National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Summary of EDMF (and some PDF cloud parameterization) research at JPL and Caltech

João Teixeira, Kay Suselj, Marcin Witek, Daniel Chung, Georgios Matheou

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Zhihong Tan, Remi Lam, Tapio Schneider

California Institute of Technology, Pasadena, California, USA

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Summary of EDMF (and some PDF cloud parameterization) research at JPL and Caltech

Science Topics:

EDMF and dry convective boundary layer - Marcin Witek, Joao Teixeira

EDMF and moist shallow convection – Kay Suselj, Joao Teixeira

EDMF and PDF-clouds in a simplified GCM to study climate change - Zhihong Tan, Remi Lam, Tapio Schneider, Joao Teixeira

LES research – Georgios Matheou, Daniel Chung

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Summary of EDMF (and some PDF cloud parameterization) research at JPL and Caltech

Projects and funding:

JPL LES model development and evaluation (JPL internal) – 2008-2011

EDMF development and implementation in US Navy mesoscale model COAMPS (ONR) – 2008-2011

EDMF and PDF-clouds development and implementation in NASA GMAO model (NASA) – 2009-2012

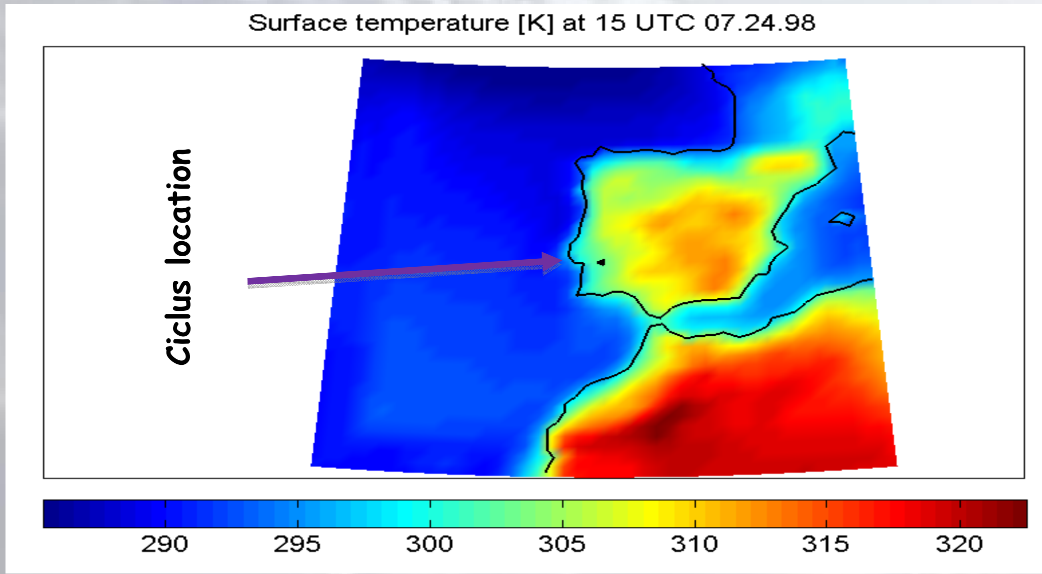
EDMF development and implementation in NCEP model (NOAA CPT) – 2010-2013

EDMF and PDF-clouds development and implementation in US Navy global model NOGAPS (ONR) – 2011-2014

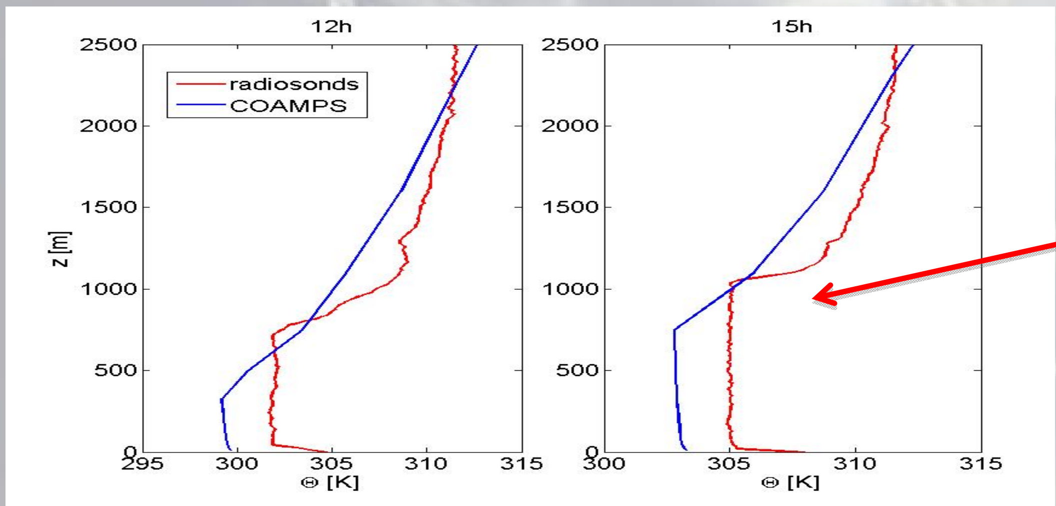
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Dry Convective Boundary Layers: example of US Navy mesoscale model COAMPS



Example – CICLUS experiment



Teixeira et al., 2004

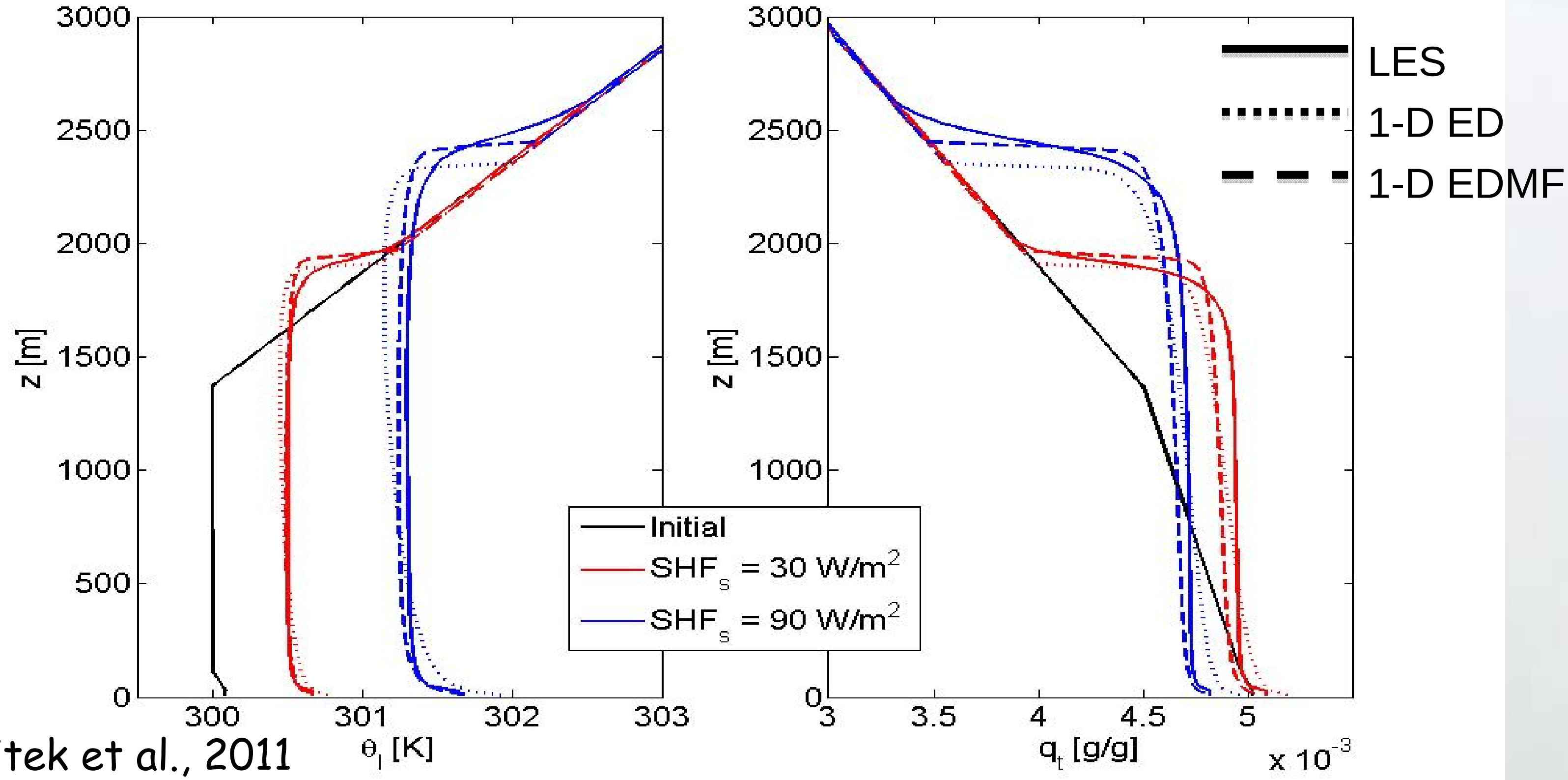
COAMPS control:

- not enough entrainment (too low and too cold boundary layer)
- profiles not well mixed

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Dry Convective Boundary Layer: θ and q_t vertical profiles after 6 hours with EDMF and TKE



Witek et al., 2011

Full EDMF simulations:

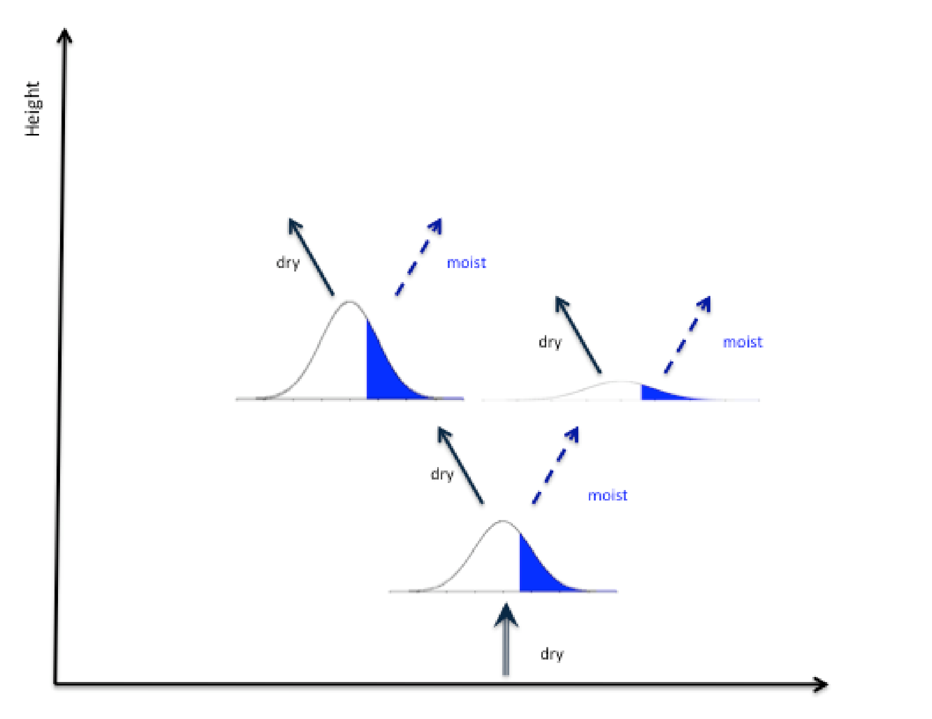
Witek et al, JAS, 2011

- surface layer more realistic
- neutral profile in the well-mixed layer
- larger entrainment leads to better inversion height
- inversion layer too sharp compared to LES

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

EDMF and Shallow convection: using PDF of updraft properties



Variance of updraft PDF:
Local balance between production and destruction

Partial updraft condensation:
- Start with single dry updraft at surface, integration in vertical
- Using updraft PDF to estimate updraft cover and water at each level
- Separation of dry and moist updraft when partial condensation occurs
- Moist and dry updraft-areas are integrated independently in vertical (with different vertical velocities)

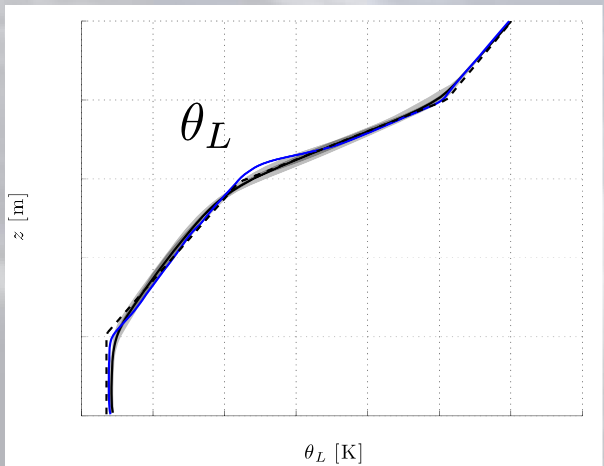
Provides estimation of updraft area and avoids need for cloud base closure

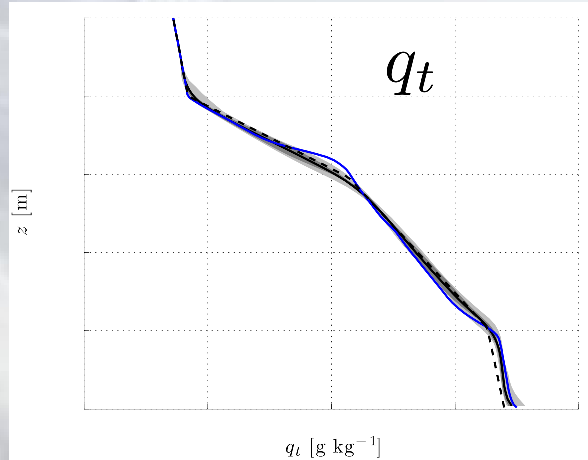
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

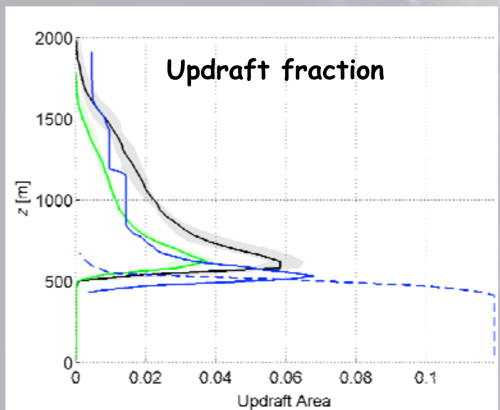
EDMF simulation of shallow cumulus BOMEX case: comparison with LES

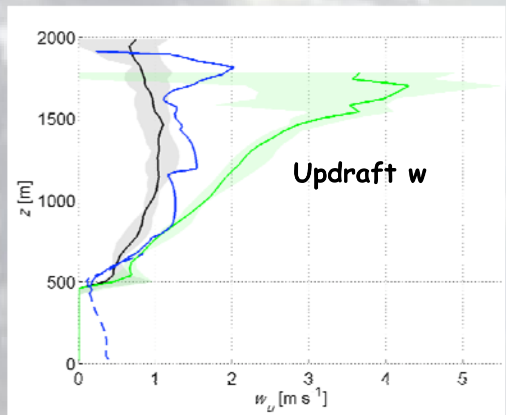
Mean profiles between 3rd and 4th simulation hour





Single column model
LES, mean





Single column model, dry
Single column model, moist
LES, cloud core, mean
LES, cloud core, range
LES, clouds, mean
LES, clouds, range

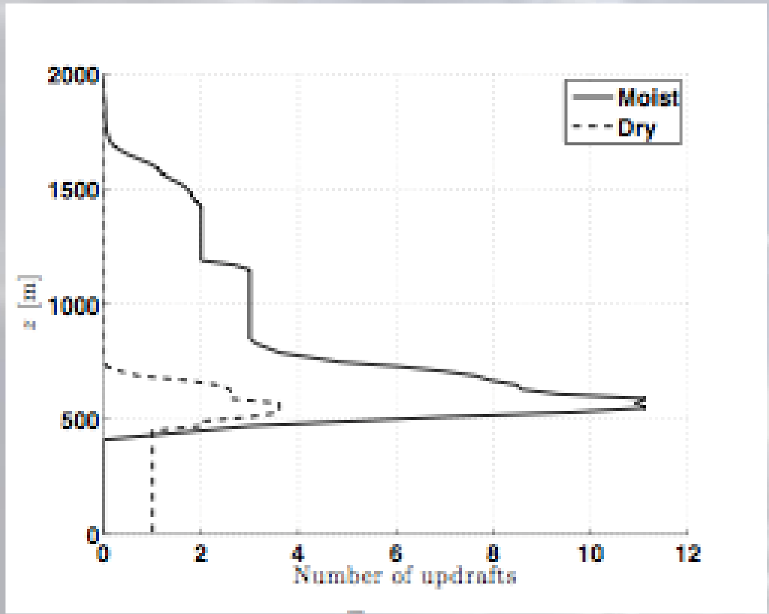
Suselj et al, JAS, 2011

New aspect: Using PDF of updraft properties

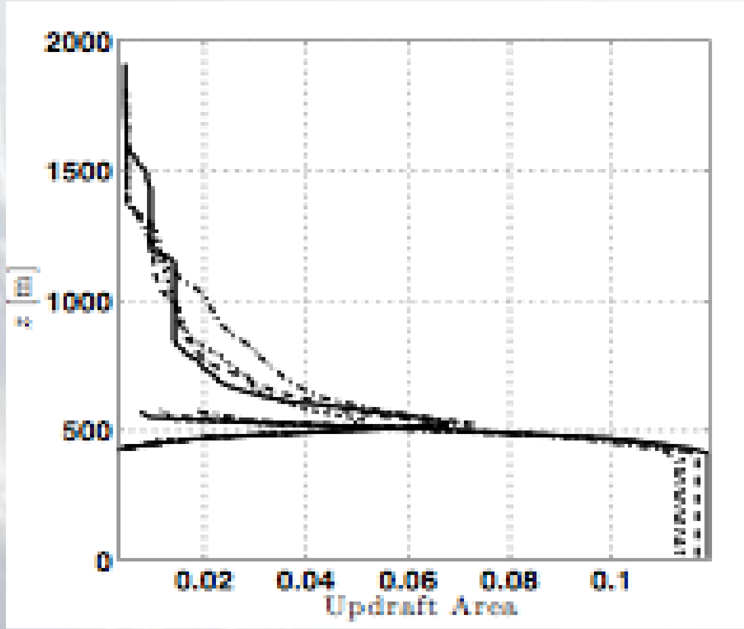
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

EDMF using PDF of updraft properties: BOMEX and the sensitivity to vertical resolution



Number of updrafts for control simulation (DZ=20 m)

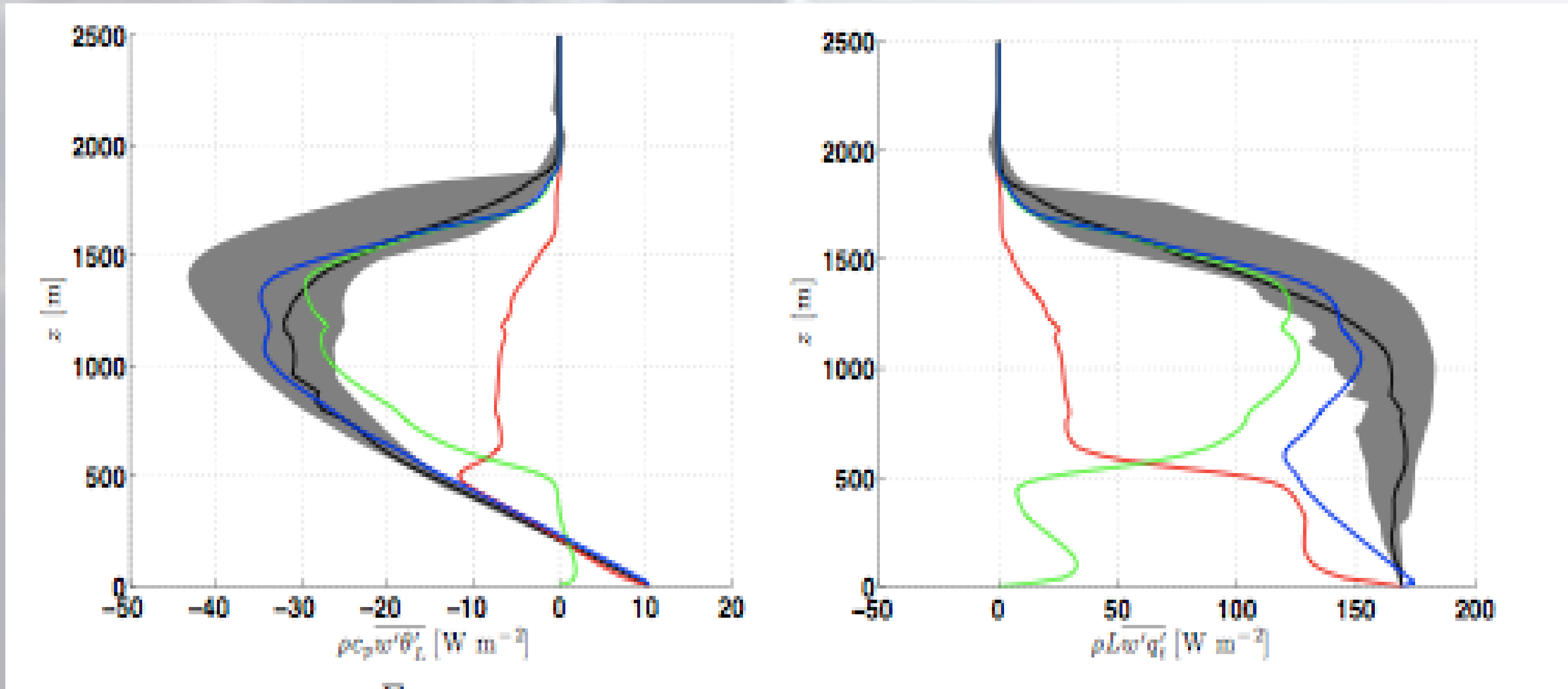


- 20 m (solid)
- 30 m (dashed)
- 40 m (dotted)
- 60 m (dash-dotted)

National Aeronautics and Space Administration

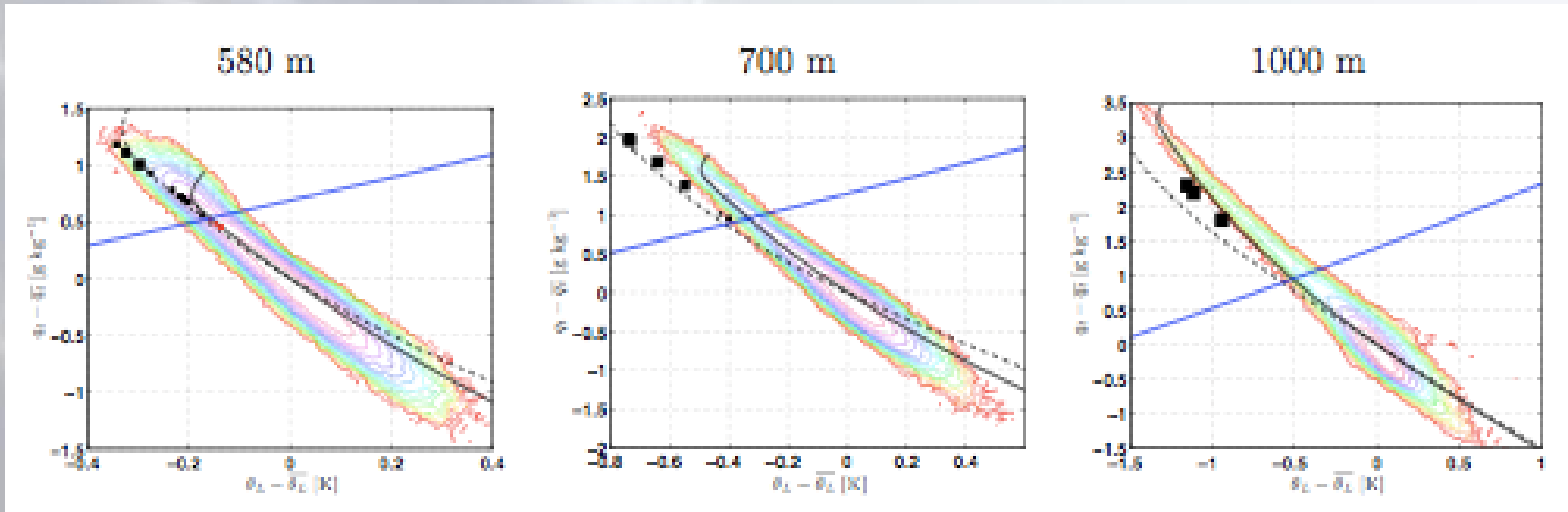
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

EDMF using PDF of updraft properties: BOMEX and the vertical fluxes



- LES (black)
- ED (red)
- MF (green)
- EDMF (blue)

EDMF using PDF of updraft properties: BOMEX and moist conserved variables PDFs



- LES (colored isolines)
- LES environmental profile (solid black line)
- updraft values (red squares represent dry, black squares moist updrafts)
- SCM environmental profile (black dashed line)
- saturation line (blue line).

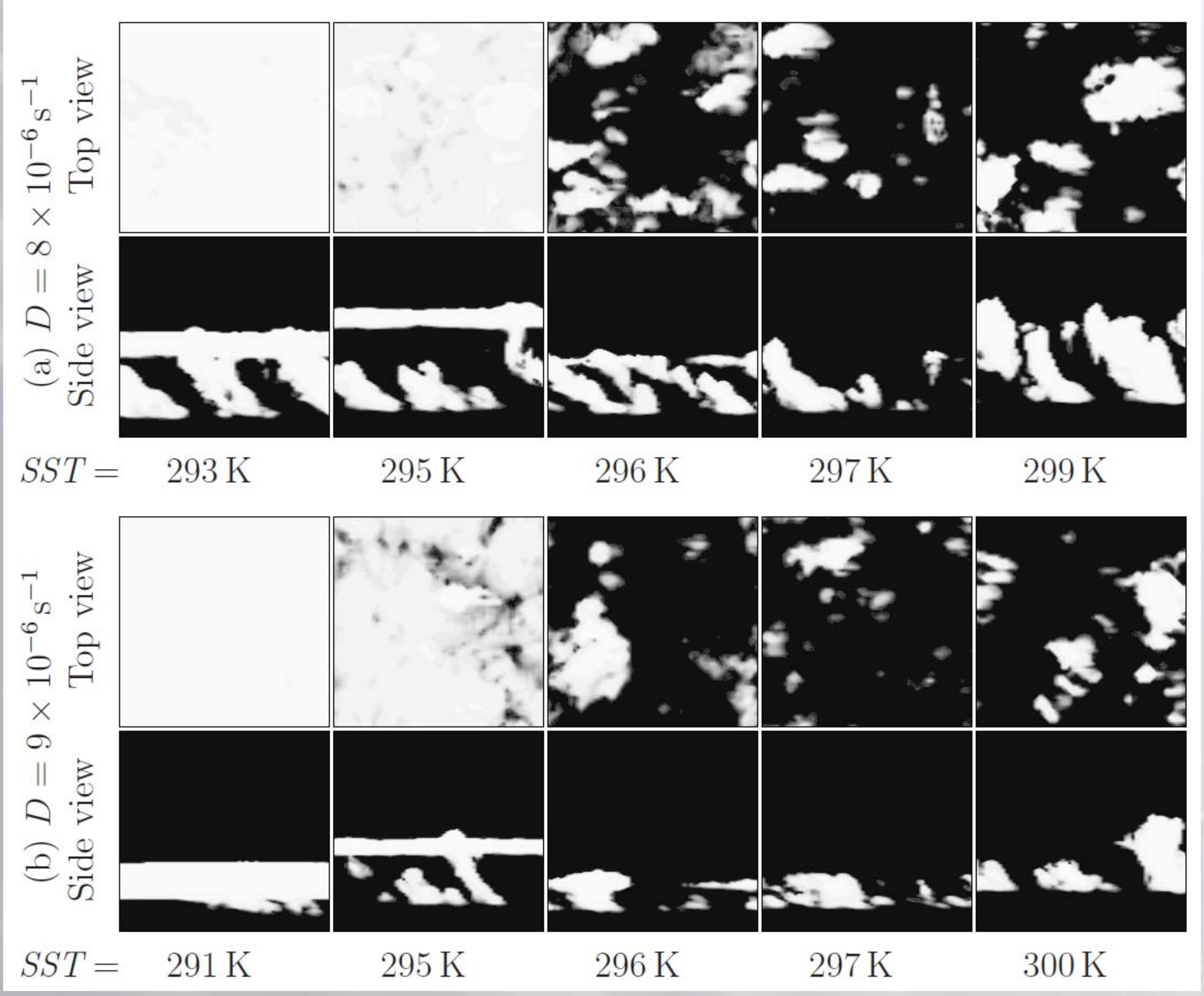
A simple LES framework to study Sc, Cu and the transition

- ASTEX initial conditions (Duynkerke et al. 1999)
- SST Monin—Obhukov surface boundary conditions
- Statistically steady (12 days)
- Imposed Large-scale advection and subsidence
- 2 K/day uniform clear-sky longwave cooling
- Cloud longwave cooling (Duynkerke et al. 1999)
- 3.2 km x 3.2 km x 3 km domain
- 20 m x 50 m x 50 m resolution
- 10 cases: 5 SSTs, 2 Divs

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

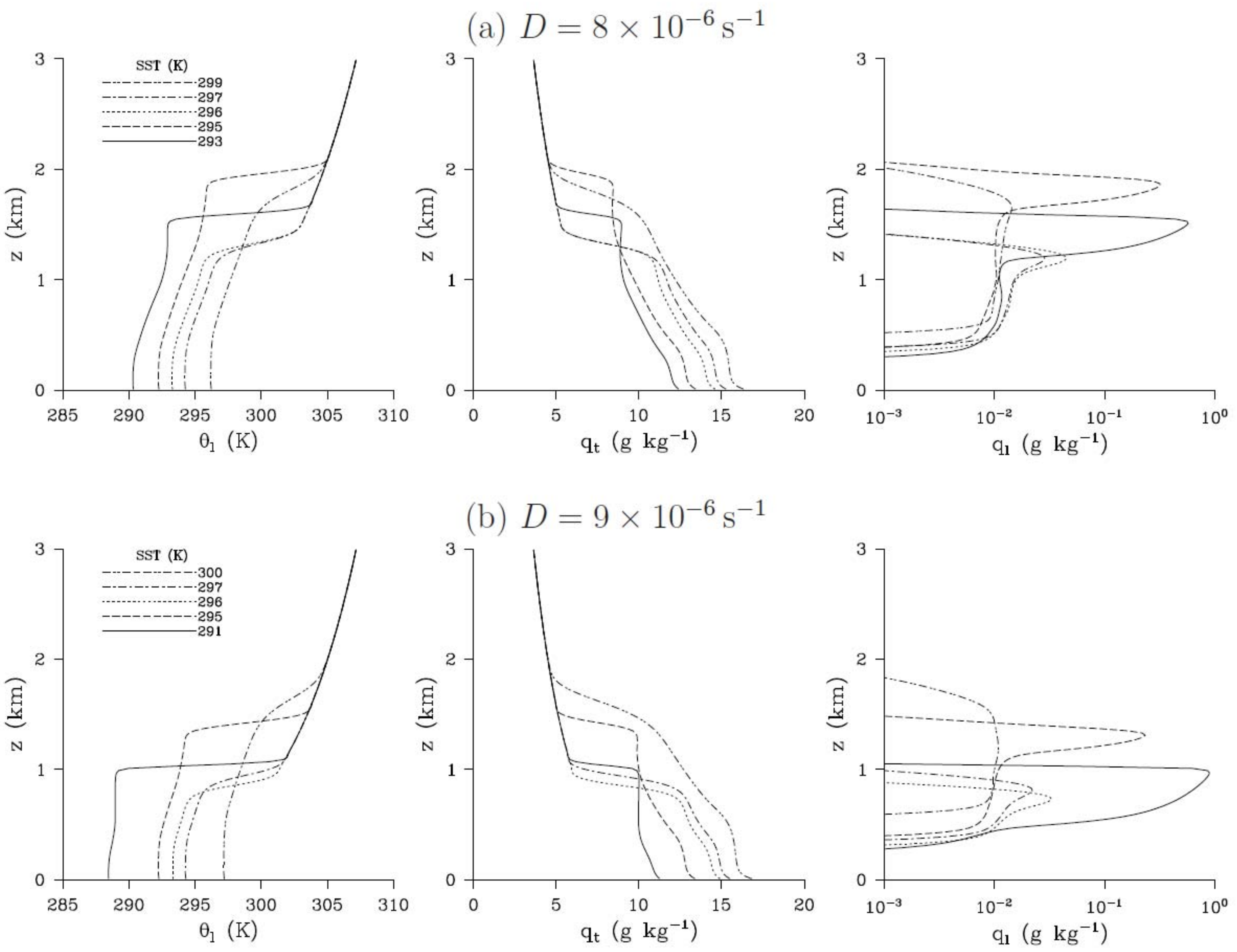
How does it look like?



National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Mean thermodynamic profiles



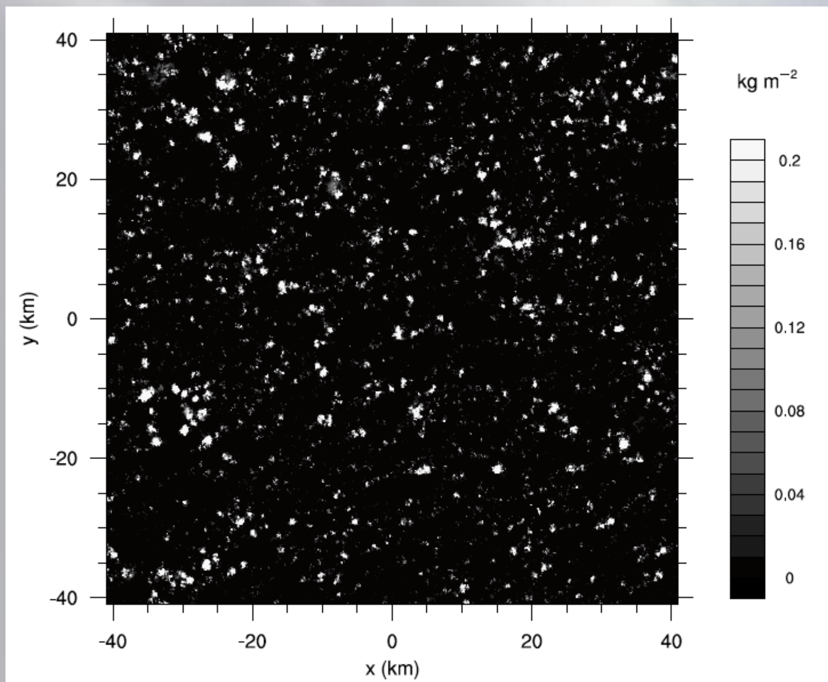
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

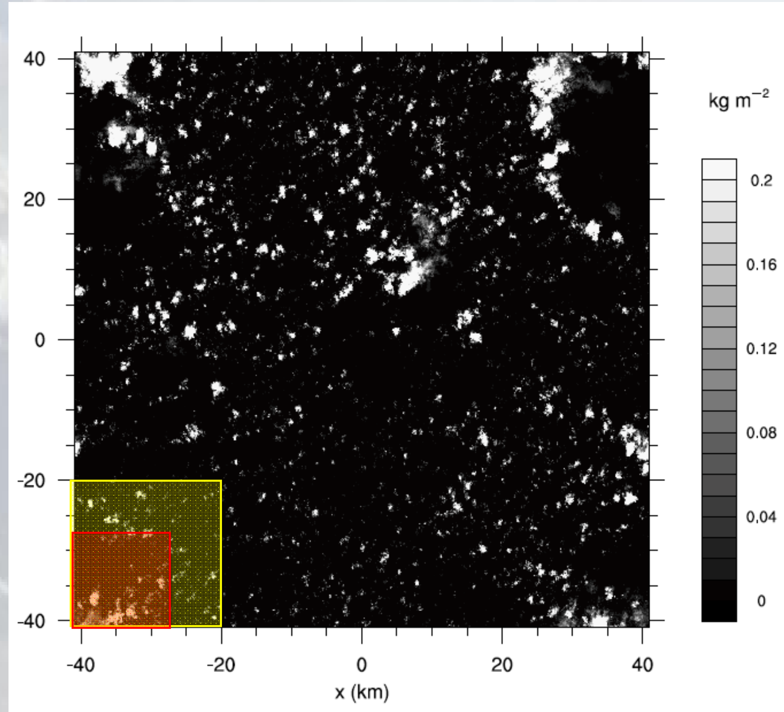
Large-domain LES: RICO

- Domain size 80 × 80 × 4 km
- Resolution is 20 m, uniform
- 4096 × 4096 × 200 = 3.3 billion cells

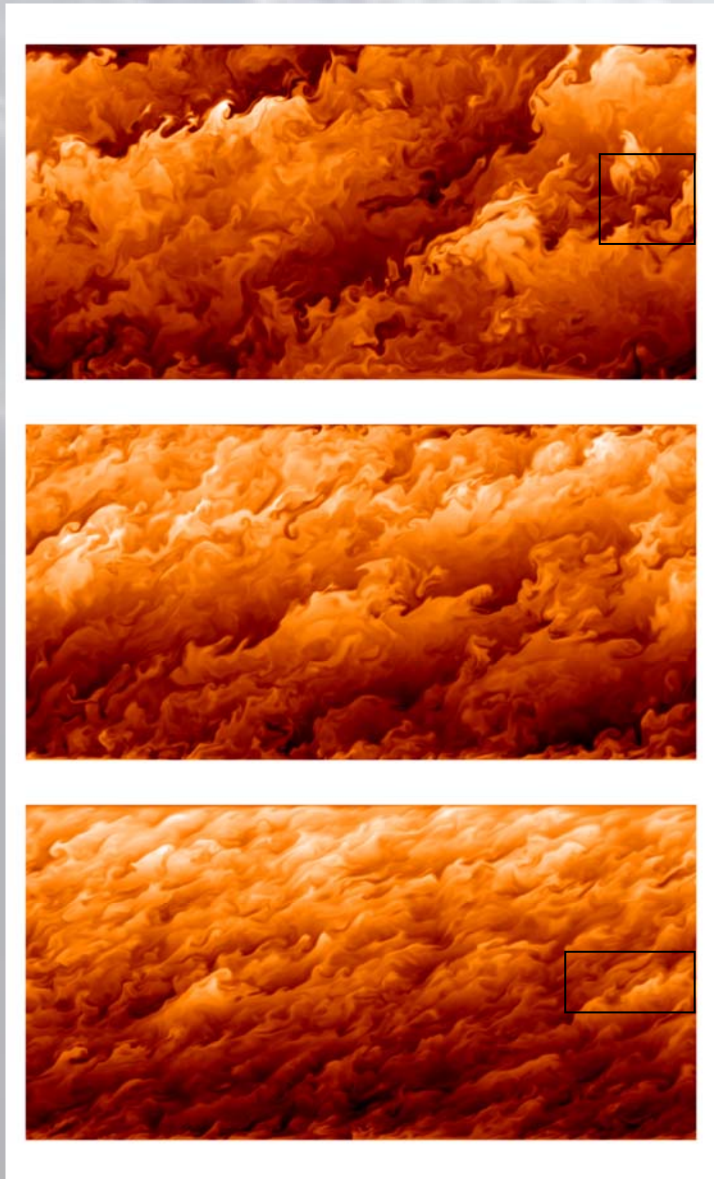
t = 10 h



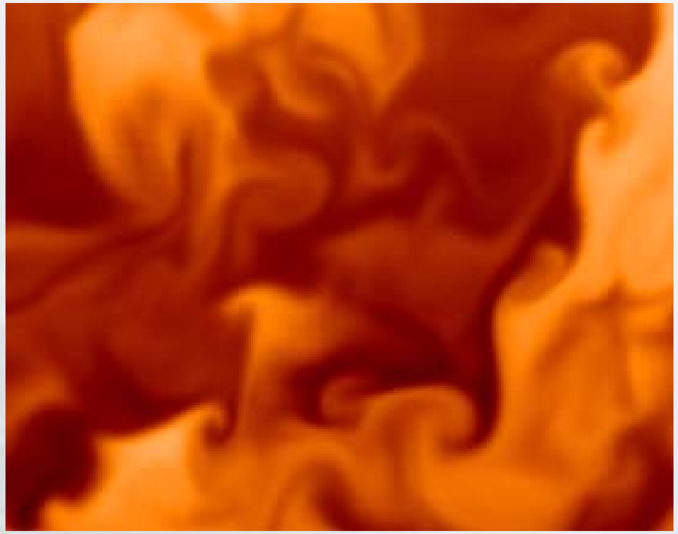
t = 15 h Matheou et al, 2011

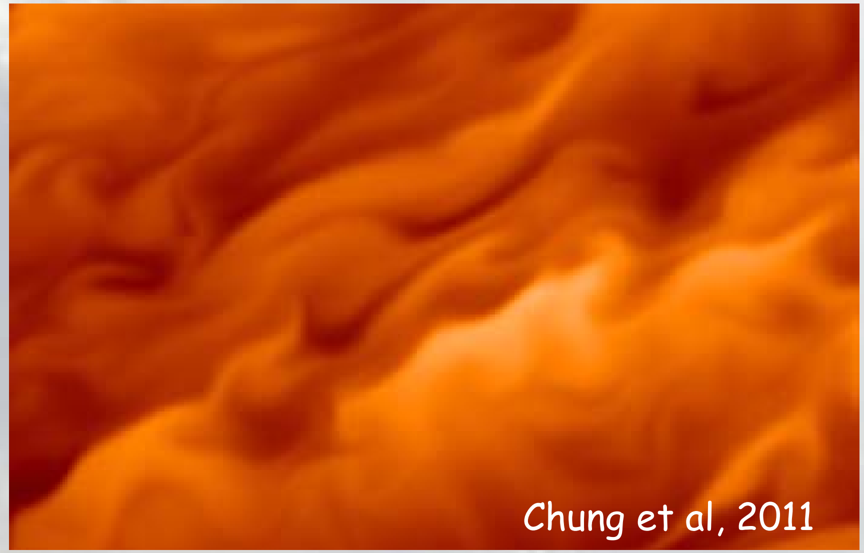


Direct Numerical Simulation (DNS) of stratified homogeneous turbulence



Stratification/stability increases



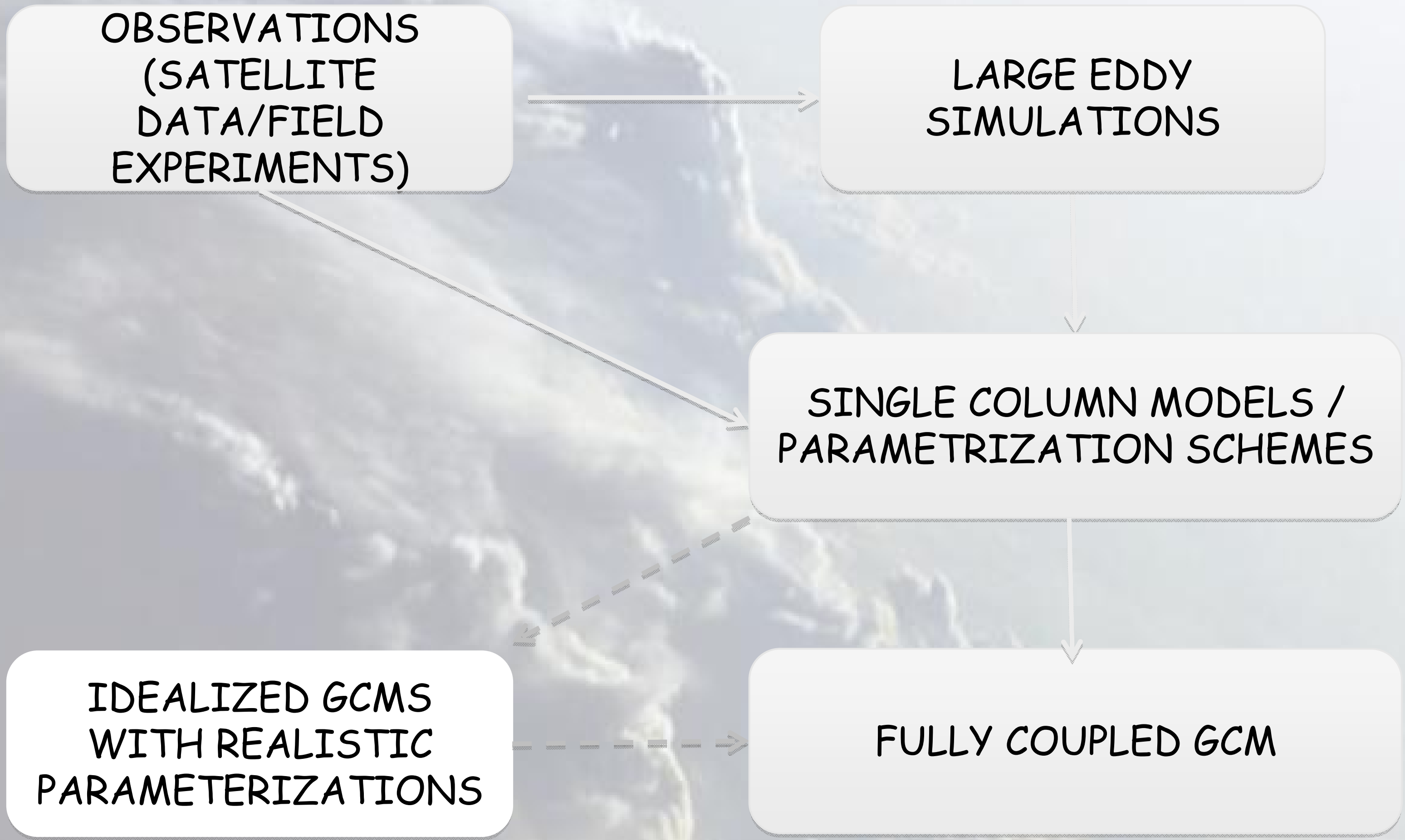


Chung et al, 2011

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Motivation for implementing EDMF in simple GCMs

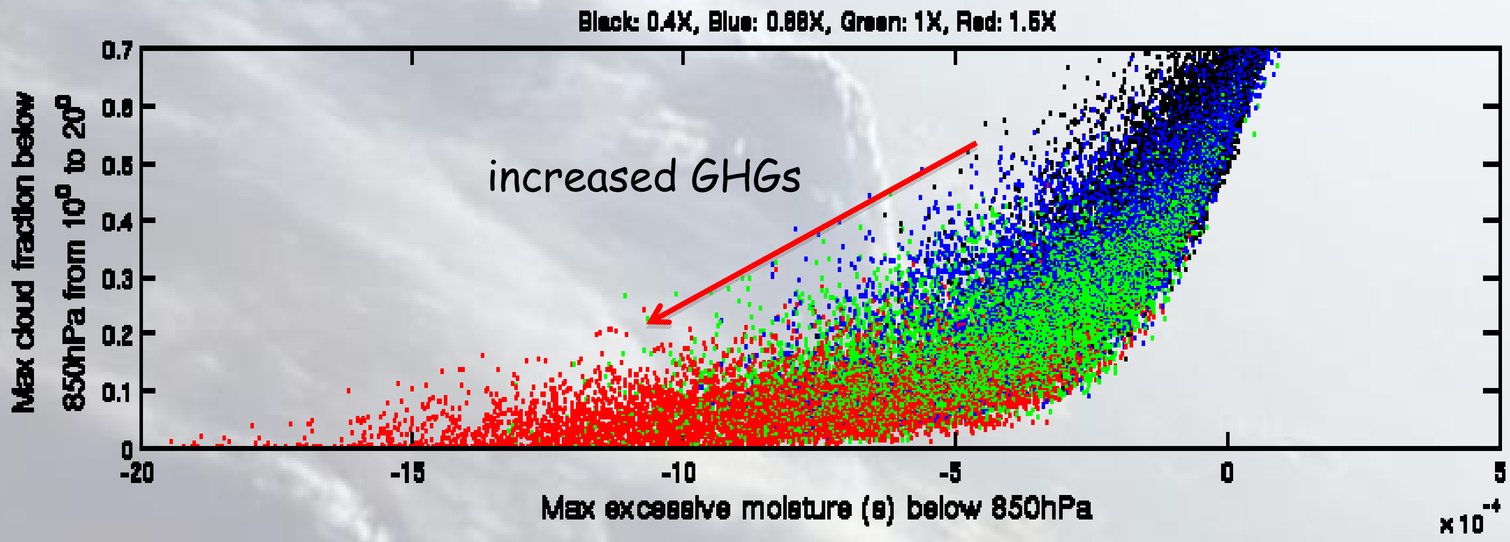


Simple GCM Description

- GFDL idealized GCM with a slab-ocean
- No diurnal or seasonal cycle
- No large-scale condensation
- No deep convection
- EDMF for sub-grid vertical mixing (dry, shallow and deep convection)
- Gaussian PDF-based cloud parameterization
- Vary the longwave optical depth (LWOD) to represent climate change with changing GHG

National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Cloud changes for increased GHGs in simple GCM



- Subtropical low clouds decrease with with warming climate – increased GHGs
- Lower tropospheric stability does not appear related to this change
- Decrease of low cloud fraction is related to decrease of s = qt - qs

Summary

1) A variety of projects related to EDMF development at JPL/Caltech

2) EDMF and TKE have been combined to represent dry and cumulus boundary layers

3) Using PDF of updraft properties leads to new EDMF shallow convection approaches: deterministic and stochastic sampling of cloud base PDF

4) LES steady-state simulations of Sc, Cu and transition help EDMF evaluation

5) EDMF and PDF-clouds have been implemented in idealized GCM to perform climate change investigations

Eddy-Diffusivity/Mass-Flux Model

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Dividing a grid square in two regions (updraft and environment) and using Reynolds decomposition and averaging leads to

$$\overline{w'\varphi'} = a_u \overline{w'\varphi'}_u + (1-a_u)\overline{w'\varphi'}_e + a_u(1-a_u)(w_u - w_e)(\varphi_u - \varphi_e)$$

where a_u is the updraft area. Assuming $a_u \ll 1$ and $w_e \sim 0$ leads to

$$\overline{w'\varphi'} = \overline{w'\varphi'}_e + a_u w_u(\varphi_u - \overline{\varphi})$$

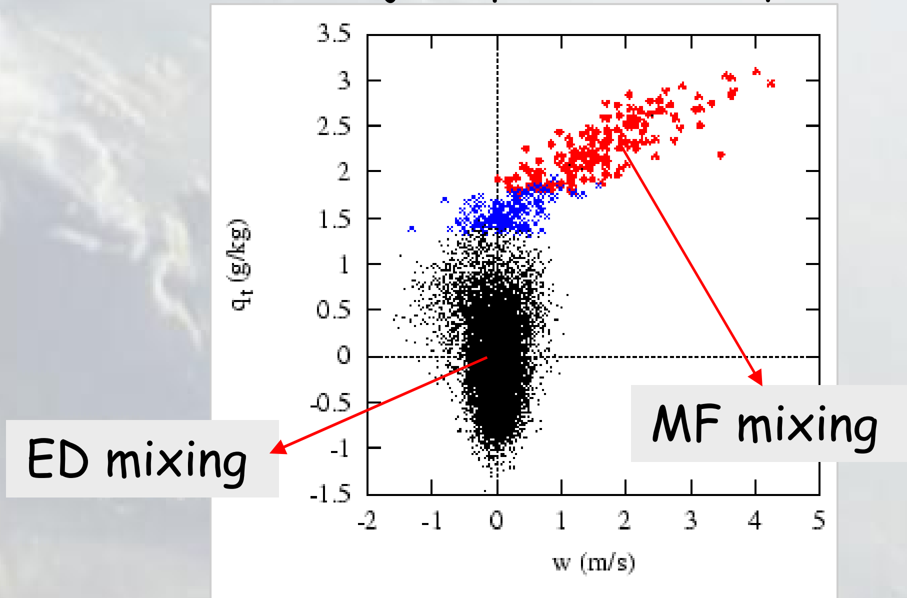
ED closure: assuming ED for 1st term and neglecting 2nd term

MF closure: neglecting 1st term and assuming $M = a_u w_u$

EDMF: $$\overline{w'\varphi'} = -k\frac{\partial\overline{\varphi}}{\partial z} + M(\varphi_u - \overline{\varphi})$$

Siebesma & Teixeira, 2000

Bimodal joint pdf of w and qt



EDMF is able to reproduce variety of boundary layer convection types

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Cloud and Convection Parameterization: Moist conserved variables

For convenience: the mean of a variable $\overline{\varphi}$ is often represented as φ

Traditional set of thermodynamic variables

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'\theta'}\right) + \frac{L}{C_p}\frac{\theta}{T}C \qquad \frac{\partial q}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'q'}\right) - C \qquad \frac{\partial l}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'l'}\right) + C$$

θ - potential temperature, q - specific humidity, l - liquid water

Moist conserved variables

$$\frac{\partial \theta_l}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'\theta_l'}\right) \qquad \frac{\partial q_t}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'q_t'}\right)$$

$$q_t = q + l$$

Total water content

$$\theta_l = \theta\left(1 - \frac{L}{C_p T} l\right)$$

Liquid water potential temperature

Two major advantages of using conserved variables:

1) The cloud/condensation term disappears from the equations

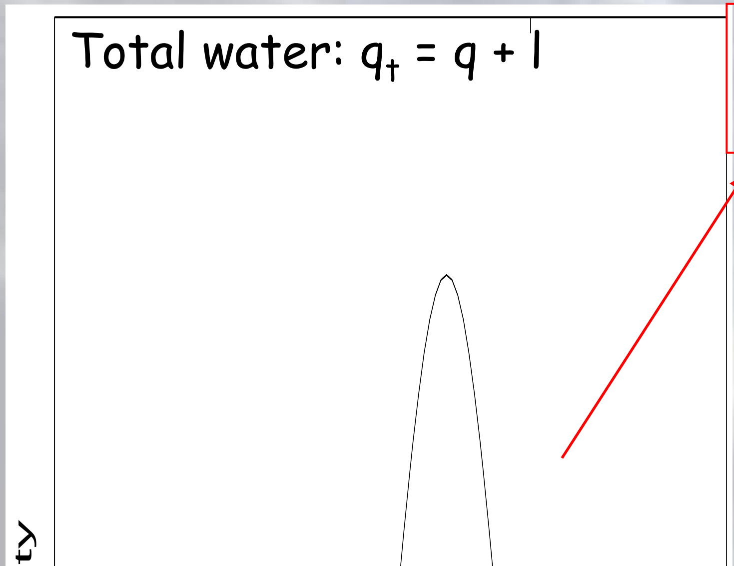
2) The ED approach is able to represent the correct cloud fluxes

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

PDF-based Cloud Parameterization

PDF cloud parameterizations are based on the pdf of q_t (in this simple example) or on the joint pdf of q_t and θ_l



Values larger than saturation are cloudy

$$a = \int_{q_s}^{+\infty} p(q_t)\,dq_t$$

a = cloud fraction

$$\bar{l} = \int_{q_s}^{+\infty} (q_t - \overline{q_s})\, p(q_t)\,dq_t$$

Mellor, 77; Sommeria & Deardorff, 77

Gaussian PDF leads to cloud fraction and liquid water as a function of Q:

$$a = \frac{1}{2} + \frac{1}{2} erf\left(\frac{Q}{\sqrt{2}}\right)$$

$$\frac{l}{\sigma} = aQ + \frac{1}{\sqrt{2\pi}} e^{-Q^2/2}$$

$$Q = \frac{q_t - q_s}{\sigma}$$

Pdf-based cloud parameterizations

How to determine the variance of total water?

1) Prognostic equation:

$$\frac{\partial}{\partial t}\left(\overline{q_t' q_t'}\right) = -2\overline{w' q_t'}\frac{\partial q_t}{\partial z} - \frac{\partial}{\partial z}\left(\overline{w' q_t' q_t'}\right) - \frac{\overline{q_t' q_t'}}{\tau_q}$$

2) Diagnostic equation:

$$\overline{q_t' q_t'} = -2\tau_q \overline{w' q_t'}\frac{\partial q_t}{\partial z}$$

Eddy-diffusivity

$$\overline{q_t' q_t'} = 2\tau_q k \left(\frac{\partial q_t}{\partial z}\right)^2$$

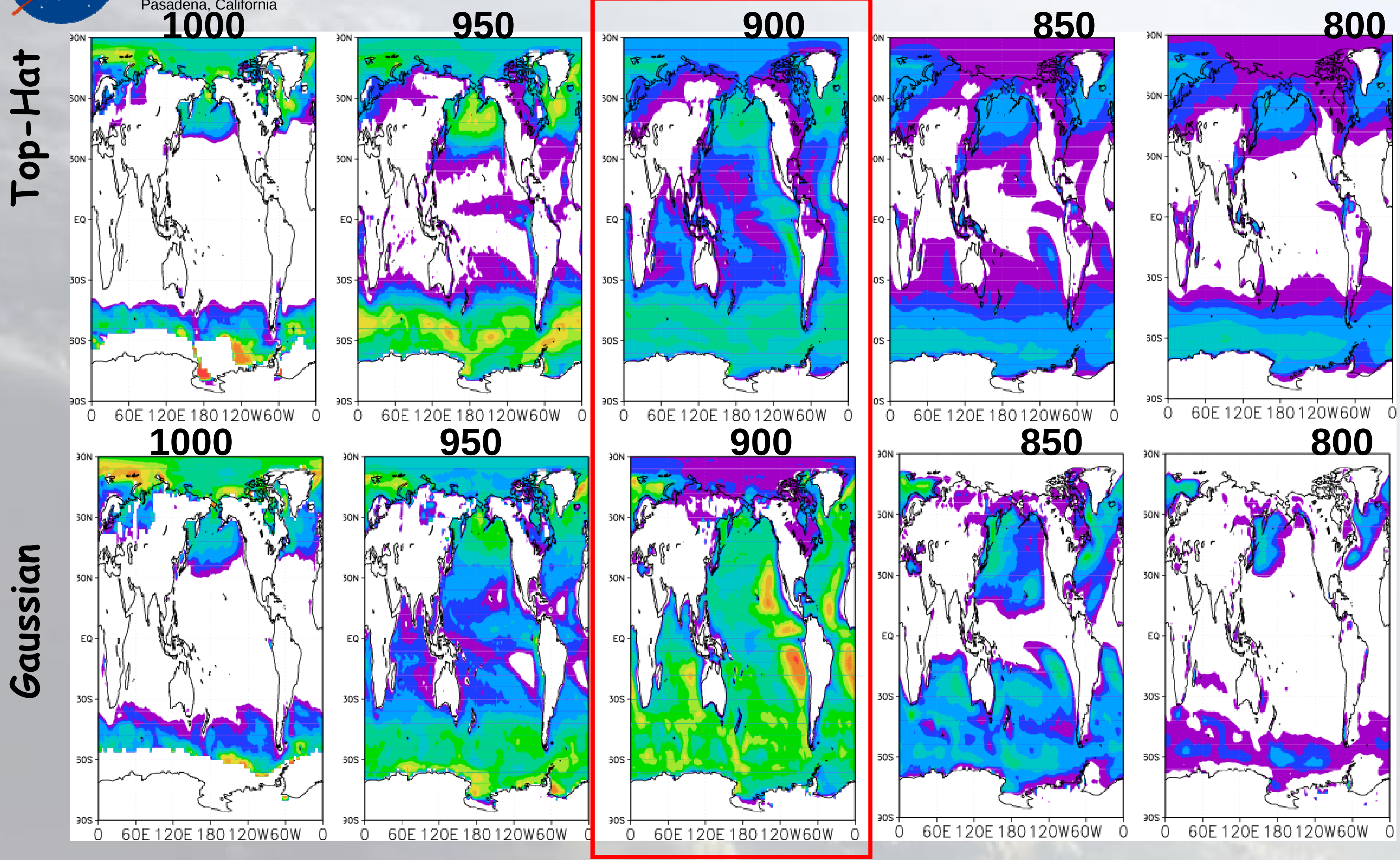
Mass-flux

$$\overline{q_t' q_t'} = -2\tau_q M \left(q_t^u - q_t\right)\frac{\partial q_t}{\partial z}$$

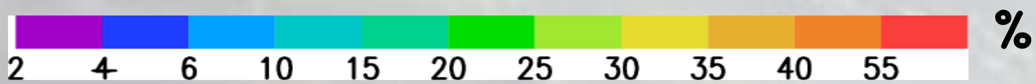
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Gaussian PDF scheme for PBL clouds implemented in GEOS-5: ED-based variance and interactive radiation



Two year simulation



National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Cloud-Fraction with different LWODs