Improving Turbulence and Cloud Representation...

...Without Breaking the Bank

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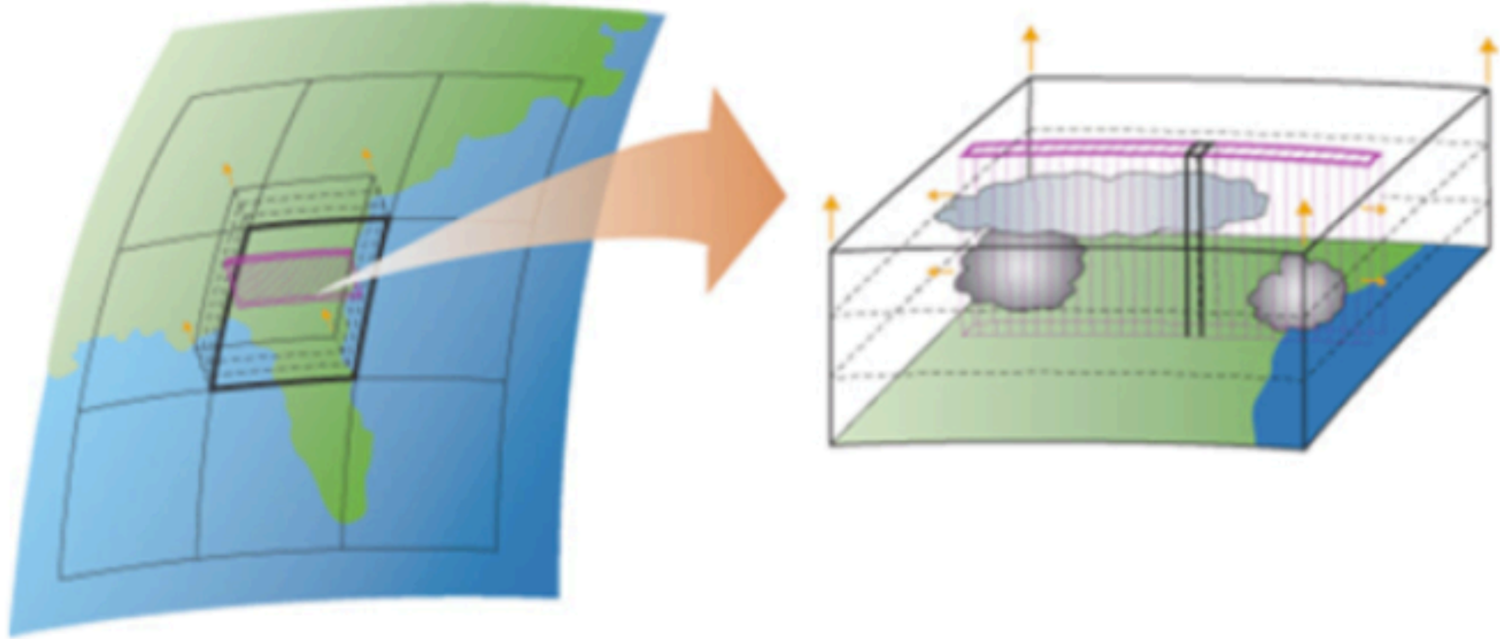
CMMAP

Reach for the sky.

Winter CMMAP Team Meeting

Berkeley, CA January 12, 2011

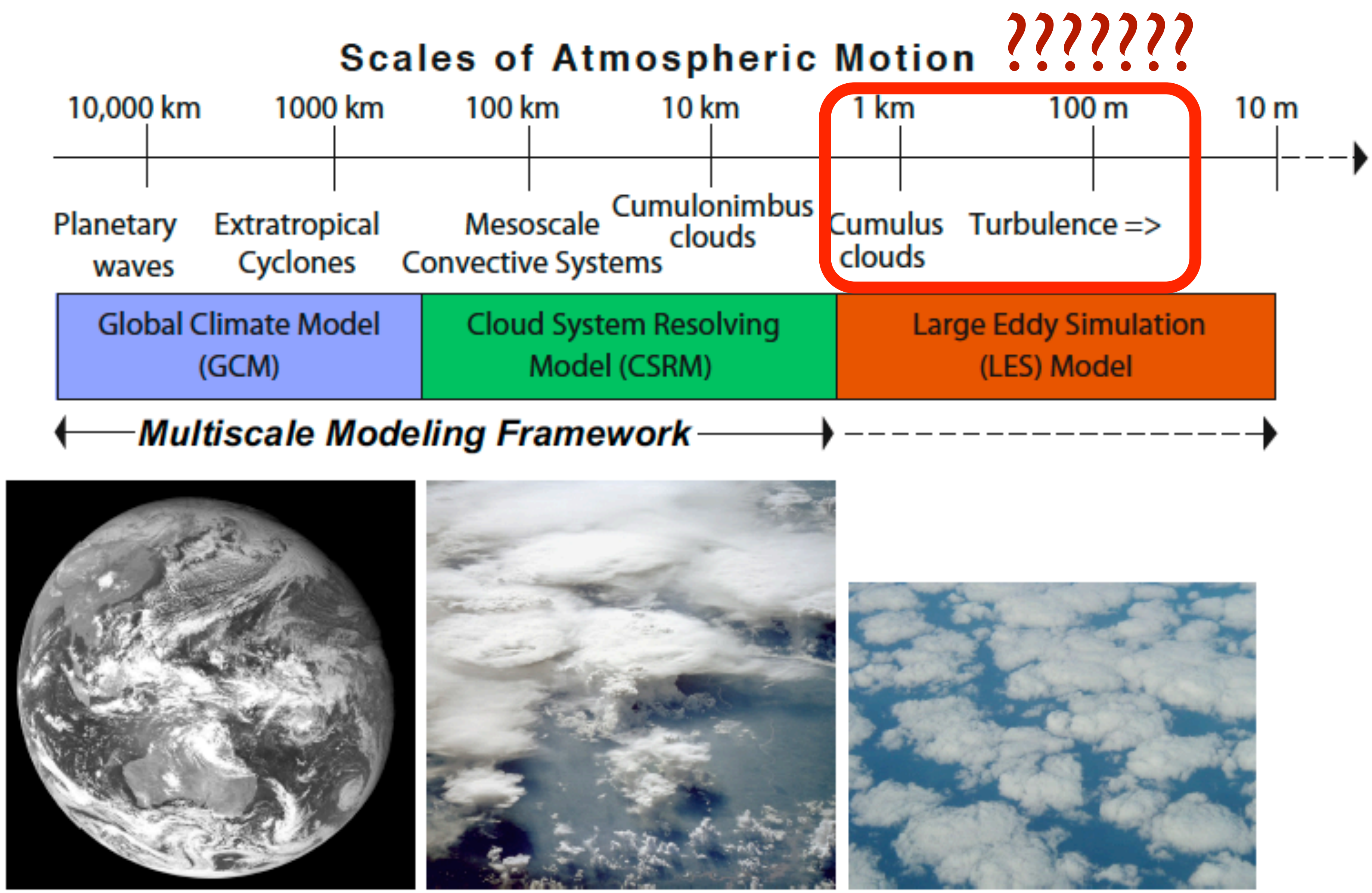
Multiscale Modeling Framework



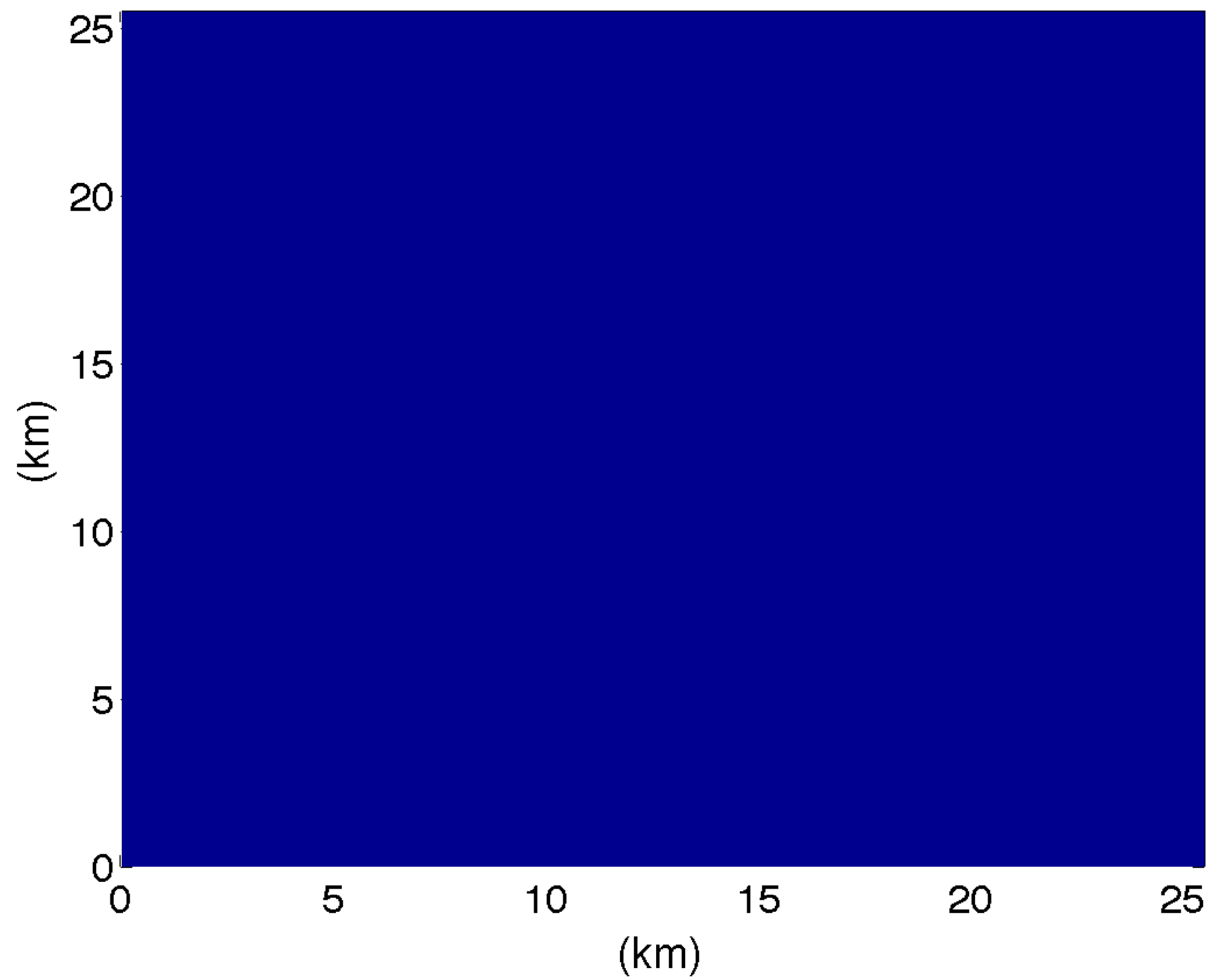
Embedded cloud resolving model (CRM) is System for Atmospheric Modeling (SAM)

CRM typically run with 4 km horizontal grid size and in two-dimension configuration

What can we "get" out of a 4 km grid spacing?



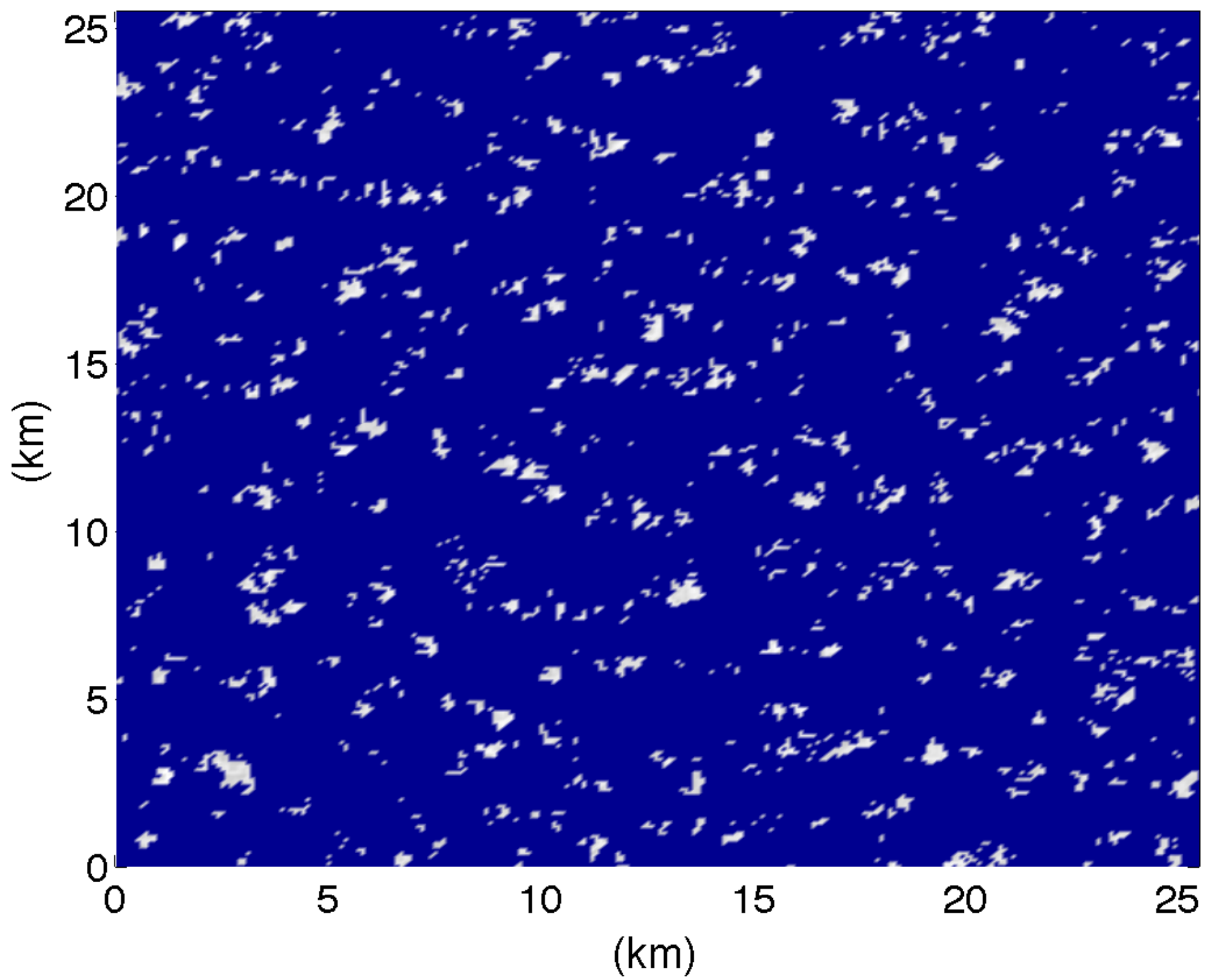
Cloud Resolving? (a simple example)



Start with an ocean surface
(birds-eye view)

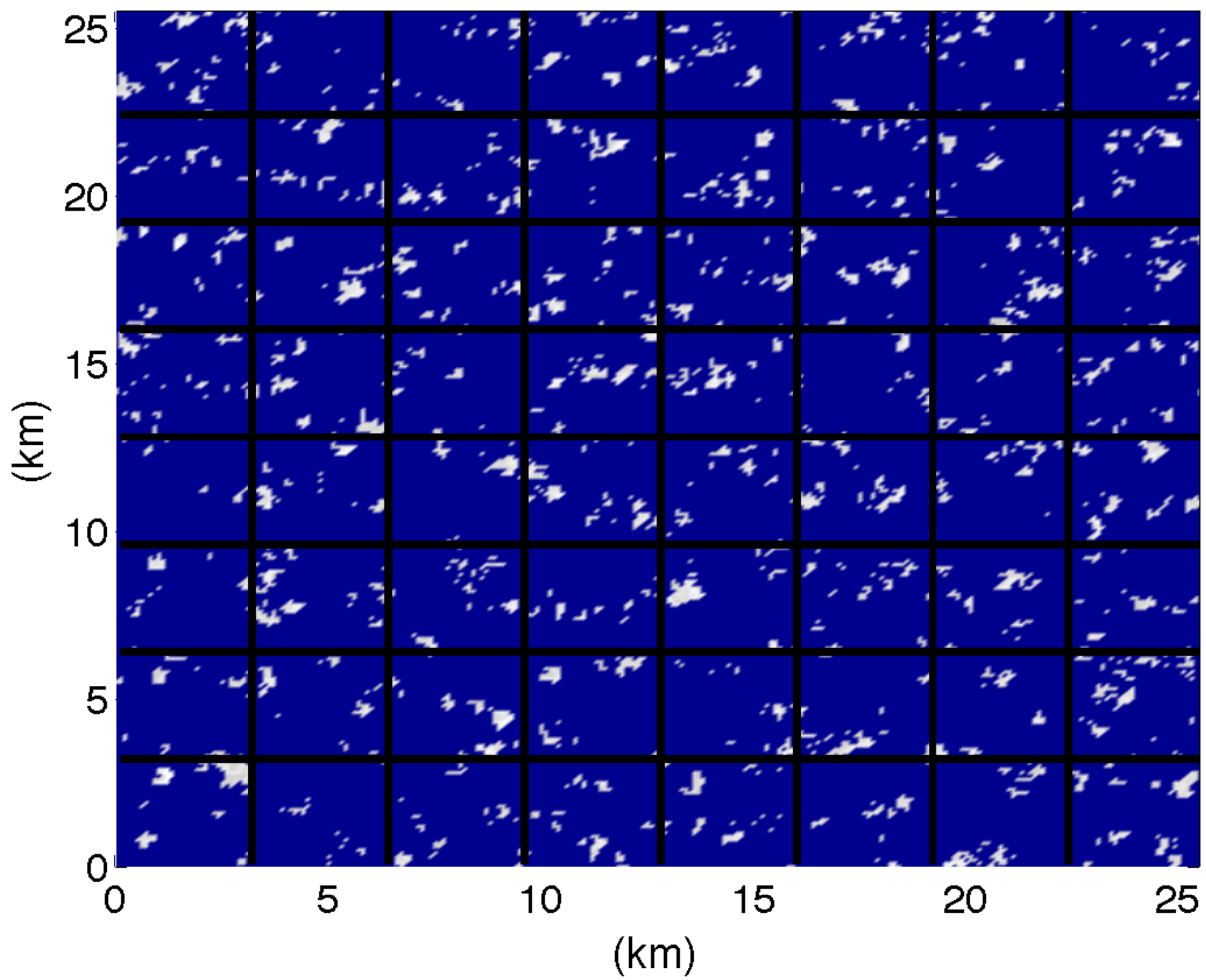
Cloud Resolving?

Just add cumulus clouds



Snapshot cloud condensate mixing ratio of trade-wind cumulus regime from high-resolution simulation (z = 600 m)

Cloud Resolving?

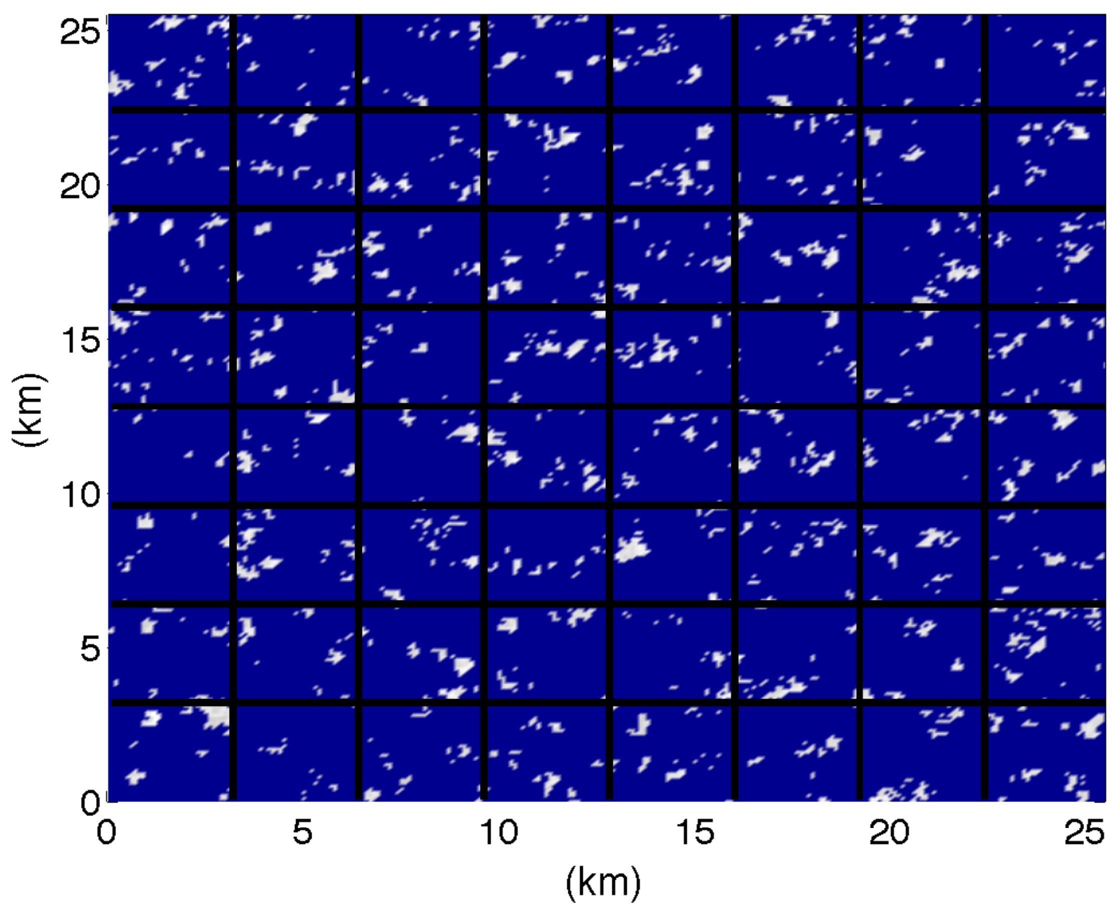


Black lines denote boundaries of CRM type grid spacing (~ 4 km)

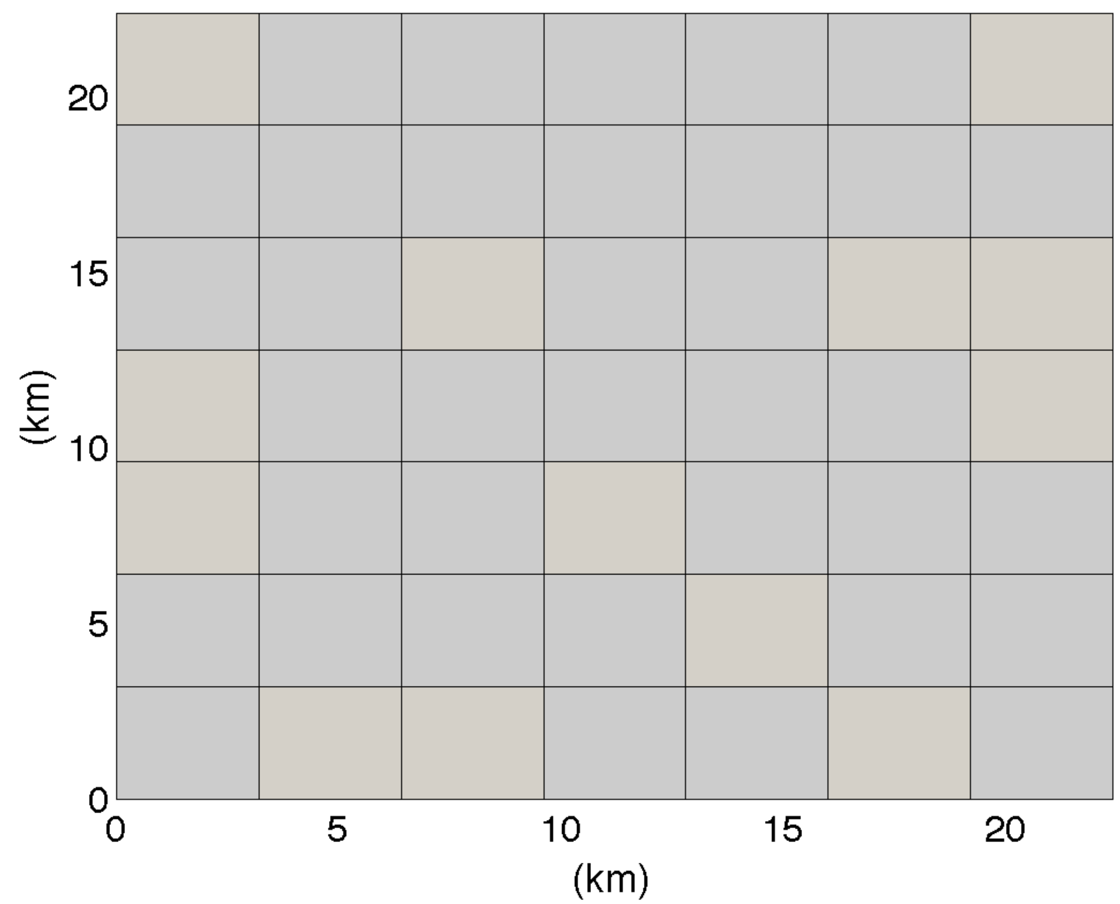
Snapshot cloud condensate mixing ratio of trade-wind cumulus from LES (z = 600 m)

Cloud Resolving?

8% cloud fraction



Snapshot of trade-wind cumulus from LES (z = 600 m)



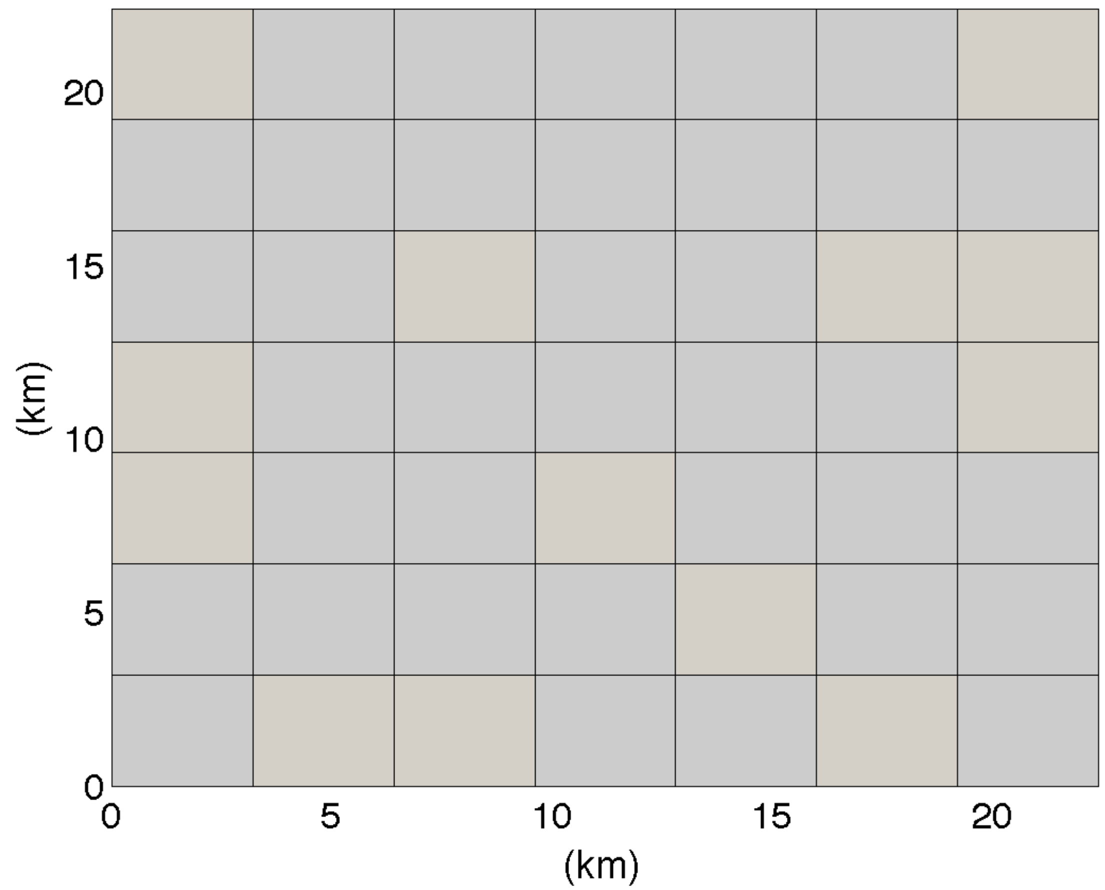
Box averaged field from LES for CRM grid (“benchmark” for coarse-grid CRM)

How does a coarse-grid CRM simulate this regime???

Cloud Resolving?

Max 9% cloud fraction from box averaged field

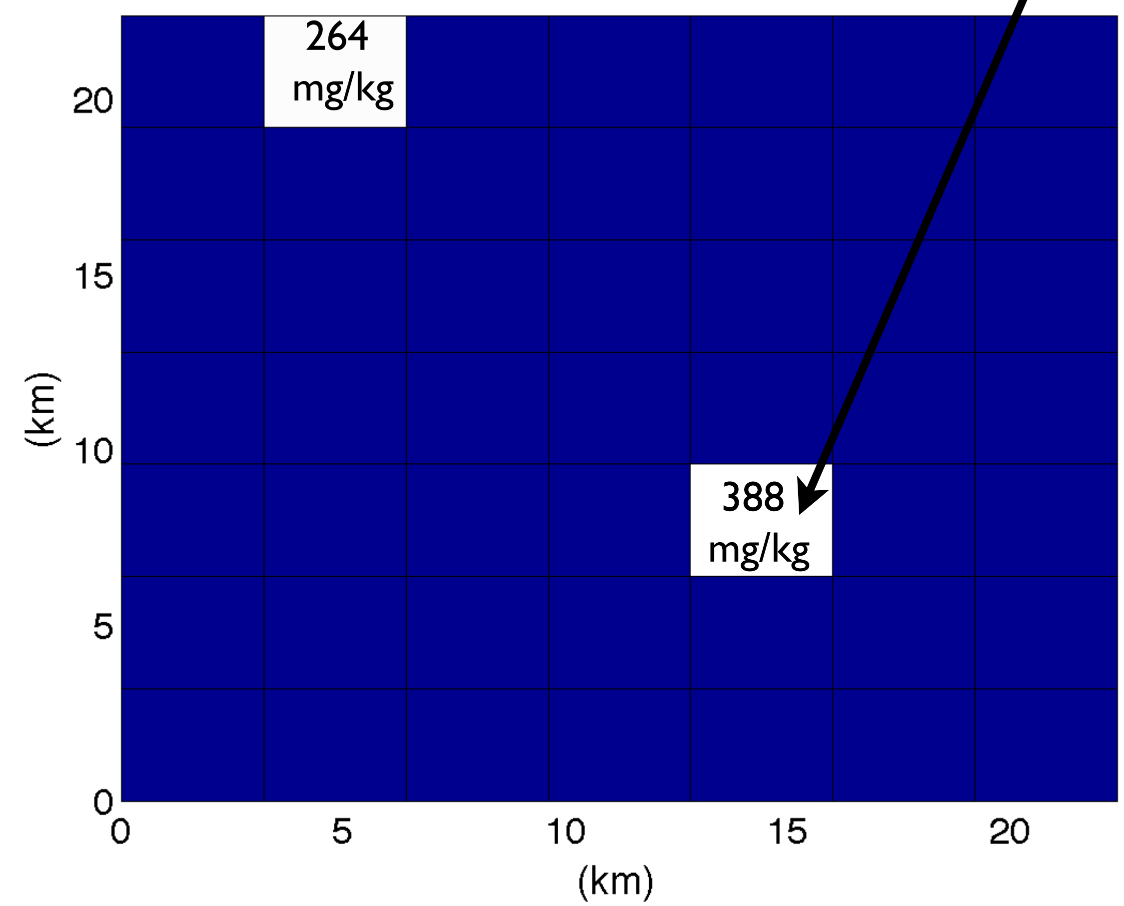
averaged q_l = 3 mg/kg



Box averaged field from LES for CRM grid
(“benchmark” for coarse-grid CRM)

Implies 100% cloud fraction

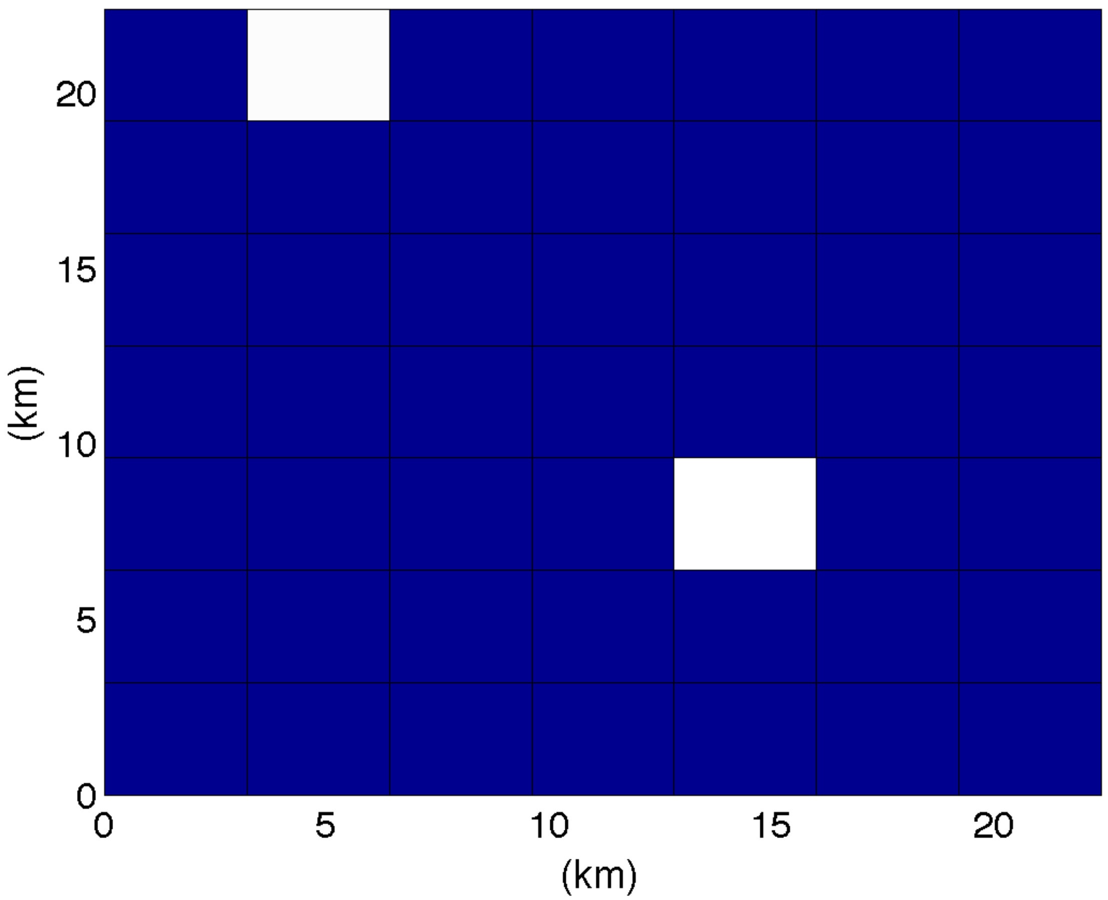
averaged q_l = 24 mg/kg



CRM simulation

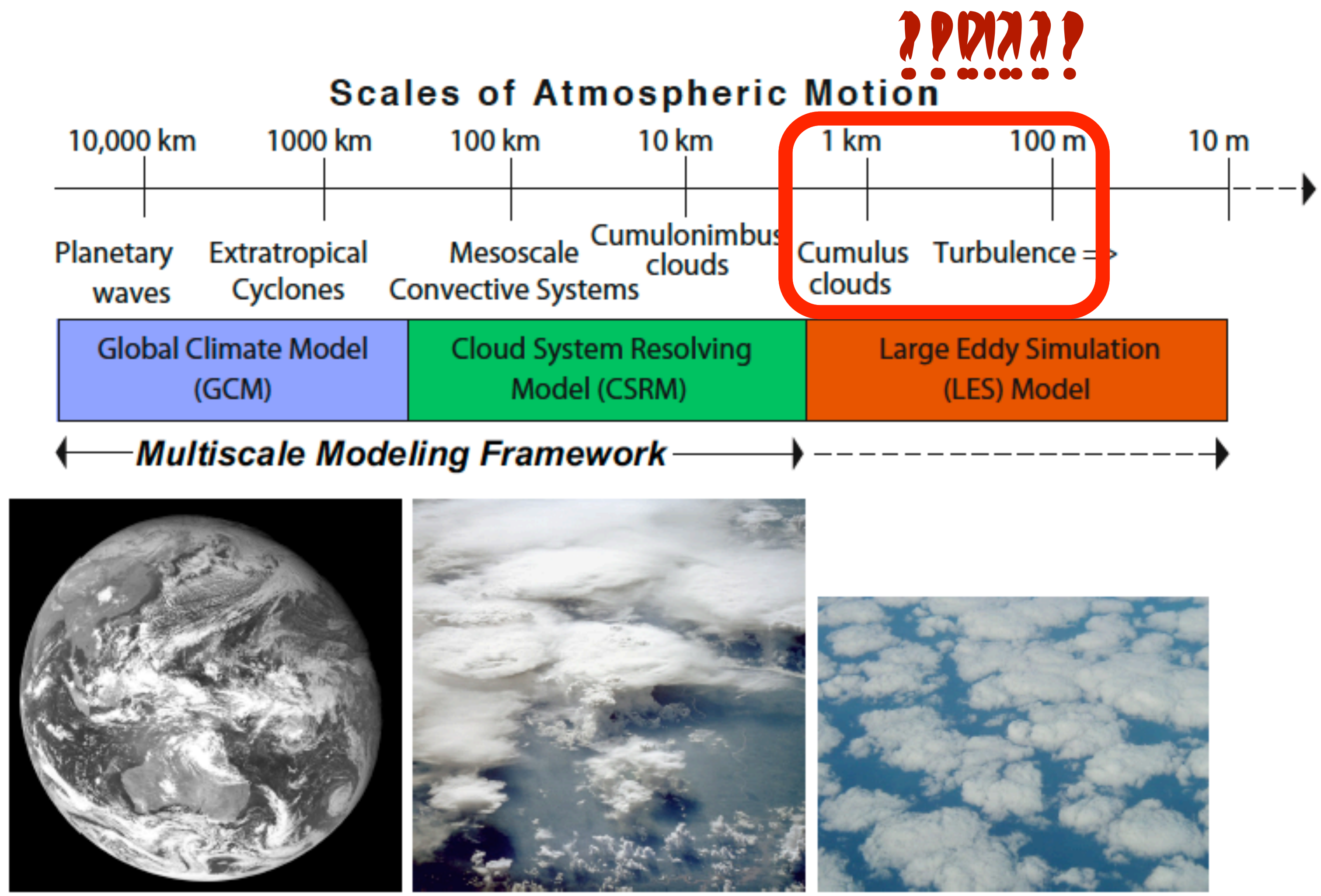
Max value from box averaged field only 6 mg/kg

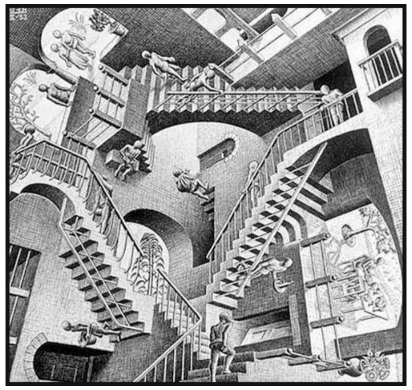
Cumulus in Current MMF Configuration



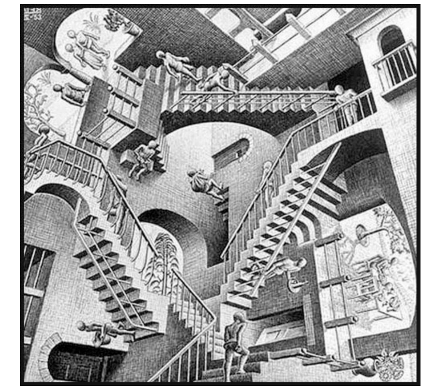
Not suggesting SAM is a deficient model... This is characteristic behavior of coarse-grid low-order closure CRMs, in general

- Occurrence of shallow cumulus underpredicted in MMF (Zhang et al. 2008)
- Shallow clouds that do form are too optically thick (Marchand et al. 2010)
  - Hence, shallow cumulus in MMF represented as scattered sheets of stratocumulus (Cheng and Xu 2008)
- Shallow clouds in CRM simulations of SAM are formed as a result of cancellation of errors
  - Inadequate turbulence representation & "all or nothing" condensation
- Better representation is needed, but we want to keep the cost minimal!

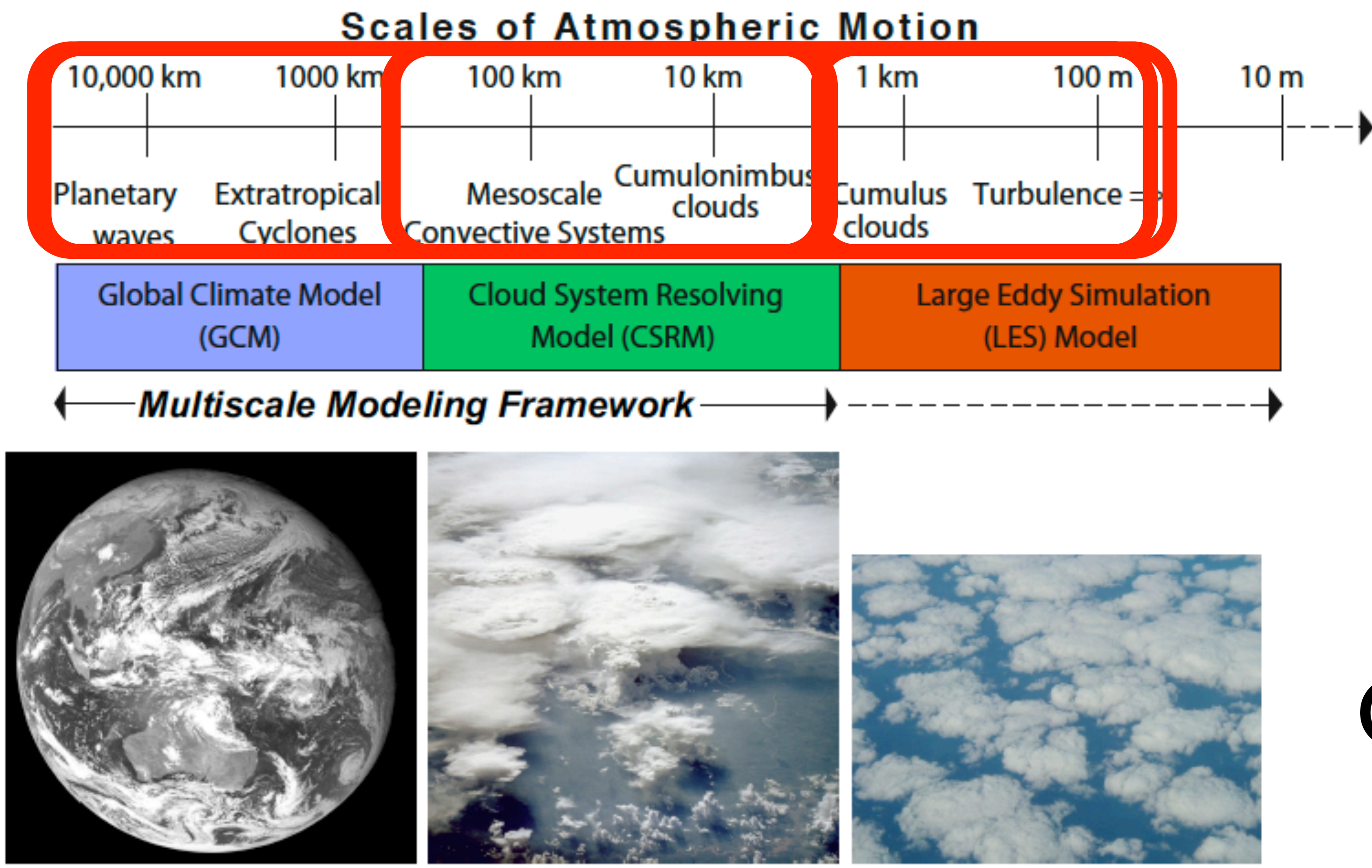

Scales of Atmospheric Motion
10,000 km
1000 km
100 km
10 km
1 km
100 m
10 m
Planetary waves
Extratropical Cyclones
Mesoscale Convective Systems
Cumulonimbus clouds
Cumulus clouds
Turbulence =>
Global Climate Model (GCM)
Cloud System Resolving Model (CSRM)
Large Eddy Simulation (LES) Model
Multiscale Modeling Framework



Not a new problem!



- Representation of shallow clouds in GCMs has long been the bane of climate modelers
- MMF offers new avenues to improve shallow cloud representation in GCMs
- Problem now focuses on improving cloud representation in coarse-grid CRMs (i.e. deep convection permitting models) rather than in highly parameterized GCMs
  - Should be easier now.... right?

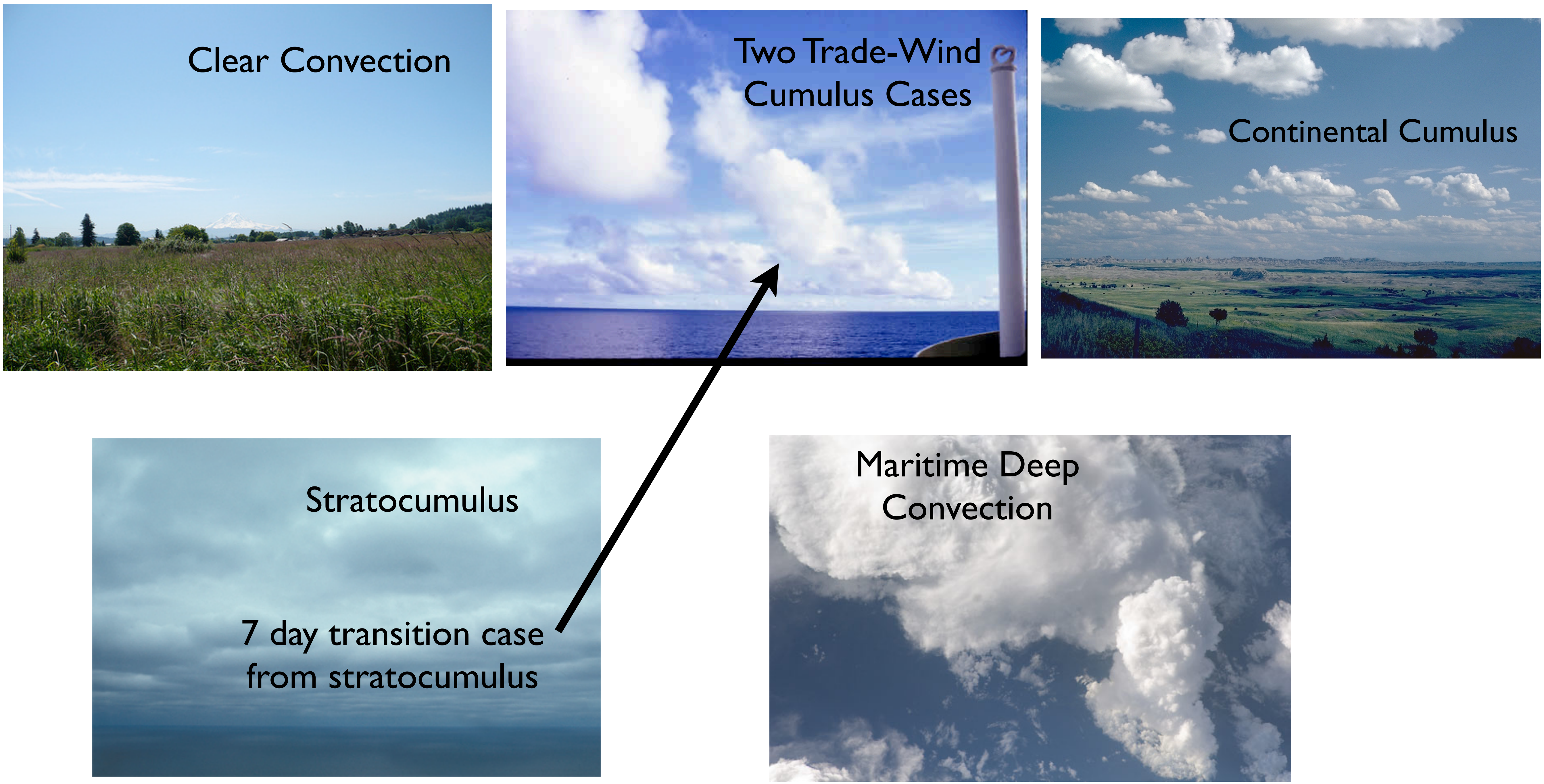


Outline

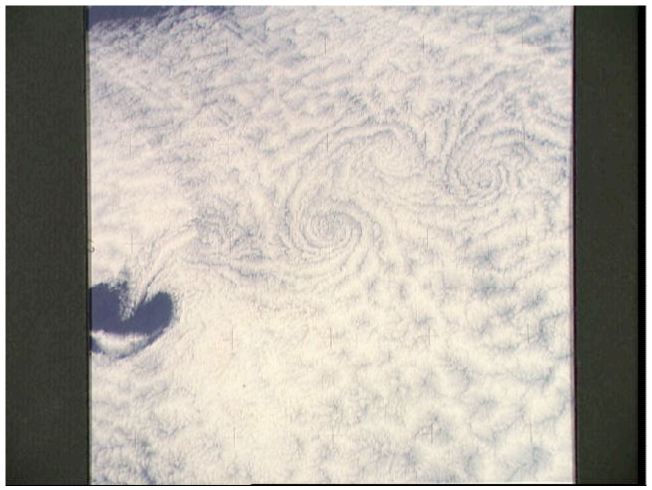
- LES :
  - Description of LES benchmarks
  - *a priori* tests
  - Description of new closure
- CRM :
  - *a posterori* test of the new closure
- GCM :
  - How does new closure perform within the MMF?

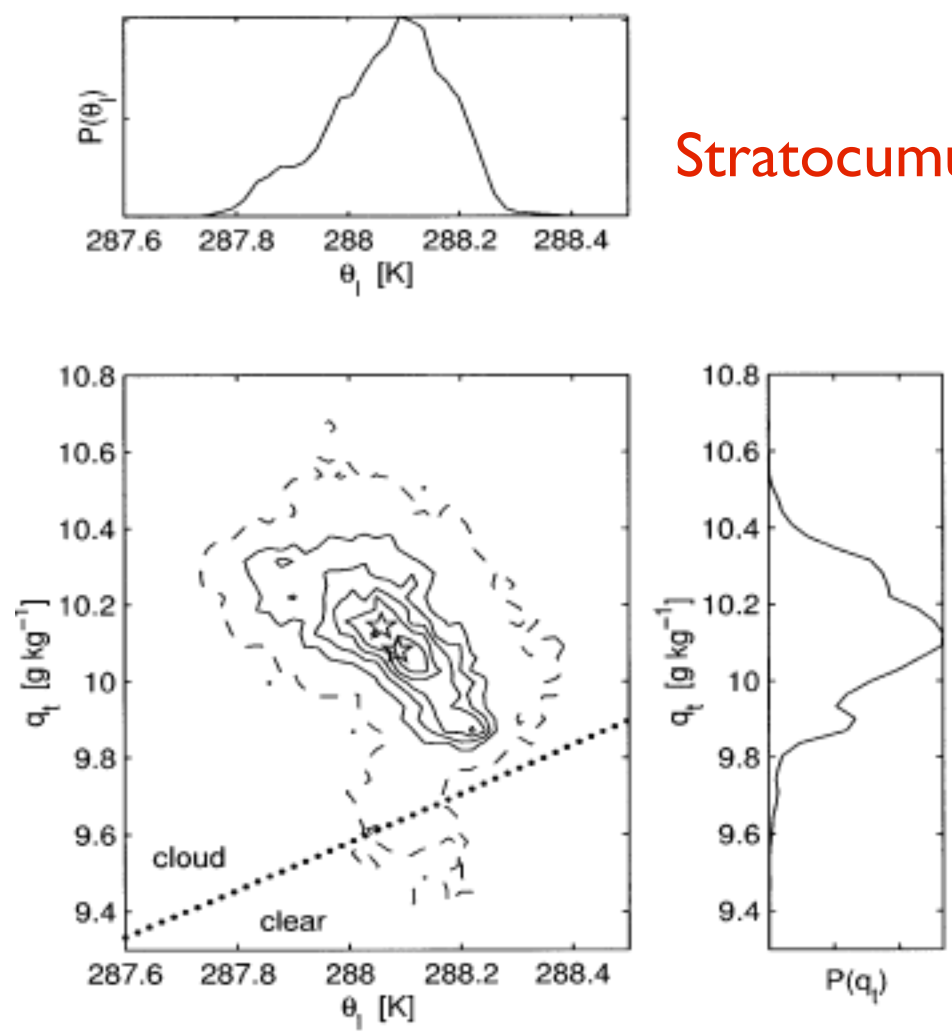
LES Simulations

- Our (large domain) LES simulations used for *a priori* and *a posteriori* testing include:

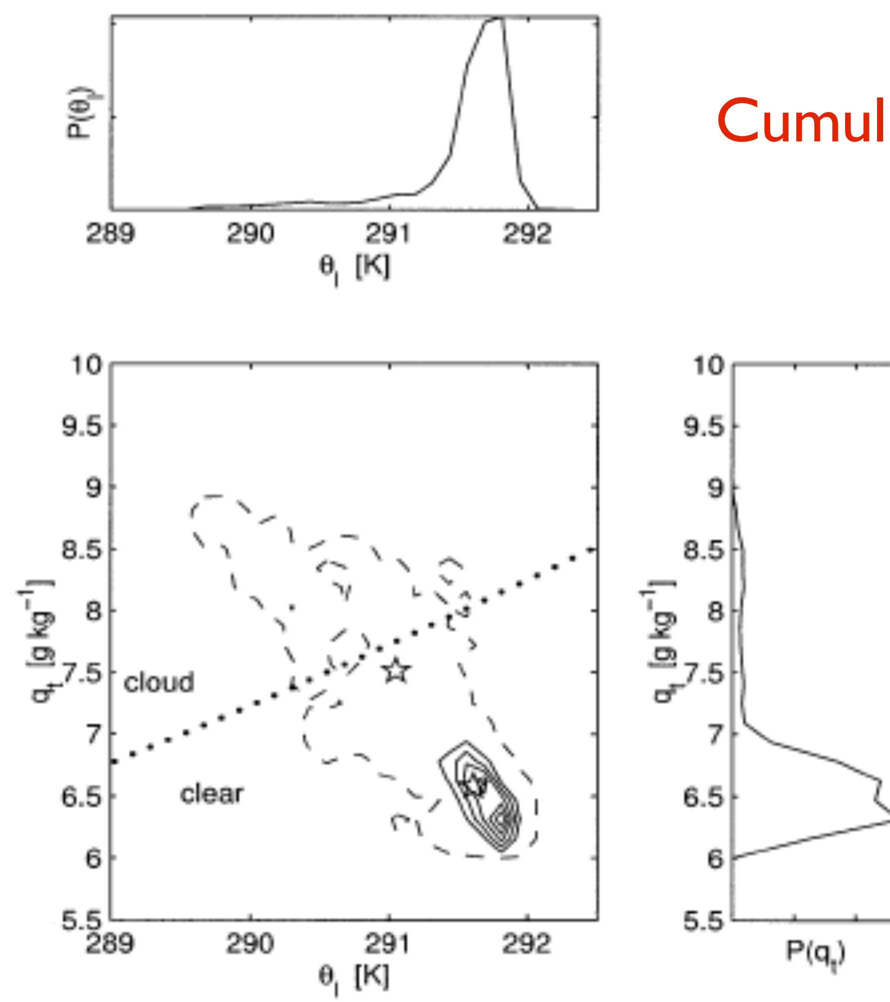


Unified Approach to Cloud Representation





Stratocumulus



Cumulus

Figures from Larson et al. (2002)

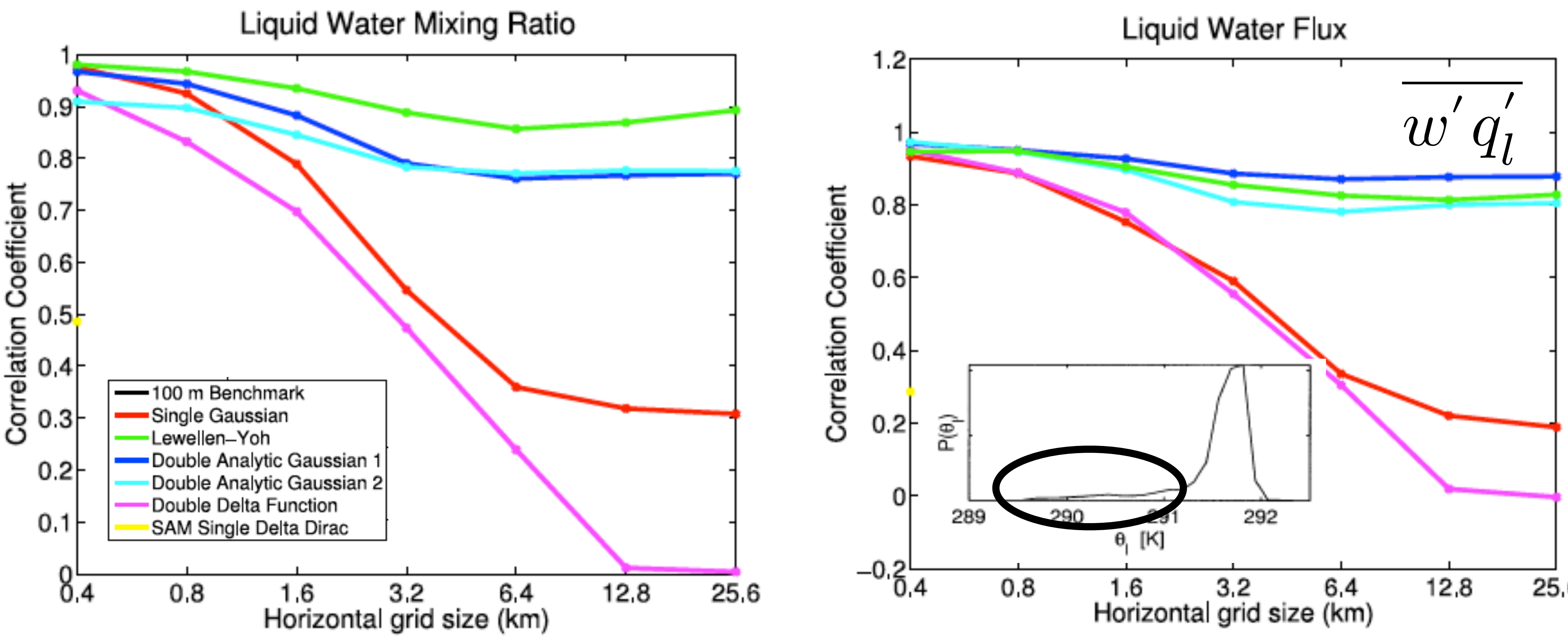
Assumed PDF Approach

- Larson et al. (2002) and Golaz et al. (2002) propose a new kind of unified closure
- Assume a functional form of a triple joint PDF $P(w, \theta_l, q_t)$
- Can obtain:
  - SGS cloud fraction and liquid water
  - higher order moments (i.e. liquid water flux, needed for buoyancy flux calculation)
- Requires information of several turbulent moments not provided by standard SAM:

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

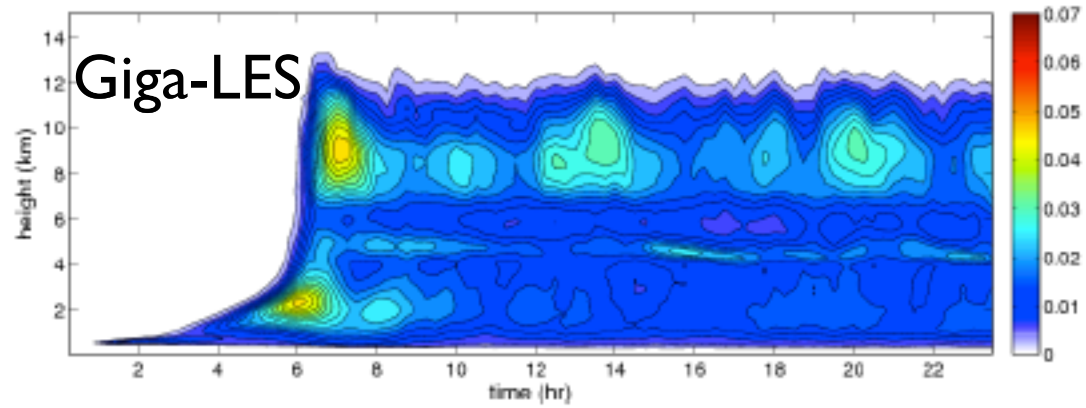
Assumed PDF Method

- *a priori* studies (Larson et al. 2002, Bogenschutz et al. 2010) show that triple-joint PDFs based on the double Gaussian form can represent shallow and deep convective regimes fairly well for a range CRM of grid box sizes

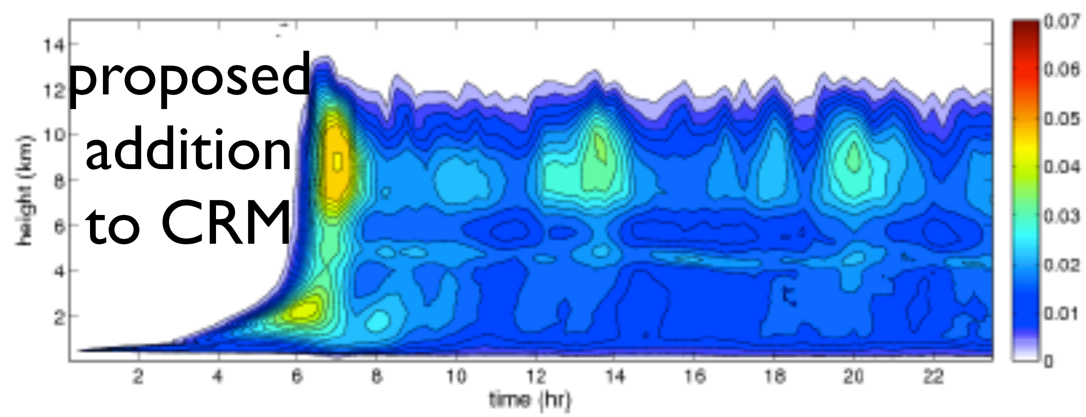


For BOMEX shallow cumulus regime, from Bogenschutz et al. (2010)
Correlation with retrieved variables from LES

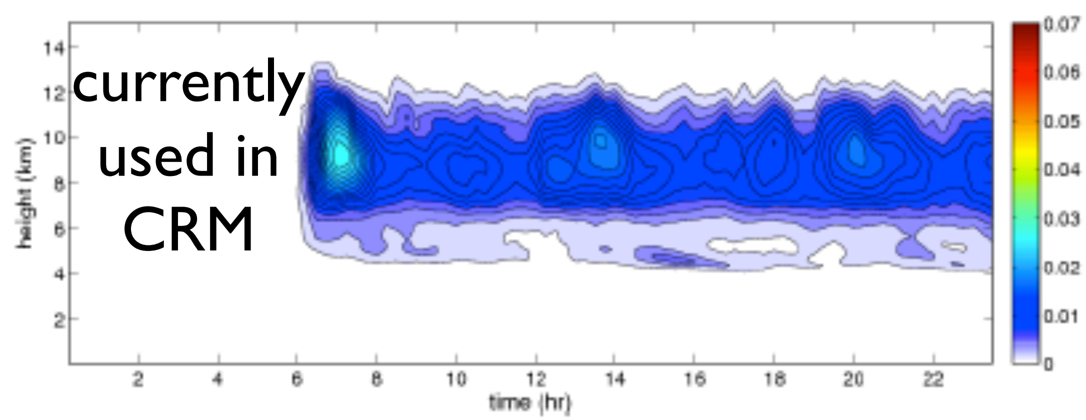
a priori PDF test for Deep Convection



(a) 100 m Benchmark



(b) 3.2 km analysis grid, Analy. Double Gaussian 1

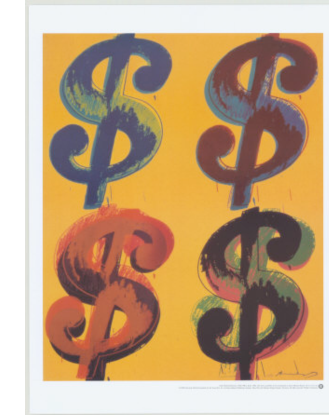


(c) 3.2 km analysis grid, Single Delta Function

From Bogenschutz et al. (2010)

evolution of the temporally
and horizontally averaged profiles
of the non-precipitating
cloud condensate from GATE

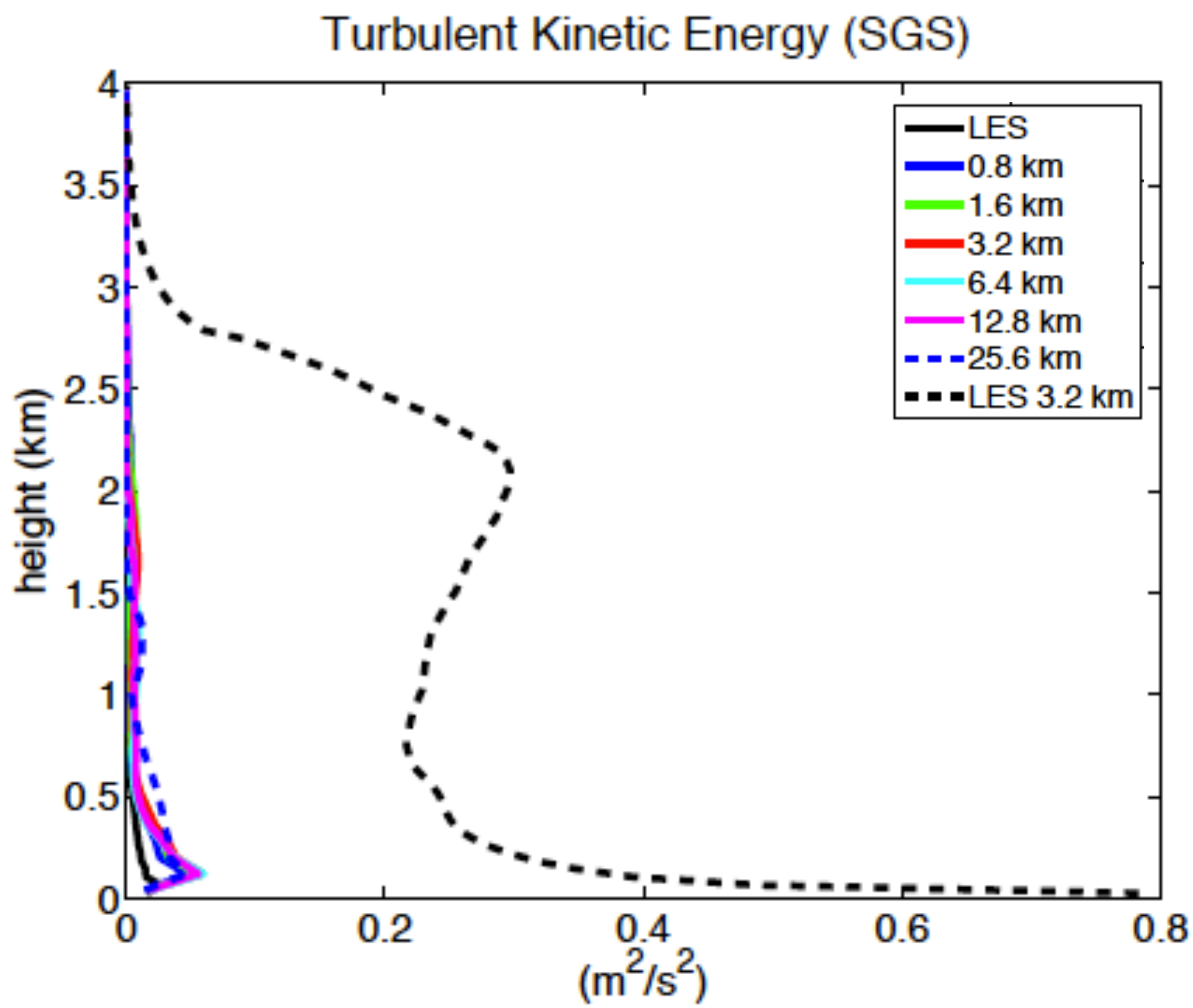
Don’t Break the Bank!



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

- Typically requires the addition of several prognostic equations into model code (Golaz et al. 2002, Cheng and Xu 2006, 2008) to determine turbulent moments
- Second-order moments diagnosed using simple formulations based on Redelsperger and Sommeria (1986) and Bechtold et al. (1995)
- Third-order moment diagnosed using algebraic expression of Canuto et al. (2001)
- The study of Cheng et al. (2010) suggest that simple closures appear to function well for boundary layer cloud regimes given the proper amount of SGS TKE can be predicted
- All diagnostic expressions for the moments are a function of SGS TKE
- So how well do coarse-grid CRMs predict SGS TKE?

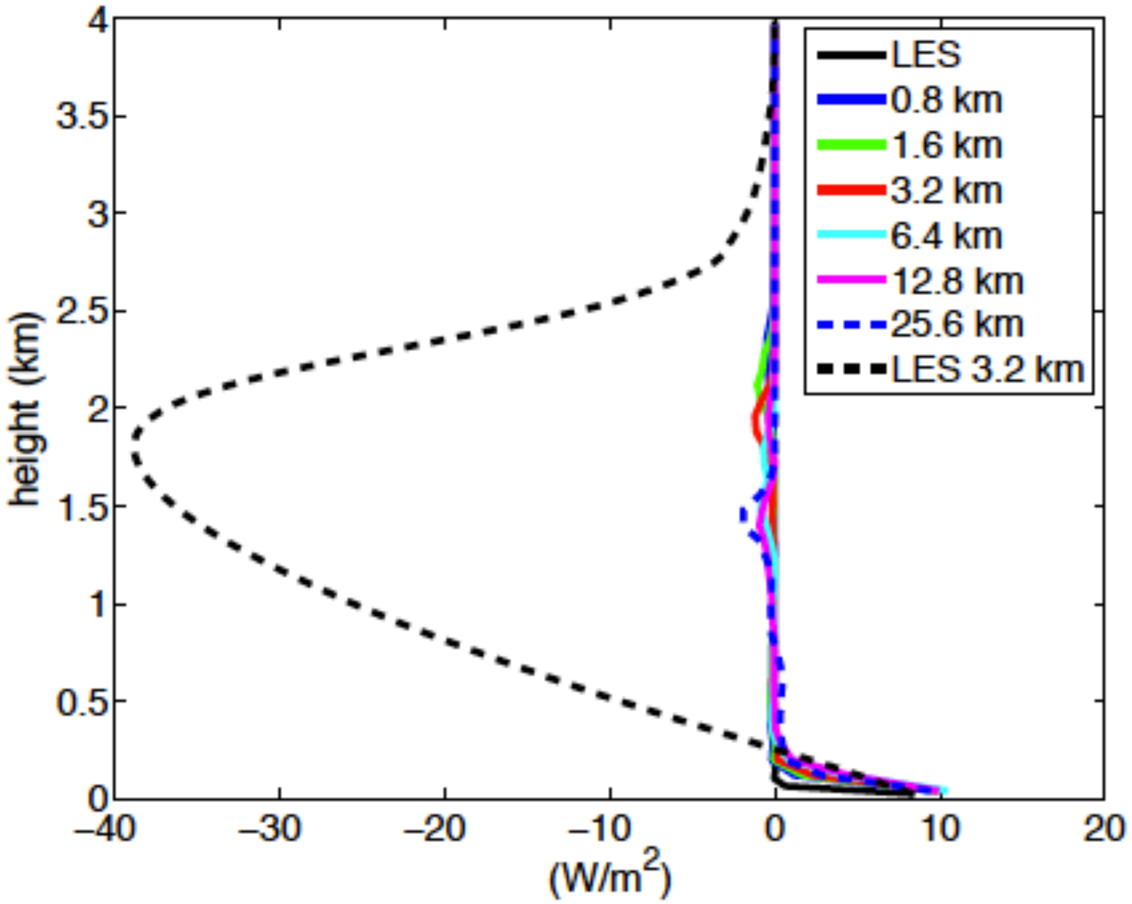
... pretty poorly, actually...



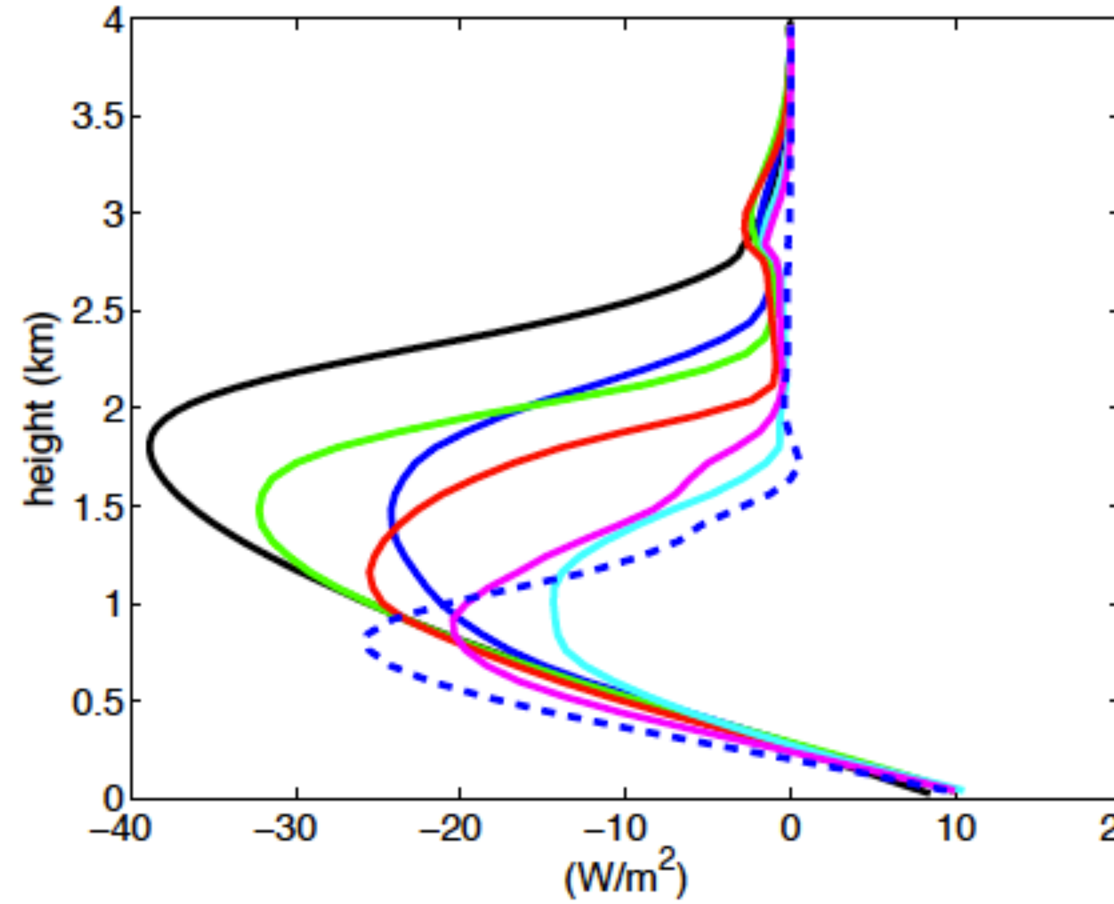
From RICO (shallow precipitating cumulus), for 2D simulations using a variety of coarse horizontal grid sizes and dz=100 m.

Dotted black line is SGS TKE diagnosed from LES for a 3.2 km grid (i.e. "truth")

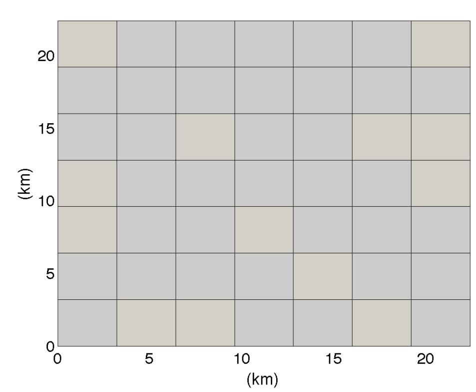
... and this translates to where it counts



(d) SGS $\overline{w' h_L'}$

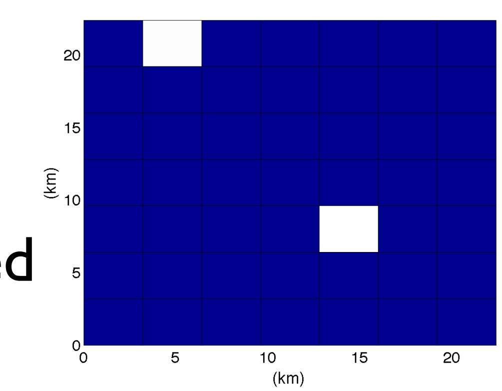


(c) Resolved+SGS $\overline{w' h_L'}$



Should be subgrid-scale!

Cloud circulations projected on the resolved scale



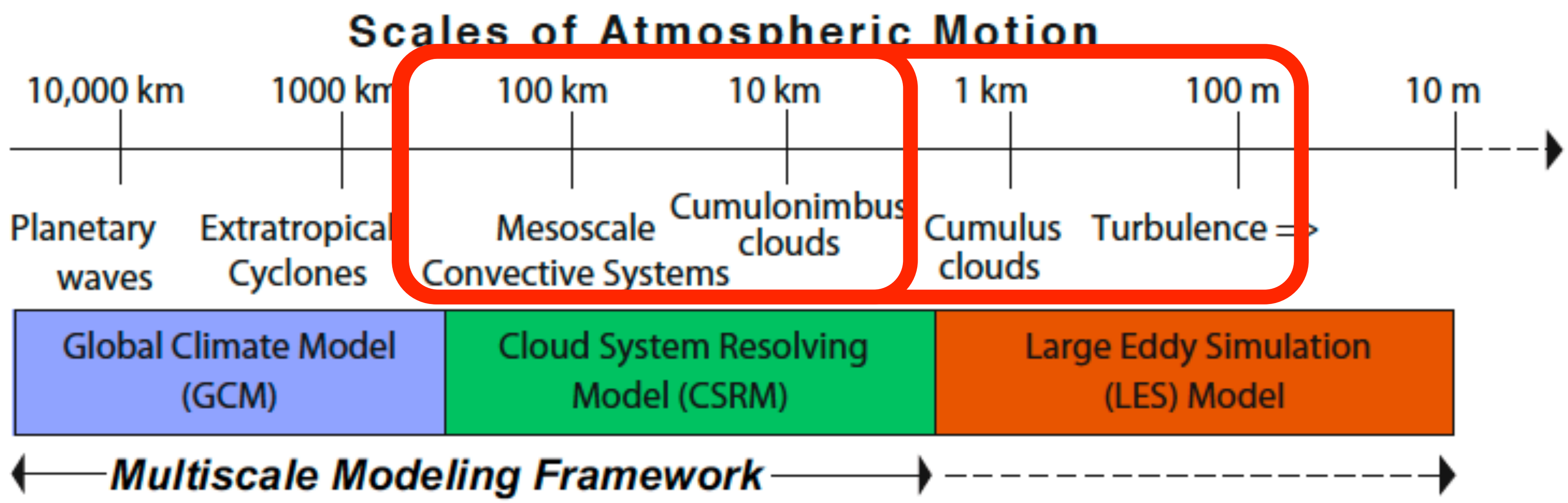
SGS turbulence problem

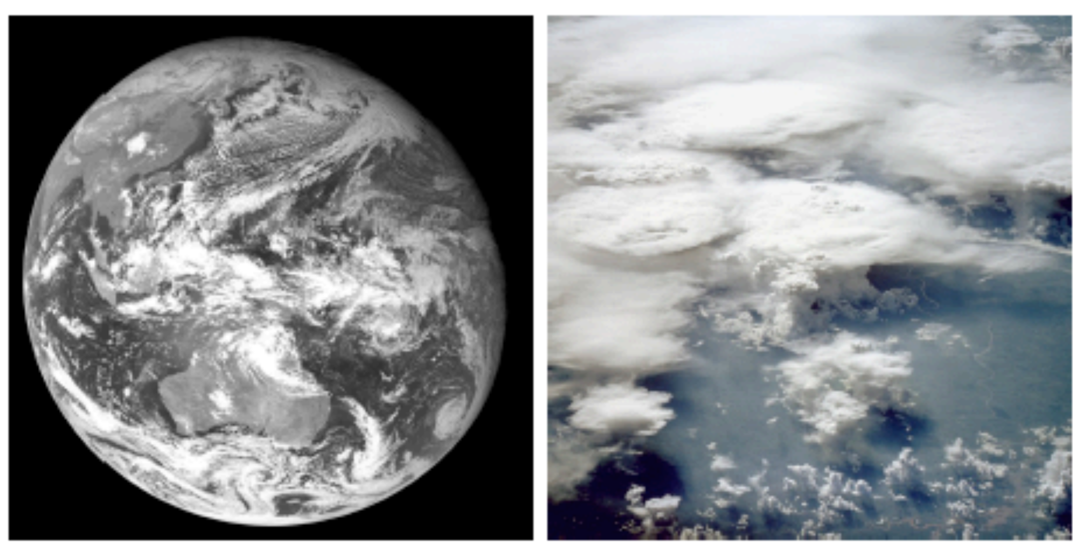
- SGS TKE in coarse-grid CRM underrepresented for two reasons:
  - SGS liquid water flux is neglected in buoyancy flux calculation
    - Needed as an important source of turbulence
  - Length scale definition results in an overtly dissipative model
    - Needed to maintain/balance turbulence

$$\frac{\partial \overline{e}}{\partial t} = -\overline{u_j}\frac{\partial \overline{e}}{\partial x_j} + \delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right) - \overline{u_i'u_j'}\frac{\partial \overline{u_i}}{\partial x_j} - \frac{\partial \overline{u'e}}{\partial x_j} - \frac{1}{\rho}\frac{\partial \overline{u_i'p'}}{\partial x_i} - c_k\frac{\overline{e}^{3/2}}{L}$$

“Offline” Tests of PDF-SAM

Standard SAM PDF-SAM





To be coined “DHOC” in upcoming publication submission

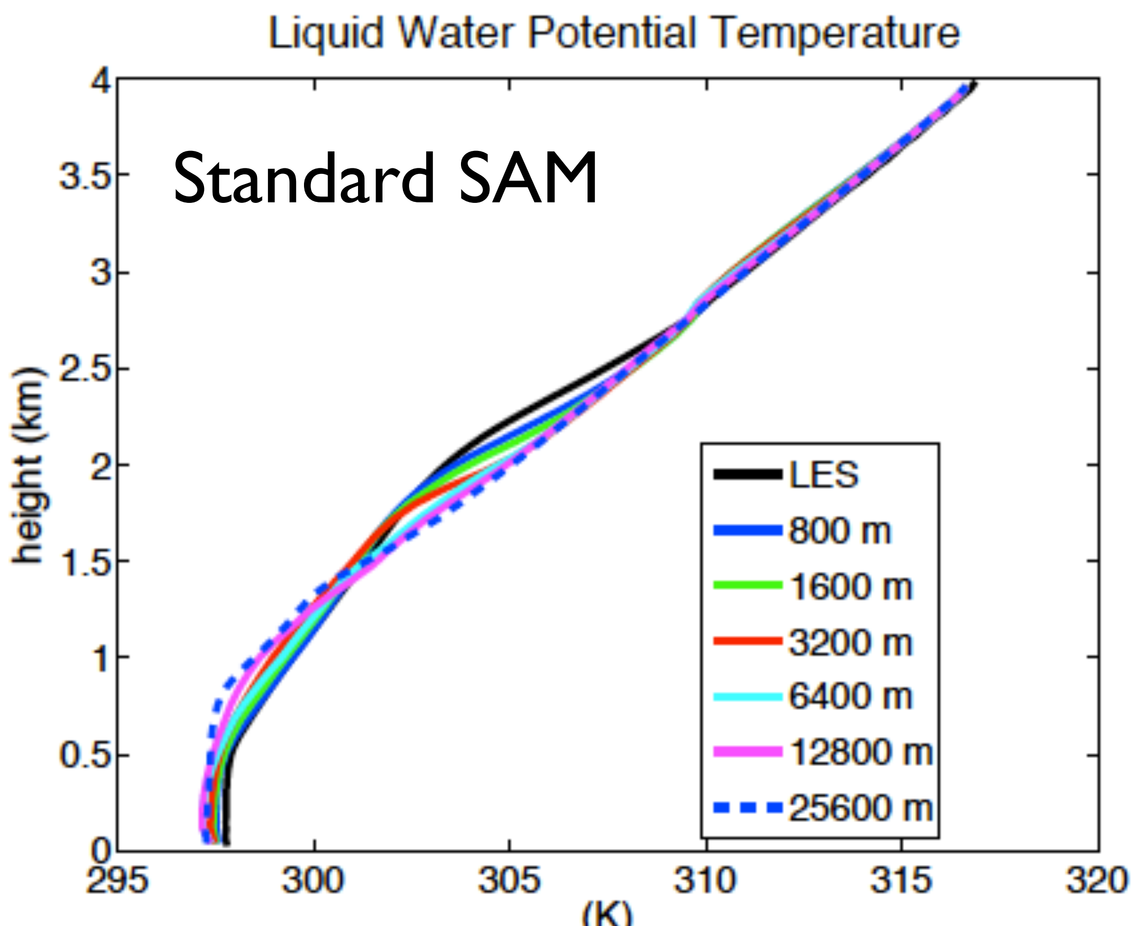
Standard SAM vs. PDF-SAM

- Standard SAM
  - 1.5 TKE closure
  - Length scale specified as dz (except in stable grid boxes)
  - “all-or-nothing” condensation
  - Buoyancy flux diagnosed from moist Brunt Vaisala frequency

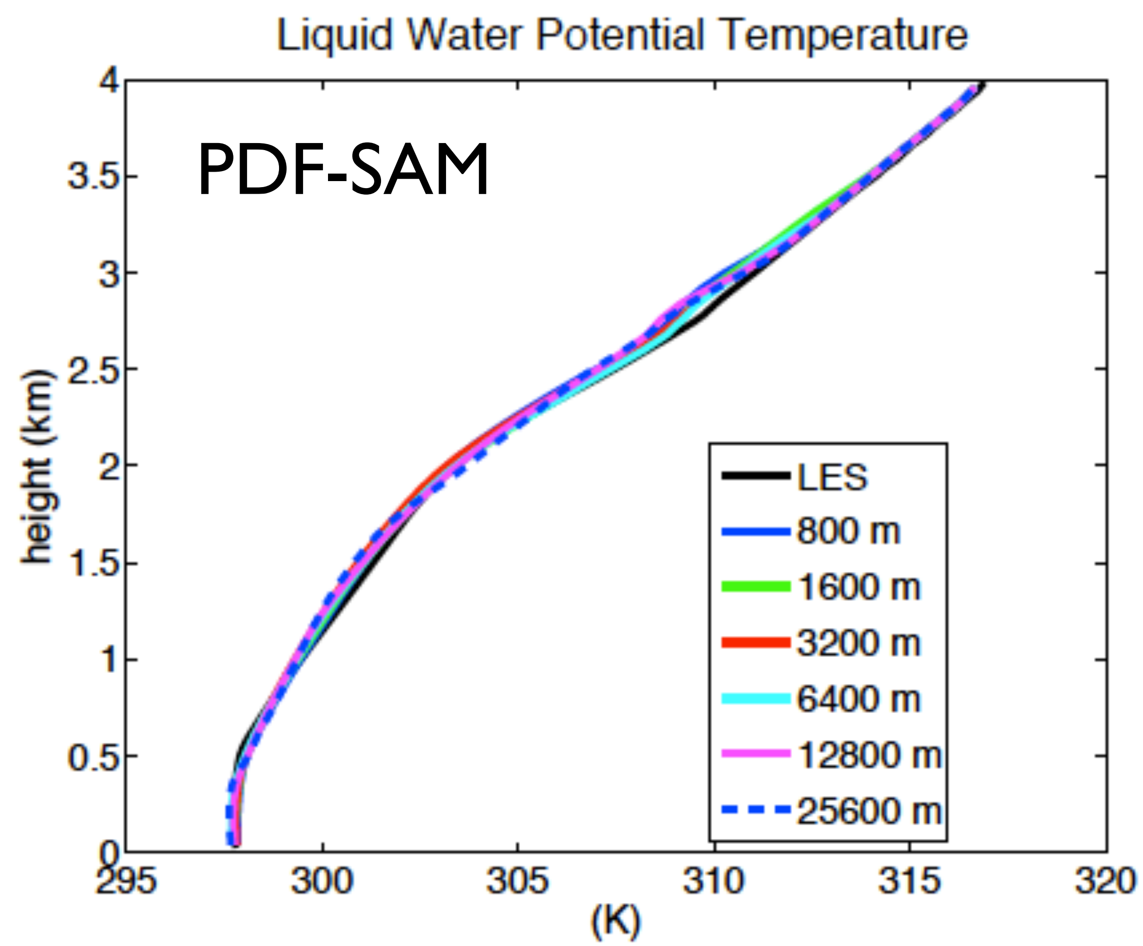
- PDF-SAM
  - 1.5 TKE closure
  - Length scale diagnosed
  - SGS condensation
  - Buoyancy flux computed as function of liquid water flux
  - No additional prognostic equations added to SAM code (only ~1.1 times more expensive)

$$\overline{w'\theta_v'} = \overline{w'\theta_l'} + \frac{1-\epsilon_o}{\epsilon_o}\theta_o \overline{w'q_t'} + \left[\frac{L_v}{c_p}\left(\frac{p_o}{p}\right)^{R_d/c_p} - \frac{1}{\epsilon_o}\theta_o\right]\overline{w'q_l'}$$

Precipitating Trade-Wind Cumulus (RICO; sensitivity to horizontal grid spacing)



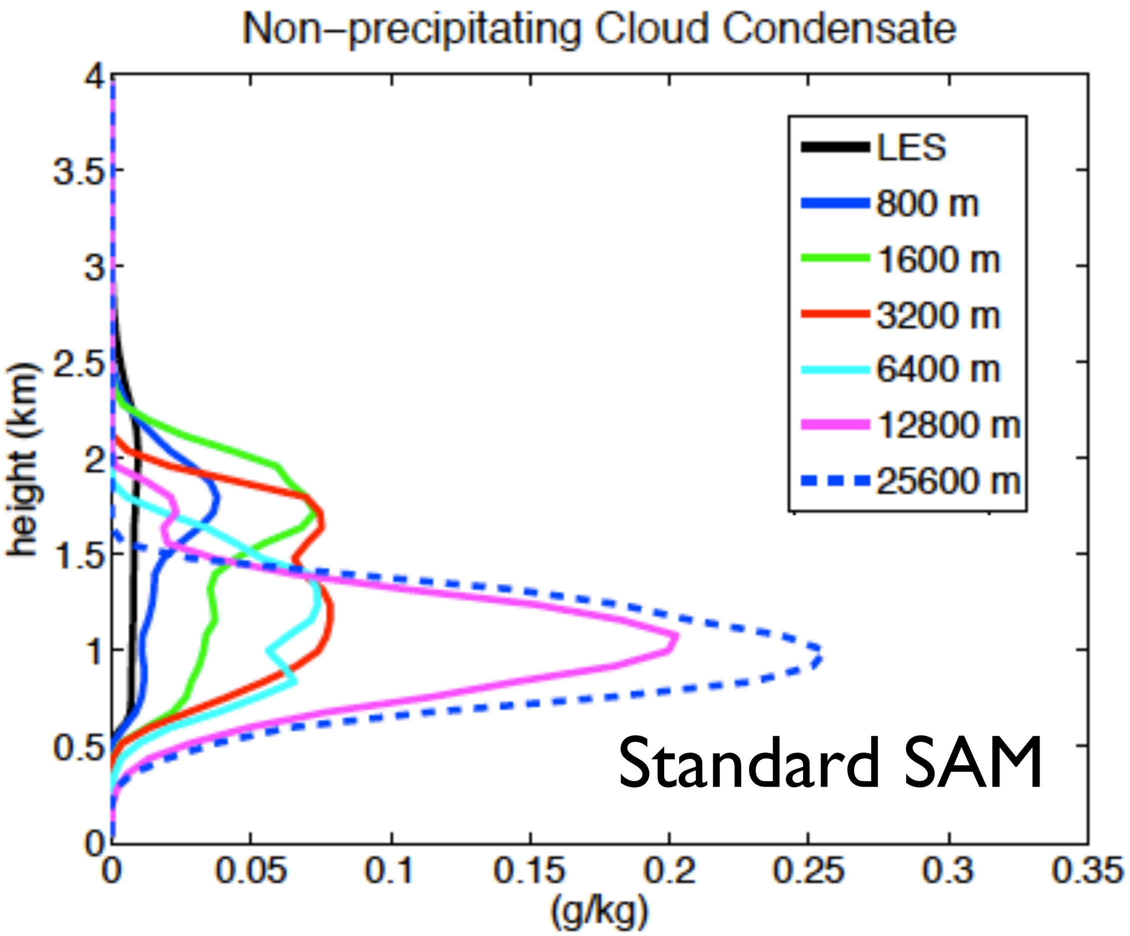
profiles averaged over last four hours of simulation

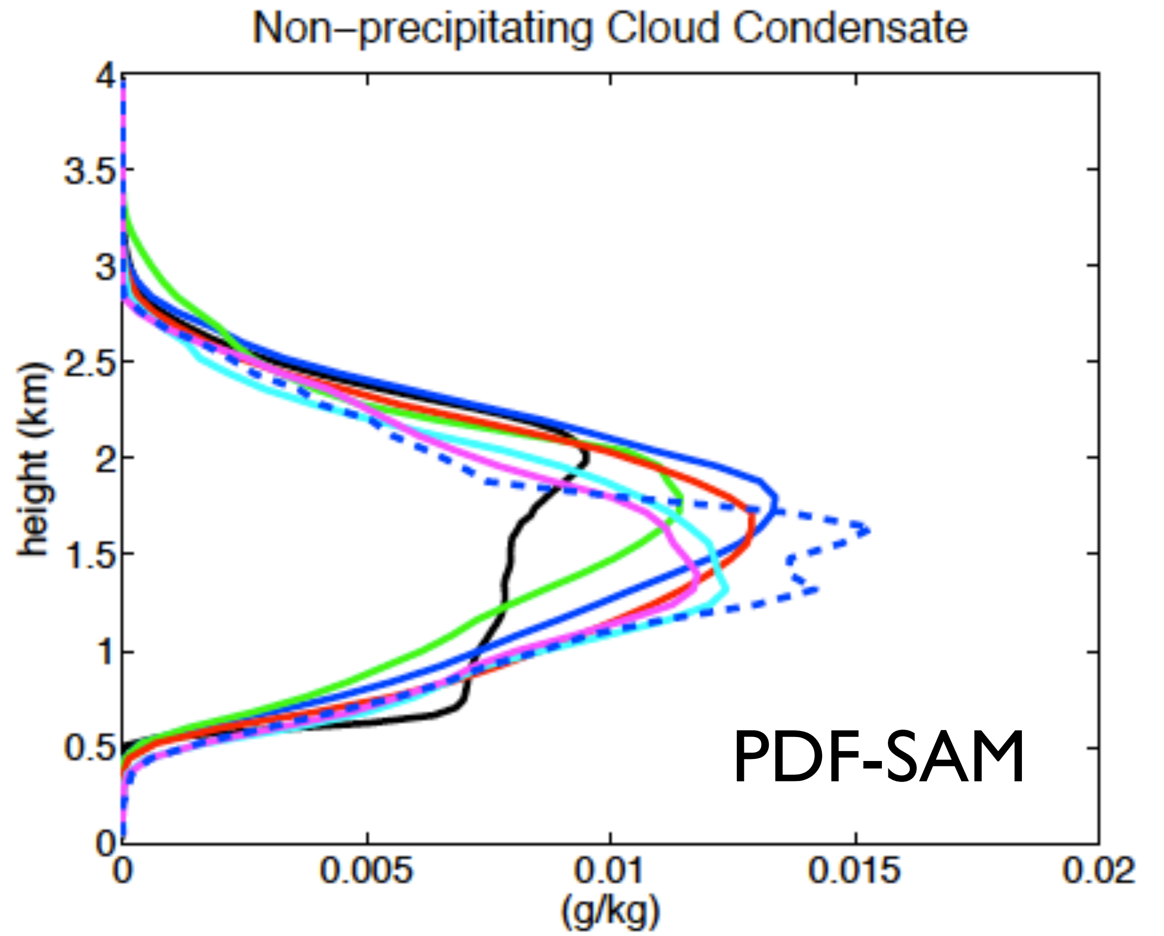


LES: dz = 40 m
dx = 100 m

2D-CRMS: dz = 100 m
dx = 800 m to 25.6 km

Precipitating Trade-Wind Cumulus (RICO; sensitivity to horizontal grid spacing)





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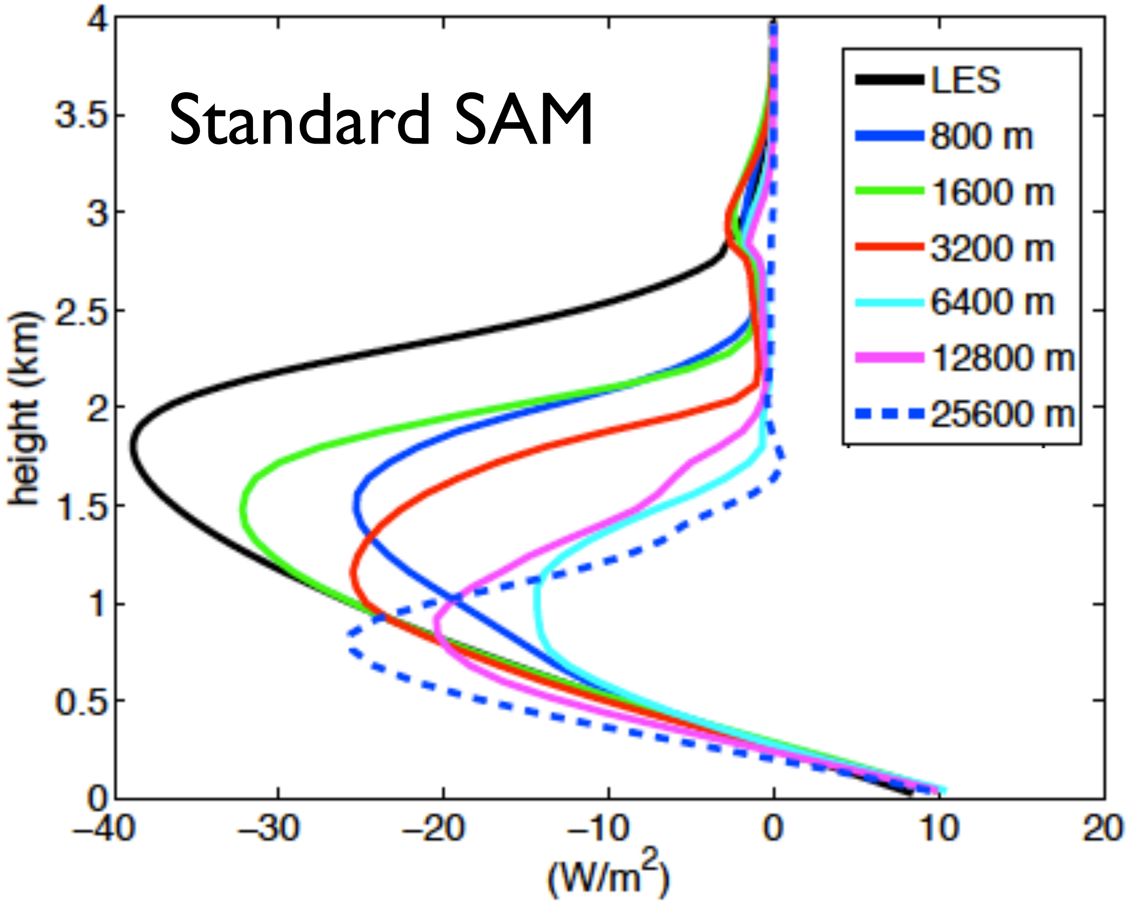
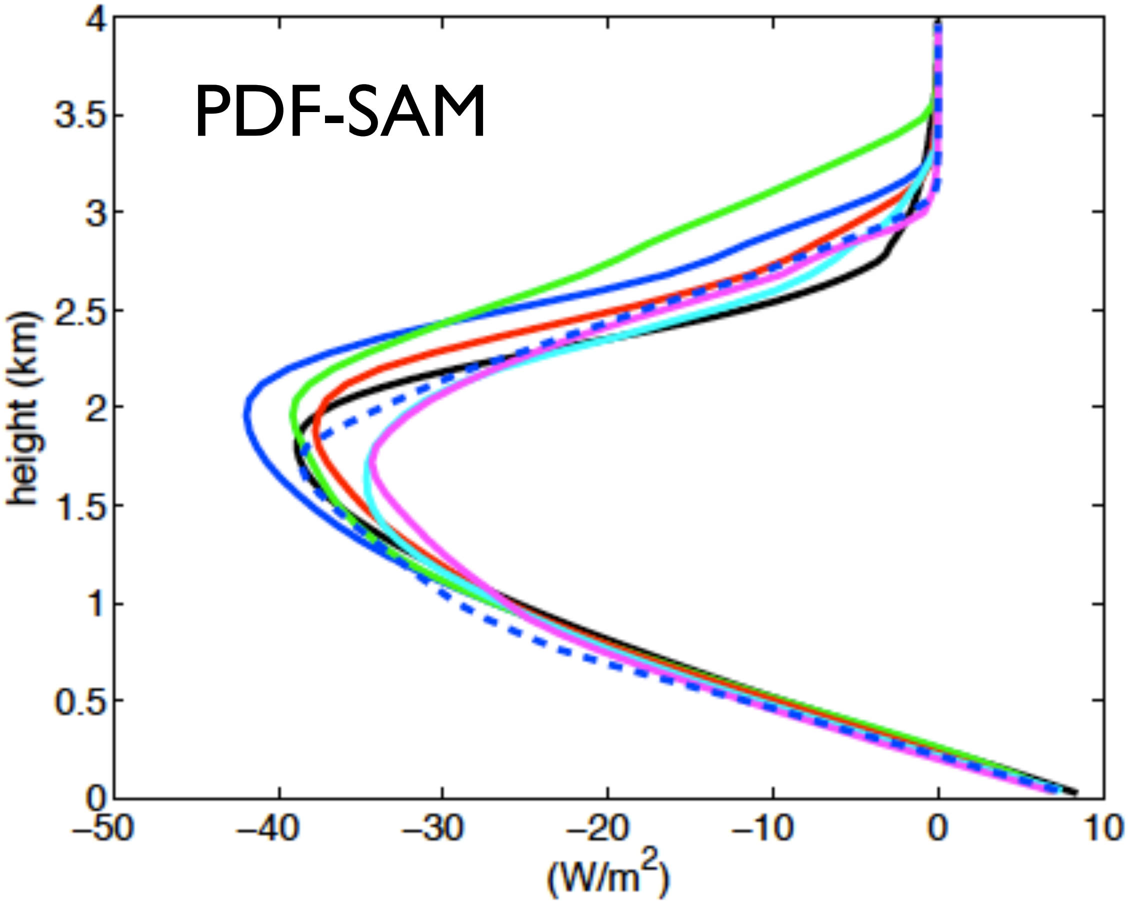


resolved + SGS $\overline{w'h'_L}$

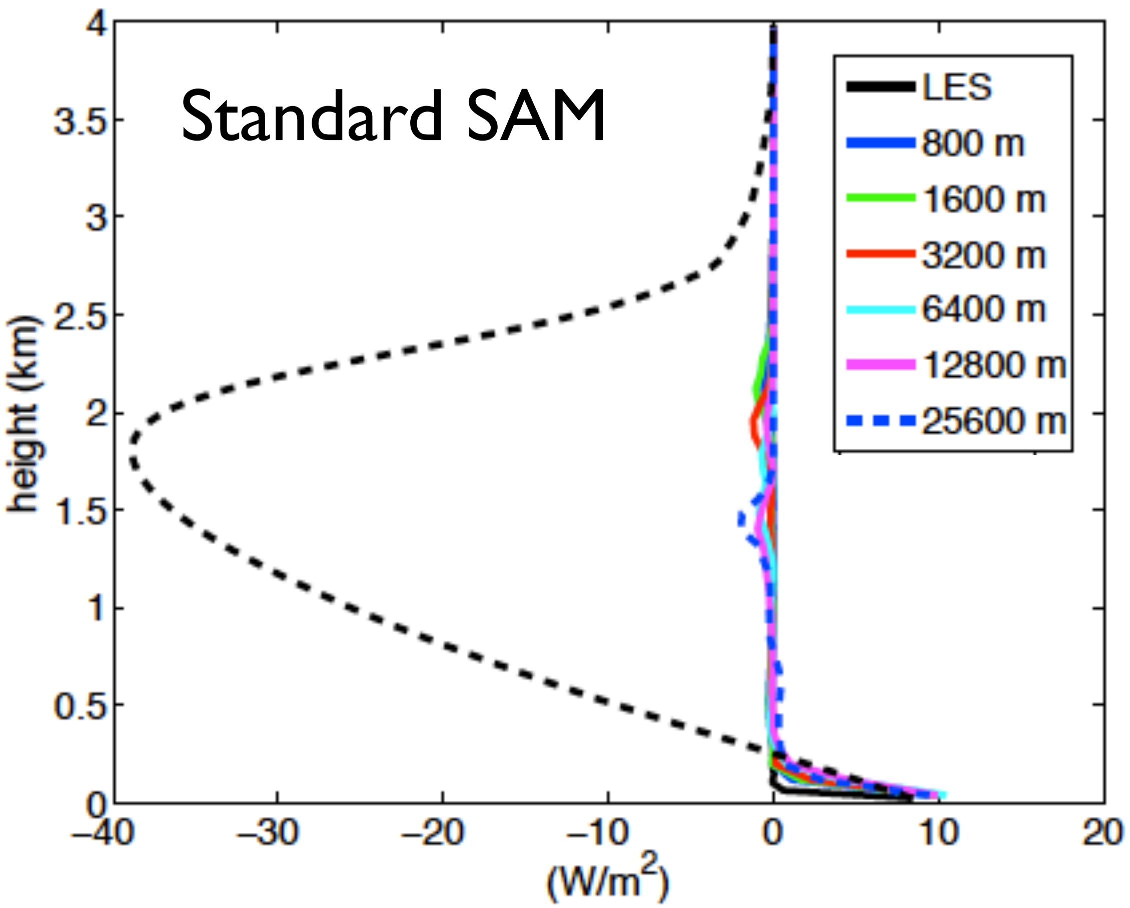
LES: dz = 40 m
dx = 100 m



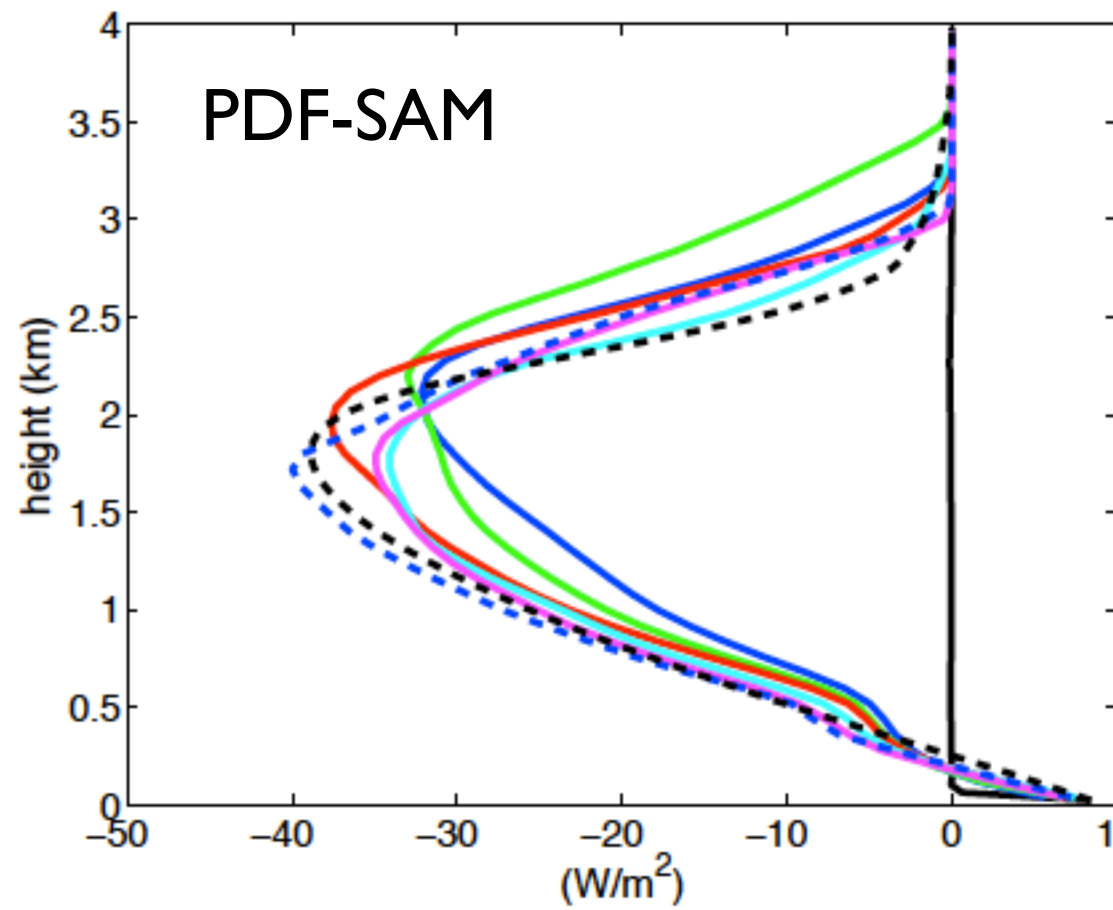
resolved + SGS $\overline{w'h'_L}$

2D-CRMS: dz = 100 m
dx = 800 m to 25.6 km

Precipitating Trade-Wind Cumulus (RICO; sensitivity to horizontal grid spacing)



SGS $\overline{w'h'_L}$



SGS $\overline{w'h'_L}$

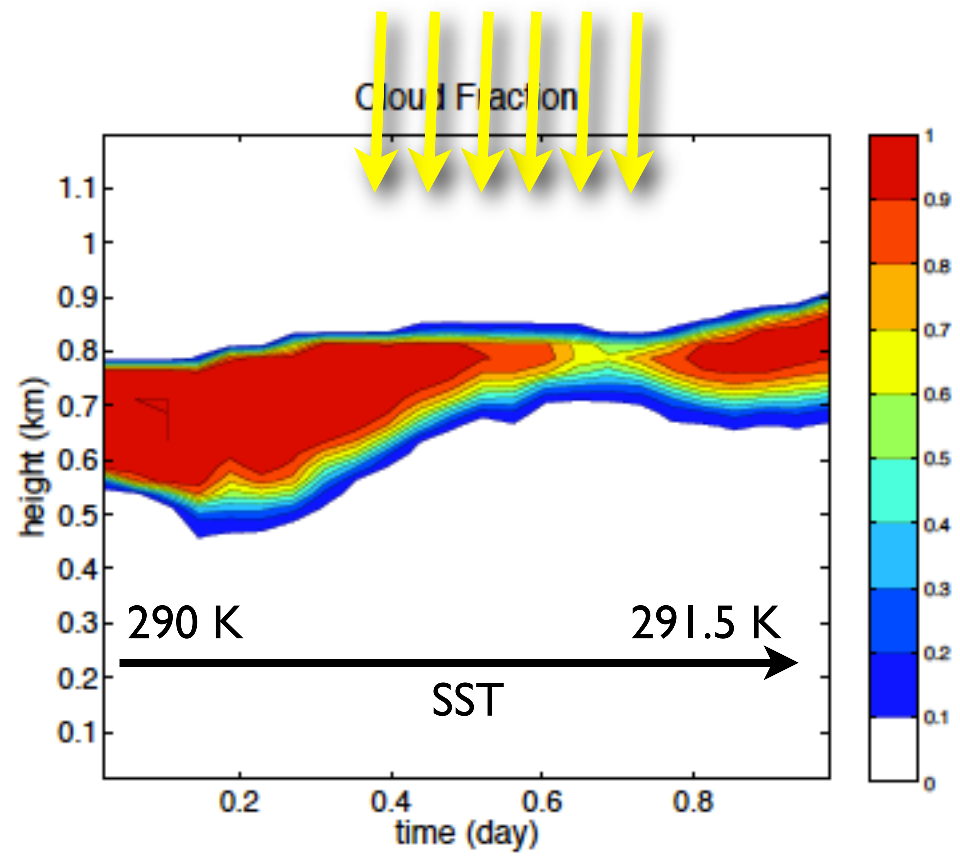
LES: dz = 40 m
dx = 100 m

2D-CRMS: dz = 100 m
dx = 800 m to 25.6 km

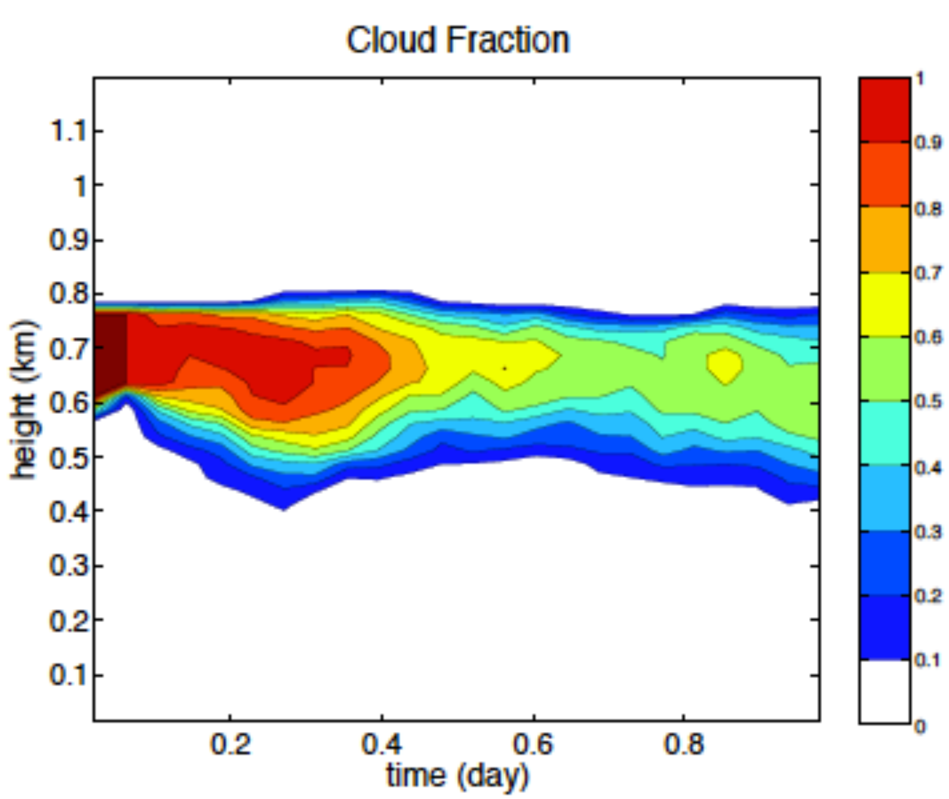
Stratocumulus

24 hour diurnally varying simulation.
Ocean Weather North ship
Lagrangian case moves
over slightly warmer SST.
Interactive shortwave & longwave radiation.

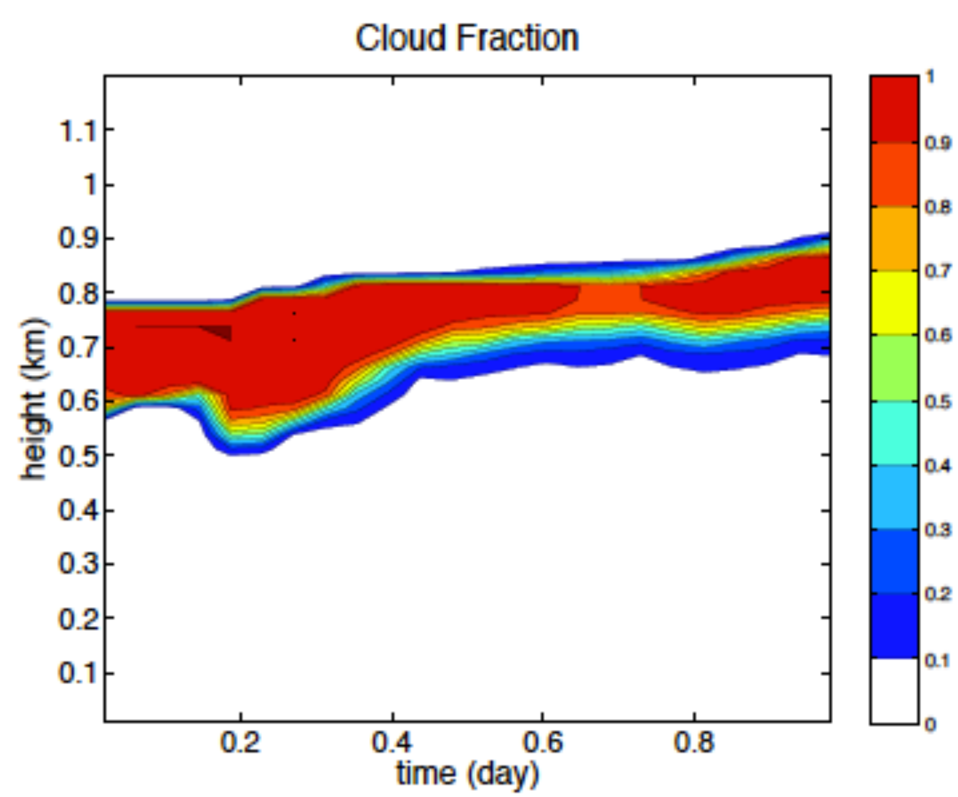
LES: dx=dy= 50 m, dz = 20 m
2D-CRMs: dx = 3.2 km, dz = 20 m



(a) Benchmark

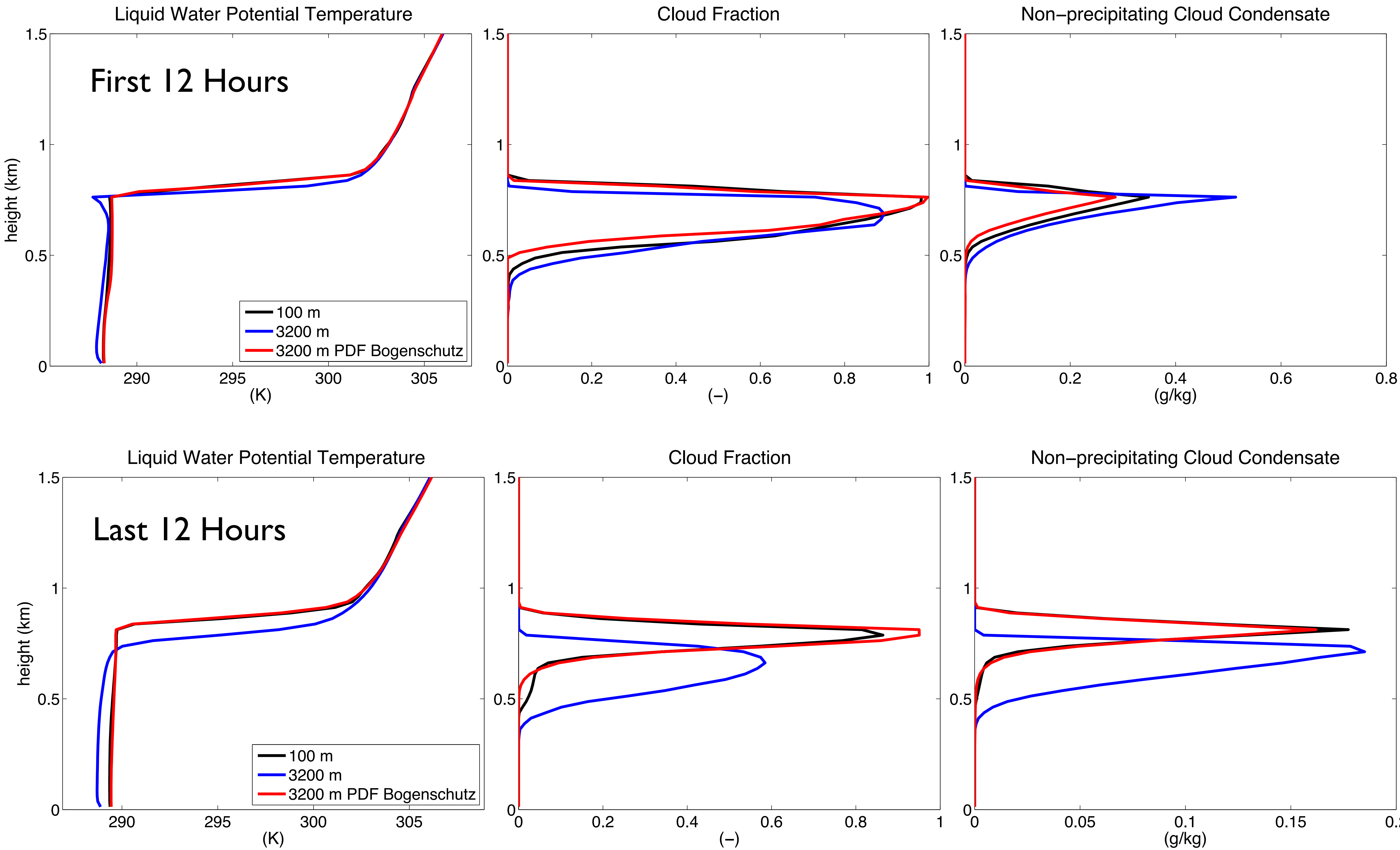


(b) Standard SAM



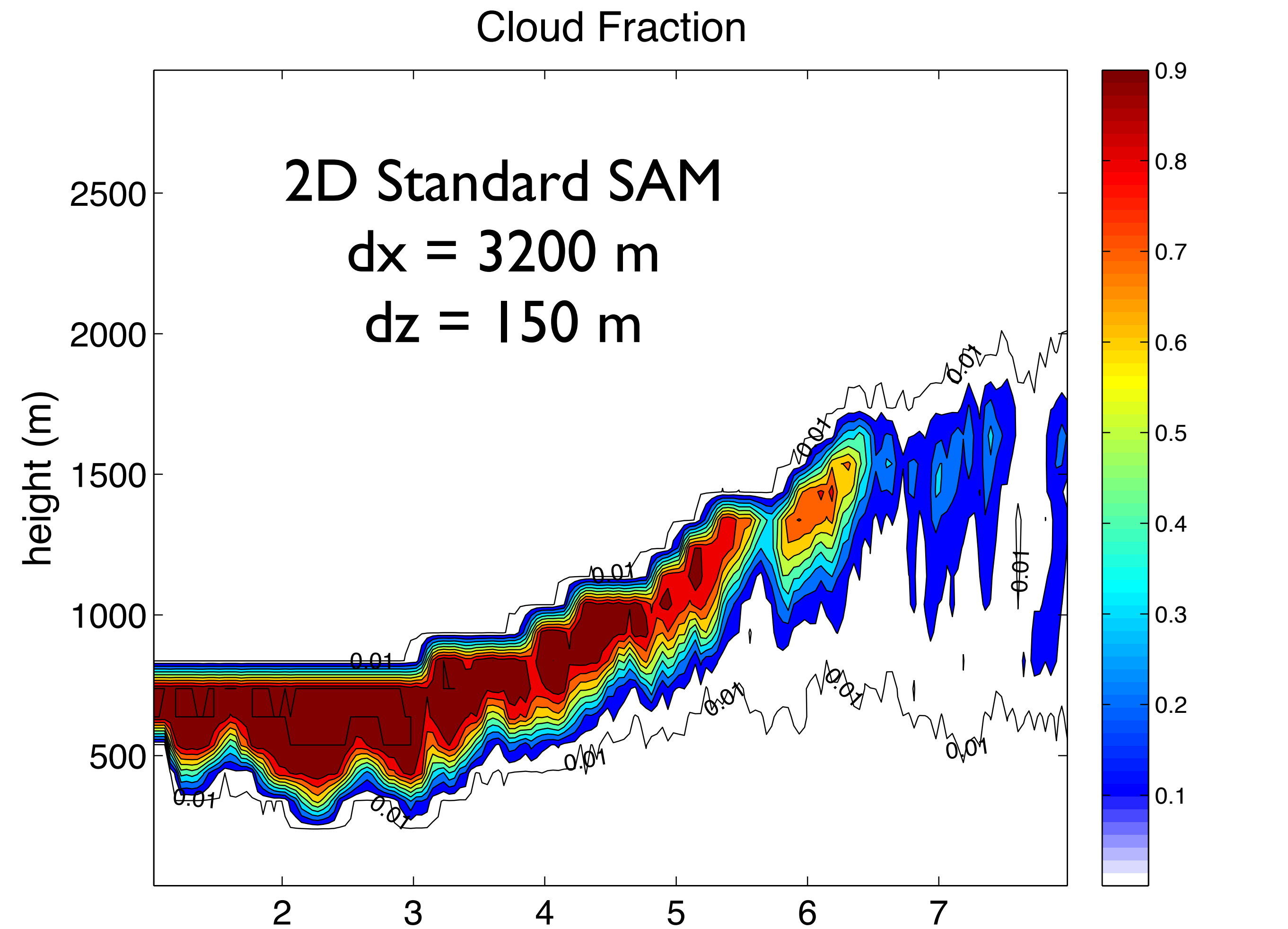
(c) PDF-SAM, L=Bogenschutz

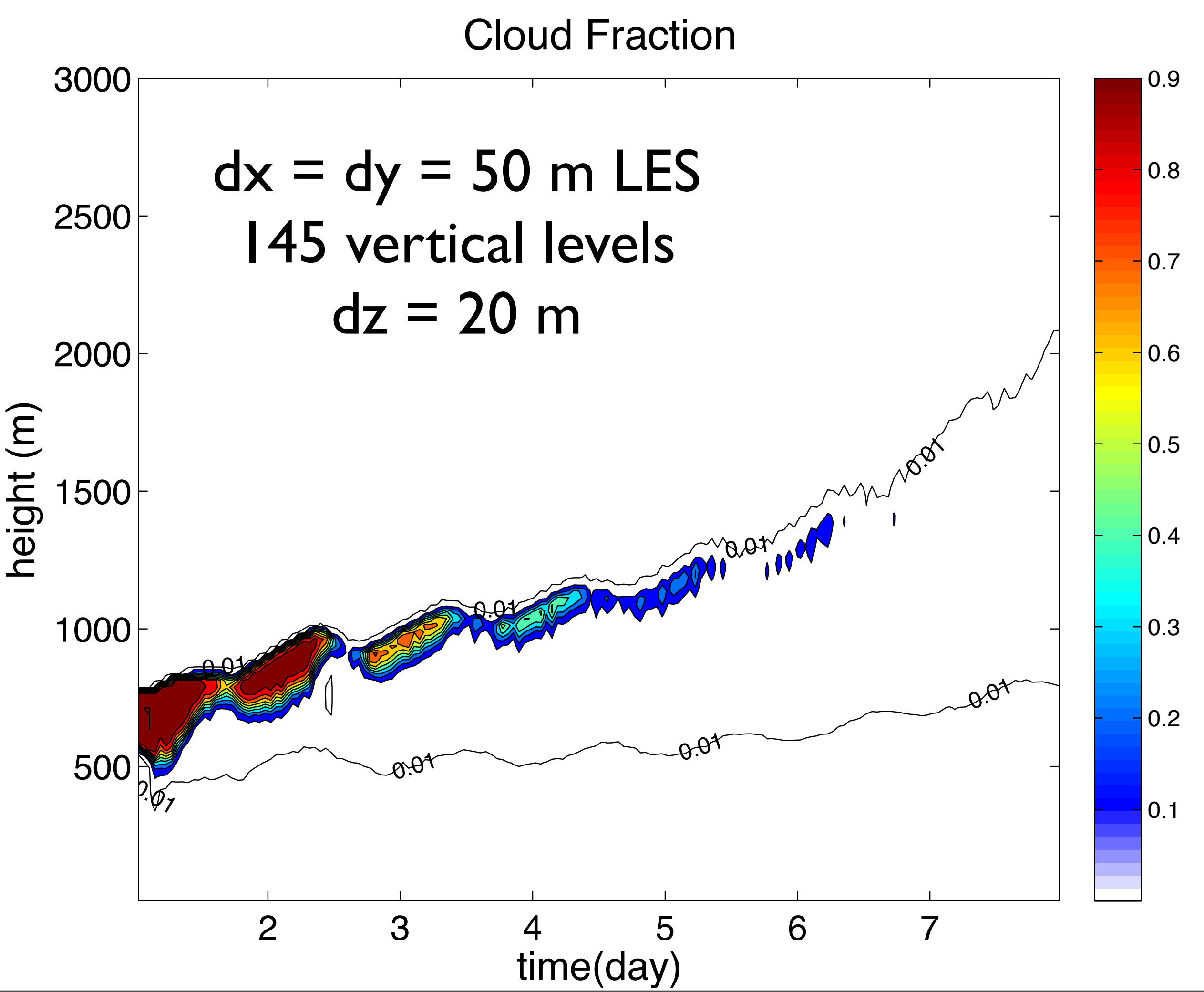
Stratocumulus (Day One of Transition)

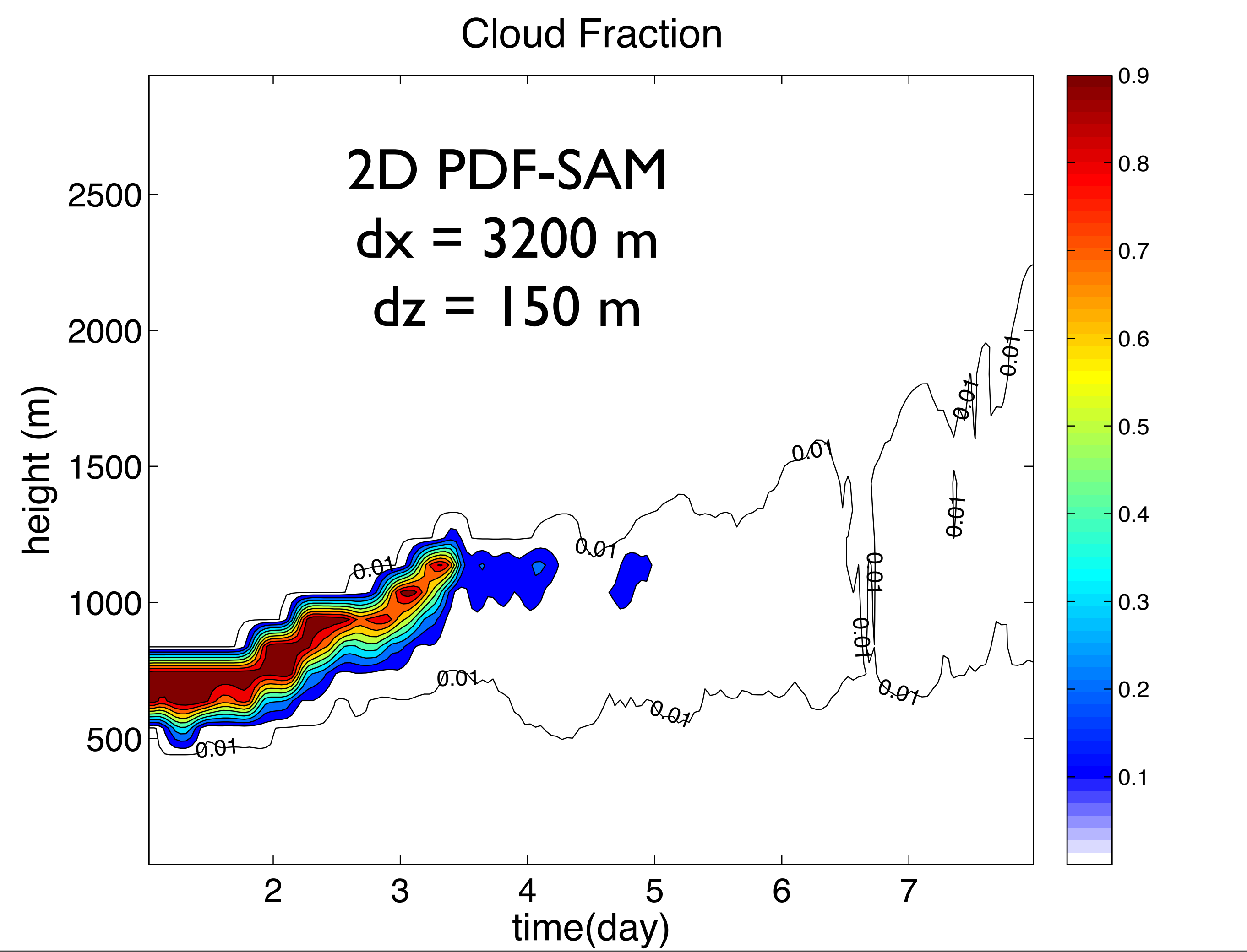


Lagrangian Transition Case

7 day case: SST Warming Linearly



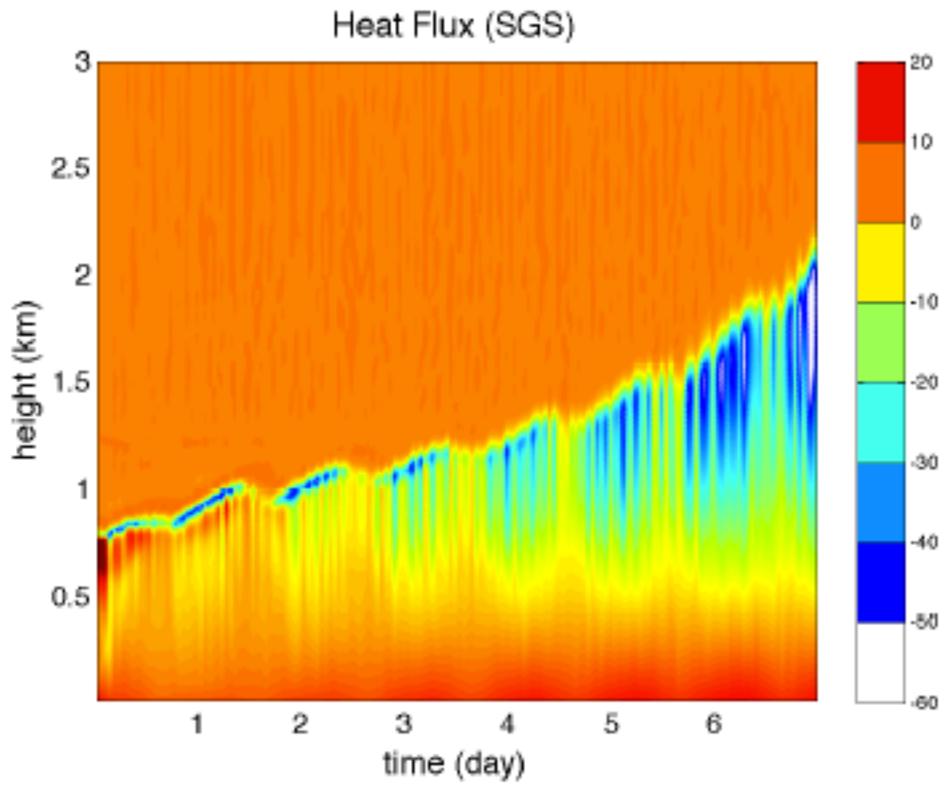




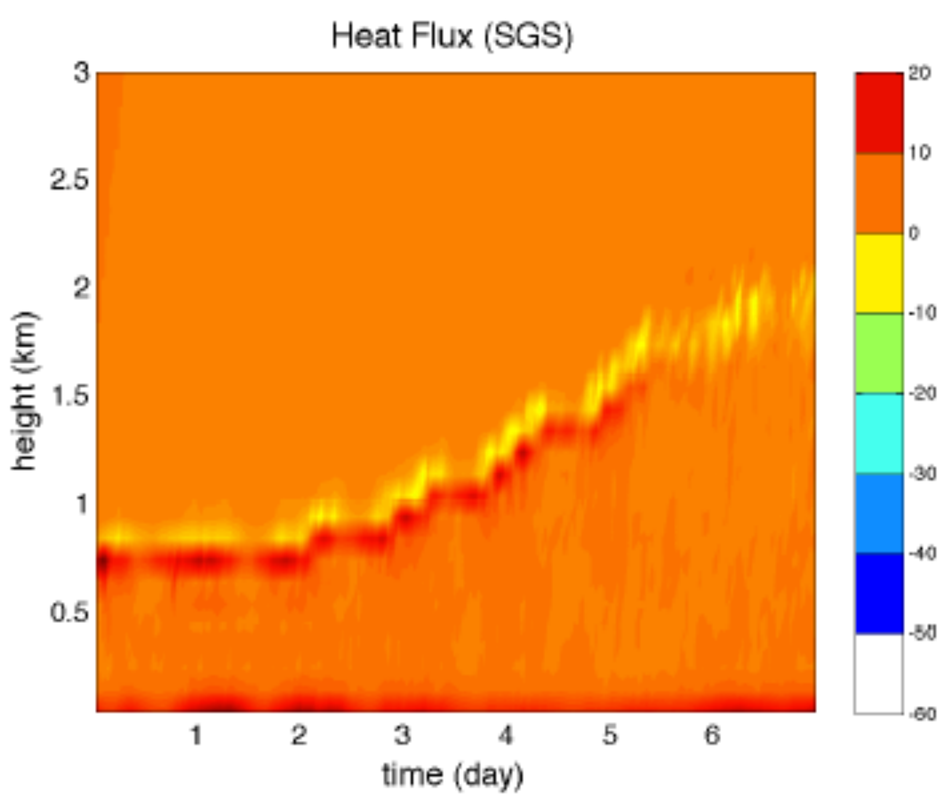
Transition Case
SGS Heat Flux

$$\overline{w' h'_L} \; (\mathrm{W/m^2})$$

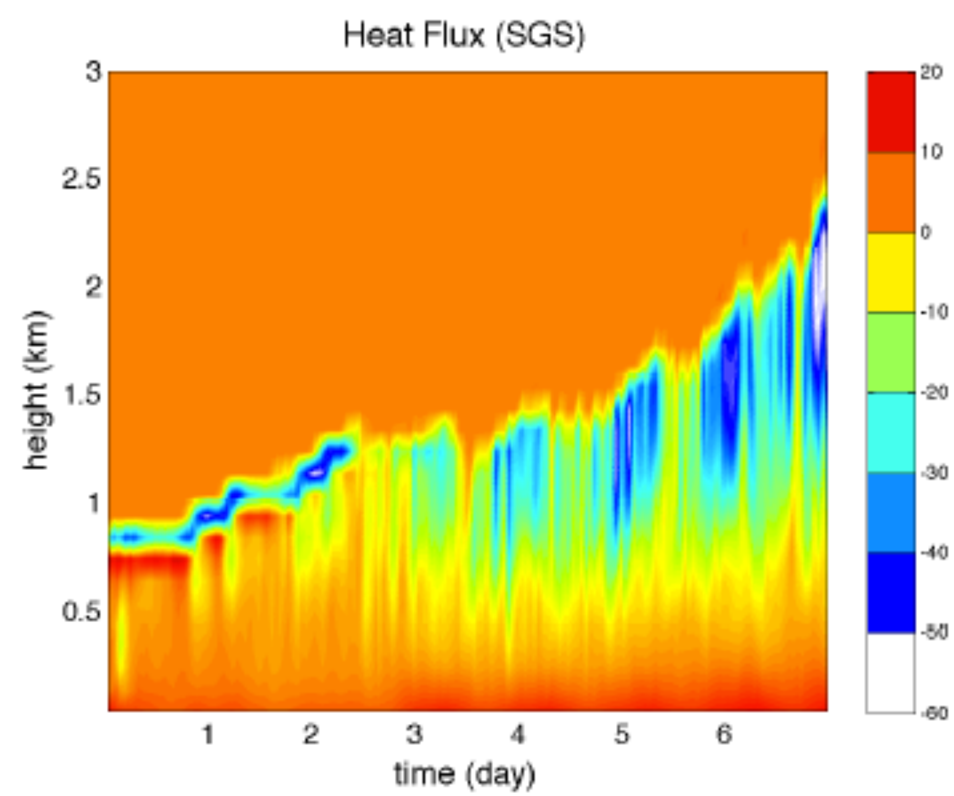
$$\Delta x = 3.2 \text{ km}$$



(a) Benchmark Retrieved SGS Fluxes



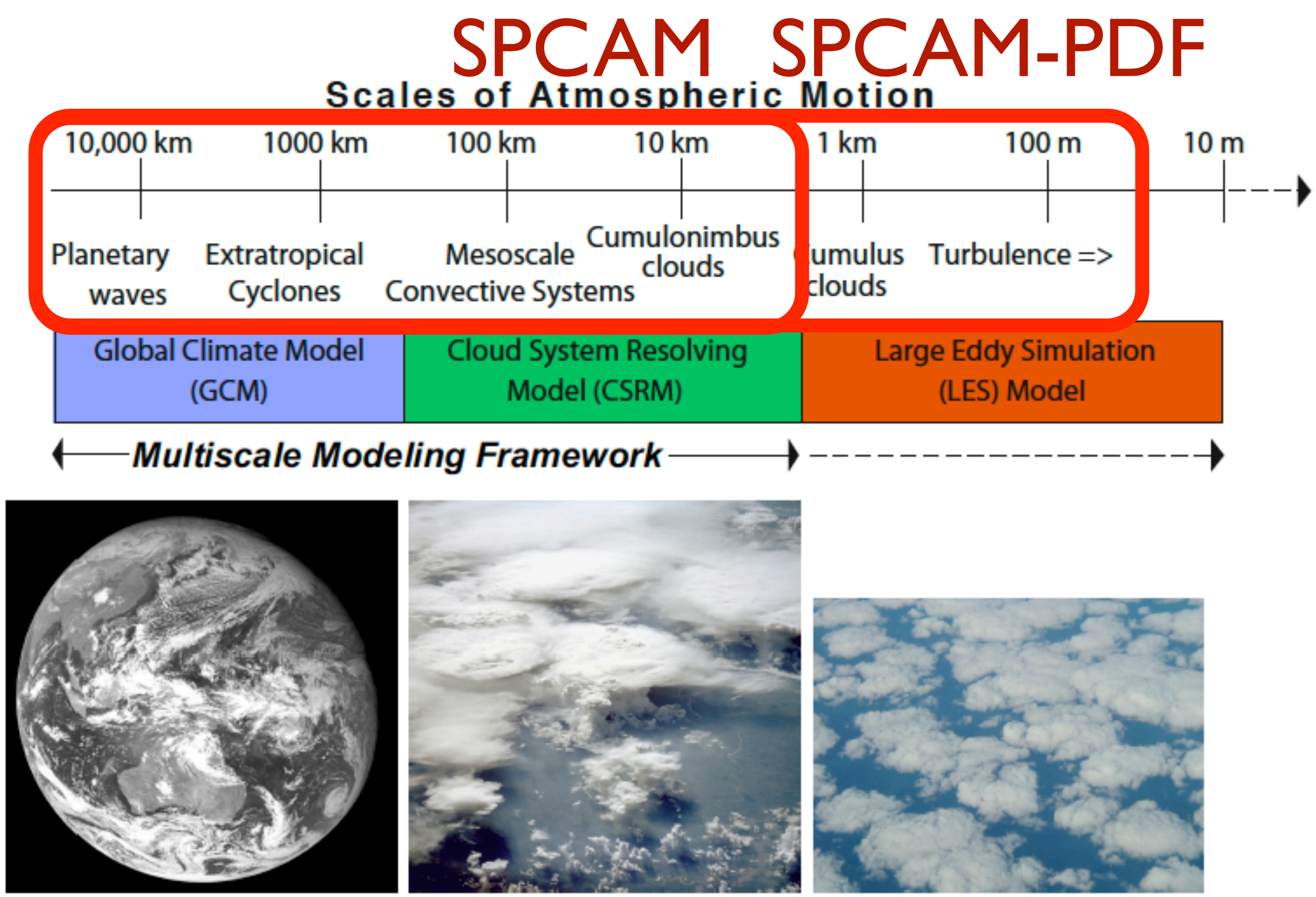
(b) Standard SAM



(c) PDF-SAM, L=Bogenschutz

MMF Testing

- PDF-SAM shows it can represent shallow convection with fidelity and is fairly robust to changes in vertical and horizontal grid spacing
- Computational cost is kept to a minimum
- How does it perform within the MMF?

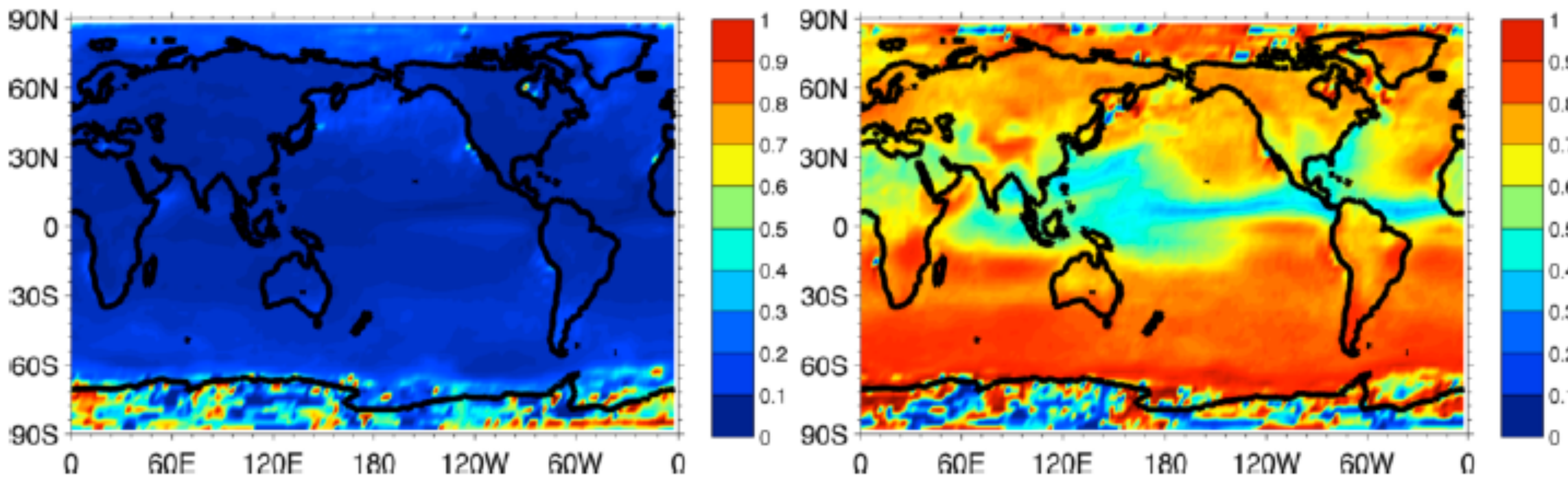


Preliminary Test of Closure Within MMF

- Code implemented to the embedded CRM 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)
- Preliminary results from June, July, August (JJA) simulation (with one month spin-up)
- In general, SPCAM-PDF improves the representation of cumulus clouds within the MMF
- However, representation of stratocumulus off western continental coasts not improved (very likely due to inadequate vertical grid spacing)

Ratio SGS/Total vertical flux of total water mixing ratio $\overline{w' q_t'}$

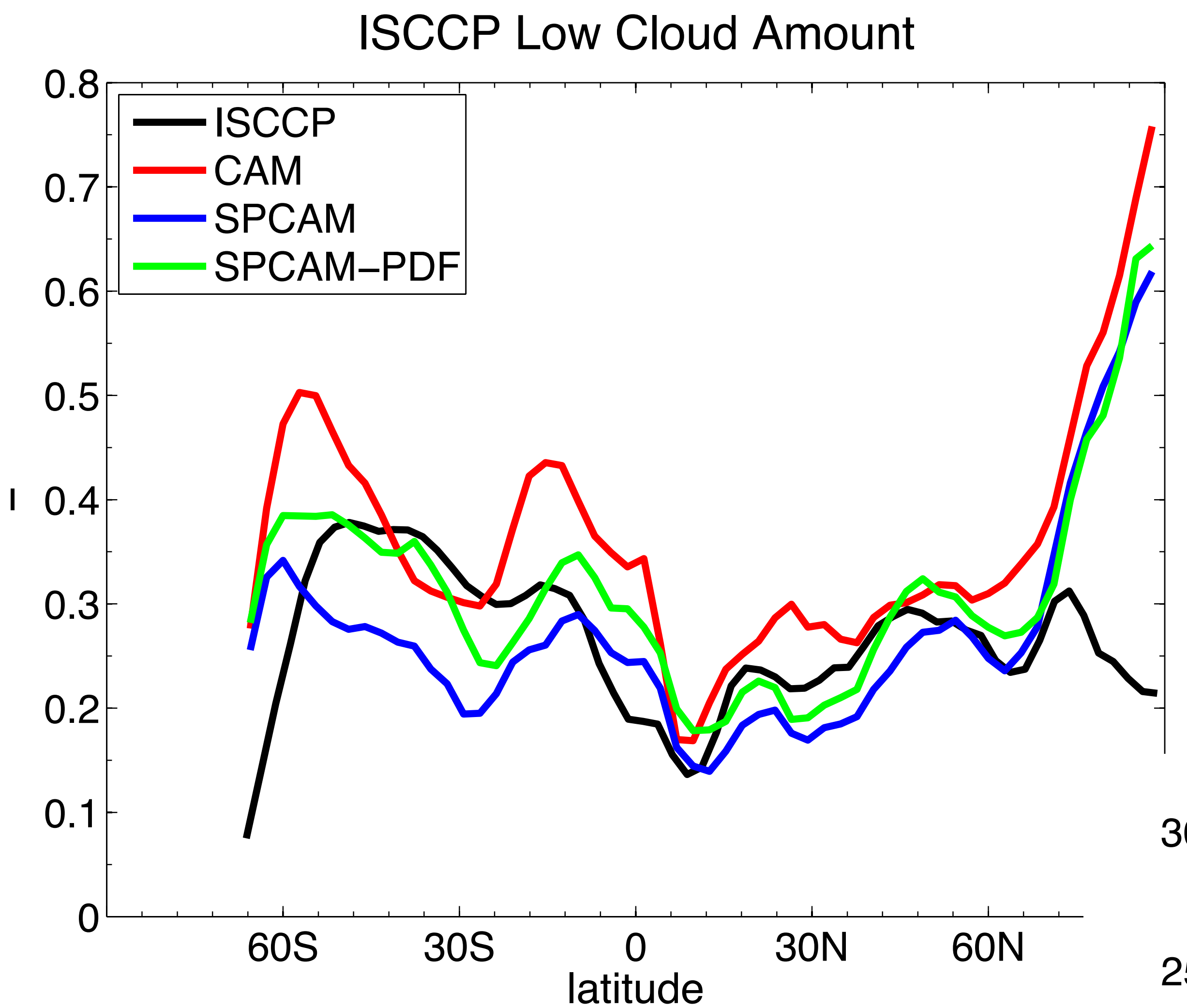
SPCAM   SPCAM-PDF

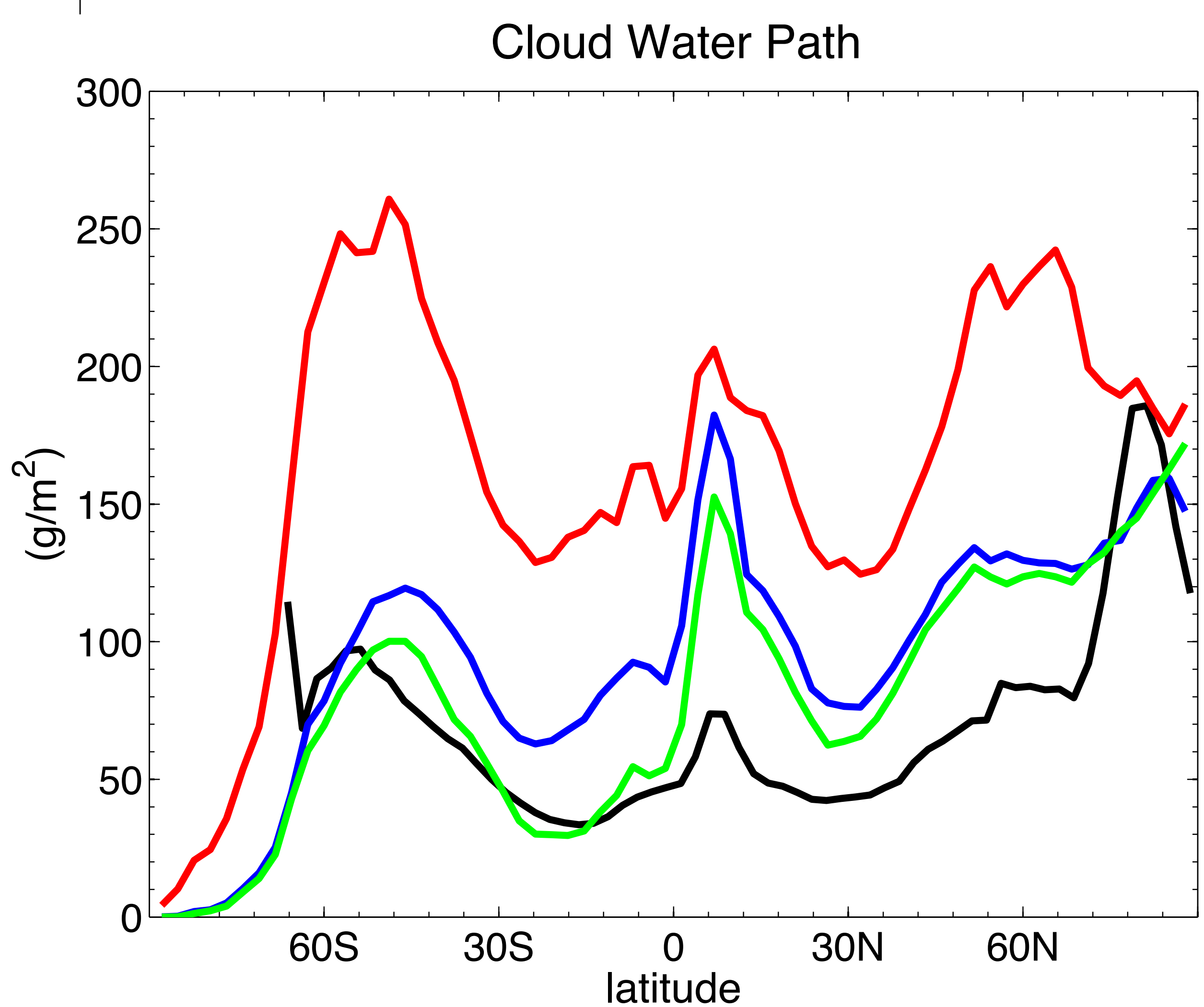


At 860 hPa

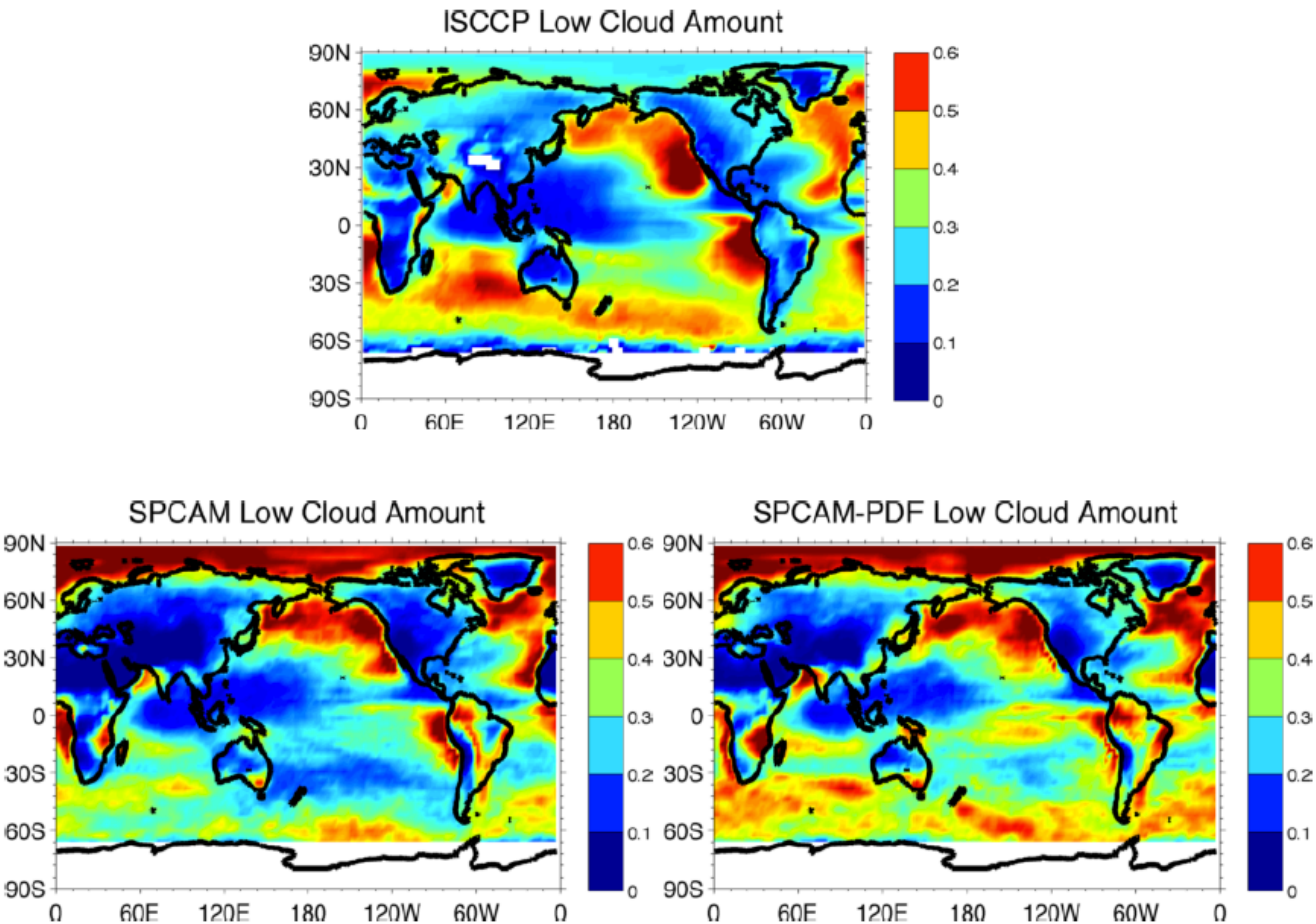
Shallow cloud circulations appear to be more realistically represented in SPCAM-PDF

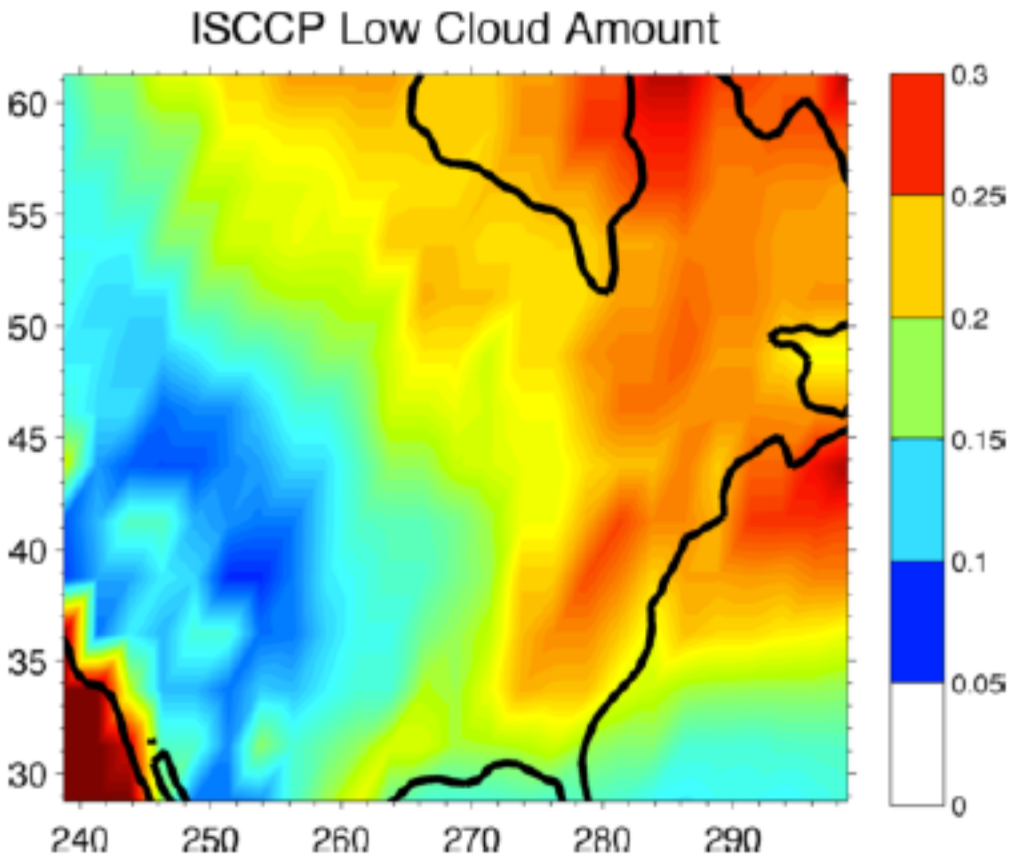
Preliminary Results



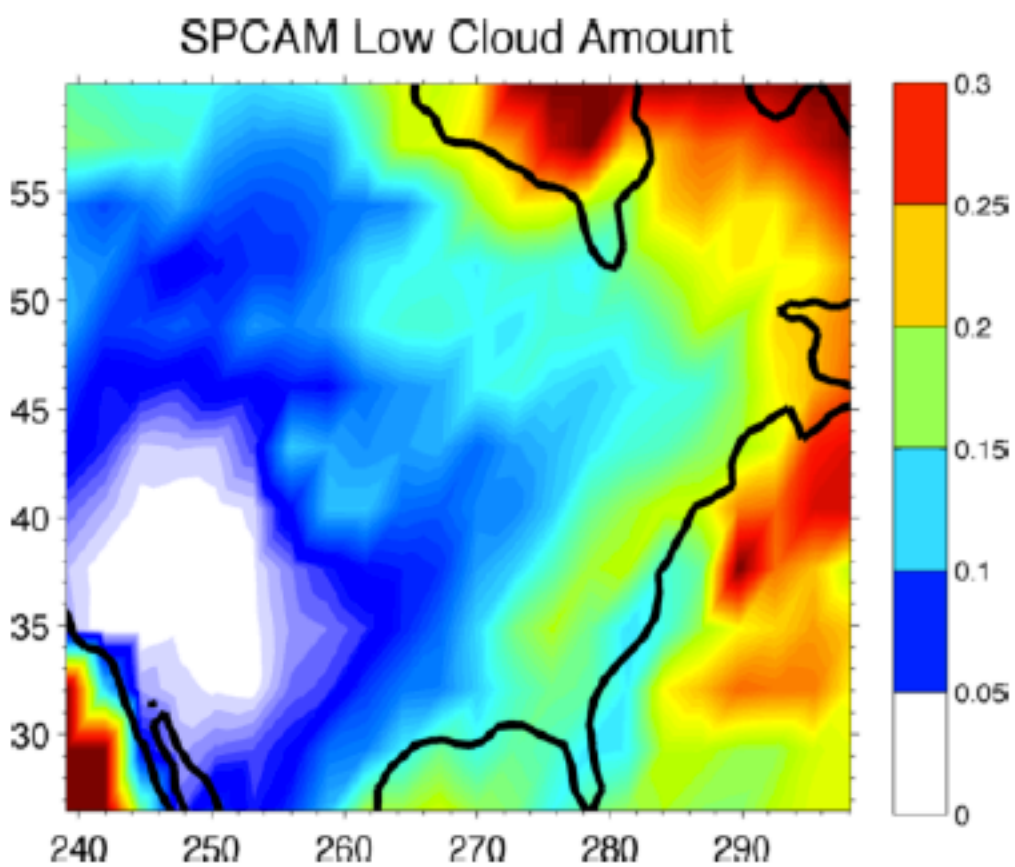


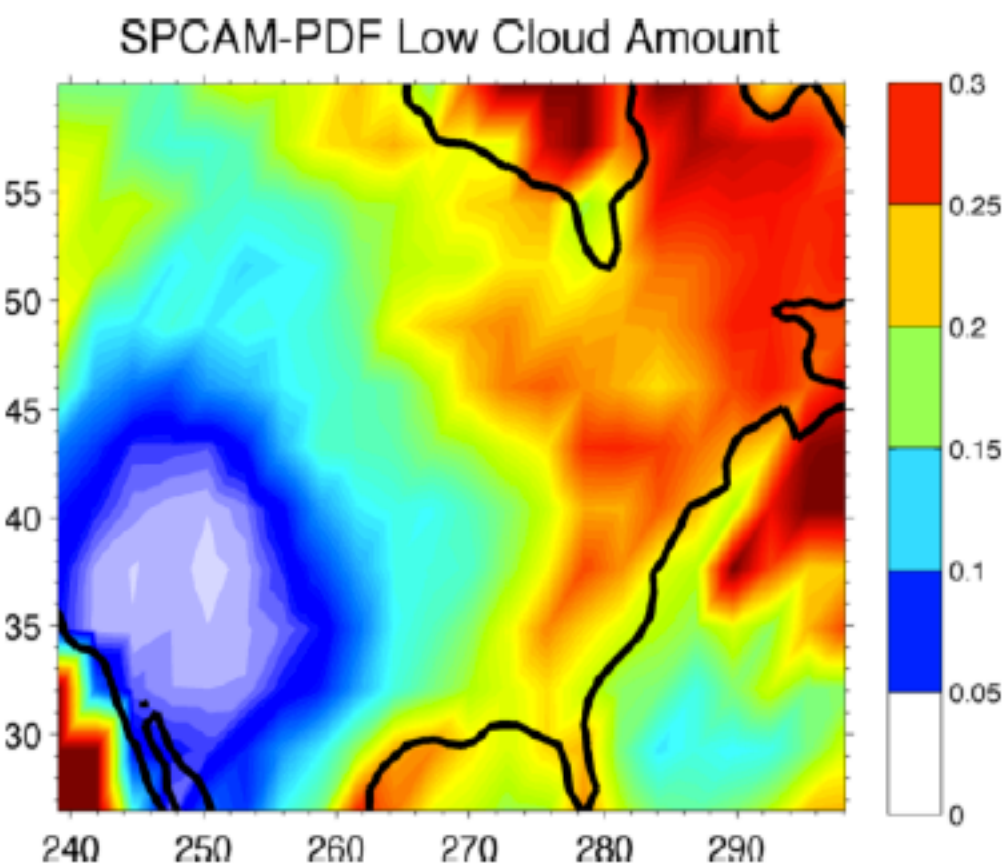
June, July, August


ISCCP Low Cloud Amount
SPCAM Low Cloud Amount
SPCAM-PDF Low Cloud Amount
90N
60N
30N
0
30S
60S
90S
0
60E
120E
180
120W
60W
0
0.6
0.5
0.4
0.3
0.2
0.1
0

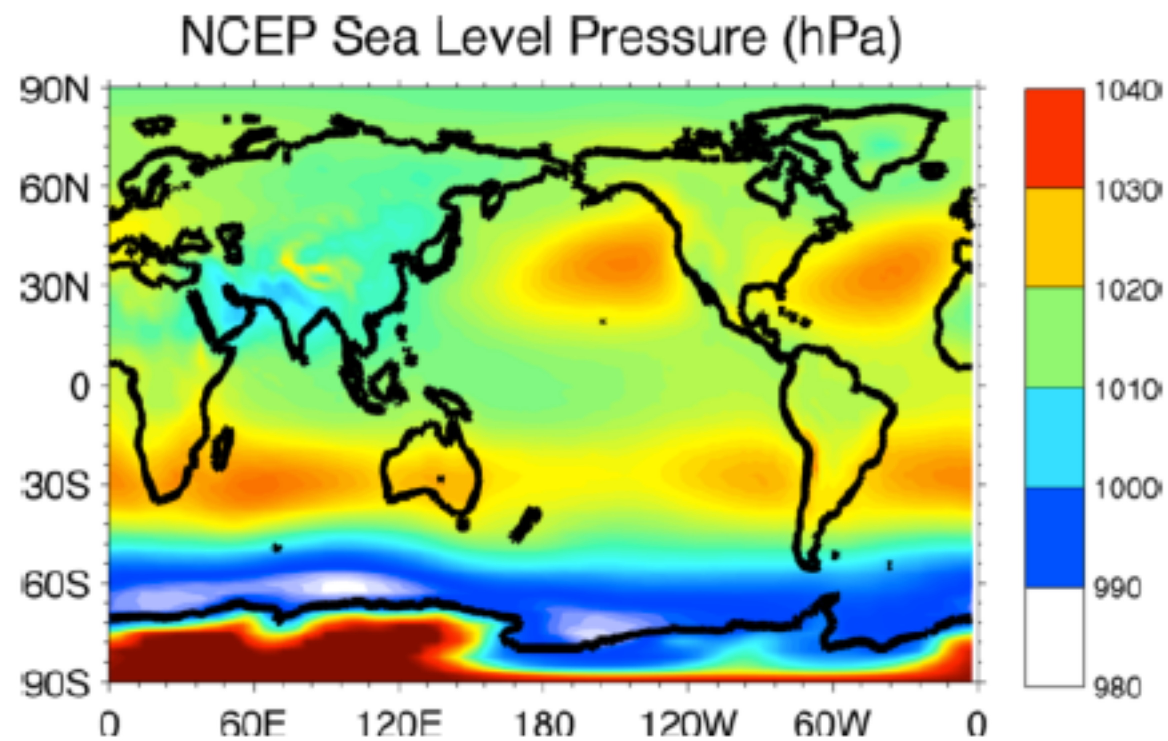


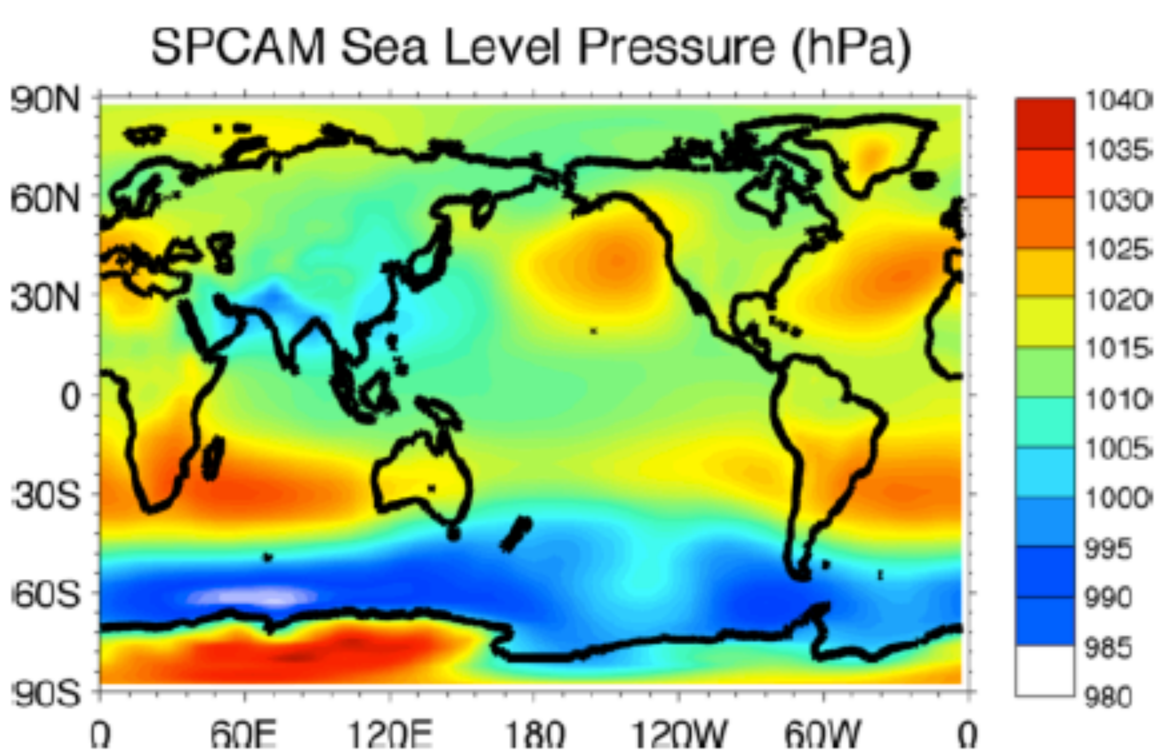
Low Clouds Over Land

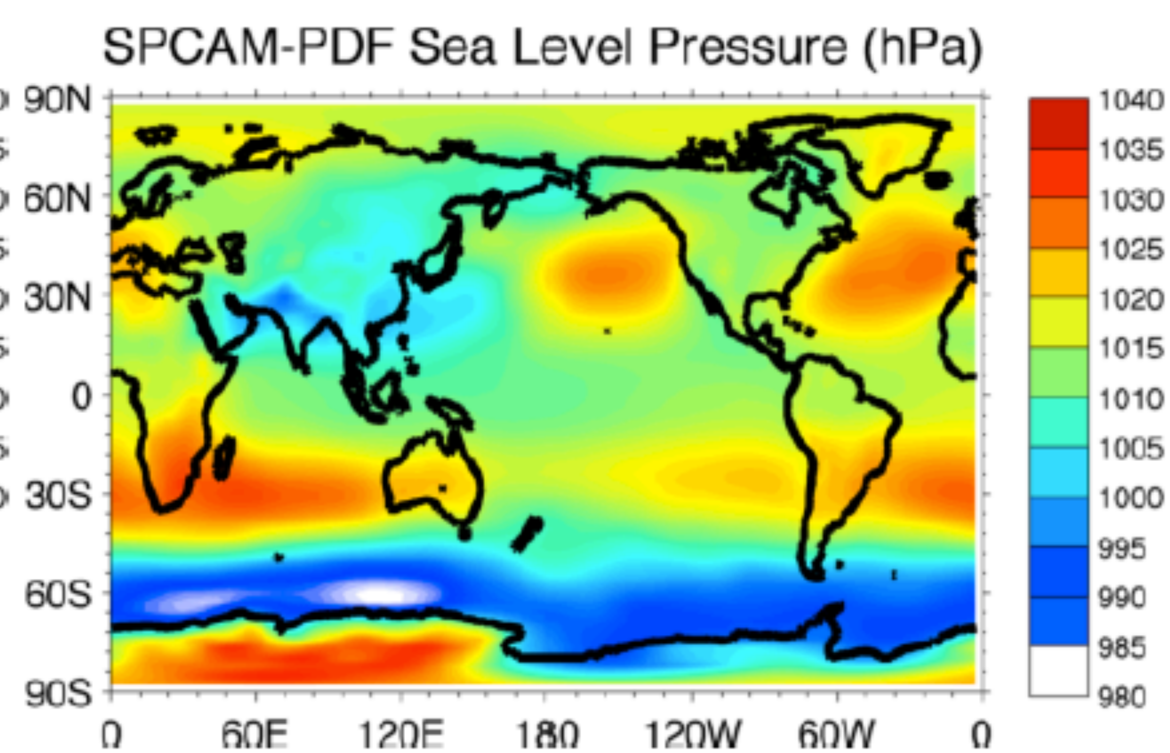




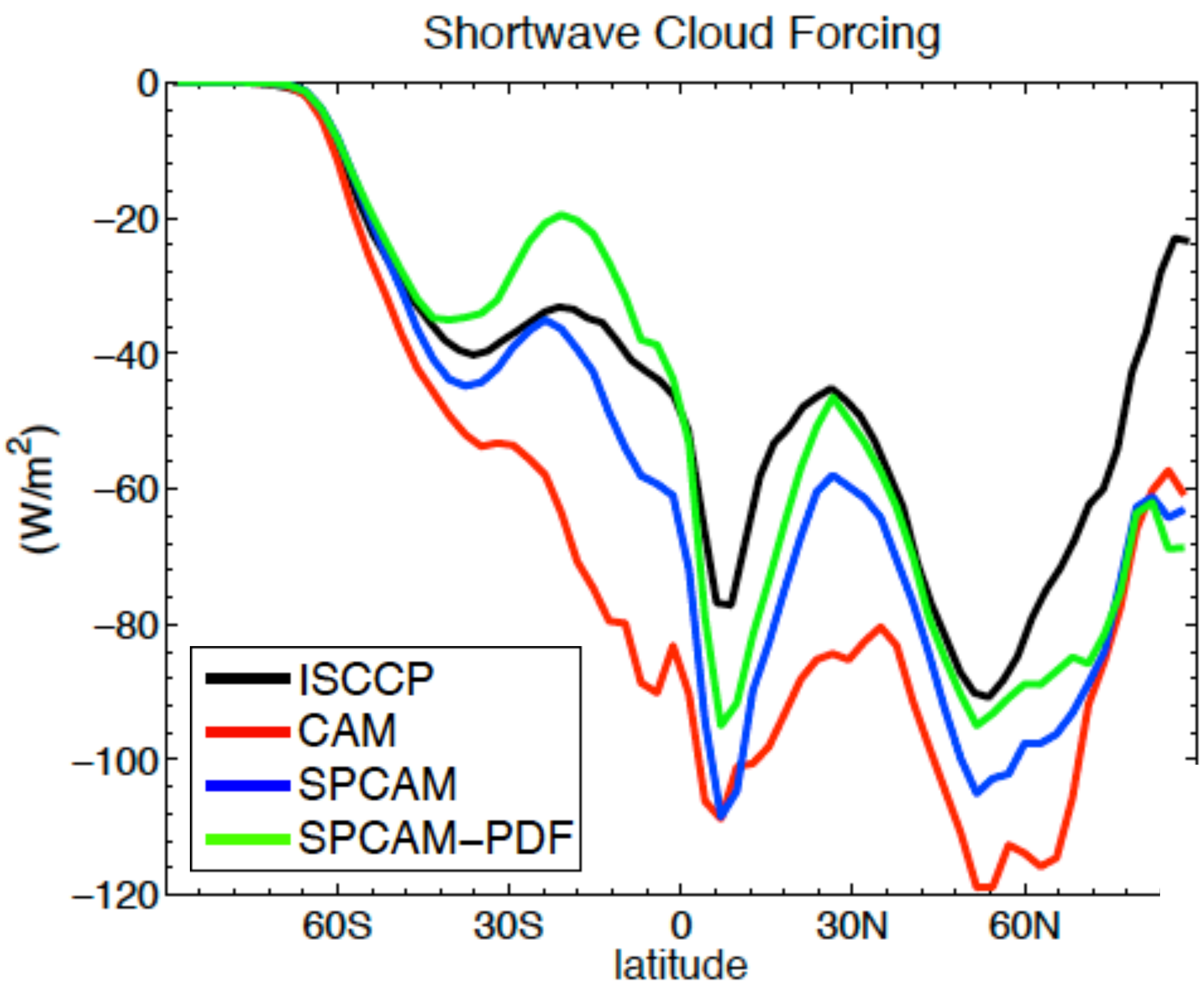
Sea Level Pressure

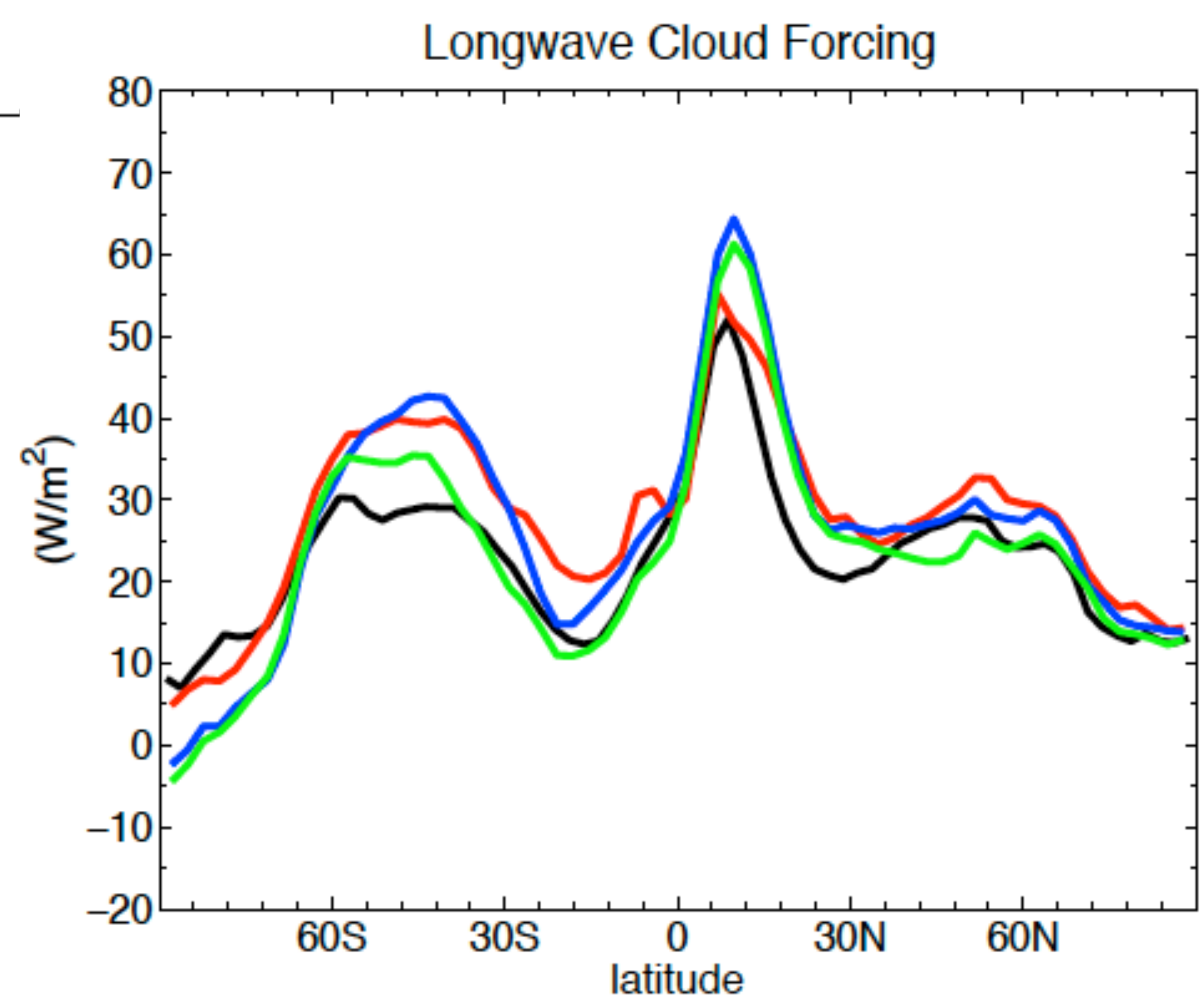






Cloud Forcing





Summary

- PDF-SAM (likely to be coined "DHOC" in publication) represents a new type of model:
    - Diagnostic higher-order closure with assumed PDF for condensation and turbulence
    - Focus is on improvement of SGS TKE
- Can represent boundary layer clouds and deep convection realistically with minimal additions to computational cost
- Representation of cumulus in MMF is improved, stratocumulus still severely underrepresented
- Simple code that has promise for easy portability to other explicit-convection models (i.e. WRF, GCRMs)

Future Work

- Longer MMF simulations must be performed/tested
  - How does it compare with IPHOC (Cheng and Xu, 2010)?
- Coupling of PDF-SAM with double moment or PDF-based microphysics schemes (Cheng and Xu 2009)
- Coupling of PDF-SAM with other simple turbulence schemes (i.e. two-part scheme of Moeng et al. 2010)
- Coupling of PDF-SAM with models to better represent stratocumulus topped inversions when dz is coarse
  - Boundary layer reconstruction (Grienier and Bretherton 2001)
  - CRM with adaptive vertical grid (Marchand and Ackerman 2010)