Progress on U.W. PBL and Macrophysics reformulations

Interactions among cloud, radiation, and PBL turbulence

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Outline

I. Inconsistency between cloud fraction and in-cloud LWC

II. Offline computation of stratiform macrophysics

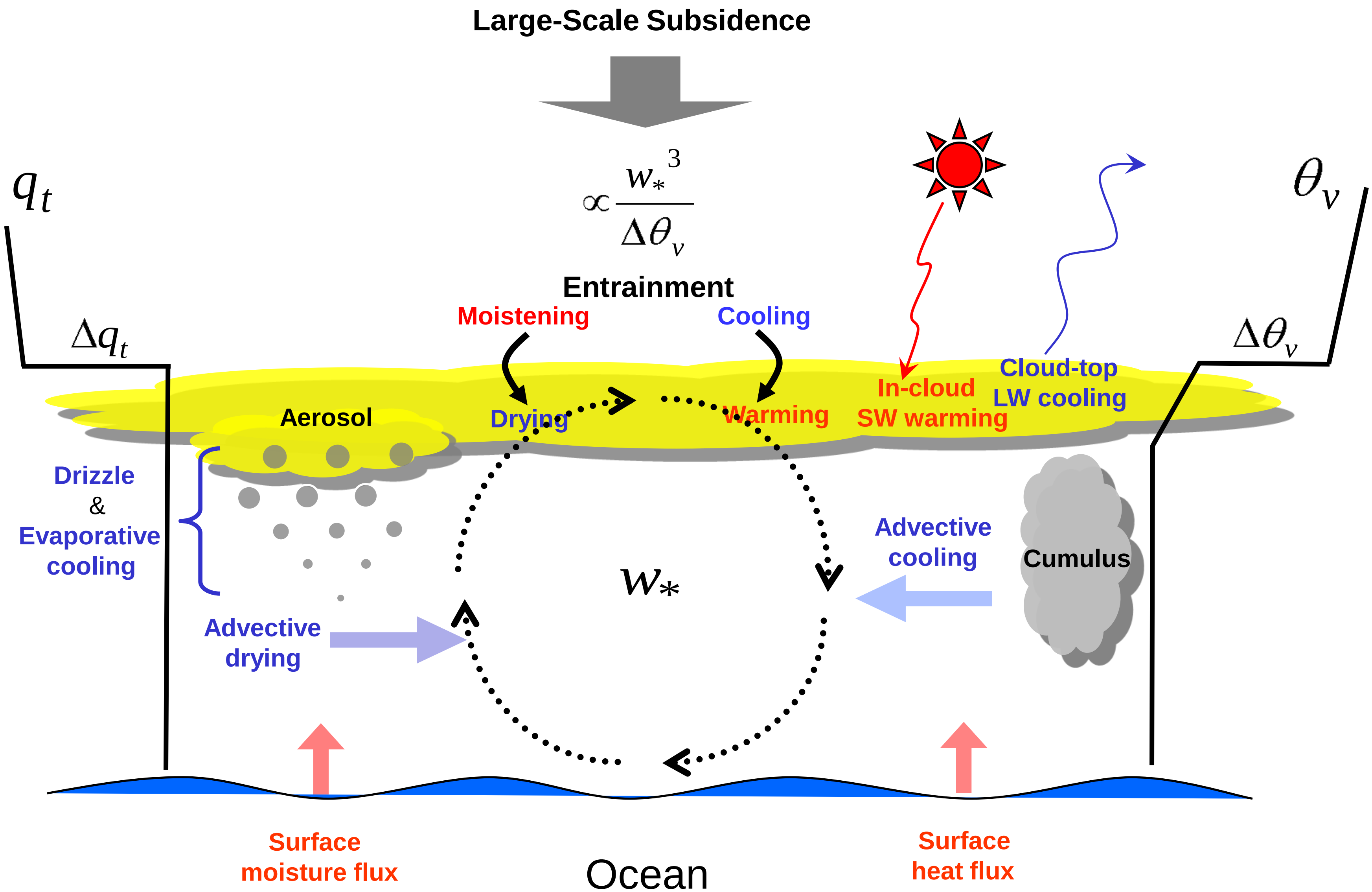
III. Introduction of a new macrophysics scheme

IV. UW PBL + UW ShCu + RK Microphysics + PBR Macrophysics

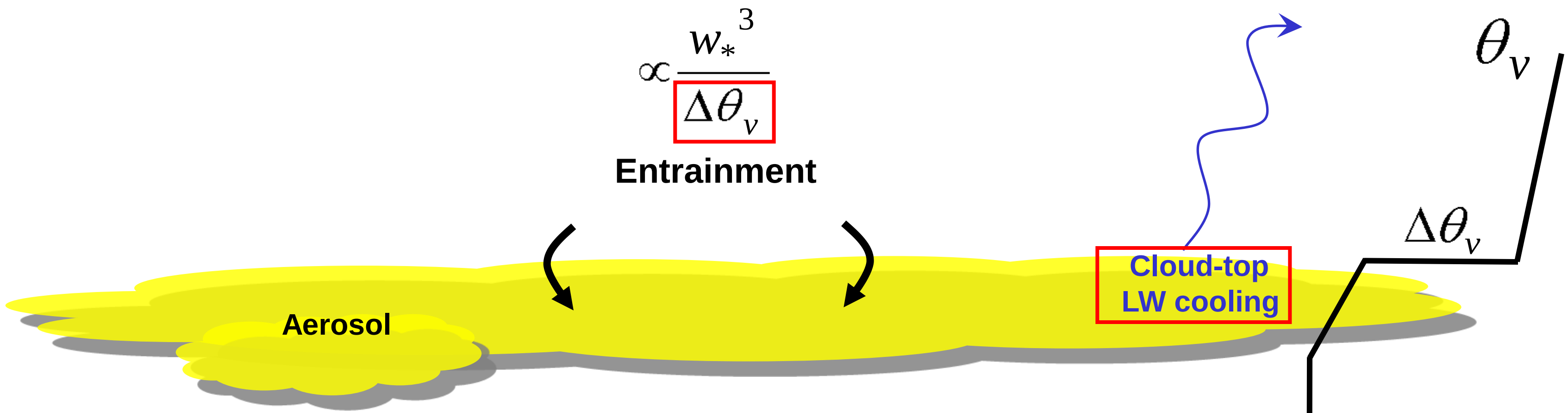
V. UW PBL + UW ShCu + MG Microphysics + PBR Macrophysics

Inconsistency between stratus fraction and in-stratus LWC

Interplay among various processes in stratocumulus



Interplay among various processes in stratocumulus



- Problem in stratiform macrophysics

→ Distortion of interaction between LW radiative cooling and inversion strength

→ Too shallow PBL and many other related problems

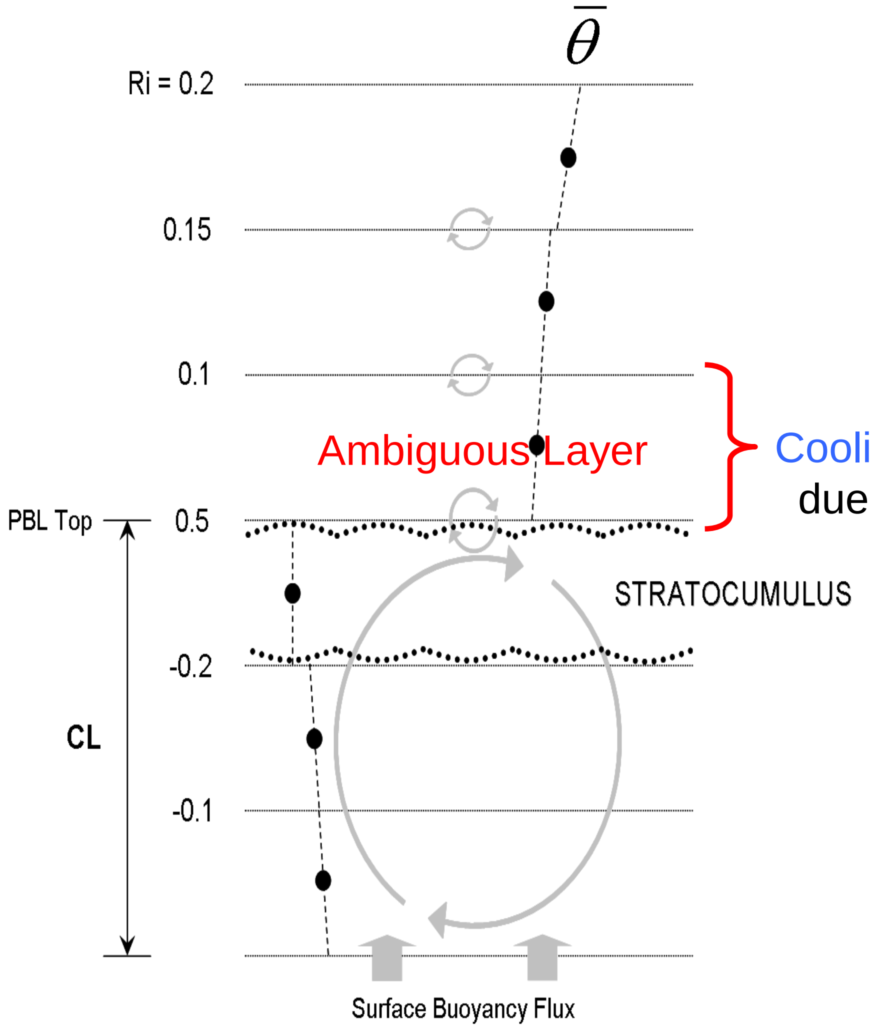
- Problem of droplet activation in MG stratiform microphysics ?

→ Too strong SW CRF

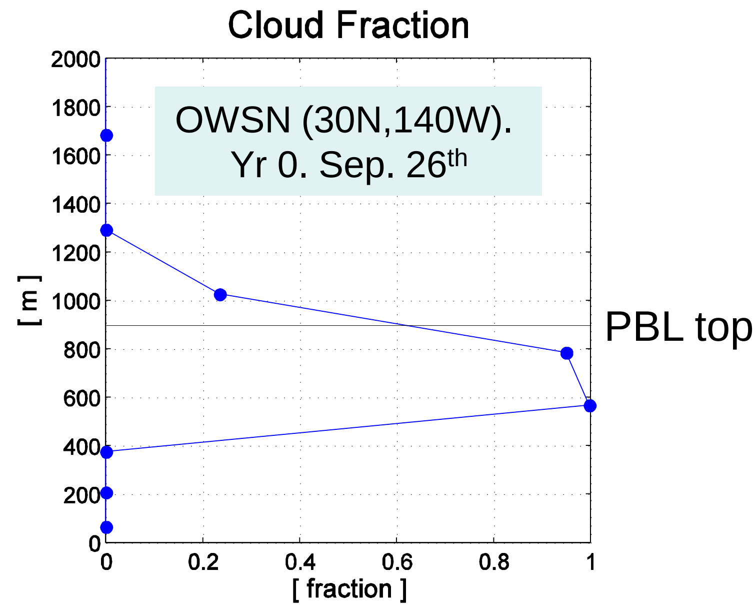
→ Too strong aerosol indirect effect in current CAM ?

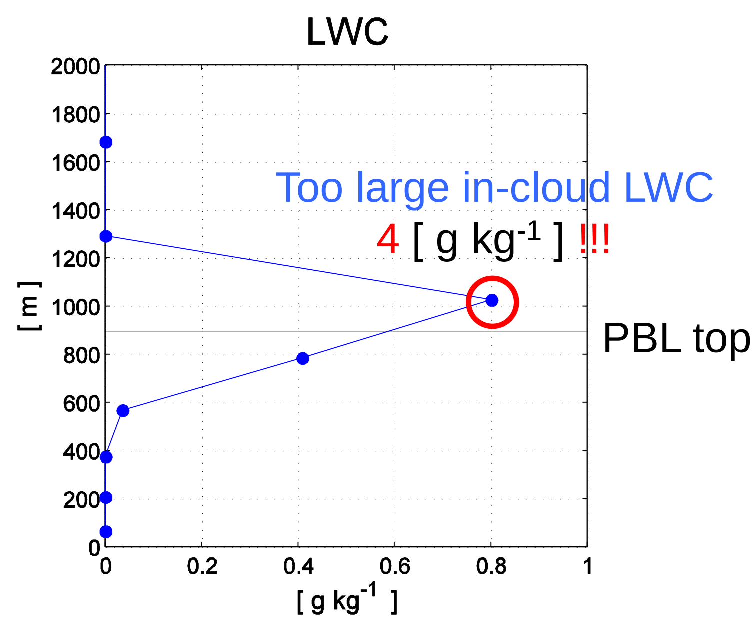
Ocean

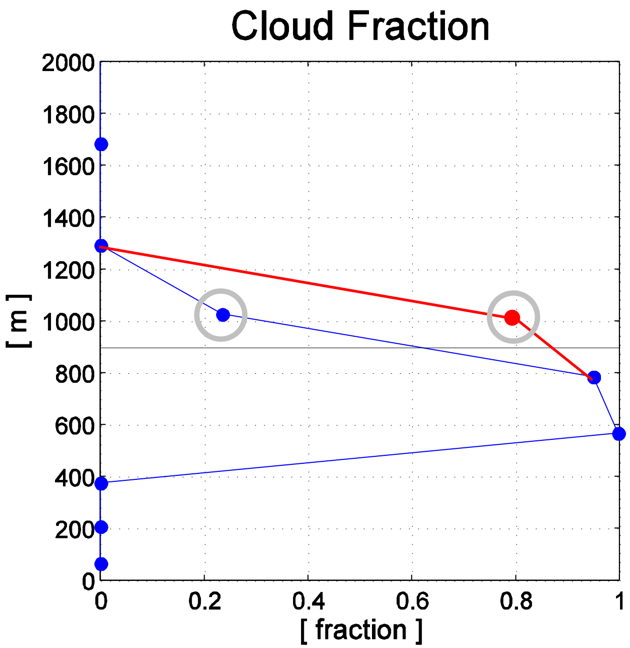
CAMUW = CAM35 + UW PBL + UW ShCu



Cooling & Moistening due to entrainment





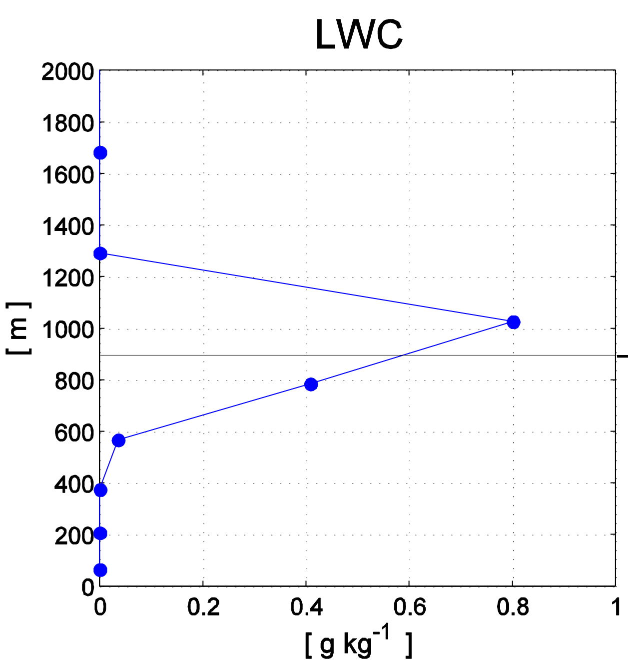


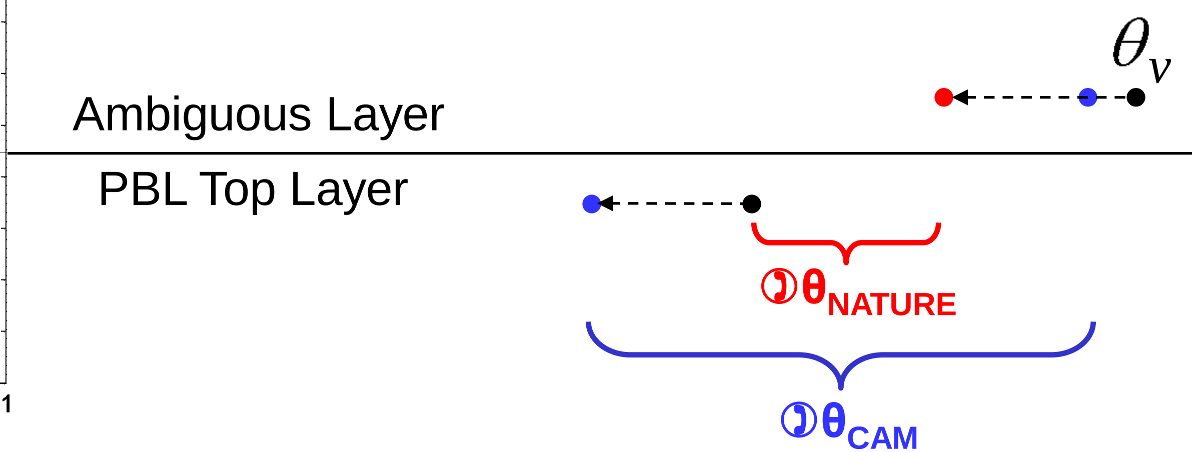
Isothermal, cloud in the PBL top layer is a black body, transparent clear air

$$\left(\frac{dT}{dt}\right)_{LW} = -\left[\frac{g}{C_p\cdot\Delta p}\right]\cdot a\cdot\varepsilon\cdot\sigma T^4$$

$$\varepsilon = 1-\exp\left(-1.66\cdot k\cdot\hat{q}_l\cdot\frac{\Delta p}{\rho\cdot g}\right) \qquad k=90.36$$

[K hr^{-1}]	CAM	Nature
Ambiguous L.	-1.2	-4.9
PBL Top L.	~ -4.0	~ 0





As a result, current CAM suffers from

→ Strong inversion at the PBL top

→ Too weak entrainment

→ Too shallow, cold, moist PBL

- Too much (less) subtropical stratocumulus in downstream (upstream)
- Suppression of nocturnal deepening of PBL
- Too strong ENSO amplitude due to too weak SST damping by weak upward LHF

Summary

Inconsistency between cloud fraction and in-cloud LWC can exert large Influences on global climate system through complex feedbacks among cloud, radiation, and moist turbulence

→ What caused inconsistency between cloud fraction and in-cloud LWC ?

What caused inconsistency between cloud fraction and in-cloud LWC ? → Stratiform Macrophysics Scheme

- Isolate stratiform macrophysics from the CAM and perform off-line computation

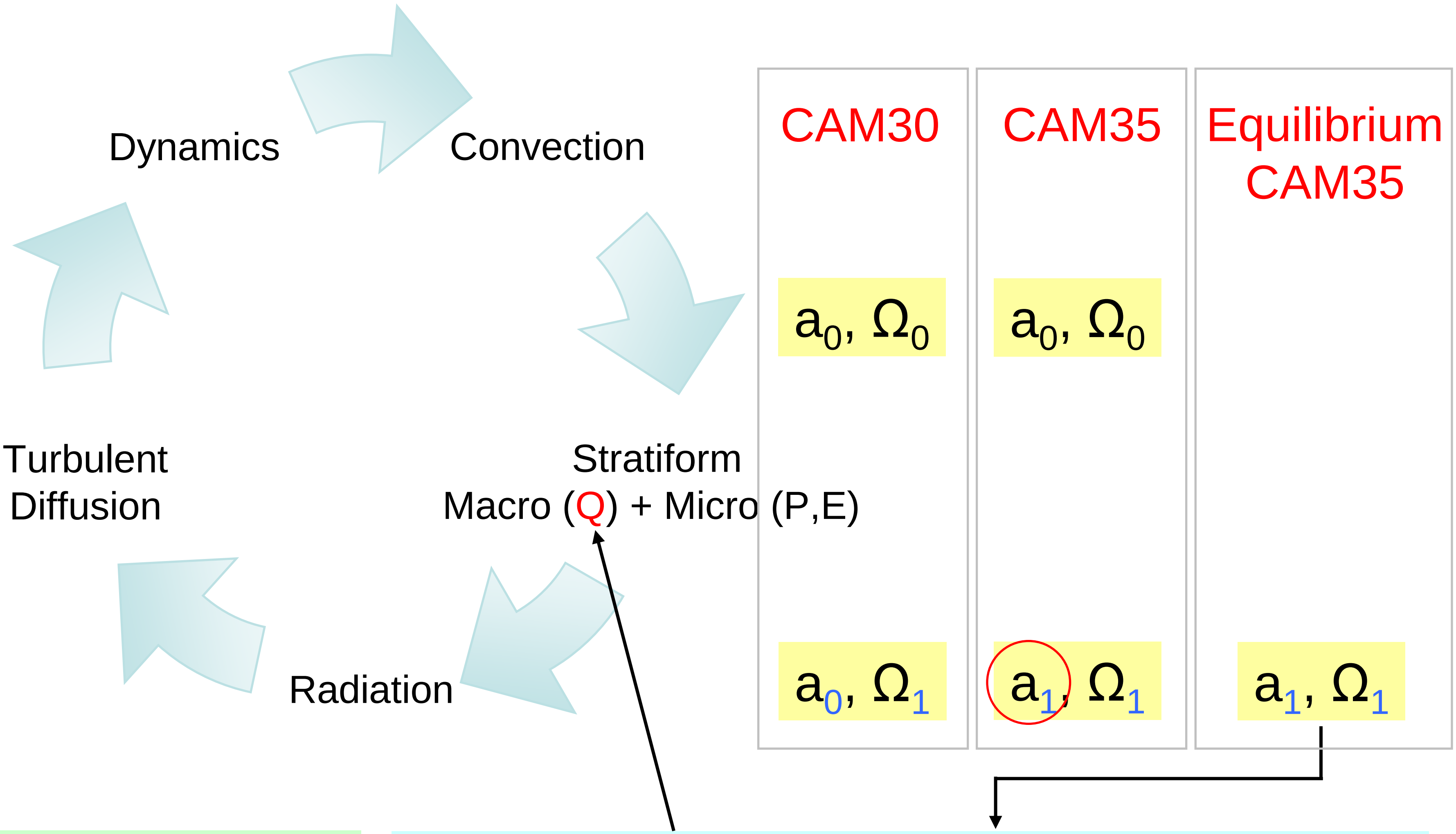
- Force the ambiguous layer at p = 900 [hPa], T = 280 [K], q_v = 6.84 [g kg^{-1}], q_l = 0.16 [g kg^{-1}], a = 0.6, Δp = 20 [hPa] with various external forcings of temperature (A_T) and water vapor (A_{qv})

- Neglect cumulus, cloud ice, and precipitation

- Examine Δa vs $\Delta q_{l,cloud}$

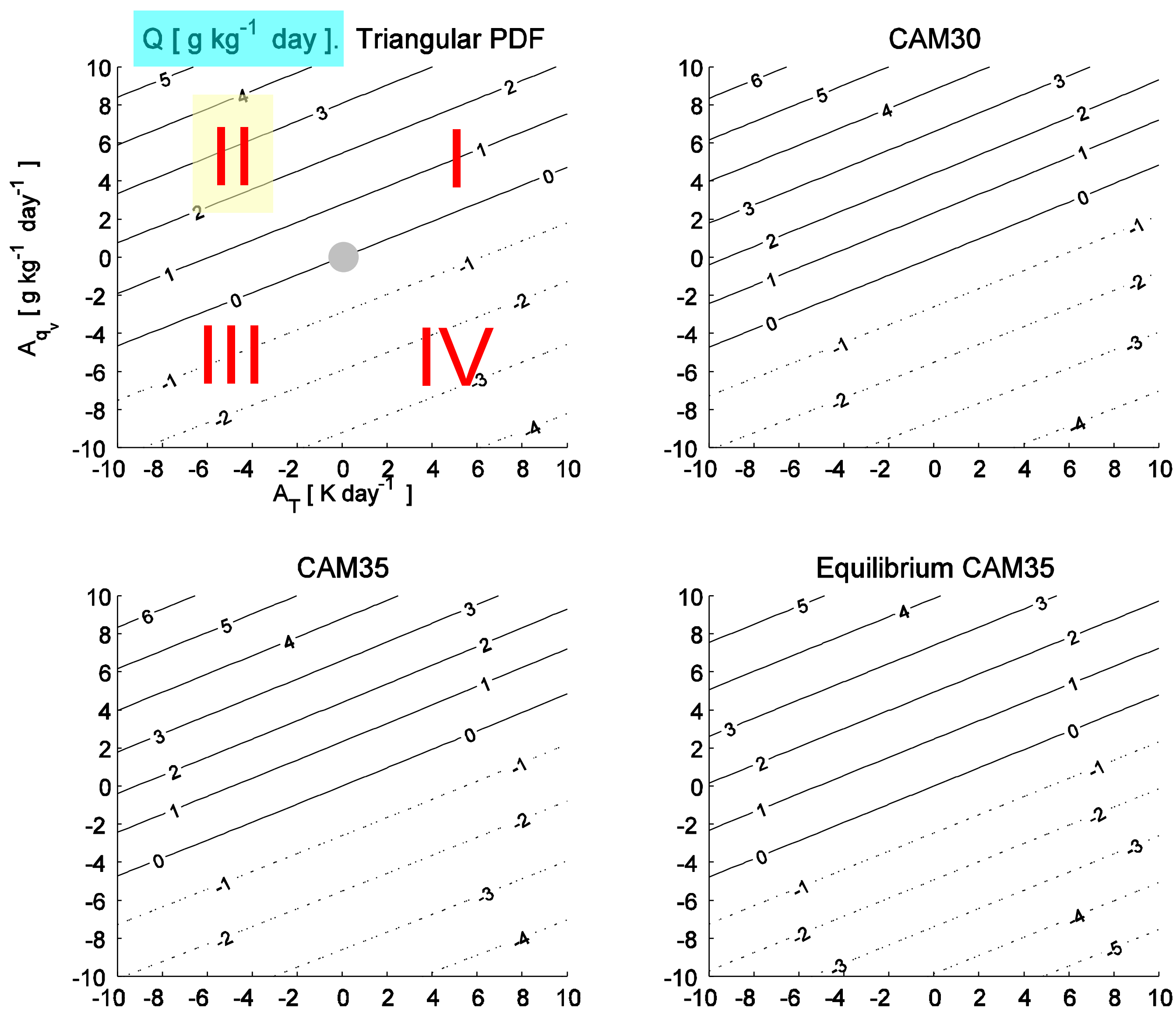
- Test for CAM30, CAM35, Equilibrium CAM35, and Triangular PDF with a half width of total specific humidity = 0.1*q_s(T,p)

How stratiform net condensation rate Q is computed in CAM

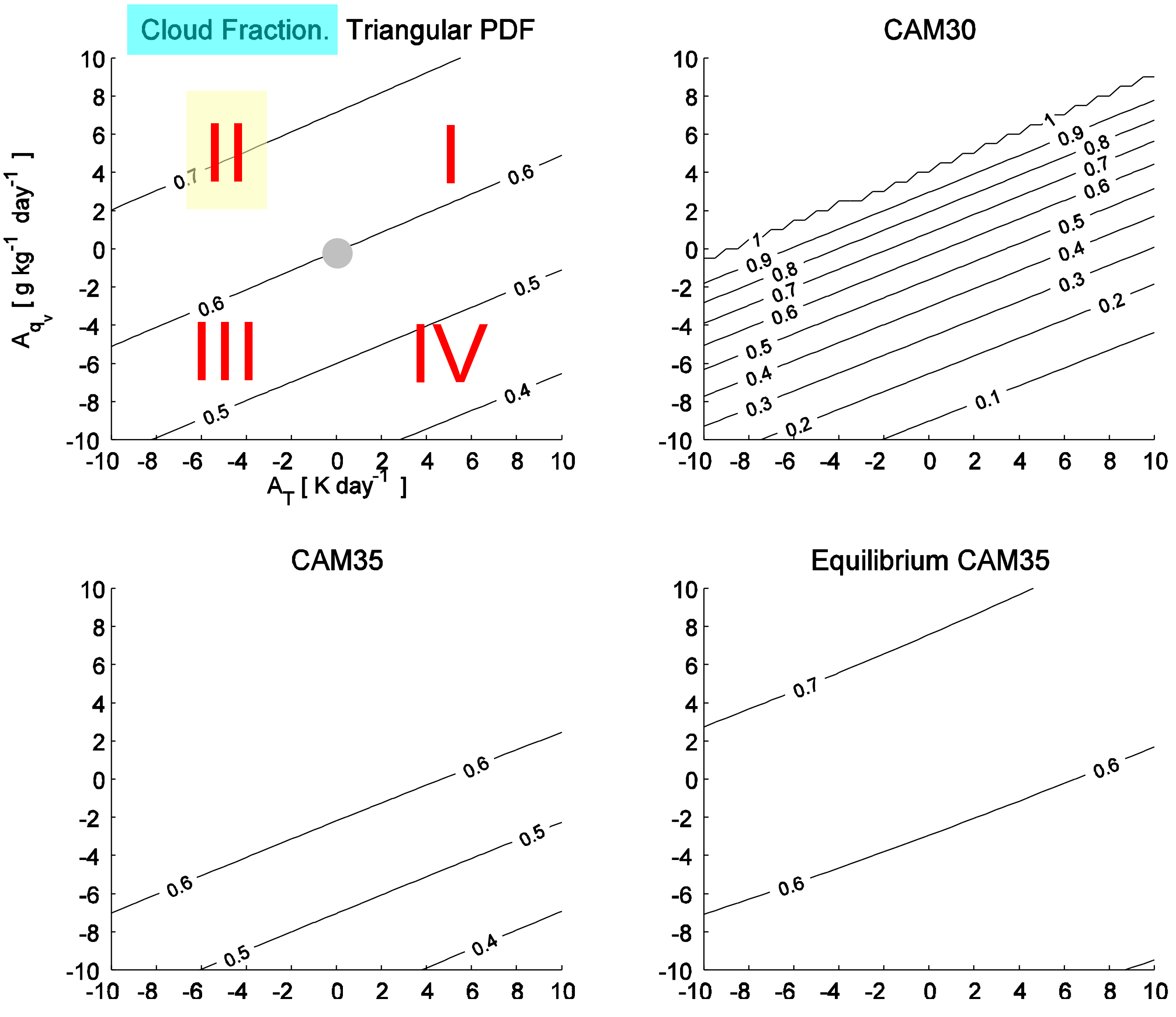


a : stratus fraction
Ω = T, q_v, q_l, q_i

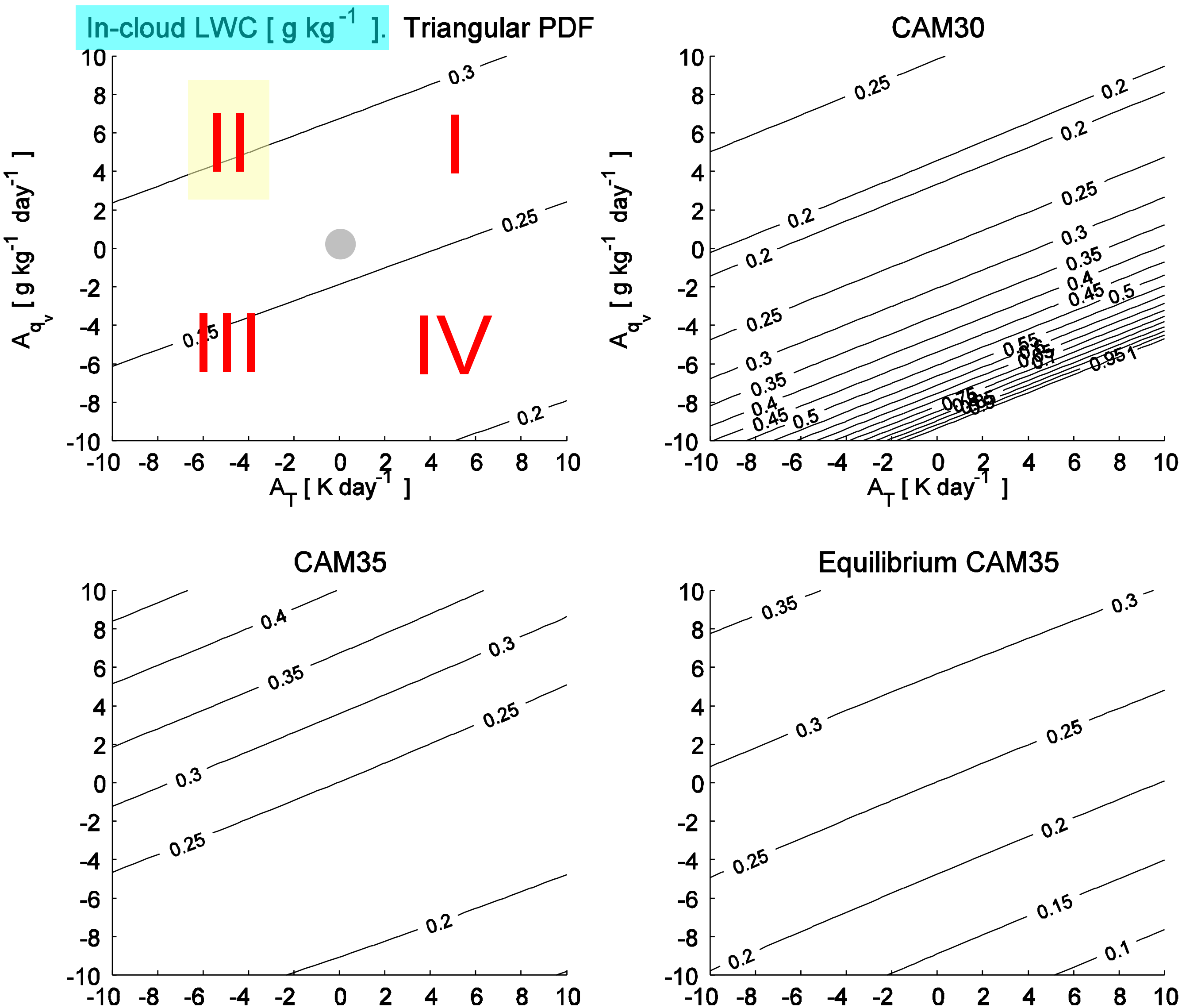
Equilibrium stratus fraction (a_1) and state variables (Ω_1) are used for computing Q at the next time step

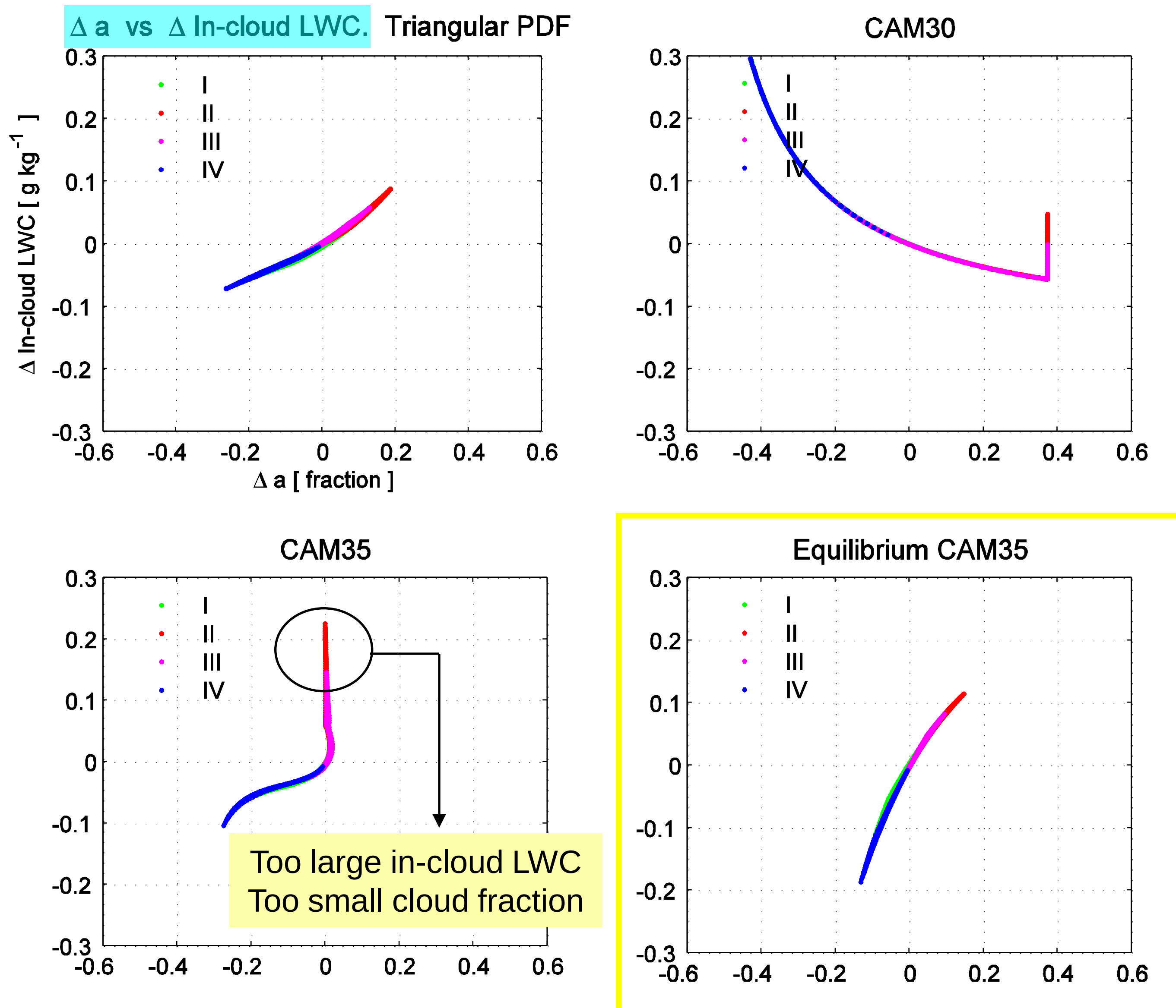


Q [g kg^-1 day].
Triangular PDF
CAM30
CAM35
Equilibrium CAM35
A_T [K day^-1]
A_qv [g kg^-1 day^-1]
I
II
III
IV

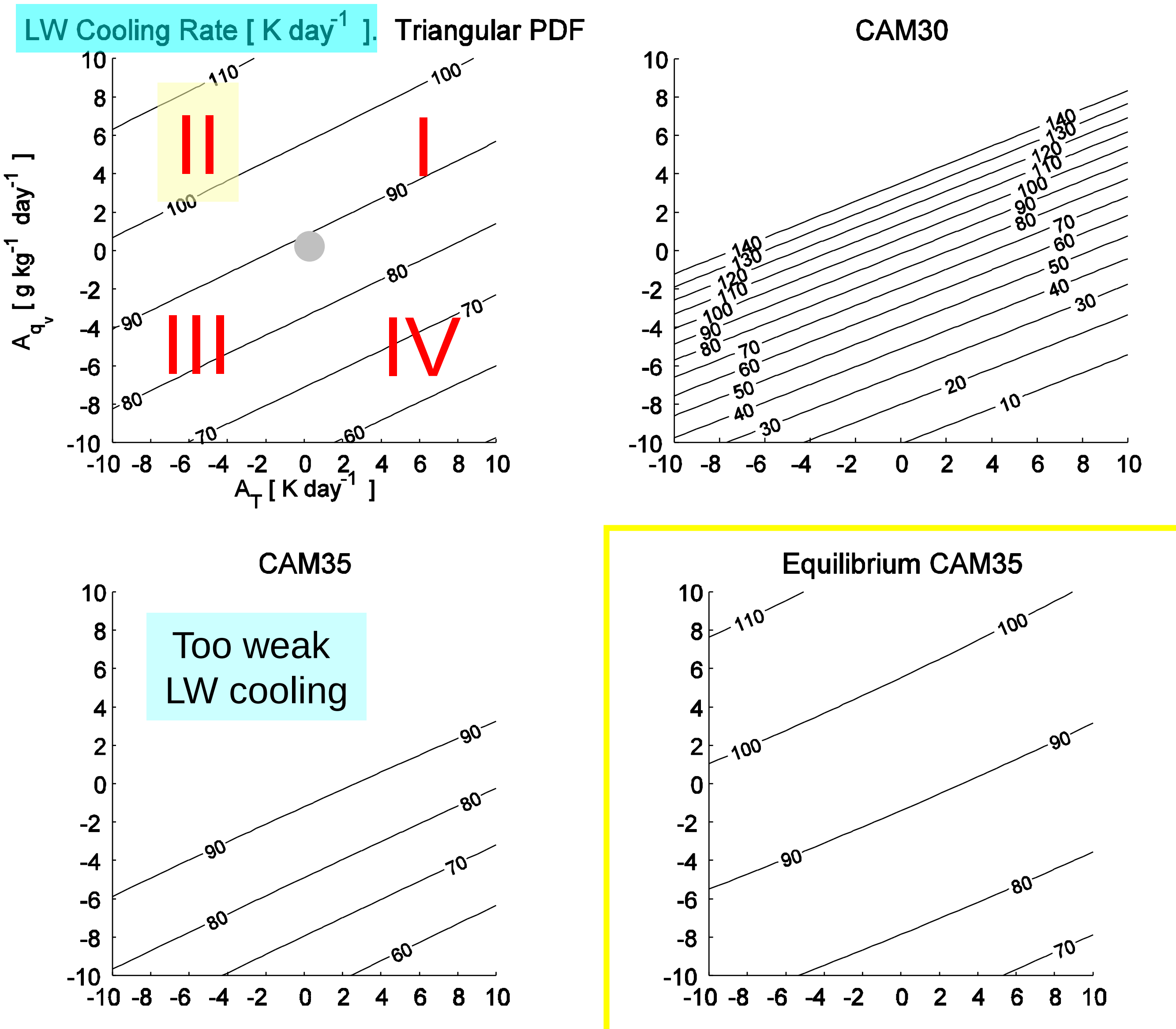


Cloud Fraction.
Triangular PDF
CAM30
CAM35
Equilibrium CAM35
A_{q_v} [g kg^{-1} day^{-1}]
A_T [K day^{-1}]
I
II
III
IV


In-cloud LWC [g kg-1]. Triangular PDF
CAM30
CAM35
Equilibrium CAM35
I
II
III
IV
A_T [K day-1]
A_qv [g kg-1 day-1]
0.3
0.25
0.2
0.35
0.4
0.45
0.5
0.15
0.1



Δ a vs Δ In-cloud LWC.
Triangular PDF
CAM30
CAM35
Equilibrium CAM35
I
II
III
IV
Δ In-cloud LWC [g kg^{-1}]
Δ a [fraction]
Too large in-cloud LWC
Too small cloud fraction



Equilibrium CAM35 produces consistent cloud fraction and in-cloud LWC.

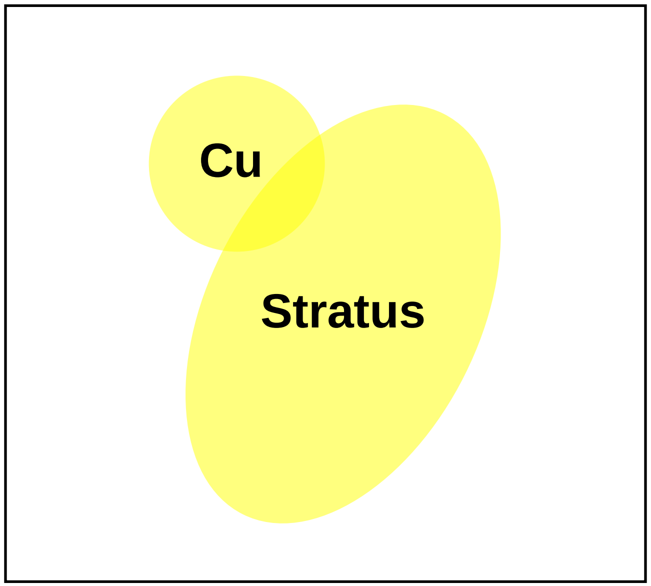
→ Realistic LW cooling rate and reasonable response of moist turbulence within PBL

A New Stratiform Macrophysics Scheme

1. Uses equilibrium cloud fraction and equilibrium state variables for computing Q

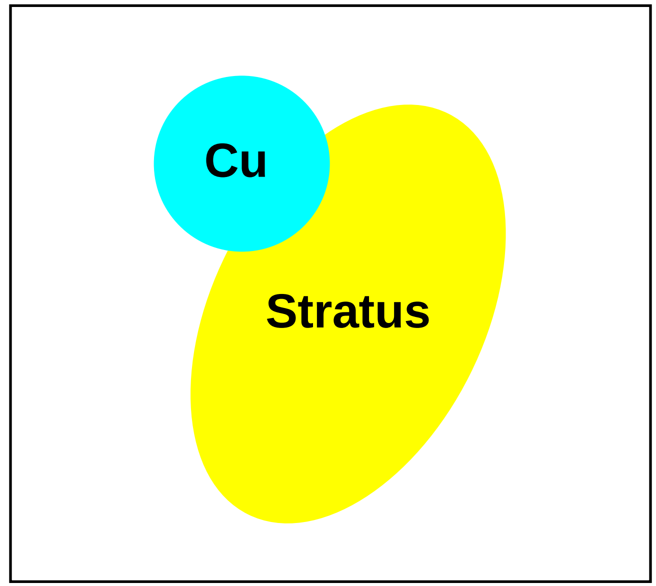
2. Formulation based on conservative scalars
   - Consistent with the assumption of uniform T within the grid
3. Incorporation of fusion heat in computing Q
   - Treatment of ice and mixed-phase clouds
4. Explicit treatment of cumulus cloud
   - Cumulus and stratus are non-overlapped in each layer and have their own in-cloud LWC and cloud fraction

Original Macrophysics



- Overlap
- In-cumulus CWC = In-stratus CWC

New Macrophysics



- Non-overlap
- In-cumulus CWC ≠ In-stratus CWC

A New Stratiform Macrophysics Scheme

1. Uses equilibrium cloud fraction and equilibrium state variables for computing Q
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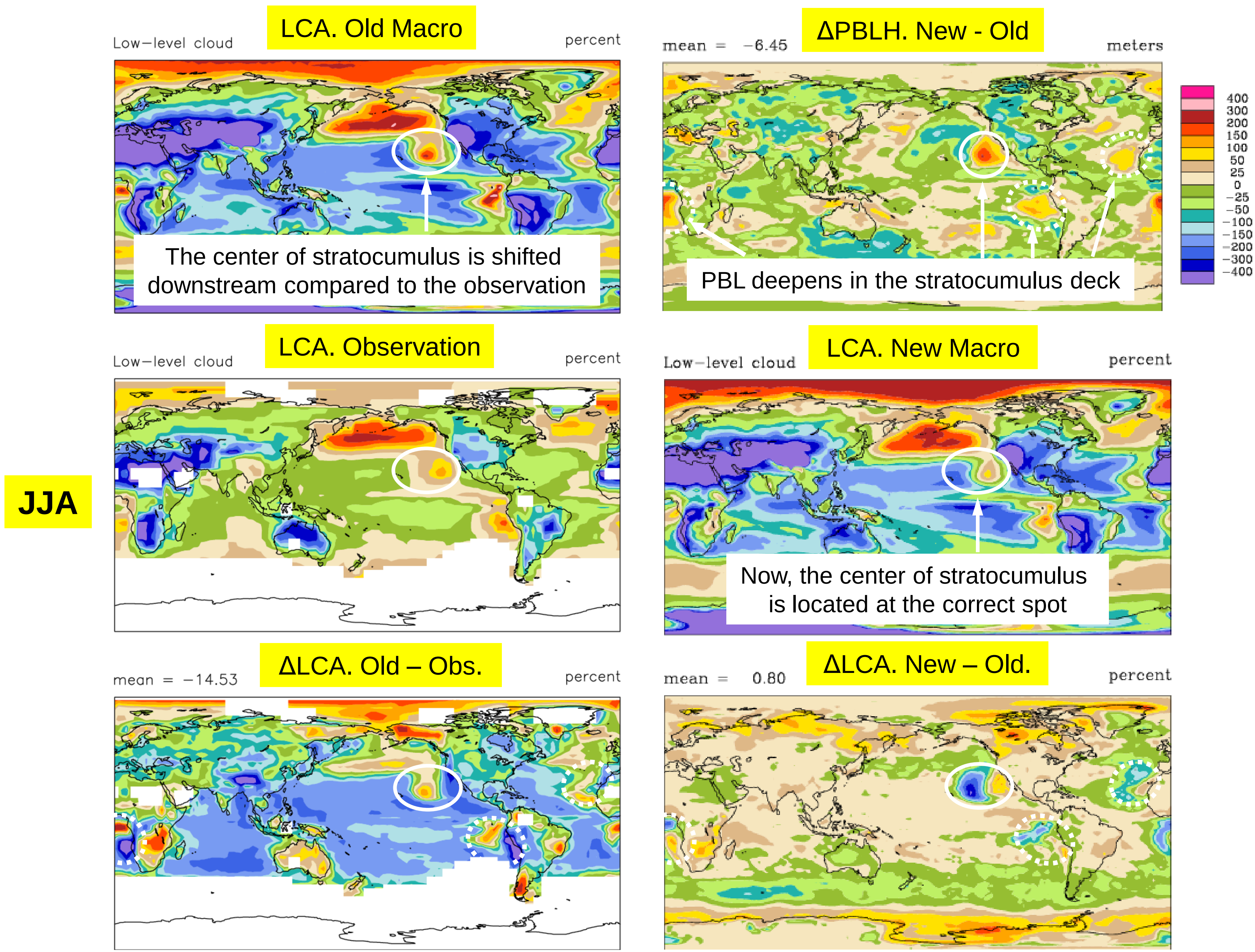
4. Explicit treatment of cumulus cloud
   - Cumulus and stratus are non-overlapped in each layer and have their own in-cloud LWC and cloud fraction
5. Has the following functionalities:
   - ❑ Stratus fraction formula based on either RH or triangular PDF (CAMstfrac)
     - For PDF-based cloud, $U_{clr} \rightarrow 1$ as $a_{st} \rightarrow 1$ consistent with the real world
   - ❑ Specify in-cloud CWC (LWC+IWC) of newly formed or dissipated stratus from zero (cc=0) to the CWC of pre-existing stratus (cc=1)
   - ❑ Force in-stratus CWC to be bounded by externally-specified limiting values (qcst_min>0, qcst_max>0) by performing pseudo condensation-evaporation in each layer.
     - Natural removal of 'empty' ($a>0$, $q_{l,cloud}=0$) and 'dense'($a=0$, $q_{l,cloud}>0$) cloud
     - Potential replacement of Vavrus polar cloud fix
   - ❑ Explicit or implicit computation of Q by choosing different iteration number (niter)
   - ❑ Potential to allow super-saturation within the stratus in any phases

CAMUW + RK Micro + New Macro

- 5 years AMIP runs using version CAM3_5_42
- Several refinements are made to UW PBL and UW shallow convection
  - Increase turbulent master length scale in the convective regime
  - Refined computation of TKE at the entrainment interfaces
  - Maximum cumulus updraft core fractional area of 10 % instead of 5 %
  - Refined identification of penetrative entrainment zone
- Cumulus fraction and in-cumulus CWC are not included in computing radiation and grid-mean CWC.
- Switches in the macrophysics scheme
  - CAMstfrac = RH cloud, cc = 1, niter = 3, qcst_min = 0.01, qcst_max = 3 [g kg^{-1}]



LCA. Old Macro
Low−level cloud
percent
The center of stratocumulus is shifted downstream compared to the observation
ΔPBLH. New - Old
mean = −6.45
meters
PBL deepens in the stratocumulus deck
400
300
200
150
100
50
25
0
−25
−50
−100
−150
−200
−300
−400
LCA. Observation
Low−level cloud
percent
LCA. New Macro
Low−level cloud
percent
Now, the center of stratocumulus is located at the correct spot
JJA
ΔLCA. Old – Obs.
mean = −14.53
percent
ΔLCA. New – Old.
mean = 0.80
percent

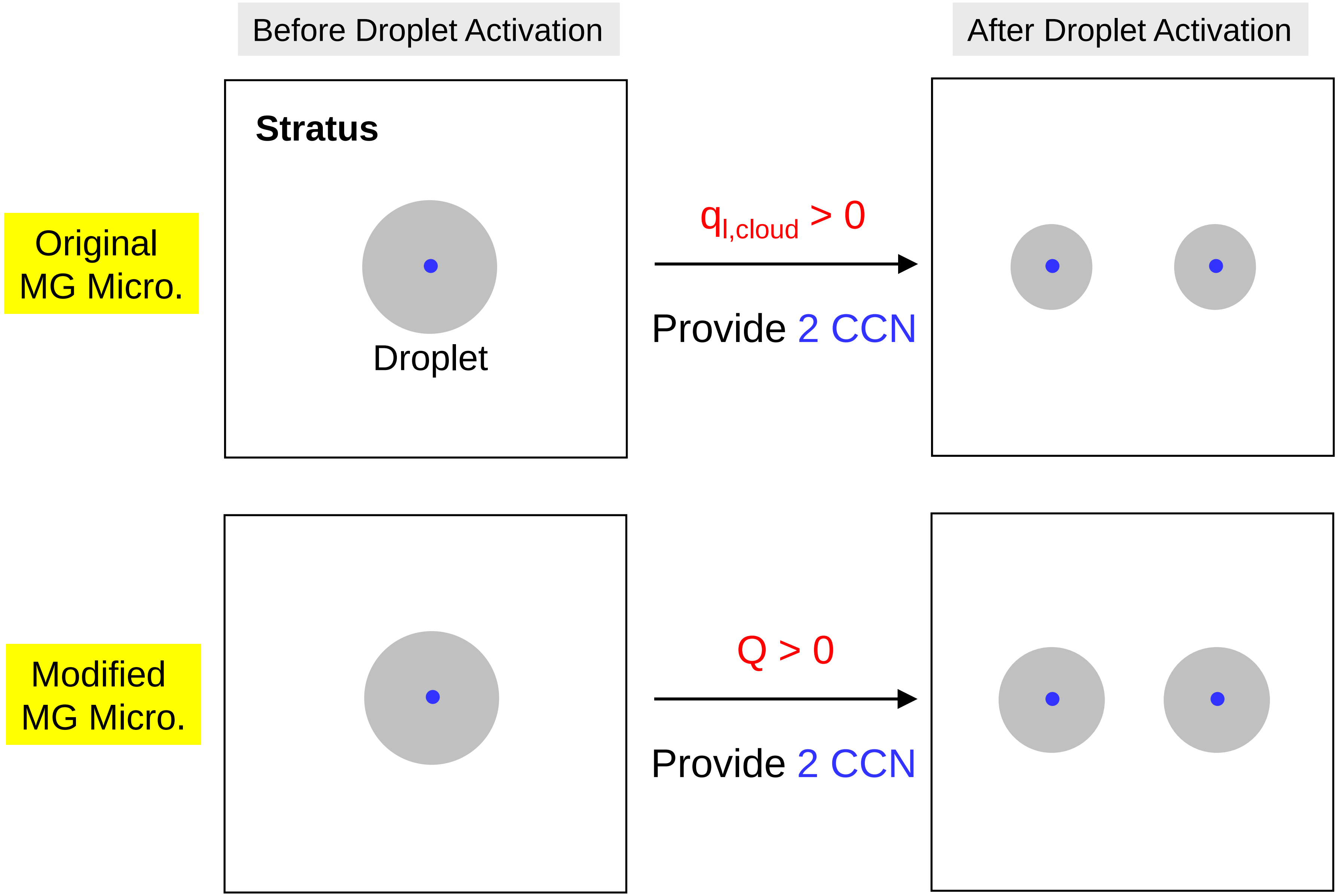
CAMUW + MG Micro + New Macro

- Condensation (Q) into cloud liquid [Q_w= (1-f)*Q] and cloud ice [Q_i= f*Q] are explicitly treated within the macrophysics scheme by setting

  $f = q_{i,cloud}/(q_{l,cloud}+q_{i,cloud})$

  - Bergeron-Findeisen process within the MG microphysics scheme is treated as a separate process independent of Q

- In the MG microphysics, droplet activation occurs
  - only when Q > 0 instead of when '$q_{l,cloud}$, $q_{i,cloud} > 0$'
  - only one time at each time step, that is, mtime = 1 instead of mtime = $\Delta t / t_o$ where t_o is a mixing time scale of aerosol within cloud



Before Droplet Activation
After Droplet Activation
Stratus
Original MG Micro.
Droplet
$q_{l,cloud} > 0$
Provide 2 CCN
Modified MG Micro.
Q > 0
Provide 2 CCN

CAMUW + MG Micro + New Macro

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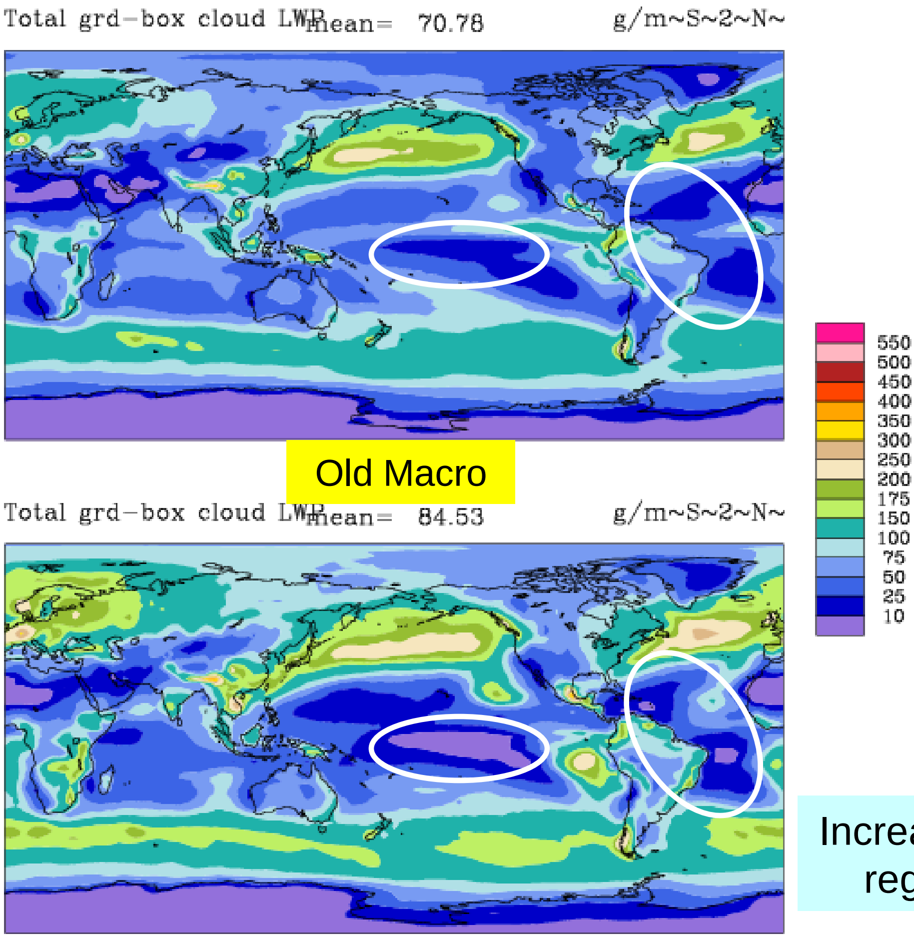
- Cumulus fraction and in-cumulus CWC are explicitly included in computation of radiation and grid-mean CWC with appropriate tunings (dp1 = 0.03, c_o = 0.02)

- Switches in the macrophysics scheme
  - CAMstfrac = RH cloud, cc = 0, niter = 3, qcst_min = 0.01, qcst_max = 3 [g/kg]

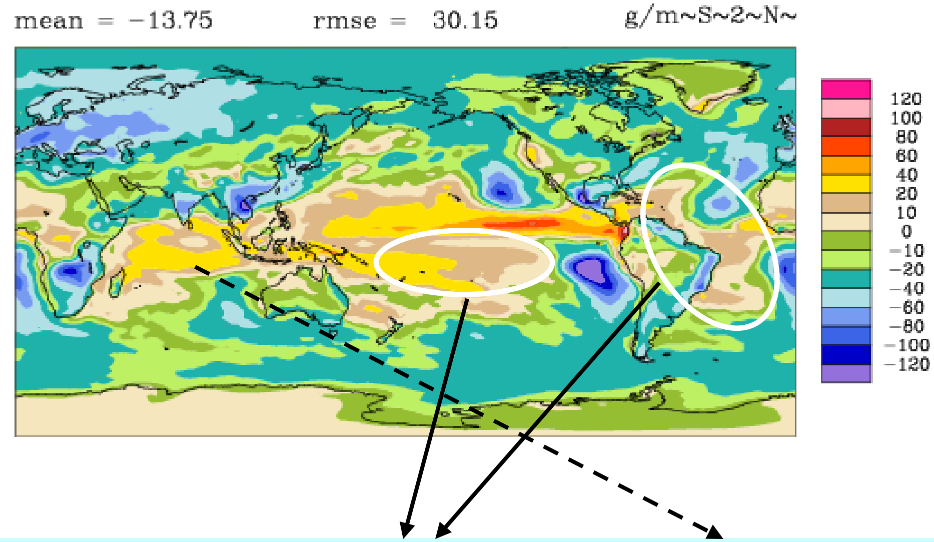
LWP. Annual Mean

New Macro

Old Macro



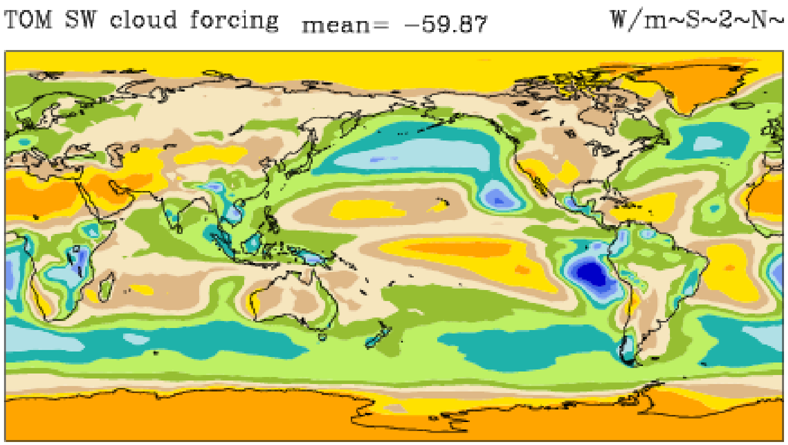
ΔLWP. New – Old



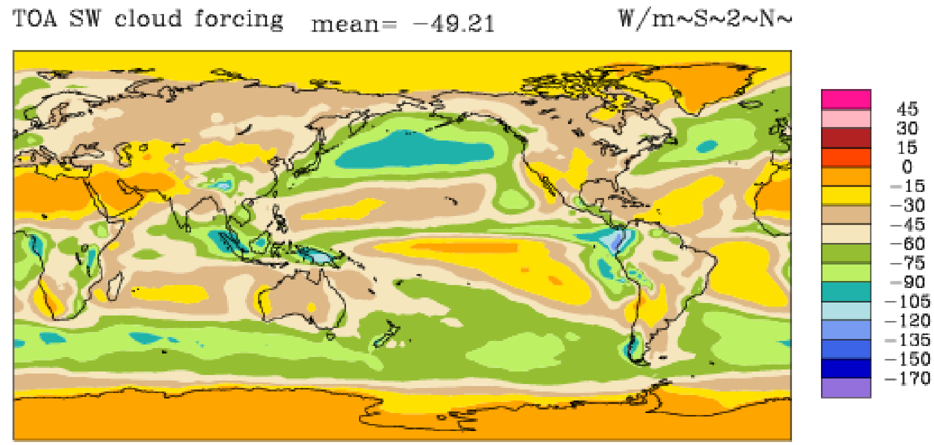
Increase of LWP in the trade cumulus & deep convection regimes due to explicit treatment of in-cumulus LWC

SWCF. Annual Mean

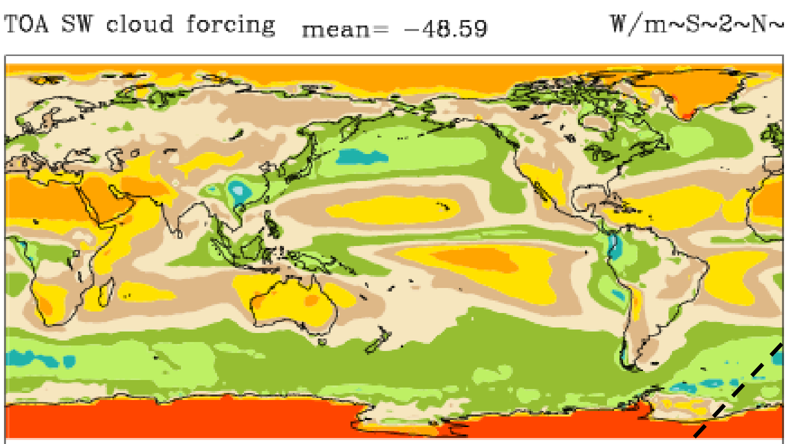
Old Macro



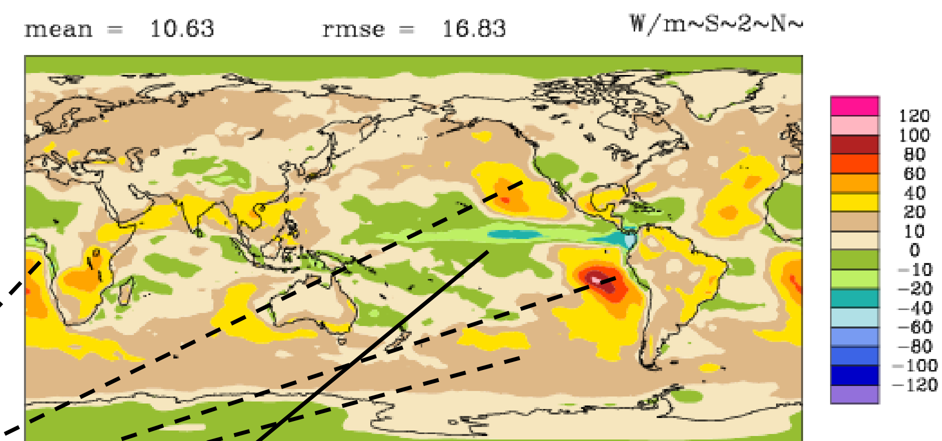
New Macro



CERES Observation

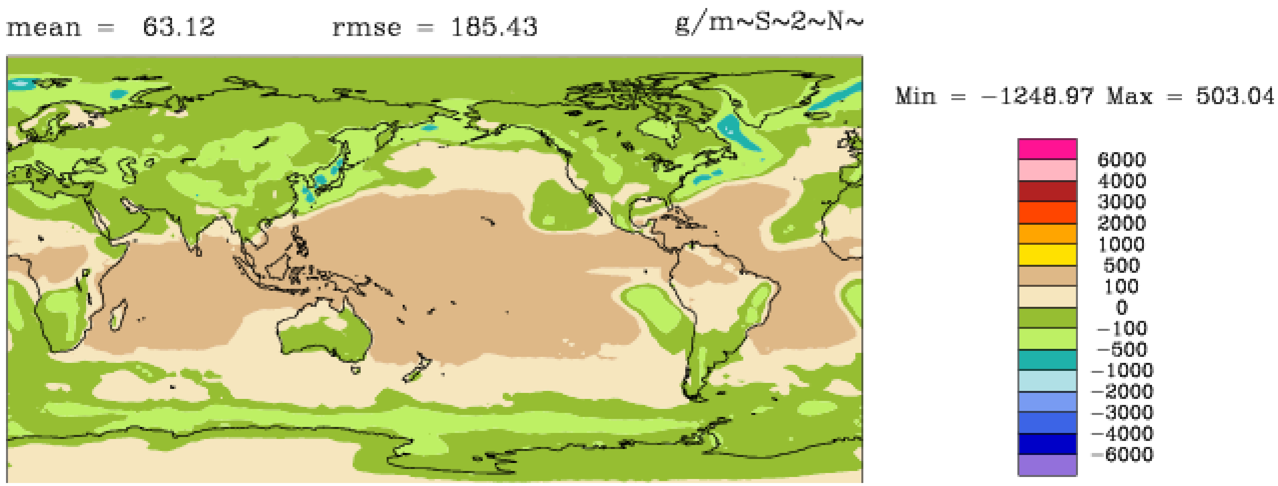


ΔSWCF. New – Old

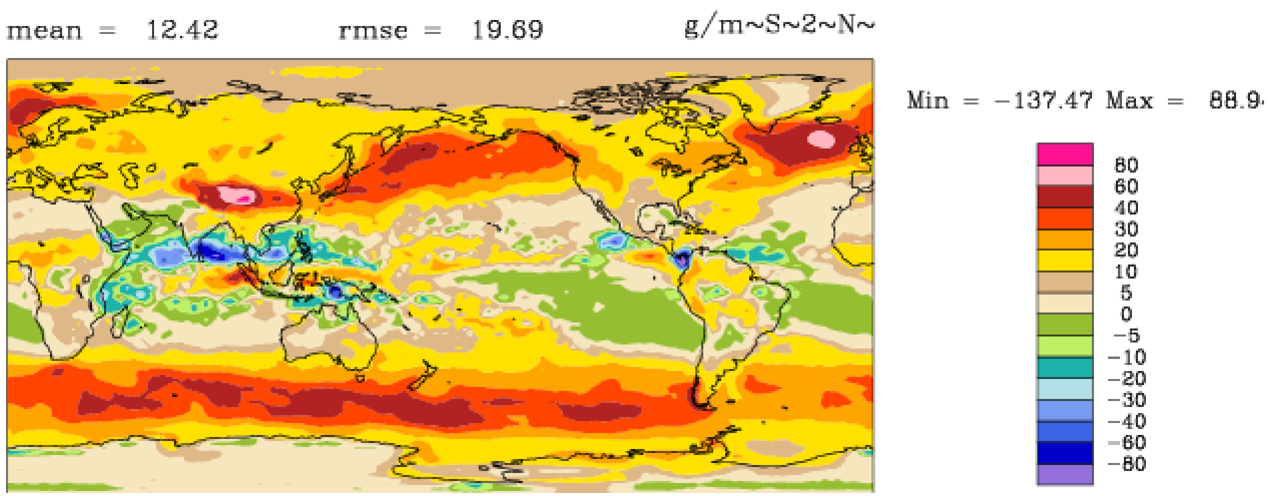


- Huge improvement of SWCF
- Enhanced SWCF in the trade due to explicit contribution of Cu CWC to radiation

Δ In-cloud LWP. New - Old



Δ In-cloud IWP. New - Old



‘Qi= f*Q’ + ‘Forcing in-stratus CWC to be bounded by two limiting values’
→ Increase of in-cloud IWC in the storm track

UW PBL + UW ShCu + MG Micro + New Macro

	RESTOM [$W\ m^{-2}$]	SWCF [$W\ m^{-2}$]	LWCF [$W\ m^{-2}$]	SWCF at 60^oS. DJF	TGCLDLWP [$g\ m^{-2}$]	PRECT [$mm\ day^{-1}$]	PREH2O [mm]	LHFLX [$W\ m^{-2}$]
Base[0]	-6.3	-63.3	32.6	-170	105	2.91	26.5	85.1
Enhance entrainment[1] (a2l = 30 ← 15)	**-4.5**	**-61.4**	32.4	**-163**	**100**	2.91	26.5	85.1
Zero-CWC of newly formed stratus[2]	-7.4	-64.2	32.3	-168	**90**	**2.99**	26.3	**87.5**
Cloud drop activation only when Q > 0[3]	**-1.7**	**-56.2**	**30.1**	**-147**	**90**	**2.96**	26.2	**86.4**
Increase activation time scale of CCN[4] (mtime = 1 ← 1.5)	-5.4	-62.0	32.2	-170	101	2.92	26.3	85.5
Enhance conversion of deep Cu LWC to precip.[5] (c_o = 0.02 ← 0.01)	-4.9	-61.7	32.1	-170	97	2.92	26.4	85.4
Reduce deep Cu fraction[6] (dp1 = 0.03 ← 0.05)	-5.6	-62.7	32.4	-170	100	2.92	26.5	85.3
Neglect Cu contribution in computing radiation	-2.6	-58.8	32.0	-157	85	2.91	26.6	85.2
0+**1**(a2l=20)+**2**+**3**+**4**+**5**	**0.3**	**-51.7**	**27.9**	**-140**	**75**	**3.07**	25.8	**89.8**
Observation	**0**	**-48.6~-54.2** (CERES, ERBE)	**27.2 ~30.4** (CERES, ERBE)	**-148** (CERES)	**78 ~ 113** (NVAP, MODIS)	**2.61** (GPCP)	**25.0** (ERA40)	**82.4** (ERA40)

Summary of Global Model Performance

Variable	**CAM30** rms error	**CAM3.5** (Revise ZM deep conv.)	**UW PBL** **UW ShCu** RK Micro ZE Macro	**UW PBL*** **UW ShCu*** **MG Micro** ZE Macro	**UW PBL** **UW ShCu** **MG Micro*** **PBR Macro**
SLP	3.5 hPa	**0.82**	**0.86**	0.88	0.85
Surface wind stress	0.05 N m^{-2}	**0.82**	0.81	**0.76**	**0.84**
Zonal wind at 300 hPa	4.5 m s^{-1}	**0.77**	0.80	**0.73**	0.74
Surface rainfall	1.7 mm day^{-1}	**0.93**	0.92	0.93	**0.99**
Air temperature at 2m	3.5 K	**0.94**	0.95	**0.91**	0.93
SWCF	22.8 W m^{-2}	1.02	**0.91**	**1.14**	**0.88**
LWCF	11.7 W m^{-2}	0.97	**0.93**	**0.86**	0.88
T	2.1 K	**0.84**	0.81	**0.97**	**0.88**
RH	11.0 %	**0.78**	0.76	0.79	0.76
Climate Bias Index (CBI)		**0.88**	**0.86**	**0.88**	**0.86**

Conclusion

- We developed a new stratiform macrophysics scheme which
  - ensures consistency between cloud fraction and in-cloud LWC by using equilibrium variables for computing Q,
  - removes many conceptual and mathematical inconsistencies in CAM’s cloud system model by
    - using conservative scalars in computing Q,
    - taking into account of fusion heat,
    - treating cumulus (CWC as well as fraction) separately from stratus,
    - mimicking a PDF-approach in computing stratus fraction and in-stratus CWC,
    - forcing in-stratus CWC to be bounded by two limiting values,
    - allowing the possibility of super-saturation within stratus

- MG microphysics is modified, so that droplet activation occurs only when Q > 0 instead of whenever stratus exists → substantially reduced the bias of SWCF → may help to reduce too strong aerosol indirect effect (-2.3 → -1.1 Wm^{-2}) ?

- Overall, our new macrophysics scheme deepens PBL in the stratocumulus deck and increases LWP in the trade cumulus regime, resulting in improved skill scores of SWCF and T. However, simulation of precipitation and surface wind stress is worsen due to enhancement of already strong hydrological cycle.

- Future and on-going works:
  - Find a tuning set to weaken hydrological cycle
  - Analysis of diurnal cycle and ENSO amplitude

Stochastic Ocean Mixed Layer Model

[Frankignoul and Hasselman 1977; Deser et al. 2003; Park et al. 2006]

$$\rho \cdot C_p \cdot \overline{H} \cdot \frac{\partial}{\partial t} SST' = -\lambda \cdot SST' + Others$$

$$\lambda \equiv -\frac{\partial Q'}{\partial SST'}$$

Q' : Downward surface heat flux anomaly

$\lambda < 0$: SST anomaly is amplified → Positive feedback

$$= \lambda_{LHF + SHF} + \lambda_{(SW + LW)_{cloud}} + \lambda_{(SW + LW)_{clear}}$$

$\lambda_{LHF + SHF}$	$\lambda_{(SW + LW)_{cloud}}$	$\lambda_{(SW + LW)_{clear}}$
PBL turbulence, convective deflation	stratocumulus, anvil cirrus	water vapor, aerosol