An economical PDF-based turbulence closure model for cloud-resolving models and global climate models

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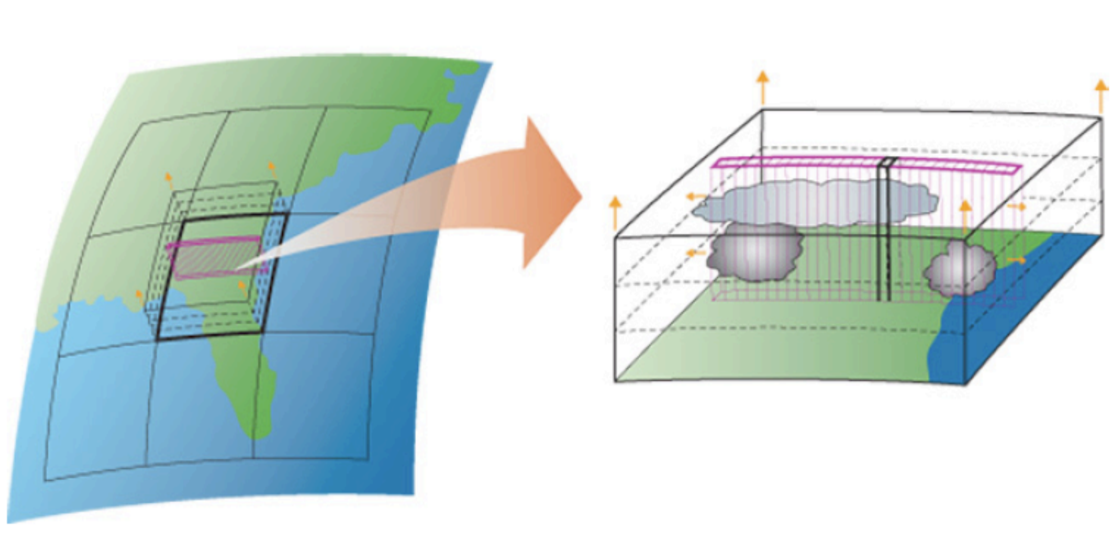
Introduction

Boundary Layer Clouds in GCMs

- Representation of boundary layer clouds in GCMs has long been the bane of climate modelers.
- MMF offers new avenues to boundary layer cloud representation in GCMs.
- In MMF, the problem becomes improving boundary layer cloud representation in coarse-grid CRMs (i.e., deep convection permitting models) in an economical way.

Multiscale Modeling Framework (MMF) embeds a 2D CRM (dx ~ 4 km) in every GCM grid column.



- Our approach has been to integrate several existing components:
  - A **prognostic SGS TKE** equation.
  - The **assumed PDF** method of Golaz et al. (2002).
  - The **diagnostic second-moment closure** of Redelsperger and Sommeria (1986).
  - The **diagnostic closure for <w'w'w'>** by Canuto et al. (2001).
  - A **turbulence length scale** related to the square root of SGS TKE (Teixeira and Cheinet 2004) and eddy length scales.
- We implemented our approach in a CRM and **tested** it **using LES** (Bogenschutz and Krueger 2013).
- We also **implemented** it **in a MMF.**

SAM-PDF: Design

Standard SAM vs SAM-PDF

The CRM that we used is SAM (System for Atmospheric Modeling) developed by Marat Khairoutdinov (Khairoutdinov and Randall 2003). SAM-PDF incorporates our new turbulence closure model.

- **Standard SAM**
  - SGS TKE is prognosed.
  - Length scale is specified as dz (or less in stable grid boxes).
  - No SGS condensation.
  - SGS buoyancy flux is diagnosed from moist Brunt Vaisala frequency.
- **SAM-PDF**
  - SGS TKE is prognosed.
  - Length scale is related to SGS TKE and eddy length scales.
  - SGS condensation is diagnosed from assumed joint PDF.
  - SGS buoyancy flux is diagnosed from assumed joint PDF.
  - Add'l moments req'd by PDF closure are diagnosed, so ***no additional prognostic equations are needed.***

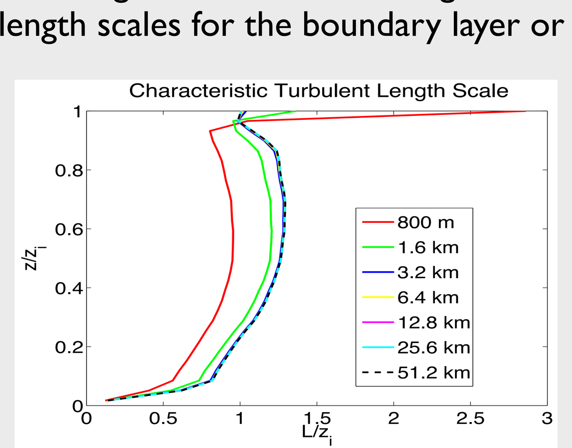
Turbulence Length Scale

- Need to parameterize dissipation rate and eddy diffusivity:

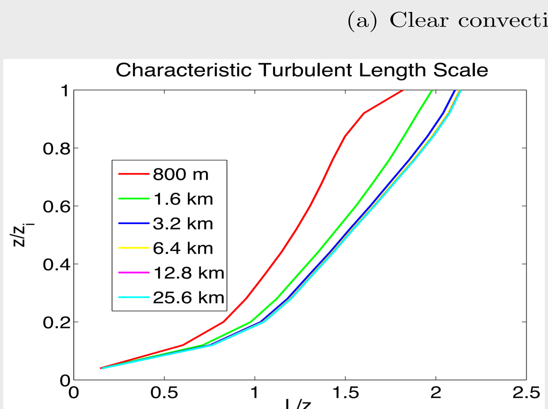
$$\epsilon = \frac{\bar{e}^{3/2}}{L} \qquad K_H = 0.1 L \bar{e}^{1/2}$$

- Cheng et al. (2010) showed that eddy diffusivity schemes function well if the profile of SGS TKE is correct.
- Teixeira & Cheinet (2004) showed that $L = \tau\sqrt{e}$ works well for the convective boundary layer.
- We formulated a general turbulence length scale related to $\sqrt{e}$ and eddy length scales for the boundary layer or the cloud layer.

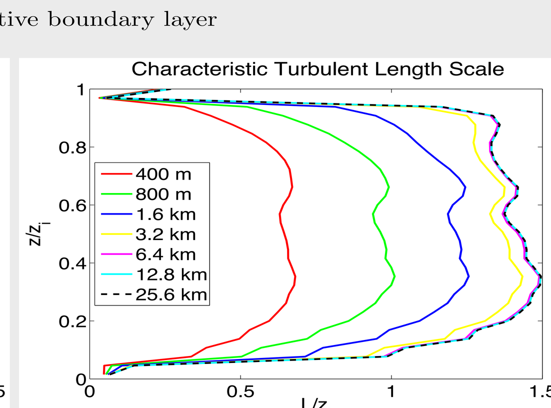
Turbulence length scale *diagnosed* from LES for various CRM grid sizes.



(a) Clear convective boundary layer

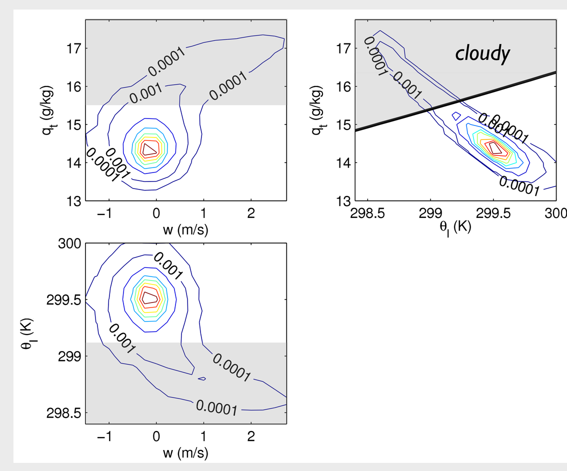


(b) Trade cumulus mixed layer



(c) Stratocumulus mixed layer

SAM-PDF: Shallow Cu



Projections of $P(w, \theta_l, q_t)$, the joint pdf, computed from a BOMEX LES in mid-cloud layer. The cloudy mass flux is given by

$$M_c = \rho \int\int\int w\, I_c(w, \theta_l, q_t, p) \times P(w, \theta_l, q_t)\, dw\, d\theta_l\, dq_t$$

where $I_c = 1$ in-cloud, 0 otherwise.

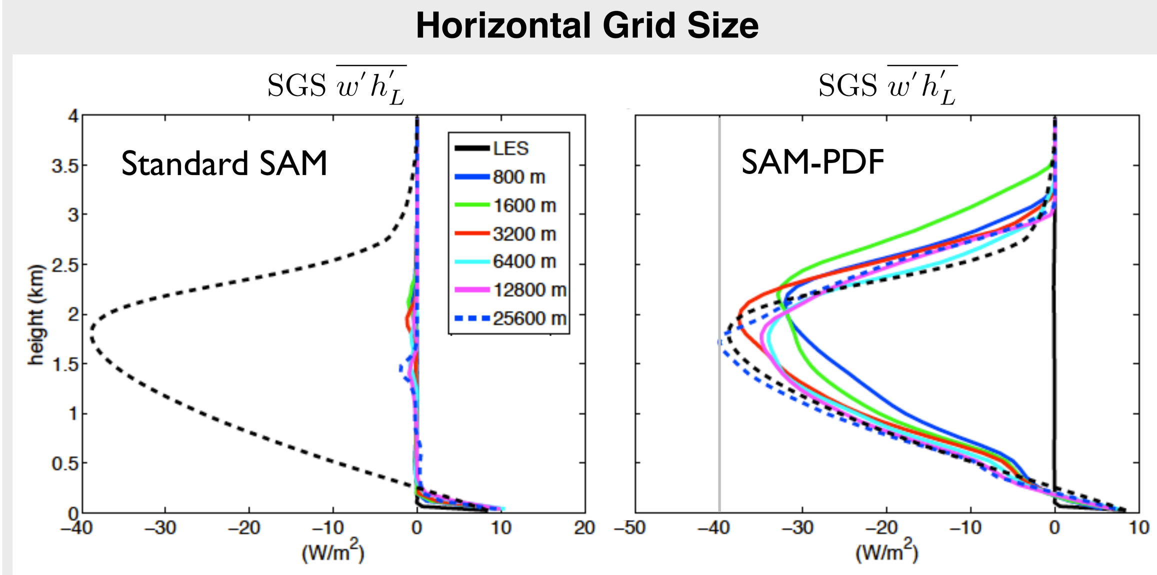
LES Benchmarks

- The following LES cases have been used to test SAM-PDF in a 2D CRM configuration:
  - Clear convective boundary layer (Wangara)
  - Trade-wind cumulus (BOMEX)
  - **Precipitating cumulus (RICO)**
  - Continental cumulus (ARM)
  - **Stratocumulus to cumulus transition**
  - Deep convection (GATE) "Giga-LES"

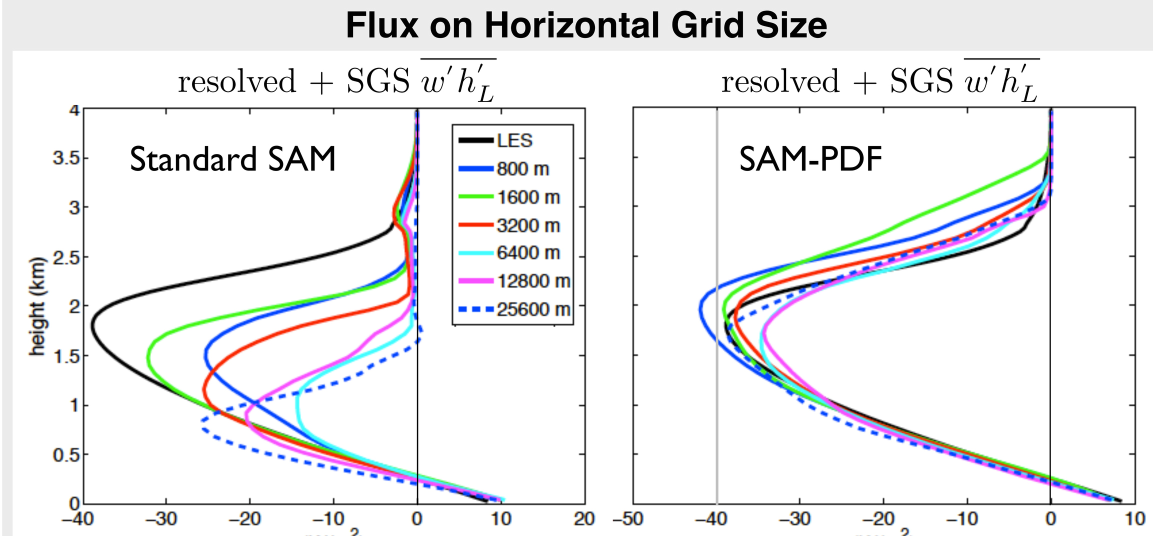
RICO: Precipitating Trade-Wind Cumulus

- LES: dz = 40 m, dx = 100 m
- 2D CRM: dz = 100 m, dz = 0.8 km to 25.6 km

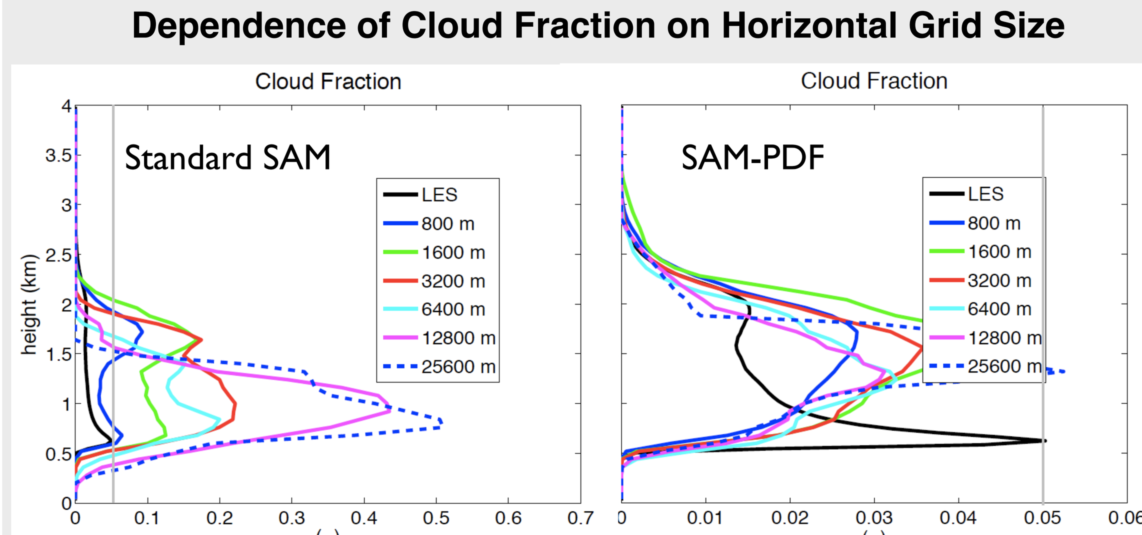
Dependence of SGS Liquid Water Static Energy Flux on Horizontal Grid Size



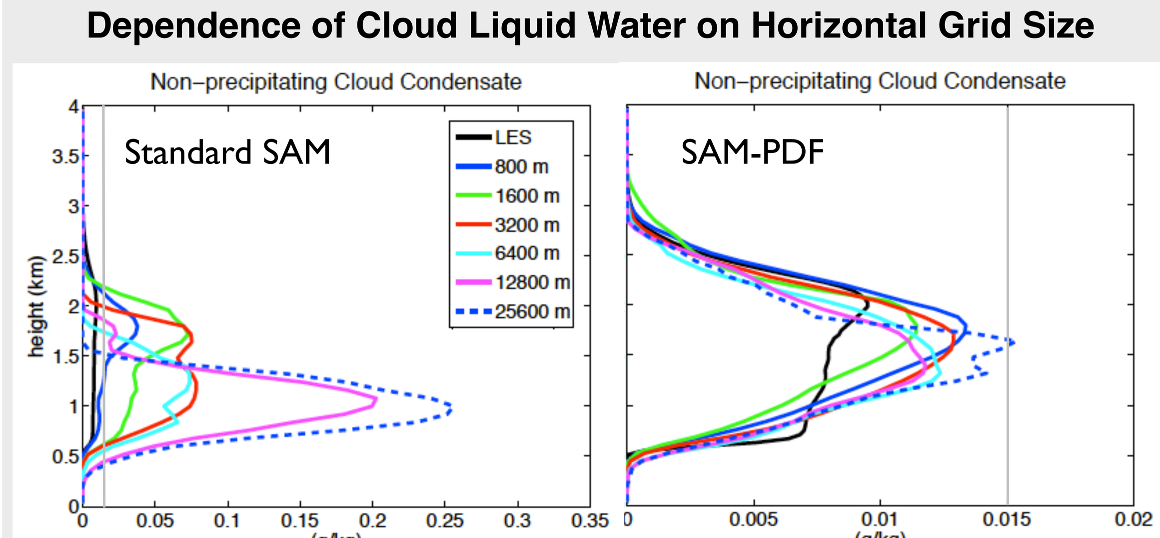
Dependence of Total (Resolved + SGS) Liquid Water Static Energy Flux on Horizontal Grid Size



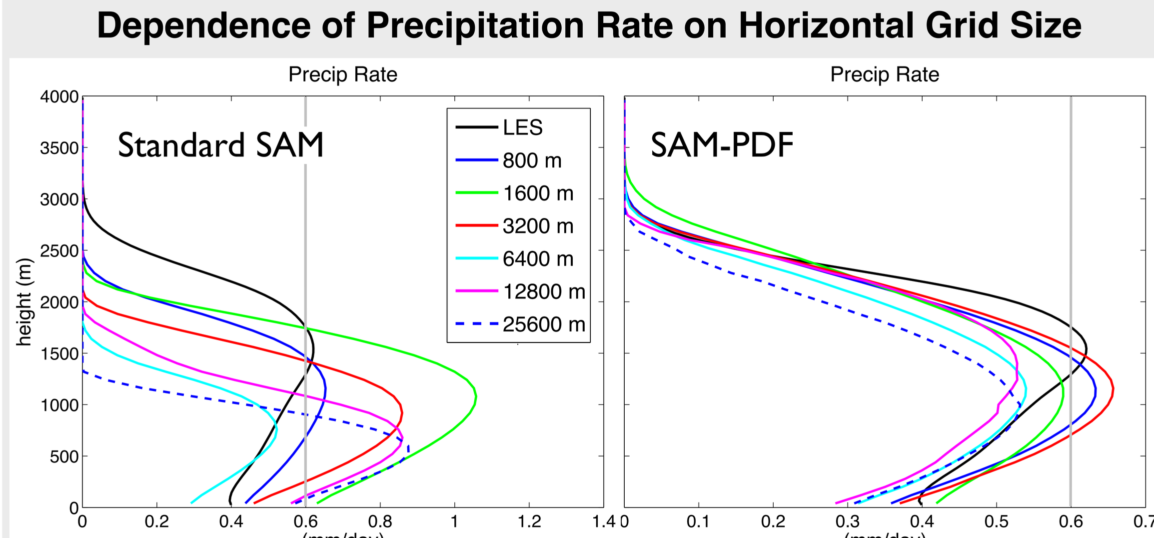
Dependence of Cloud Fraction on Horizontal Grid Size



Dependence of Cloud Liquid Water on Horizontal Grid Size

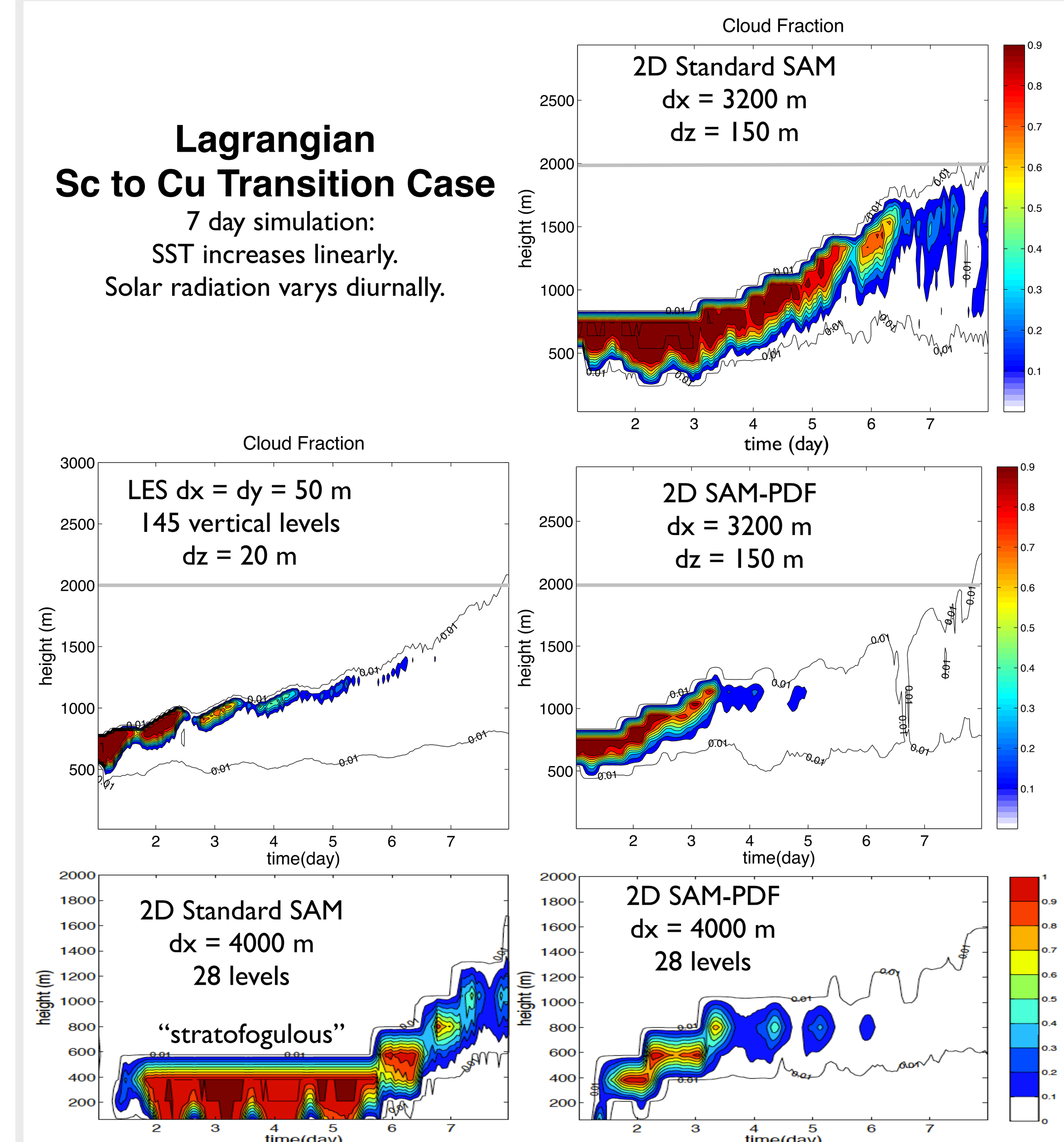


Dependence of Precipitation Rate on Horizontal Grid Size



Observed surface precip rate was ~0.3 mm/day.

SAM-PDF: Sc to Cu



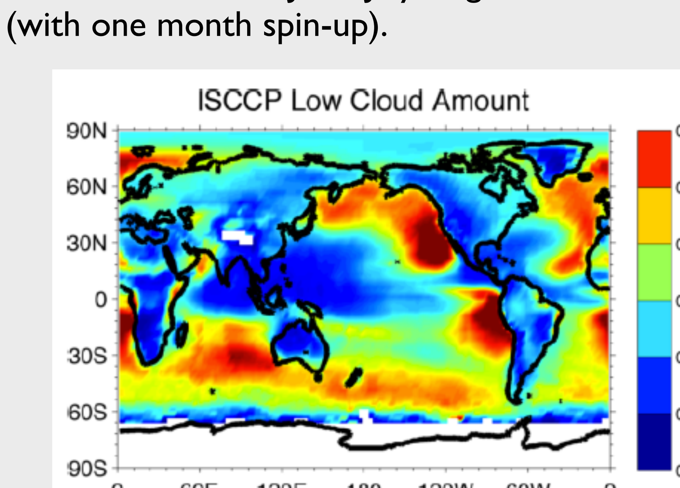
With MMF Vertical Grid Spacing (dz ~ 200-300 m in boundary layer)

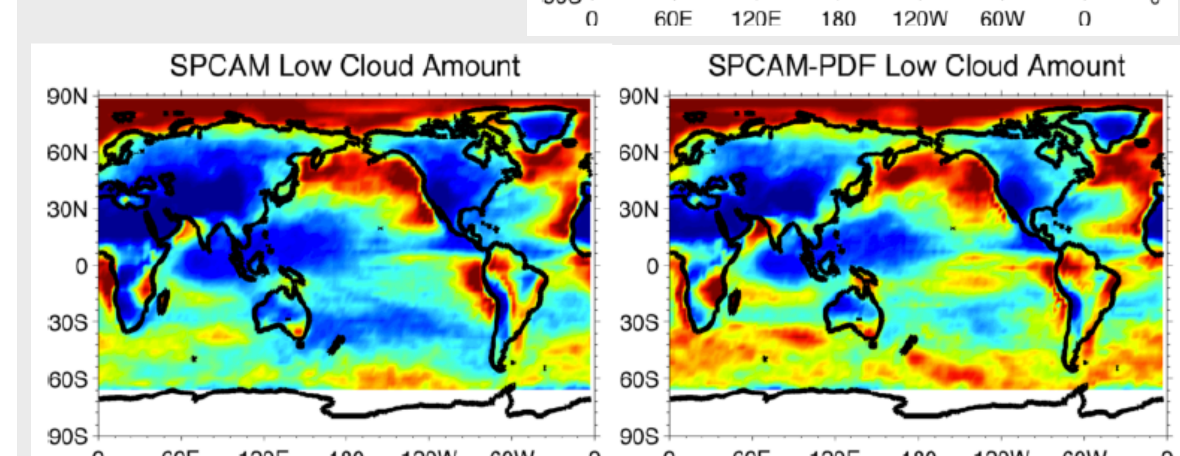
MMF-PDF

Preliminary Test of Closure within MMF

- Code implemented in the embedded CRMs within the MMF.
- SGS cloud fraction and liquid water content passed to radiation code (computed on the CRM grid every 15 minutes).
- SPCAM & SPCAM-PDF run in T42 configuration with 30 vertical levels (embedded CRM: dx = 4 km, dz ~ 200-300 m in boundary layer).
- Preliminary results below are from June, July, August (JJA) simulation (with one month spin-up).

In MMF-PDF, shallow Cu are improved by the new turbulence model but Sc are still severely under-represented, likely due to inadequate vertical resolution.





Summary

- SAM-PDF includes these desirable features:
  - A diagnostic higher-order closure with assumed double Gaussian joint PDF.
  - A turbulence length scale that depends on SGS TKE and large-eddy length scales.
  - It can realistically represent many boundary layer cloud regimes in models with $\Delta x \sim$ 0.5 km or larger, with virtually no dependence on horizontal grid size.
  - It is economical, with potential for easy portability to other explicit-convection models (e.g., WRF, GCRMs) and GCMs.

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