Physics and dynamics coupling across scales in CESM: Meeting the challenge of high-resolution

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DoE Climate and Earth System Modeling PI Meeting, Washington DC, September 2011

New SciDAC project focused on global, uniform high-resolution atmospheric models

Outline

1) Some problems at high-resolution

2) This project
    A) Overview
    B) New Tools
        i) CAM-SE/HOMME
        ii) CLUBB
        iii) Sub columns/Flexible coupling
    C) Precipitation physics

3) Precipitation loading effects

Outline

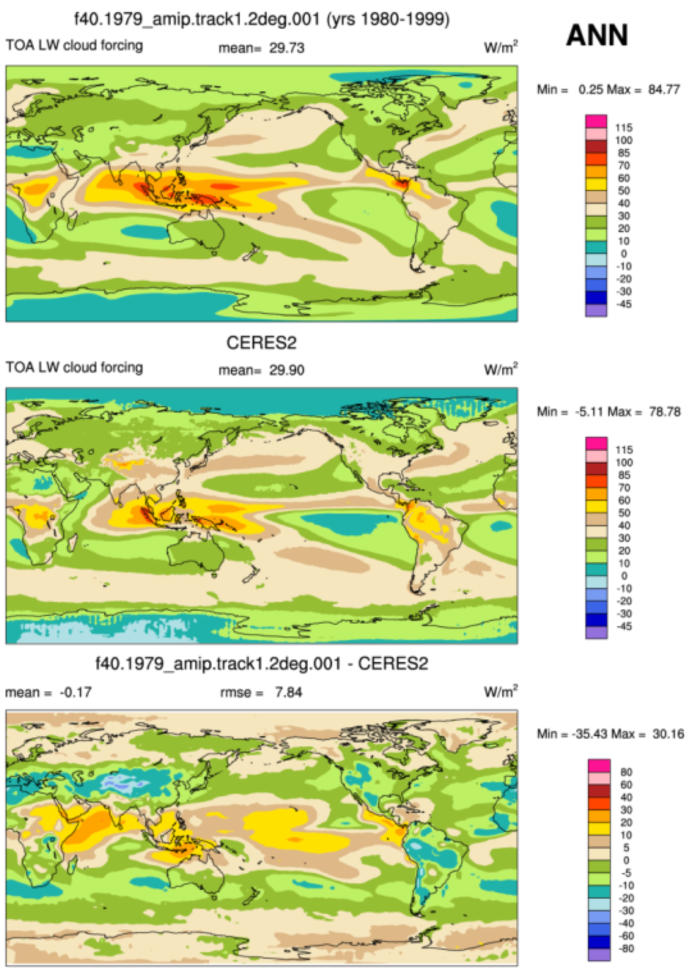
1) Some problems at high-resolution

Many things don't improve.

Some things get worse.

CAM 4 LWCF

2.0x2.5 degree

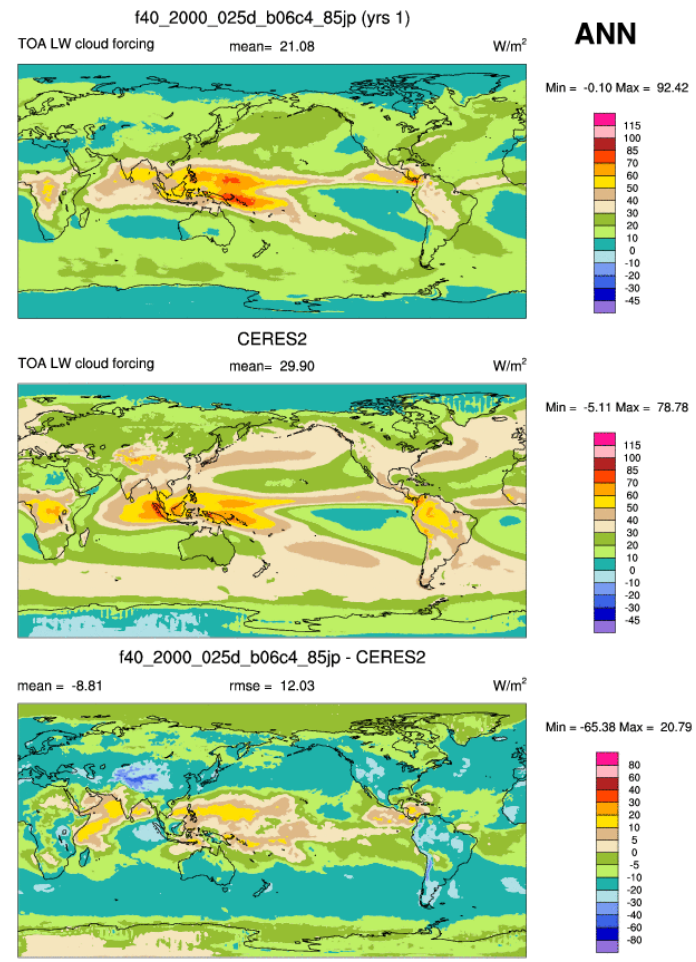


CAM

Obs.

Diff.

0.23x0.31 degree

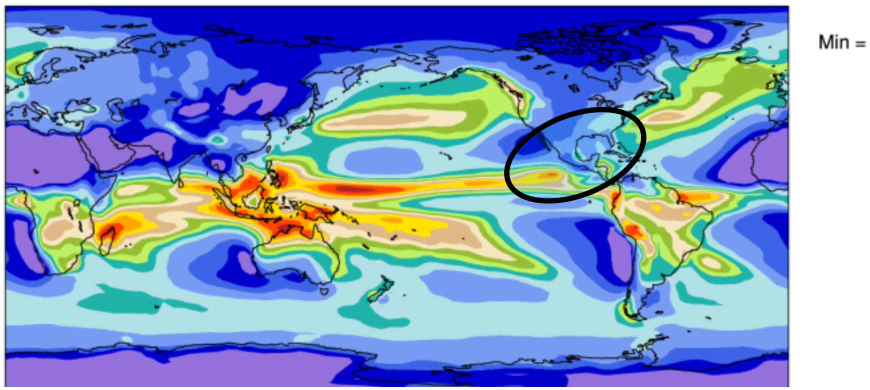


LWCF is well tuned at 2 degree resolution.
Drops sharply at 0.25 -- esp. in storm tracks
(30% global decrease, *factor of two in midlatitudes*)

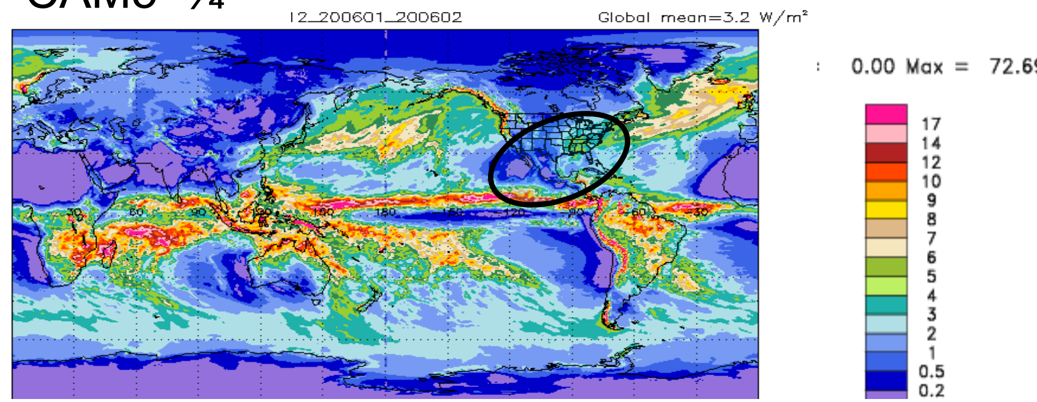
Precipitation patterns are relatively insensitive to resolution

Some improvement: *SE US winter precip up, NE tropical Pacific down. (Orography?)*

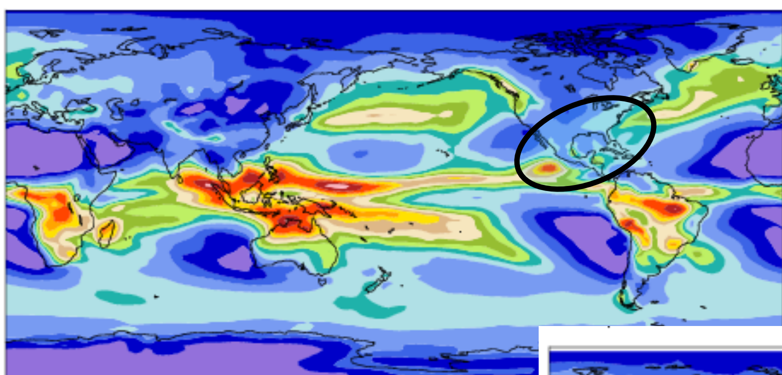
CAM5 2°



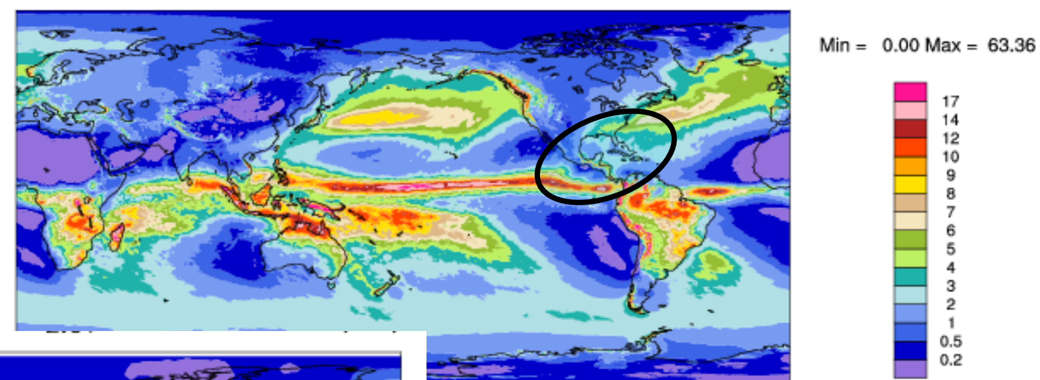
CAM5 ¼ °



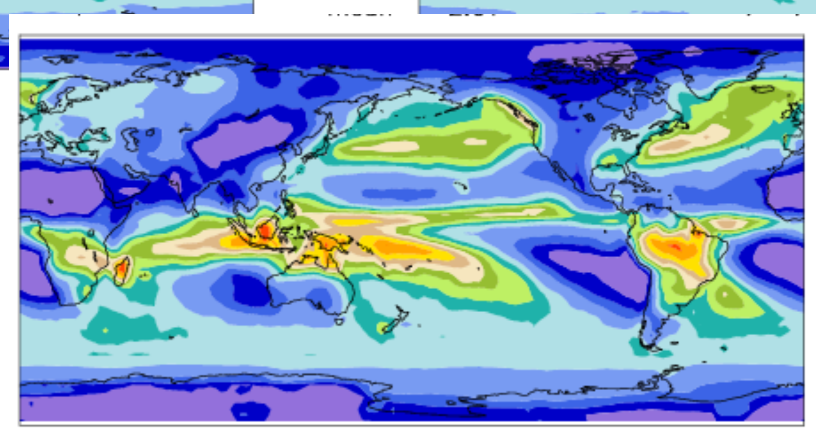
CAM4 2°



CAM4 ¼ °



GPCP obs.

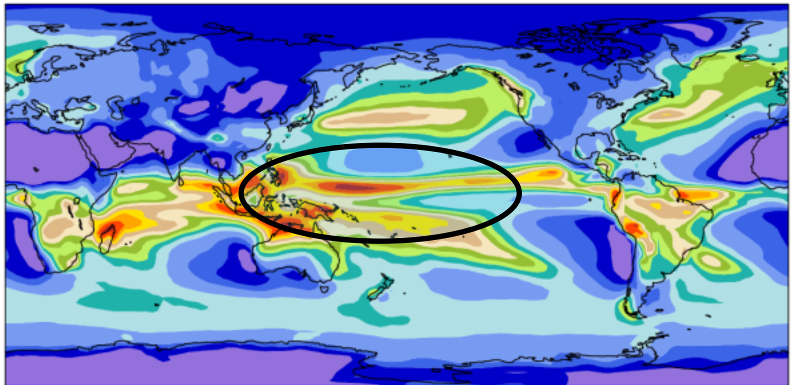


DJF

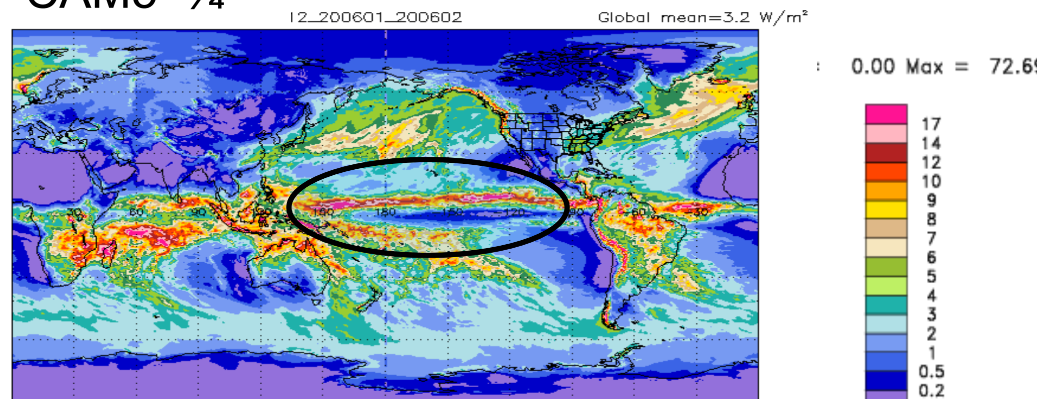
Precipitation patterns are relatively insensitive to resolution

Some degradation – *ITCZs intensified, more "doubled"*

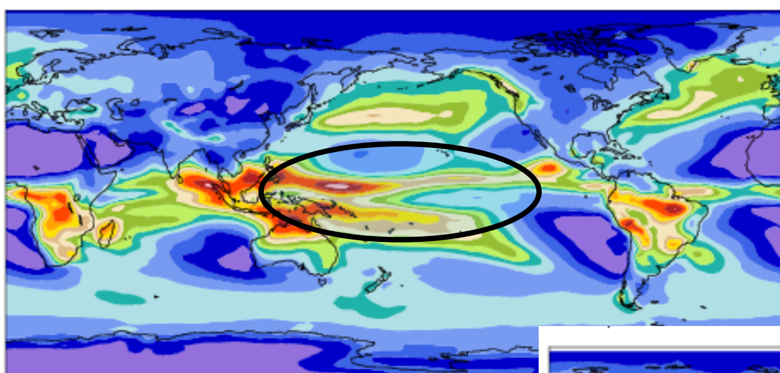
CAM5 2°



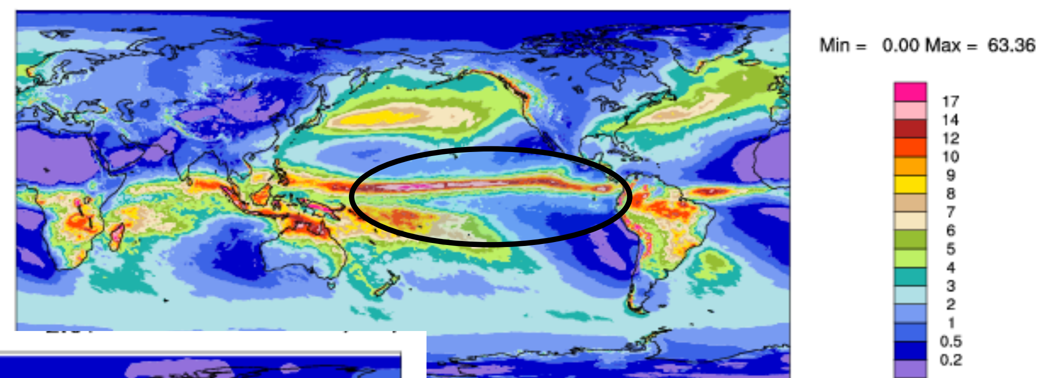
CAM5 ¼ °



CAM4 2°



CAM4 ¼ °



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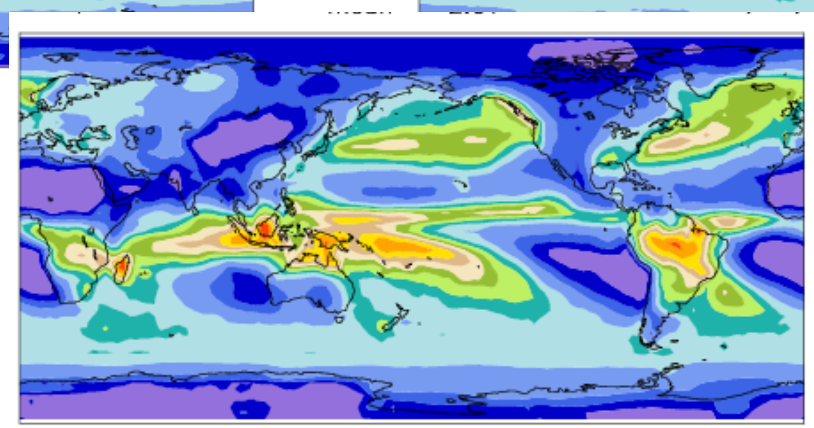

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Potential parameterization problems related to scale

Cloud “macro-physics”

- Fraction/variance schemes may not know about grid size

Cloud microphysics

- Nonlinear source/sink terms tuned for grid mean values
- Diagnostic vs prognostic precipitating species

Convection

- Insufficient sample size for equilibrium closures
- Local (gridcolumn-wise) compensating subsidence
- Inadequate plume model
- … … … ???

Gravity wave drag

- Effects confined to gridcolumns

All of these (+PBL and ShCu) may also lack memory across timesteps

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3) Precipitation loading effects

Project Overview

Goal: Improved performance for high-resolution (<25km) simulations using CAM-SE/HOMME

Approach(es): *Begin with CAM-5 physics*

Basic

- Prognostic precipitation including atmospheric mass contributions
  - *dry mass vertical coordinate*

New parameterizations

- CLUBB (prognostic PDF scheme)
- UNICON (dual plume convection scheme, S. Park)

New coupling strategies

- Sub-columns/flexible physics-dynamics grids

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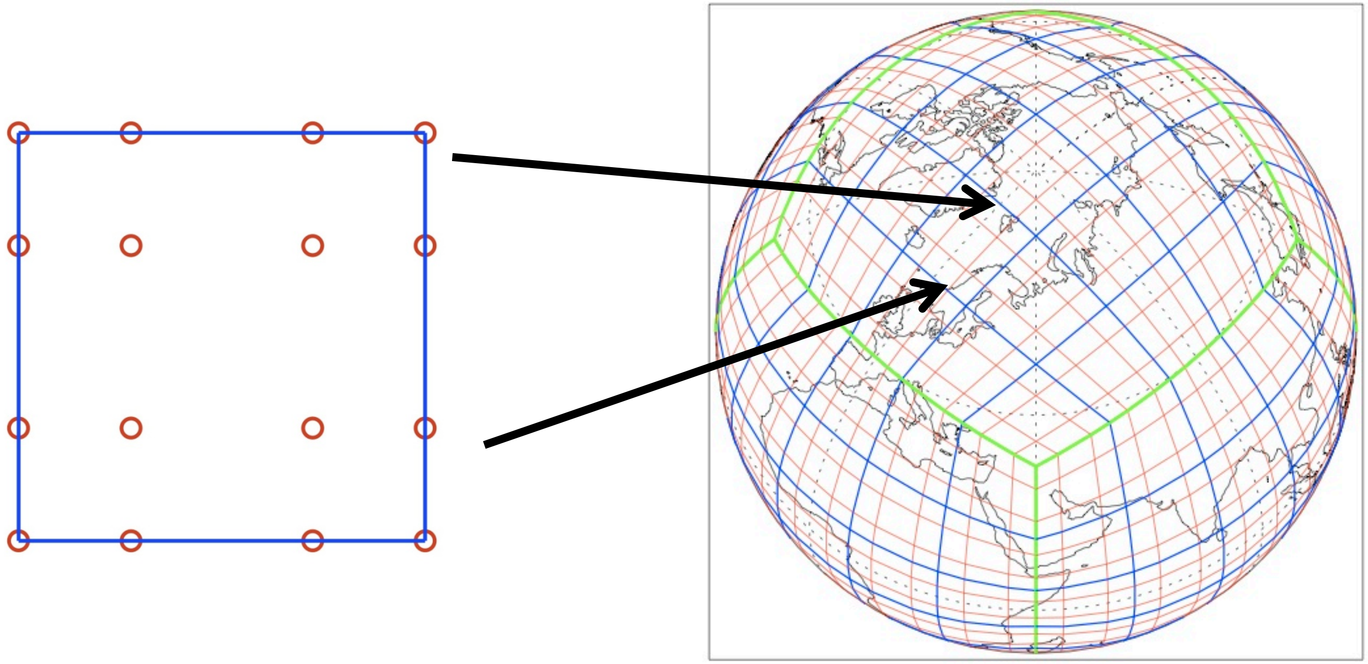
CAM-SE (spectral element) dynamical core

(M. Taylor)

$$\Psi_k(x,y) = \sum_{i+j\leq 3} c_{i,j} x^i y^j$$



Cloud Layers Unified by Binormals (CLUBB)

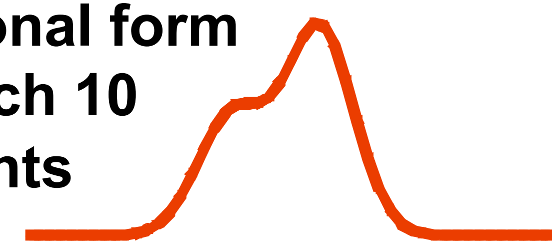
Joint PDFs of T,q,w with assumed, binormal shapes

(V. Larson)

Advance 10 prognostic equations

$\overline{w}, \overline{\theta_l}, \overline{q_t}, \overline{w'^2}, \overline{w'^3}, \overline{q_t'^2}, \overline{\theta_l'^2}, \overline{q_t'\theta_l'}, \overline{w'q_t'}, \overline{w'\theta_l'}$

Select PDF from given functional form to match 10 moments



Diagnose cloud fraction, liquid water from PDF

Δt

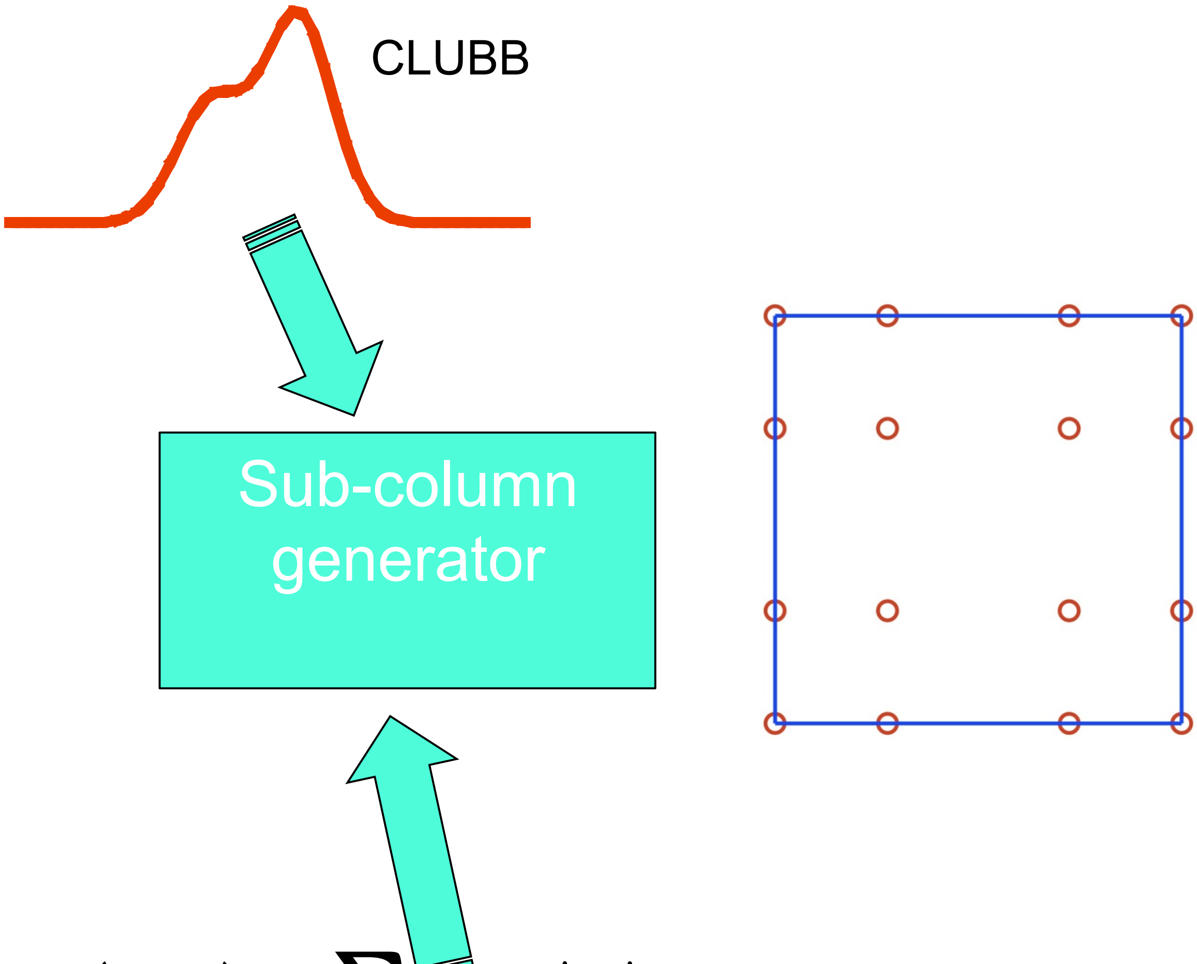
Use PDF to close higher-order moments, buoyancy terms

$\overline{w'q_t'^2}, \overline{w'\theta_l'^2}, \overline{w'q_t'\theta_l'}, \overline{w'^2q_t'}, \overline{w'^2\theta_l'}, \overline{w'^4}, \overline{q_t'\theta_v'}, \overline{\theta_l'\theta_v'}, \overline{w'\theta_v'}, \overline{w'^2\theta_v'}$

Can be used as a "traditional" parameterization of PBL, ShCu and cloud macrophysics, or as input for sub-column generation.

Sub-columns/Flexible coupling

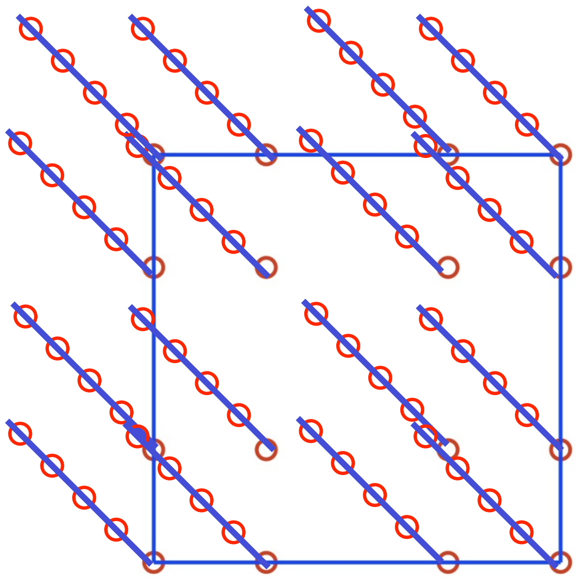
See poster (#6) by Vince Larson



$$\Psi_k(x,y) = \sum_{i+j\leq 3} c_{i,j}\,x^i y^j$$

SE polynomial reconstructions

Sub-columns/Flexible coupling



Sub-columns are drawn from scale aware sub-grid PDFs

Intended to represent scales down to CRM grid sizes

Should allow adoption of CRM-style microphysics with minimal retuning

Tuning is turned into a problem of generating sub-grid structure. _Easier to validate with data, CRM results_

Poor man's, statistically-driven superparameterization

Exploits SP-CAM infrastructure development (Gettelman)

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Precipitation dynamics

Current schemes in climate models are diagnostic due to large time-steps

Makes accurate treatment of processes like re-evaporation difficult

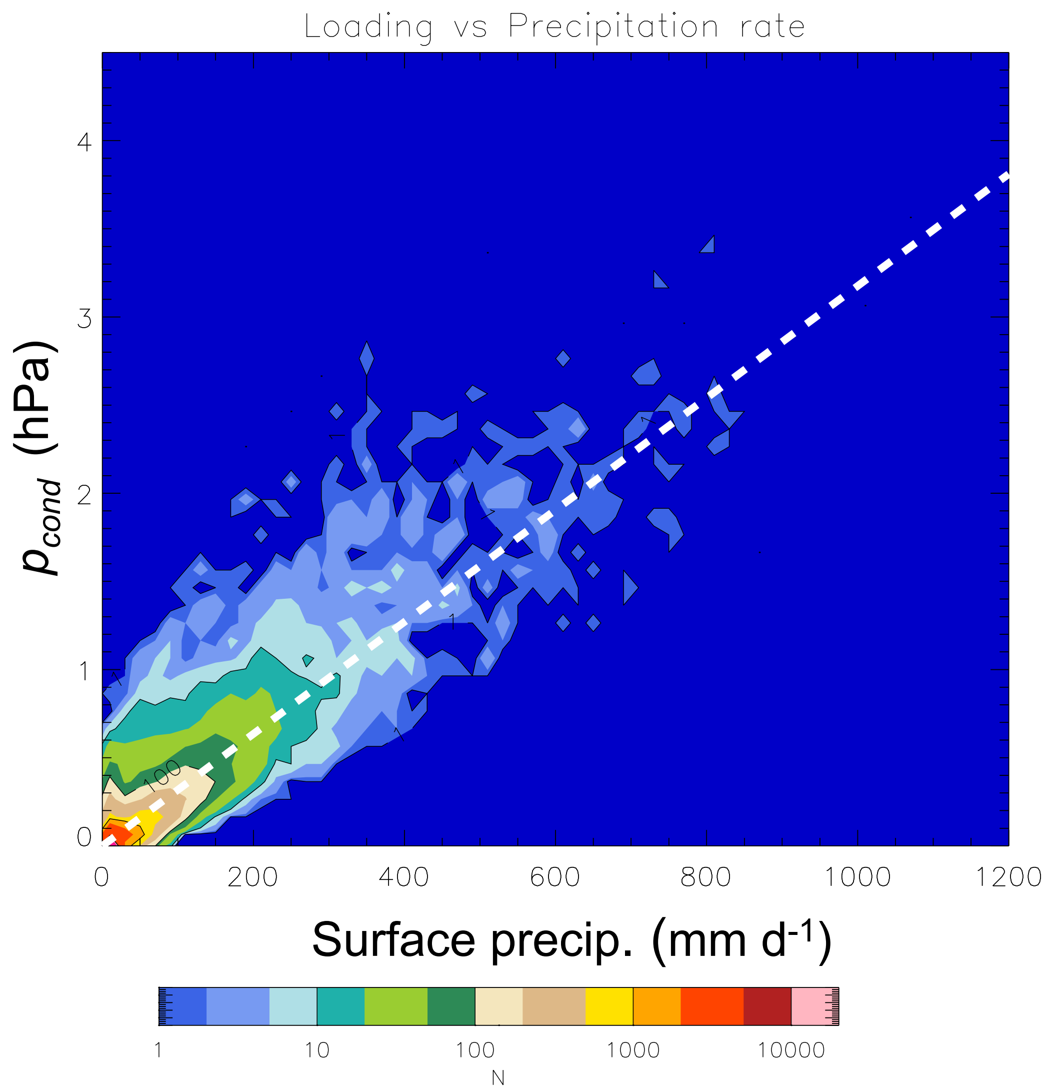
CAM ignores weight of precipitating condensates in pressure calculation

As part of this effort prognostic precipitation species will be incorporated in CAM microphysics. Initial implementation will probably rely on simple sub-stepping. Mass of precipitation will be included in pressure field

(Gettelman, Bacmeister,Truesdale)

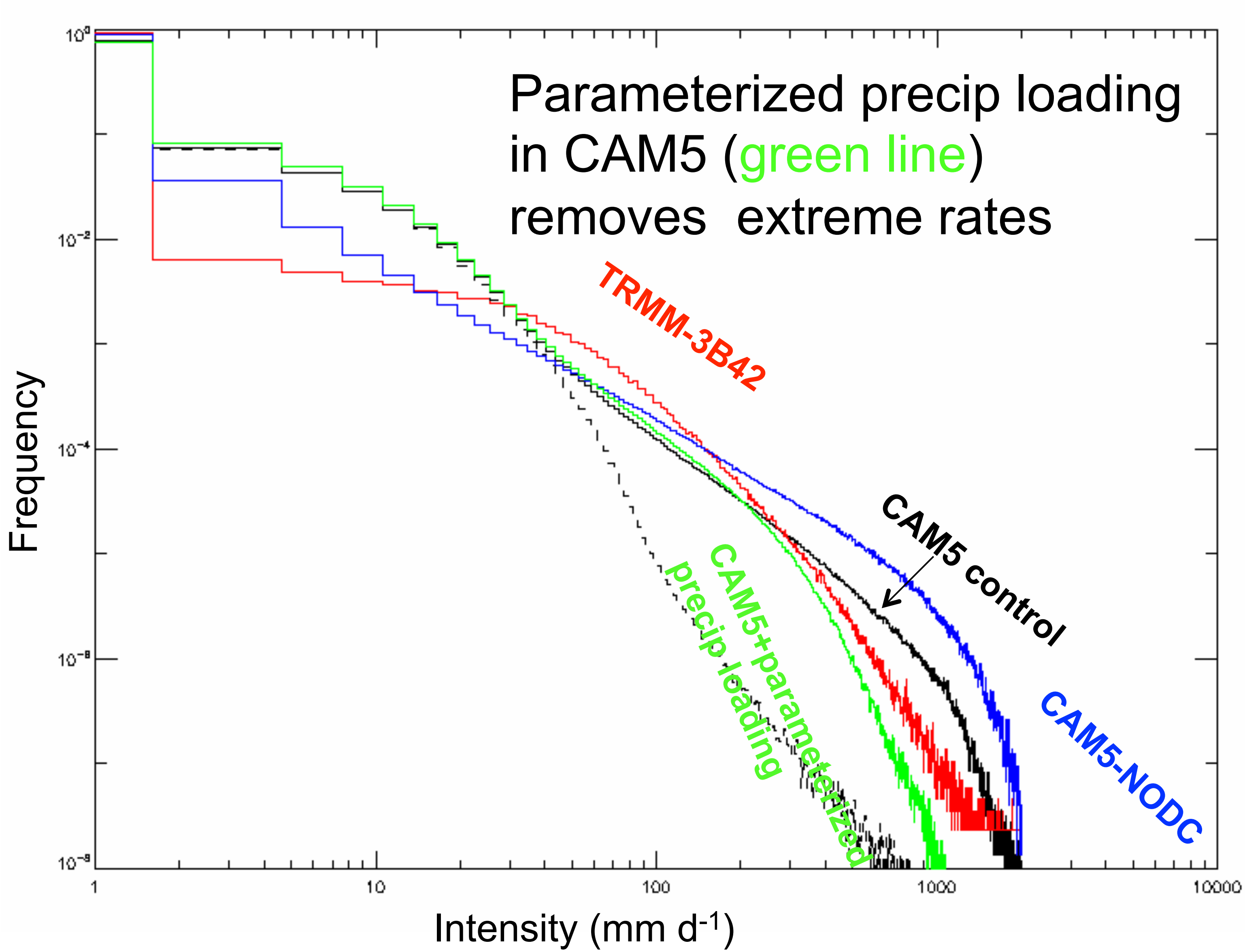
$$p_{cond} = \int_{z}^{z_{top}} g(\rho_l + \rho_i + \rho_r + \rho_s + \rho_{g,h})\, dz' \quad \text{vs Surface precip.}$$

Derived from 5 day, 500m WRF simulation results coarse grained to 25km

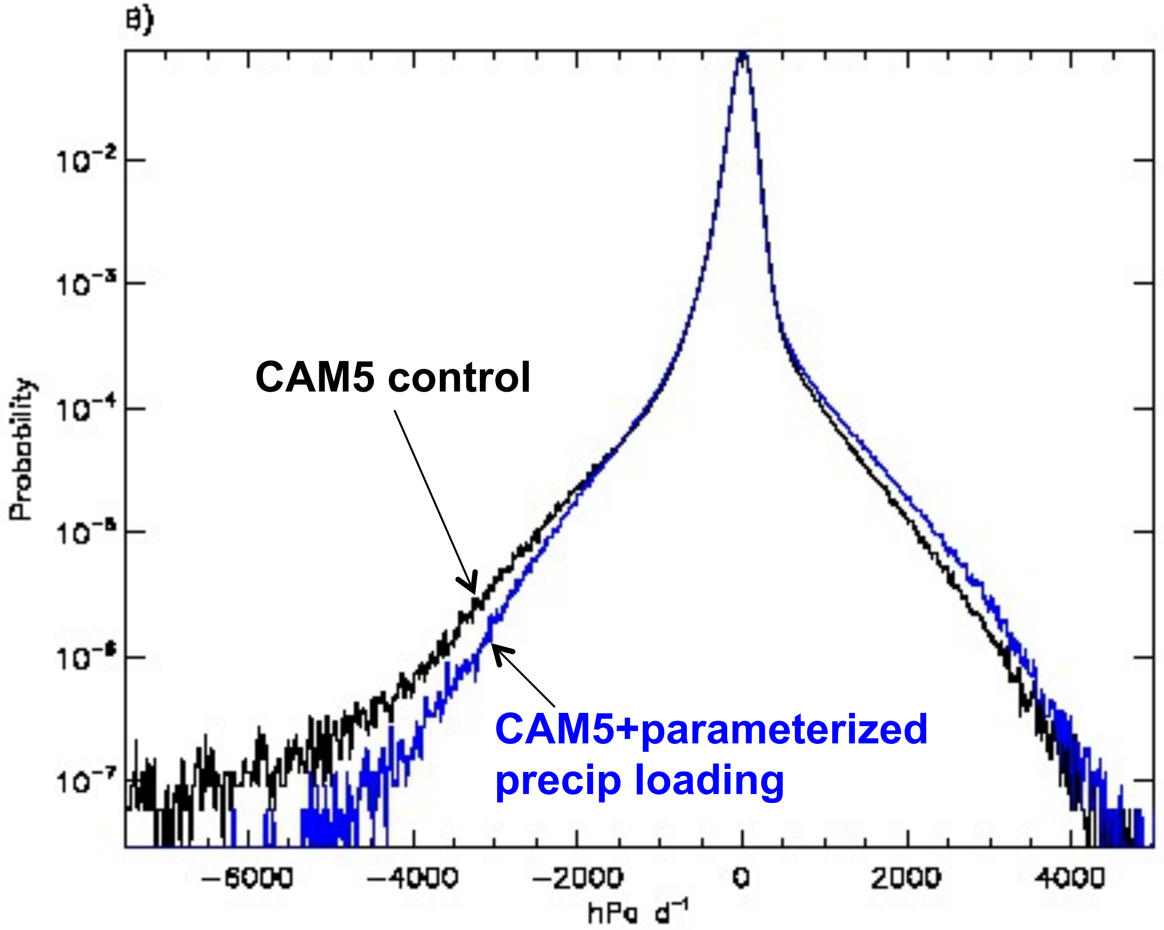


In this WRF simulation, nonhydrostatic effects were tiny compared to precip loading down to scales ~5 km

PDFs of tropical precipitation (30S-30N) rates Aug 2005



PDF of vertical motion at 850 hPa during August 2005



Effects on tropical cyclogenesis are under investigation

Re-evaporation could multiply direct loading effect by up to ~8x

"Issues"

Cost of sub-columns. Hope to keep globally-averaged number of *active* sub-columns small (3-5) then use some tricky load balancing

Validation. Initial targets are fast cloud and precipitation phenomena, e.g., intensity PDFs, diurnal cycles. Short CAPT-style comparisons with high-resolution satellite (e.g. CloudSat) and field measurements will be used. But sooner or later longer time scale behavior will need to be addressed

Summary

New project aimed at improved high-resolution atmospheric models.

Several development threads

- Better precipitation dynamics – *prognostic treatment, mass included in pressure*
- New parameterizations – *CLUBB prognostic PDF scheme, UNICON unified convection*
- New sub-column based coupling for physics

THANK YOU

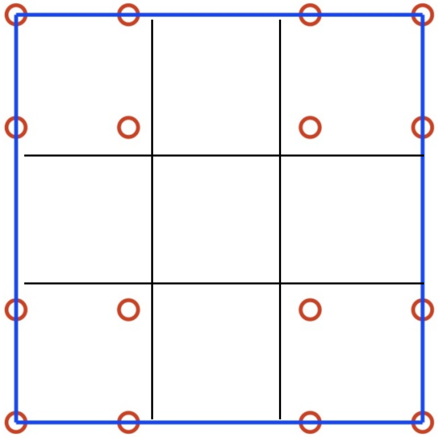
The NESL Mission is:
To advance understanding of weather, climate, atmospheric composition and processes;
To provide facility support to the wider community; and,
To apply the results to benefit society.

CLUBB to be implemented as a trad param as well as sub-column generator

Validation to take place initially in CAPT mode

Cost of sub-c is an issue

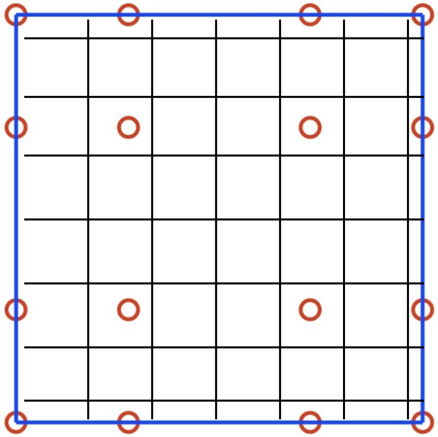
Sub-columns/Flexible coupling



Polynomial reconstructions allow straightforward generation of other physics-dynamics coupling structures, e.g. equal area averages

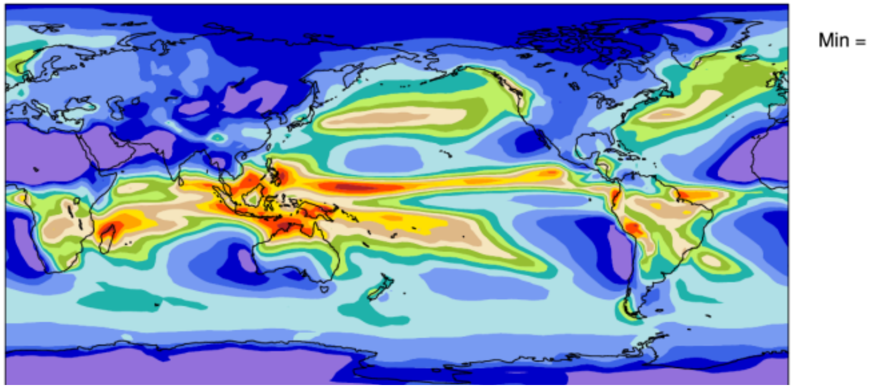
Exploits CSLAM development (Lauritzen, White)

Sub-columns/Flexible coupling

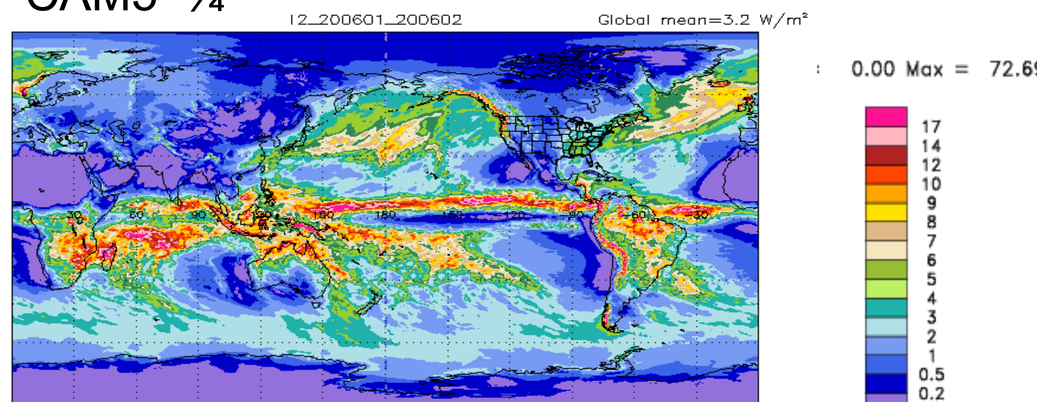


Precipitation patterns are relatively insensitive to resolution

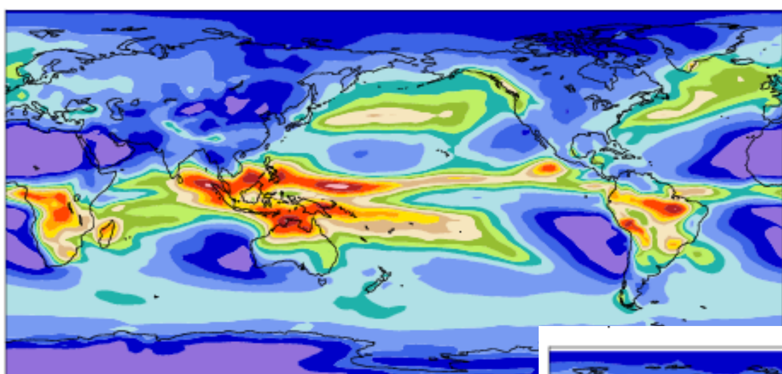
CAM5 2^o



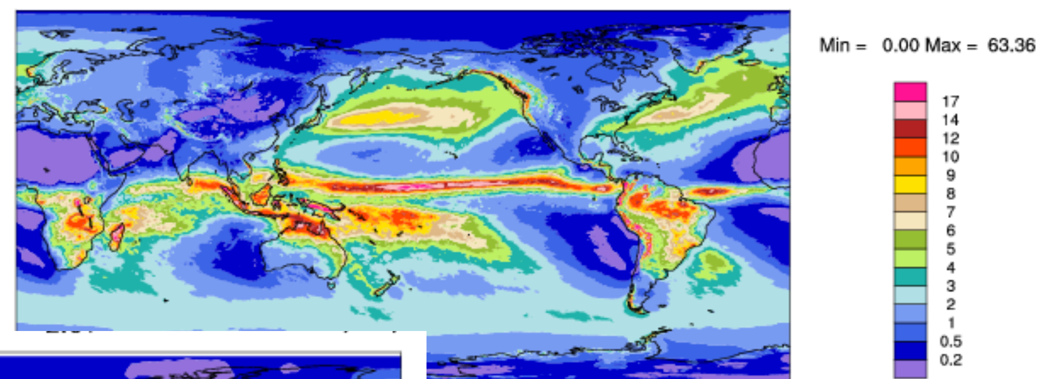
CAM5 ¼ ^{o}



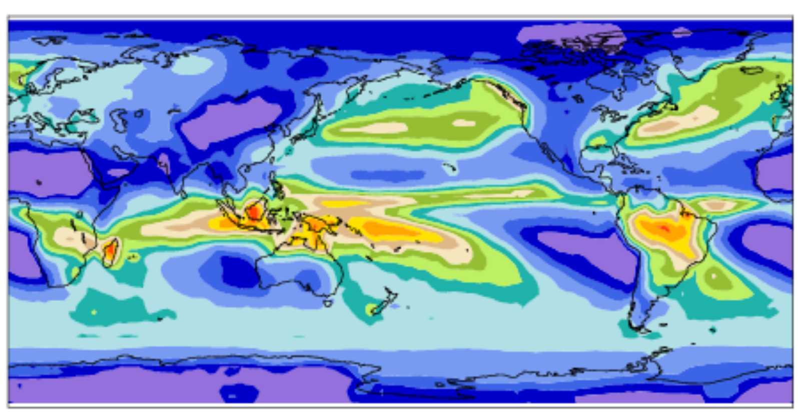
CAM4 2^o



CAM4 ¼ ^{o}

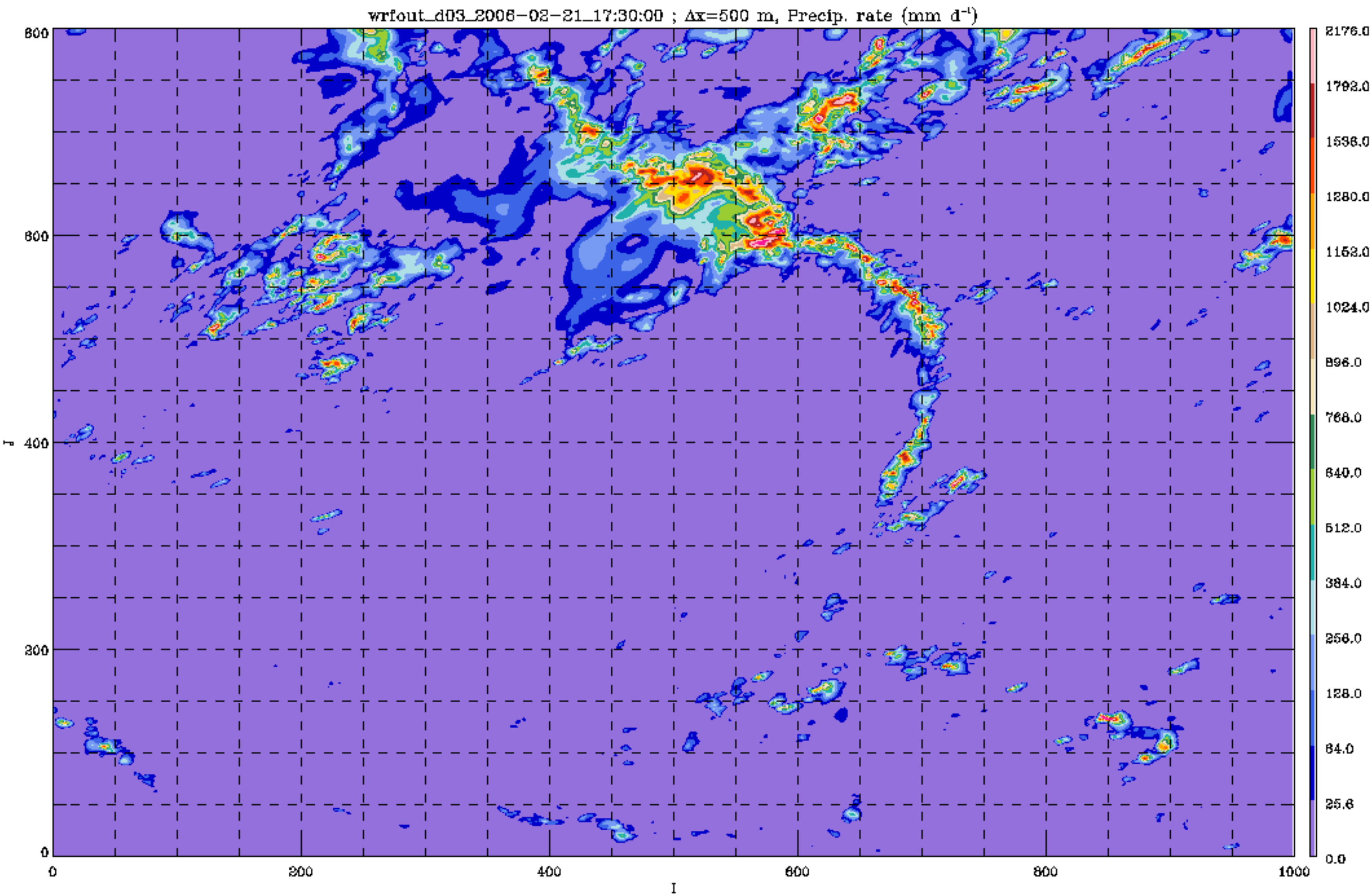


GPCP



DJF

15-min average precipitation rate (*Hong and Lim 2006 microphysics*)



Dashed lines show 50x50 gp (25km x 25km) squares used to coarse grain WRF fields to produce “high-res AGCM” fields

Hydrostatic Balance w/ and w/out condensate loading

$$\pi_{hyd} = \int_{z}^{z_{top}} \frac{g}{c_p \Theta_{\{v,cond\}}} dz' + \pi_{top}$$

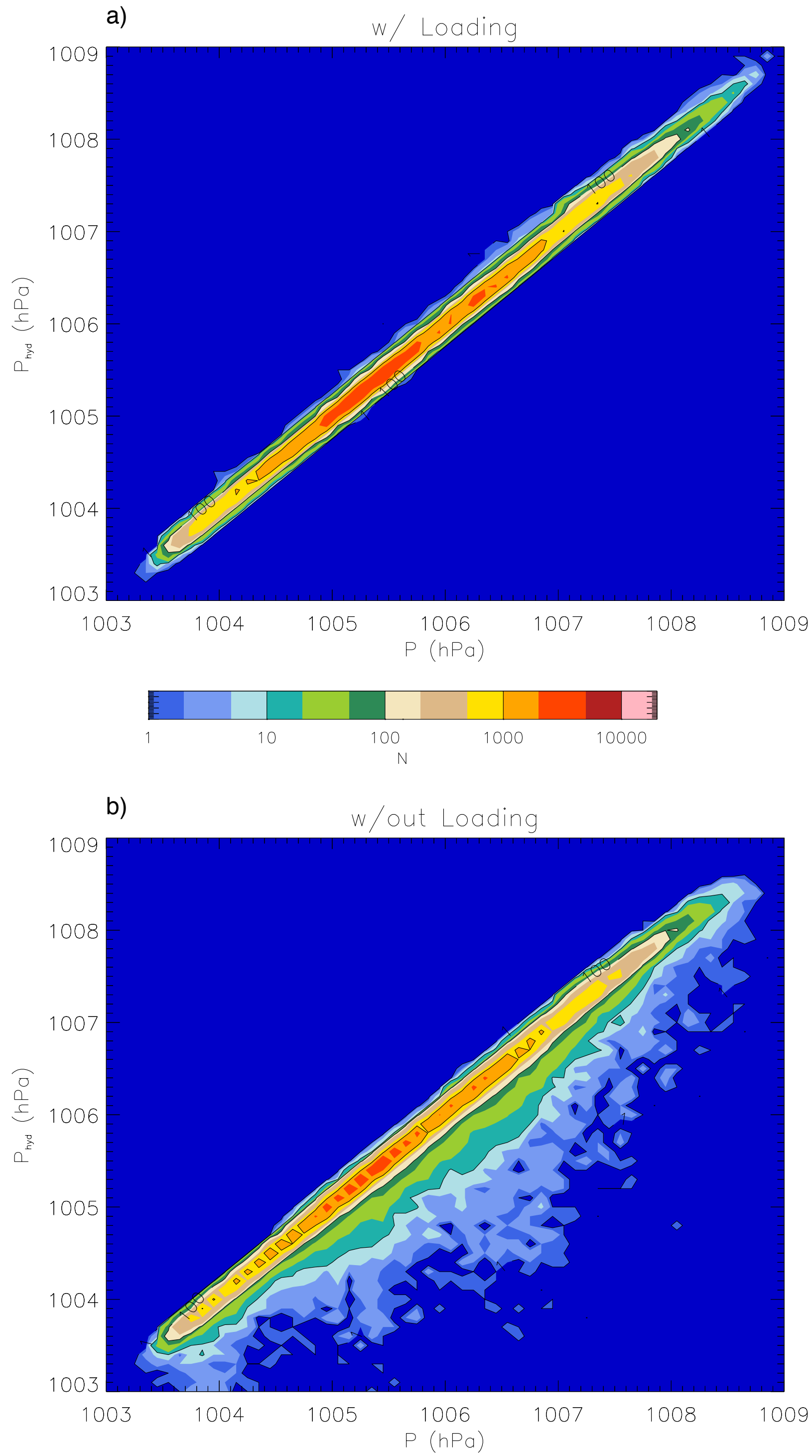
$$p_{hyd} = p_{00} \, \pi_{hyd}^{\;1/\kappa}$$

w/out loading:

$$\Theta_v = \Theta\left(1. + 0.61q\right)$$

with loading:

$$\Theta_{cond} = \Theta\left(1. + 0.61q - q_{liq} - q_{ice} - q_{rain} - q_{graup} - q_{snow}\right)$$


a)
w/ Loading
1009
1008
1007
1006
1005
1004
1003
P_{hyd} (hPa)
1003 1004 1005 1006 1007 1008 1009
P (hPa)
100
1
10
100
1000
10000
N
b)
w/out Loading
1009
1008
1007
1006
1005
1004
1003
P_{hyd} (hPa)
1003 1004 1005 1006 1007 1008 1009
P (hPa)
100