Turbulent dissipation is not pressure damping: Moving beyond Mellor's single master length scale

Zhun Guo, Vincent E Larson

University of Wisconsin Milwaukee

guozhun@uwm.edu

Jun/16/2020

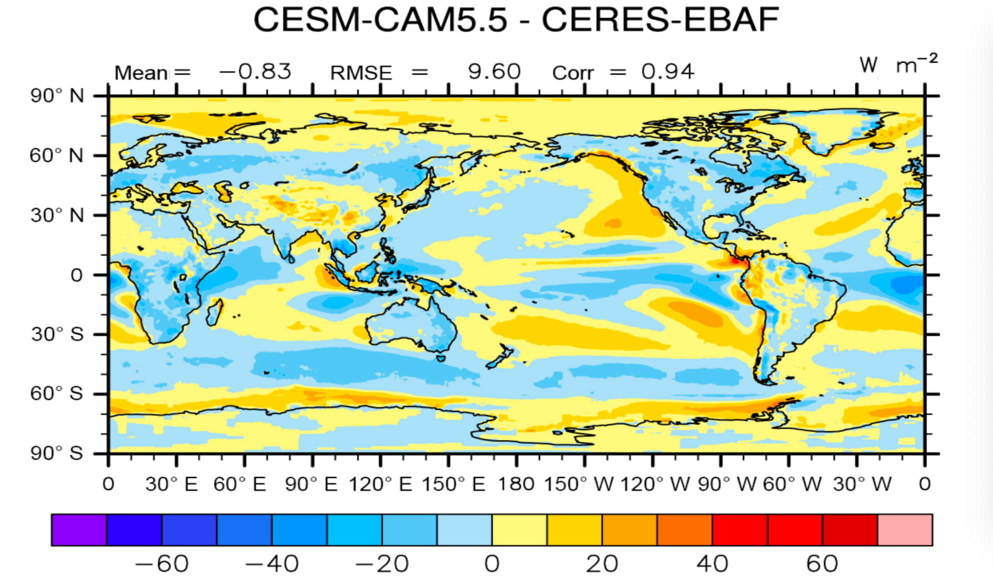
Outline

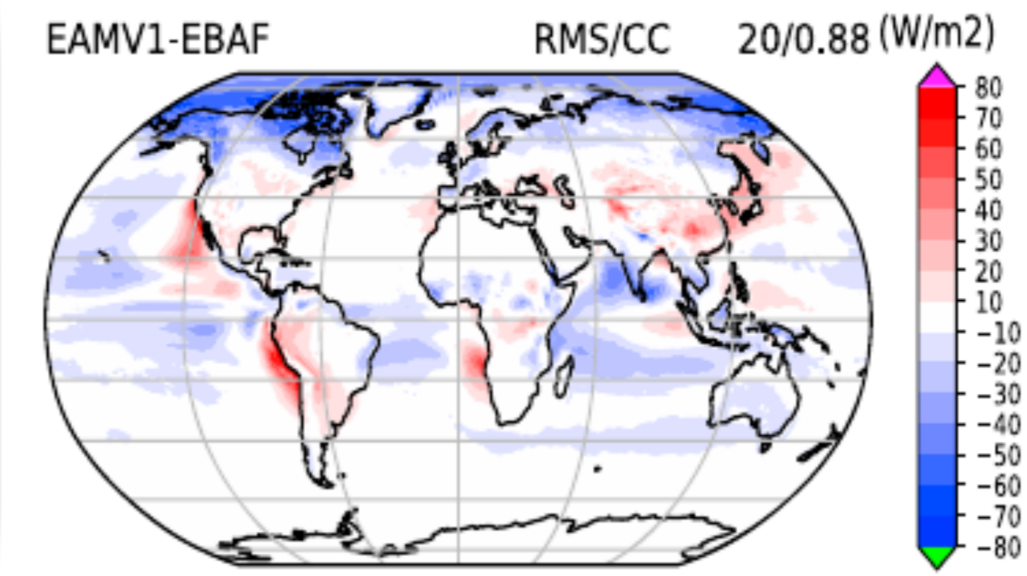
- Background
- Turbulent time scale of dissipation and non-hydrostatic pressure fluctuations in nature are different
- Design Multi-time-scale parameterization
- Global results and sensitivity studies
- Conclusions

Some of the largest errors in Global models are related to cloud

1. **Stratocumulus and shallow Cumuli are not distinct enough**
2. **Coastal stratocumulus is underestimated**

They are evident in SWCF:





Cited from *Bogenschutz et al. 2018 GMD*

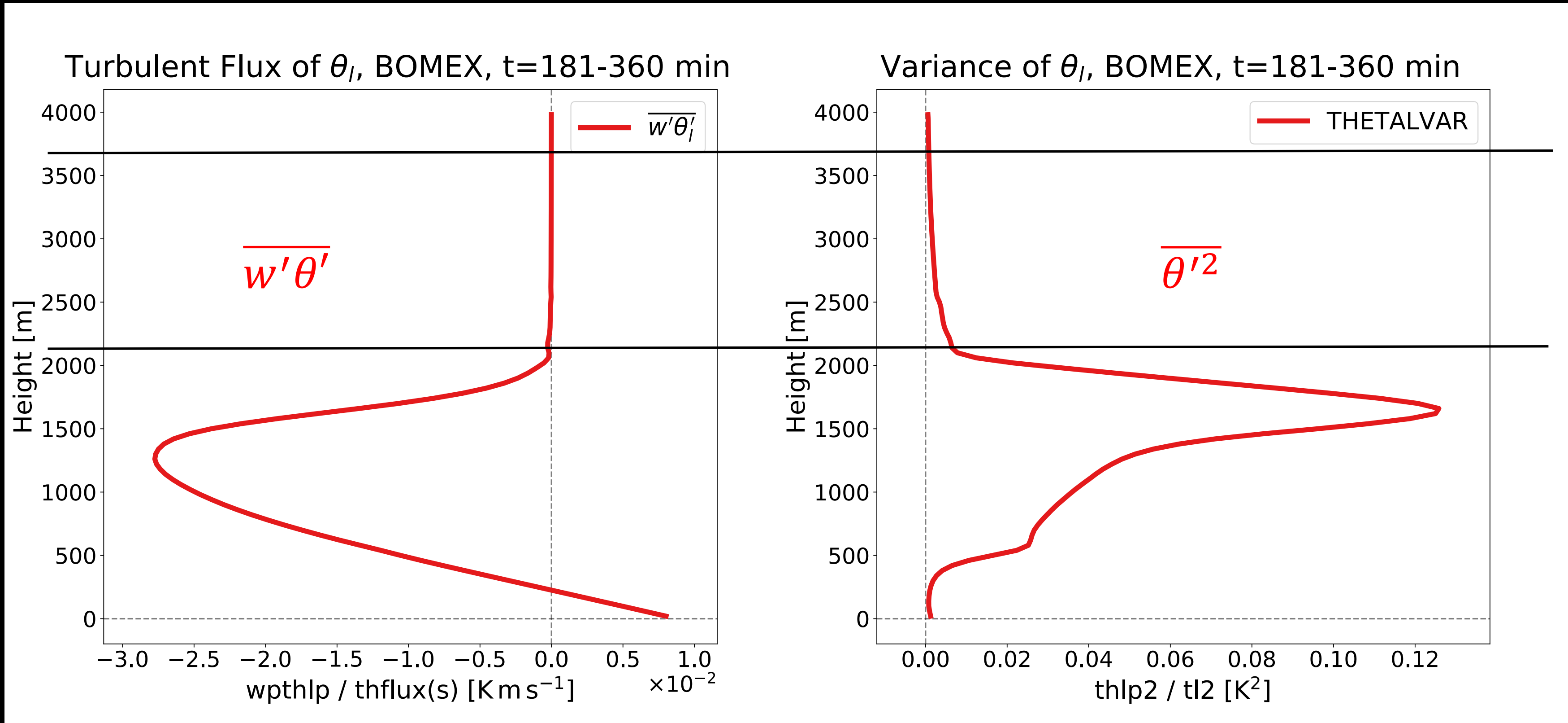
Cited from *Rasch et al. 2019 JAMES*

Motivations

Small-scale turbulent variability in moisture and heat content can be damped by two distinct processes:

1. variability can be damped by turbulent dissipation; that is, variability can be smoothed out by molecular diffusivity or viscosity.
2. the motion of a parcel of fluid can be opposed (i.e. “damped”) by non-hydrostatic pressure fluctuations.

In stably stratified layer above cloud top, turbulent flux has stronger damping than variance



Non-breaking Gravity wave does not transport heat, but the undulation lets scalar variances to be large.

Why turbulent time scale of turbulence dissipation and non-hydrostatic pressure fluctuations should be different?

1. $0 \approx \frac{\partial \overline{x'^2}}{\partial t} = -\overline{w'x'}\frac{\partial \bar{x}}{\partial z} - \frac{1}{\tau_x}\left(\overline{x'^2}\right) - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{x'^2 w}}{\partial z}$

2. $0 \approx \frac{\partial \overline{w'x'}}{\partial t} = -\overline{w'^2}\frac{\partial \bar{x}}{\partial z} + (1 - C7)\frac{g}{\theta_0}\overline{x'^2} - \frac{1}{\tau_{wx}}\left(\overline{w'x'}\right) - \frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2 x}}{\partial z}$

x could be θ_l or q_t

Consider a stably stratified inversion with no turbulent cascade. For non-breaking gravity waves, $\overline{w'x'} = 0$, $\overline{x'^2} > 0$, so we have:

$\tau_x \rightarrow \infty$ (because turbulent dissipation is weak)

$\&$

$\tau_{wx} \rightarrow 0$ (because pressure damping is strong)

$$\tau_x \neq \tau_{wx}$$

Multi time scale (τ) parameterization : τ_{noN}

First, for layers that are neutral or buoyantly unstable ($N \leq 0$):

$$\frac{1}{\tau_{noN}} = C_{i\tau bkgnd}\frac{1}{\tau_{const}} + C_{i\tau sfc}\frac{u_*}{k(Z - Z_{displace})} + C_{i\tau shear}\sqrt{\frac{\partial \bar{u}}{\partial z}^2 + \frac{\partial \bar{v}}{\partial z}^2} \quad (3)$$

1. Background Damping $C_{i\tau bkgnd}\frac{1}{\tau_{const}}$, layers that are shear-free and located well above the lower surface.
2. Surface Damping $C_{i\tau sfc}\frac{u_*}{k(Z - Z_{displace})}$, Von Karman constant k, u_* friction velocity.
3. Shear Damping $C_{i\tau shear}\sqrt{\frac{\partial \bar{u}}{\partial z}^2 + \frac{\partial \bar{v}}{\partial z}^2}$, wind shear would generate turbulence and hence dissipation.

In the stable layers, we damp fluxes more

However, in a stably stratified layer ($N \geq 0$), pressure terms will have an extra contribution :

$$\frac{1}{\tau_N} = C_{i\tau N} max(0, N) \quad (4)$$

stable stratification suppresses scalar fluxes more in non-cloudy layers than it does in cumulus layers

$$\frac{1}{\tau_{N,clr}} = C_{i\tau N,clr} max(0, N) H(-cf + cf_0) \quad (5)$$

For flux equations, we have

$$\frac{1}{\tau_{wx}} = \frac{1}{\tau_{noN}} + \frac{1}{\tau_N} + \frac{1}{\tau_{N,clr}} \quad (6)$$

In stable layers, we damp variances less

For damping term of variance, we have

$$\frac{1}{\tau_{x'2}} = Ri^{-1}(\frac{1}{\tau_{noN}}). \qquad (7)$$

Ri is Richardson number

Multi-time-scale scheme is faster and has fewer tunable parameters

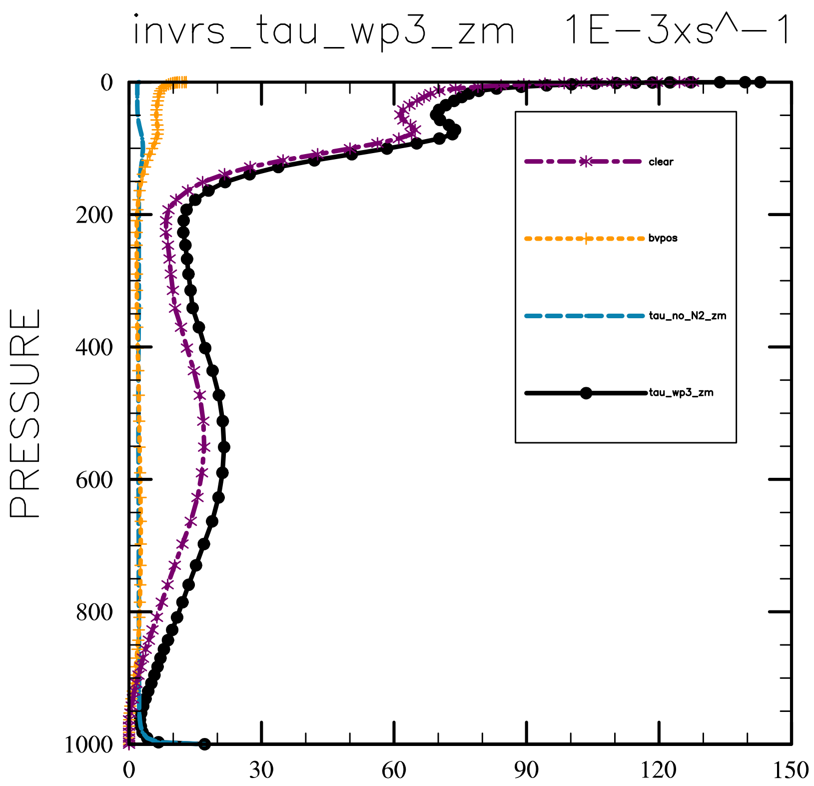
- *Multi-time-scale scheme* decreases the total runtime of CLUBB core by about 15%
- It reduces the number of tunable parameters

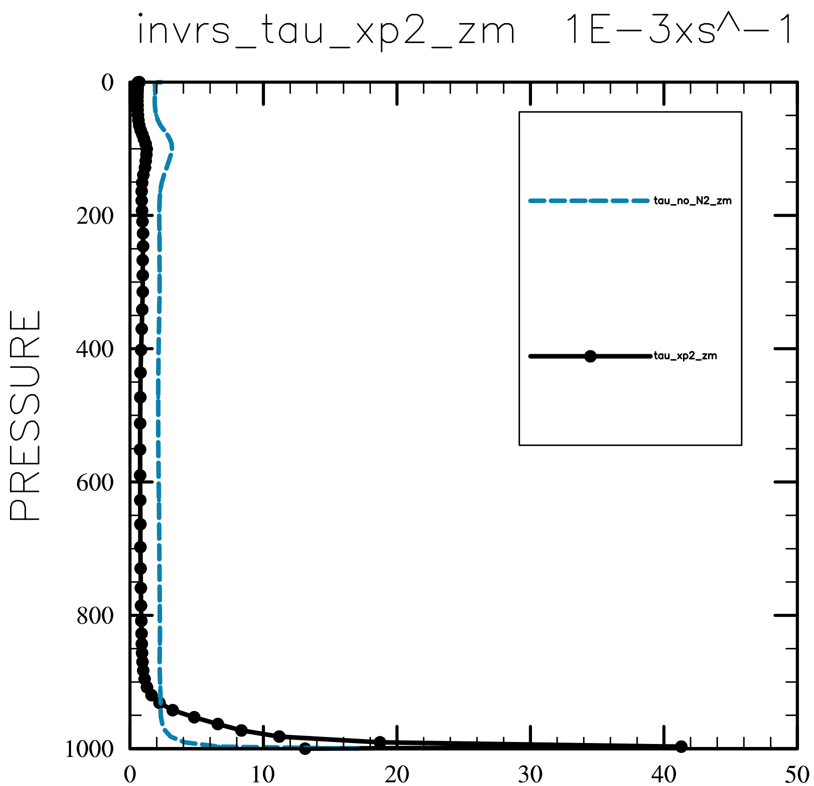
Lscale scheme	Tau scheme
C1	/
C1b	/
C1c	/
C2rt	/
C2thl	/
C2rtthl	/
C6rt	/
C6rtb	/
C6rtc	/
C6thl	/
C6thlb	/
C6thlc	/
C14	/
/	Ciτsfc
/	Ciτshea
/	Ciτbkgn
/	CiτN
/	CiτN,clr

$\frac{1}{\tau}$s in global model (Hawaii)

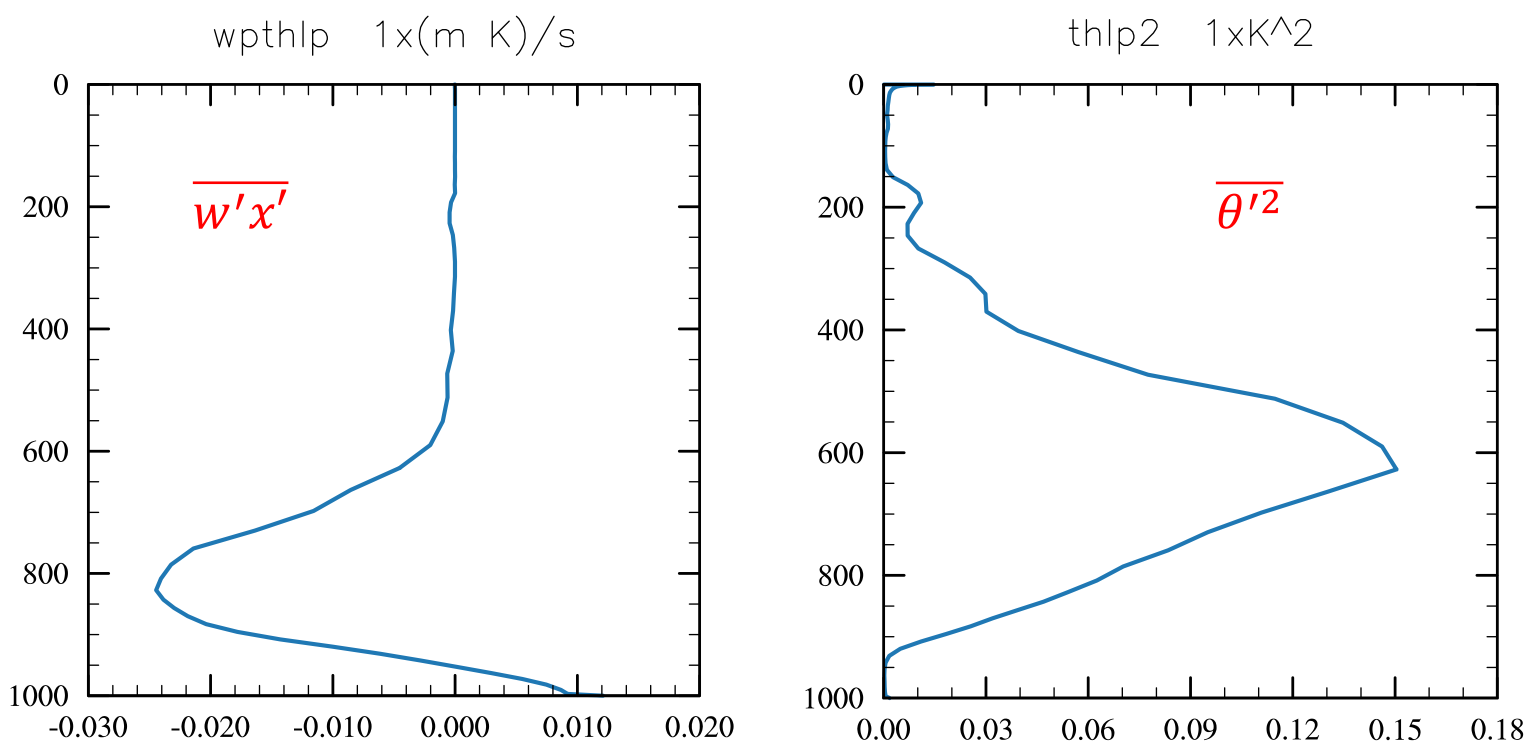
$$\frac{1}{\tau_{wx}} = \frac{1}{\tau_{noN}} + \frac{1}{\tau_N} + \frac{1}{\tau_{N,clr}}$$

$$\frac{1}{\tau_{x'^2}} = Ri^{-1}\left(\frac{1}{\tau_{noN}}\right)$$





The profiles of Hawaii look more cumulus-like



Does introducing a Multi-time-scale parameterization improve global simulations?

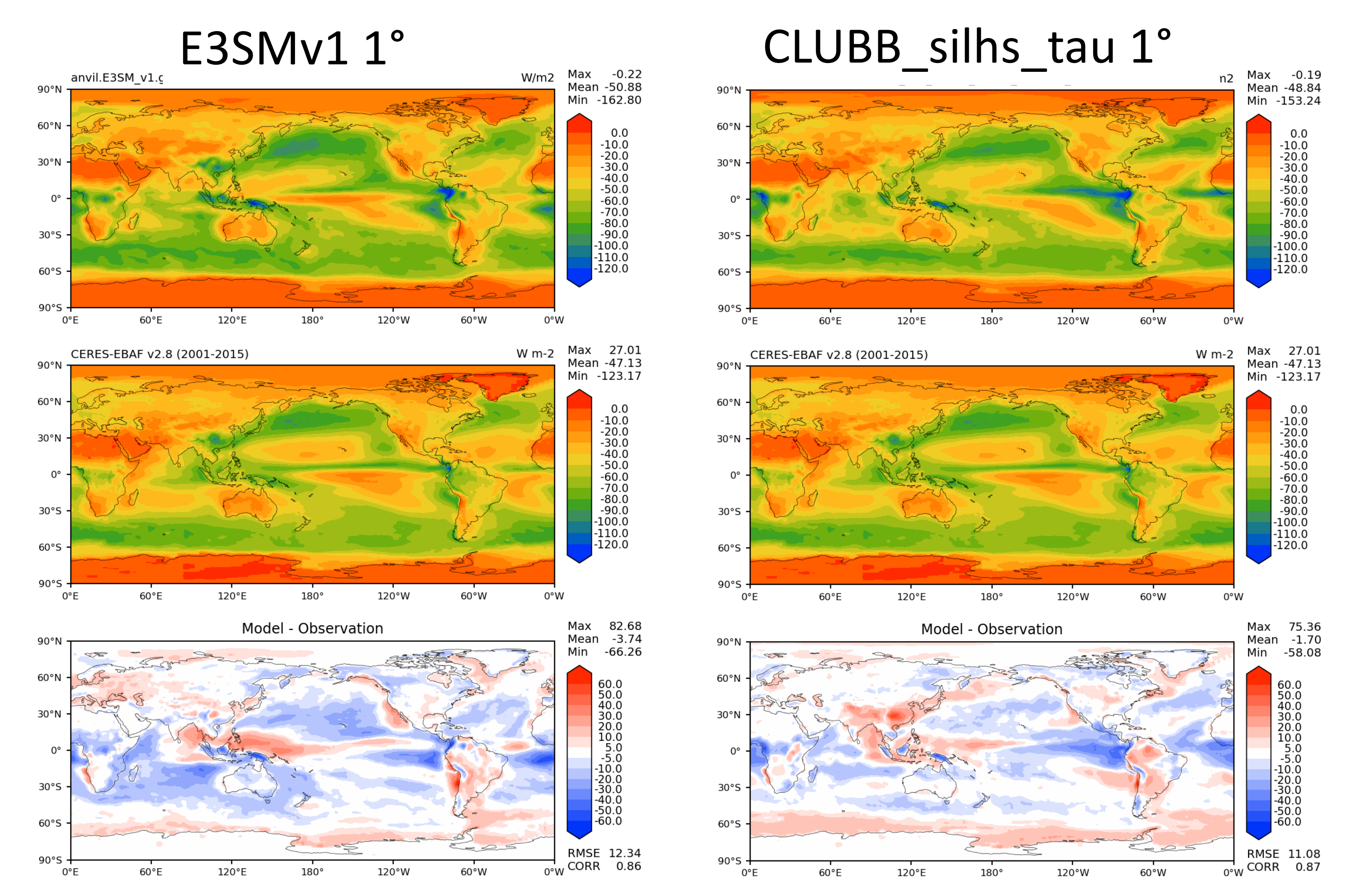
- We'll show some 1° (2°) simulations.
- **Format of the following 2D figures**

Left panels:	**Right panels:**
Default E3SMv1	E3SM-CLUBB-SILHS**-tau (no ZM)**

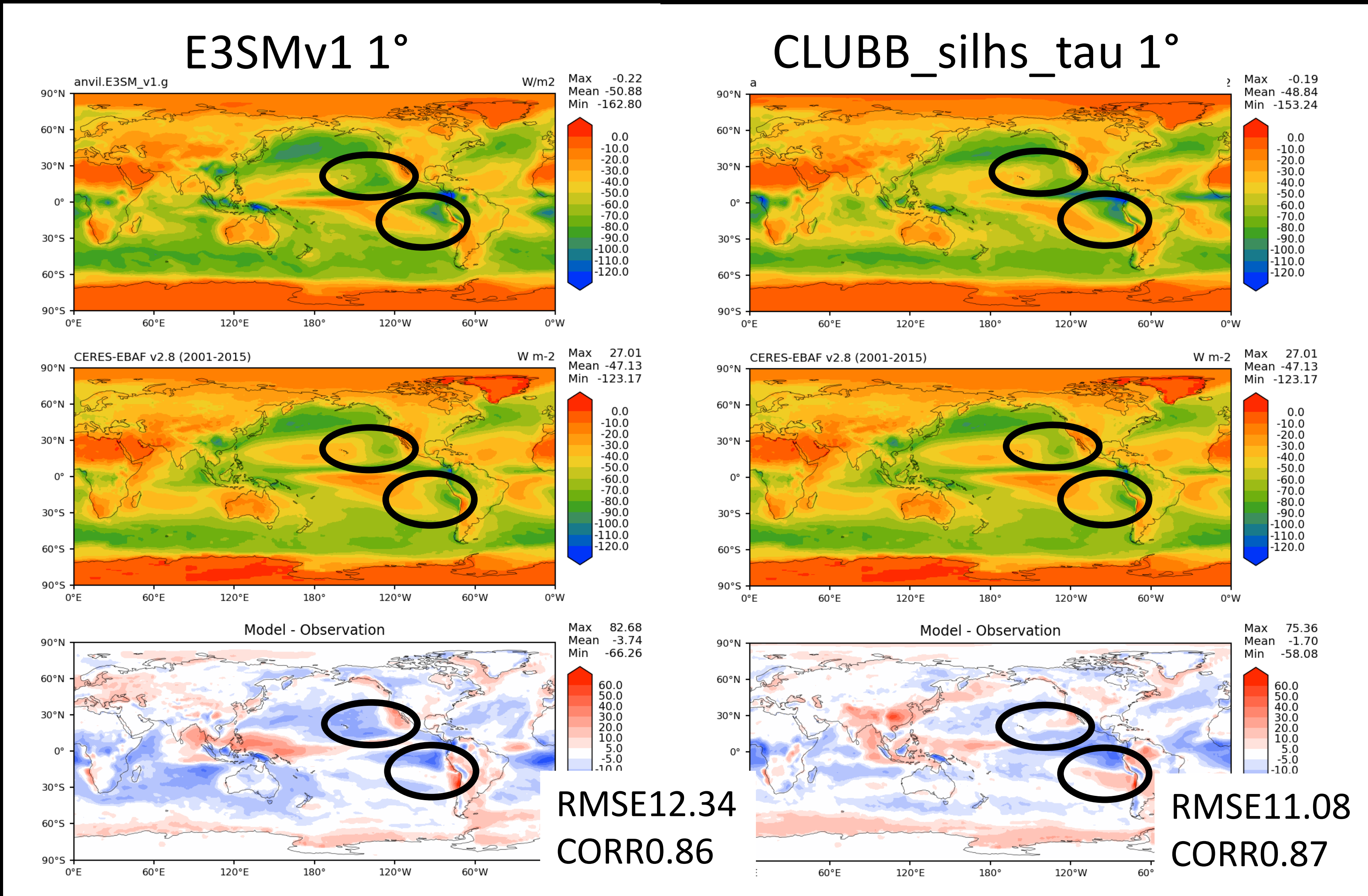
- **Format of the following Profiles**

E3SMv1 1°	CLUBB_silhs_tau 1°
E3SMv1 2°	CLUBB_silhs_tau 2°

Multi-time-scale improves coastal SC and distinction between SC and CU

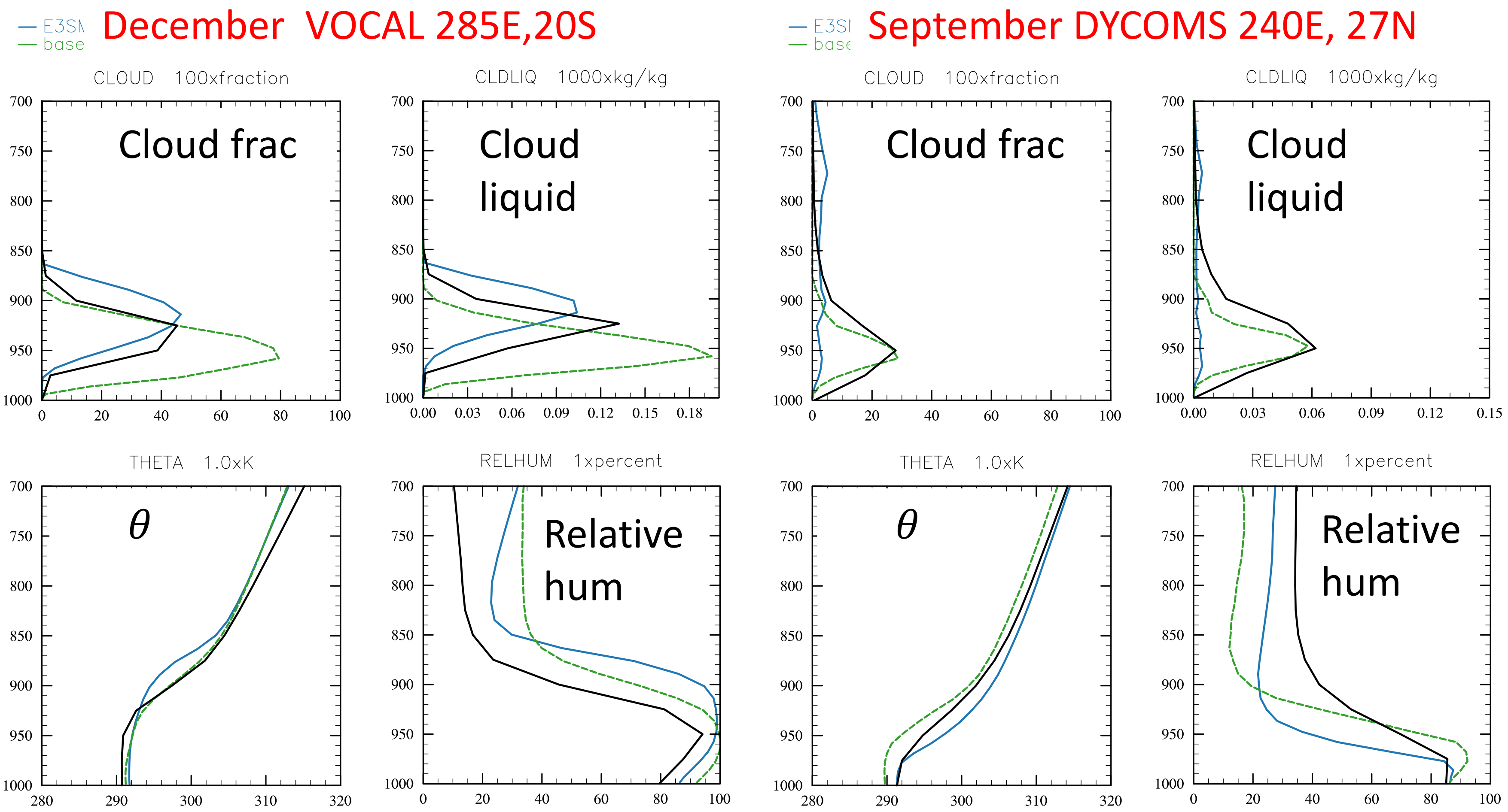


Multi-time-scale improves coastal SC and distinction between SC and CU



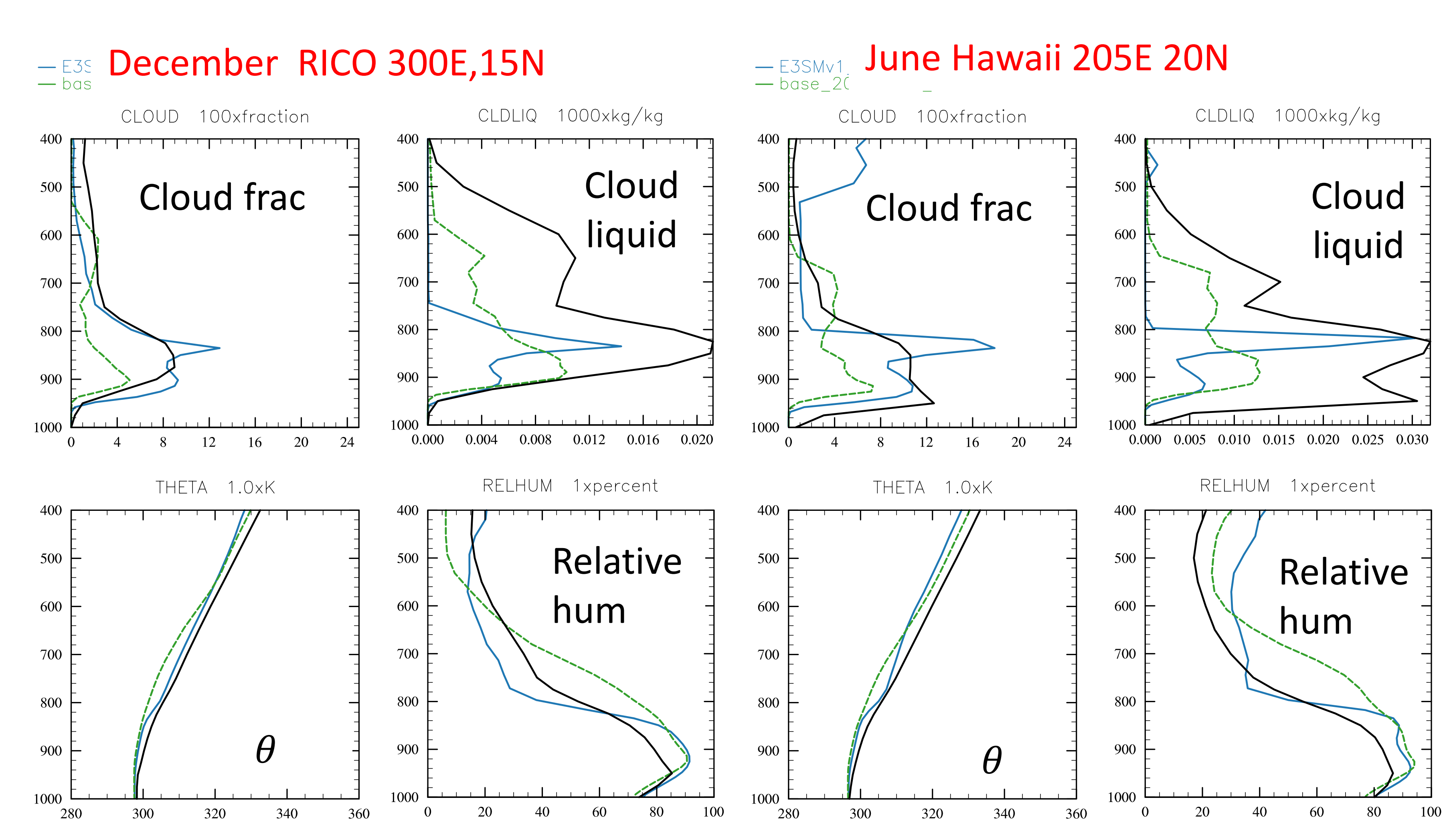
SC increases near the coast

ERAI
E3SMv1
CLUBB_silhs_tau

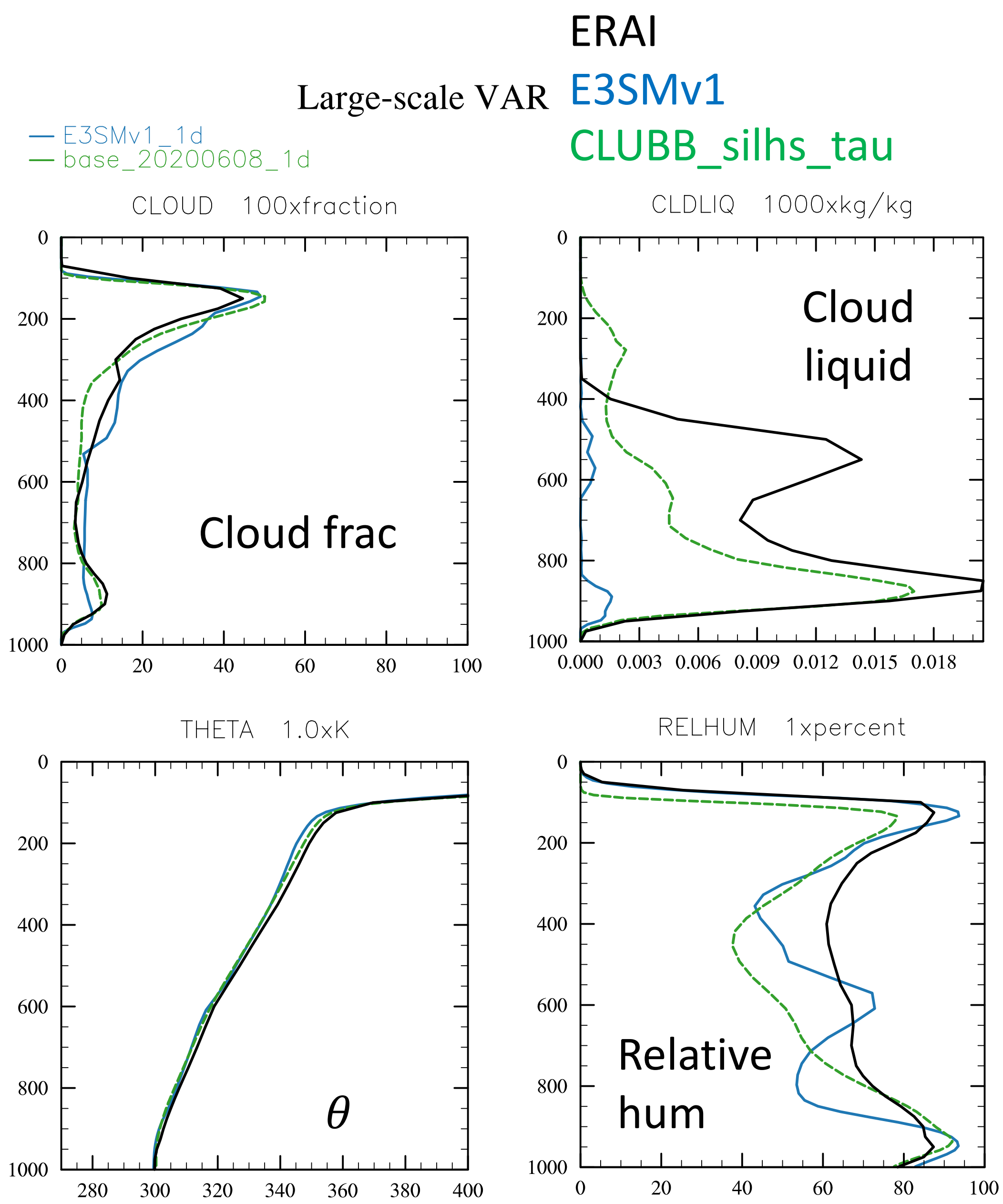


CLUBB_silhs_tau maximizes near cloud base in cumulus regimes

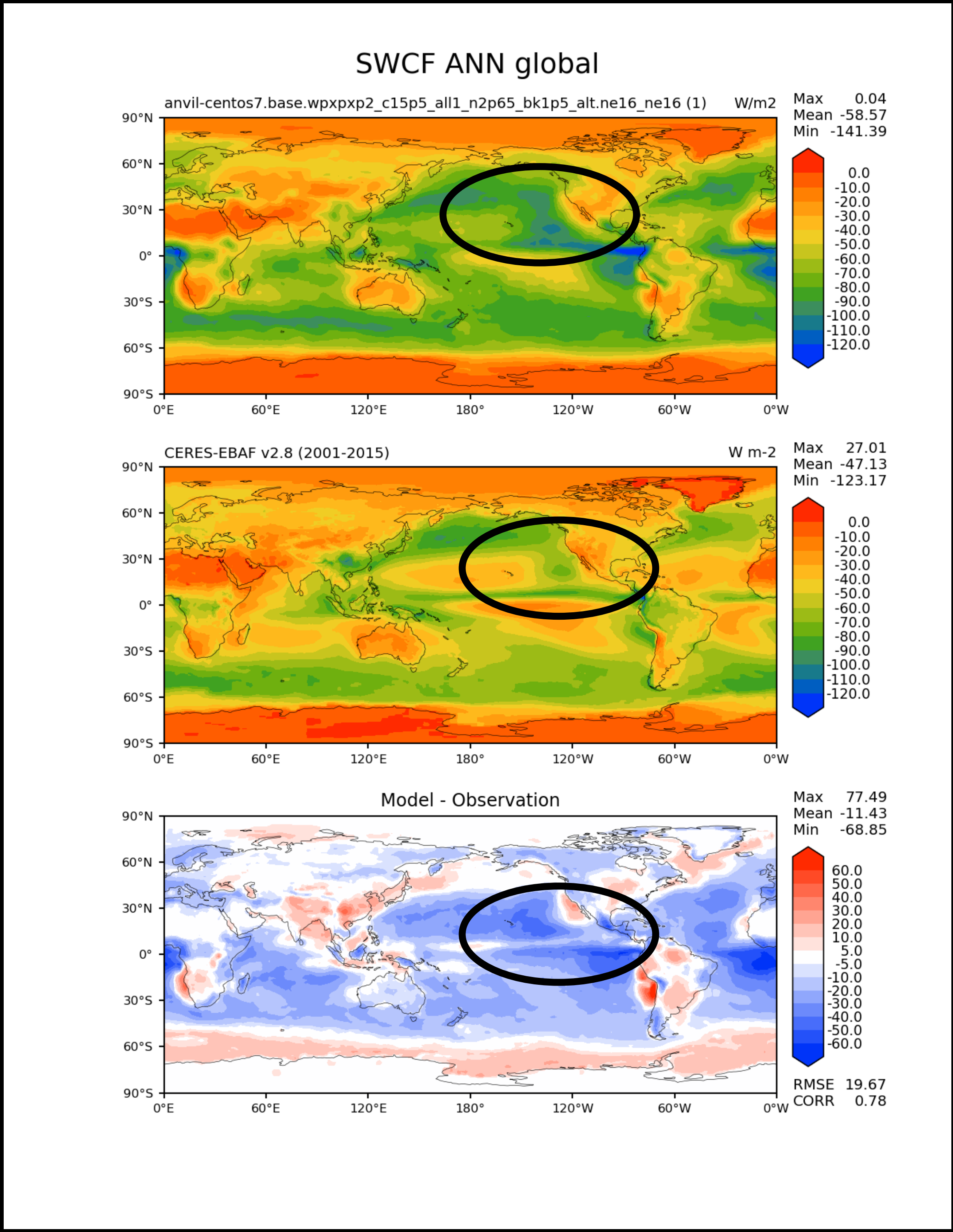
ERAIM
E3SMv1
CLUBB_silhs_tau



CLUBB-SILHS-tau reproduces reasonable deep cumuli in West Pacific Warm Pool



If we set $\tau_x = \tau_{wx}$, then there is less distinction between SC and CU



Conclusions

- Turbulent time scale of turbulence dissipation and non-hydrostatic pressure fluctuations need to be parameterized separately;
- Introducing "*Multi-time-scale parameterization*" in higher-order-closure scheme is necessary;
- *Multi-time-scale parameterization* allows us to brighten coastal stratocumulus;
- Use of the new *multi-time-scale parameterization* in a global model improves the distribution of stratocumulus and shallow cumulus clouds.

Thank you for your attentions!