An economical scale-aware parameterization for representing subgrid-scale clouds and turbulence in cloud-resolving models and global models

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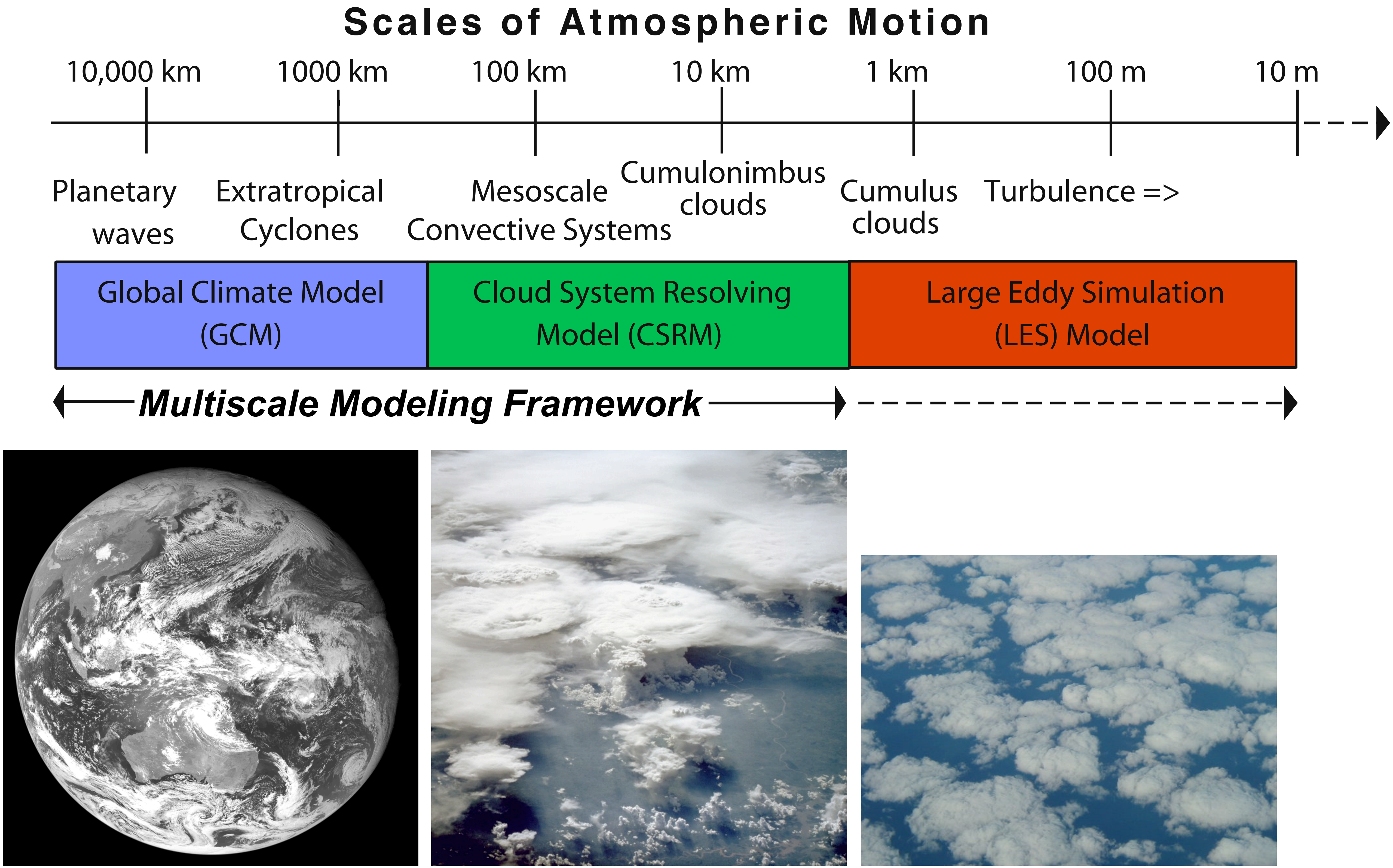
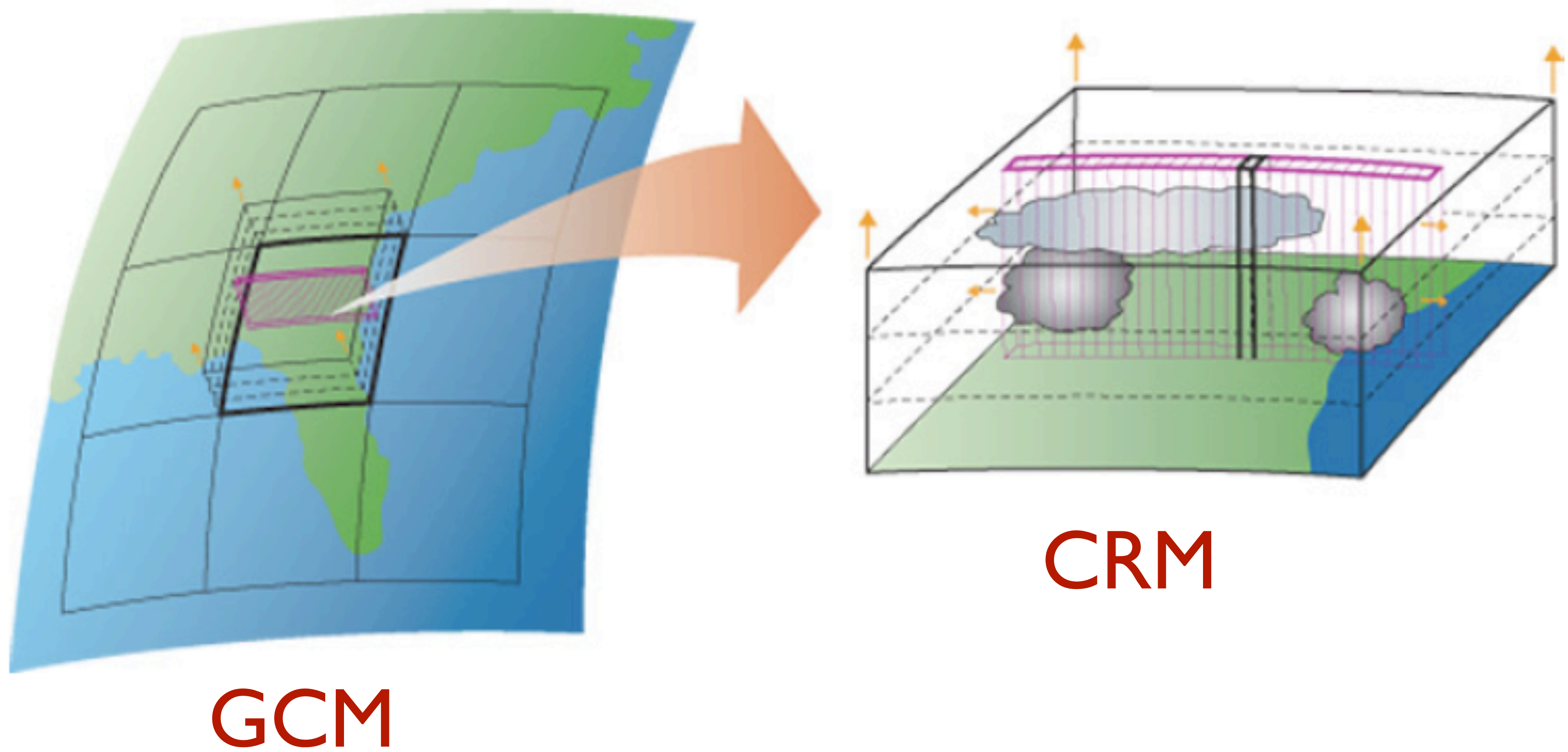
Photo: Lis Cohen


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

Multiscale Modeling Framework



In MMF, a 2D CRM is embedded in each grid column of the GCM.

Community Atmosphere Model (CAM)
+ System for Atmospheric Modeling (SAM)
=> Super-Parameterized CAM (SP-CAM)

SAM was developed by Marat Khairoutdinov (http://rossby.msrc.sunysb.edu/~marat/SAM.html

Boundary layer clouds in cloud-system-resolving models (CSRMs)

- CSRMs may have horizontal grid sizes of 4 km or more.
- Such CSRMs are used in MMF, GCRMs (global CSRMs), and many NWP models.
- In such models, CSRMs are expected to represent all types of cloud systems.
- However, many cloud-scale circulations are not resolved by CSRMs.
- Representations of SGS (subgrid-scale) circulations in CSRMs can be improved.

- One approach for better representing SGS clouds and turbulence is the *Assumed PDF Method.*

- This method parameterizes SGS clouds and turbulence in a unified way.

- It was initially developed for boundary layer clouds and turbulence.

- It is a very promising method for use in coarse-grid CSRMs, such as those used in the SP-CAM.

Steps in the Assumed PDF Method

The Assumed PDF Method contains 3 main steps that must be carried out for each grid box and time step:

(1) Prognose means and various higher-order moments.

(2) Use these moments to select a particular PDF member from the assumed functional form.

(3) Use the selected PDF to compute many higher-order terms that need to be closed, e.g. buoyancy flux, cloud fraction, etc.

Our PDF includes several variables

We use a three-dimensional PDF of vertical velocity, w, total water (vapor + liquid) mixing ratio, q_t, and liquid water potential temperature, θ_l :

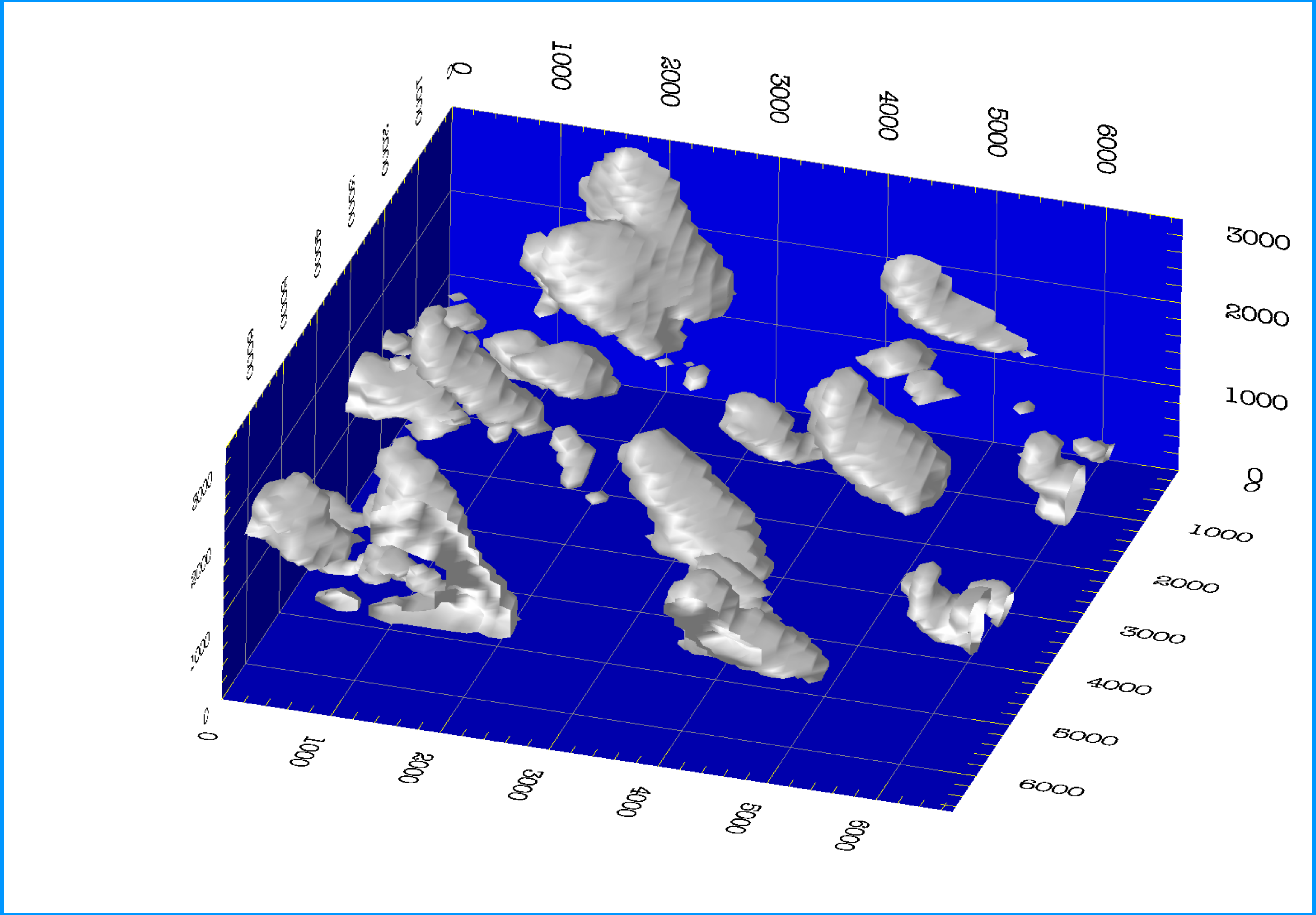
$$P = P(w, q_t, \theta_l)$$

This allows us to couple subgrid interactions of vertical motions and buoyancy.

Randall et al. (1992)

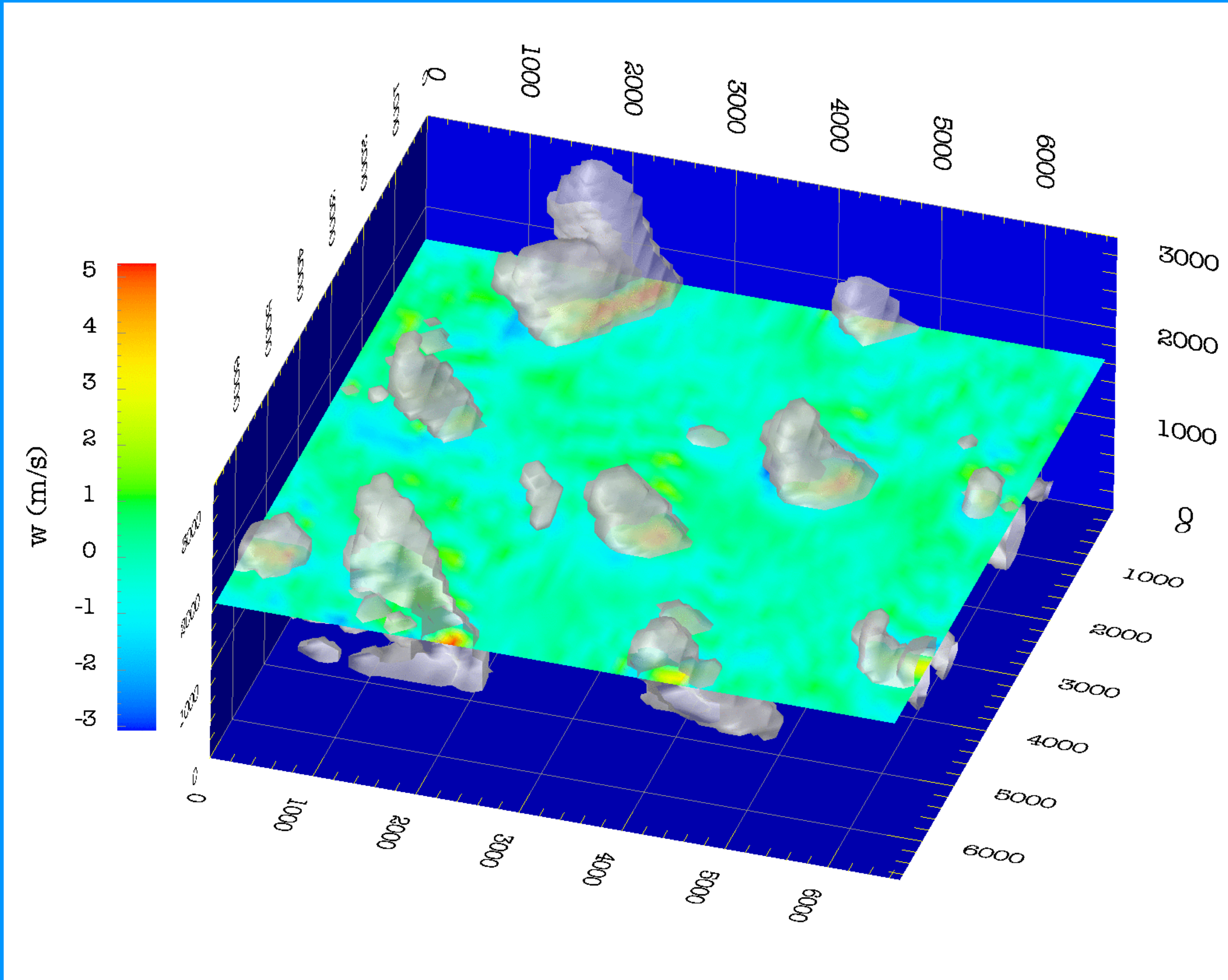
PDFs of cumulus clouds

Isosurface of cloud water: 0.001 (g/kg)



(courtesy of W. R. Cotton & J.-C. Golaz)

PDFs of cumulus clouds



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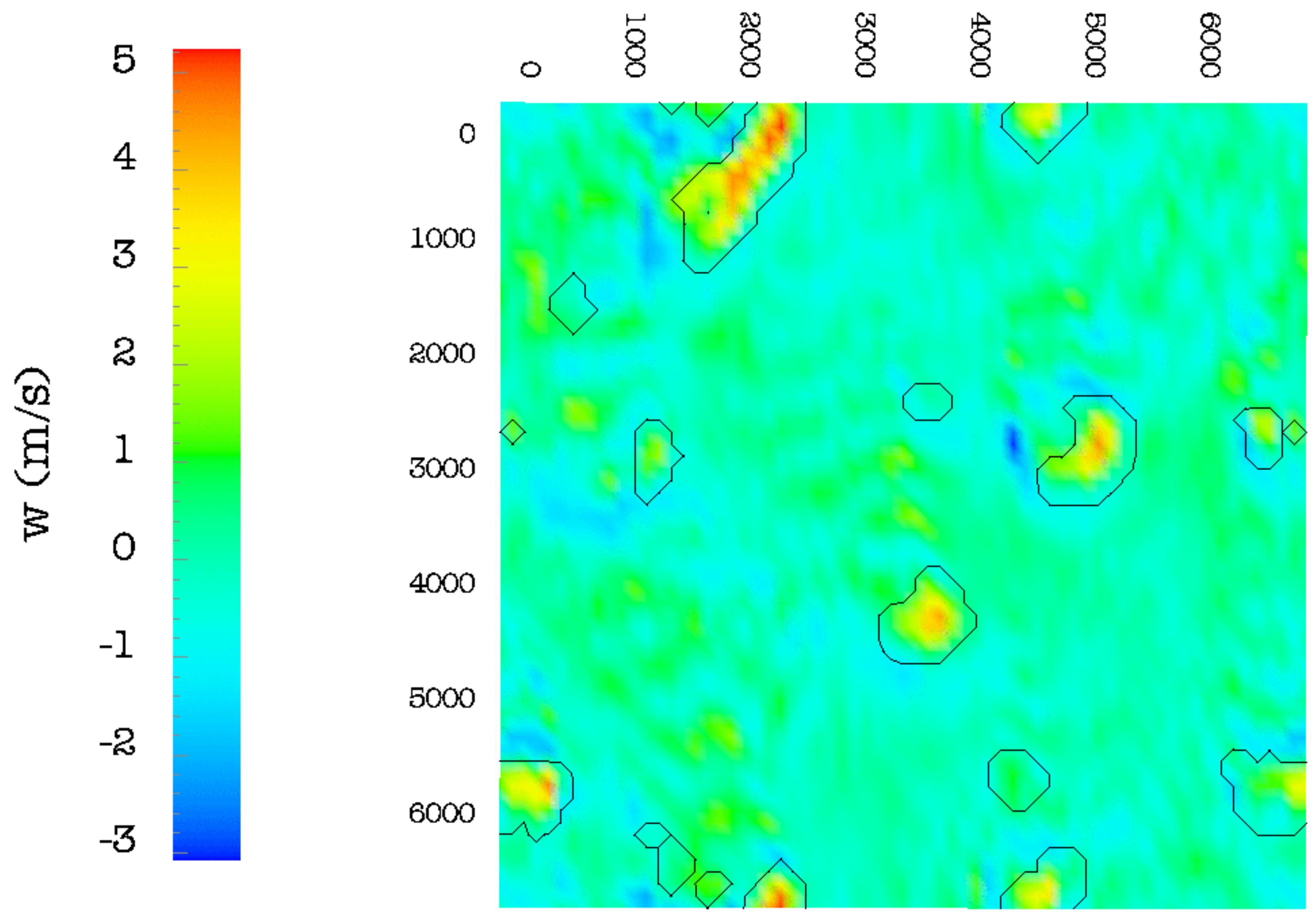
PDFs of cumulus clouds

Horizontal cross section of vertical velocity; z=1680(m)



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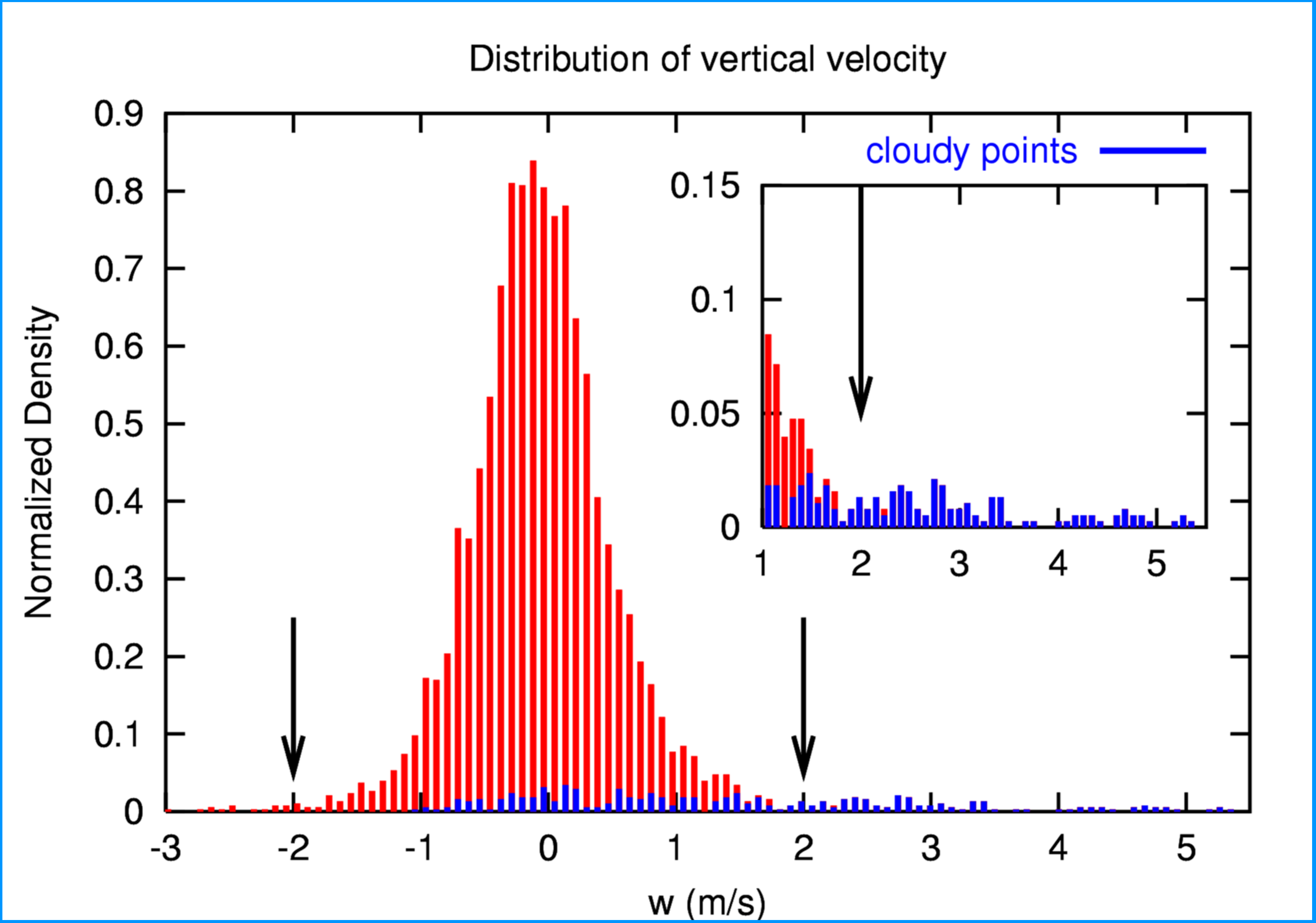
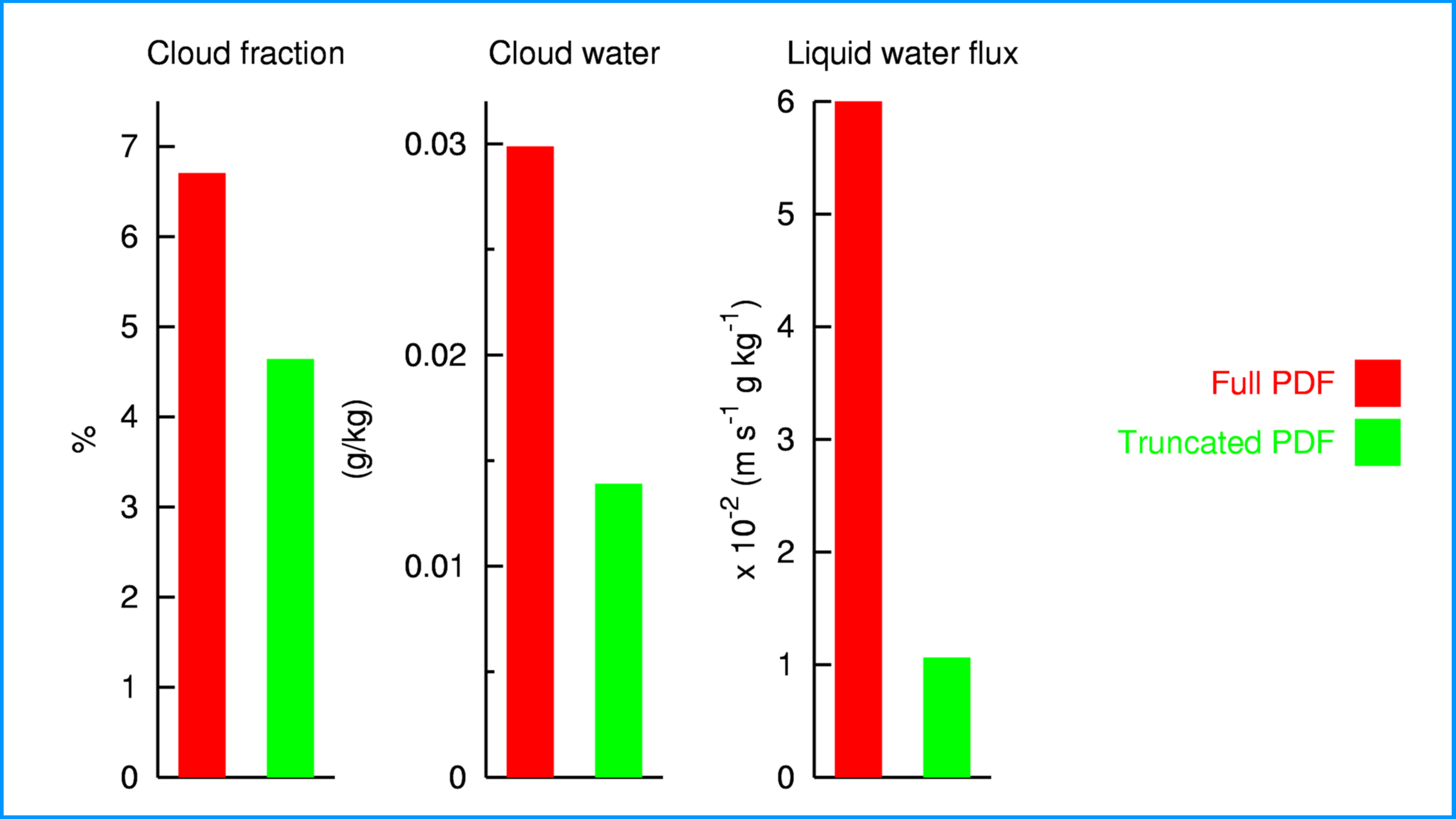
PDFs of cumulus clouds



(courtesy of W. R. Cotton & J.-C. Golaz)

PDFs of cumulus clouds

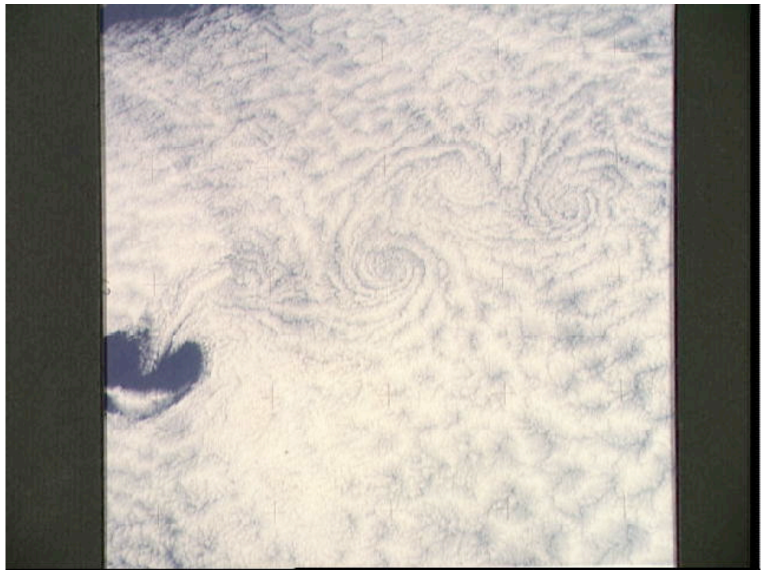


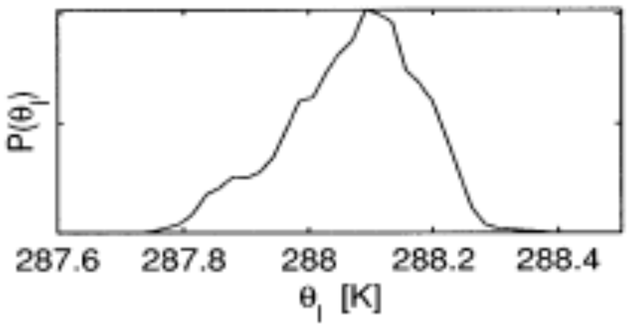
(courtesy of W. R. Cotton & J.-C. Golaz)

Approach

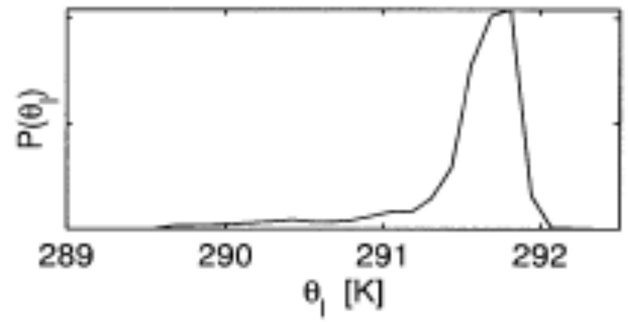
- One major difficulty of the PDF approach is to find a family of PDF that is both:
  - Flexible enough to represent cloud regimes with cloud fraction ranging from a few per cent to overcast.
  - Simple enough to allow analytical integration of moments over the PDF.

Unified Approach to Cloud Representation

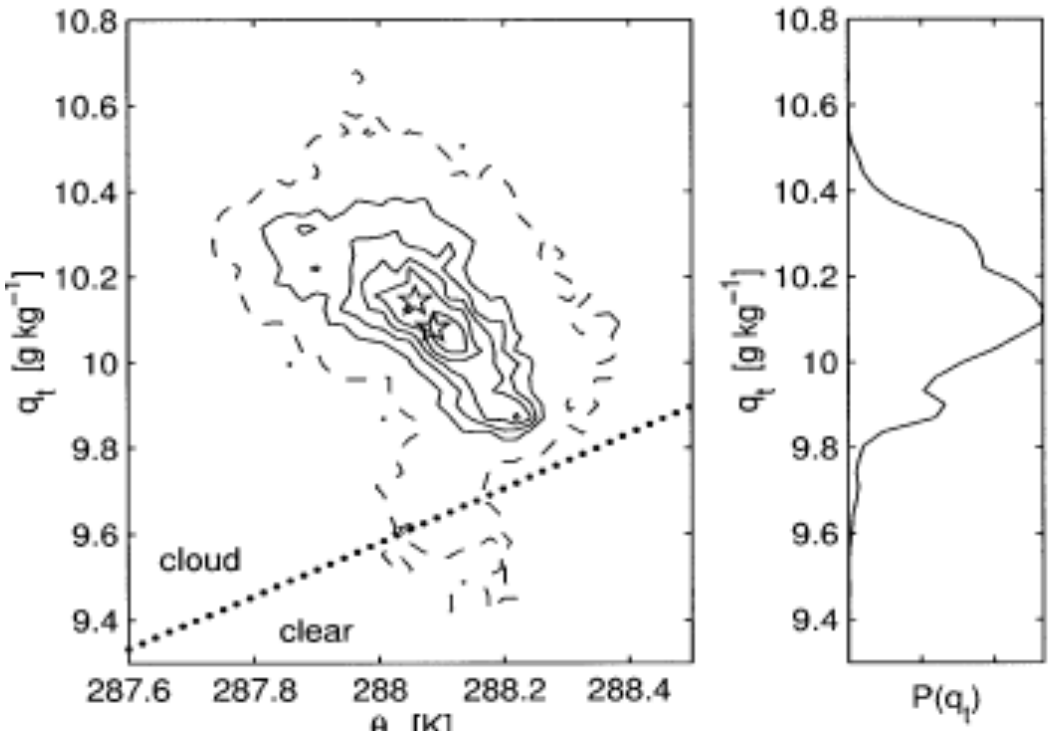


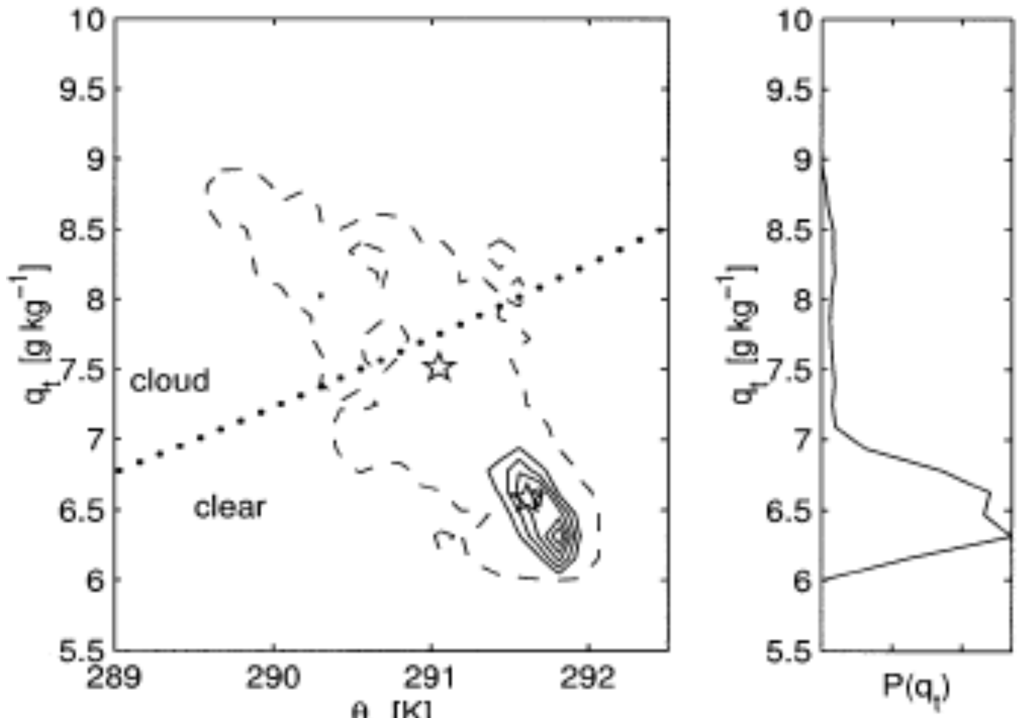


Stratocumulus



Cumulus



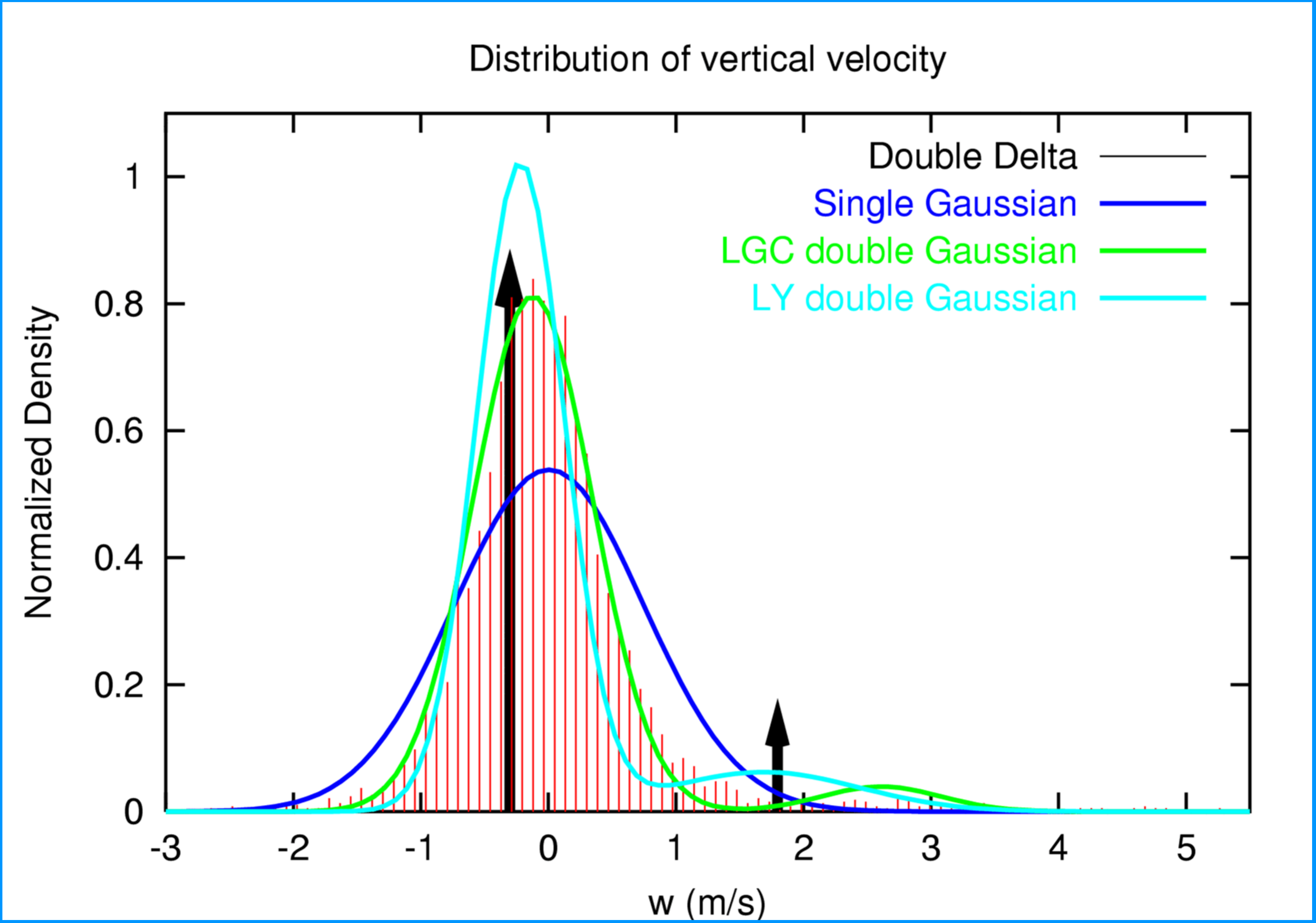


Figures from Larson et al. (2002)

Approach

- Examples of families of PDFs that have been proposed in the past include:
  - Single Gaussian distribution to account for subgrid-scale cloud fraction and cloud water (e.g., Sommeria and Deardorff 1977; Mellor 1977).
  - Double Dirac delta function: one delta function to represent the cloudy part of the disbituion and the other the environment (e.g., Randall et al. 1992; Lappen and Randall 2001a,b,c).

Example of a PDF fit



(courtesy of W. R. Cotton & J.-C. Golaz)

Fitting PDFs

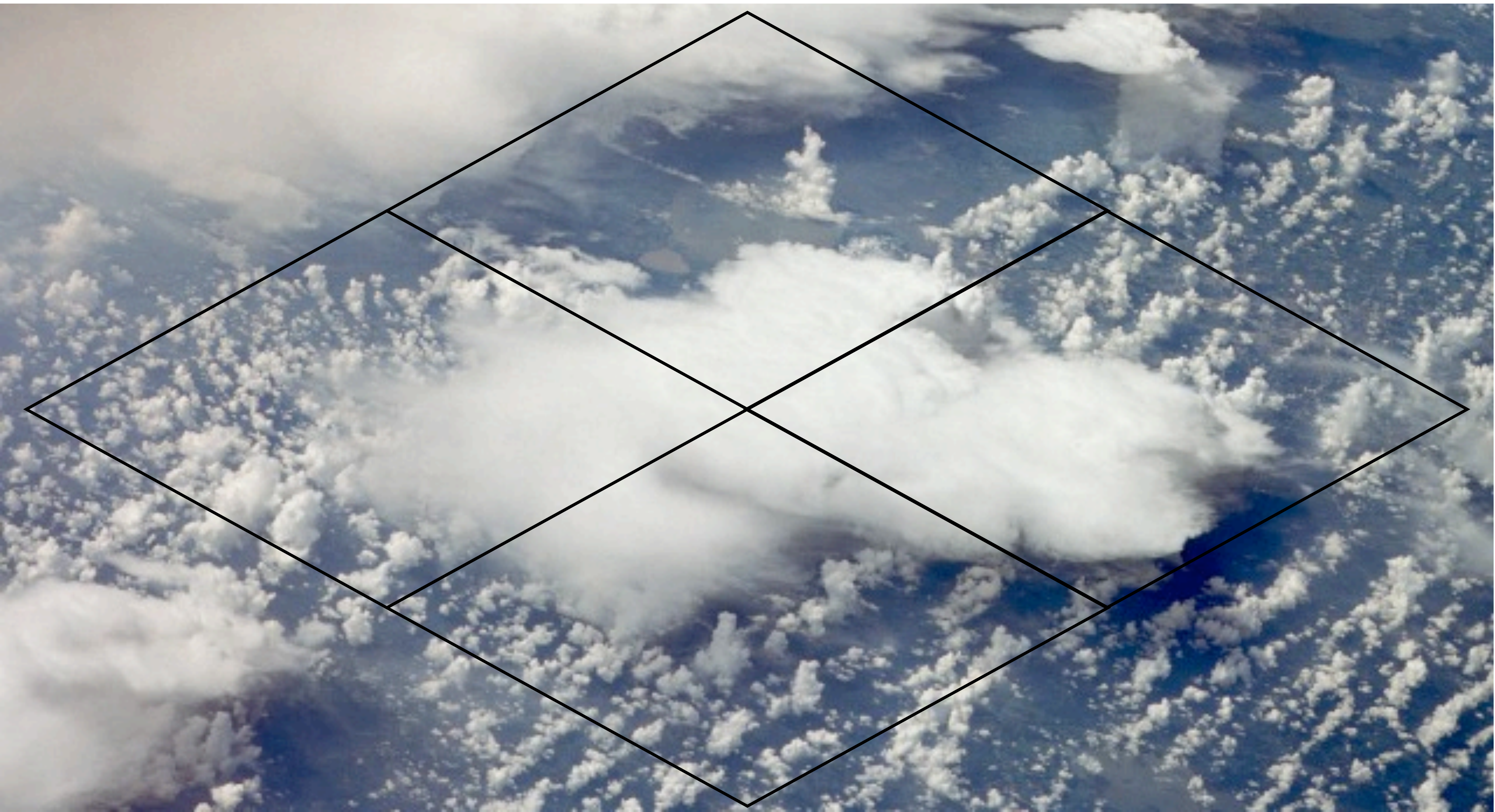
- Now, let's fit various families of PDFs to the LES data to see how they perform.
- Fit three dimensional joint PDFs.
- Test four different families of PDFs:
  - Double Dirac delta functions: 7 parameters (Randall et al. 1992)
  - Single Gaussian: 9 parameters (extension of Sommeria and Deardorff 1977).
  - LGC double Gaussian: 10 parameters (Larson et al. 2002)
  - LY double Gaussian: 12 parameters (Lewellen and Yoh 1993).

(courtesy of W. R. Cotton & J.-C. Golaz)

Evaluations of the PDFs

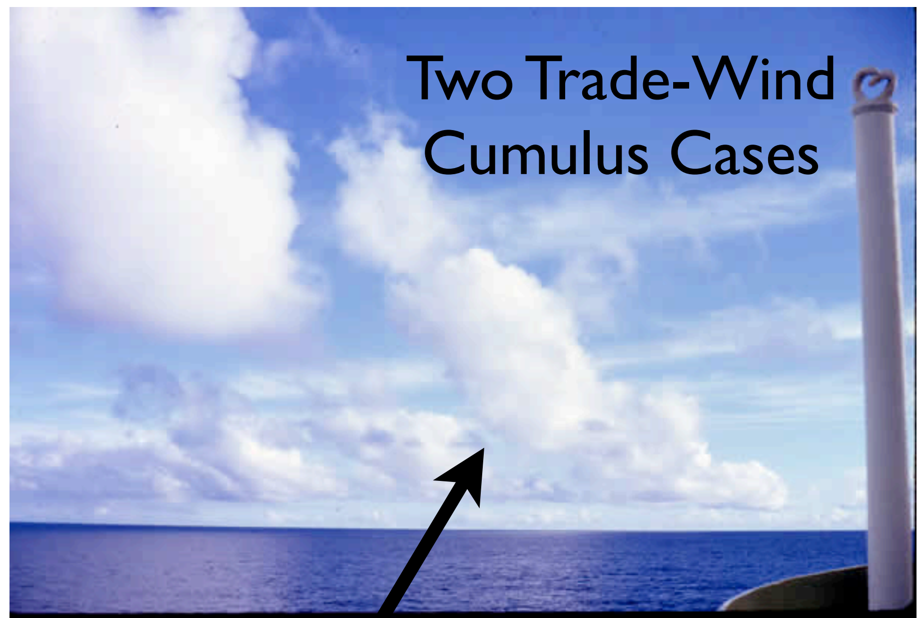
- To get a better idea of the performance of the various families of PDFs, use LES results.
- Compute
  - Cloud fraction
  - Cloud water
  - Liquid water flux

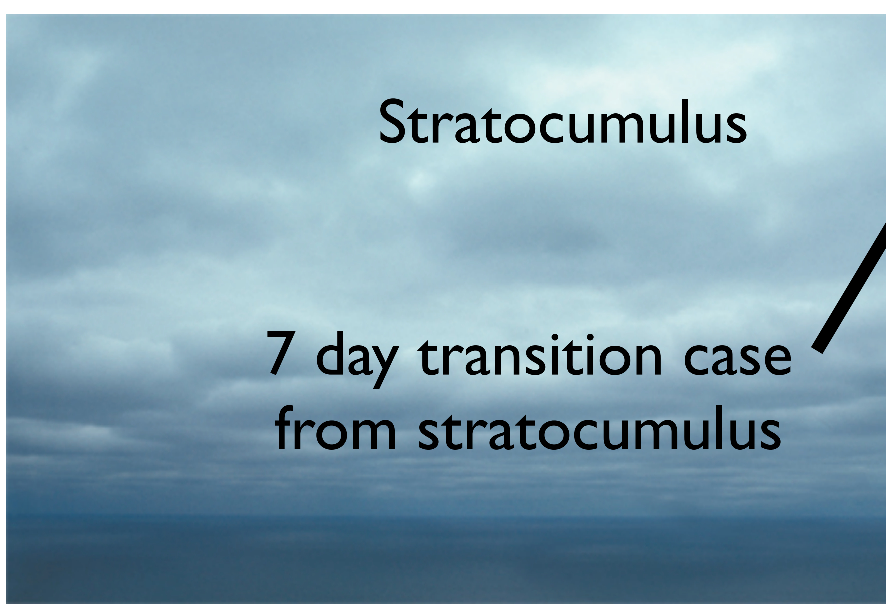
Calculate moments to specify PDF from LES for various horizontal grid sizes



LES Simulations

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





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Assumed Probability Density Functions for Shallow and Deep Convection

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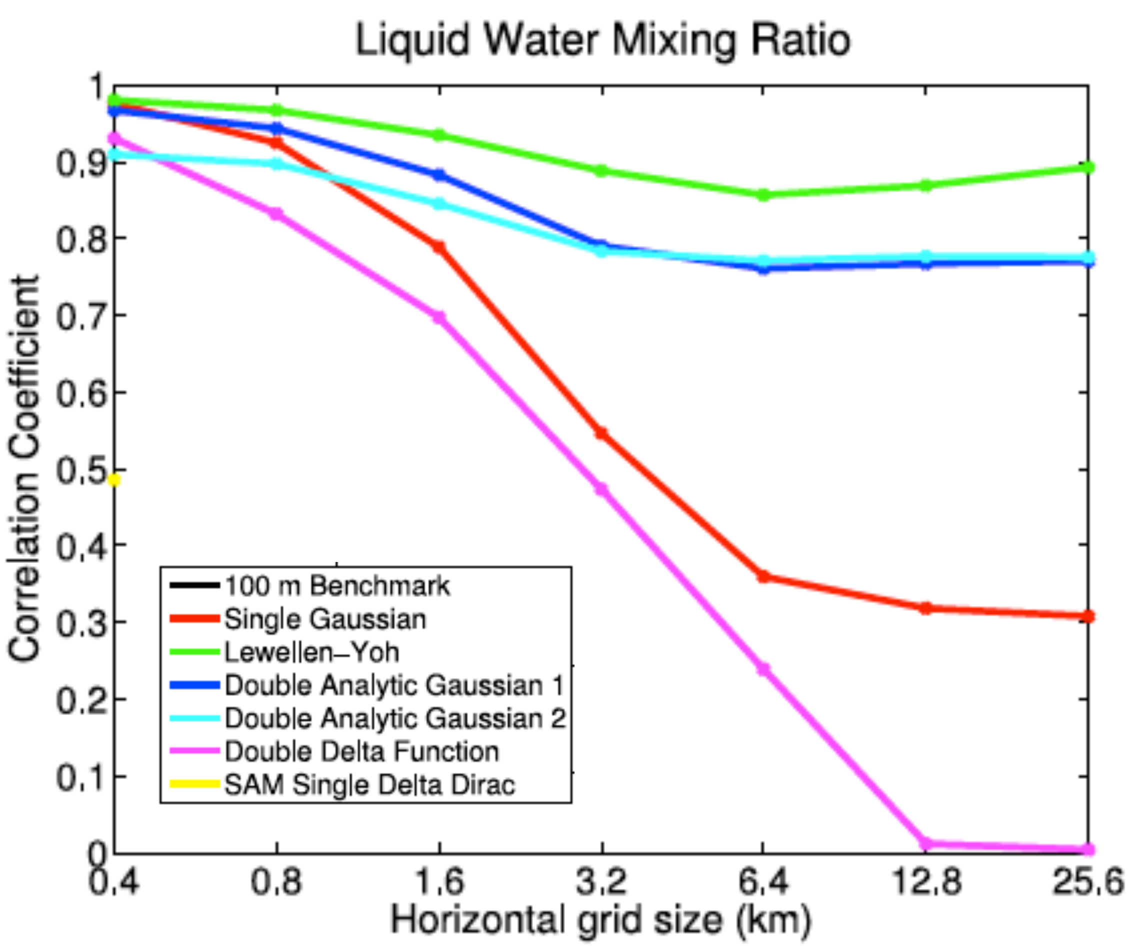
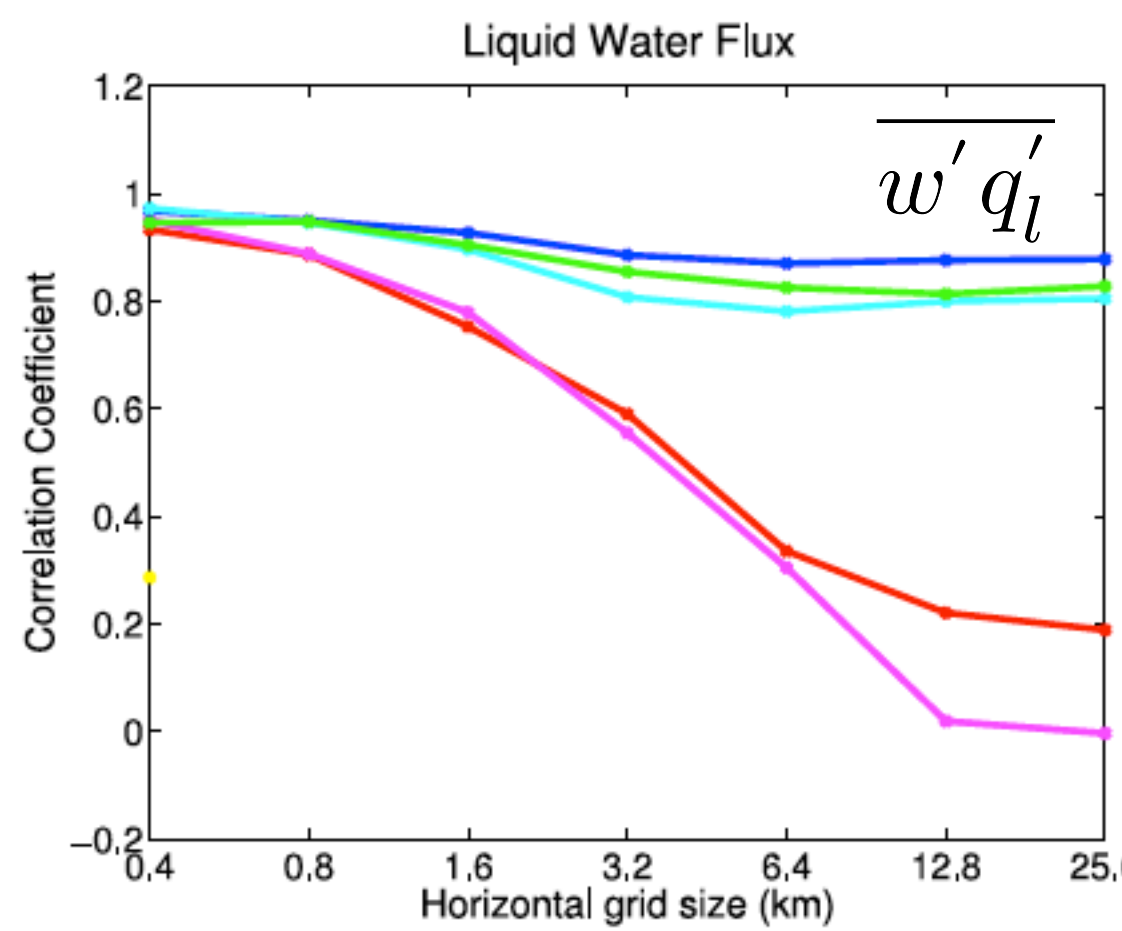
The assumed joint probability density function (PDF) between vertical velocity and conserved temperature and total water scalars has been suggested to be a relatively computationally inexpensive and unified subgrid-scale (SGS) parameterization for boundary layer clouds and turbulent moments. This paper analyzes the performance of five families of PDFs using large-eddy simulations of deep convection, shallow convection, and a transition from stratocumulus to trade wind cumulus. Three of the PDF families are based on the double Gaussian form and the remaining two are the single Gaussian and a Double Delta Function (analogous to a mass flux model). The assumed PDF method is tested for grid sizes as small as 0.4 km to as large as 204.8 km. In addition, studies are performed for PDF sensitivity to errors in the input moments and for how well the PDFs diagnose some higher-order moments.

In general, the double Gaussian PDFs more accurately represent SGS cloud structure and turbulence moments in the boundary layer compared to the single Gaussian and Double Delta Function PDFs for the range of grid sizes tested. This is especially true for small SGS cloud fractions. While the most complex PDF, Lewellen-Yoh, better represents shallow convective cloud properties (cloud fraction and liquid water mixing ratio) compared to the less complex Analytic Double Gaussian 1 PDF, there appears to be no advantage in implementing Lewellen-Yoh for deep convection. However, the Analytic Double Gaussian 1 PDF better represents the liquid water flux, is less sensitive to errors in the input moments, and diagnoses higher order moments more accurately. Between the Lewellen-Yoh and Analytic Double Gaussian 1 PDFs, it appears that neither family is distinctly better at representing cloudy layers. However, due to the reduced computational cost and fairly robust results, it appears that the Analytic Double Gaussian 1 PDF could be an ideal family for SGS cloud and turbulence representation in coarse-grid CRMs, mesoscale models, and GCMs if the required input moments can be predicted or diagnosed accurately.

Assumed PDF Method

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





From Bogenschutz et al. (2010), for BOMEX shallow cumulus regime

Assumed PDF Approach

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

- Typically requires the addition of several prognostic equations into model code (Golaz et al. 2002, Cheng and Xu 2006, 2008) to estimate the turbulence moments required to specify the PDF.

- Our approach is called *Simplified Higher-Order Closure* (SHOC):

  - Second-order moments diagnosed using simple formulations based on Redelsperger and Sommeria (1986) and Bechtold et al. (1995)

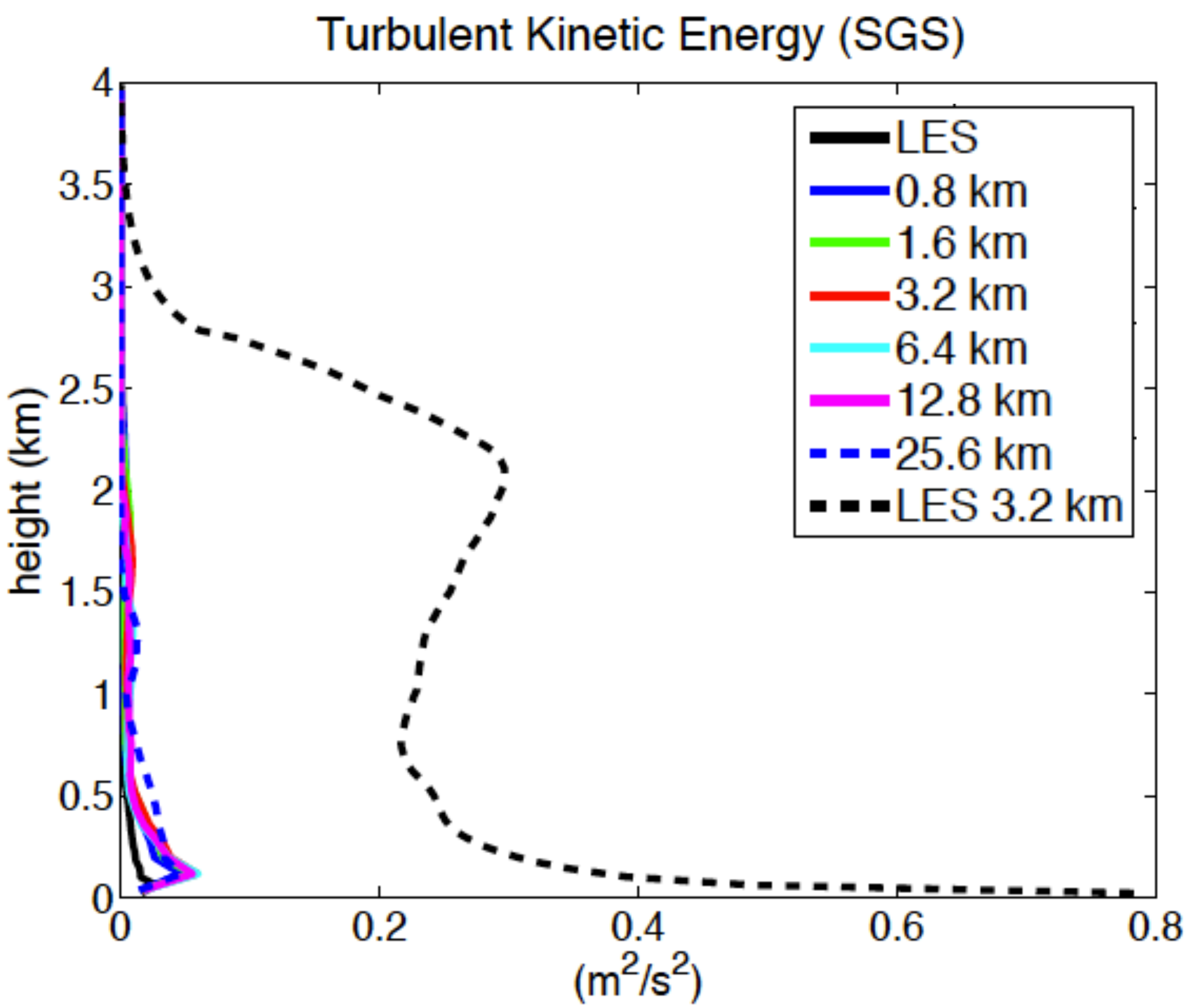
  - Third-order moment diagnosed using algebraic expression of Canuto et al. (2001)

  - All diagnostic expressions for the moments are a function of prognostic SGS TKE.

Assumed PDF Approach

- Cheng et al. (2010) suggest that simple turbulence closures appear to function well for boundary layer cloud regimes if the proper amount of SGS TKE is predicted.
- So, how well does coarse-grid SAM predict SGS TKE?

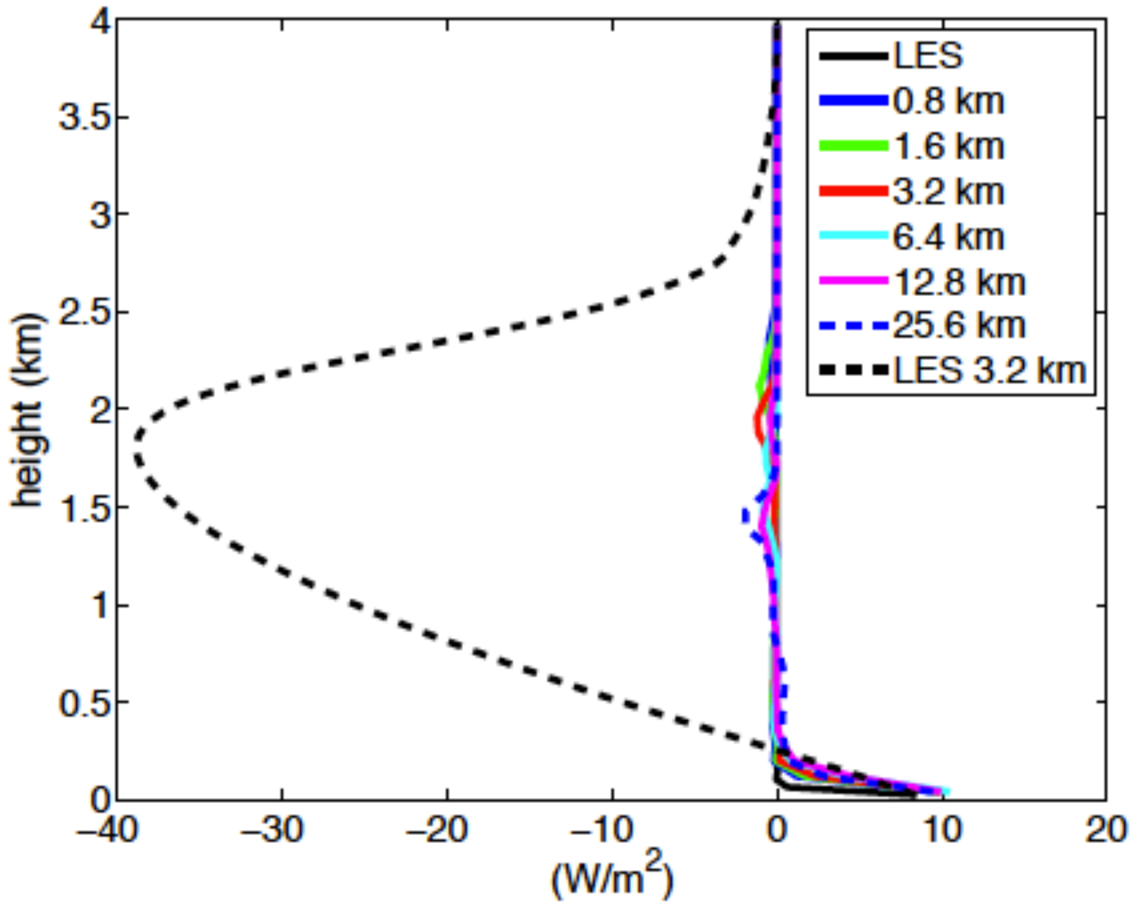
... pretty poorly, actually...



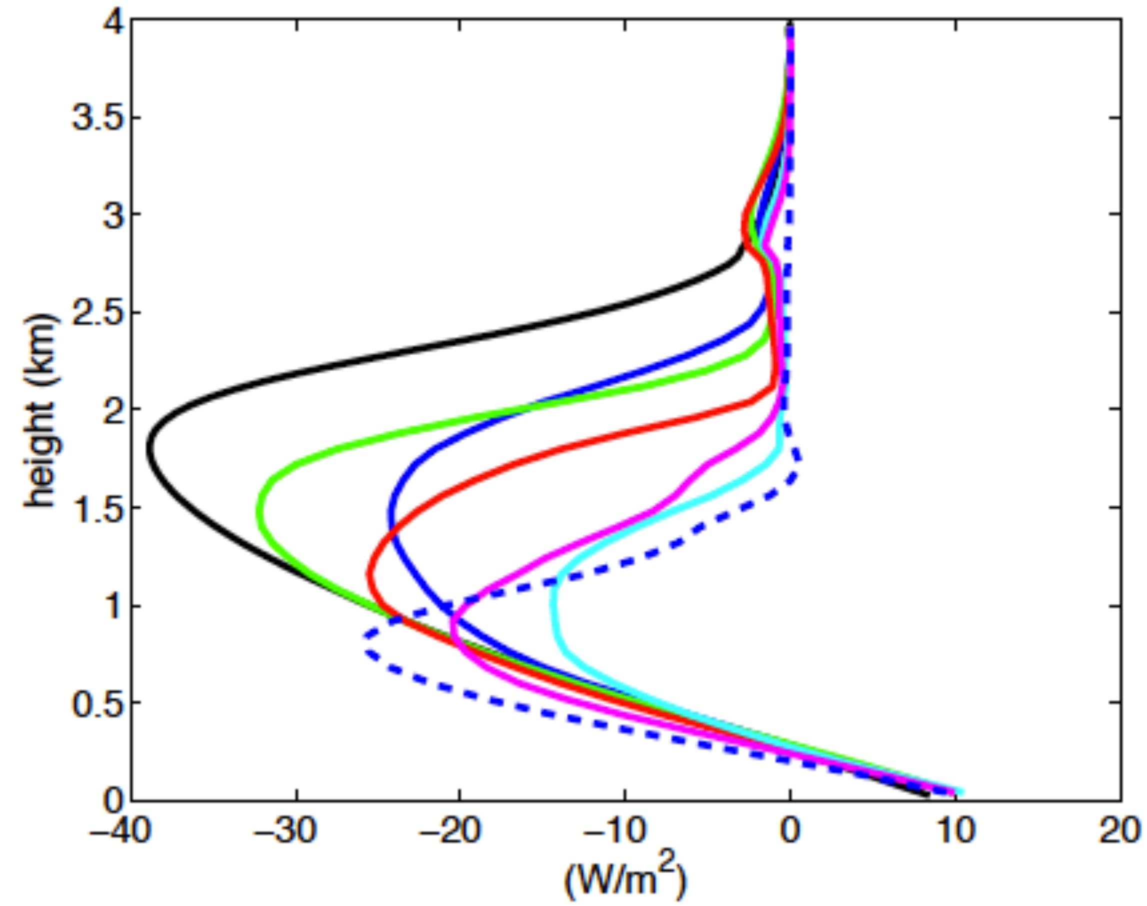
From RICO (shallow precipitating cumulus), for 2D simulations using a variety of coarse horizontal grid sizes and dz=100 m.

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

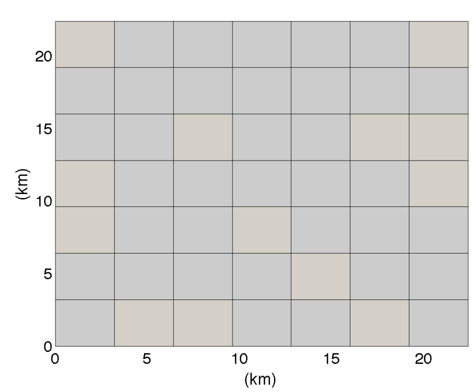
... and this produces (unrealistic) grid-scale clouds



(d) SGS $\overline{w'h'_L}$

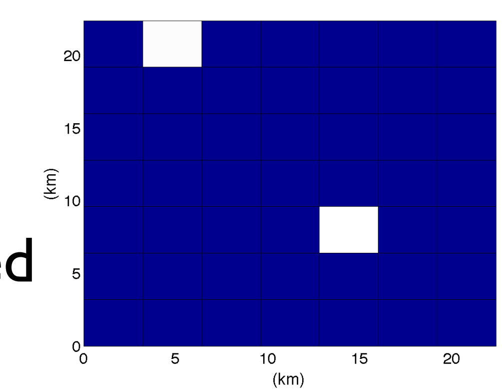


(c) Resolved+SGS $\overline{w'h'_L}$



Should be subgrid-scale!

Cloud circulations projected on the resolved scale



SGS turbulence problem

- SGS TKE in coarse-grid SAM is too small for two reasons:
  - SGS liquid water flux is neglected in buoyancy flux calculation.
    - An important source of turbulence
  - Turbulence length scale is related to vertical grid size.
    - Should be related to large-eddy scale

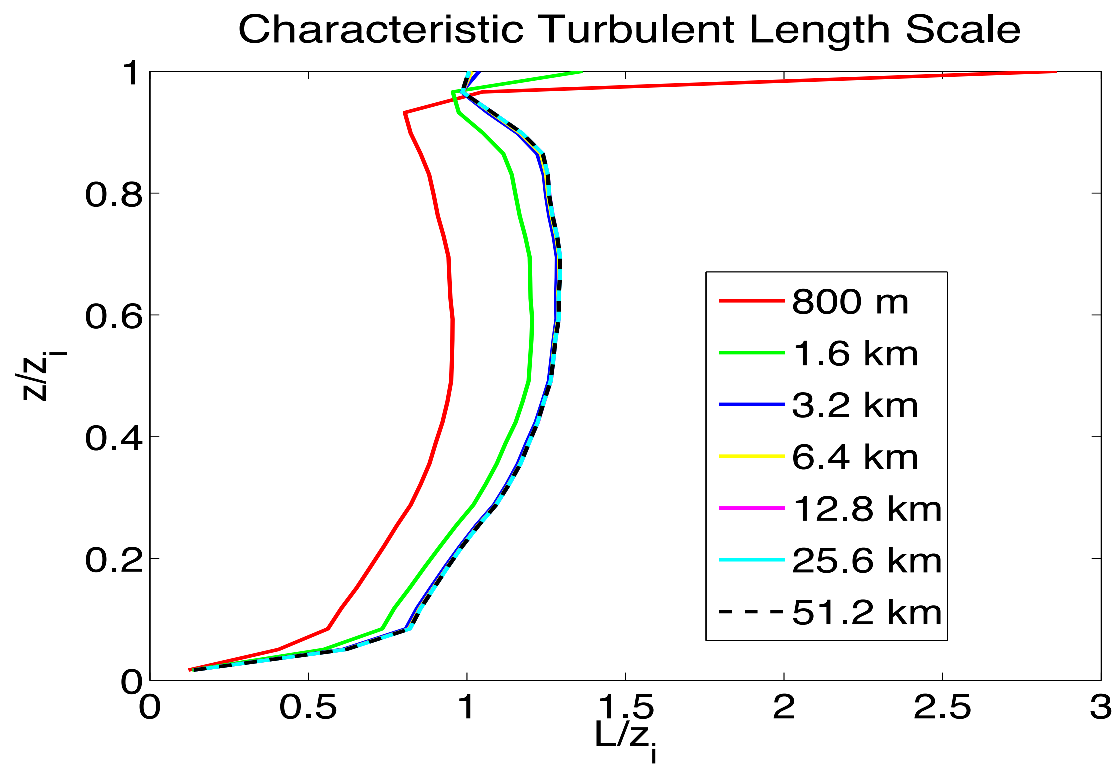
Turbulence Length Scale

- Need to parameterize dissipation rate and eddy diffusivity:

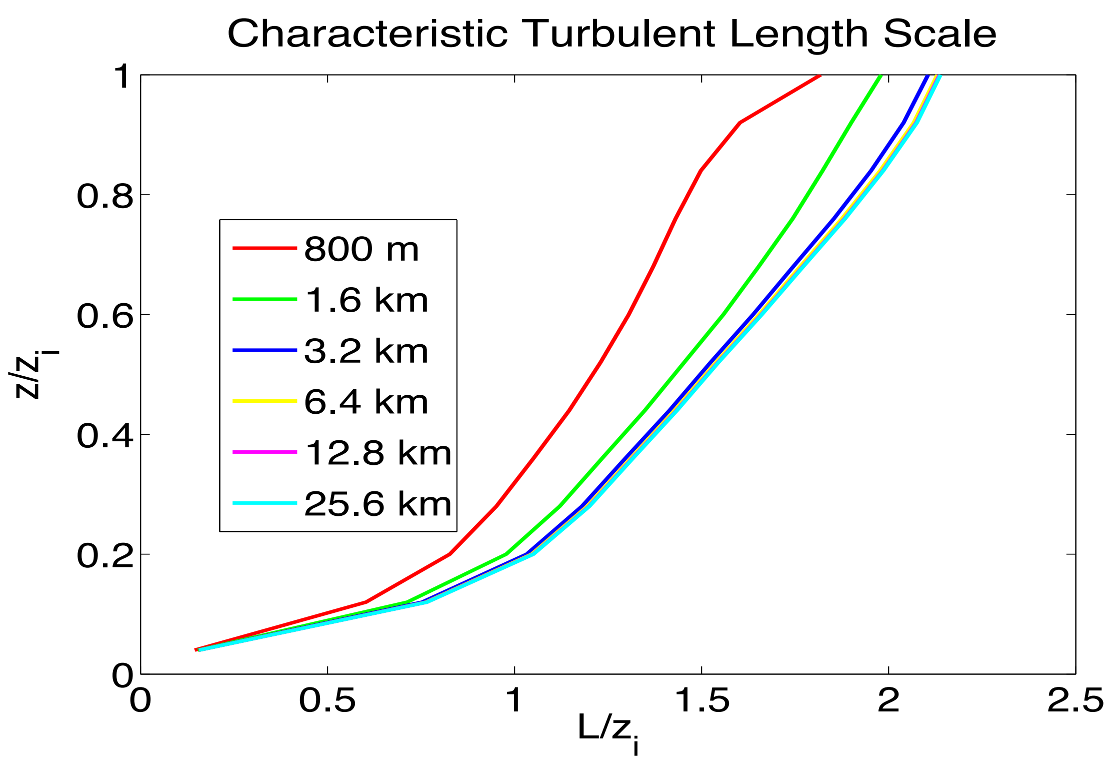
$$\epsilon = \frac{\overline{e}^{3/2}}{L} \qquad K_H = 0.1L\overline{e}^{1/2}$$

- 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.

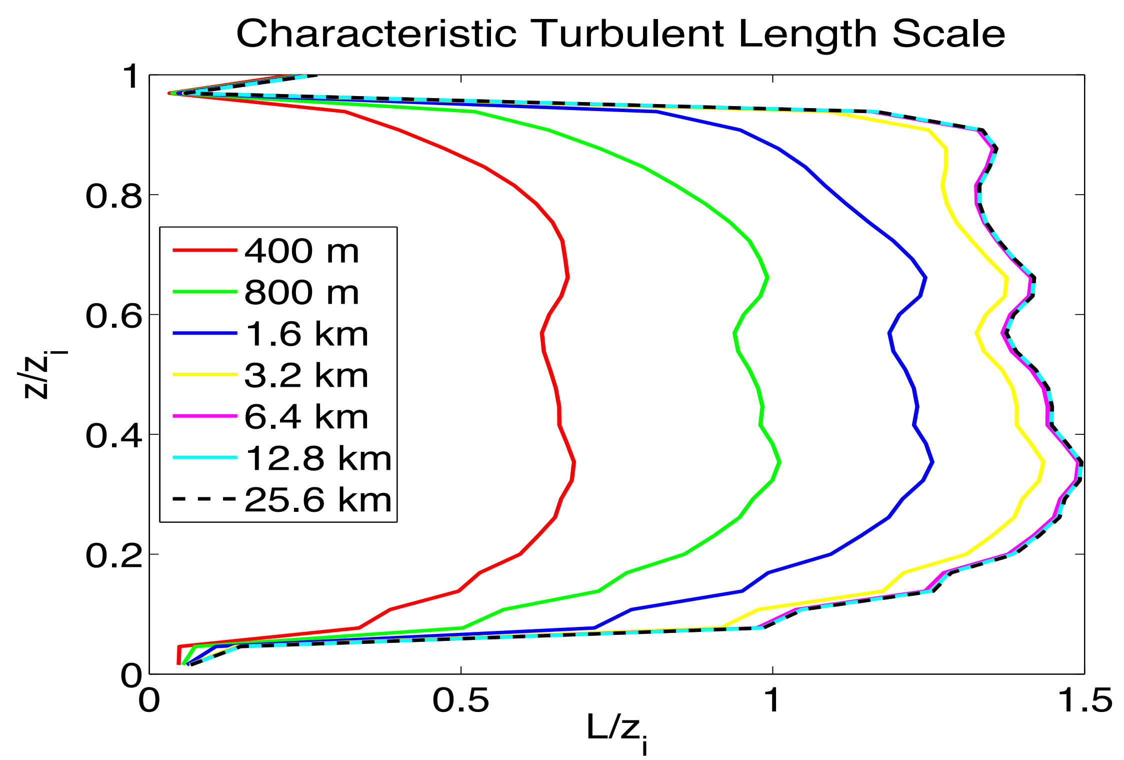
Turbulence length scale *diagnosed* from LES for various CRM grid sizes.



(a) Clear convective boundary layer



(b) Trade cumulus mixed layer



(c) Stratocumulus mixed layer

Standard SAM vs SAM-PDF

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.***

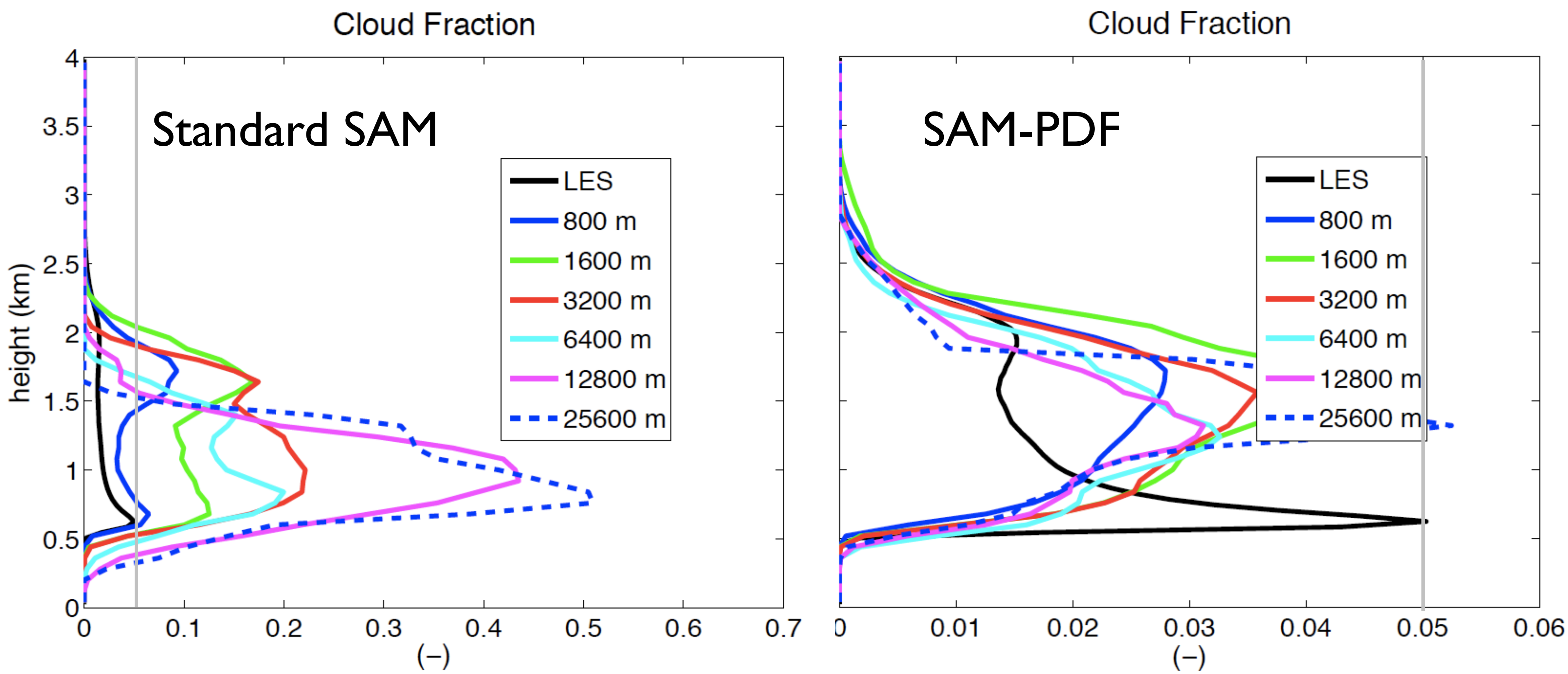
LES Benchmarks

- 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

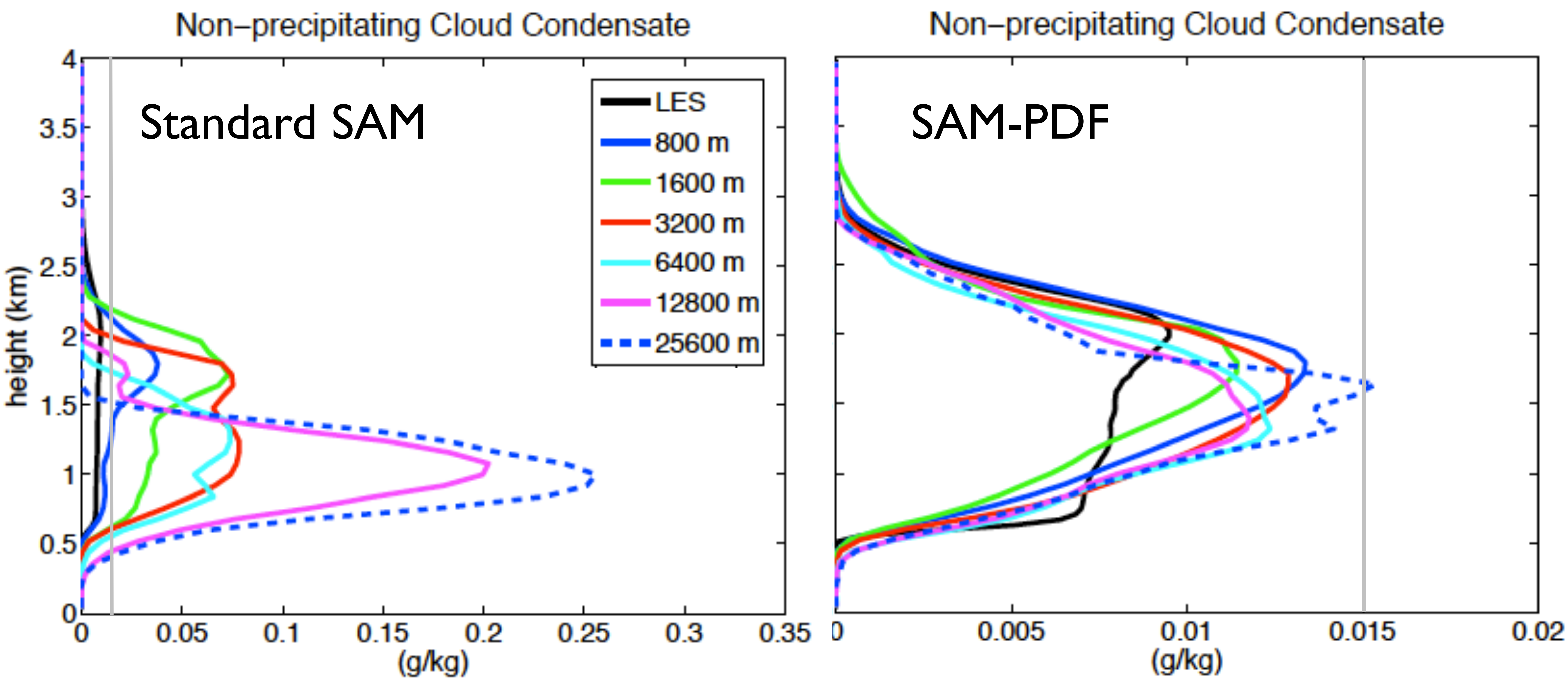
- LES: dz = 40 m, dx = 100 m
- 2D CRM: dz = 100 m, dz = 0.8 km to 25.6 km

Dependence of Cloud Fraction on Horizontal Grid Size



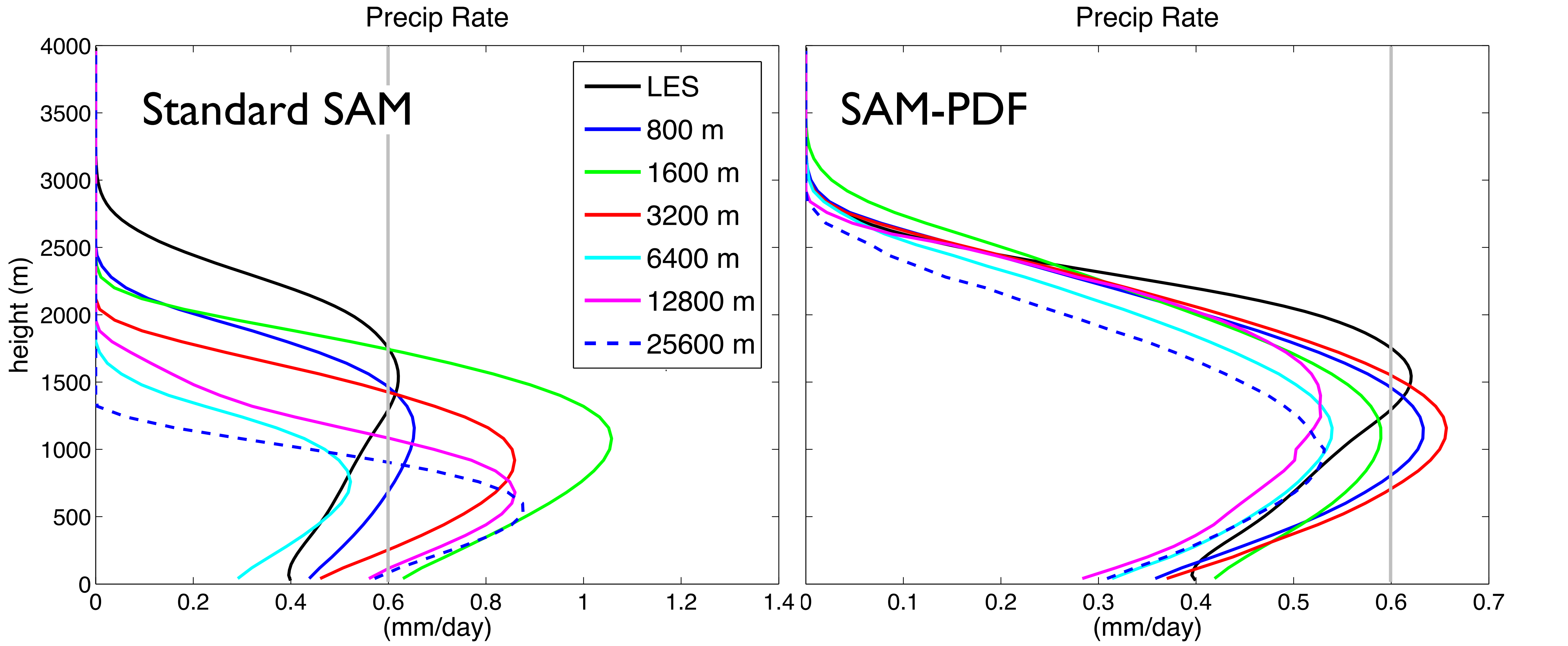
RICO: Precipitating Trade-Wind Cumulus

Dependence of Cloud Liquid Water on Horizontal Grid Size



RICO: Precipitating Trade-Wind Cumulus

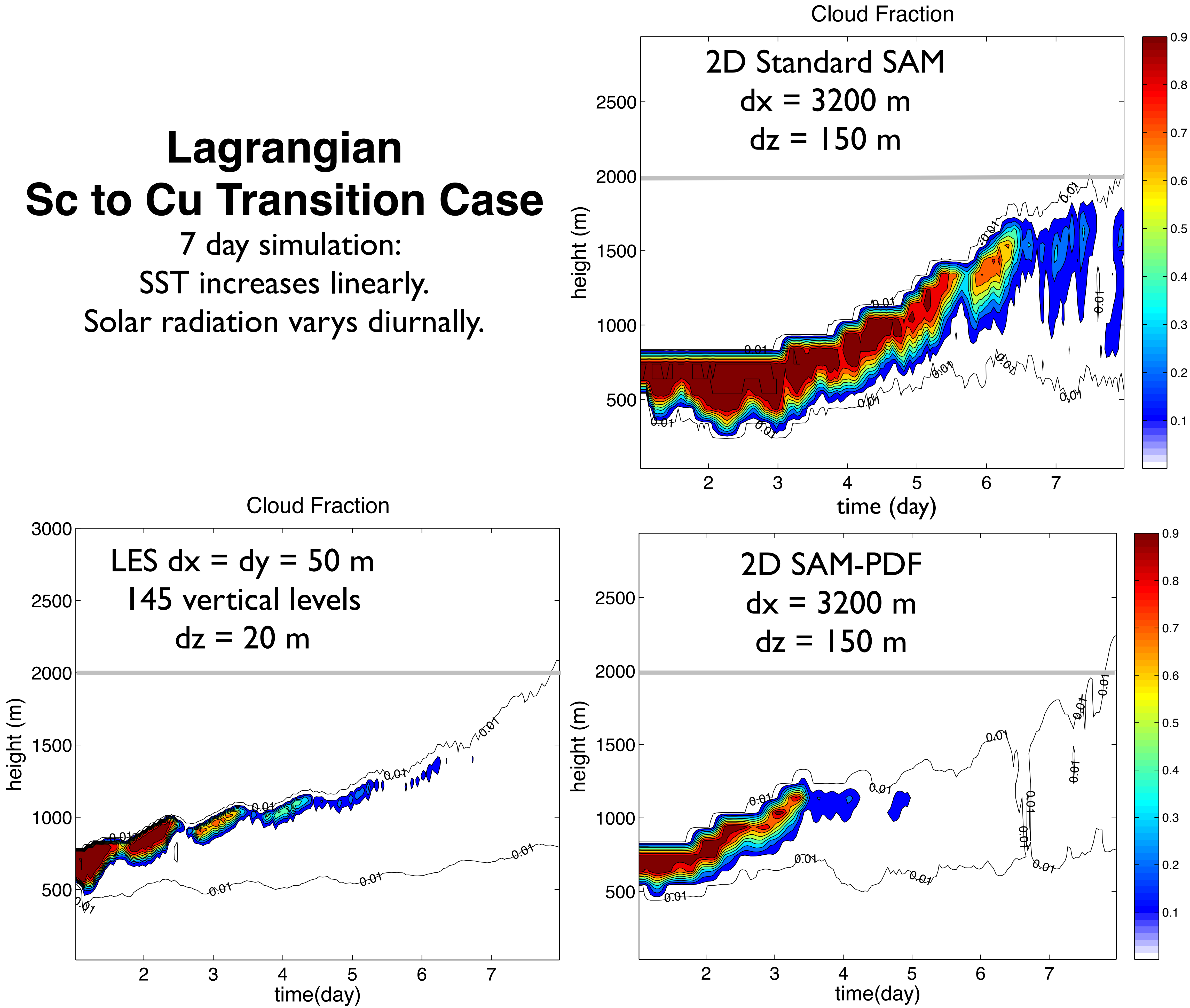
Dependence of Precipitation Rate on Horizontal Grid Size

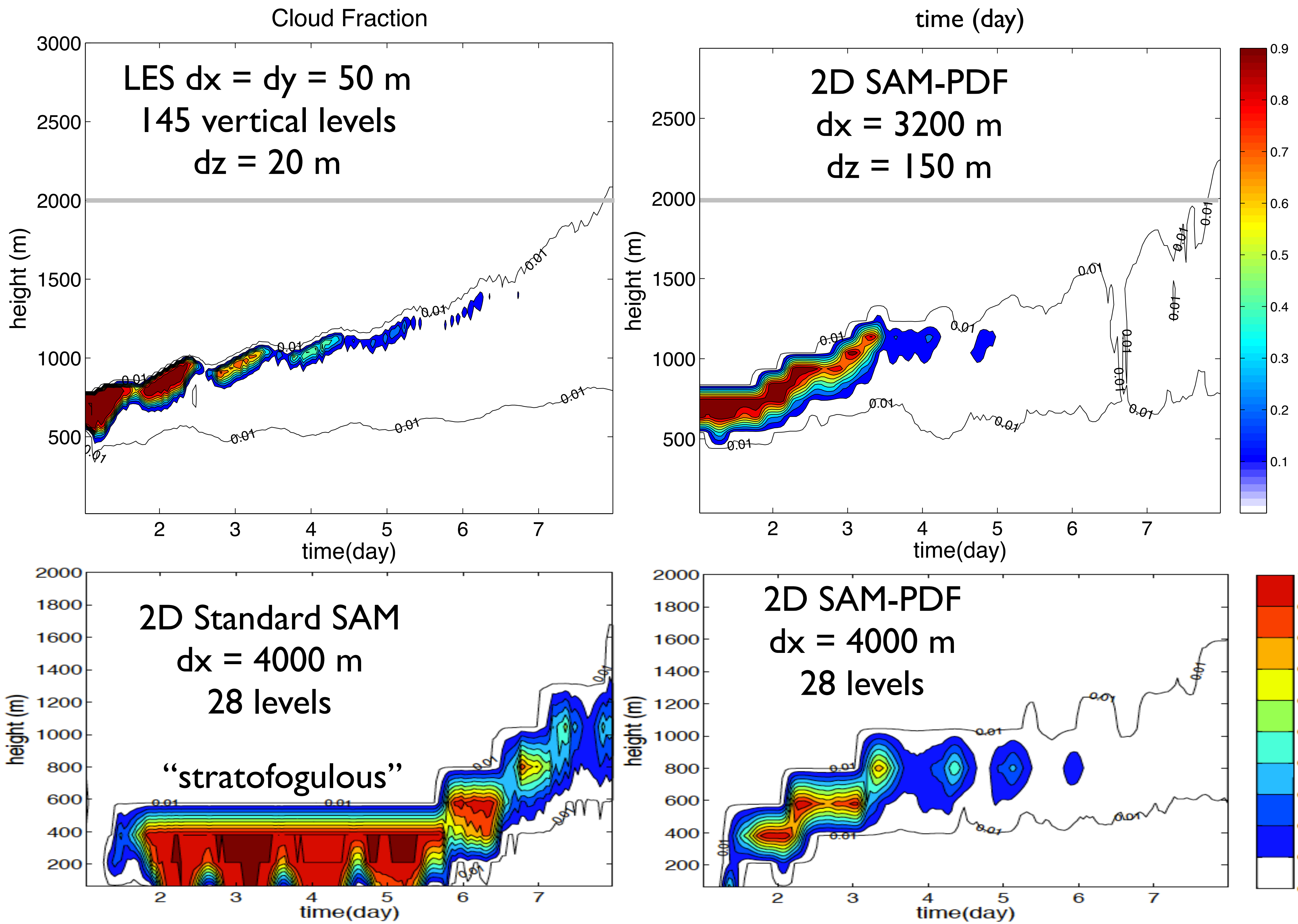


Observed surface precip rate was ~0.3 mm/day.

Lagrangian
Sc to Cu Transition Case

7 day simulation:
SST increases linearly.
Solar radiation varys diurnally.



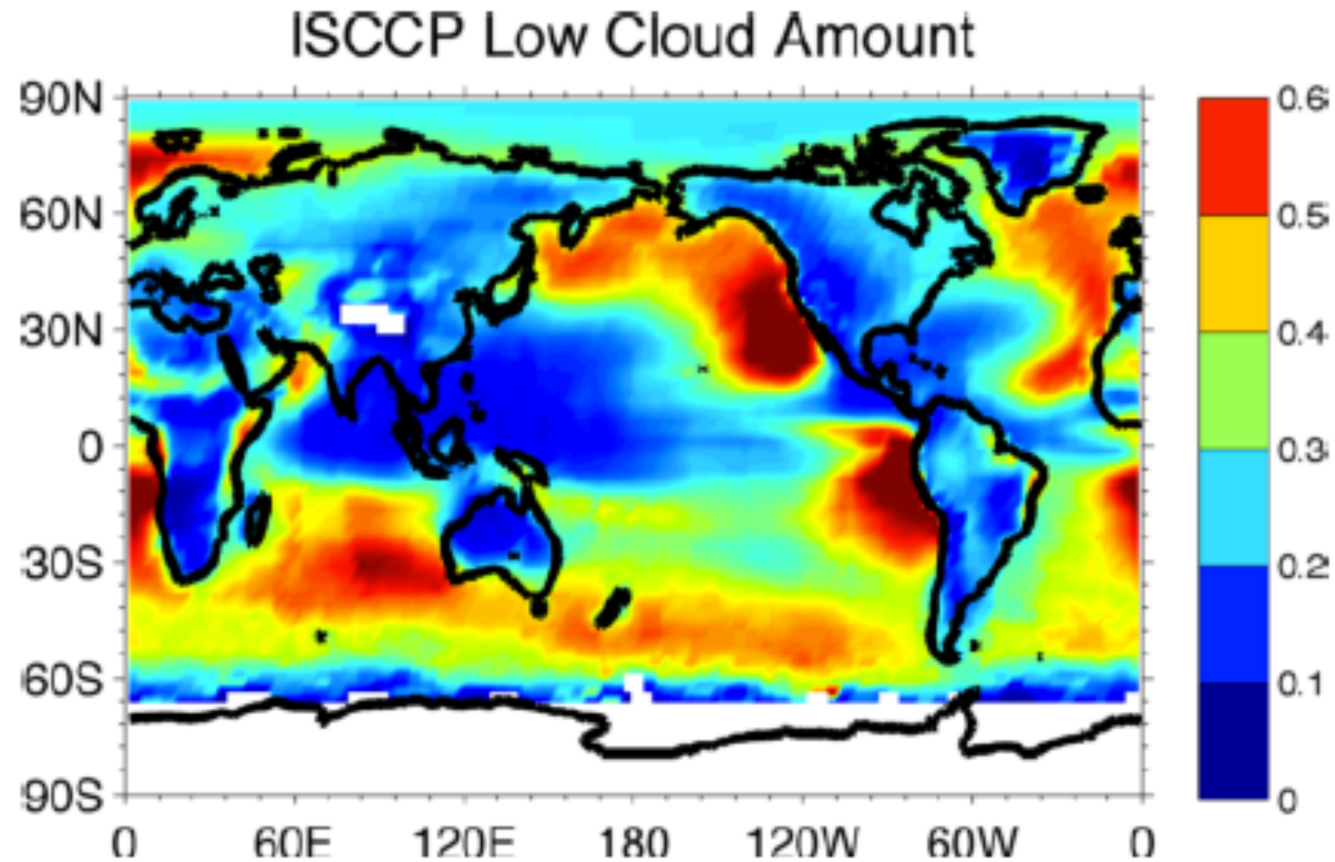


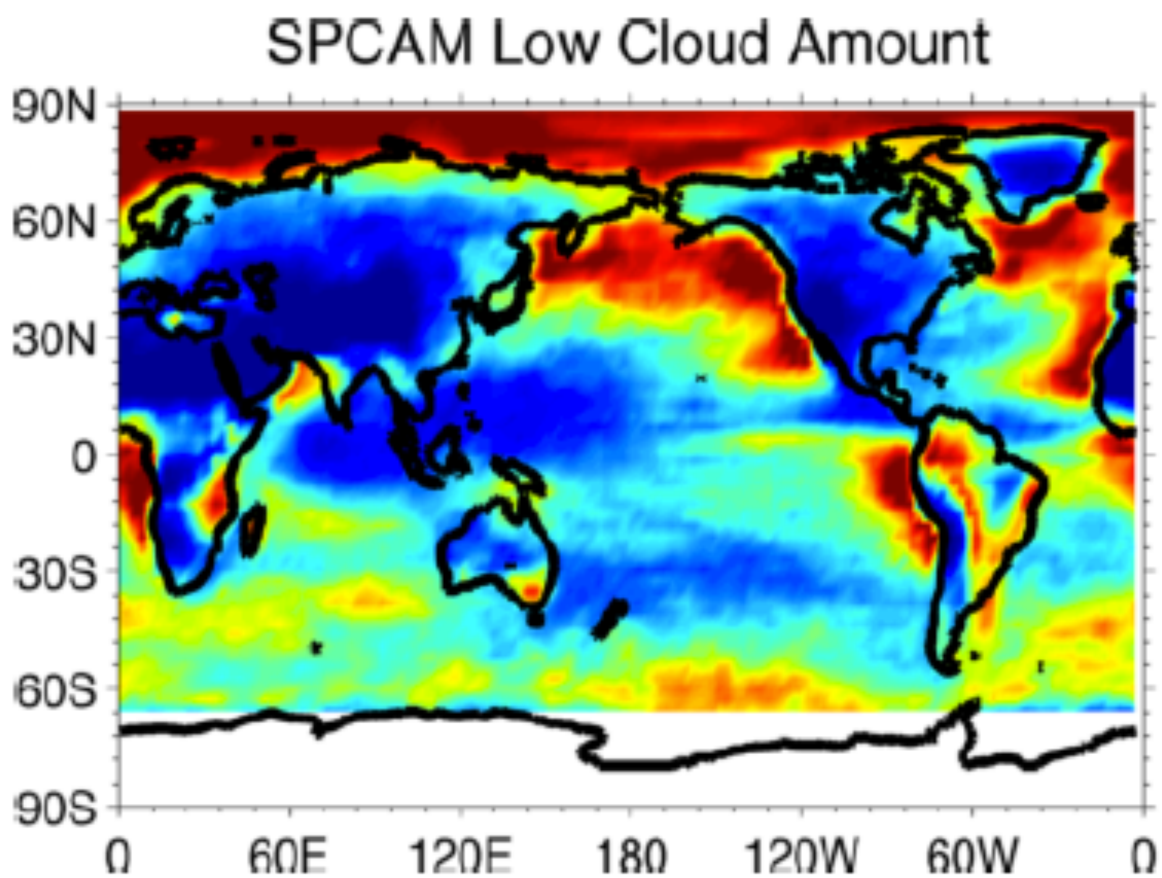
With MMF Vertical Grid Spacing (dz ~ 200-300 m in boundary layer)

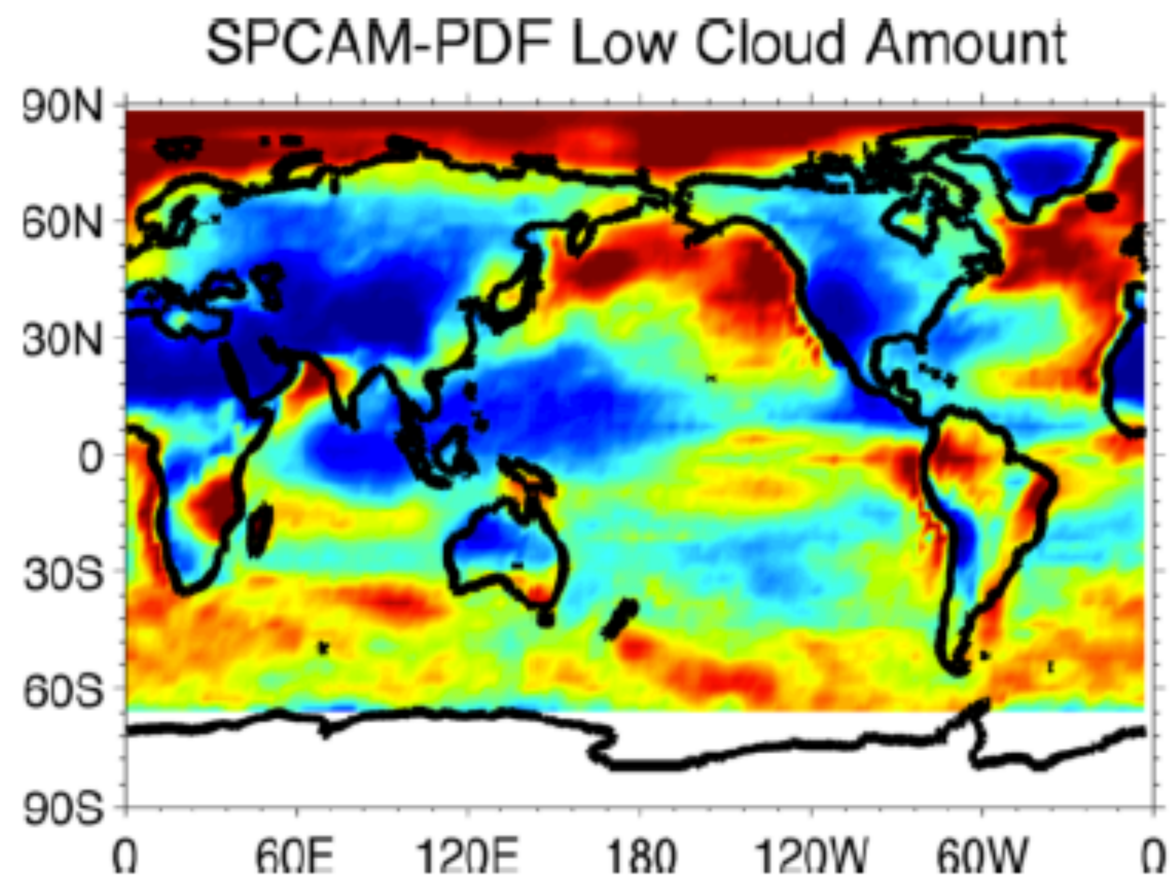
Preliminary Test of Closure within MMF

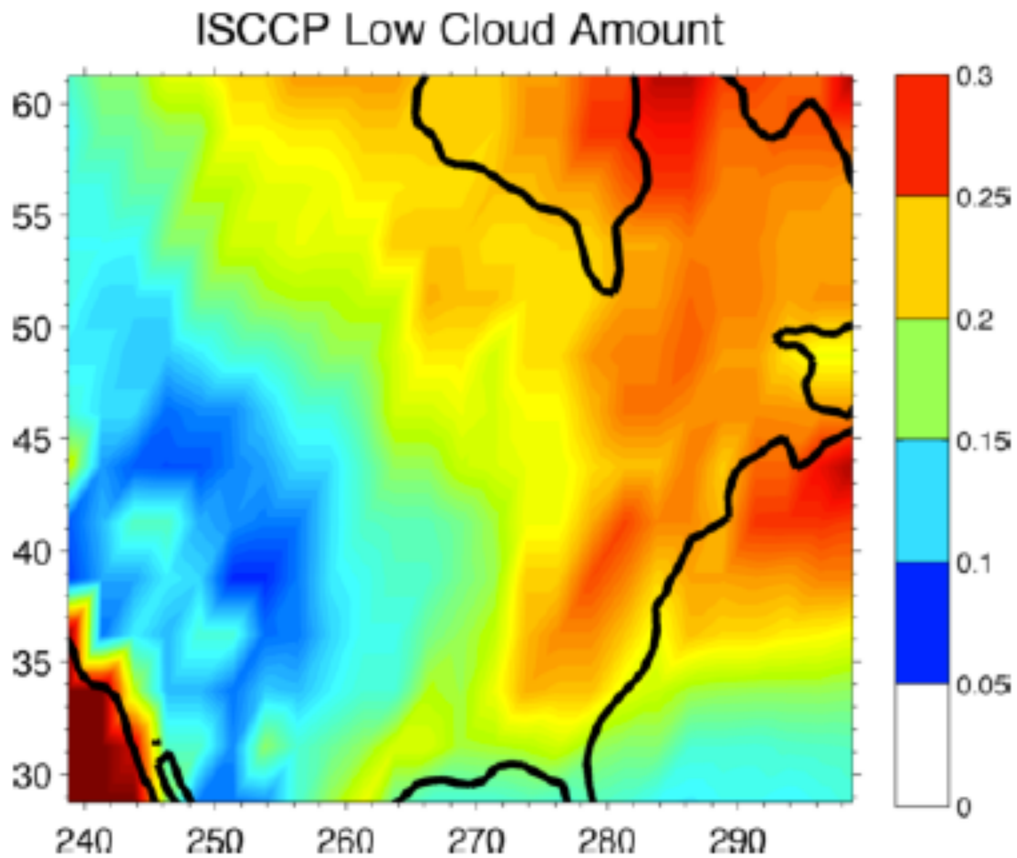
- Code implemented in the embedded CRMs within the MMF.
- SGS cloud fraction and liquid water content passed to radiation code (computed on the CRM grid every 15 minutes).
- SPCAM & SPCAM-PDF run in T42 configuration with 30 vertical levels (embedded CRM: dx = 4 km, dz ~ 200-300 m in boundary layer).
- 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.

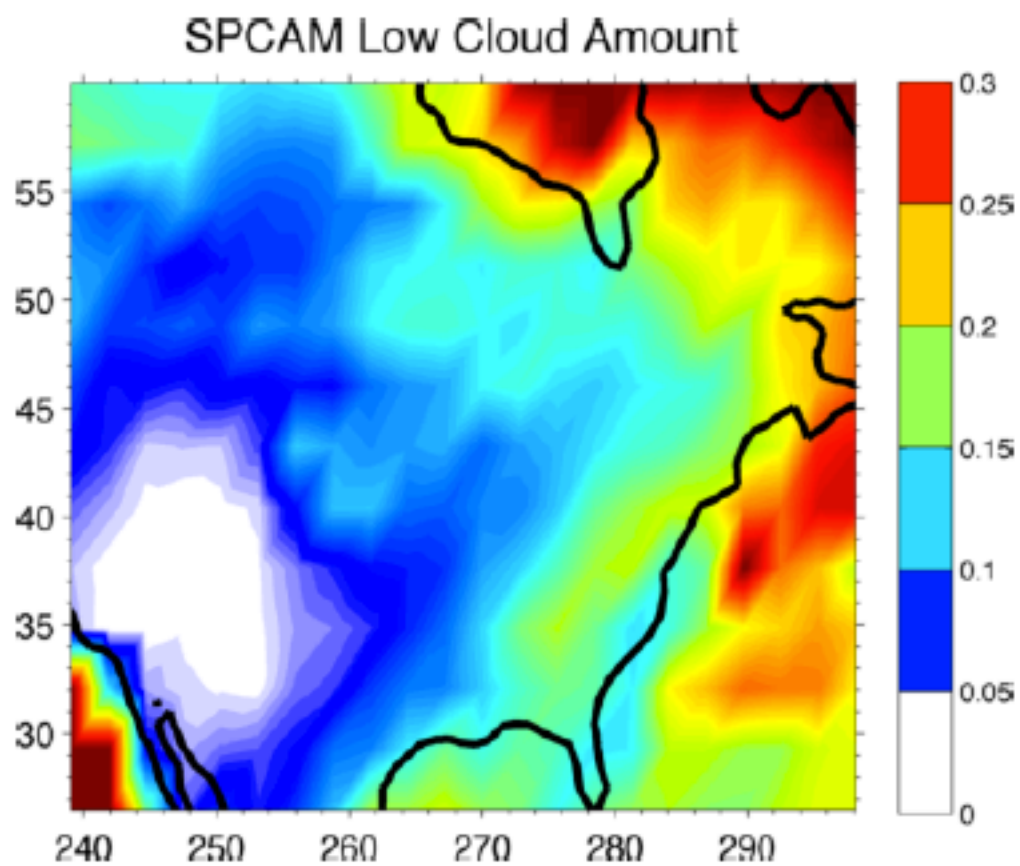


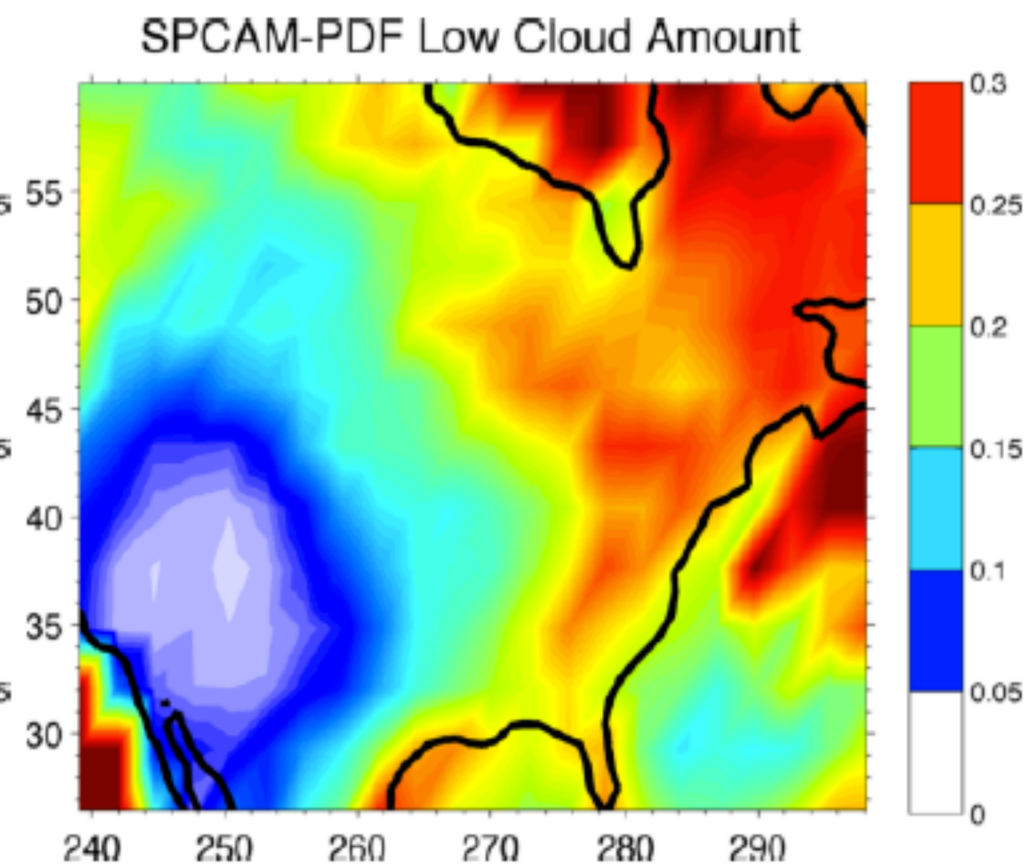






Low Clouds Over Land





Summary

- SHOC 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 dx ~ 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.