An Updated CLUBB PDF Closure Scheme to Improve Low Cloud Simulation in CAM6

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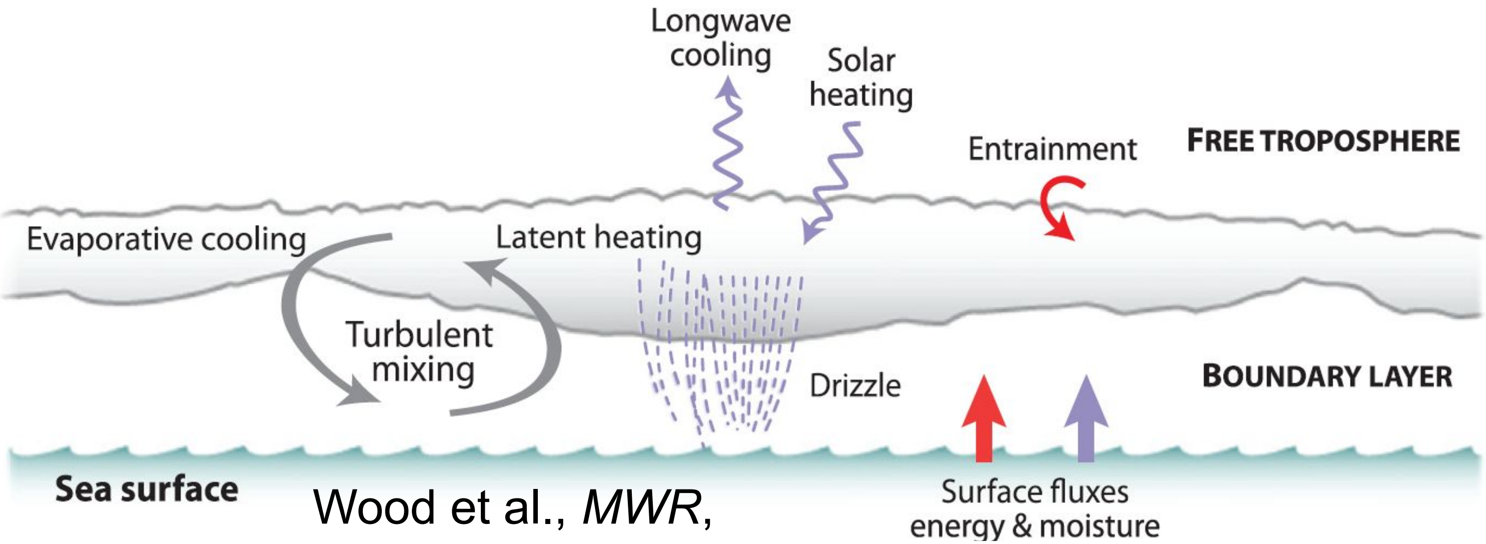
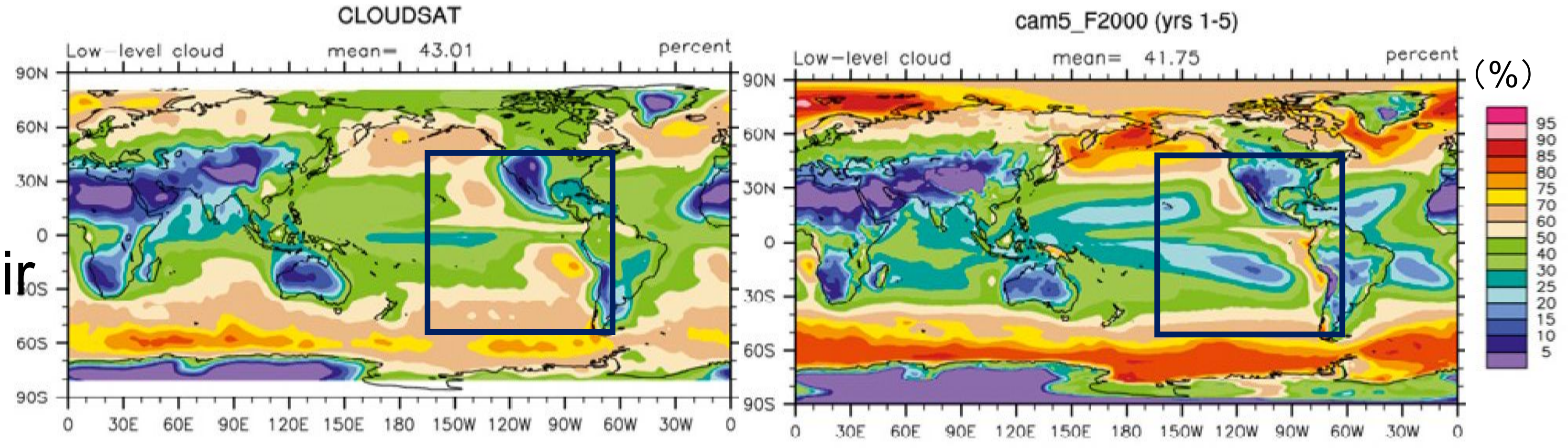
Challenges in marine low cloud simulation

- Low clouds are regarded as the most significant source of uncertainties in cloud feedback and climate sensitivity



Wood et al., *MWR*, 2012

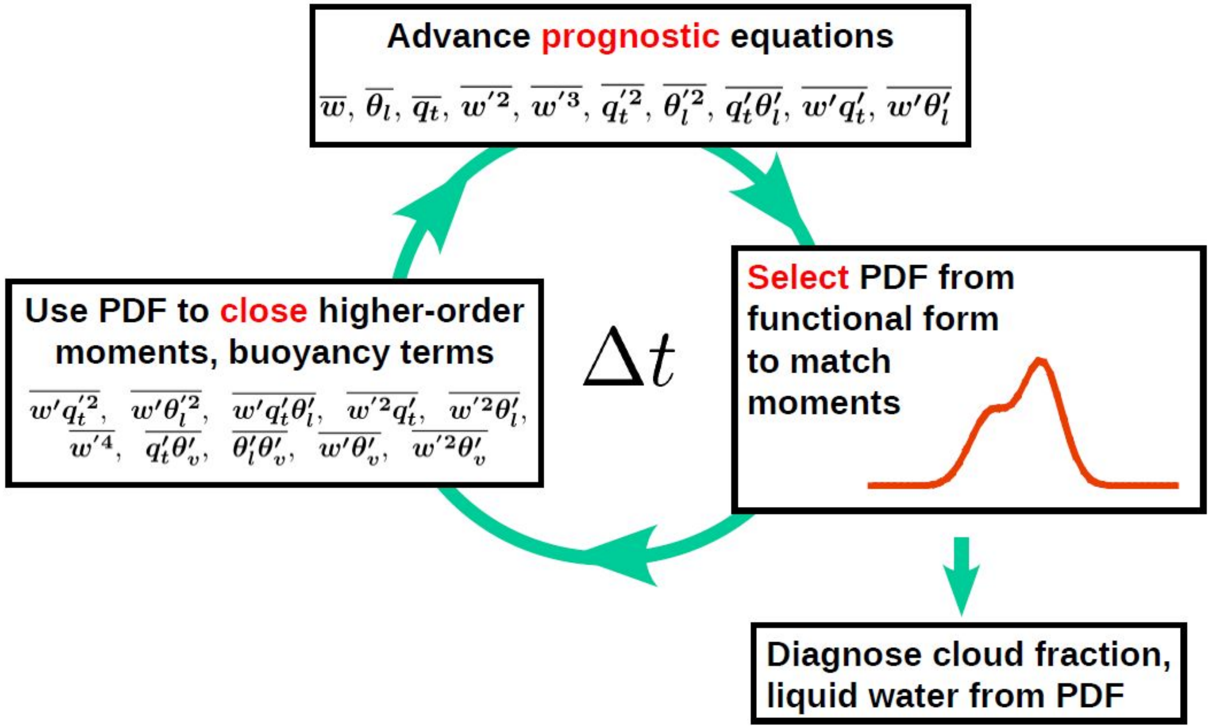
- Low clouds simulation depends on small-scale turbulent processes and their interaction with radiation.



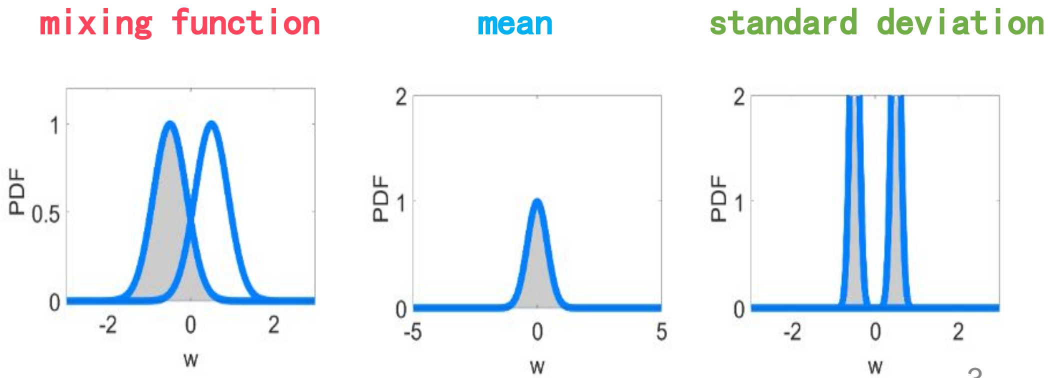
Bogenschutz et al., *JC*, 2013

Cloud Layers Unified by Binormals (CLUBB)

- CLUBB: an assumed PDF, higher-order turbulence closure parameterization.
- Assumed PDF: a double Gaussian functional form of the joint PDF of vertical velocity (w), total water mixing ratio (q_t) and liquid water potential temperature (θ_l)
- A unified treatment of boundary layer turbulence, shallow convection, and cloud macrophysics

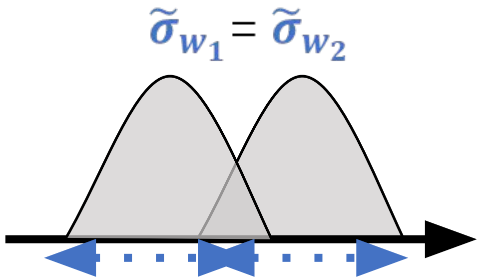


$$P(\widehat{w}, \tilde{q}_t, \tilde{\theta}_l)$$
$$= aG_1(\widehat{w}_1, \tilde{\theta}_{l1}, \tilde{q}_{t1}, \tilde{\sigma}_{w_1}, \tilde{\sigma}_{\theta_{l1}}, \tilde{\sigma}_{q_{t1}})$$
$$+ (1-a)G_2(\widehat{w}_2, \tilde{\theta}_{l2}, \tilde{q}_{t2}, \tilde{\sigma}_{w_2}, \tilde{\sigma}_{\theta_{l2}}, \tilde{\sigma}_{q_{t2}})$$



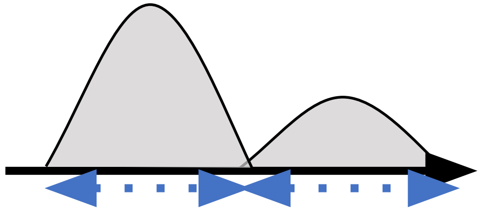
Problems with the default CLUBB PDF closure scheme

- Default PDF closure scheme in CAM6 (Analytic Double Gaussian 1, ADG1): equal width for the two individual Gaussian PDFs of *w* (Larson et al., *JAS*, 2002)



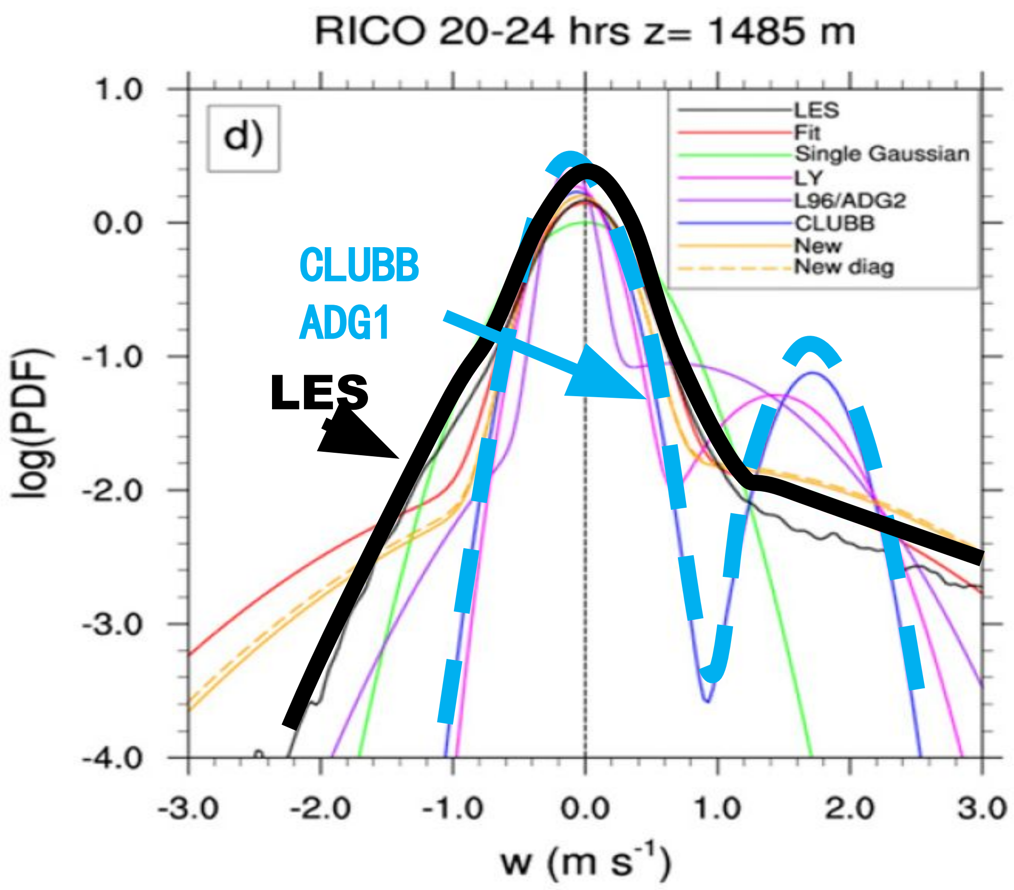
Equal PDF width of vertical velocity

When PDF changes



Limits PDF variability

- ADG1 produces double peaks in *w*-PDF.



Fitch, *JAS*, 2019

Updating the unequal width PDF closure scheme

Unequal width of w (Fitch, *JAS*, 2019)

$$\tilde{\sigma}_{w_1} = \begin{cases} 1 & if\ |K-3| < 0.5 \\ 1.26|K-3|^{0.28} & if\ |K-3| \geq 0.5 \end{cases}$$

$$\tilde{\sigma}_{w_2} = 1 - \frac{0.4|Sk_w|}{\sqrt{0.3 + {Sk_w}^2}}$$

- The relationship between kurtosis (K) and skewness (Sk_w)

$$K = \begin{cases} 1.48{Sk_w}^2 + 3\ , if\ Sk_w < 1.4 \\ 3.84{Sk_w}^2 + 3\ , \quad if\ Sk_w \geq 1.4 \end{cases} \qquad K = \frac{\overline{w'^4}}{\overline{w'^2}^2}$$

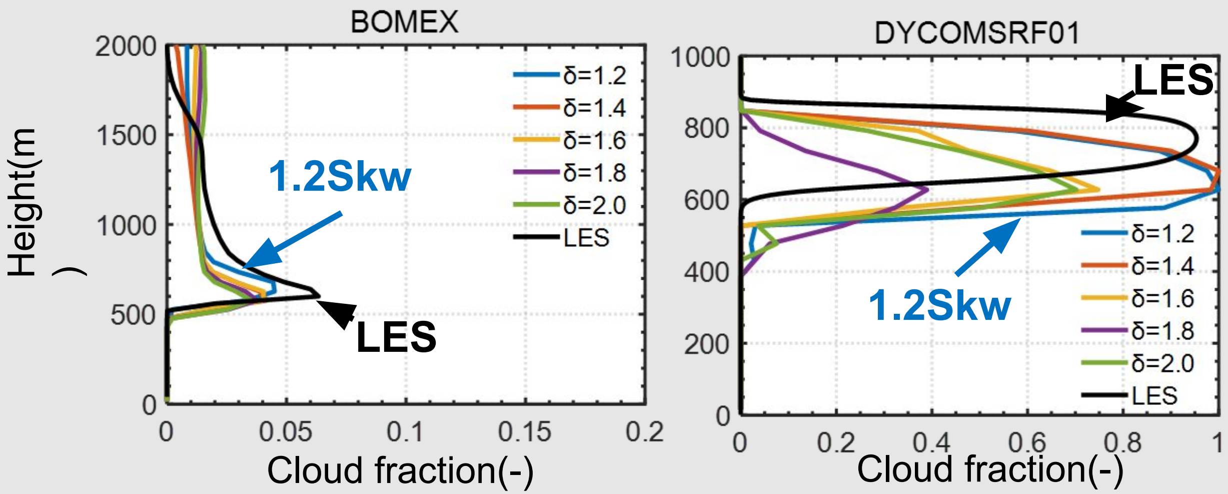
Updating q_t and θ_l width

- The first Gaussian PDF widths are modified to match w width modification

$$\sigma_{r_{t1}}^2 = \frac{\alpha_{r_t}}{a r_t'^2} w f_1 \times 1.2Skw$$

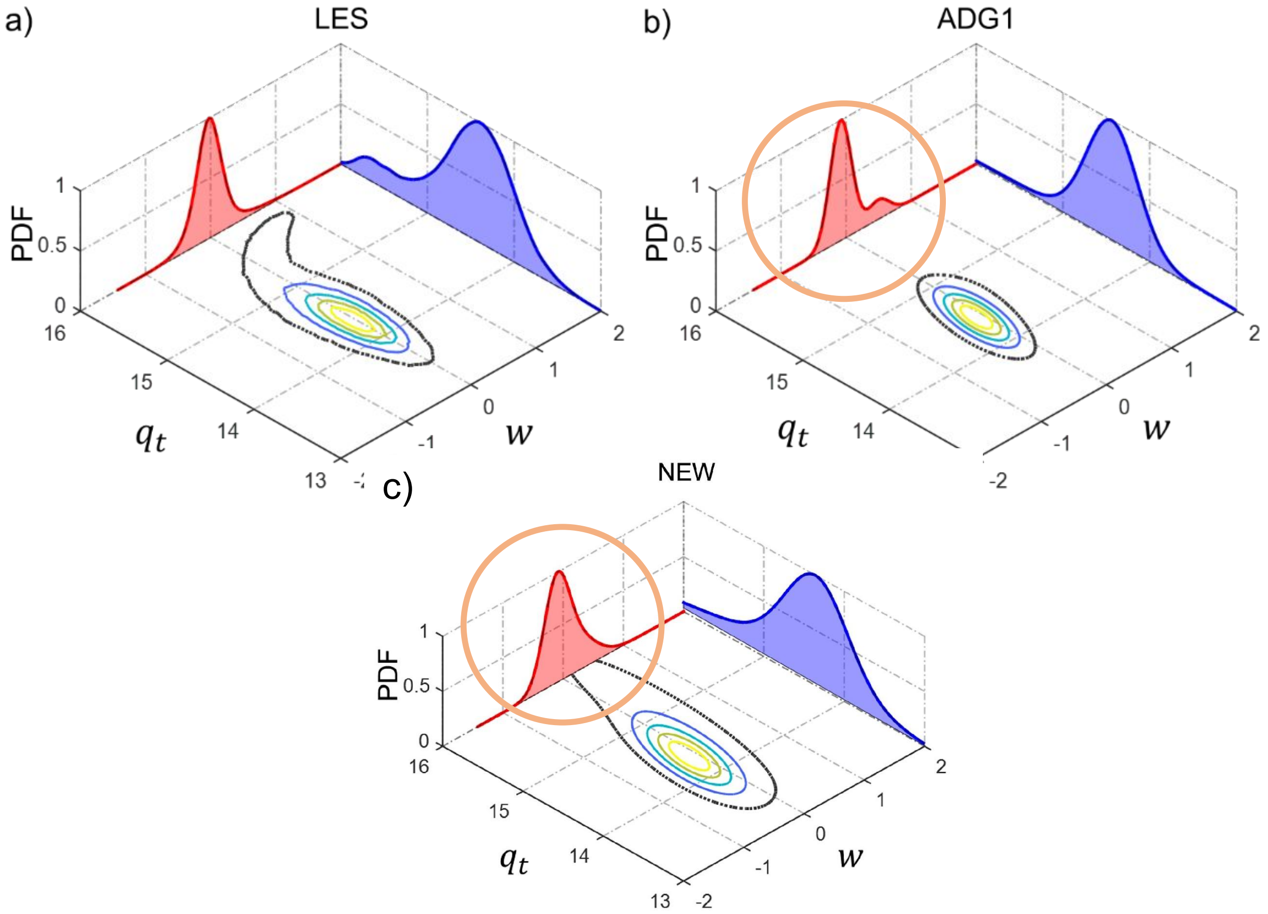
$$\sigma_{\theta_{l1}}^2 = \frac{\alpha_{\theta_l}}{a \theta_l'^2} w f_1 \times 1.2Skw$$

Single column simulations

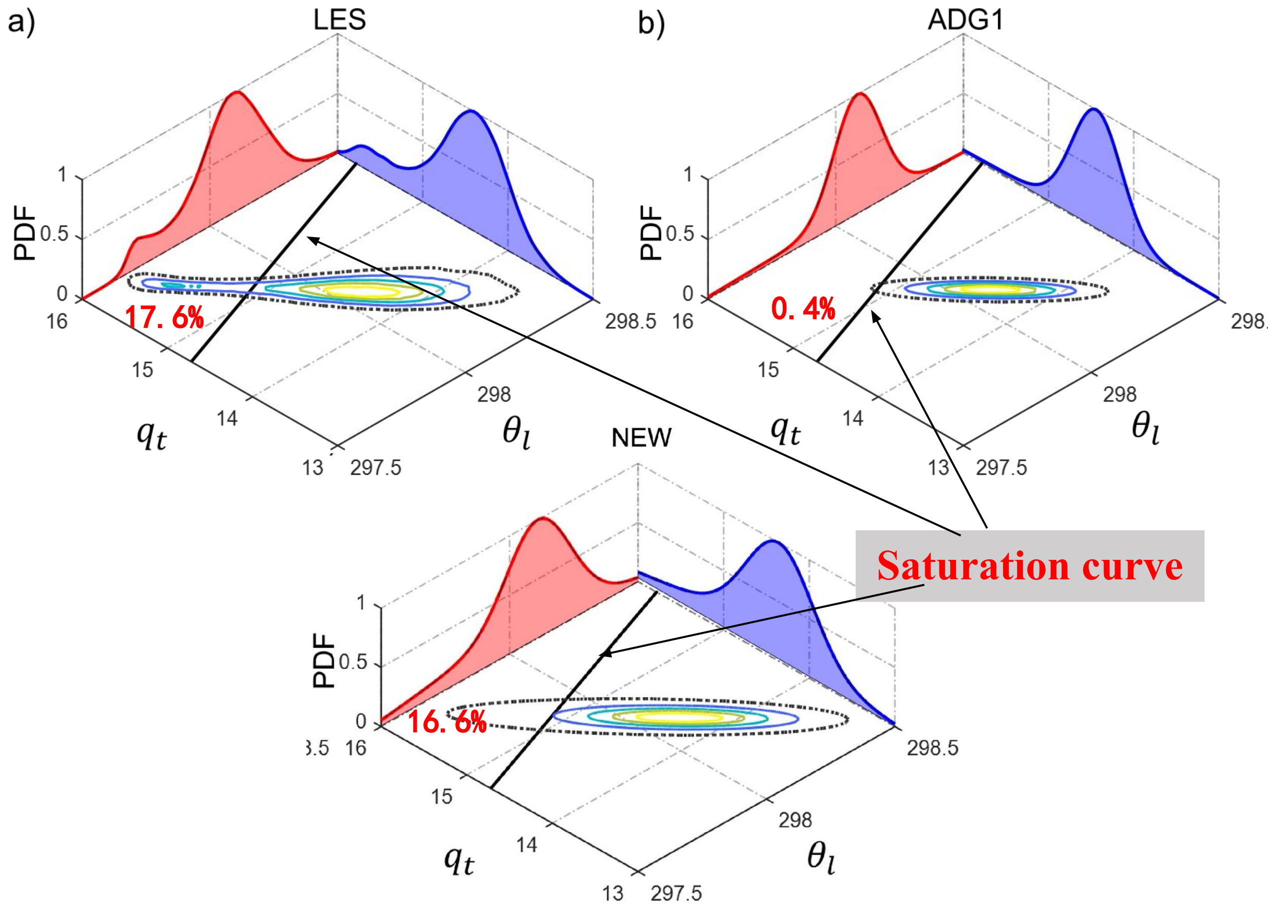


Evaluating the new PDF closure scheme

- NEW agrees better with the LES in simulating the *w*-PDF distribution, and the saturation area



w-q_t joint distribution



θ_l-q_t joint distribution

CAM6 AMIP experiment

- The 6-year experiments are performed, the last 5-year results are analyzed
- Prescribed climatological SST and sea ice were used in these experiments

ADG1 — CLUBB default equal width PDF closure scheme

NEW — New unequal width PDF closure scheme

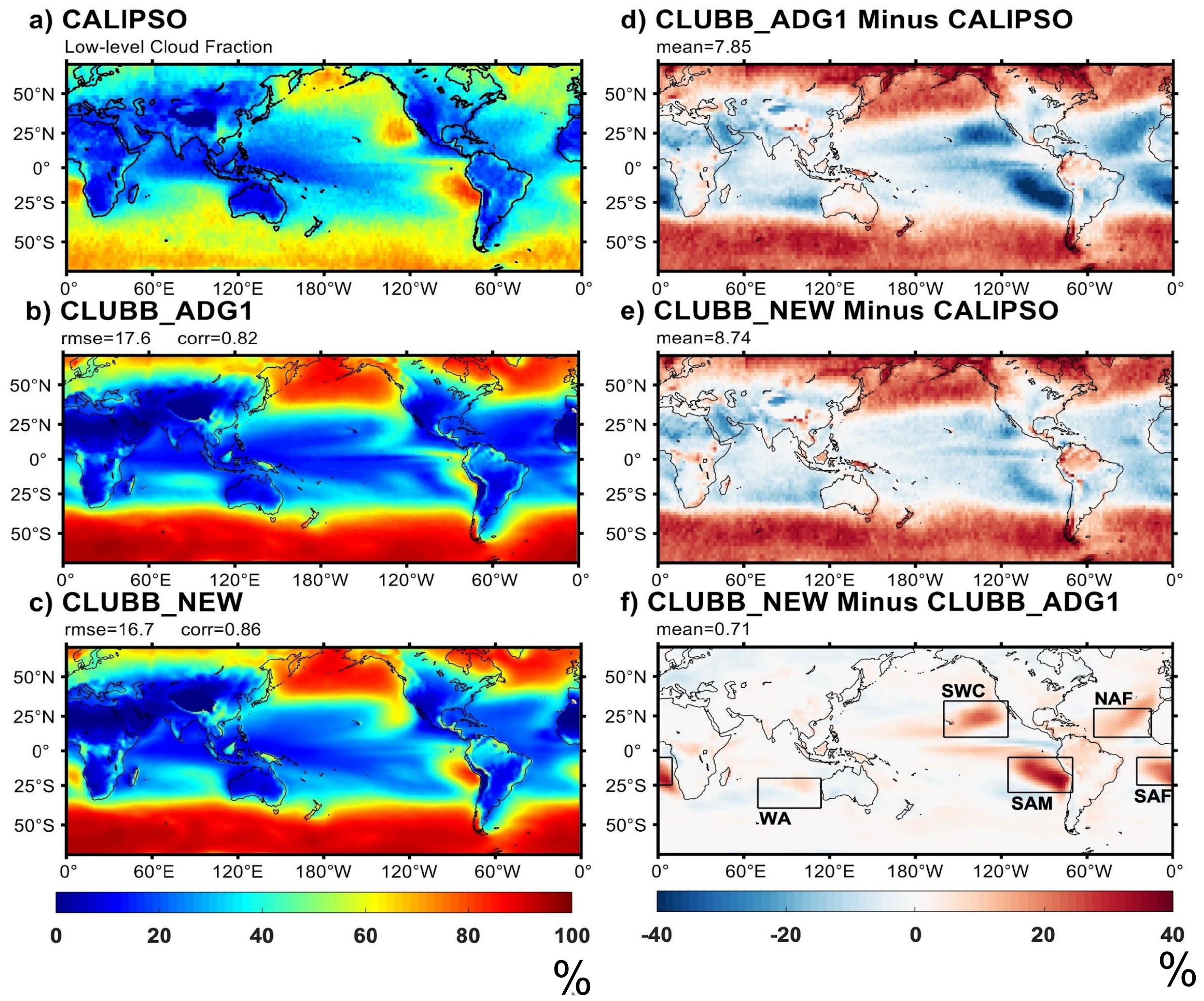
Group	Name	Resolution	SST setting
Present day	ADG1	0.9°*1.25°, 32 lev	AMIP
	NEW	0.9°*1.25°, 32 lev	AMIP
SST+4K	ADG1+4k	0.9°*1.25°, 32lev	AMIP+4k
	NEW+4k	0.9°*1.25°, 32lev	AMIP+4k

➪ Low cloud fraction

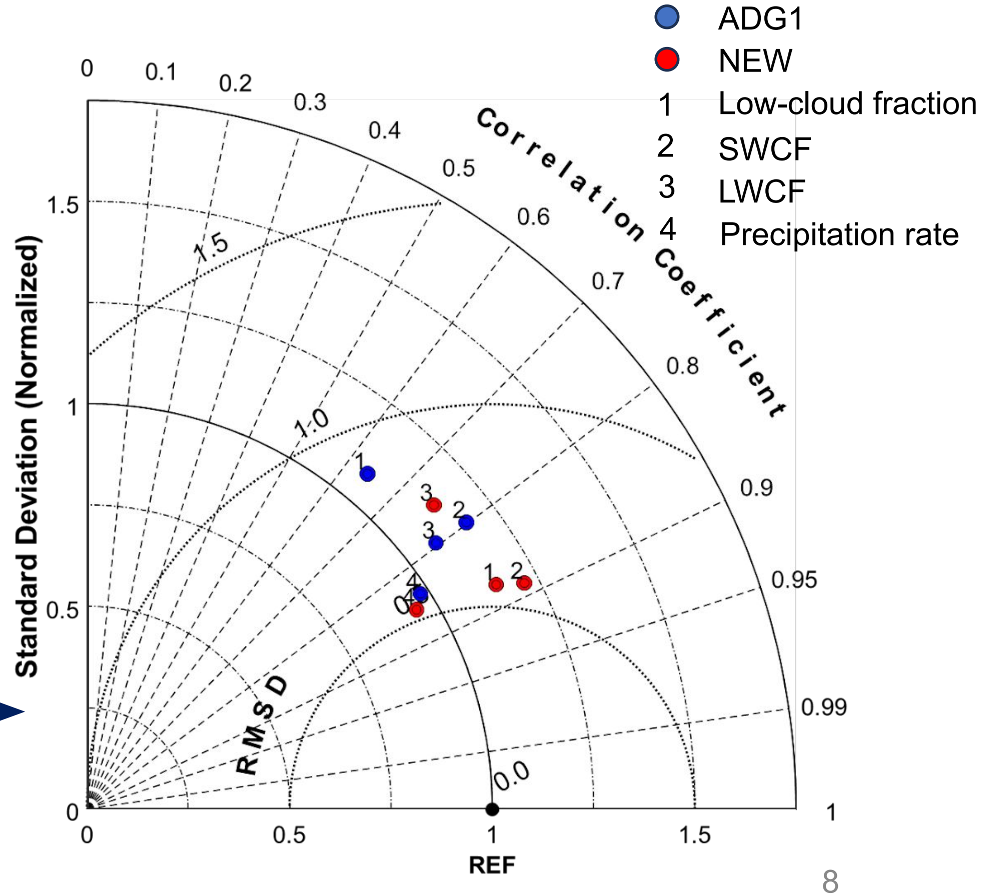
➪ cloud feedback

Improvement in the low cloud simulation

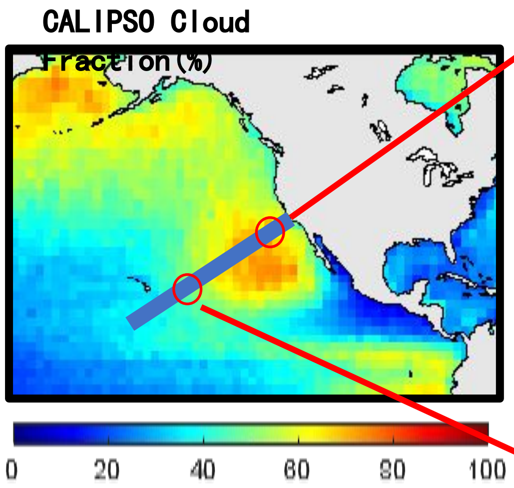
- The new PDF closure scheme improves low cloud fraction by 20~30% in most stratocumulus-to-cumulus transition regions.



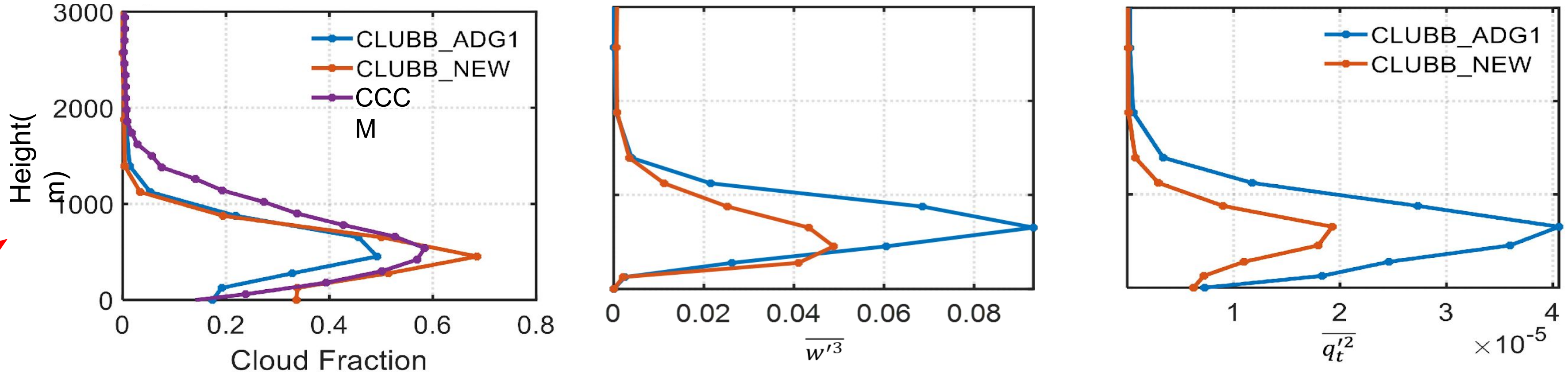
Five Sc-Cu Regions



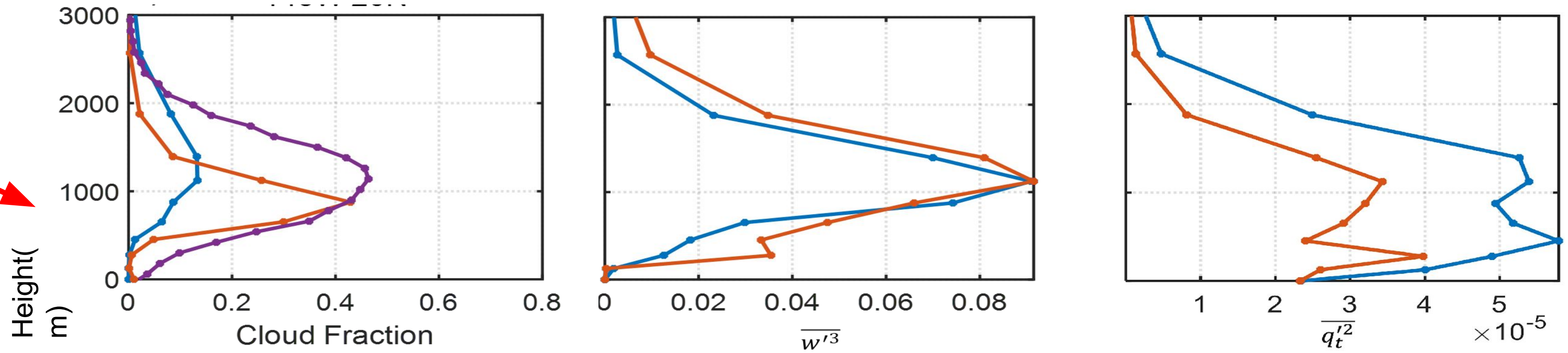
Changes in the turbulence statistics moment



Stratocumulus (128W, 32N)



Shallow cumulus (145W, 20N)



Li T. et al., *JAMES*, 2023

Straocumulus: smaller $\overline{w'^3}$

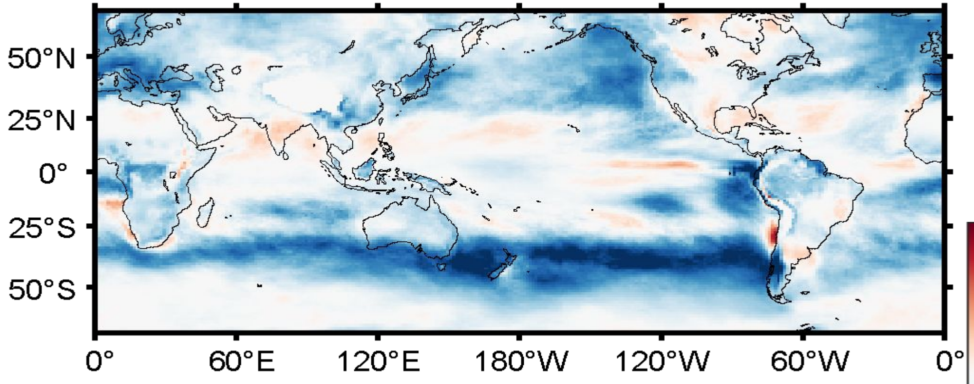
Shallow cumulus: larger $\overline{w'^2}$

Both cloud types: smaller $\overline{q_t'^2}$

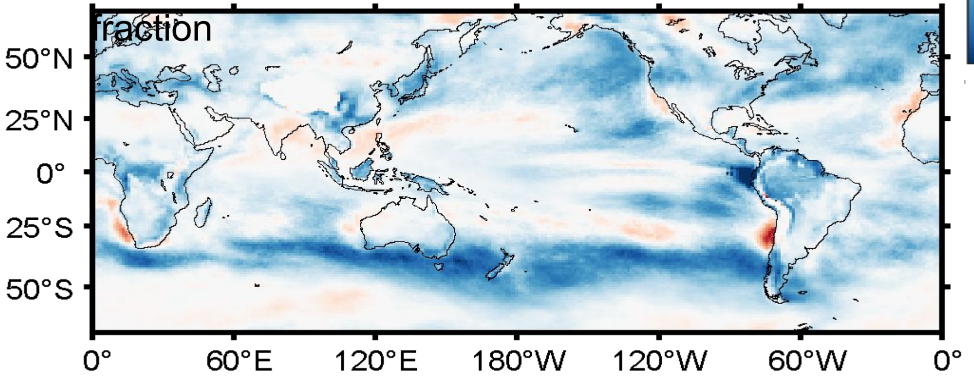
Impact on cloud feedback

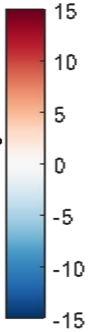
- The new scheme simulates weak positive low cloud feedback, as it simulates less increase in skewness in +4K experiment

ADG1+4k minus ADG1
Difference in low cloud fraction



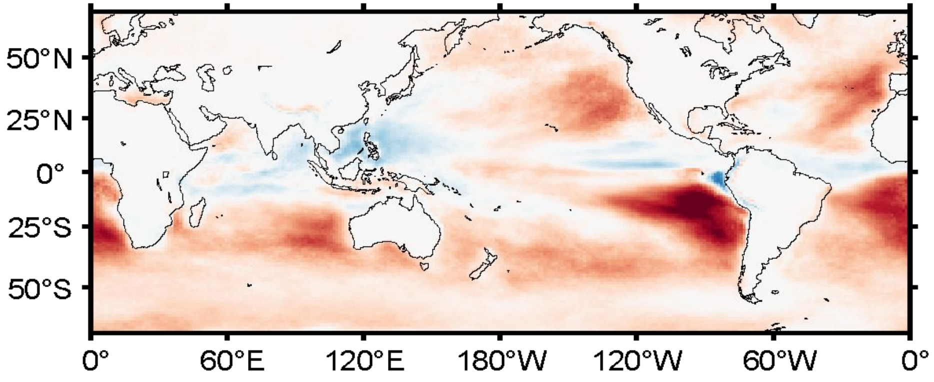
NEW+4k minus NEW
Difference in low cloud fraction



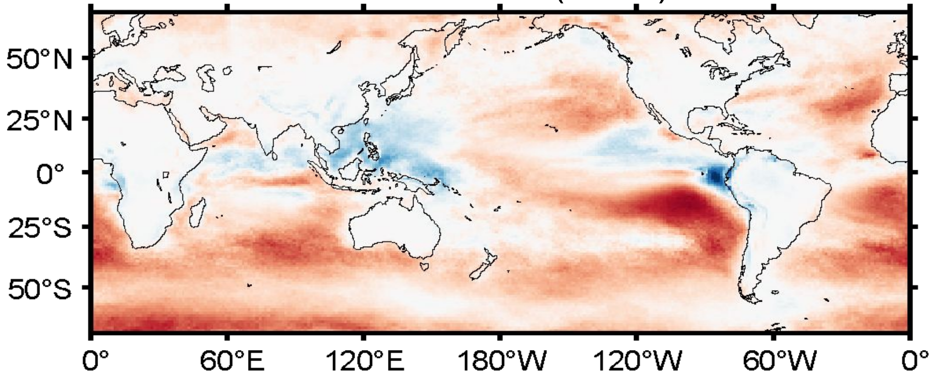


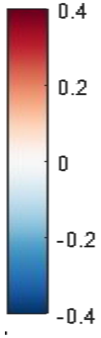
SST increase leads to increase in skewness, and further increase in shallow convection

ADG1+4k minus ADG1
Difference in skewness of *w* (<1km)



NEW+4k minus NEW
Difference in skewness of *w* (<1km)





Summary

- A new unequal width PDF closure is adopted in CLUBB, and is found to increases low cloud fraction by 20~30% in most Sc-to-Cu transition regions
- The new closure scheme simulates more symmetric turbulence in stratocumulus and stronger turbulent transport in shallow cumulus. Furthermore, the updated closure scheme enhances the cloud fraction near the cloud base by interacting with the microphysical scheme
- The new scheme simulates weaker positive low cloud feedback, despite simulated stronger low cloud fraction in the present day, as it simulates less increase in skewness in the +4k experiment.

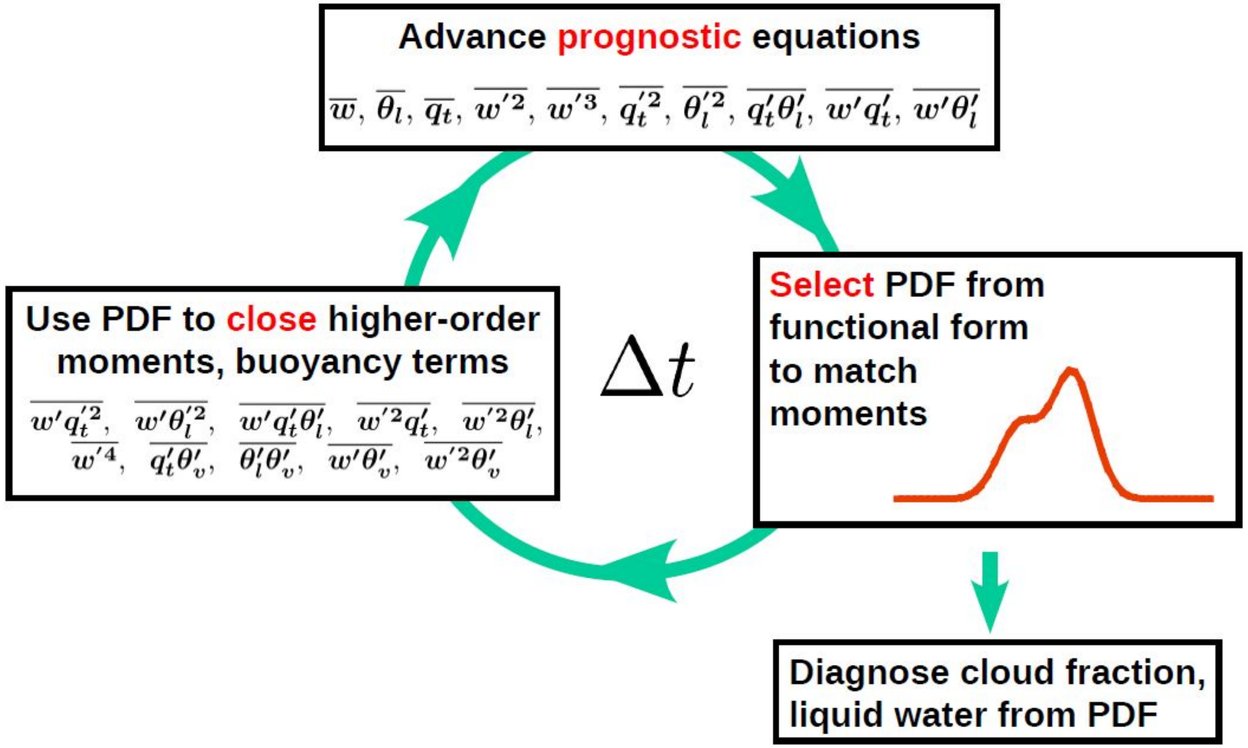
Li, T., Wang, M., Guo, Z., Yang, B., Xu, Y., Han, X., & Sun, J., 2022: An updated CLUBB PDF closure scheme to improve low cloud simulation in CAM6, *JAMES*, 14, https://doi.org/10.1029/2022MS003127

Thanks!   Questions/comments?

CLUBB: a unified treatment of cloud and turbulence processes

- Cloud Layers Unified by Binormals (CLUBB) is an assumed PDF higher-order turbulence closure parameterization.

- CLUBB unify the treatment of boundary layer turbulence, shallow convection, and cloud macrophysics .



- CLUBB adopts a double Gaussian functional form of the joint PDF(P) of vertical velocity (w), total water mixing ratio (q_t) and liquid water potential temperature (θ_l).

$$P(\hat{w}, \tilde{q}_t, \tilde{\theta}_l)$$

$$= aG_1(\hat{w}_1, \tilde{\theta}_{l1}, \tilde{q}_{t1}, \tilde{\sigma}_{w_1}, \tilde{\sigma}_{\theta_{l1}}, \tilde{\sigma}_{q_{t1}})$$

$$+ (1-a)G_2(\hat{w}_2, \tilde{\theta}_{l2}, \tilde{q}_{t2}, \tilde{\sigma}_{w_2}, \tilde{\sigma}_{\theta_{l2}}, \tilde{\sigma}_{q_{t2}})$$