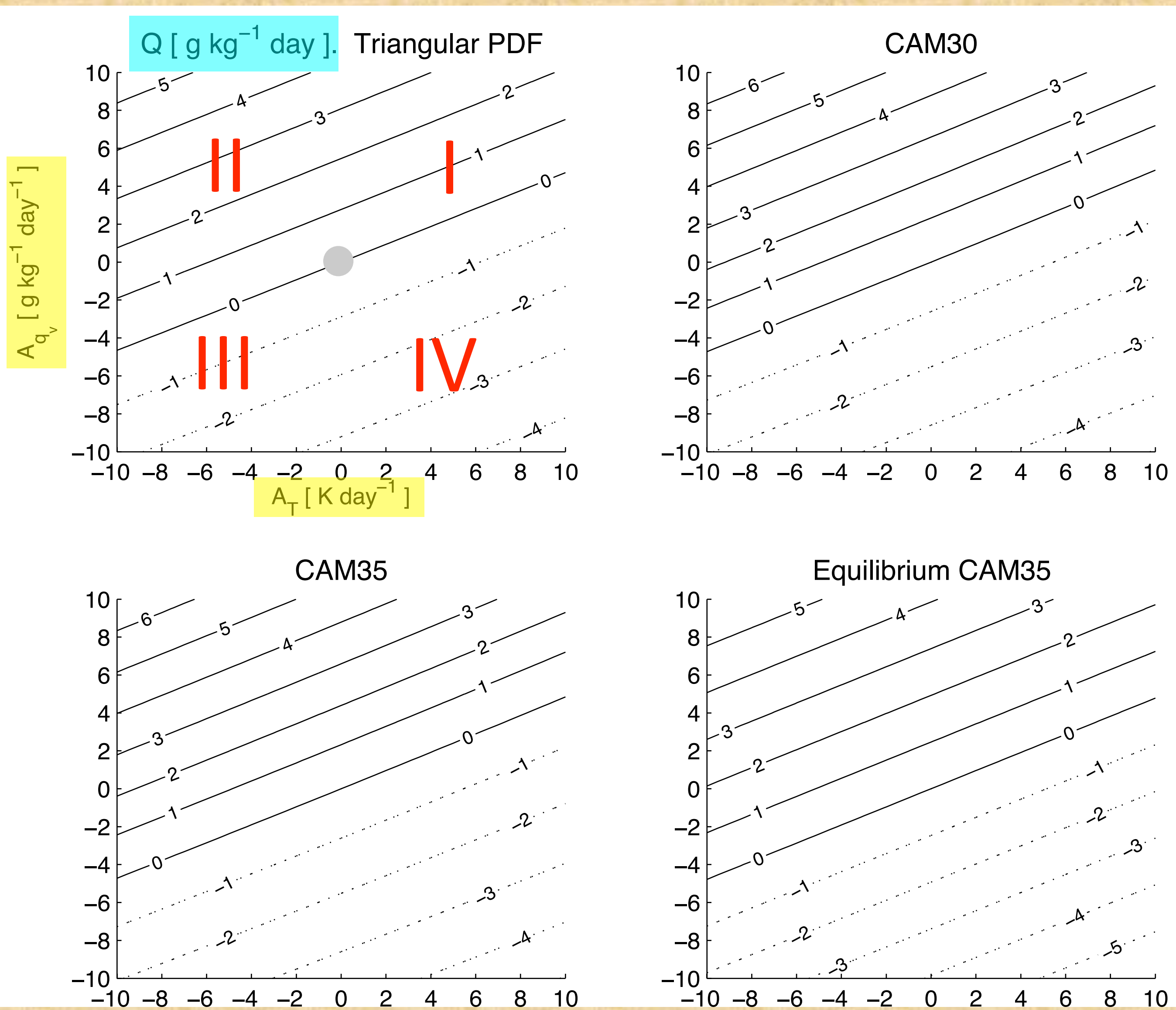
∞t

Radiation

PBL Process

Dynamics

Convection

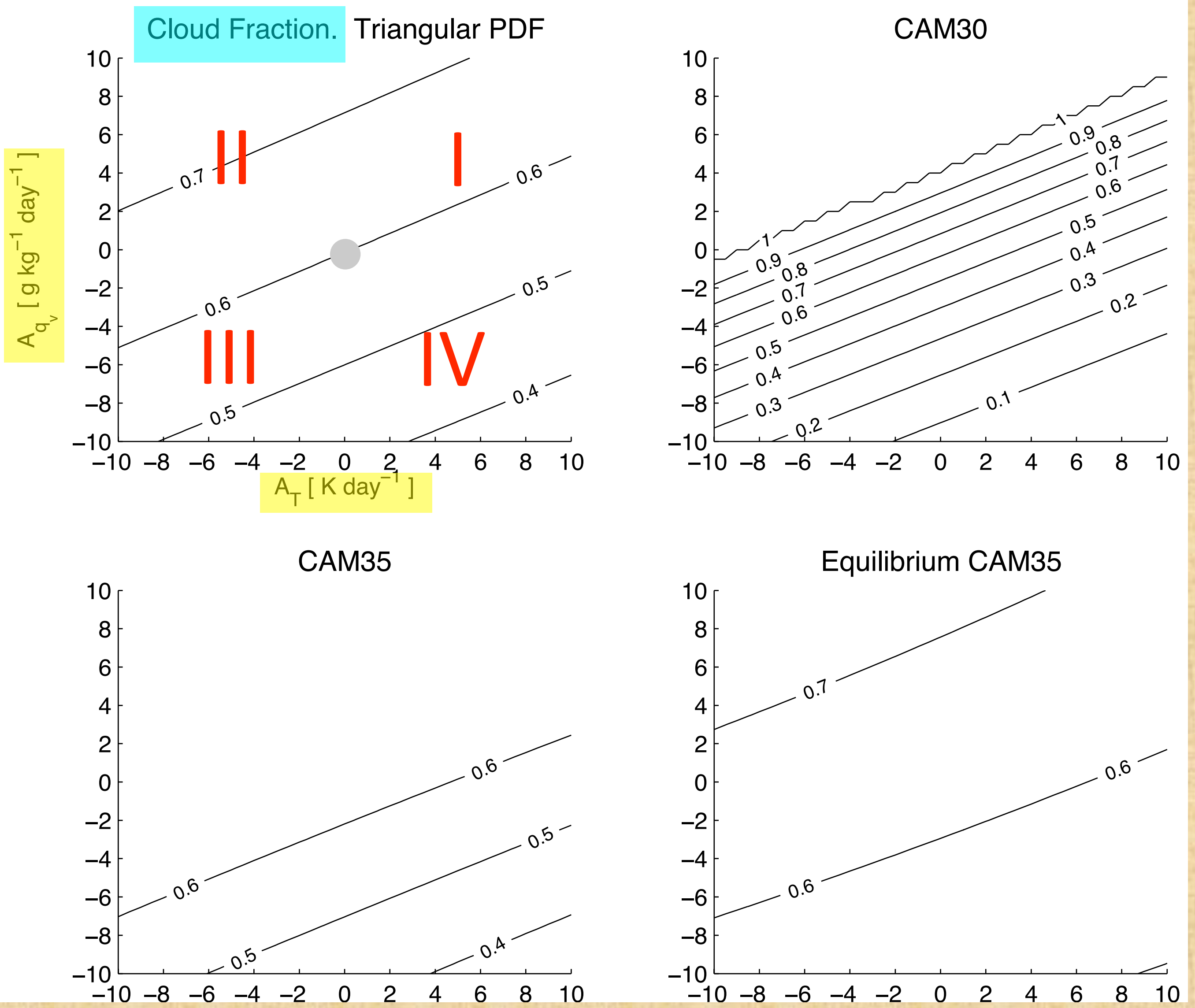


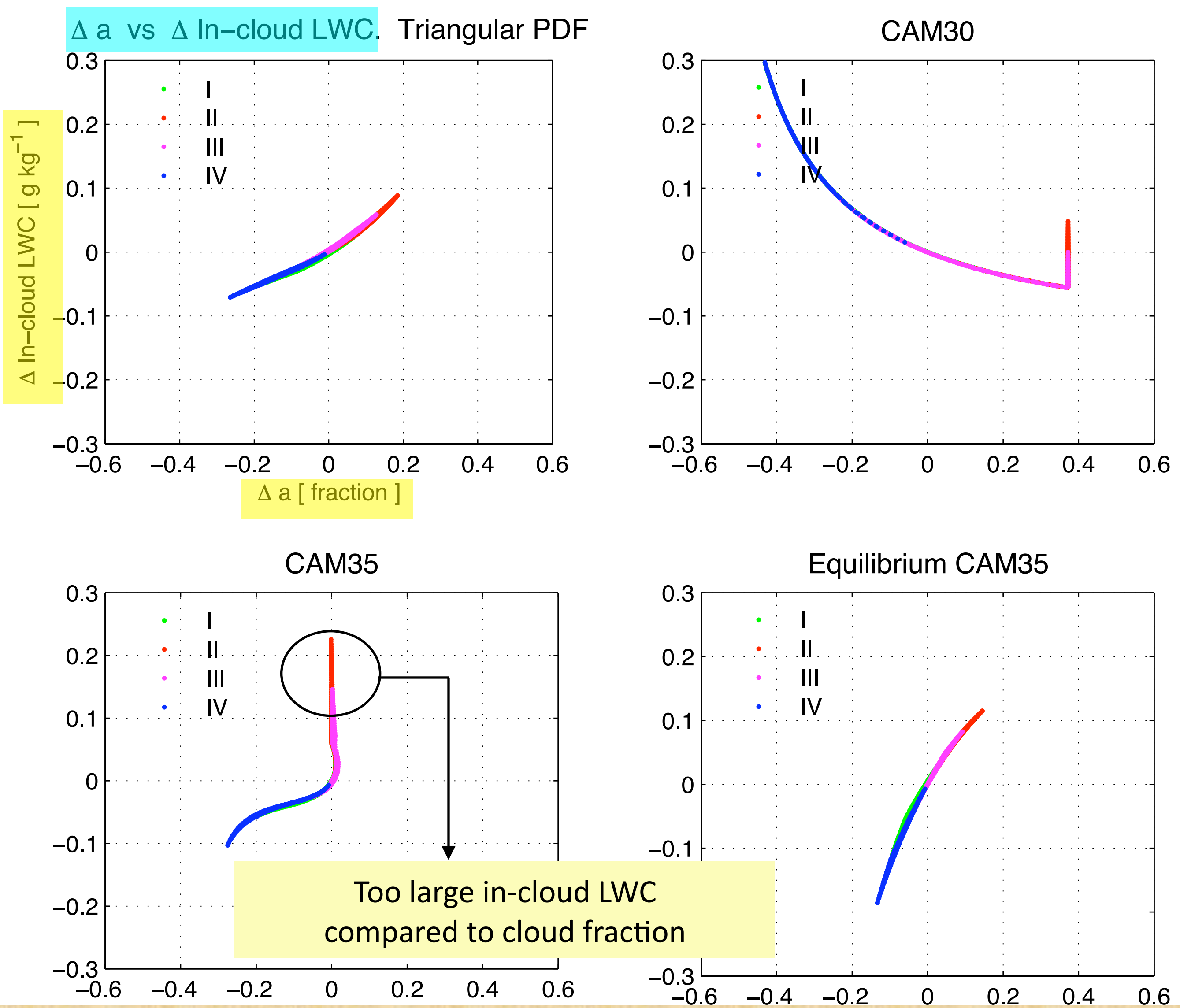
Q [g kg^{-1} day]. Triangular PDF

CAM30

CAM35

Equilibrium CAM35


Cloud Fraction.
Triangular PDF
CAM30
CAM35
Equilibrium CAM35
A_{q_v} [g kg^{-1} day^{-1}]
A_T [K day^{-1}]
I
II
III
IV
0.7
0.6
0.5
0.4
1
0.9
0.8
0.3
0.2
0.1
10
8
6
4
2
0
−2
−4
−6
−8
−10



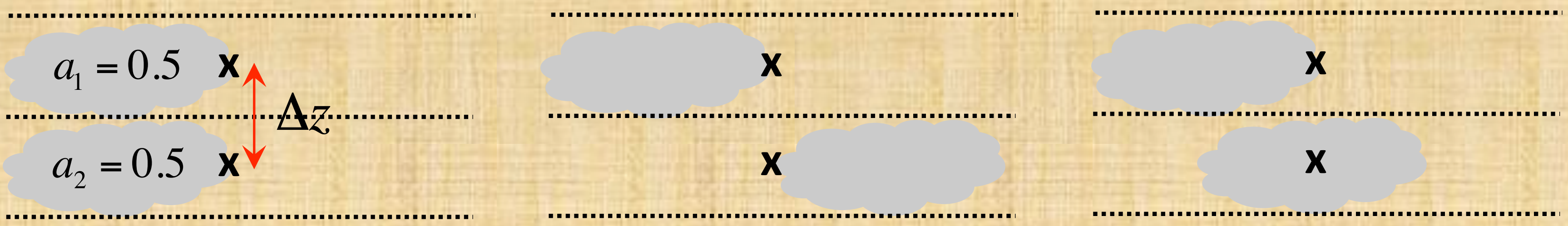
Too large in-cloud LWC
compared to cloud fraction

Vertical Cloud Overlap

Maximum Overlap

Minimum Overlap

Random Overlap



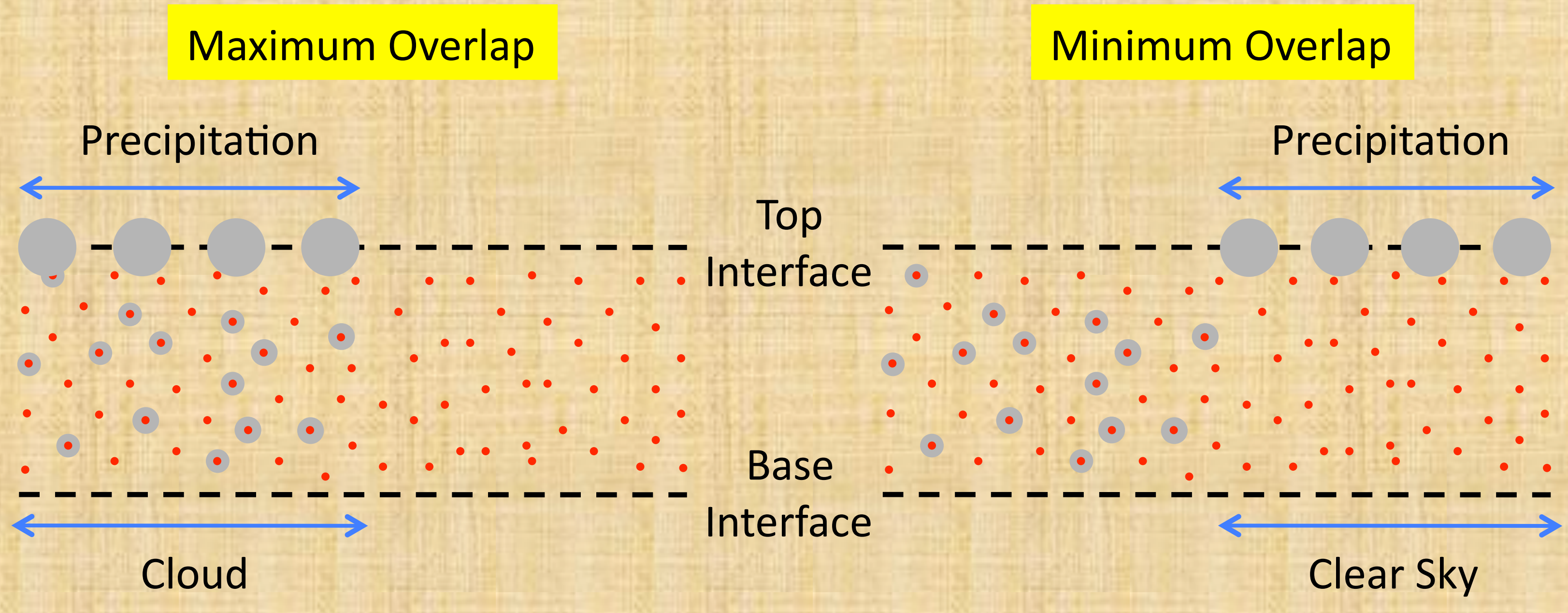
$a_{\max,overlap} = 0.5$

$a_{\min,overlap} = 0$

$a_{ran,overlap} = 0.25$

$$a_{overlap} = \lambda \cdot a_{\max,overlap} + (1 - \lambda) \cdot a_{ran,overlap}$$

$$\lambda = \exp(-\Delta z / 2000)$$



• : Aerosol ● : Cloud Droplet ⬤ : Precipitation Droplet

Parameterization of 'Cloud Overlap Structure'

has direct influences on

→ Production of Precipitation

→ Evaporation of Precipitation

→ Deposition of Aerosol → *Aerosol Indirect Effect*

→ Radiation

→ etc. (wet chemistry…)

3 Cloud Types in CAM3

- Cumulus

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

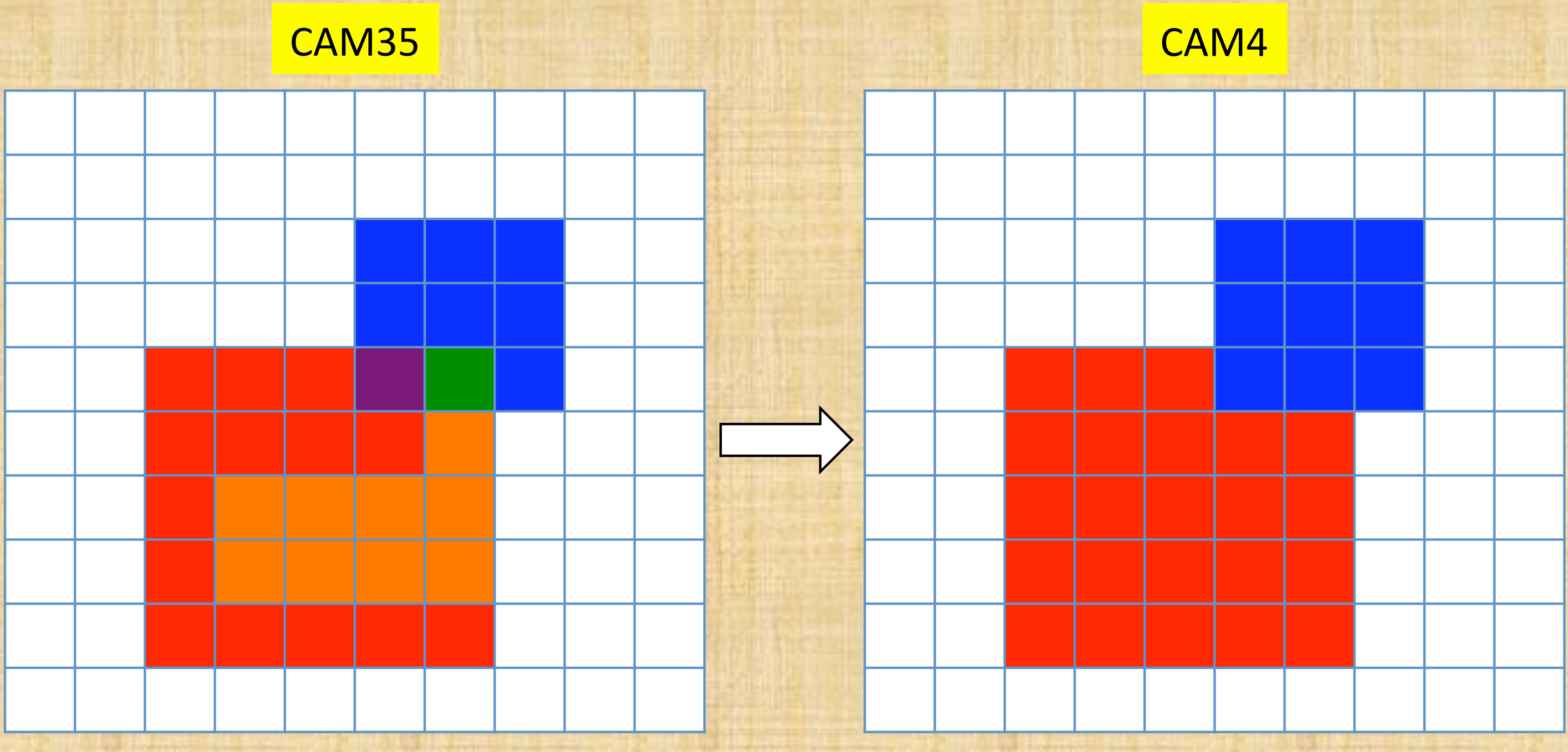
- RH (Relative Humidity) Stratus

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

- KH (Klein-Hartmann) Stratus

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

Horizontal Geometry of Clouds in CAM



🟦 : Cumulus

🟥 : RH Stratus

🟨 : KH Stratus

🟪 : RH Stratus + Cumulus

🟧 : RH Stratus + KH Stratus

🟩 : KH Stratus + Cumulus

🟦 : Cumulus

🟥 : RH Stratus = Stratus

Vertical Cloud Overlap in CAM

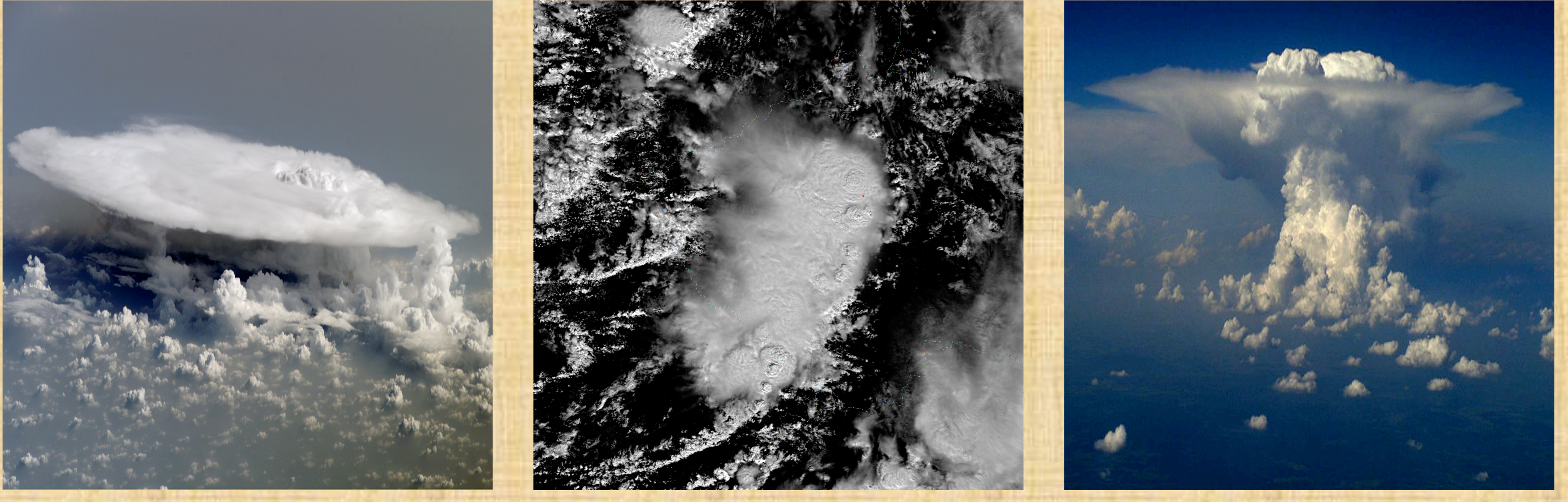
- Radiation (SW and LW)
  - Combine ‘cumulus’ and ‘stratus’ into ‘one single cloud’ in each layer.
  - Maximum overlap in each of three regions representing the lower, middle, and upper troposphere and random overlap between these regions.

- Convection (deep and shallow convections)
  - Whenever convective precipitation flux is positive, convective precipitation area is 1.

- Stratiform Microphysics
  - Stratus is maximally overlapped with stratiform precipitation area.

- Wet Deposition of Aerosol
  - Use additional overlapping assumptions different from the above….

We need to use a unified vertical cloud overlap structure for all schemes by considering different vertical overlapping natures of cumulus and stratus.



- Cumulus is not horizontally overlapped with stratus in a single layer.
- Cumulus has its own LWC different from the LWC of stratus.
  → Cumulus and stratus have different radiative properties.
- Cumulus has a different vertical overlapping structure from stratus :
  → Cumulus is maximally overlapped with cumulus regardless of vertical separation distance.

Unified Cloud Overlapping Scheme

- Horizontal Geometry
  - ‘Cumulus’ and ‘Stratus’ are non-overlapped

- Vertical Geometry
  - Cumulus: ‘Maximally’ overlapped
  - Stratus: ‘Randomly’ overlapped

Overlapping Area Between
‘Convective Precipitation Area’ and ‘Stratus Cloud Fraction’

$$\overline{a}_s^c = \sum_{i=i_{\min}}^{i_{\max}} \left[\frac{i}{N}\right] \cdot \left[\frac{P(i)}{P_{TOT}}\right]$$

$$i_{\min} = \max(0, \max(N \cdot a^c - n, 0) - N \cdot a_r)$$

$$i_{\max} = \min(N \cdot a_s, N \cdot a^c - \max(n - N \cdot a^m, 0))$$

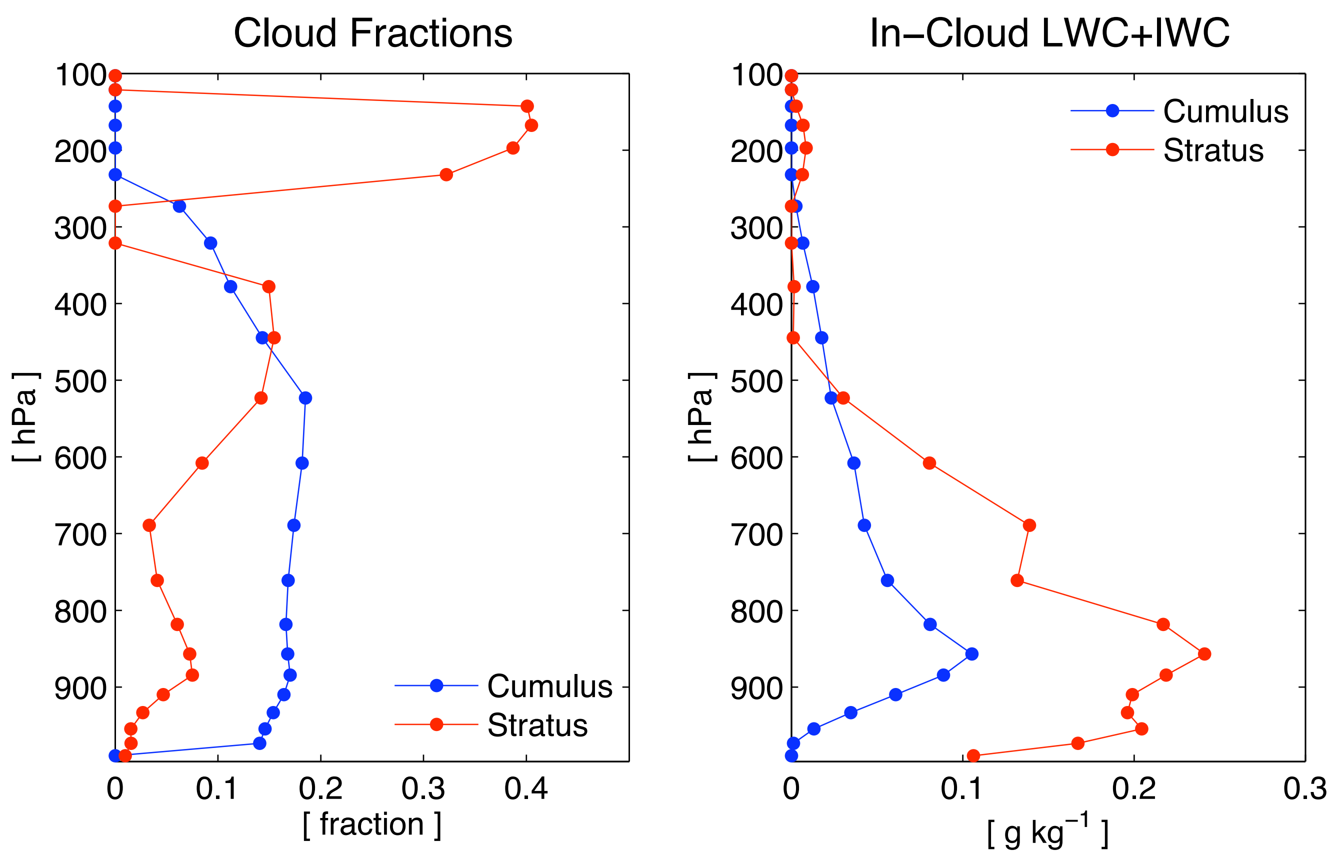
$$P(i) = \left({}_{N\cdot a_s}C_i\right) \cdot \left({}_{N\cdot a^c}P_i\right) \cdot \left\{ \sum_{j=j_{\min}}^{j_{\max}} \left[\left({}_{N\cdot a_c}C_j\right) \cdot \left({}_{N\cdot a^m}P_j\right) \cdot \left({}_{N\cdot a^c - i}P_{N\cdot a_c - j}\right) \cdot \left({}_{N - N\cdot a^c - j}P_{N\cdot a_s - i}\right) \right] \right\} \cdot \left({}_{N\cdot a_r}P_{N\cdot a_r}\right)$$

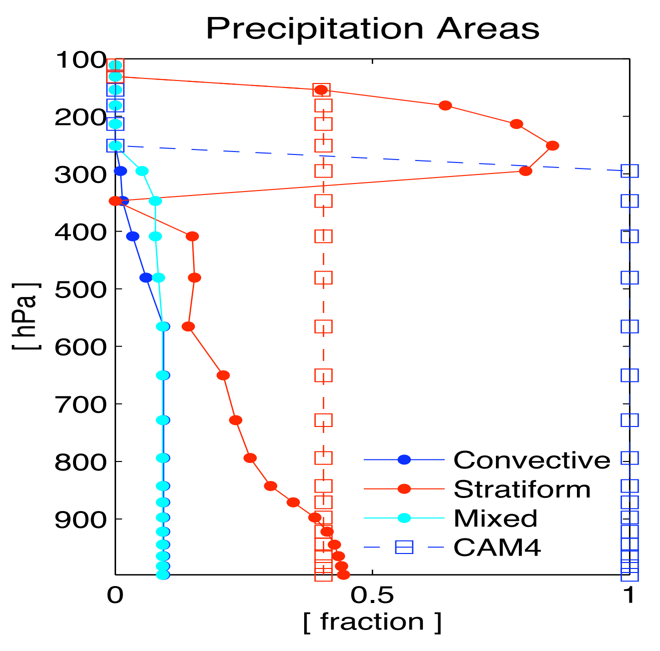
$$j_{\min} = \max(N \cdot (a_c - a^c) + i, 0)$$

$$j_{\max} = \min(N \cdot a_c, N \cdot a^m, N \cdot (1 - a^c - a_s) + i)$$

Western Pacific Warm Pool

(6.6ºN,100ºE). ANN.




Precipitation Areas
100
200
300
400
500
600
700
800
900
[hPa]
0
0.5
1
[fraction]
Convective
Stratiform
Mixed
CAM4

on in CAM !

SUMMARY

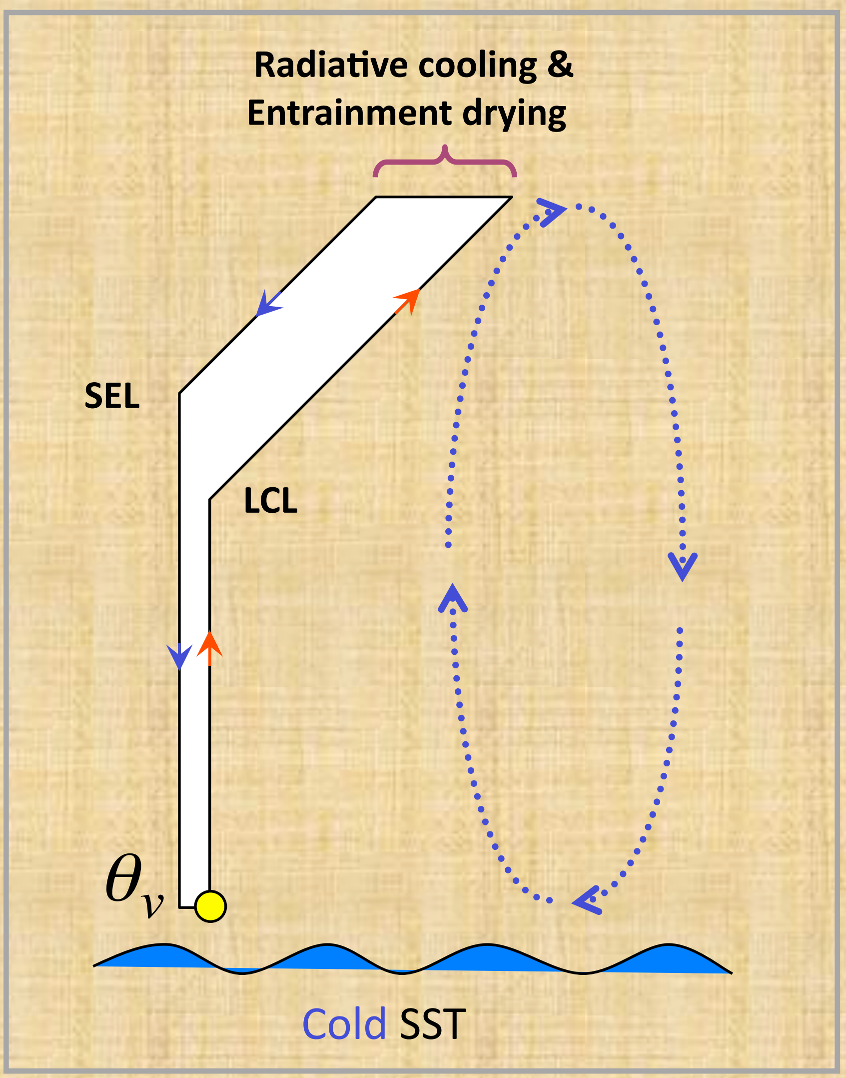
I. Parameterization of Symmetric Turbulence

- Dry Turbulence Scheme (CAM3 PBL)
- Moist Turbulence Scheme (CAM4 PBL)
  - Treatment of elevated source of TKE associated with cloud → successful simulation of cloud-topped PBL as well as dry stable and dry unstable PBL

II. Cloud Macrophysics

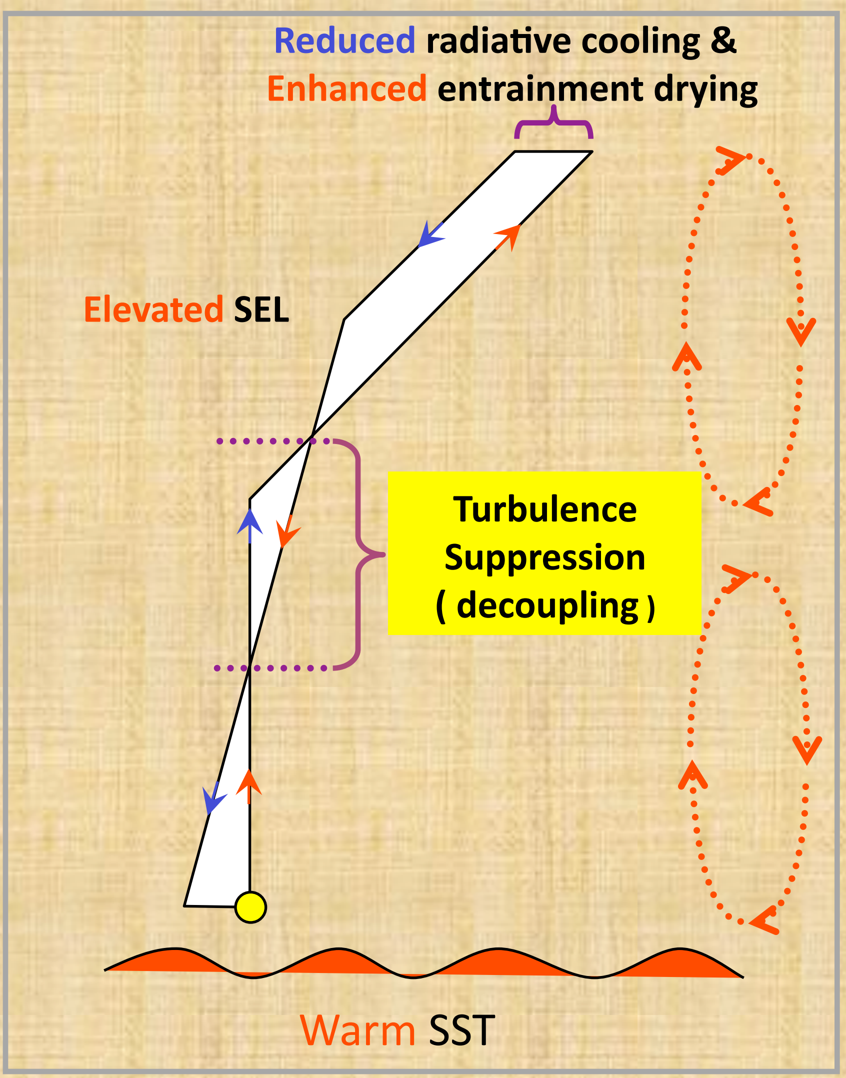
- Net Condensation Rate of Water Vapor into Cloud Liquid (Q)
  - Bulk Saturation Adjustment
  - PDF-Based Saturation Adjustment
- Cloud Fraction (a)
  - Quadratic formula of a(U)
  - a(U) from the PDF-based approach
  - Consistency between cloud fraction and in-cloud LWC
- Vertical Overlap of Cloud Fraction
  - Unified cloud overlapping scheme for simultaneous treatment of cumulus and stratus

Response of MSC to increasing SST



Radiative cooling &
Entrainment drying

Cold SST



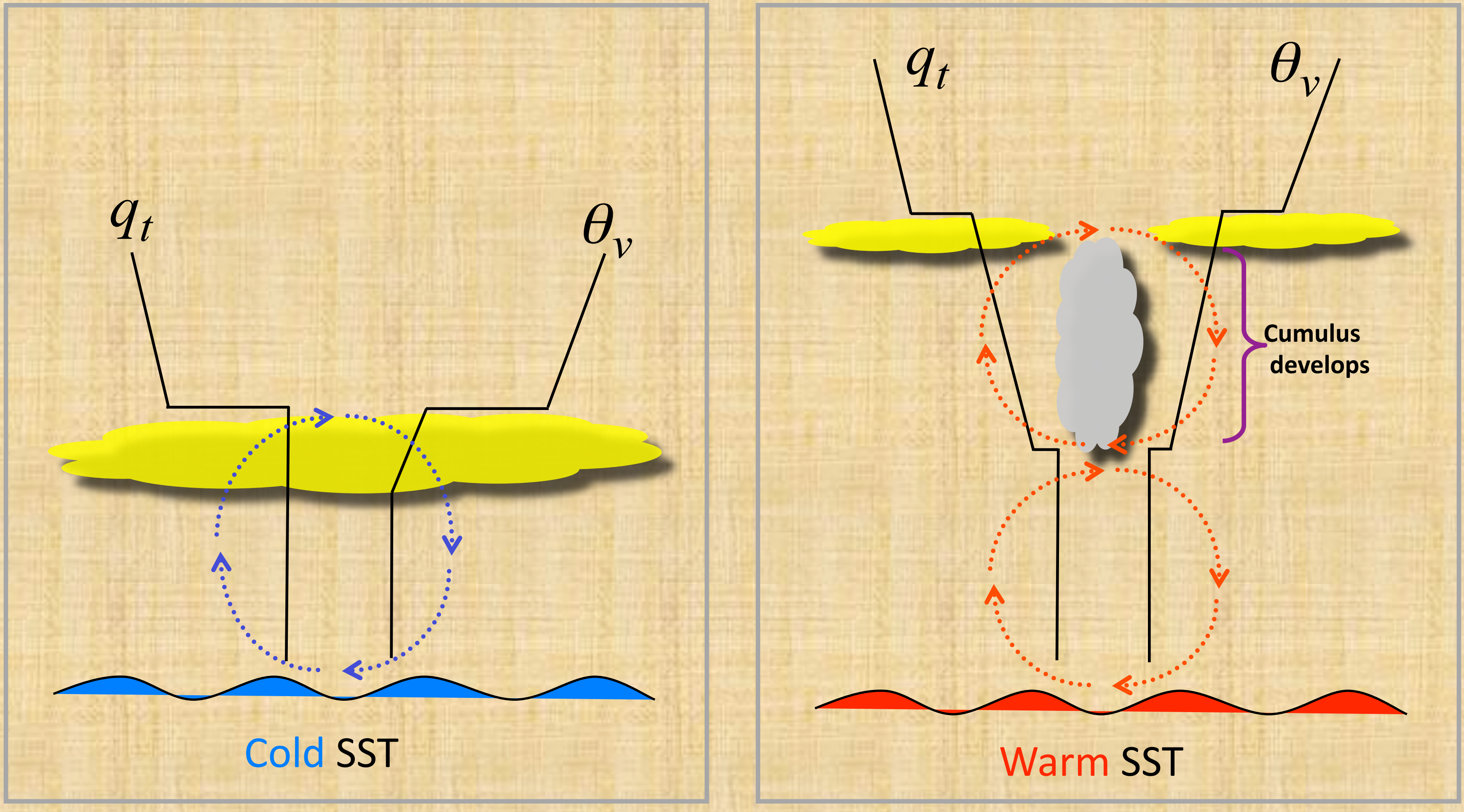
Reduced radiative cooling &
Enhanced entrainment drying

Elevated SEL

Turbulence
Suppression
(decoupling)

Warm SST

Deepening-Decoupling and Dissipation of Stratocumulus



Transition of MBL from well-mixed stratocumulus to the decoupled state.

Stratocumulus – SW Radiation

Diurnal Cycle

Morning

Mid Afternoon

EPIC. 2001. Oct.