National Aeronautics and
Space Administration

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

# Turbulence, Convection and Climate Prediction: the Eddy-Diffusivity/Mass-Flux (EDMF) Approach

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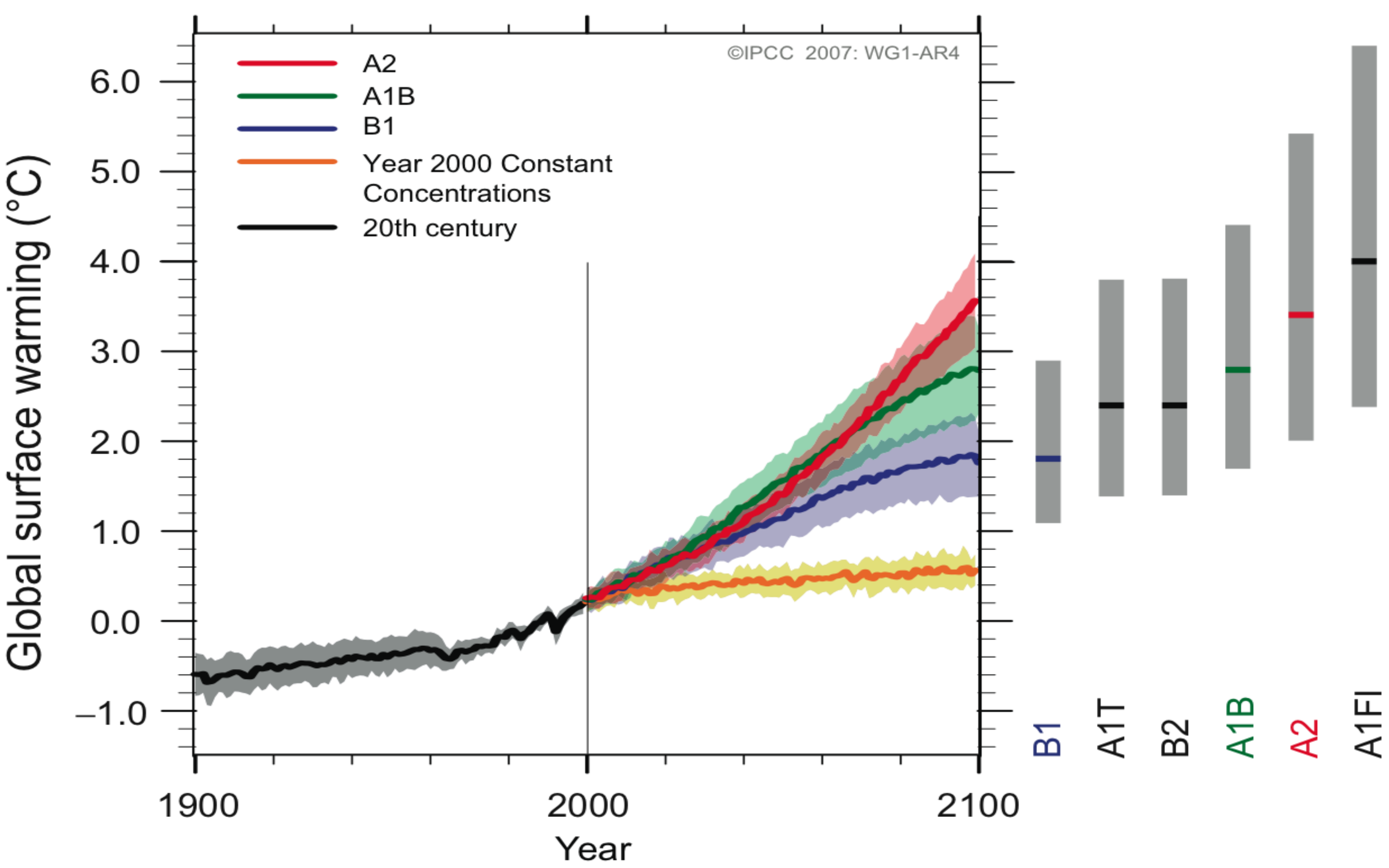
# Climate Change Prediction

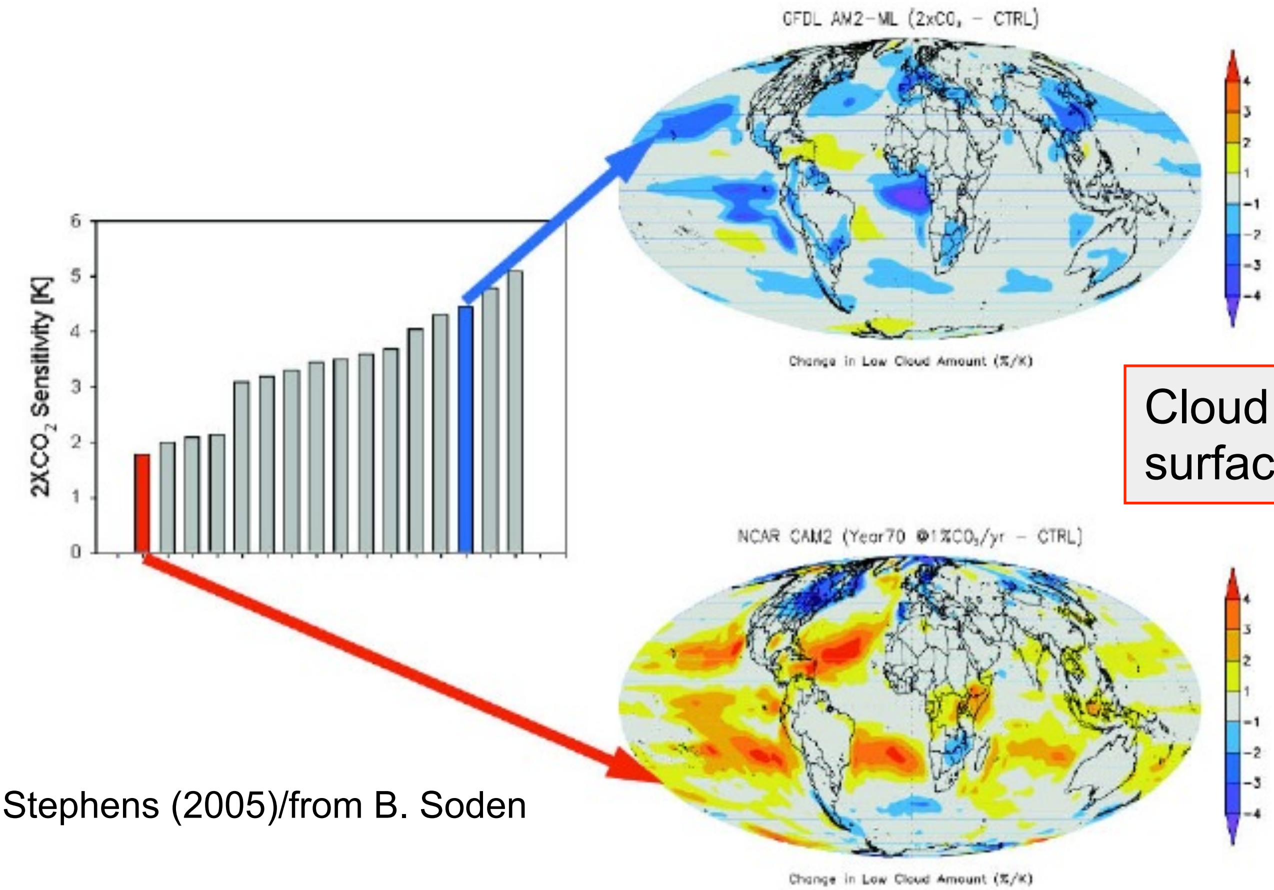


Multi-model Averages and Assessed Ranges for Surface Warming

Significant uncertainties in climate prediction:
Turbulence, convection and clouds

# Climate is changing … YET there is large uncertainty in climate prediction

Cloud feedbacks remain key source of uncertainty in climate prediction



Stephens (2005)/from B. Soden

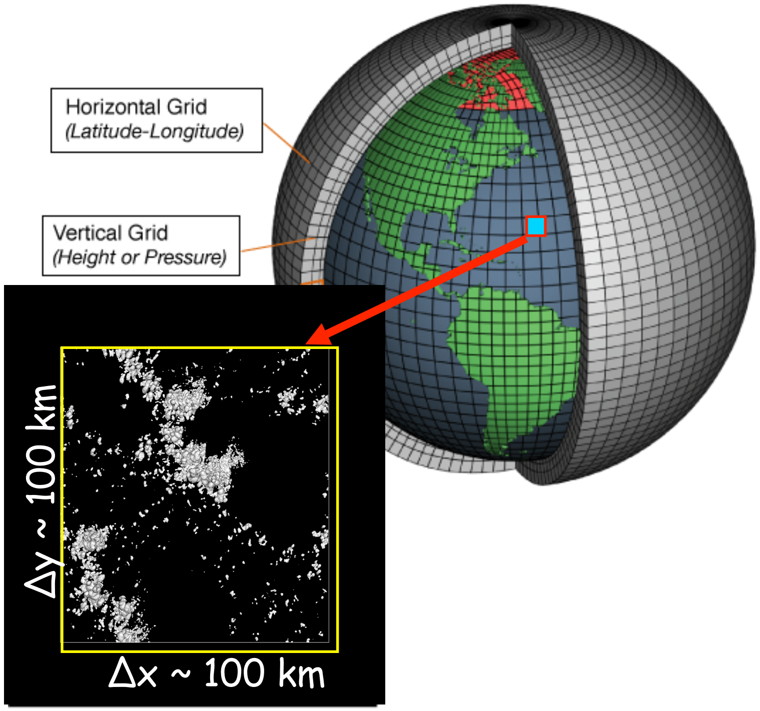
Doubling $CO_2$ ➔ less low clouds in GFDL ➔ 4 K global warming

Cloud albedo > sea surface albedo

Doubling $CO_2$ ➔ more low clouds in NCAR ➔ 2 K global warming

Unclear if cloud feedback is positive or negative

# Climate and Weather Models



3D Atmospheric Models:

3D Large-scale dynamics +
One-dimensional physics

Reynolds decomposition and averaging:

$$\varphi = \bar{\varphi} + \varphi' \quad \Rightarrow \quad \boxed{\frac{\partial \bar{\varphi}}{\partial t} + \frac{\partial}{\partial x}\left(\bar{u}\bar{\varphi}\right) + \frac{\partial}{\partial y}\left(\bar{v}\bar{\varphi}\right) + \frac{\partial}{\partial z}\left(\bar{w}\bar{\varphi}\right) = -\frac{\partial}{\partial z}\left(\overline{w'\varphi'}\right) + \bar{S},}$$

Key parameterization problem: turbulence and convection

# Eddy-Diffusivity (ED) approach

In ED closure the sub-grid flux is parameterized as

$$\overline{w'\varphi'} = -k\frac{\partial\overline{\varphi}}{\partial z}$$

where k is the diffusivity coefficient. The mixing length approach (e.g. Taylor, Prandtl) is $k_\varphi = c_\varphi l w_t$

where $w_t$ is a turbulent velocity and $l$ is a mixing length.

ED is successful in representing:

- Surface layer (MO theory), momentum mixing
- Neutral/stable boundary layers => Logarithmic-law:

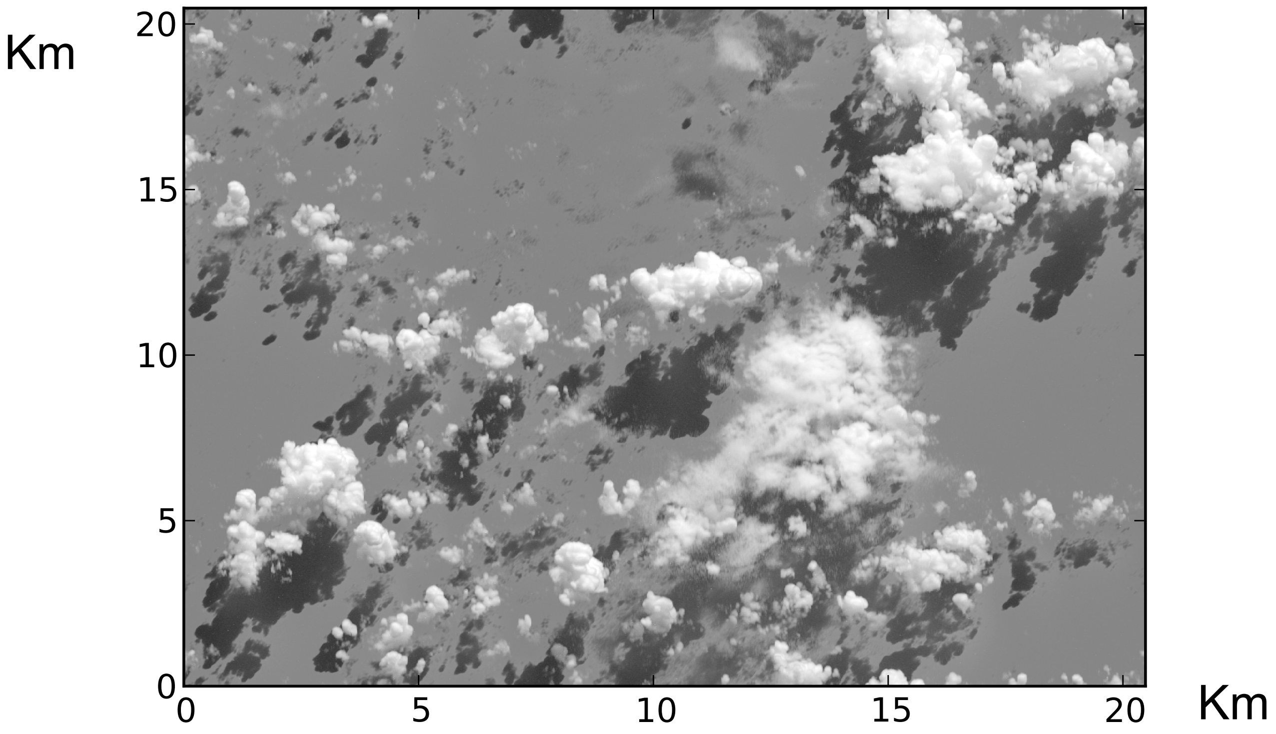
Surface layer (constant flux): $\overline{u'w'} = -U_*^2 = const.$

$w_t \propto U_*$ and $l \propto z$ leads to

$$\overline{u'w'} = -k\frac{\partial u}{\partial z} \Rightarrow zU_*\frac{\partial u}{\partial z} \propto U_*^2 \qquad \Rightarrow u \propto U_* \ln\left(z/z_0\right)$$

# Large-Eddy Simulation (LES) models

- LES models solve filtered version of Navier-Stokes equations
- High-resolutions (~ 1 - 100m) in all 3 dimensions
- LES models resolve most of the essential turbulence/convection
- Closures still needed for scales < 10m (but simpler than GCMs)



Matheou et al., MWR, 2011

# An Integrated Approach: Eddy-Diffusivity/Mass-Flux (EDMF)

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

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

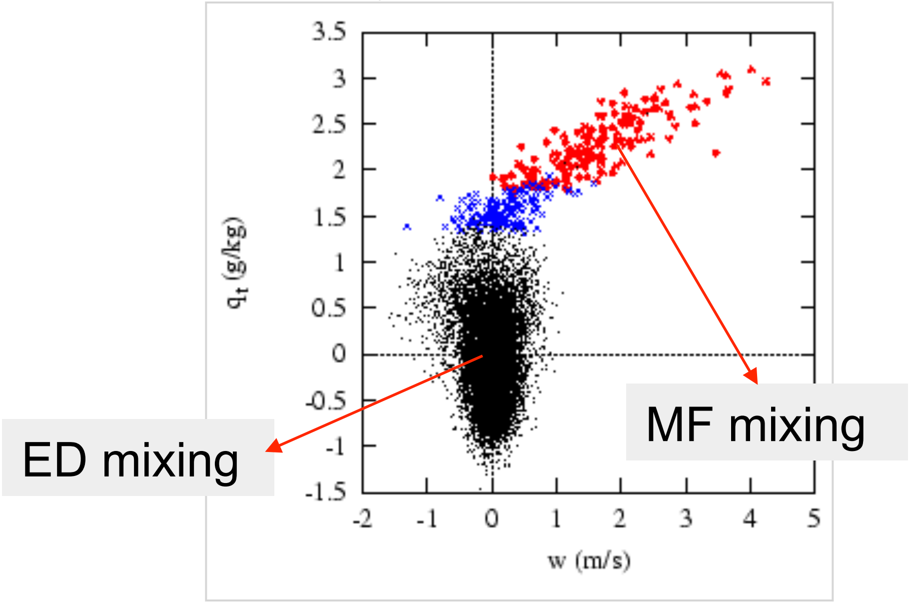
ED closure: assuming ED for 1st term and neglecting 2nd term

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

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

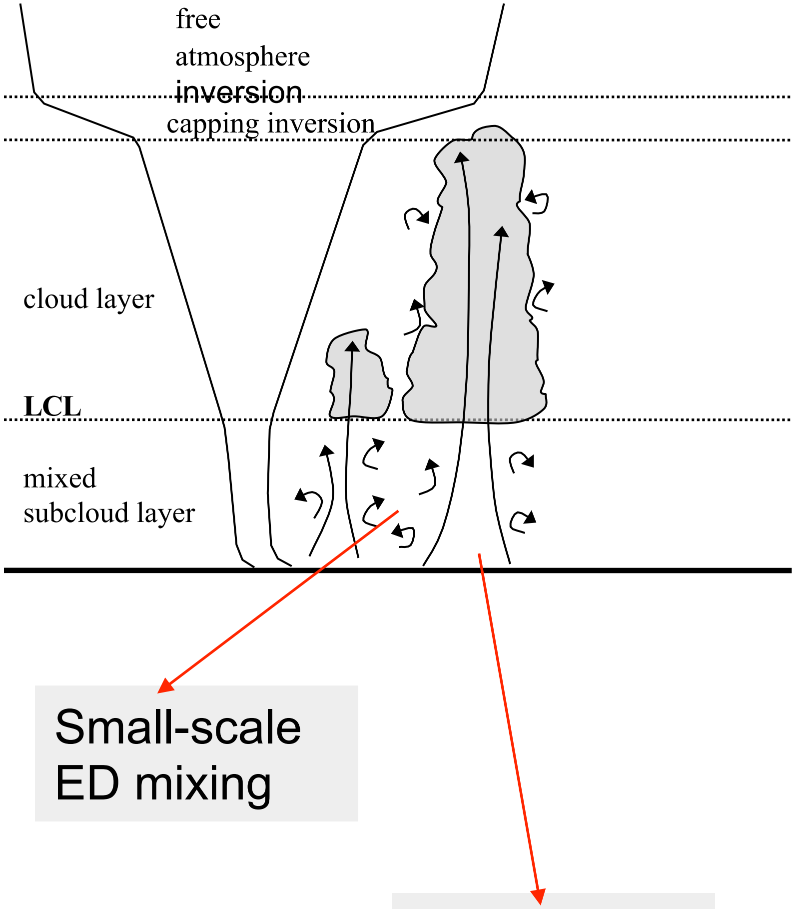
Siebesma & Teixeira, 2000

Bimodal joint pdf of w and qt



EDMF represents different turbulence and convection scales

# Mass-Flux Model for Plumes/Updrafts



Small-scale
ED mixing

Large-scale
MF mixing

1) Integrating over plume area
2) Assuming steady-state
3) Neglecting some sources/sinks

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon(\phi_u - \overline{\phi}) \text{ for } \phi \in \{\theta_{\mathrm{l}}, q_t\}$$

$$M = \sigma_u w_u$$

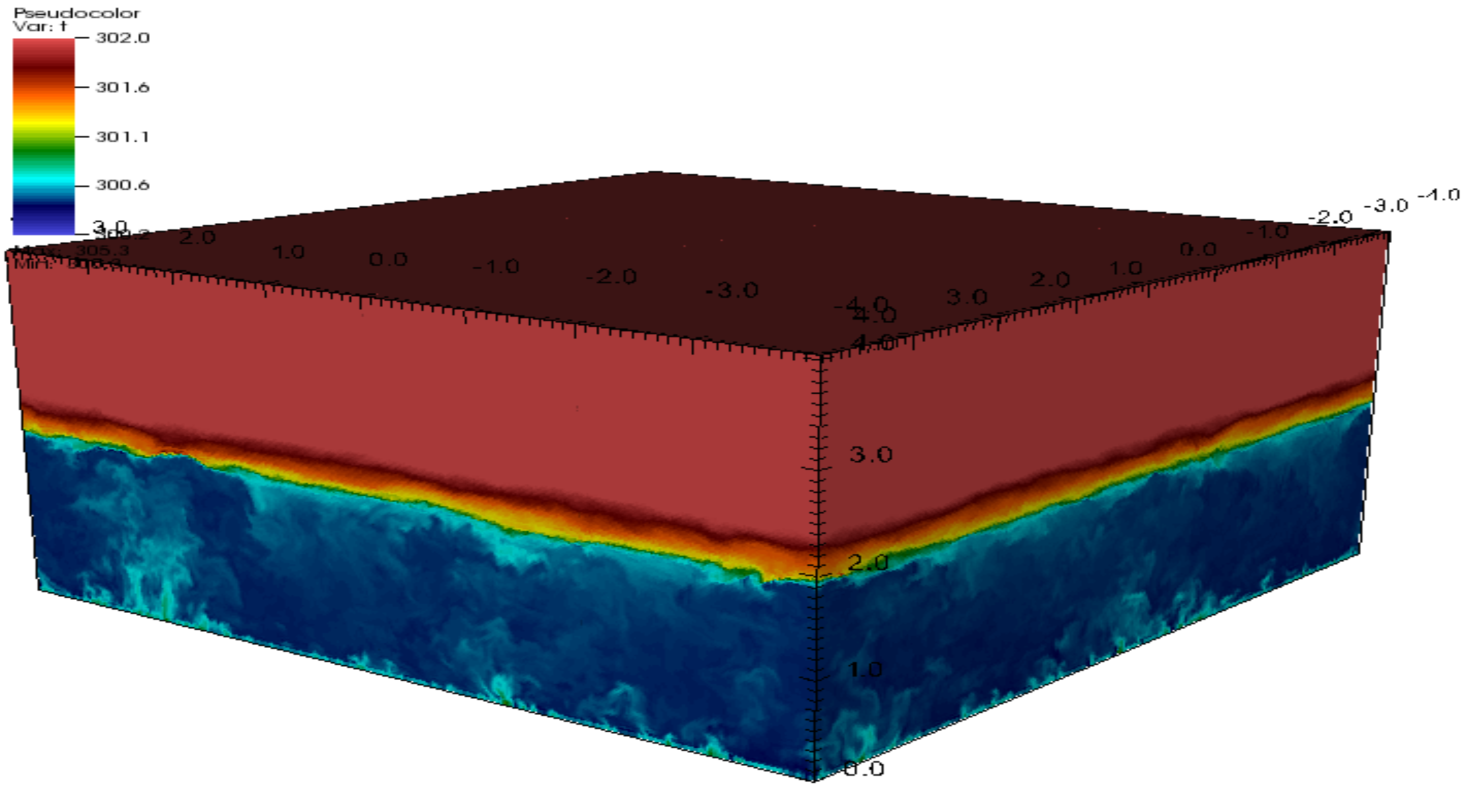
$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = -b\varepsilon\, w_u^2 + a\frac{g}{\theta_0}\left(\theta_{v,u} - \overline{\theta_v}\right)$$

$\sigma_u$ is updraft/plume area fraction and is fixed for each plume in our approach

Lateral entrainment rate: $\varepsilon = \dfrac{1}{w_u \tau} = \dfrac{1}{h_c}$

# LES of Dry Convection

## Potential temperature over the desert during day time

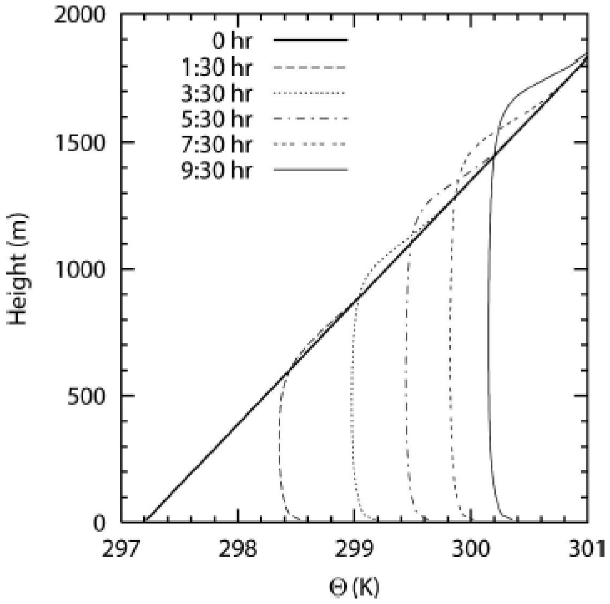


Convective plumes bring heat from surface to atmosphere, often against the mean gradient of potential temperature

# Dry Convective Boundary Layer

## Well-mixed in potential temperature driven by surface heating

LES simulation of dry convective boundary layer



Siebesma, Soares & Teixeira, JAS, 2007

Potential temperature and specific humidity equations (no clouds):

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

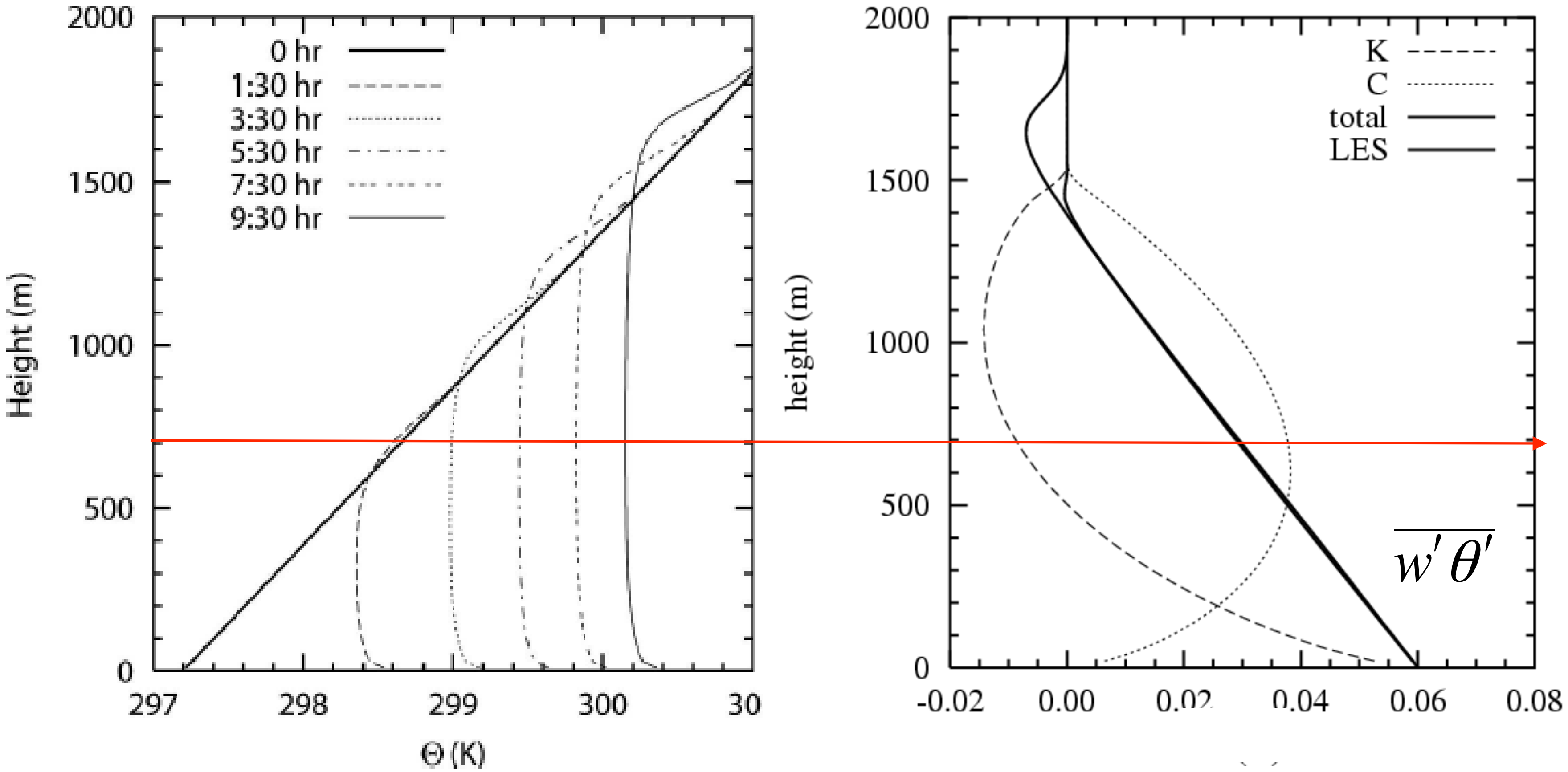
$$\frac{\partial q}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'q'}\right)$$

Current climate & weather models cannot reproduce key properties:

1) Top entrainment
2) Counter-gradient flux

# Counter-Gradient Problem

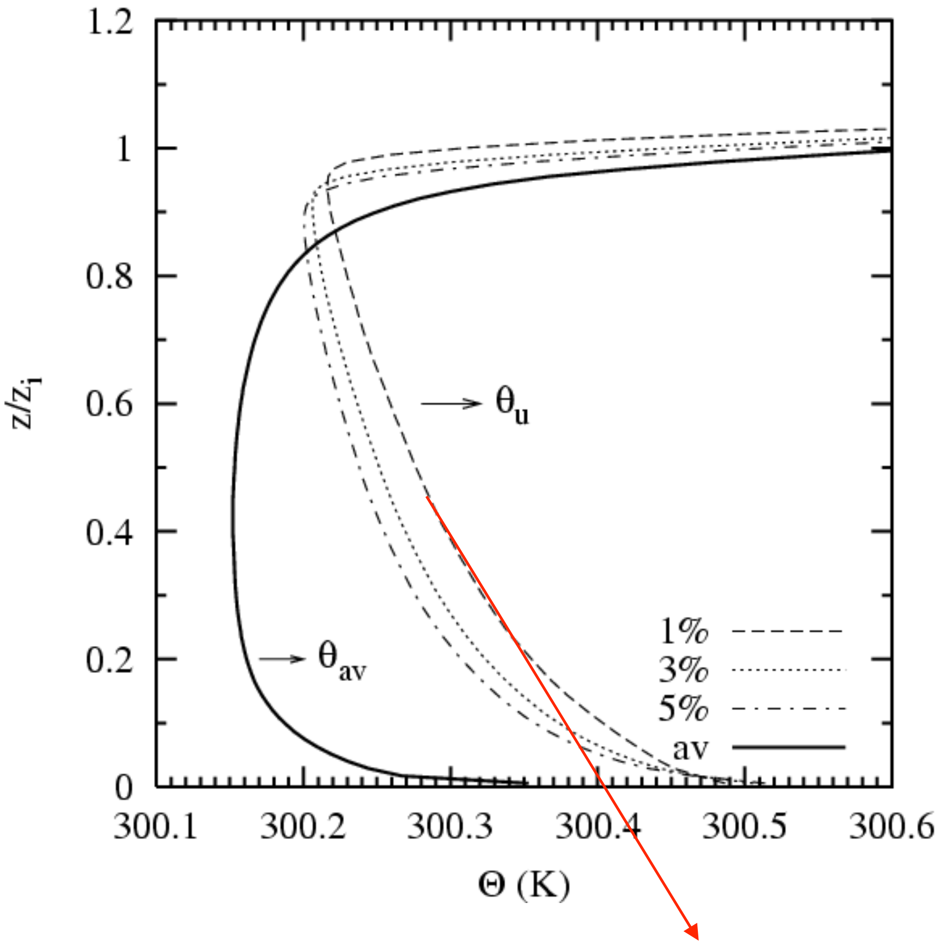
Positive buoyancy flux against the mean gradient: ED fails



An old solution (e.g.
Ertel, 1942) fails as well:

$$\overline{w'\theta'} = -K\frac{\partial\overline{\theta}}{\partial z} + K\gamma$$

# MF component: Using LES to derive updraft model in dry convective boundary layer



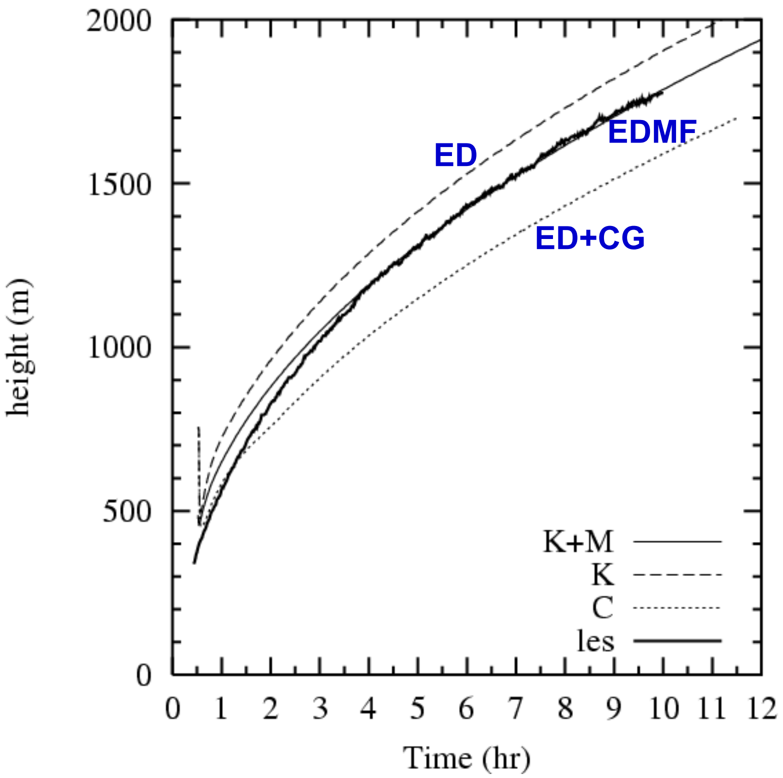
Updraft at height z:
grid points that contain the highest p% of vertical velocities.

p=1%,3%,5%

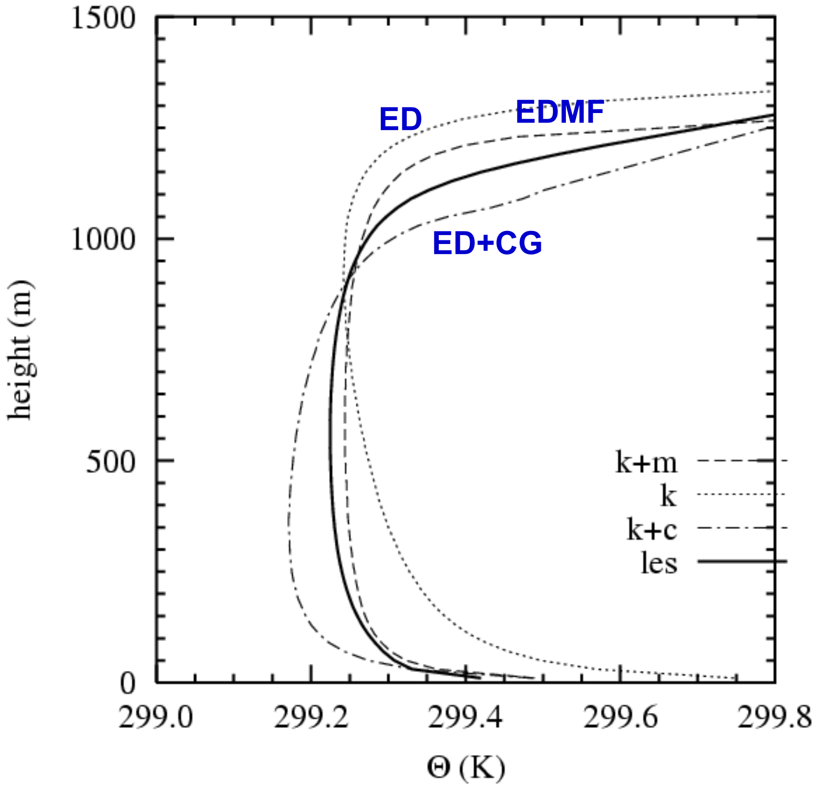
$$\overline{w'\theta'} = M(\theta_u - \bar{\theta})$$

MF component represents strong updrafts / counter-gradient flux

# Dry Convective Boundary Layer



PBL height growth



Mean profiles after 4 hours

EDMF : Realistic PBL growth and mixed layer profile (counter-gradient effect)

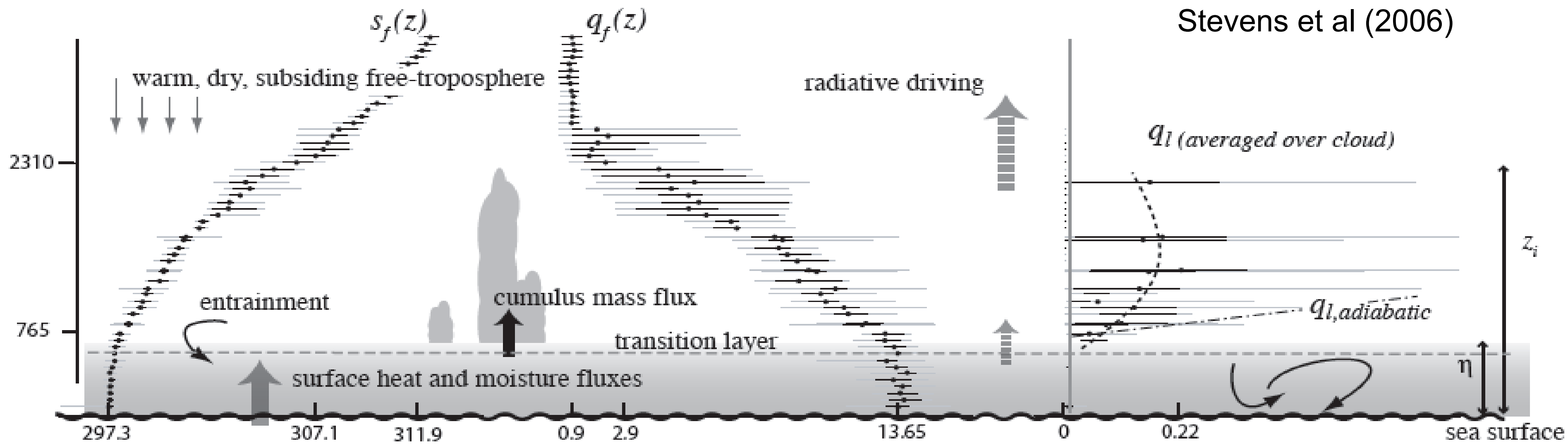
ED : Unstable Profile in lower PBL and too fast PBL growth

ED + Counter-Gradient (CG): Too slow PBL growth (small entrainment)

Siebesma, Soares & Teixeira, JAS, 2007

# Shallow Moist Convection: Observations

Small values of cloud cover ~ 5 to 30 %



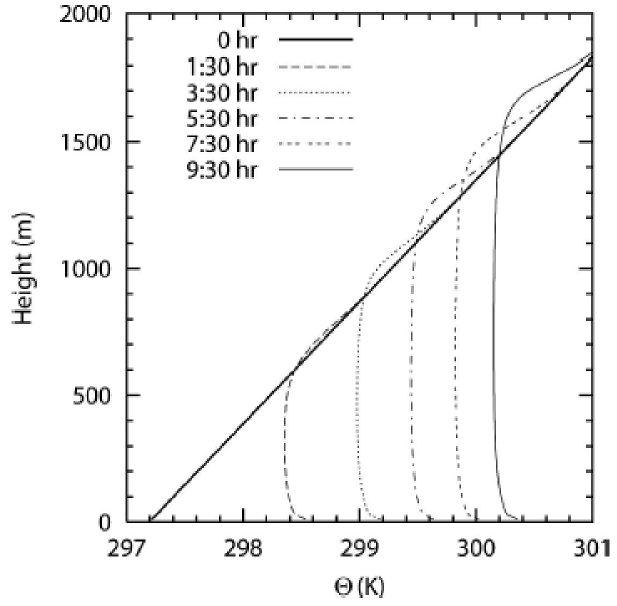
Stevens et al (2006)

Small cloud cover, deeper boundary layers and smoother vertical structures

# Convective Boundary Layers

## Dry convection is simpler

Siebesma, Soares & Teixeira, JAS, 2007



LES of dry convection

Cloudy case is more complex - a few more variables are needed:

- Moist conserved variables

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

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

- Buoyancy: virtual potential temperature

$$\theta_v = \theta\left(1 + 0.61q - l\right)$$

- Saturation: relative humidity

$$RH = \frac{q}{q_s(T,p)}$$

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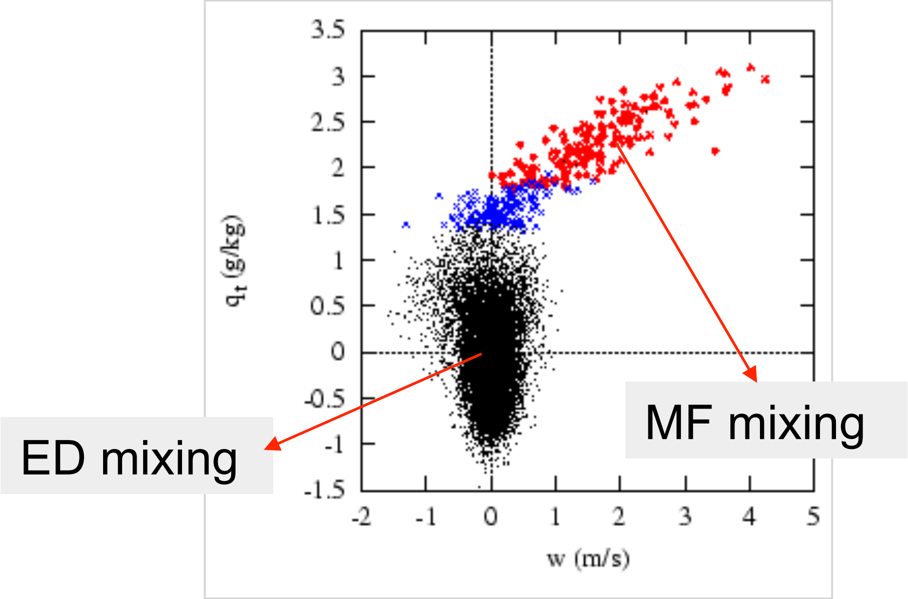


ED mixing

MF mixing

EDMF represents different turbulence and convection scales

# EDMF: Some Equations

ED component is TKE-based with EDMF buoyancy flux:

$$\frac{\partial e}{\partial t} = -\frac{\partial}{\partial z}\overline{w'e} - w\frac{\partial e}{\partial z} - \overline{w'u'}\frac{\partial u}{\partial z} - \overline{w'v'}\frac{\partial v}{\partial z} + \frac{g}{\theta_v}\overline{w'\theta_v'} - \varepsilon_e\,,$$

## Parameterization of cloud-base PDF of updraft properties

Variance diagnostic equation (dissipation balances production):

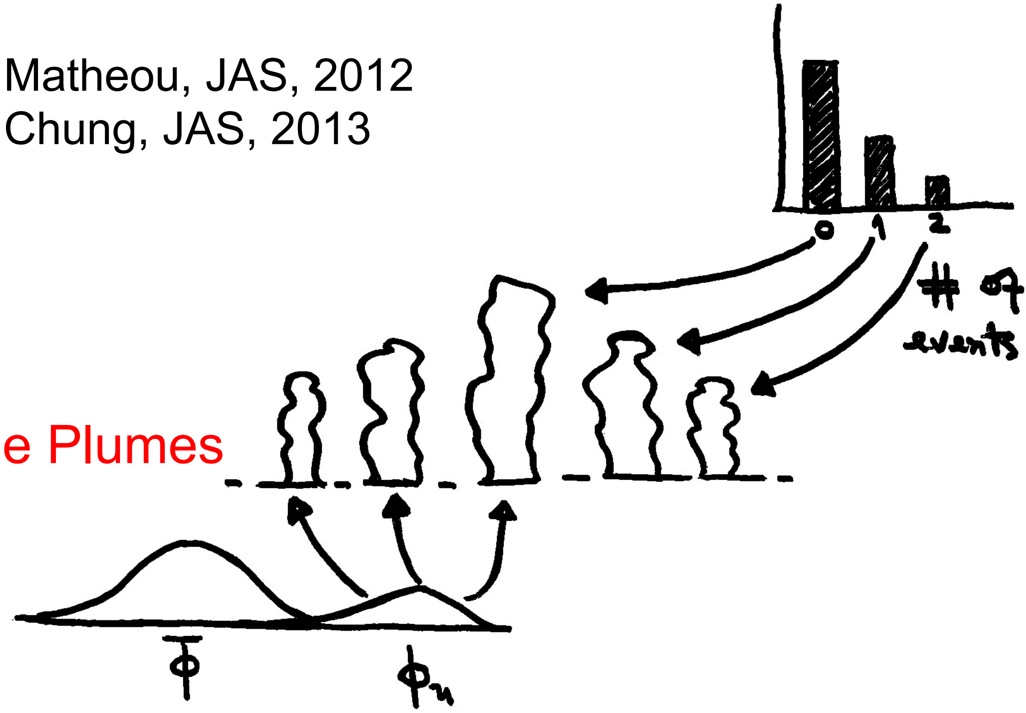
$$2\overline{w_u'\varphi_u'}\frac{\partial \varphi_u}{\partial z} = (C/\tau)\overline{\varphi_u'\varphi_u'}$$

Which leads to

$$\overline{\varphi_u'\varphi_u'} = \frac{3}{2}\frac{\tau_u^2}{C}w_u^2\epsilon^2(\varphi_u - \varphi)^2,$$

# EDMF and moist convection: updraft PDF and stochastic entrainment

Suselj, Teixeira & Matheou, JAS, 2012
Suselj, Teixeira & Chung, JAS, 2013



3) Stochastic lateral entrainment

partly following
Romps & Kuang,
JAS, 2010

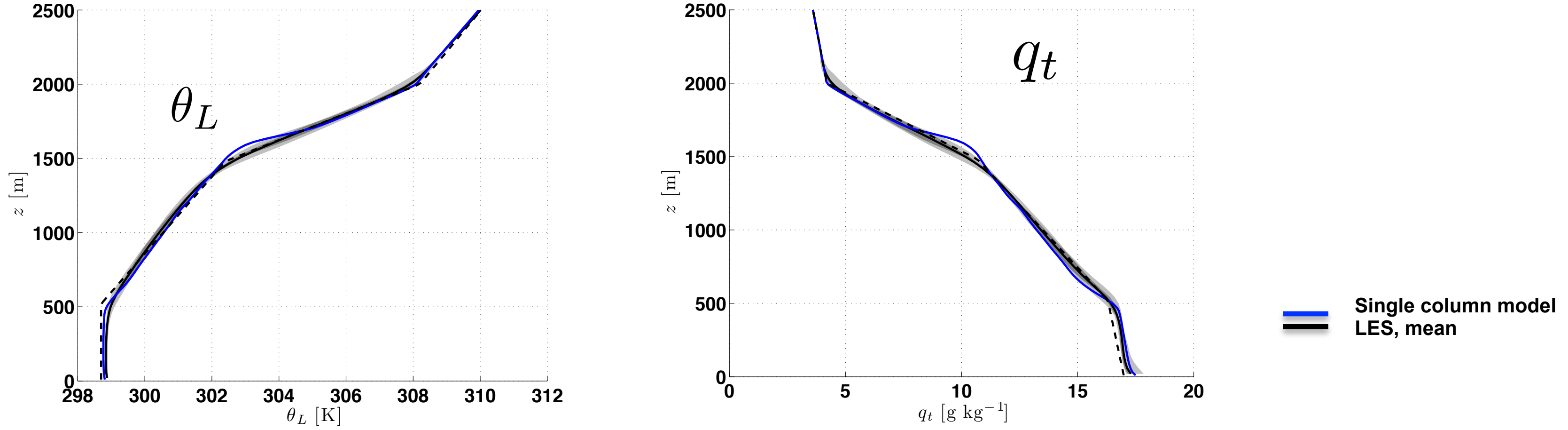
Multiple Plumes

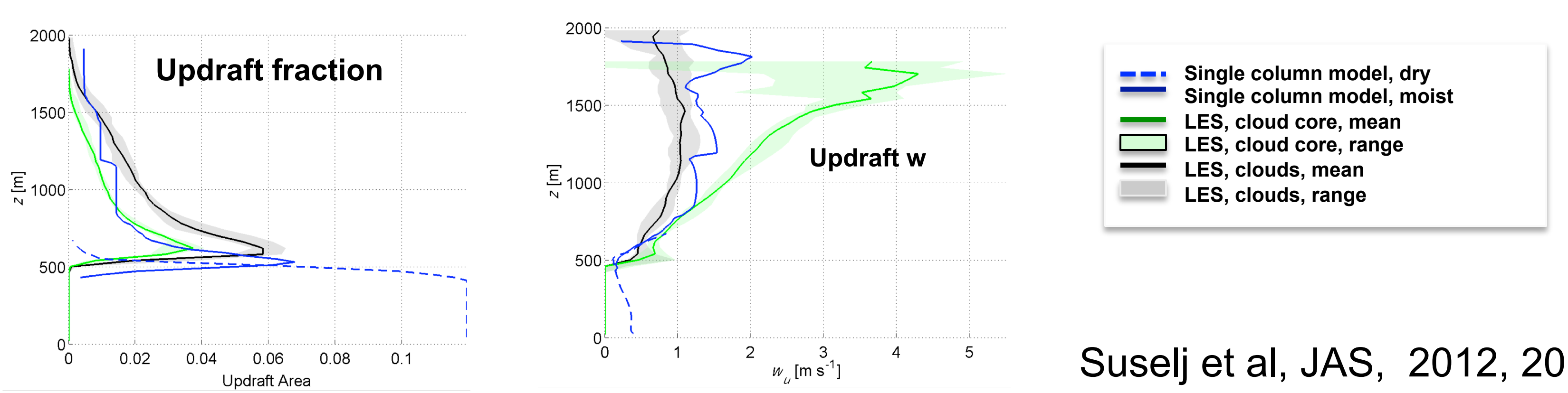
1) Parameterization of PDF of updraft properties at cloud base
2) Monte Carlo sampling of updraft PDF to produce multiple plumes

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

# EDMF simulation of BOMEX cumulus case: comparison with LES

## Mean profiles between 3rd and 4th simulation hour

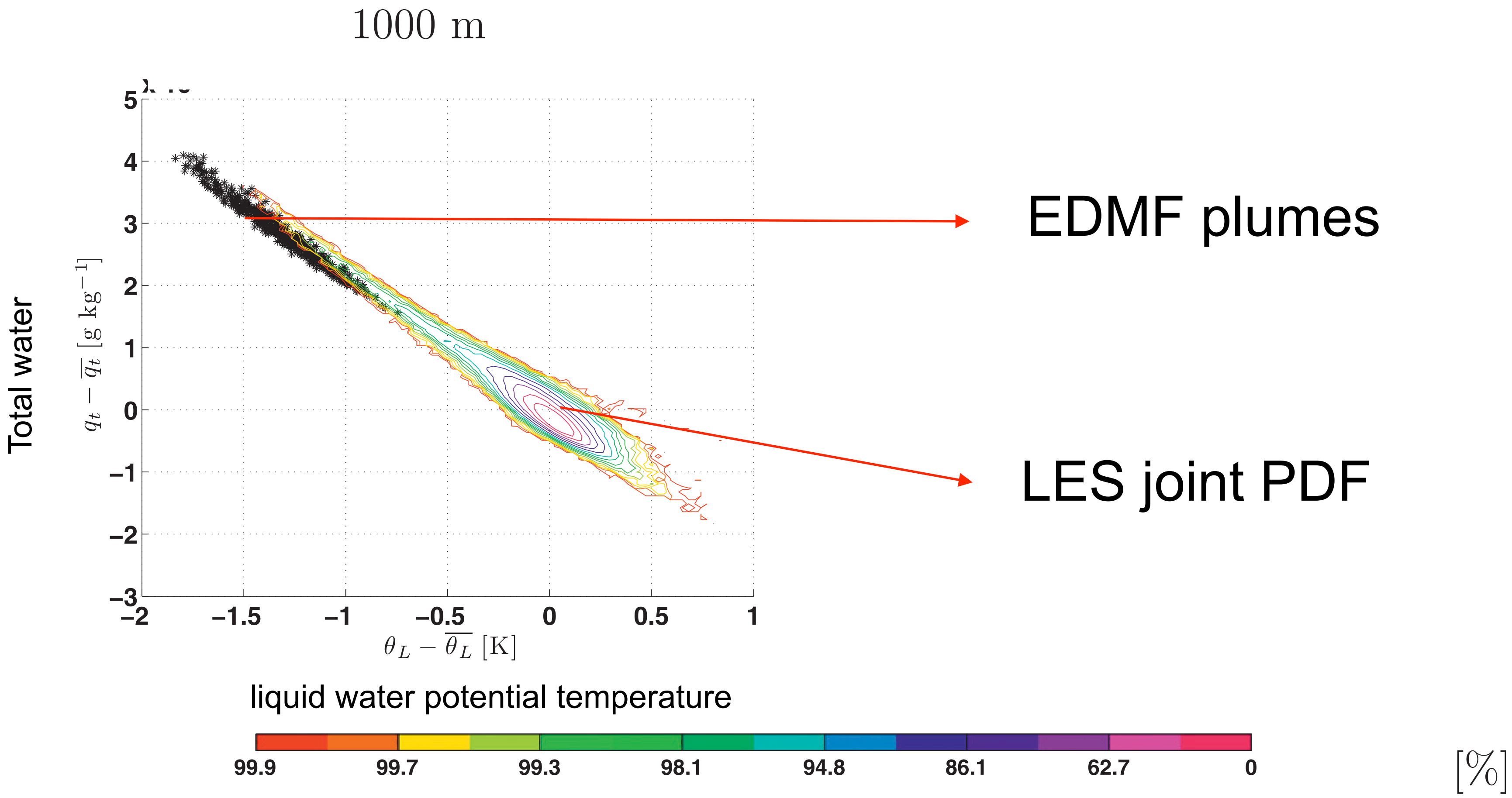




Suselj et al, JAS, 2012, 2013

## New aspect: Using PDF of updraft properties and stochastic entrainment

# BOMEX: LES PDF vs EDMF plumes



Total water

liquid water potential temperature

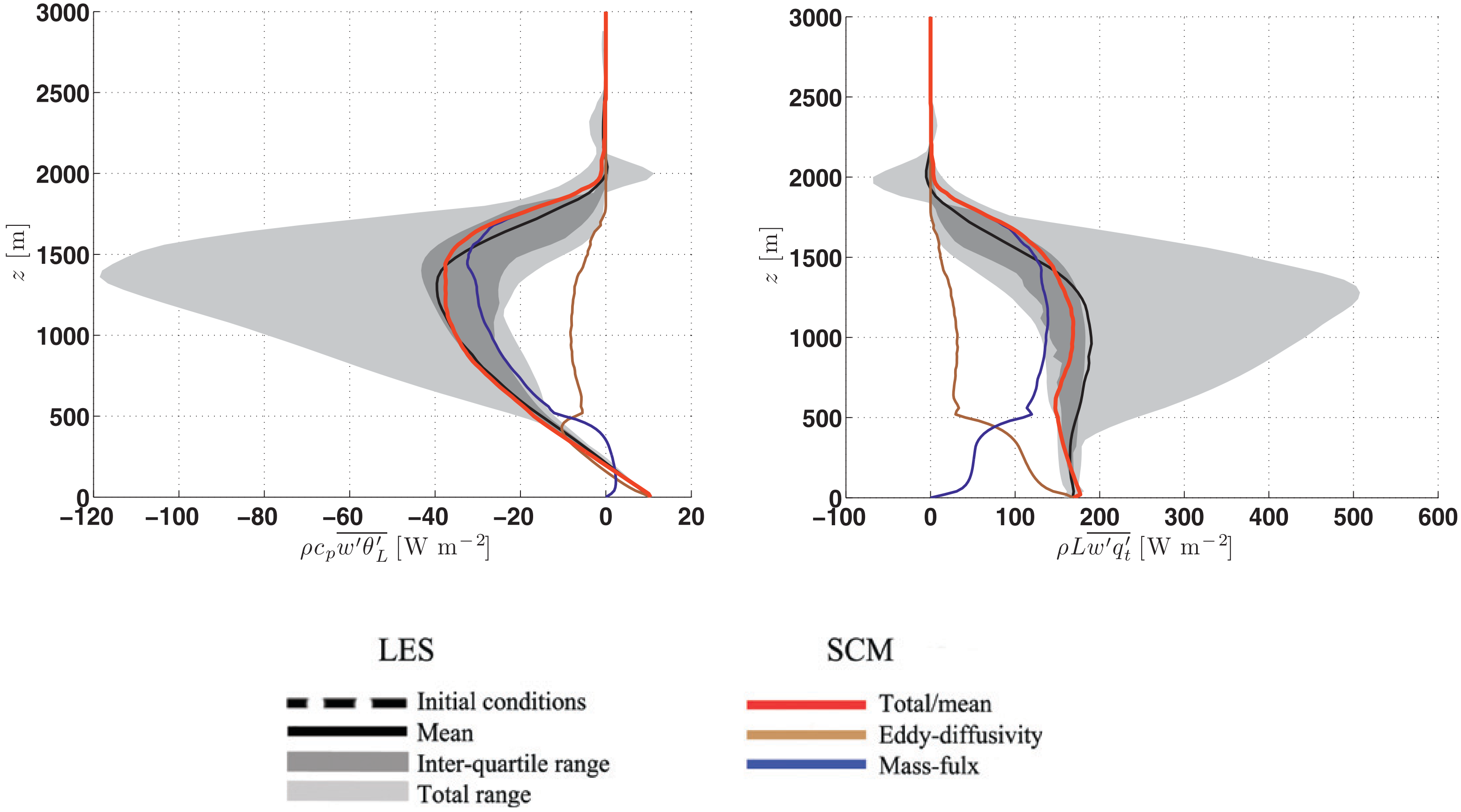
EDMF plumes

LES joint PDF

## EDMF multiple plumes represent skewed part of PDF

# EDMF and BOMEX: ED versus MF

## Vertical sub-grid fluxes

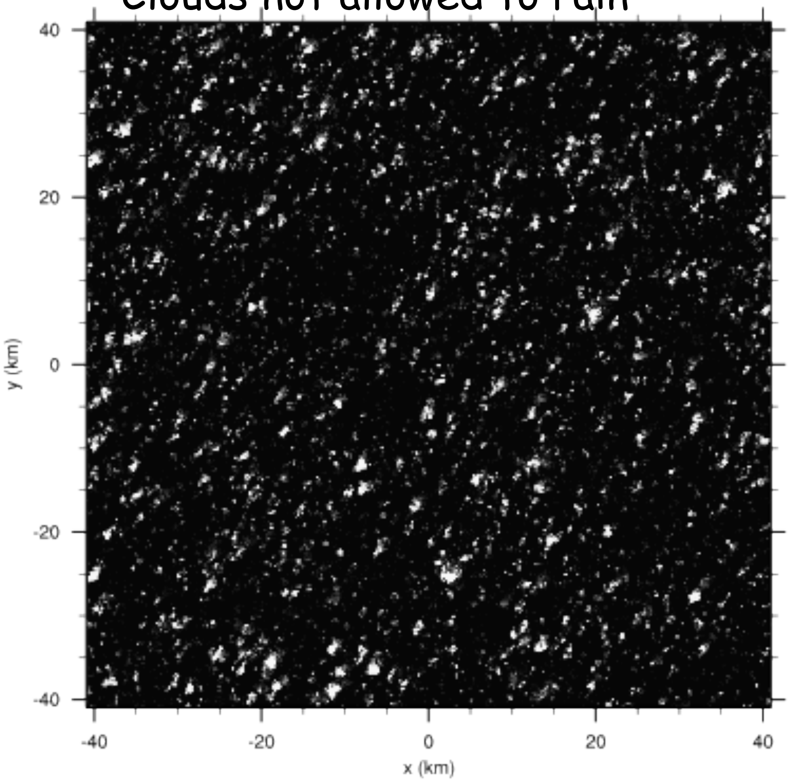


Sub-grid fluxes are well represented – Some ED in cloud layer

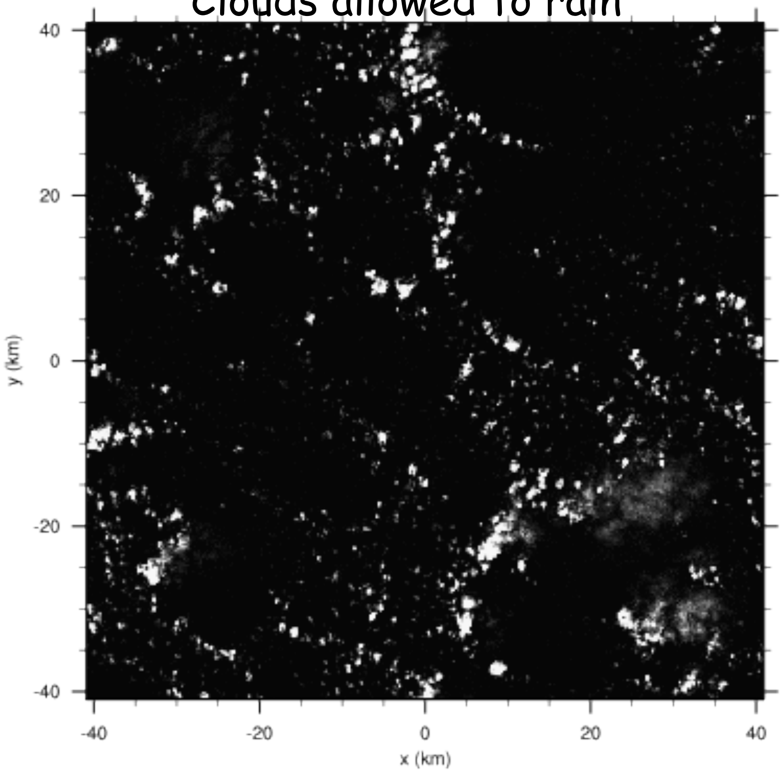
# Large-Eddy Simulation (LES) models: the impact of microphysics on dynamics

- Non-precipitating moist convection easier to parameterize
- Precipitating convection exhibits extremely complex 3D dynamics
- Challenge: a realistic model of statistics of precipitating convection

Clouds not allowed to rain



Clouds allowed to rain



Matheou et al., MWR, 2011

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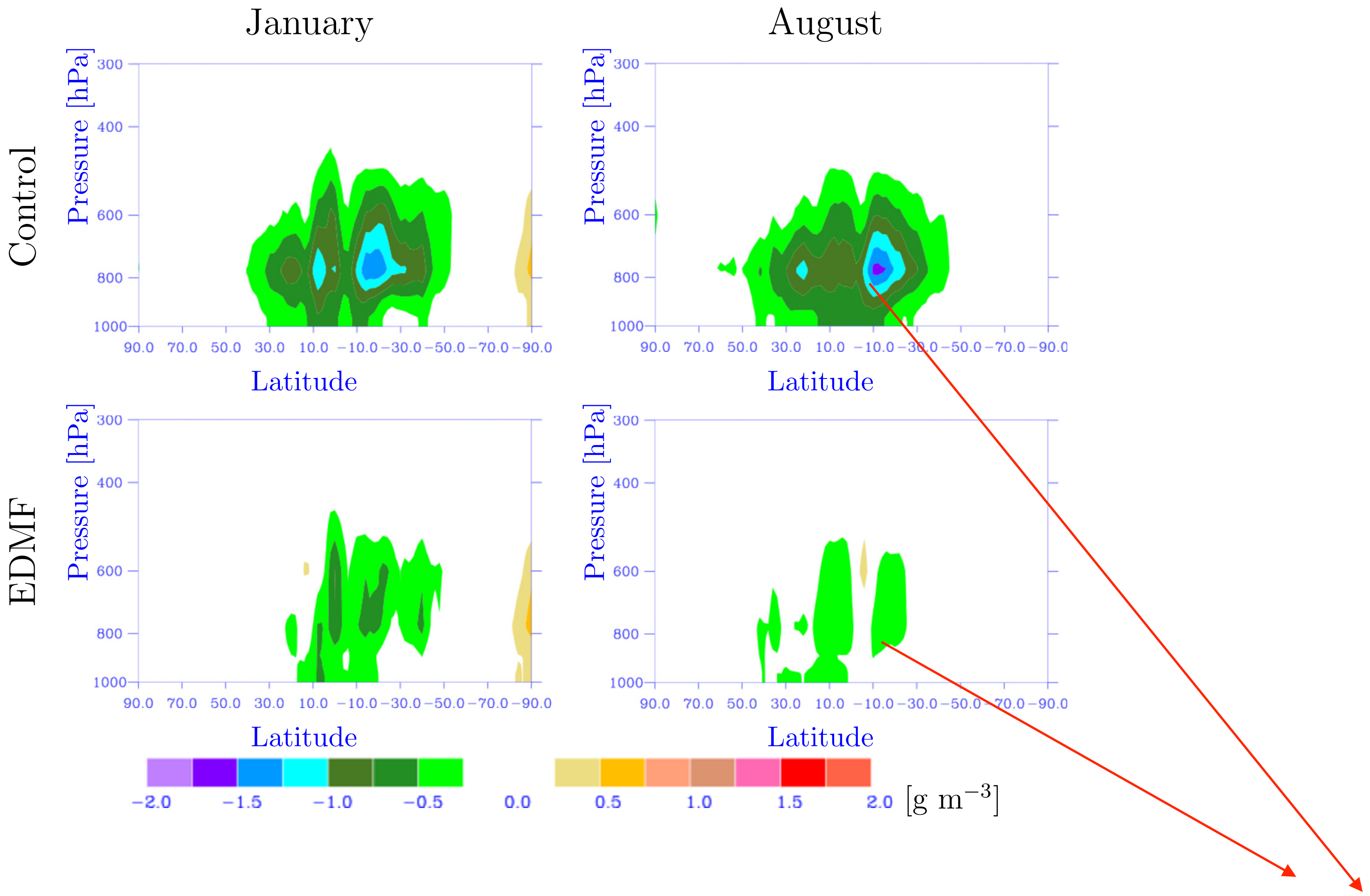
# EDMF in US Navy global model NAVGEM: Water Vapor



Significant reduction of dry bias with EDMF

# Summary

- EDMF combines ED and MF to represent in a unified way turbulence and convection in atmospheric models

- EDMF solves key problems: counter-gradient flux, top entrainment, skewness of vertical transport in cumulus

- New stochastic EDMF version parameterizes cloud base PDF to generate multiple plumes to represent shallow convection

- EDMF implemented into global models: ECMWF, NAVGEM
- Unified parameterization of turbulence and convection in atmospheric models: We are getting close