The behavior of two climate models that include a PDF-based cloud parameterization

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6 Nov 2012, ECMWF

Outline

- Description of our cloud parameterization ("CLUBB")
- Single-column simulations
- Comparison of global simulations versus satellite observations
- Conclusions

Our parameterization for clouds and turbulence: CLUBB

We have constructed a 1D (single-column) cloud parameterization based on the Assumed PDF Method. It is called ``*CLUBB*."

CLUBB denotes ``Cloud Layers Unified By Binormals."

CLUBB parameterizes clouds and turbulence, and can be used to drive microphysics.

Golaz et al. (2002b)

The parameterization problem[1]

A parameterization needs to supply subgrid-scale fluxes of heat, moisture, and momentum (and PDFs of cloud fraction and liquid water for microphysics and radiation):

Heat

$$\frac{\partial \bar{\theta}_l}{\partial t} = -\bar{w}\frac{\partial \bar{\theta}_l}{\partial z} - \frac{\partial}{\partial z}\overline{w'\theta_l'} + \bar{R} + \left.\frac{\partial \bar{\theta}_l}{\partial t}\right|_{ls} \quad (1)$$

Moisture

$$\frac{\partial \bar{q}_t}{\partial t} = -\bar{w}\frac{\partial \bar{q}_t}{\partial z} - \frac{\partial}{\partial z}\overline{w'q_t'} + \left.\frac{\partial \bar{q}_t}{\partial t}\right|_{ls} \quad (2)$$

Momentum

$$\frac{\partial \bar{u}}{\partial t} = -\bar{w}\frac{\partial \bar{u}}{\partial z} - f(v_g - \bar{v}) - \frac{\partial}{\partial z}\overline{u'w'} \quad (3)$$

$$\frac{\partial \bar{v}}{\partial t} = -\bar{w}\frac{\partial \bar{v}}{\partial z} + f(u_g - \bar{u}) - \frac{\partial}{\partial z}\overline{v'w'} \quad (4)$$

Red and Magenta = calculated by host model

Blue = calculated by parameterization

[1]Peter Stone of MIT.

Broad philosophy: To model these terms, CLUBB tries to emulate aspects of what a LES model does, but using horizontal averages

Like LES, CLUBB starts with the governing equations.

Unlike LES, CLUBB the equations are averaged to form a 1D (single-column) model.

Like LES, CLUBB has memory, but only of prior timestep.

Unlike LES, CLUBB has no representation of horizontal spatial structure of clouds (e.g. clumping in space).

CLUBB contains a number of prognostic higher-order equations

In CLUBB, the set of prognosed moments includes:

$$\text{Means}: \quad \frac{\partial \bar{u}}{\partial t} = \ldots \quad \frac{\partial \bar{v}}{\partial t} = \ldots \quad \frac{\partial \bar{q}_t}{\partial t} = \ldots \quad \frac{\partial \bar{\theta}_l}{\partial t} = \ldots$$

$$\text{2nd}-\text{order}: \quad \frac{\partial \overline{w'q_t'}}{\partial t} = \ldots \quad \frac{\partial \overline{w'\theta_l'}}{\partial t} = \ldots \quad \frac{\partial \overline{w'^2}}{\partial t} = \ldots$$

$$\frac{\partial \overline{q_t'^2}}{\partial t} = \ldots \quad \frac{\partial \overline{\theta_l'^2}}{\partial t} = \ldots \quad \frac{\partial \overline{q_t'\theta_l'}}{\partial t} = \ldots$$

$$\text{3rd}-\text{order}: \quad \frac{\partial \overline{w'^3}}{\partial t} = \ldots$$

w = vertical velocity $\quad q_t$ = total water specific humidity

θ_l = liquid water potential temperature

CLUBB prognoses a third-order moment (w'^3). This aids the simulation of (skewed) Cu.

An example of a second-order moment equation

$\overline{r_t'^2} = \overline{q_t'^2}$ = variance of total water (vapor+liquid) mixing ratio.

$$\frac{\partial \overline{r_t'^2}}{\partial t} = \underbrace{-\bar{w}\frac{\partial \overline{r_t'^2}}{\partial z}}_{ma} \underbrace{- \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w' r_t'^2}}{\partial z}}_{ta} \underbrace{-2\overline{w' r_t'}\frac{\partial \bar{r}_t}{\partial z}}_{tp} \underbrace{- \frac{C_2}{\tau}\left(\overline{r_t'^2} - r_t|^2_{\mathrm{tol}}\right)}_{dp1}$$

$$\underbrace{+ \frac{\partial}{\partial z}\left[\left(K_{w2} + \nu_2\right)\frac{\partial}{\partial z}\overline{r_t'^2}\right]}_{dp2} + \left.\frac{\partial \overline{r_t'^2}}{\partial t}\right|_{\mathrm{pd}} + \left.\frac{\partial \overline{r_t'^2}}{\partial t}\right|_{\mathrm{cl}}$$

We close a number of the terms in the equations by integrating them over the PDF of subgrid variability

This reduces the number of equations that we need to prognose.

It also ensures a consistent closure for all terms closed using the PDF.

We can generalize the PDF to include several variables

We use a three-dimensional PDF of vertical velocity, total water mixing ratio, and liquid water potential temperature:

$$P = P(w, q_t, \theta_l)$$

(We can also include hydrometeor mixing ratios and number concentrations in the PDF.)

Randall et al. (1992)

The Assumed PDF Method

Unfortunately, predicting the PDF directly is too expensive.

Instead we use the *Assumed* PDF Method. We *assume* a *functional form* of the PDFs, and determine a *particular instance* of this functional form for each grid box and time step. (The form we assume is a double Gaussian PDF.)

Therefore, the PDF varies in space and evolves in time.

E.g., Manton and Cotton (1977)

The Double Gaussian PDF Functional Form

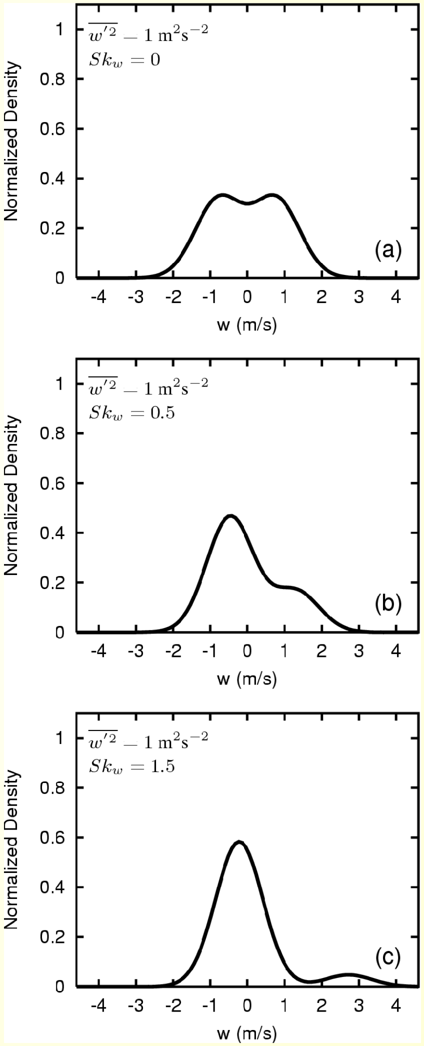
A double Gaussian PDF is the sum of two Gaussians. It satisfies *three important properties*:

(1) It allows both negative and positive skewness.

(2) It has reasonable-looking tails.

(3) It can be multi-variate.

We do not use a completely general double Gaussian, but instead restrict the family in order to simplify and reduce the number of parameters.



Steps in the Assumed PDF Method

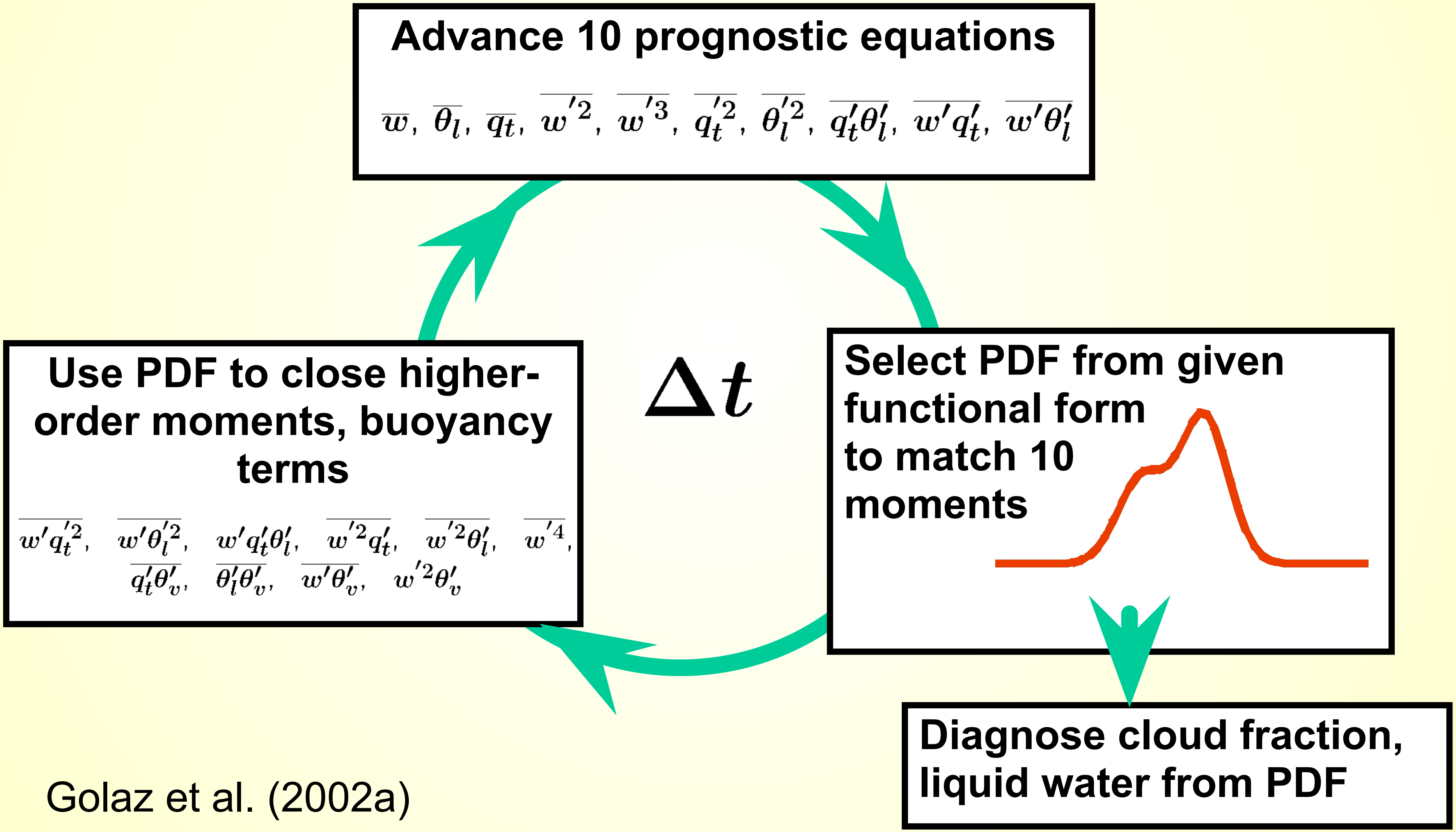
The Assumed PDF Method contains 3 main steps that must be carried out for each grid box and time step:

(1) Prognose grid box means and various higher-order moments.

(2) Use these moments to select a particular PDF instance from the assumed functional form.

(3) Use the selected PDF to compute average of various higher-order terms that need to be closed, e.g. buoyancy flux, cloud fraction, etc.

Schematic of the Assumed PDF method



Golaz et al. (2002a)

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We have implemented and tested CLUBB in GFDL AM3 and NCAR CAM5

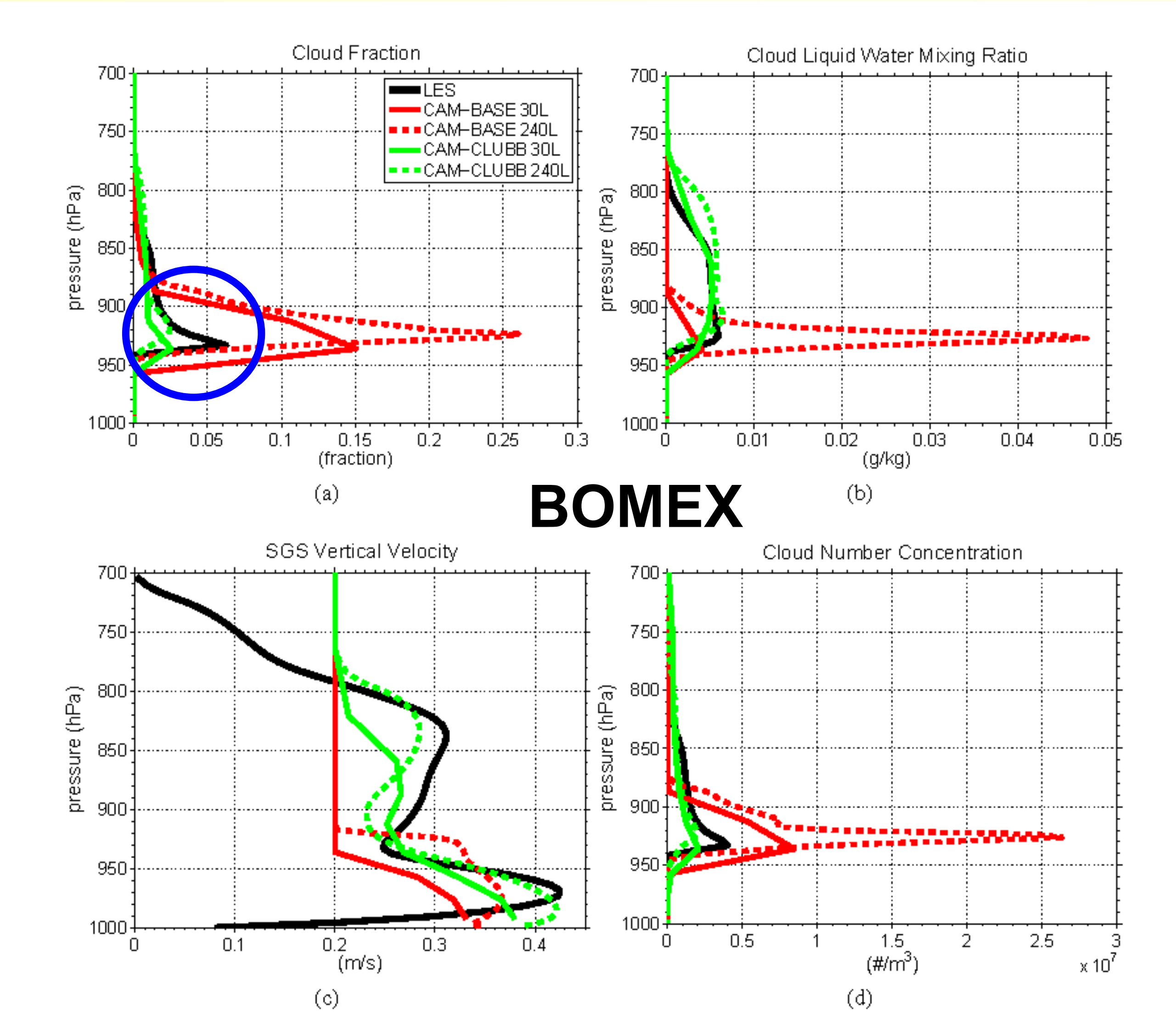
- Boundary Layer
- Shallow Convection
- Cloud Macrophysics
- Deep Convection
- Microphysics (Morrison-Gettelman)
- Radiation
- Aerosols

Replaced by CLUBB

In the next two slides, we present single-column simulations from CAM-CLUBB

The microphysics and radiation come from CAM.

Single-column and large-eddy simulations of trade-wind cumulus



SCAM-CLUBB (green) underestimates shallow Cu cloud fraction as compared to LES (black).

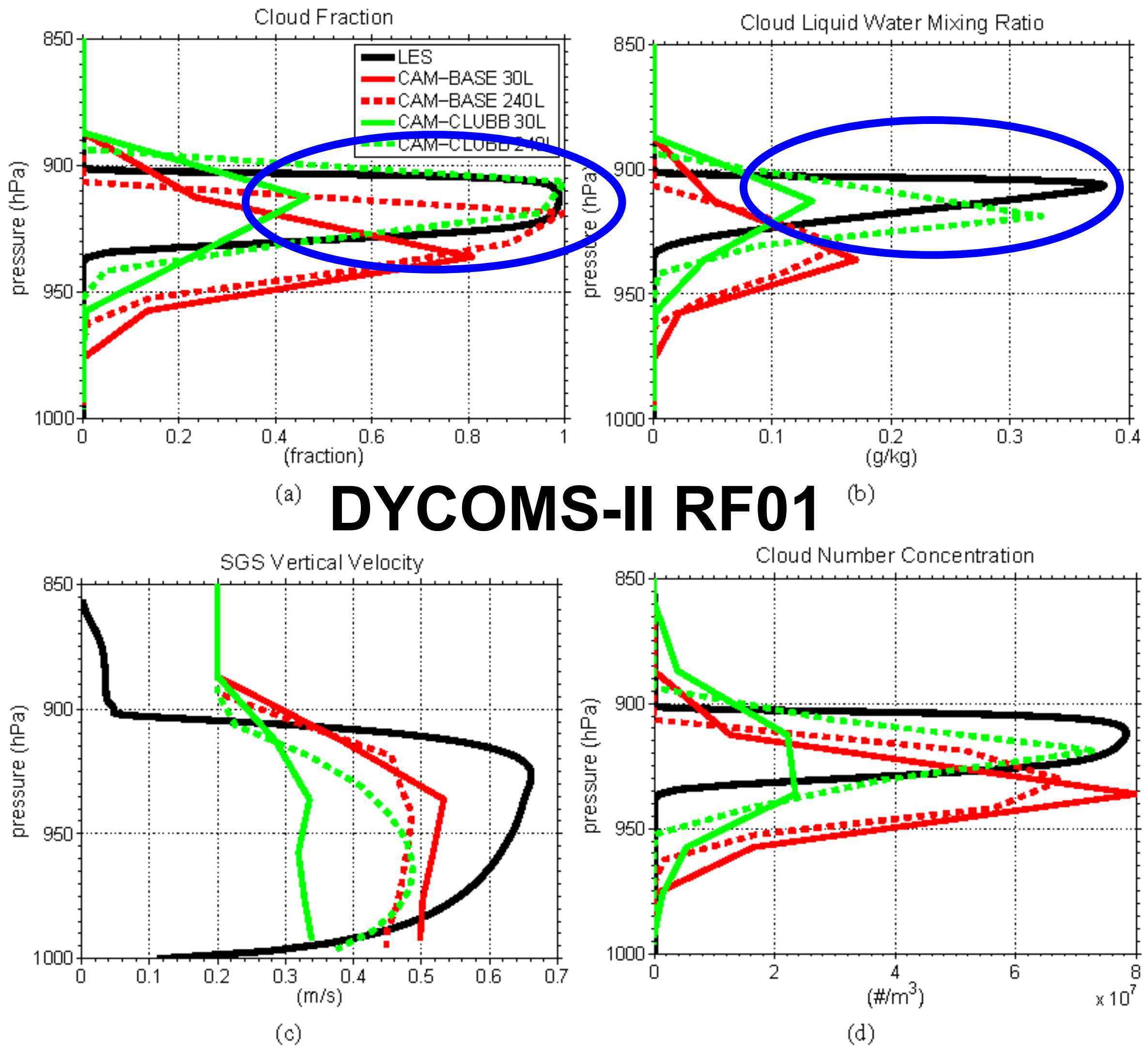
But the results are relatively insensitive to changes in vertical grid spacing.

Bogenschutz et al. (2012)

Single-column and large-eddy simulations of marine stratocumulus

SCAM-CLUBB (green lines) underpredicts cloud fraction and liquid water in marine Sc (DYCOMS-II RF01) at coarse vertical grid spacing.

Bogenschutz et al. (2012)



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Obtaining competitive global results requires some tuning

For instance, in the CAM-CLUBB results to be shown, we multiplied both accretion and autoconversion by a factor of 3.

Increasing the accretion and autoconversion rates may be justifiable because the correlations between hydrometeors are ignored in climate simulations

The enhancement of precipitation varies regionally. It is large in shallow Cu regions and smaller in marine Sc regions near the western coasts.

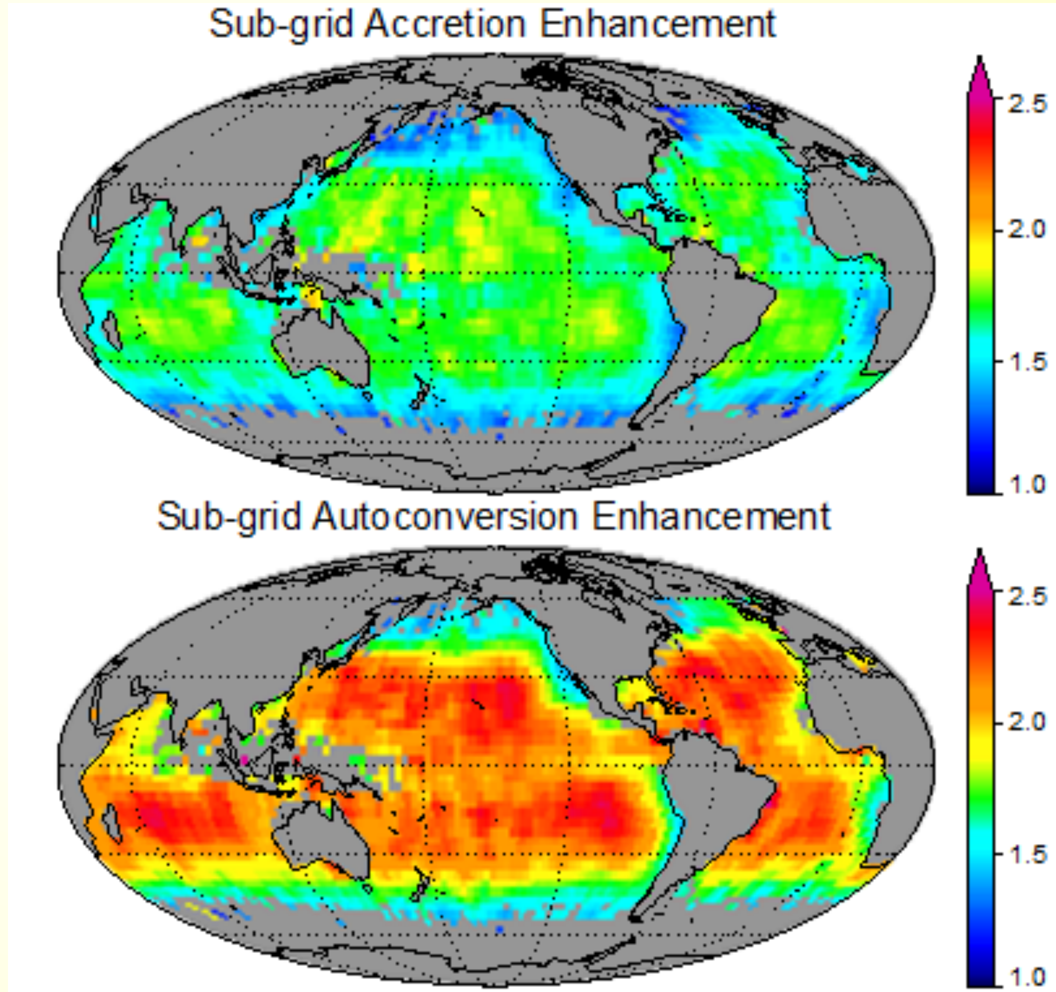


Figure courtesy of Matt Lebsock

Global plots of cloud fields

In the left panel, we show:

AM3

Observations

AM3 - Observations

In the right panel, we show:

AM3CLUBB

Observations

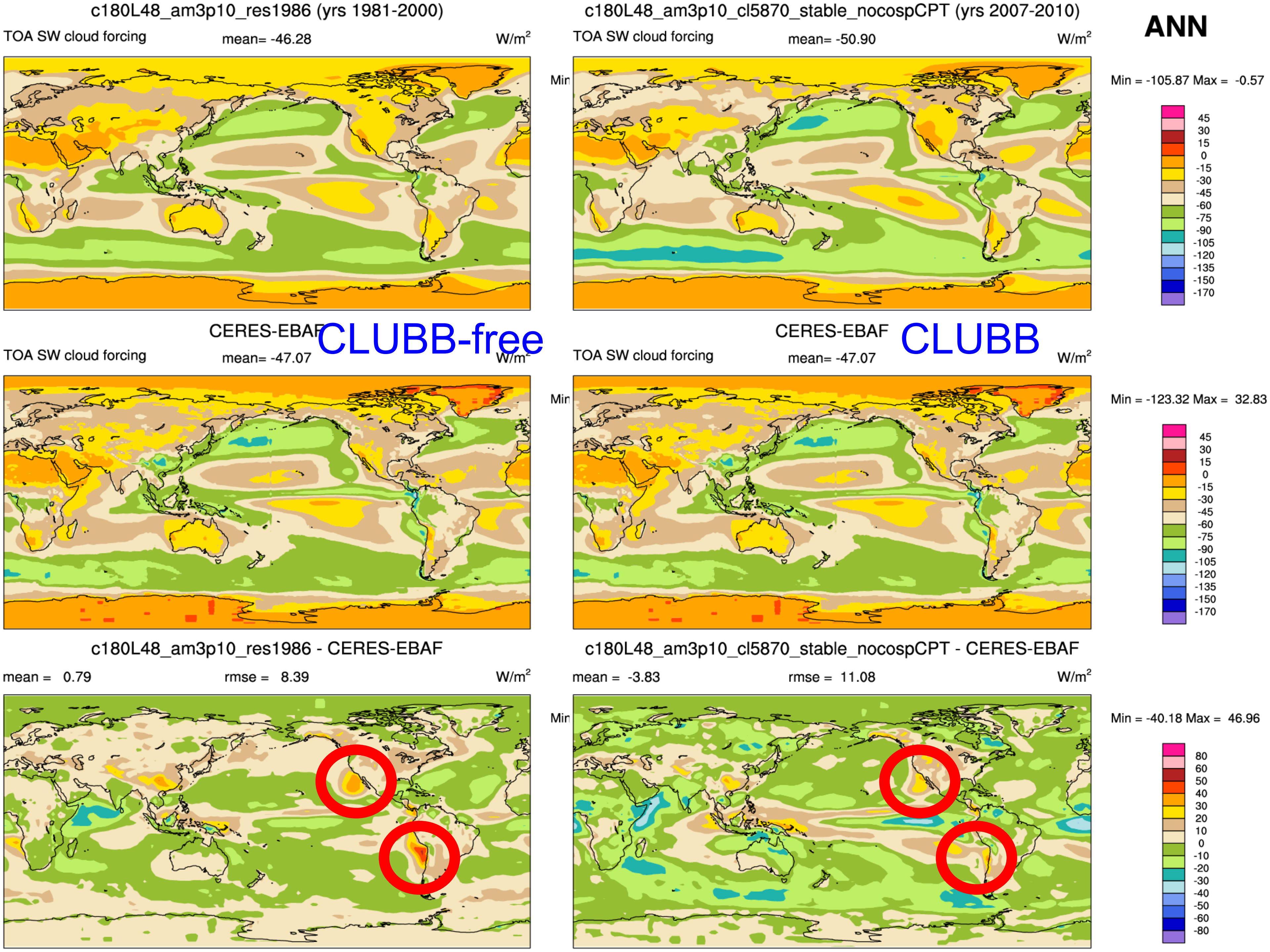
AM3CLUBB - Observations

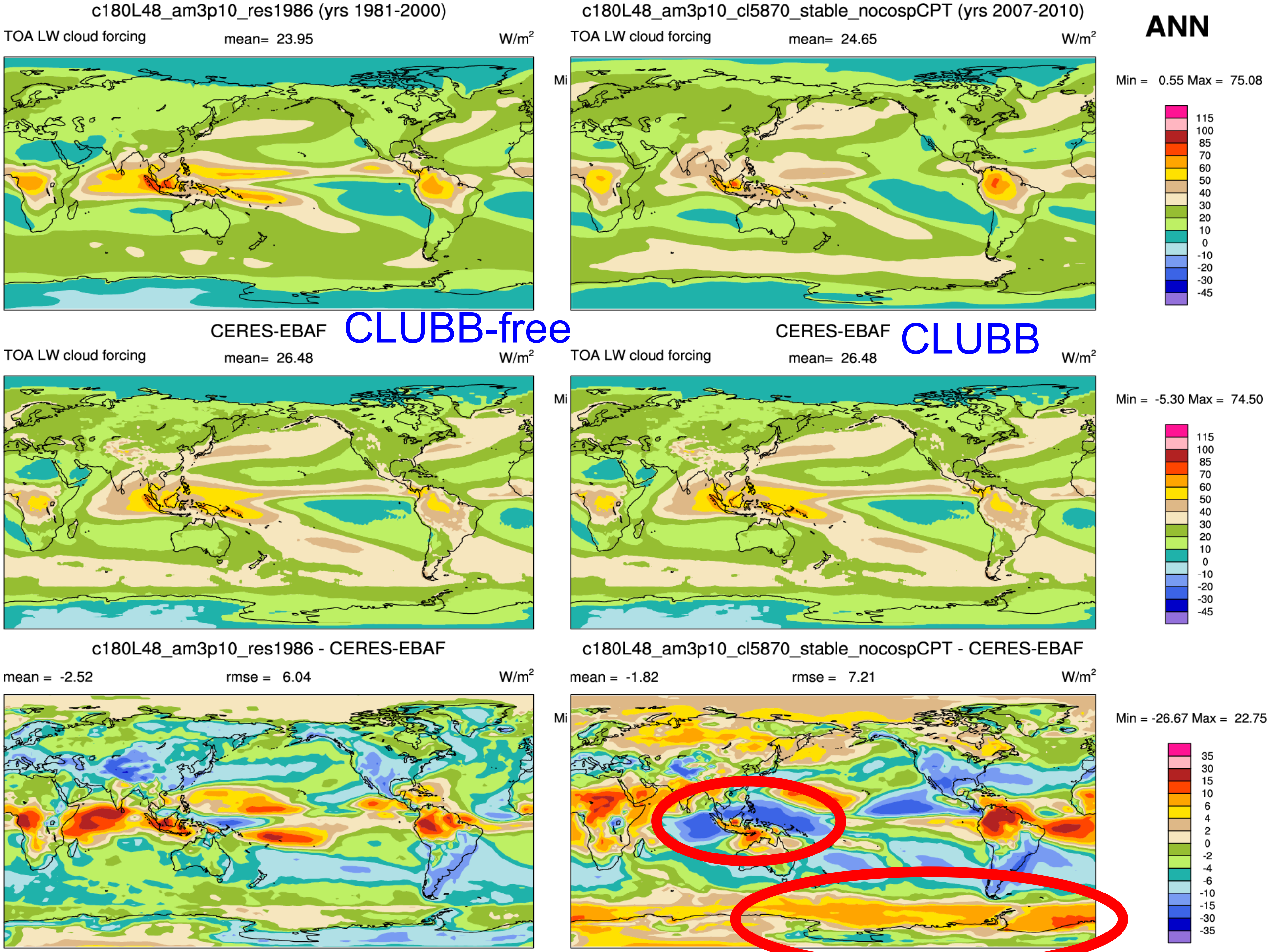
AM3 and AM3-CLUBB versus satellite observations

CLUBB fosters formation of near-coastal stratocumulus.

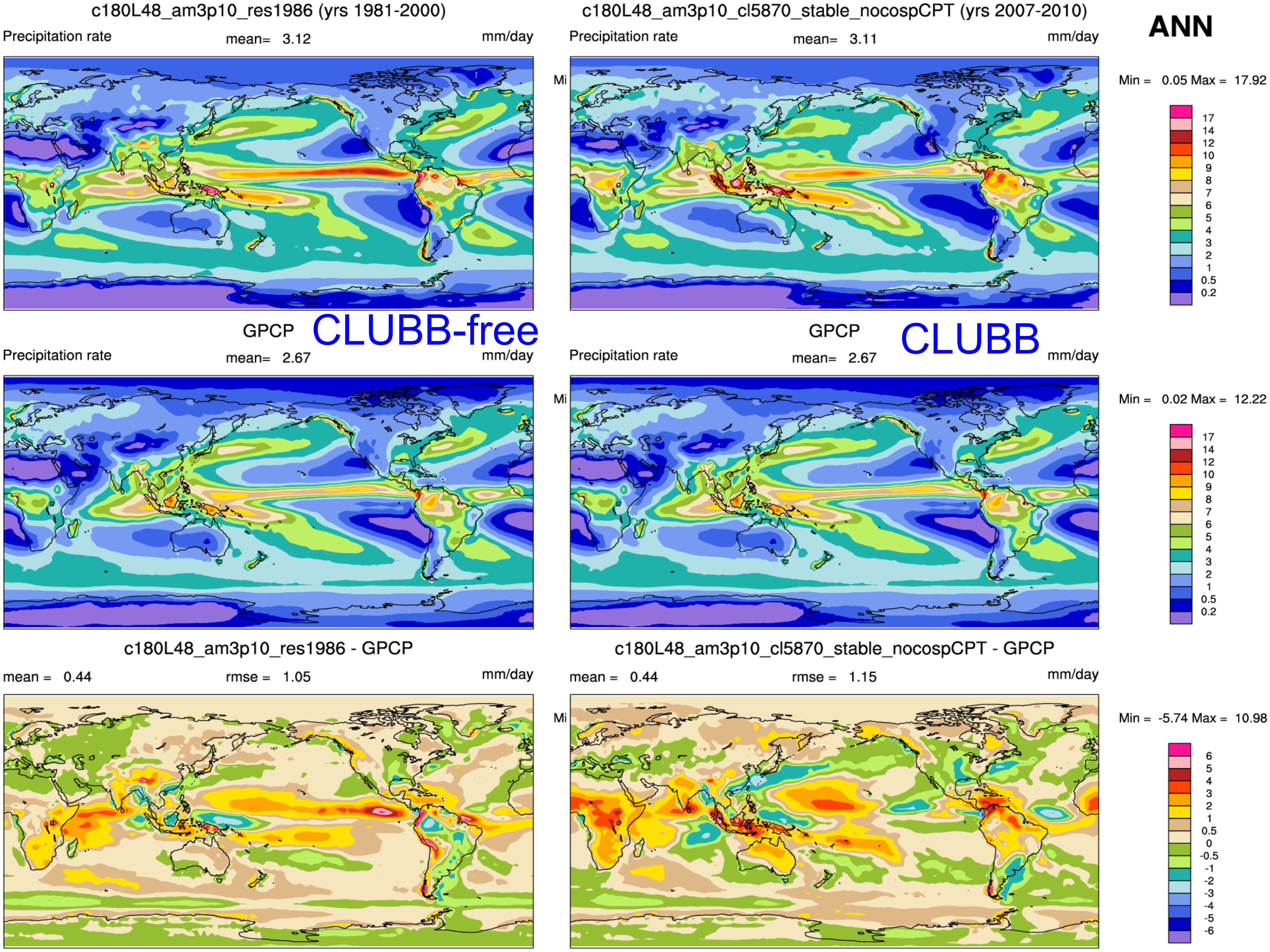
CLUBB underestimates high-altitude ice clouds.

Plots are courtesy of Huan Guo.


c180L48_am3p10_res1986 (yrs 1981-2000)
TOA SW cloud forcing
mean= -46.28
W/m²
c180L48_am3p10_cl5870_stable_nocospCPT (yrs 2007-2010)
TOA SW cloud forcing
mean= -50.90
W/m²
ANN
Min = -105.87 Max = -0.57
45
30
15
0
-15
-30
-45
-60
-75
-90
-105
-120
-135
-150
-170
CERES-EBAF
CLUBB-free
TOA SW cloud forcing
mean= -47.07
W/m²
CERES-EBAF
CLUBB
TOA SW cloud forcing
mean= -47.07
W/m²
Min = -123.32 Max = 32.83
45
30
15
0
-15
-30
-45
-60
-75
-90
-105
-120
-135
-150
-170
c180L48_am3p10_res1986 - CERES-EBAF
mean = 0.79
rmse = 8.39
W/m²
c180L48_am3p10_cl5870_stable_nocospCPT - CERES-EBAF
mean = -3.83
rmse = 11.08
W/m²
Min = -40.18 Max = 46.96
80
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-80



ANN
c180L48_am3p10_res1986 (yrs 1981-2000)
TOA LW cloud forcing
mean= 23.95
W/m2
c180L48_am3p10_cl5870_stable_nocospCPT (yrs 2007-2010)
TOA LW cloud forcing
mean= 24.65
W/m2
Min = 0.55 Max = 75.08
115
100
85
70
60
50
40
30
20
10
0
-10
-20
-30
-45
CERES-EBAF
CLUBB-free
TOA LW cloud forcing
mean= 26.48
W/m2
CERES-EBAF
CLUBB
TOA LW cloud forcing
mean= 26.48
W/m2
Min = -5.30 Max = 74.50
c180L48_am3p10_res1986 - CERES-EBAF
mean = -2.52
rmse = 6.04
W/m2
c180L48_am3p10_cl5870_stable_nocospCPT - CERES-EBAF
mean = -1.82
rmse = 7.21
W/m2
Min = -26.67 Max = 22.75
35
30
15
10
6
4
2
0
-2
-4
-6
-10
-15
-30
-35

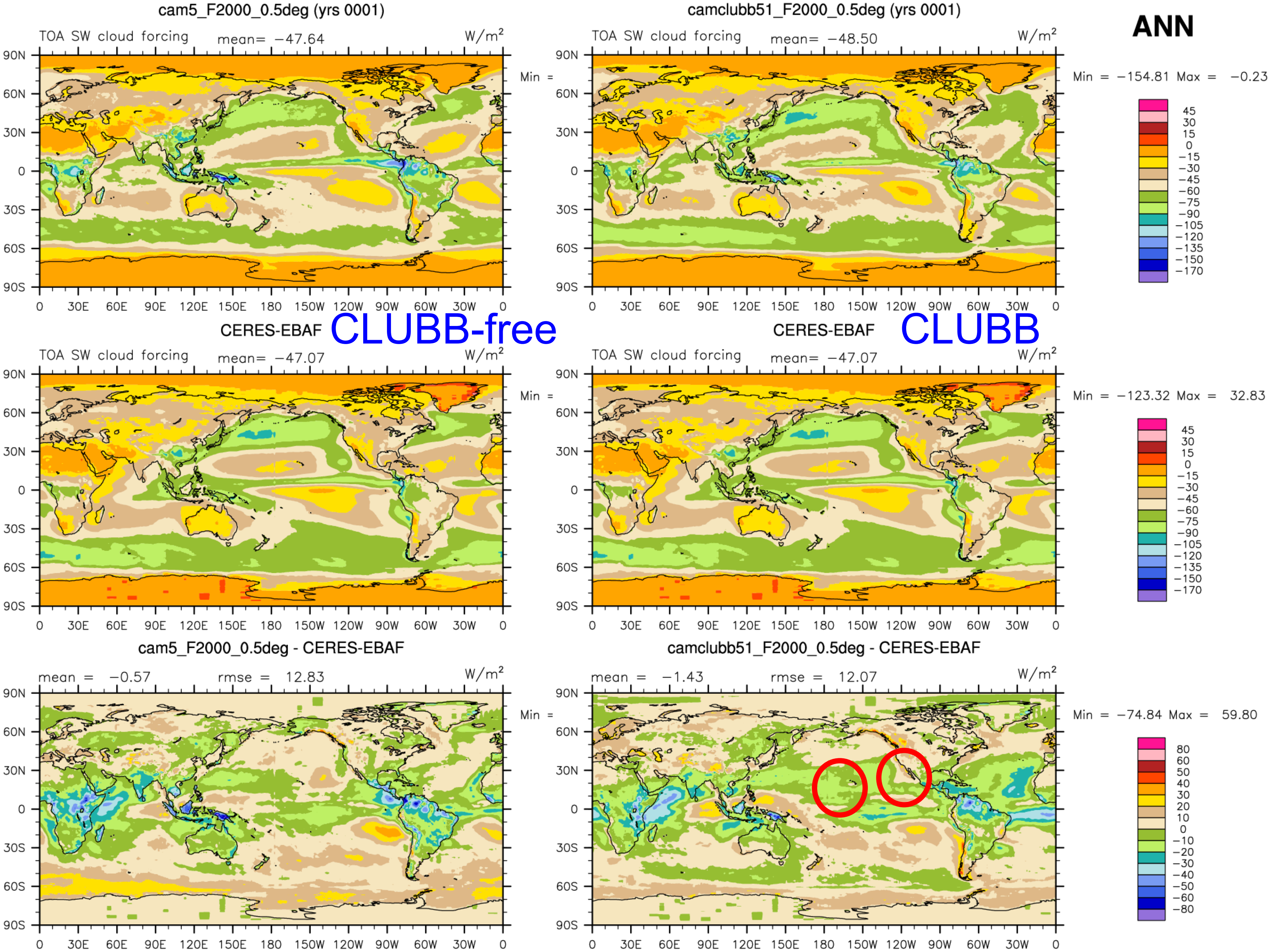

c180L48_am3p10_res1986 (yrs 1981-2000)
Precipitation rate
mean= 3.12
mm/day
c180L48_am3p10_cl5870_stable_nocospCPT (yrs 2007-2010)
Precipitation rate
mean= 3.11
mm/day
ANN
Min = 0.05 Max = 17.92
17
14
12
10
9
8
7
6
5
4
3
2
1
0.5
0.2
GPCP
CLUBB-free
Precipitation rate
mean= 2.67
mm/day
GPCP
CLUBB
Precipitation rate
mean= 2.67
mm/day
Min = 0.02 Max = 12.22
c180L48_am3p10_res1986 - GPCP
mean = 0.44
rmse = 1.05
mm/day
c180L48_am3p10_cl5870_stable_nocospCPT - GPCP
mean = 0.44
rmse = 1.15
mm/day
Min = -5.74 Max = 10.98
6
5
4
3
2
1
0.5
0
-0.5
-1
-2
-3
-4
-5
-6

CAM5 and CAM-CLUBB versus satellite observations

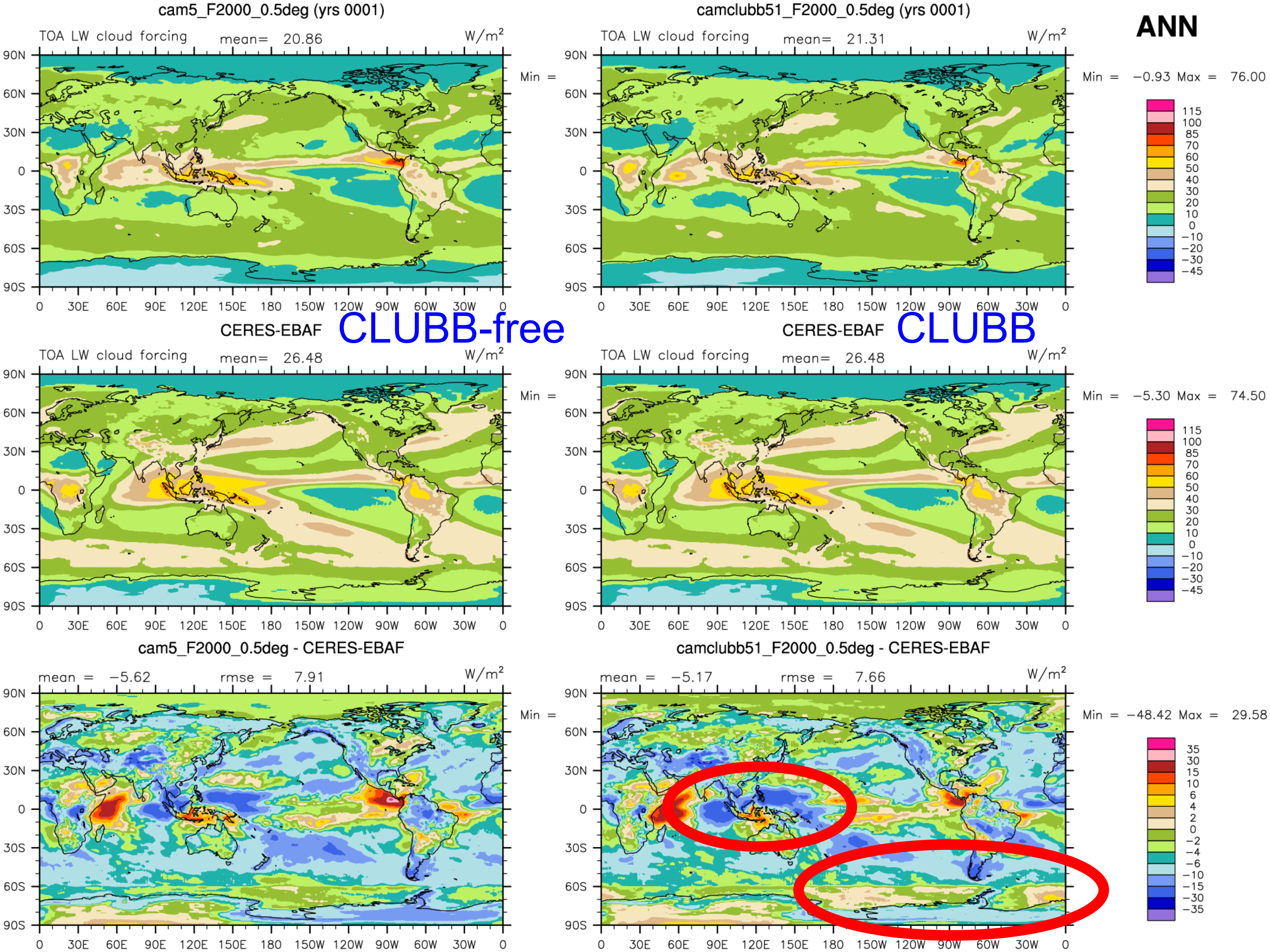
CAM-CLUBB has some of the same errors as AM3-CLUBB (too much cloud in shallow Cu regions; not enough high cloud in western Pacific warm pool).

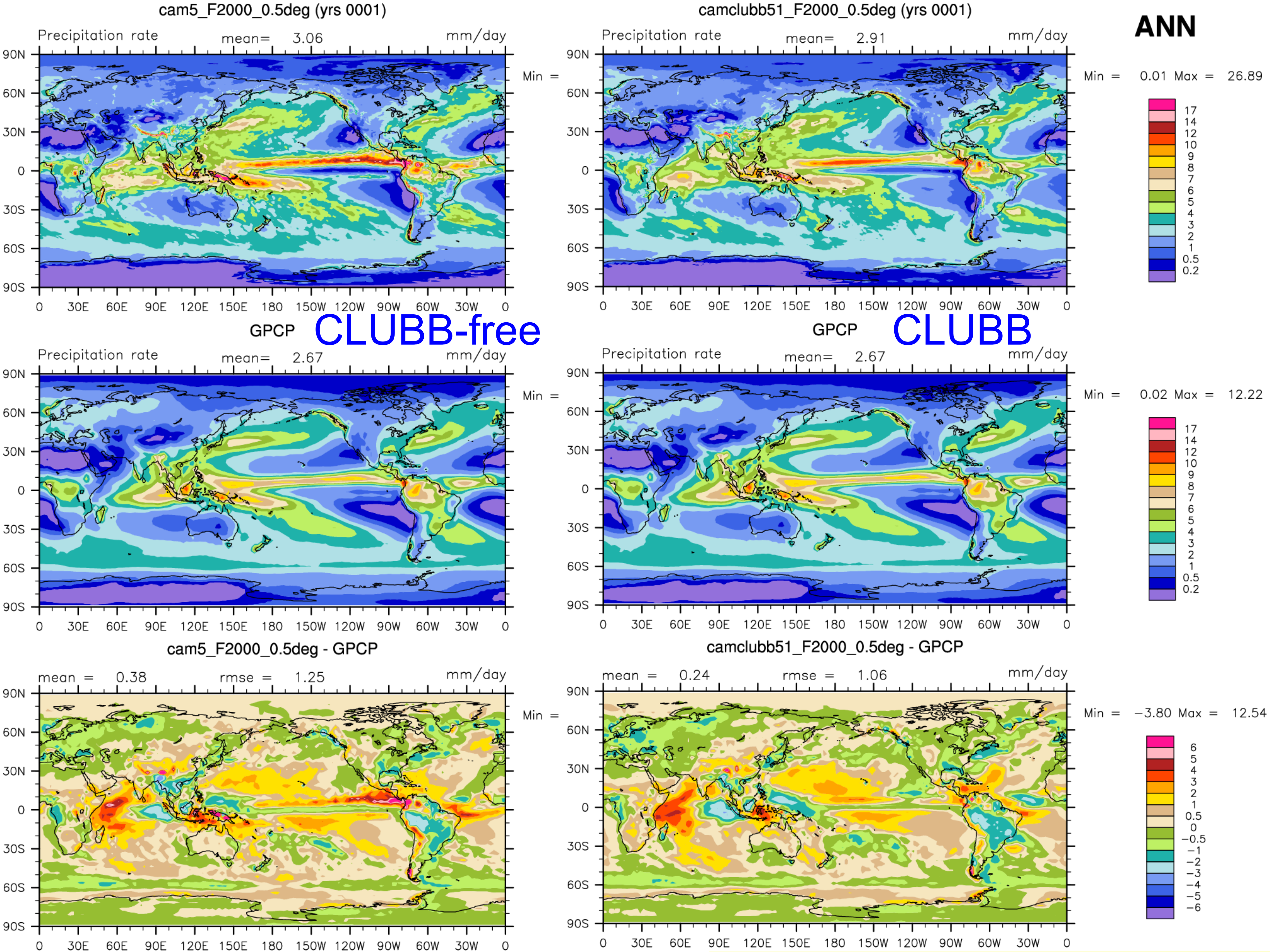
However, CAM-CLUBB has less error in the clouds at 60 degrees south.

Plots are courtesy of Pete Bogenschutz



ANN
cam5_F2000_0.5deg (yrs 0001)
TOA SW cloud forcing mean= −47.64 W/m²
camclubb51_F2000_0.5deg (yrs 0001)
TOA SW cloud forcing mean= −48.50 W/m²
Min = −154.81 Max = −0.23
CERES-EBAF
CLUBB-free
TOA SW cloud forcing mean= −47.07 W/m²
CERES-EBAF
CLUBB
TOA SW cloud forcing mean= −47.07 W/m²
Min = −123.32 Max = 32.83
cam5_F2000_0.5deg - CERES-EBAF
mean = −0.57 rmse = 12.83 W/m²
camclubb51_F2000_0.5deg - CERES-EBAF
mean = −1.43 rmse = 12.07 W/m²
Min = −74.84 Max = 59.80
Min =
45 30 15 0 −15 −30 −45 −60 −75 −90 −105 −120 −135 −150 −170
80 60 50 40 30 20 10 0 −10 −20 −30 −40 −50 −60 −80
90N 60N 30N 0 30S 60S 90S
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0


cam5_F2000_0.5deg (yrs 0001)
camclubb51_F2000_0.5deg (yrs 0001)
ANN
TOA LW cloud forcing
mean= 20.86
W/m²
mean= 21.31
Min = −0.93 Max = 76.00
CERES-EBAF
CLUBB-free
CLUBB
mean= 26.48
Min = −5.30 Max = 74.50
cam5_F2000_0.5deg - CERES-EBAF
camclubb51_F2000_0.5deg - CERES-EBAF
mean = −5.62
rmse = 7.91
mean = −5.17
rmse = 7.66
Min = −48.42 Max = 29.58


cam5_F2000_0.5deg (yrs 0001)
Precipitation rate mean= 3.06 mm/day
camclubb51_F2000_0.5deg (yrs 0001)
Precipitation rate mean= 2.91 mm/day
ANN
Min = 0.01 Max = 26.89
GPCP
CLUBB-free
Precipitation rate mean= 2.67 mm/day
GPCP
CLUBB
Precipitation rate mean= 2.67 mm/day
Min = 0.02 Max = 12.22
cam5_F2000_0.5deg - GPCP
mean = 0.38 rmse = 1.25 mm/day
camclubb51_F2000_0.5deg - GPCP
mean = 0.24 rmse = 1.06 mm/day
Min = −3.80 Max = 12.54
17 14 12 10 9 8 7 6 5 4 3 2 1 0.5 0.2
6 5 4 3 2 1 0.5 0 −0.5 −1 −2 −3 −4 −5 −6
90N 60N 30N 0 30S 60S 90S
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0

Conclusions

- Results from single-column simulations do not always translate to global simulations.

- Present-day GCMs fail to include the correlation of cloud water and rain water. This omission probably diminishes the simulated precipitation formation rate.

- AM3-CLUBB and CAM-CLUBB are almost competitive with their default counterparts, AM3 and CAM5.

Thanks for your hospitality!