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A Sensitivity Study of cloud properties to CLUBB Parameters in the Single Column Community Atmosphere Model (SCAM5)

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Applying Uncertainty Quantification (UQ) approach to CAM5_CLUBB

- Uncertainty Quantification (UQ) provides a way to systematically while efficiently examine the parameter sensitivity in a complex system
- UQ has been demonstrated to be a useful tool for advancing climate modeling. Several examples from PNNL:
  - Model Calibration and Optimization:
    - *Yang, Qian et al., 2012; Yan, Qian et al., 2013* (WRF, deep convection);
    - *Yang, Qian et al., 2013* (CAM5, stratiform-convection precipitation partition)
  - Quantifying parameter uncertainty and sensitivity:
    - *Zhao et al., 2013* (CAM5, radiation flux);
    - Wan et al., *2015* (CAM5, short ensembles vs. long term climate simulation);
    - *Qian et al., 2014* (CAM5, precipitation including extremes and diurnal cycle)
  - Determining source-receptor relationship
    - *Ma et al., 2013* (CAM5, black carbon)
- Applying UQ to CAM5_CLUBB
  - Quantifying the parameter uncertainty and sensitivity

Methodology

- Model: Single-column version of CAM5.3 with CLUBB
- Sampling approach: Quasi-Monte Carlo

	Regime type	Vertical level	QMC Samples	Time Period
BOMEX (Barbados Oceanographic and Meteorological Experiment)	Maritime shallow cumulus	30 240	P16:*256* P29:*1024* P35:*2048*	5~6hr
DYCOMS-II RF01 (Dynamics and Chemistry of Stratocumulus)	Maritime Stratocumulus	30 240	P16:*256* P29:*1024* P35:*2048*	3~4hr
RICO (Rain in Cumulus Over Ocean)	Precipitating marine shallow cumulus	30 240	P16:*256* P29:*1024* P35:*2048*	5~6hr

- Emulator: a Generalized linear model (GLM) is constructed to determine how individual parameters contribute to the total variance of simulated model fields

Performance metric (Taylor, 2001; Yang et al., 2013)

$$score = \log\left[\frac{\left(\frac{\sigma_{LES}}{\sigma_{mod}} + \frac{\sigma_{mod}}{\sigma_{LES}}\right)^2 (1 + R_0)^k}{(1 + R)^k}\right]$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

$$R = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_{modi} - \overline{x_{mod}})(y_{LESi} - \overline{y_{LES}})}{\sigma_{mod}\sigma_{LES}}$$

σ is the spatial standard deviation,

N is total number of vertical grid point,

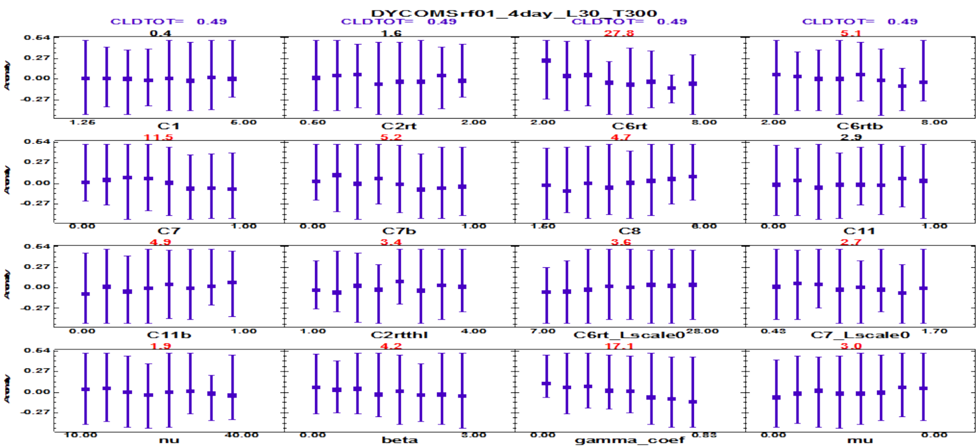
i represents individual grid point,

R is the correlation coefficient between single-column (mod) and LES.

R0 =1 maximum possible spatial correlation coefficient

k=4 control the relative weight of spatial correlation

Stratocumulus case (DYCOMSII_RF01): cloud fraction in L30



- Parameters related to the total water flux equation is the most effective ones.
- C6rt (27.8%), C7 (11.5%) contribute the most to cloud fraction variance

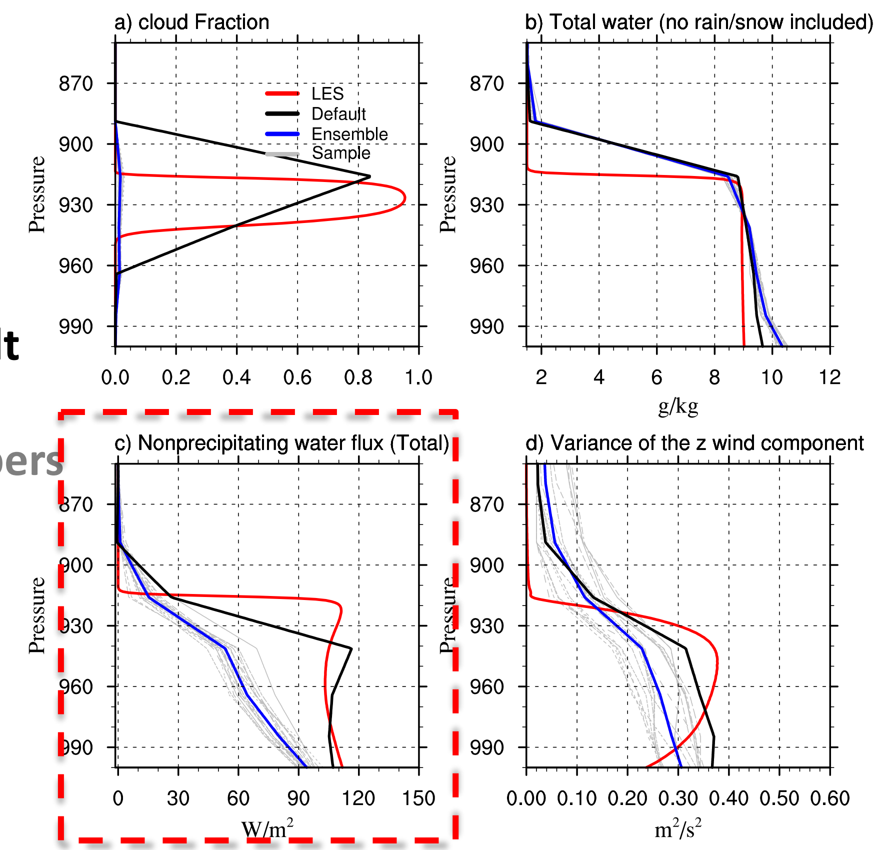
Total water flux Eq.

$$\frac{\partial \overline{w'q_t'}}{\partial t} = -\bar{w}\frac{\partial \overline{w'q_t'}}{\partial z} - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2 q_t'}}{\partial z} - \overline{w'^2}\frac{\partial \bar{q}_t}{\partial z} - \overline{w'q_t'}\frac{\partial \bar{w}}{\partial z} + \frac{g}{\theta_{vs}}\overline{q_t'\theta_v'} - \frac{C_6}{\tau}\overline{w'q_t'} + C_7\overline{w'q_t'}\frac{\partial \bar{w}}{\partial z} - C_7\frac{g}{\theta_{vs}}\overline{q_t'\theta_v'} + \frac{\partial\left[(K_w+\nu)\frac{\partial \overline{w'q_t'}}{\partial z}\right]}{\partial z} + \left.\frac{\partial \overline{w'q_t'}}{\partial t}\right|_{sicl} + \left.\frac{\partial \overline{w'q_t'}}{\partial t}\right|_{cl} + \left.\frac{\partial \overline{w'q_t'}}{\partial t}\right|_{mfl}$$

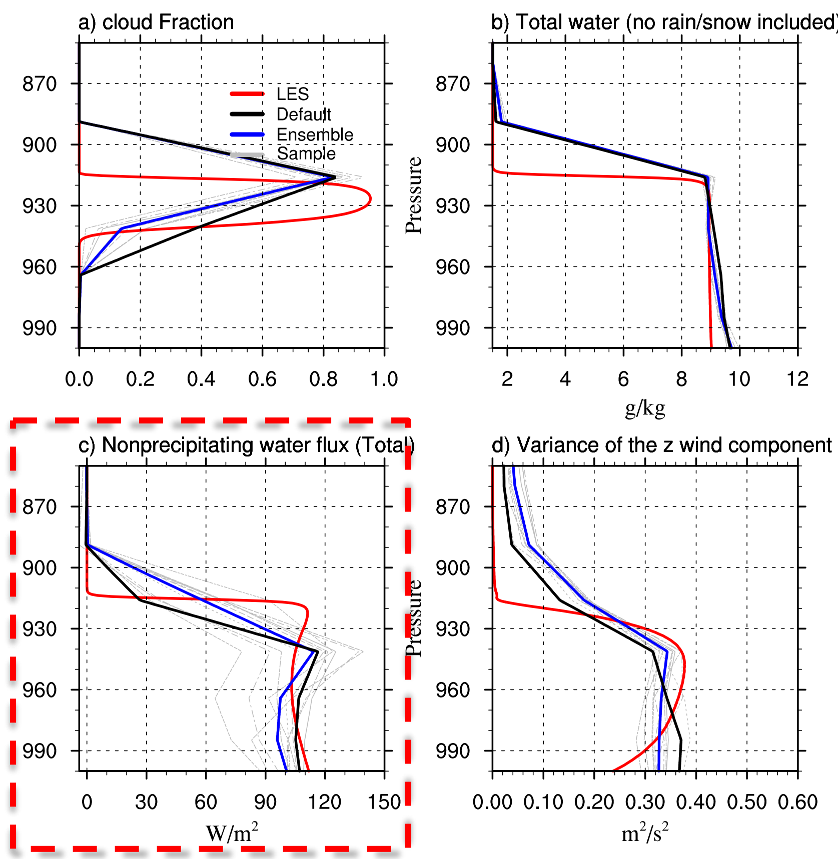
Stratocumulus case: Why C6, C7 are effective

LES
Default
Mean
Members

Top 10 worst members

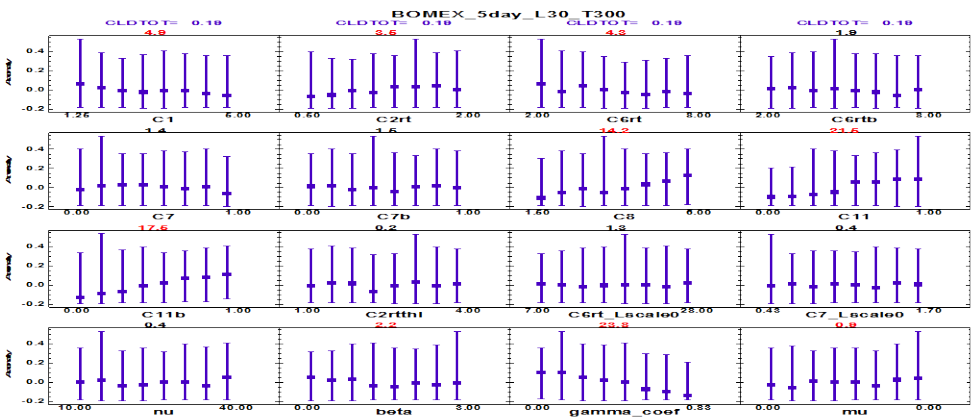


Top 10 best members



- Total water flux is critical for stratocumulus cloud simulations

Shallow cumulus case (BOMEX): Cloud Fraction



- Parameters related to skewness of vertical velocity are critical
- γ (23.8%), C11 (21.5%), C11b (17.5%) and C8 (14.2%) contribute the most to cloud fraction variance

w'^{3} Eq.

$$
\begin{aligned}
\frac{\partial \overline{w'^3}}{\partial t} = & -\bar{w}\frac{\partial \overline{w'^3}}{\partial z} - \frac{1}{\rho_s}\frac{\partial \overline{w'^4}}{\partial z} + 3\frac{\overline{w'^3}}{\rho_s}\frac{\partial \rho_s \overline{w'^2}}{\partial z} - 3\overline{w'^3}\frac{\partial \bar{w}}{\partial z} + \frac{3g}{\theta_{vs}}\overline{w'^2\theta_v'} \\
& + C_{15}K_m\left(\frac{g}{\theta_{vs}}\frac{\partial \overline{w'\theta_v'}}{\partial z} - \left(\frac{\partial \overline{u'v'}\frac{\partial \bar{u}}{\partial z}}{\partial z} + \frac{\partial \overline{u'v'}\frac{\partial \bar{v}}{\partial z}}{\partial z}\right)\right) \\
& - \frac{C_8}{\tau}(-3C_{8b}Skw^4 + 1)\overline{w'^3} - C_{11}\left(3\overline{w'^3}\frac{\partial \bar{w}}{\partial z} + \frac{3g}{\theta_{vs}}\overline{w'^2\theta_v'}\right) \\
& + \frac{\partial\left[(\mathrm{K_w} + \nu)\frac{\partial \overline{\mathrm{w'^3}}}{\partial \mathrm{z}}\right]}{\partial \mathrm{z}}
\end{aligned}
$$

Shallow cumulus case: Why *C11, C8 and γ* are effective L30

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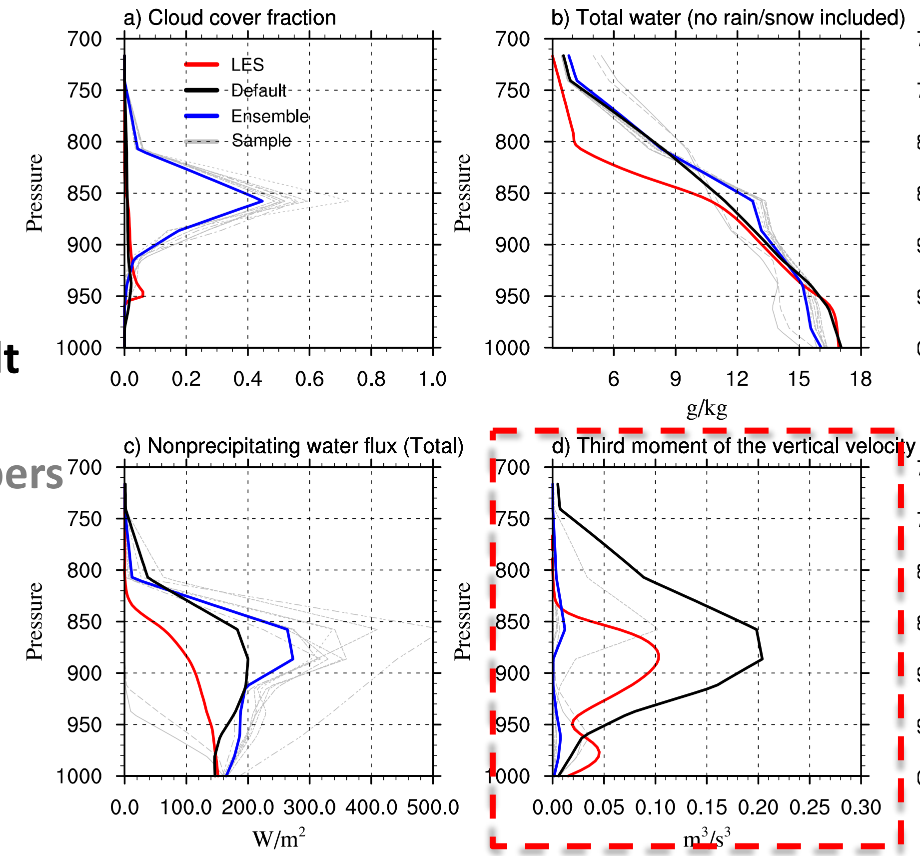
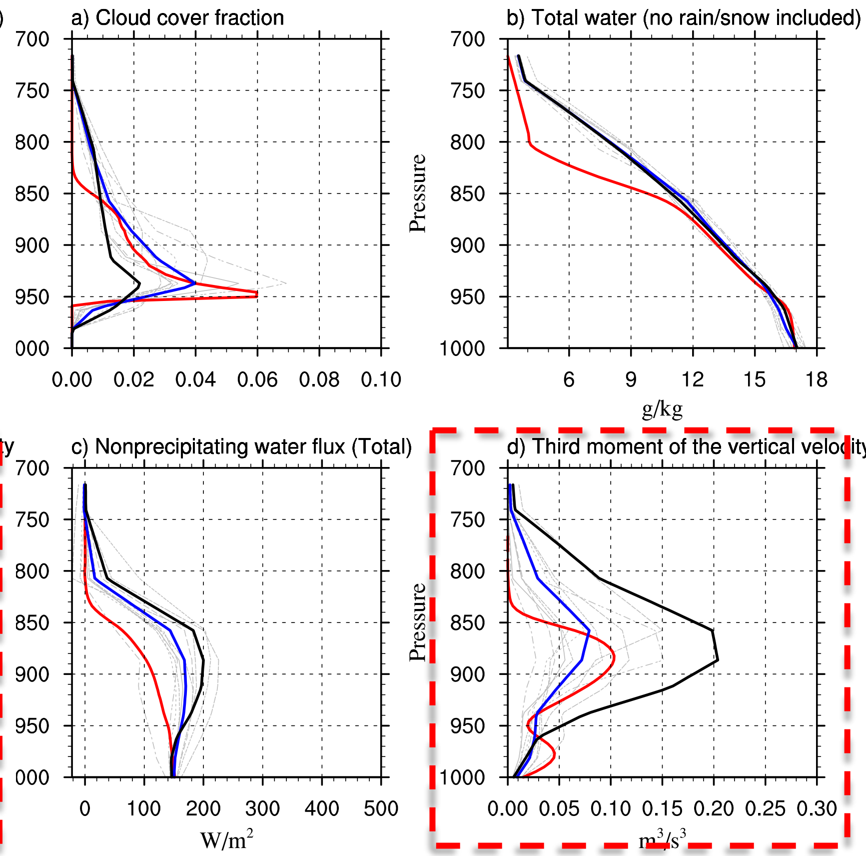
LES
Default
Mean
Members

Top 10 worst members

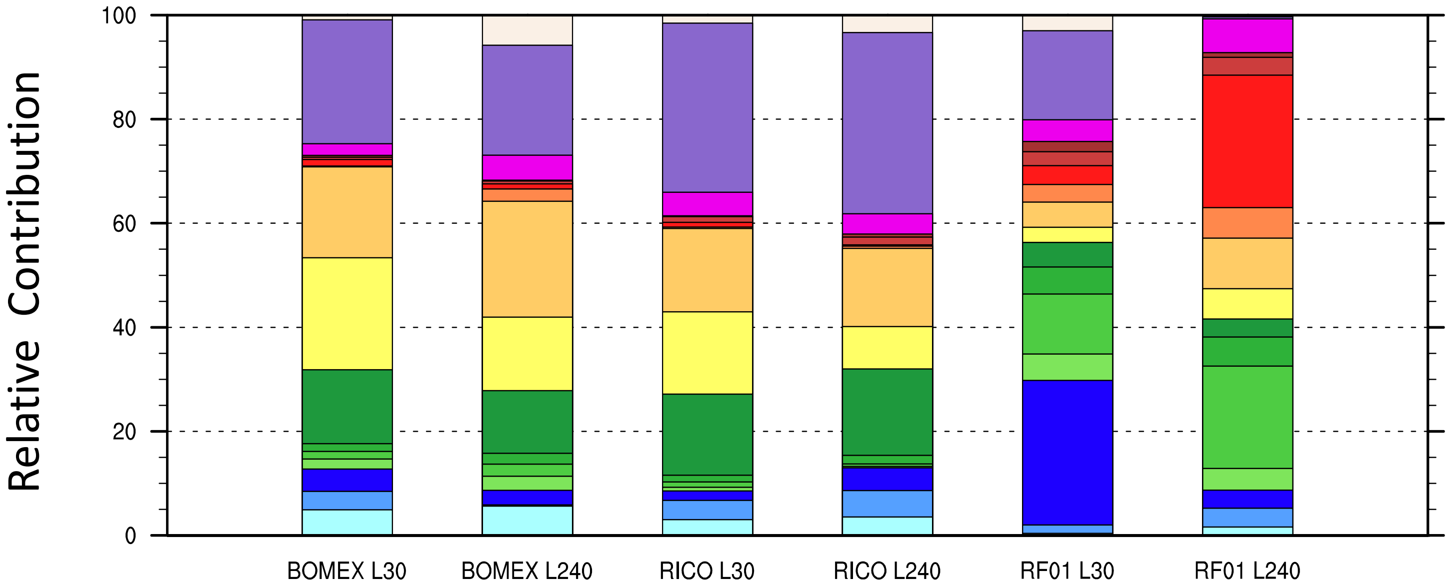


Top 10 best members



- The third-order moment of vertical velocity is critical for shallow convection simulation

Dependence of Vertical Resolution



30 Levels vs. 240 Levels
for BOMEX, RICO and DYCOMS RF01

Best Performance Member

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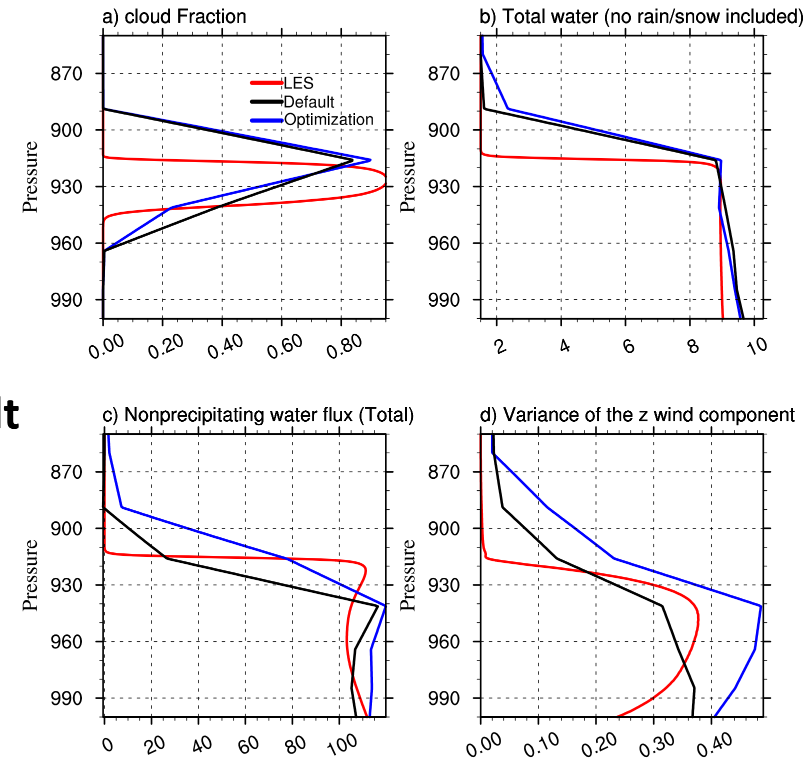
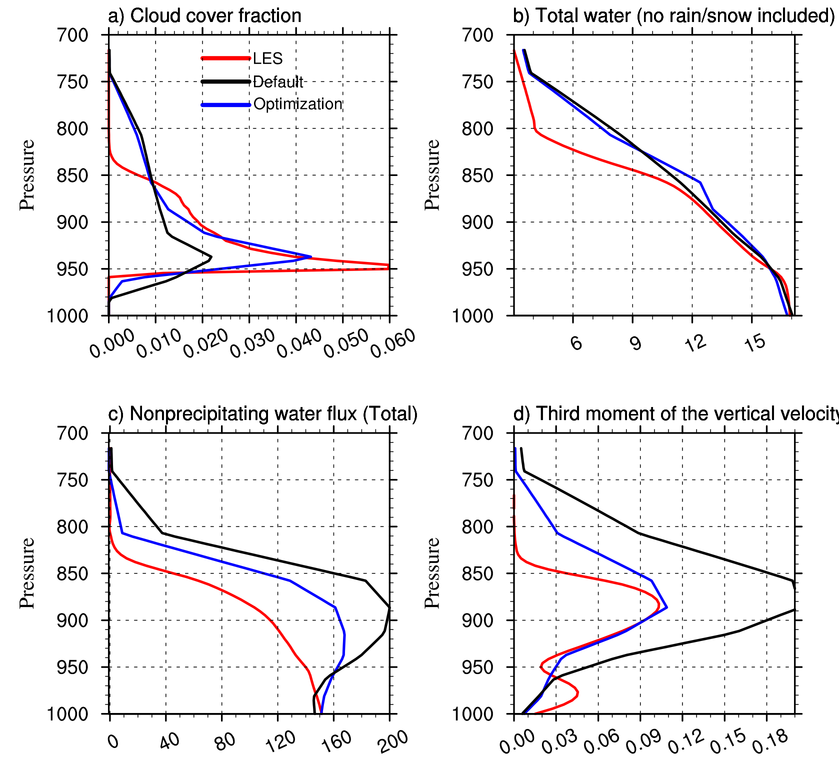
DYCOMS_RF01 (stratocumulus)



BOMEX (shallow convection)



LES
Default
Best

- A set of "best" parameters substantially improve shallow convection simulation for BOMEX (effects are small for DYCOMS_RF01)

Change in Key parameters:

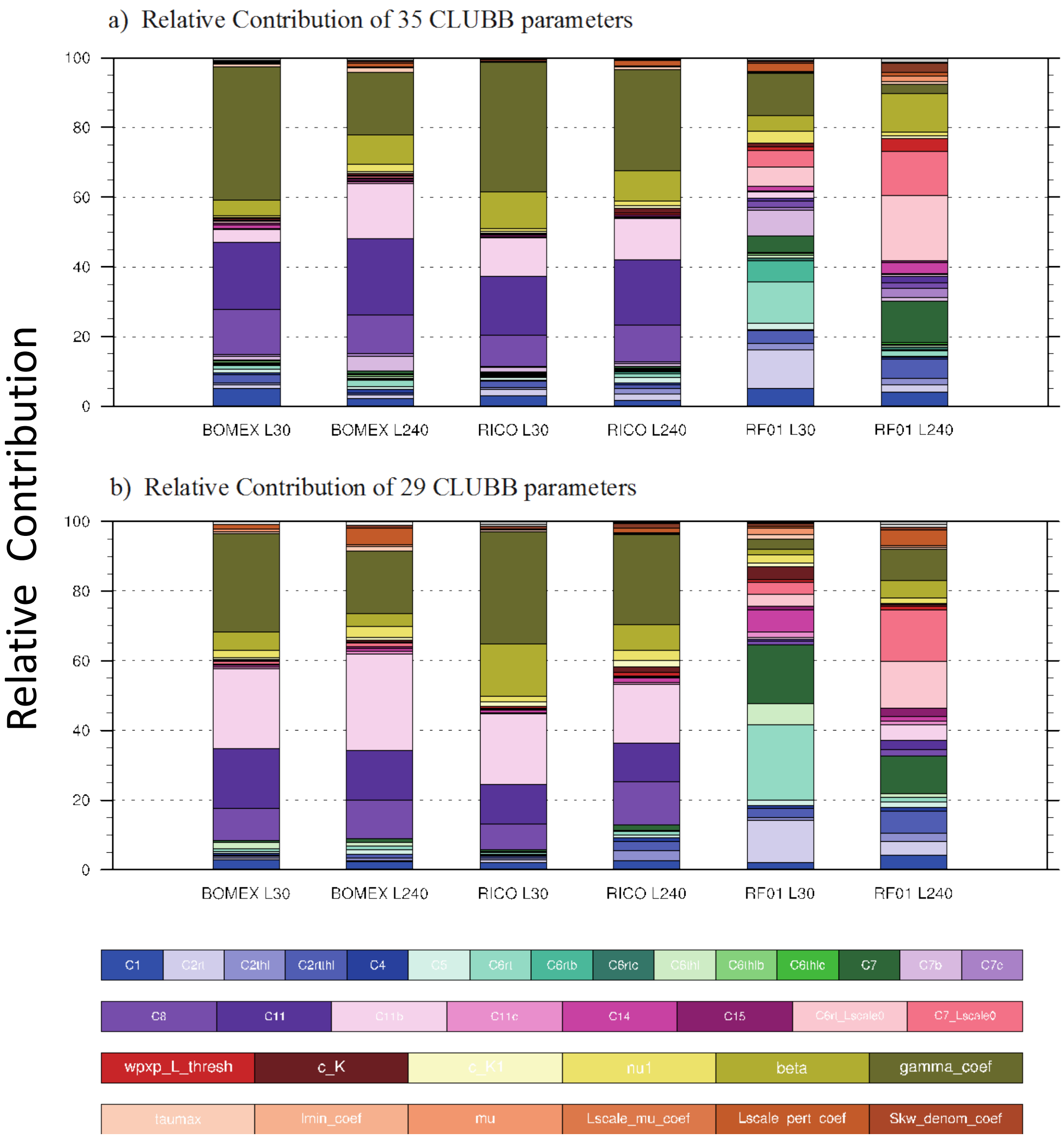
C6rt: 4.00➔ 2.34; C7: 0.50➔ 0.33 ; C6rt_Lscale0: 14.00 ➔ 23.94; C2rt:1.00 ➔ 0.60
γ: 0.32 ➔ 0. 80 ; C11: 0.80 ➔0.65; C11b: 0.35➔ 0.53; C8: 3.00➔ 2.34

Conclusions and Future work

- Only a small number of tunable parameters are needed to explain most of the variance in simulated cloud fields.
- The most effective tunable parameters for stratocumulus clouds are those related to the total water flux equation, while the most effective tunable parameters for shallow convection are those related to the skewness of vertical velocity
- Vertical Resolution has a small impact on the sensitive parameters in shallow convection, but a huge impact in stratocumulus.
- We are currently applying UQ approach to quantify the parameter sensitivity of the global simulations of CAM5 with CLUBB. (ne16np4 & 30 levels & 16 selected parameters)

Thanks

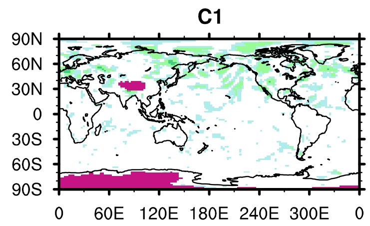
Dependence of Parameters Selection

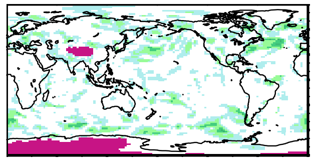


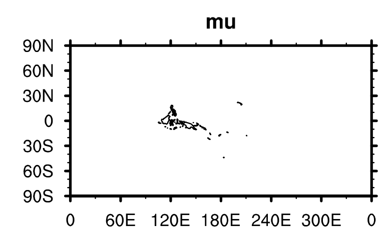
35 Para (2048 members)

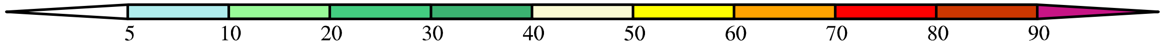
29 Para (1024 members)

Spatial distribution of contribution (Jan)









- γ contribute the most to cloud fraction variance

A unified cloud parameterization has long been the goal of modeling communities

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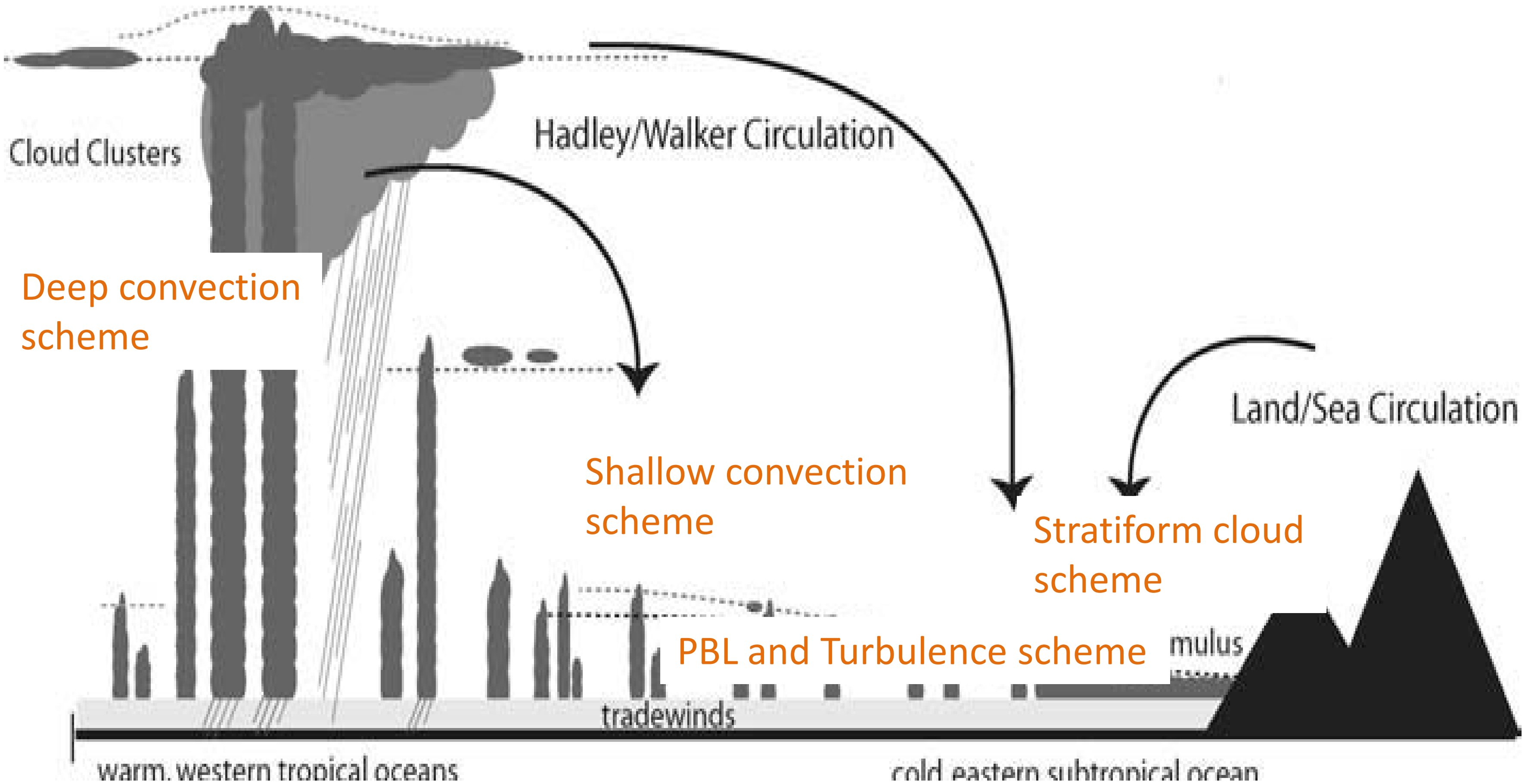


Arawaka, 1975

Methodology

- Model: Single-column version of CAM5.3 with CLUBB (vertical resolution: 30, 240 levels) (*Bogenschutz et al., 2012; 2013*)
- Three cases (Large-eddy simulations are used as benchmark):
  - DYCOMS_RF01: Maritime Stratocumulus
  - BOMEX: Maritime shallow cumulus
  - RICO: precipitating marine shallow cumulus
- Sampling approach: Quasi-Monte Carlo, 2048/1024/256 samples for each ensemble with 35/29/16 tunable CLUBB parameters
- Emulator: a Generalized linear model (GLM) is constructed to determine how individual parameters contribute to the total variance of simulated model fields

Selection of parameters (35/29/16)

Tuning Parameter

0.1

rage calculation of Lscale

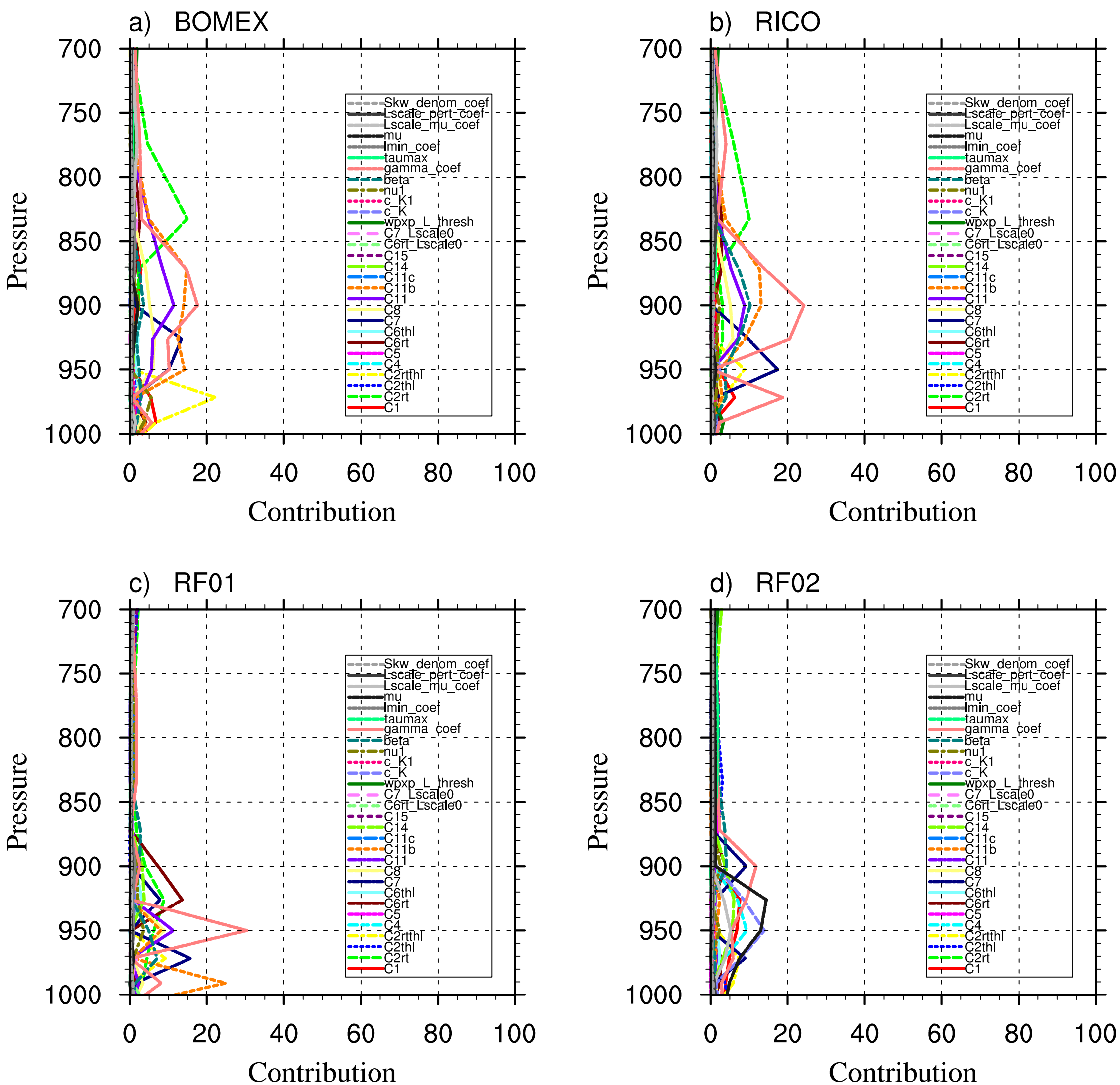
Methodology (Sampling and quantification)

- a generalized linear model (GLM)

where represents the i^{th} realization of the j^{th} parameter; Y_i represents the i^{th} response variable; and represent the coefficients of linear and two-way interaction terms

$$Y^i = \beta_0 + \sum_{j=1}^{n} \beta_j * p_j^i + \sum_{j=1}^{n} \sum_{k=1}^{n} \beta_{j,k} * p_j^i * p_k^i + \varepsilon_i, \qquad \varepsilon_i \overset{iid}{\sim} N(0, \sigma^2)$$

Vertical profile of absolute contribution

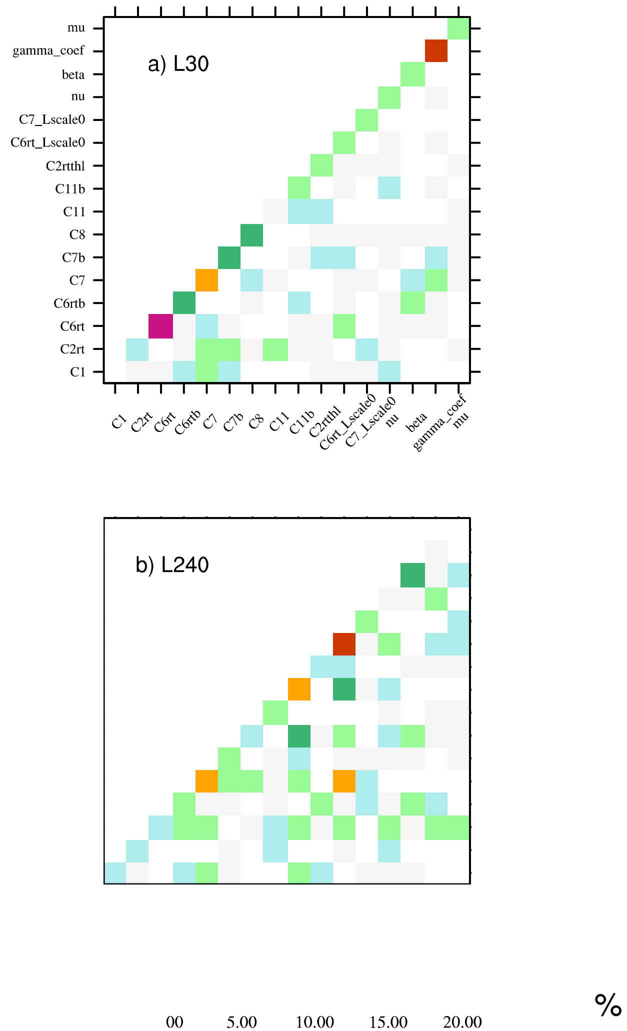


Additional Damping

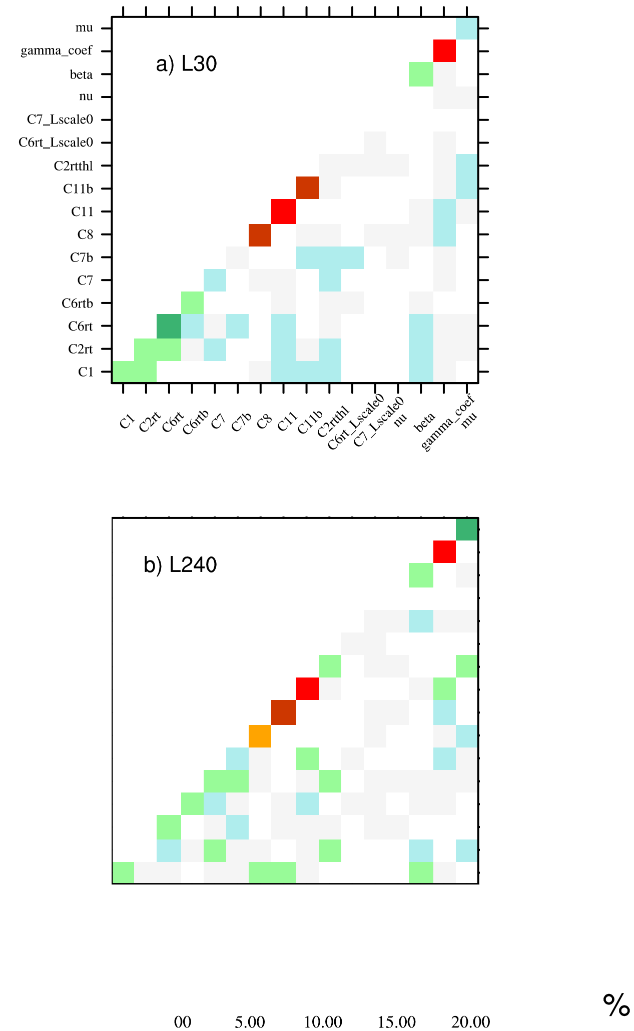
$$C6_{rt}\_skw\_fnc = \begin{cases} C6_{rt}\_Lscale + \dfrac{C6_{rt}\_skw\_fnc - C6_{rt}\_Lscale}{wpxp\_L\_thresh} \times Lscale; & Lscale < wpxp\_L\_thresh \\ C6_{rt}\_skw\_fnc; & \end{cases}$$

Interact Contributions

Stratocumulus

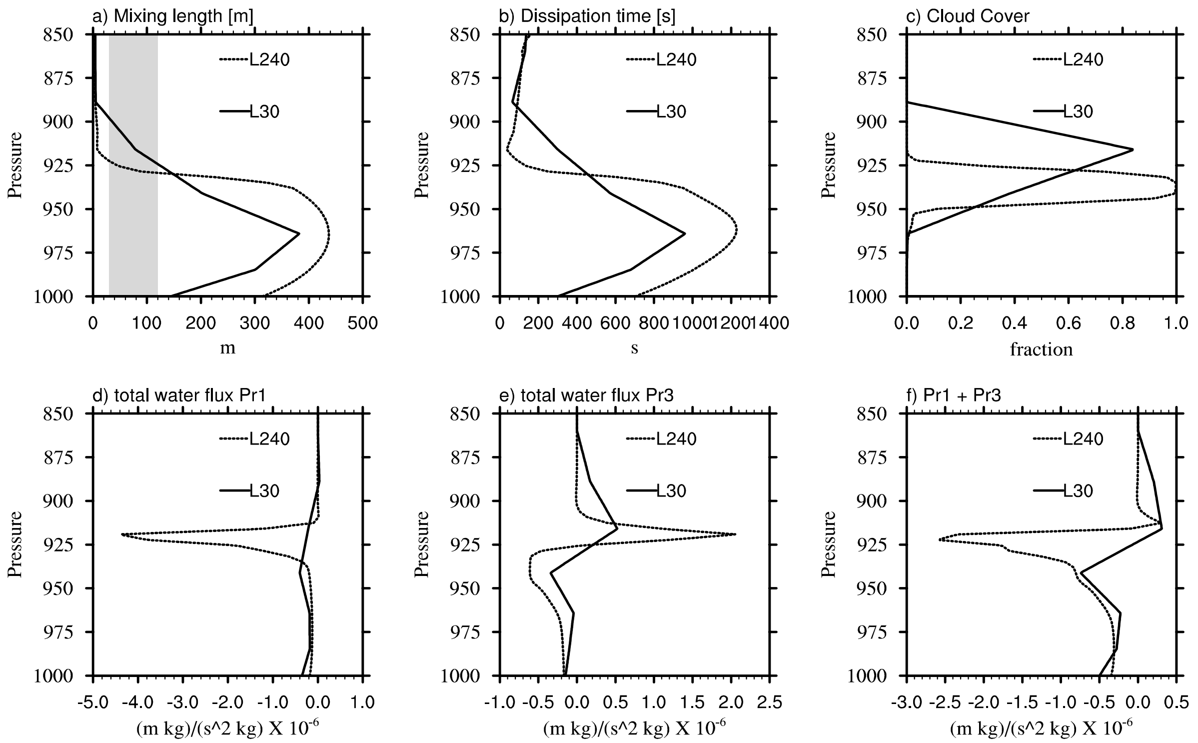


Shallow convection



Dependents on Vertical Resolution

Stratocumulus



eddy mixing length (or dissipation time) plays a more important role in stratocumulus simulations and depends more strongly on the vertical resolution in stratocumulus than in shallow convections

CLUBB provides a potential solution as a unified parameterization

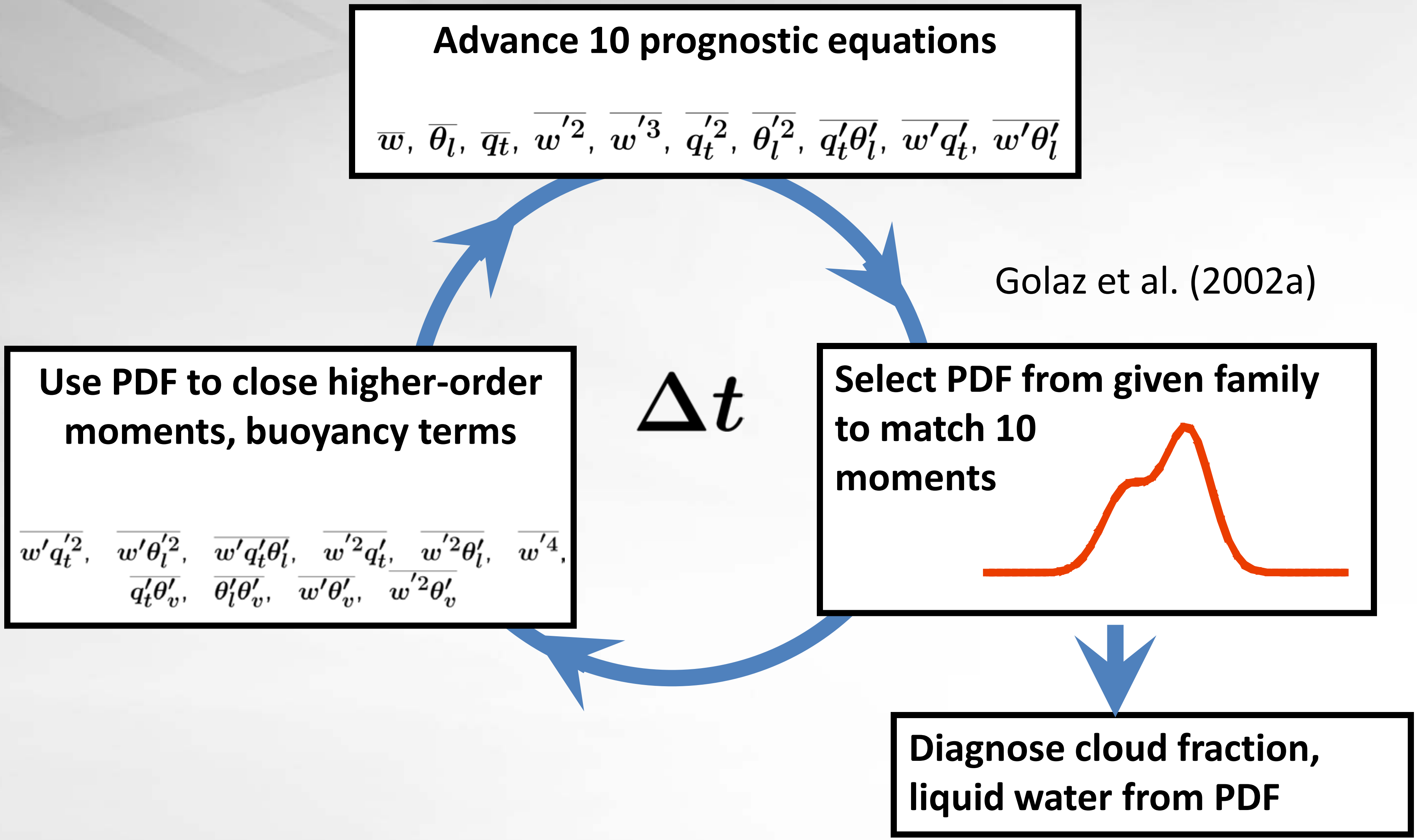
- Cloud Layers Unified By Binomalls (CLUBB): High-order closure, assumed PDF approach

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

w, vertical velocity; q_t, total water mixing ratio; θ_l liquid water potential temperature

- CLUBB has been implemented into NCAR CAM5 and GFDL AM3 to replace their turbulence, shallow convection, and stratiform cloud schemes and has been shown to produces credible global simulations (*Bogenschutz et al., 2013; Guo et al., 2013*)
- Under SciDAC, CLUBB is being extended to deep convection
- Multiple tunable parameters are included in CLUBB's prognostic equations

CLUBB provides a potential solution as a unified parameterization



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