Mean-state acceleration for cloud-resolving and superparameterized simulations

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Motivation

- Challenge: LES, CRMs, and superparameterization are expensive (computationally limited by the smallest spatial and shortest time scales)

- Mean atmospheric state often evolves slowly relative to turbulent motions (hours or days versus minutes)

Mean-state acceleration

Artificially accelerate slow mean-state evolution

- Consider scalar field $\phi(\boldsymbol{x}, t)$ with evolution eq.

$$\frac{\partial \phi}{\partial t} = f(\phi, t) \Longrightarrow \begin{cases} \dfrac{\partial \overline{\phi}}{\partial t} = \overline{f}(\phi, t) \\ \dfrac{\partial \phi'}{\partial t} = f'(\phi, t) \end{cases}$$

- In each time step, magnify the mean-state tendency by an *acceleration factor, a*:

$$\frac{\partial \overline{\phi}}{\partial t} = a\overline{f}(\phi, t)$$

or

$$\boxed{\frac{\partial \phi}{\partial t} = f(\phi, t) + \underbrace{(a-1)\overline{f}(\phi, t)}_{\text{"acceleration tendency"}}}$$

LES Implementation in SAM6.7

- Accelerated variables: $\phi \in \{s_{li}, q_t, u, v\}$
- Un-accelerated variable: q_p (no long-term storage; stability concerns)
- Apply acceleration after all other processes in each time step:

"Accelerated time step"

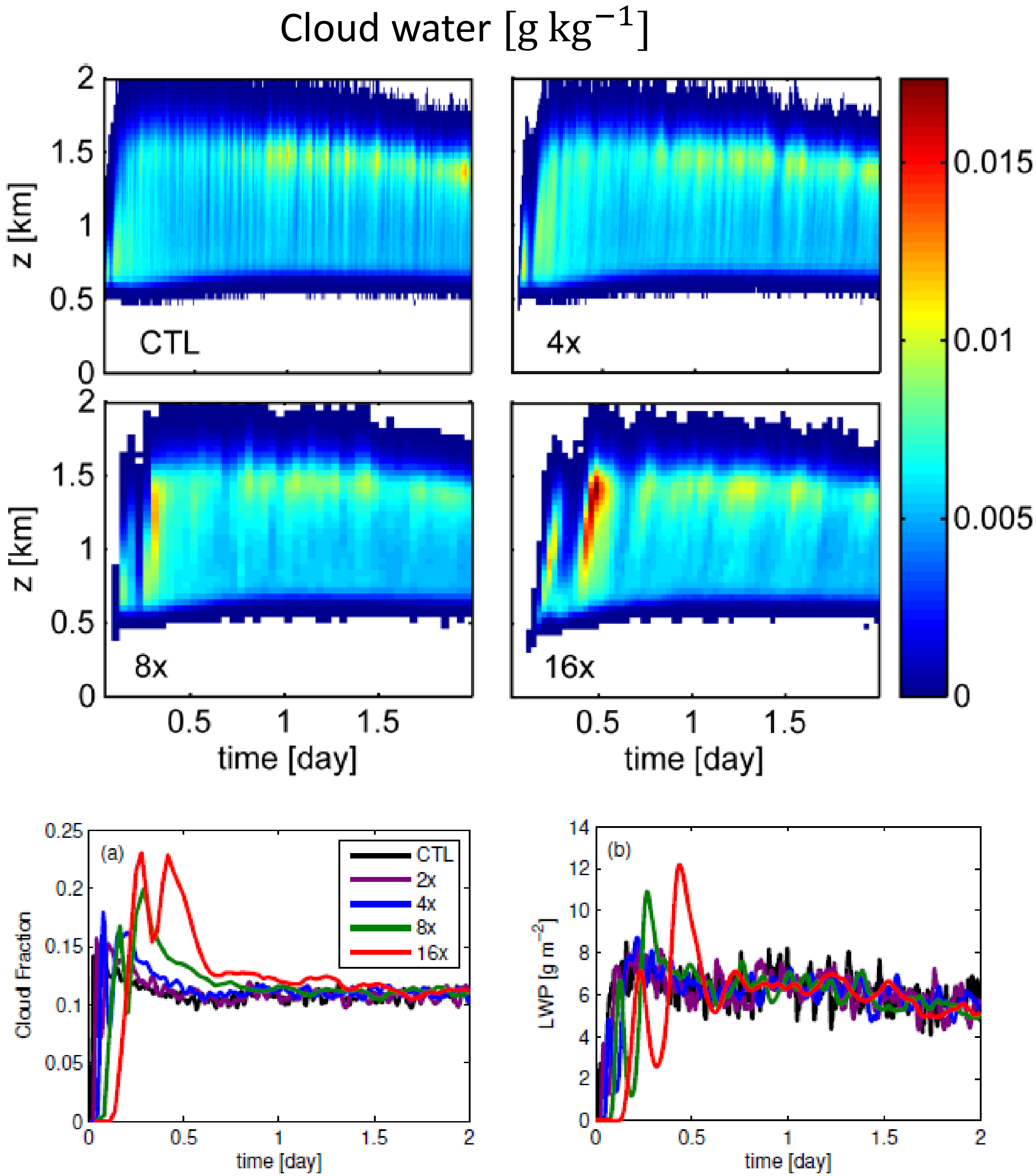
1. Standard time step: $\phi(t) \rightarrow \phi(t + \Delta t)$
2. Apply acceleration:
   $$\phi(t + a\Delta t) = \phi(t + \Delta t) + (a - 1)\left(\overline{\phi(t + \Delta t)} - \overline{\phi(t)}\right)$$
3. If negative q_t is produced at some grid point, bring it up to zero by removing constant fraction of the q_t at other grid points in the same level.

We use the System for Atmospheric Modeling (SAM) version 6.7 (maintained by Marat Khairoutdinov)

BOMEX

Nonprecipitating shallow cumulus

Remarkably similar evolution, even for 16x acceleration



DYCOMSII RF01

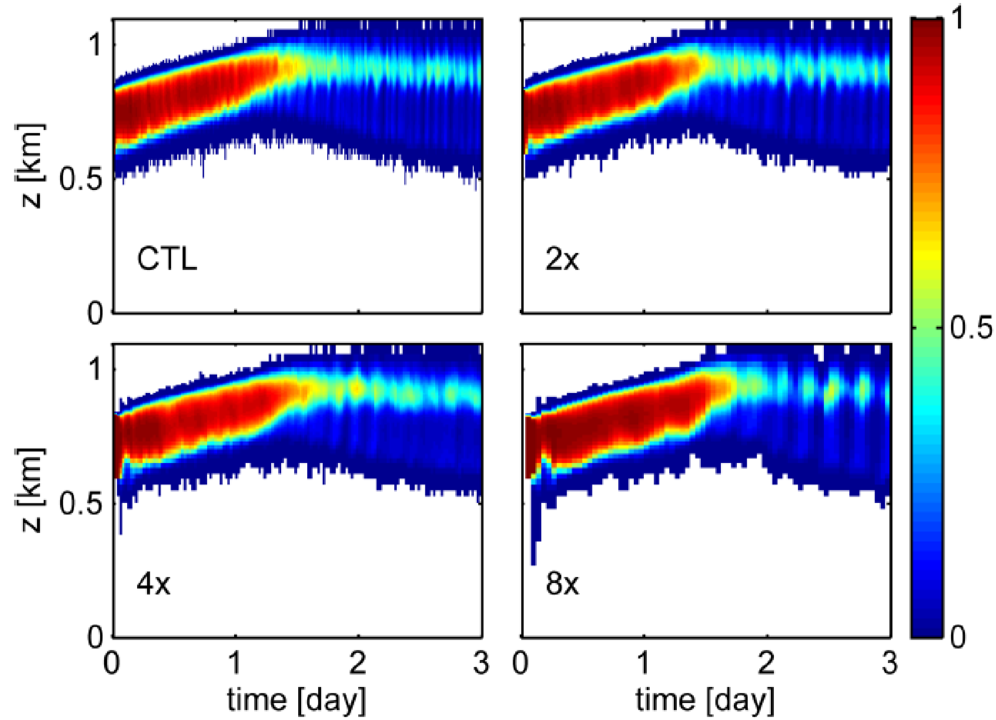
Nocturnal nonprecipitating Sc

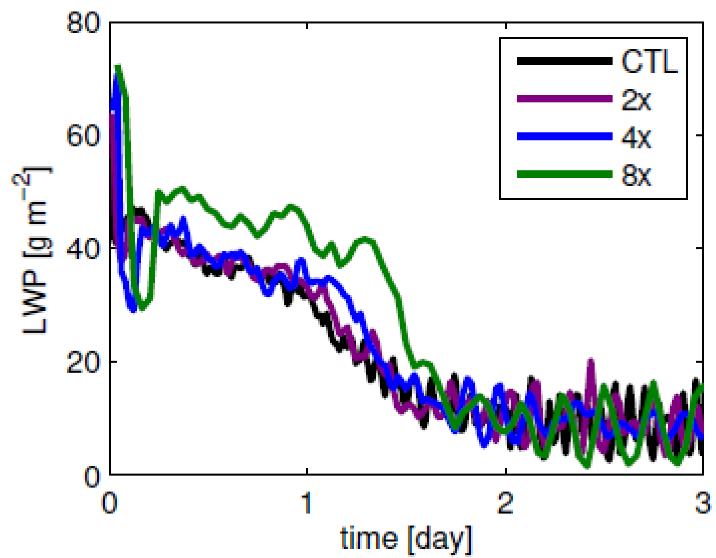
2x, 4x nearly identical to CTL

Slightly more LWP for 8x, but qualitatively similar evolution

Stable for $a > 32$x, but increasingly high LWP, delayed decoupling transition

Cloud Fraction

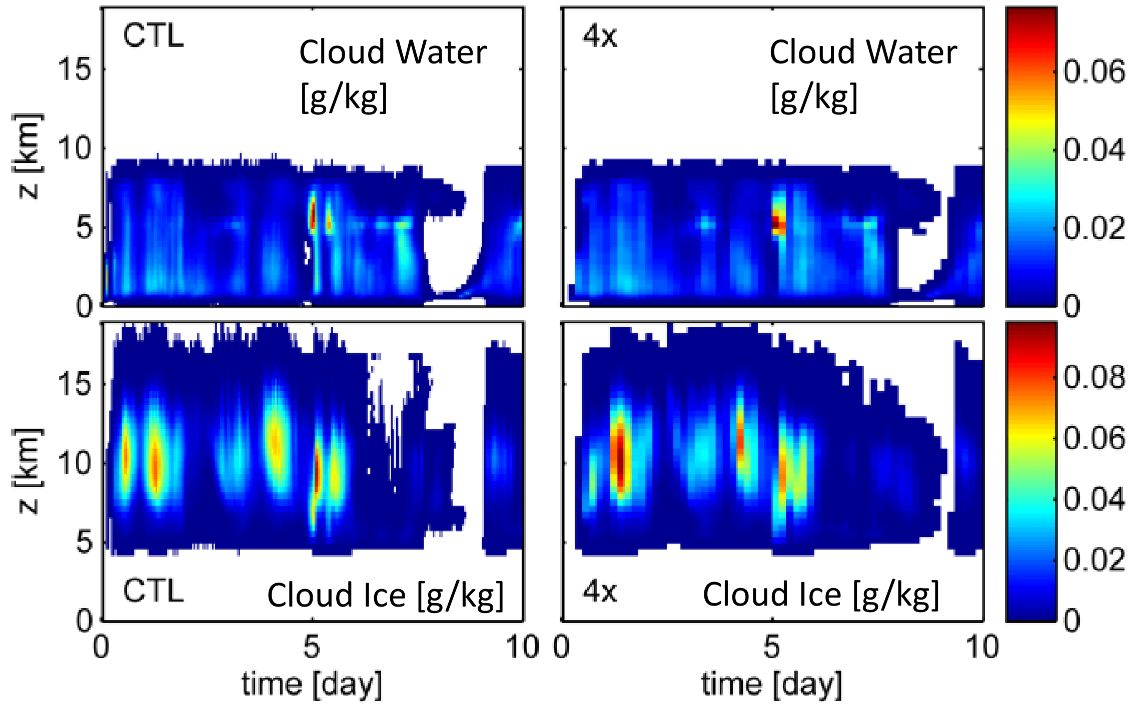




KWAJEX

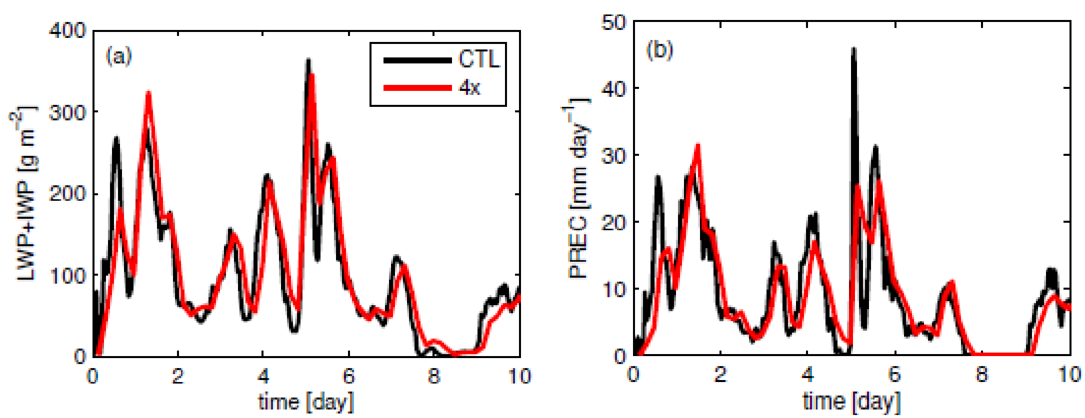
Tropical deep convection

- Time-dependent forcing
- 50-day simulation
  (10 days shown)
- Stability-limited to 4x
  acceleration



4x and CTL generally similar

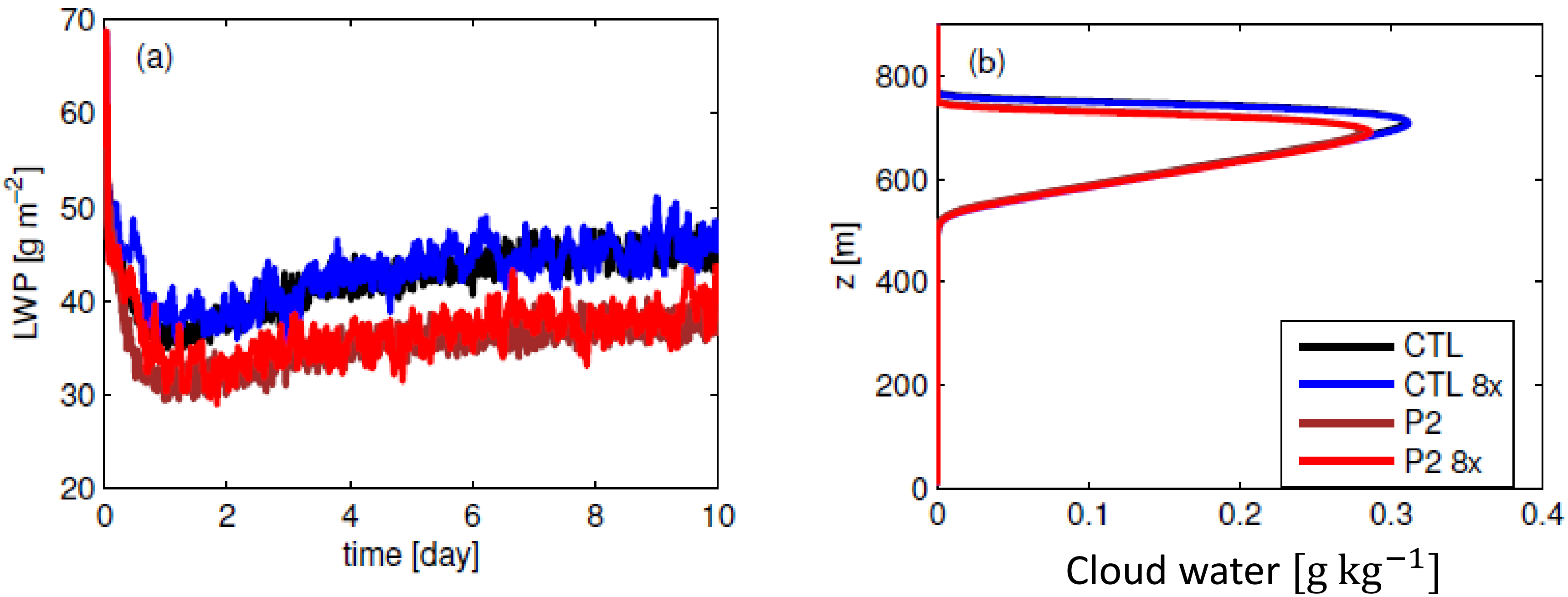
Precipitation lag in 4x (consequence of not accelerating q_p)



Application to Cloud Feedbacks

CGILS S12 location (well-mixed coastal Sc)

- CTL: Current-day climate, fixed SST
- P2: 2K local SST increase; free-troposphere moist-adiabatically warmed by 2K remote boundary-layer warming

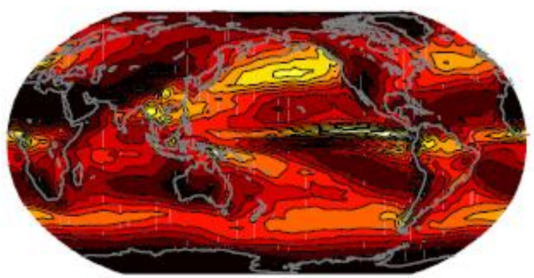


8x speedup with negligible change in cloud response!

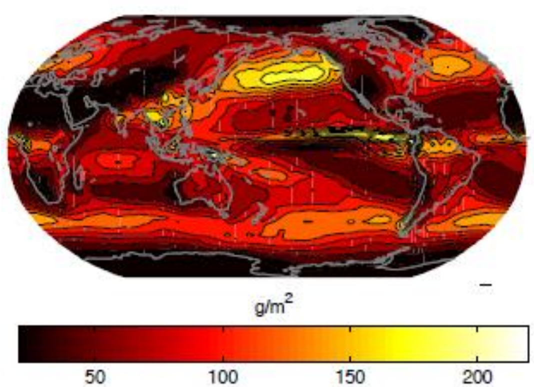
2x accelerated SPCAM captures cloud LWP and precipitation patterns

Mean Cloud LWP

2x Acceleration

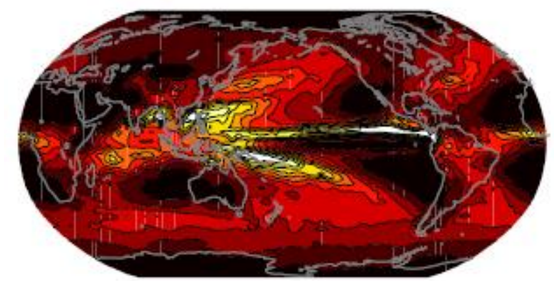


Control

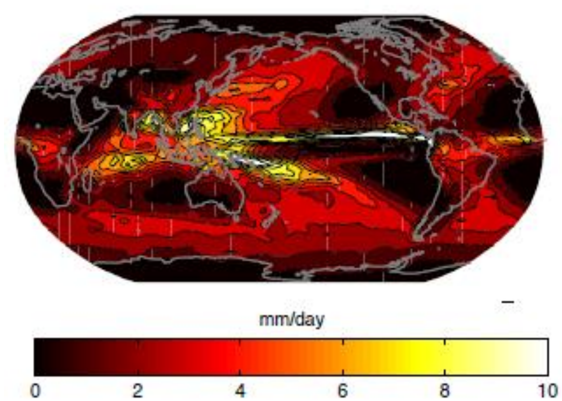


Precipitation Rate

2x Acceleration

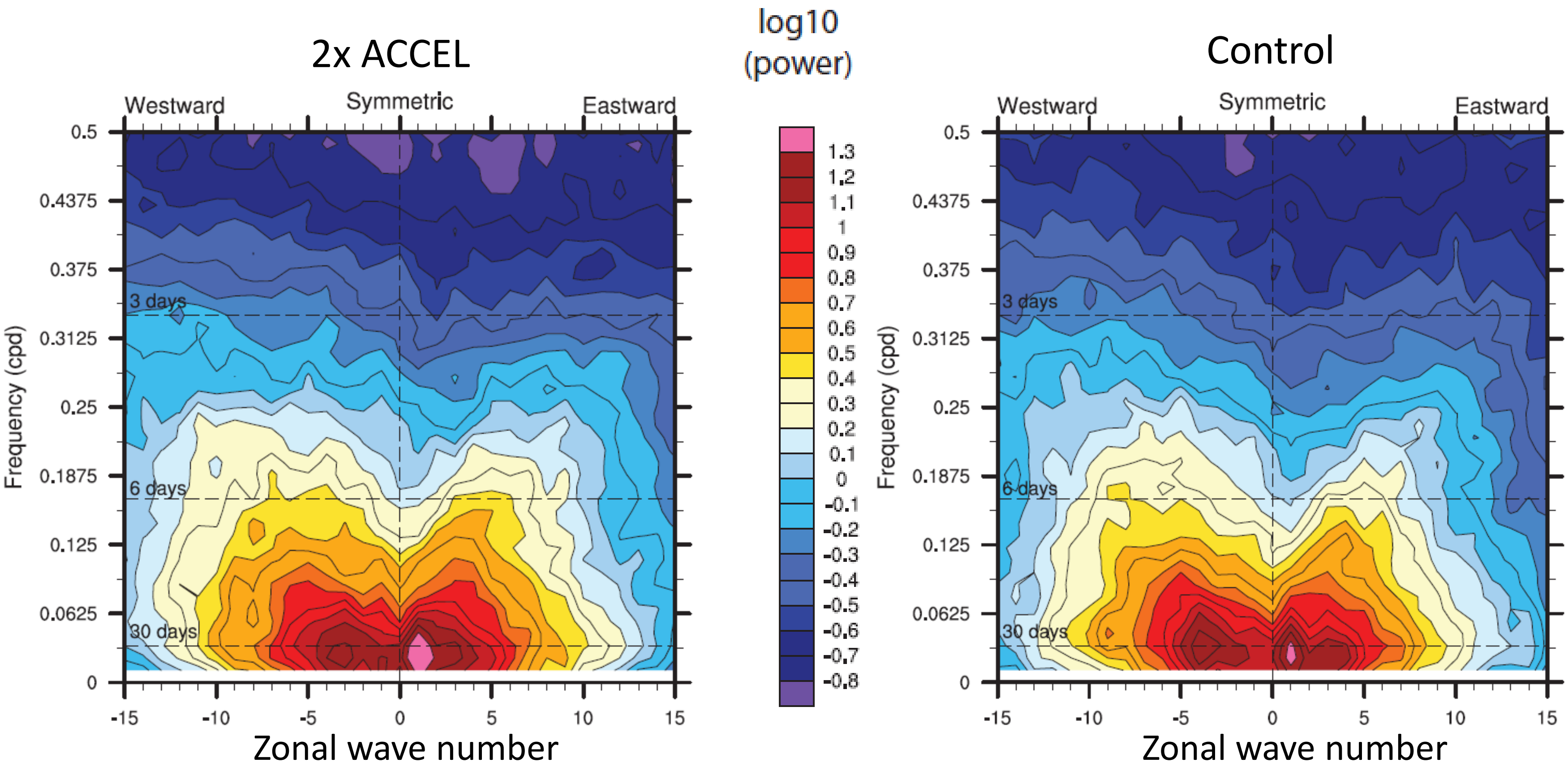


Control



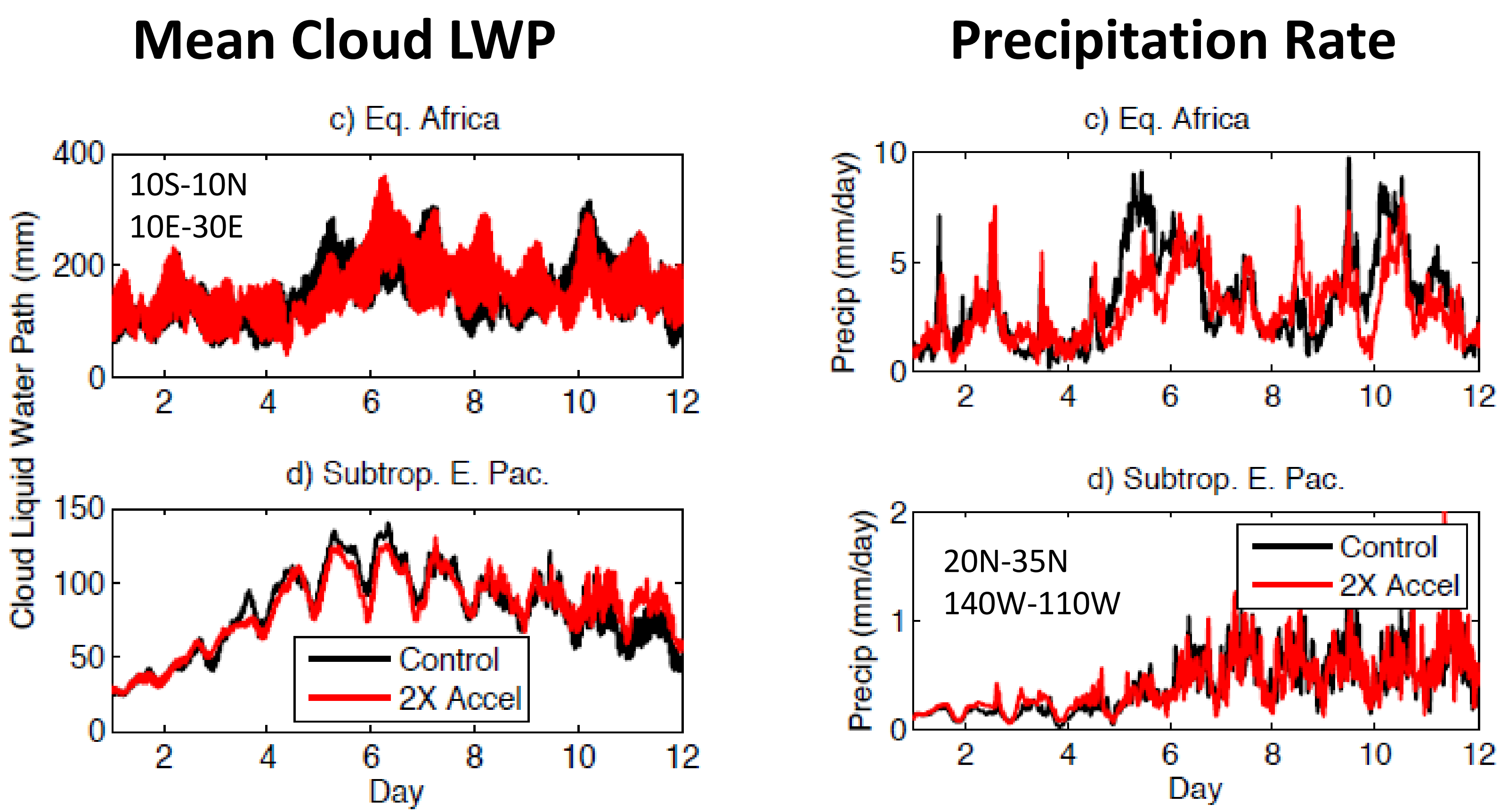
4-year superparameterized climatological simulations (1981-1984)

Similar equatorial wave characteristics between 2x accelerated and control SPCAM simulations



Wave number-frequency spectrum of equatorially symmetric 10S-10N averaged anomalies of OLR

2x (time) accelerated SPCAM with 4x "sparse space" acceleration



12-day simulations combining 2x acceleration with "micro-CRM" (8 CRM columns instead of 32; *Pritchard et al, 2014*)

Summary

- Mean state acceleration is a robust method for speeding up CRM and superparameterized simulations in which the turbulent circulations and clouds are evolving faster than the CRM horizontal mean state.

- Straightforward to implement.

- Depending on the problem, 2x-8x or more speedup achieved without serious degradation of the solution.

Jones, C. R., C. S. Bretherton, and M. S. Pritchard:
Mean state acceleration of cloud resolving models and large eddy simulations. Submitted to *J. Adv. Model. Earth Sys.*, 5/2015.

Case Study and Model Setup

Table 1. LES details[a]

Case	$\Delta x \times \Delta y$ [m]	Δz [m]	$n_x \times n_y$	n_z	Rad	Comments
DYCOMSII-RF01	25×25	5[b]	128×128	96	Idealized	Geostrophic, No precip
BOMEX	100×100	40	256×256	96	None	Geostrophic
KWAJEX	1000×1000	100-1000	256×256	64	Interactive (CAM3)	Nudged
CGILS S12	25×25	5[b]	96×96	192	RRTM	UV,QT nudged

[a] Cases and variables are as described in the text.

[b] Stretched grid with 5 m spacing near the inversion.

LES Model: System for Atmospheric Modeling (SAM) 6.7, maintained by Marat Khairoutdinov
- Khairoutdinov and Kogan microphysics (except KWAJEX: Default SAM 1 Moment Micro)

SPCAM 3.0:

- GCM: Spectral dynamical core (T42 Truncation); 30 vertical levels; time step = 30 min;
- 2D CRMs: 32 columns x 4 km horizontal resolution; 20 second time step
- Accelerate only $\{s_{li}, q_t\}$; No q_t correction

References: SAM: Khairoutdinov and Randall, 2003
DYCOMS: Stevens et al., 2005
BOMEX: Siebesma et al., 2003
KWAJEX: Blossey et al., 2007
CGILS S12: Blossey et al., 2013; Bretherton et al., 2013; Zhang et al., 2013

Application to Superparameterization

Stringent test of acceleration technique
the embedded CRMs subjected to realistic forcings across wide range of spatial and temporal scales.

- Pilot SPCAM3.0 implementation by Mike Pritchard
- Accelerated variables: $\{s_{li}, q_t\}$
- No q_t correction

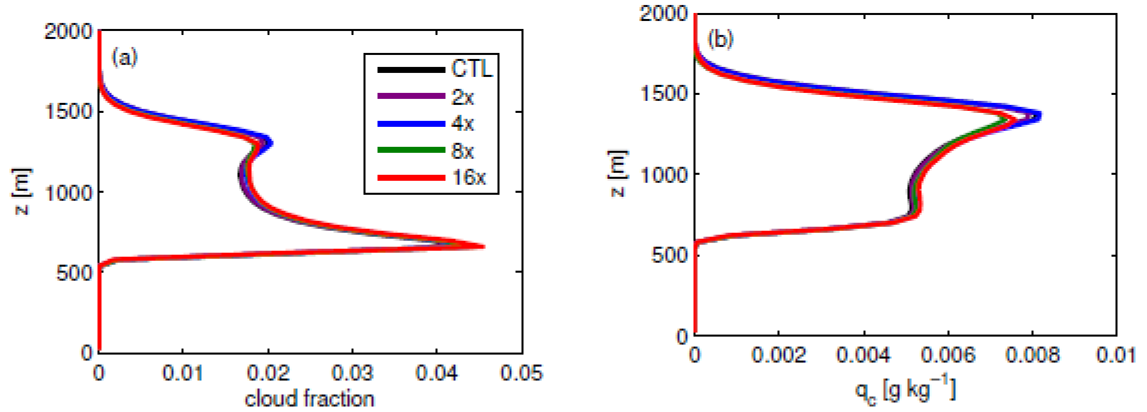


Figure 3. BOMEX 36-48 h mean profiles of (a) cloud fraction and (b) q_c.

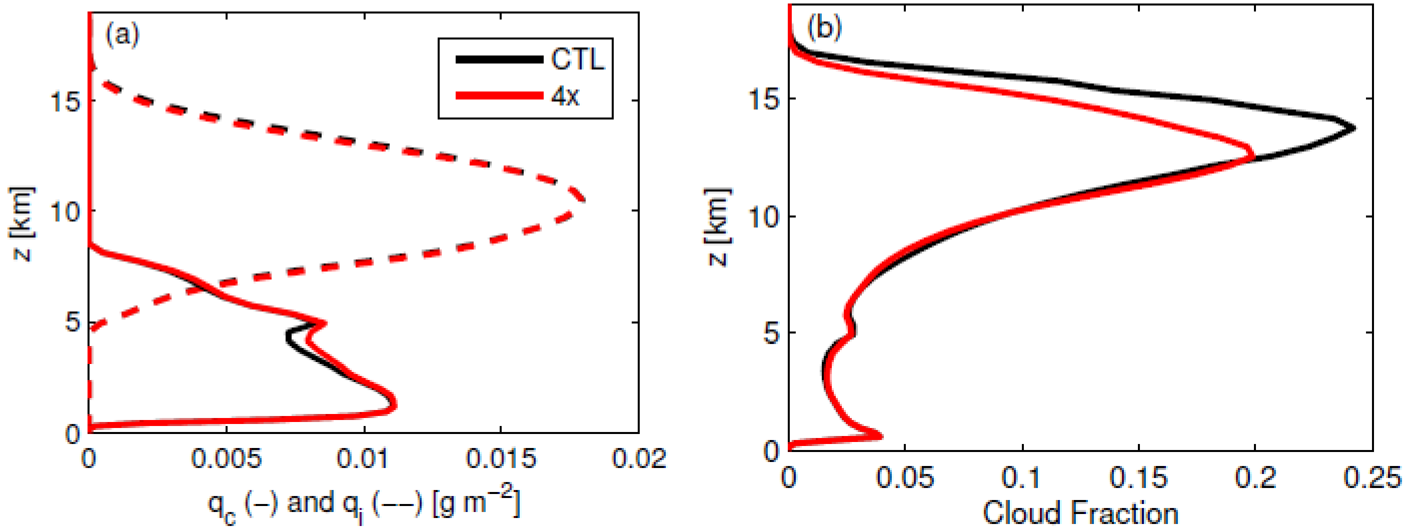


Figure 7. KWAJEX 50-day averaged profiles of (a) cloud water and ice profiles, and (b) cloud fraction.