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Cloud Feedbacks and Climate Models

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Together with many people including S. Cardoso (IDL/NCAR), A. Gettelman (NCAR), B. Kahn, S. Klein (LLNL), P. Miranda (IDL), A.P. Siebesma (KNMI), P. Soares (IDL), Y. Zhang (LLNL) and the GPCI group

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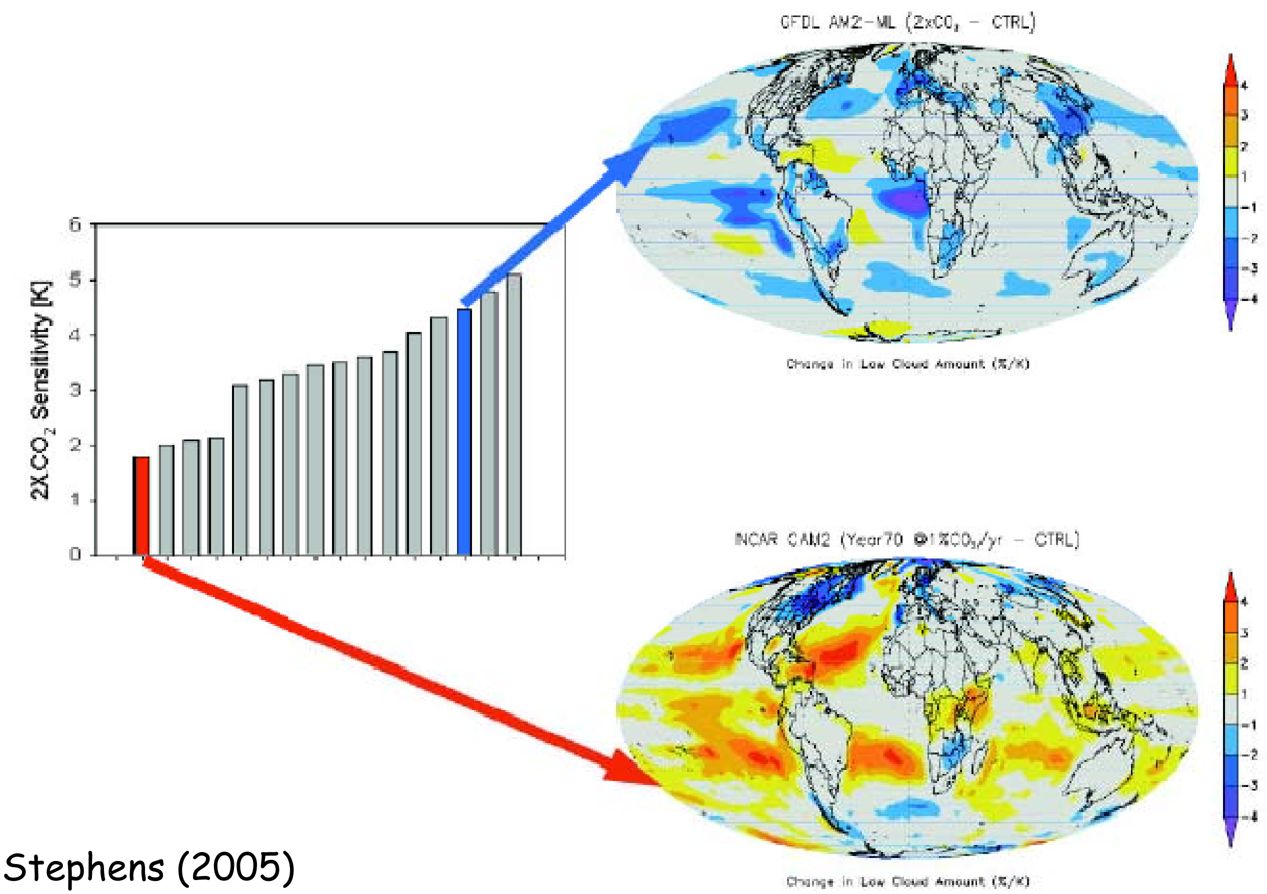
Climate is changing … YET there is large uncertainty in climate prediction

IPCC 2007: "Cloud feedbacks remain the largest source of uncertainty"



Stephens (2005)

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

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

How good are models? What is the problem? representation of small-scales

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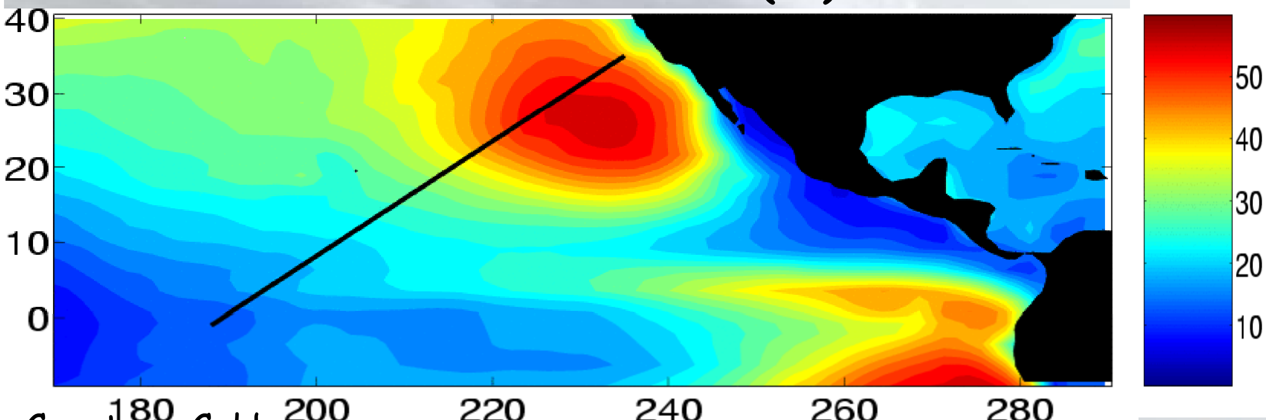
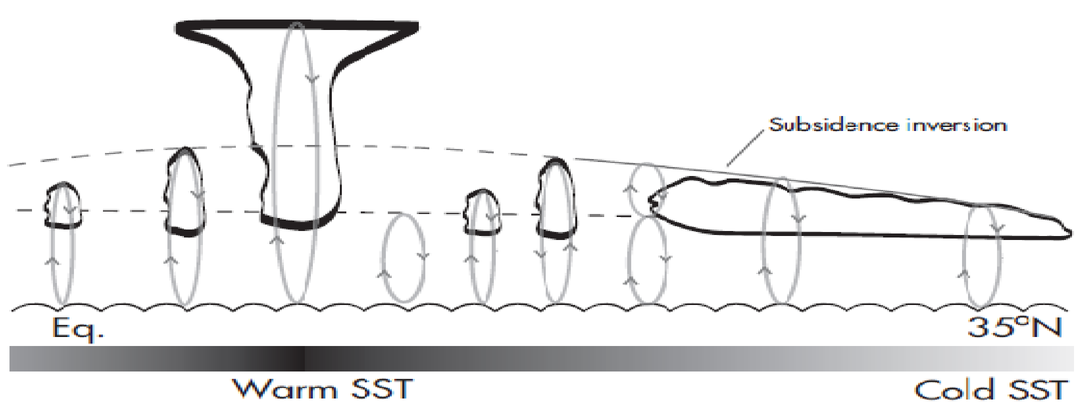
GCSS Pacific Cross-section Intercomparison (GPCI): status and progress

ISCCP Low Cloud Cover (%)



Courtesy C. Hannay

GPCI is a working group of the GEWEX Cloud Systems Study (GCSS)



Participation of 23 climate/weather prediction models

Models and observations are analyzed along a transect from stratocumulus, across shallow cumulus, to deep convection

Subtropics to tropics transition: satellite observations of mean relative humidity and cloud occurrence

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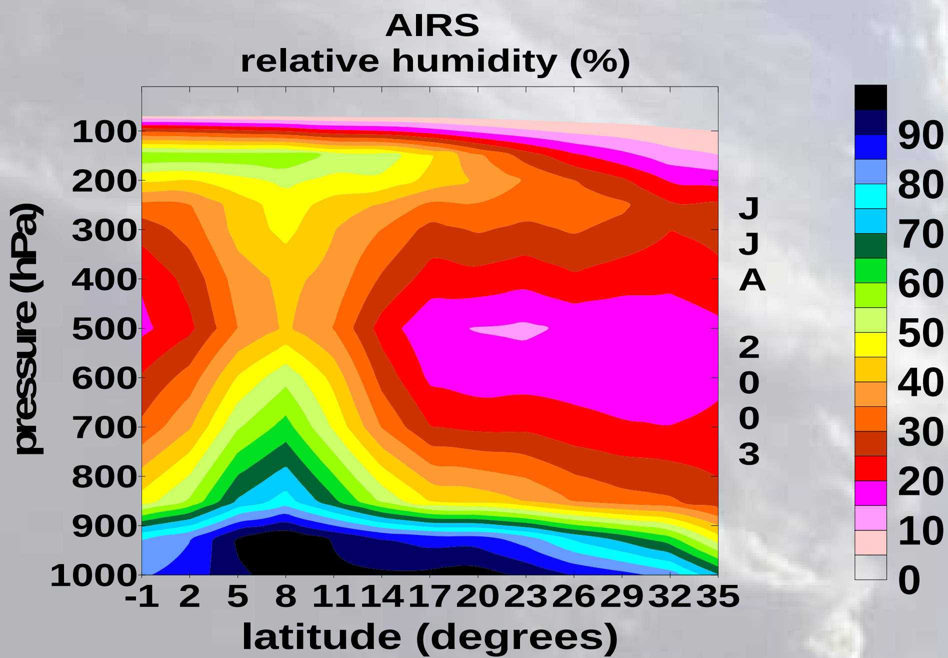
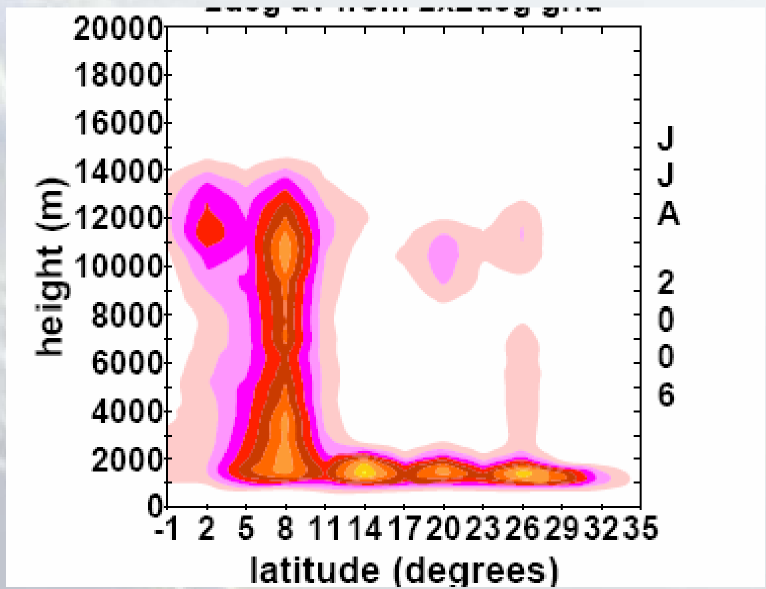
AIRS relative humidity JJA 2003



CloudSat cloud occurrence JJA 2006



Satellites show transition from subtropical PBL clouds to deep tropical convection … these observations did not exist when we started planning for the cross-section.

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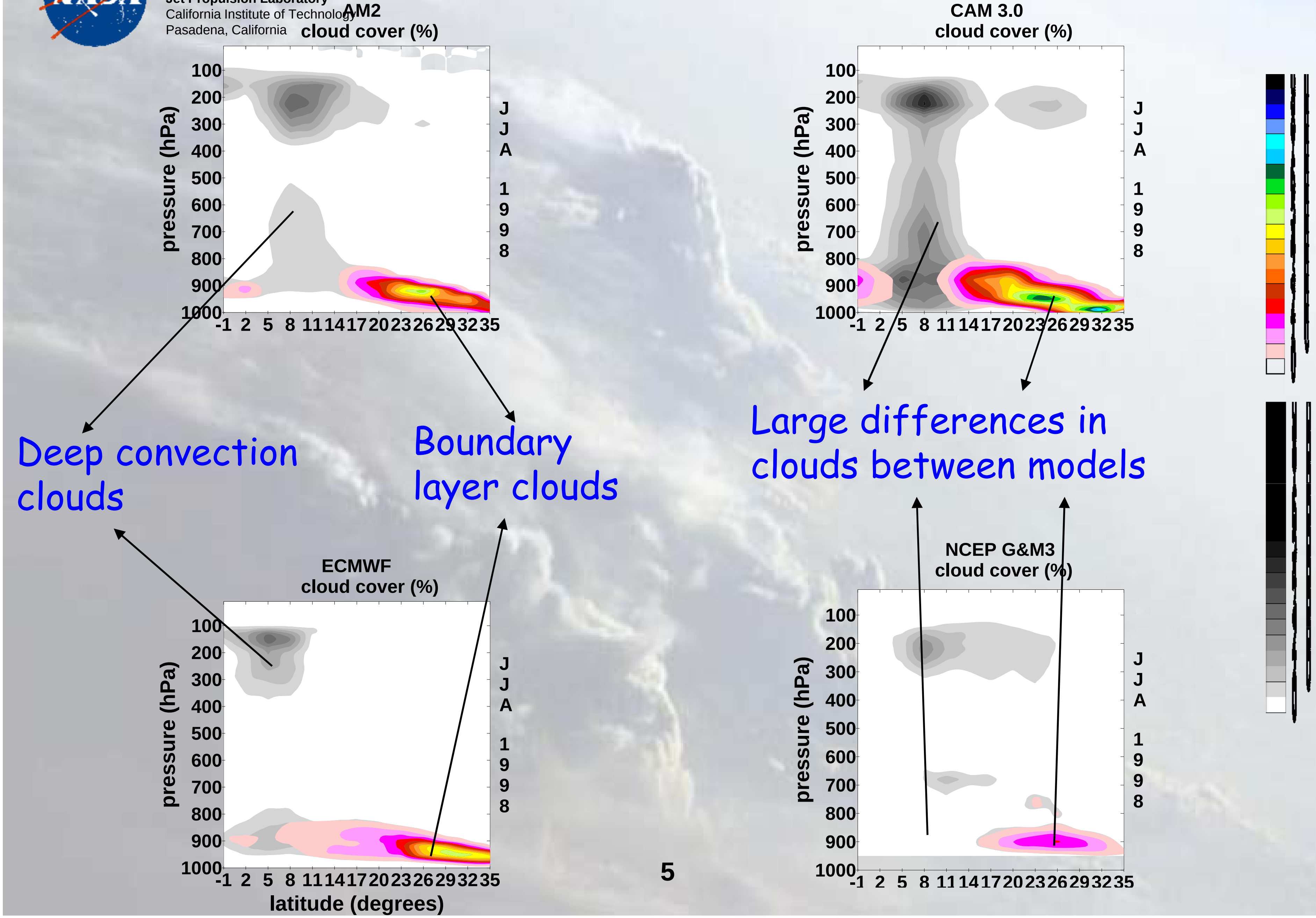
Cloud Cover along GPCI



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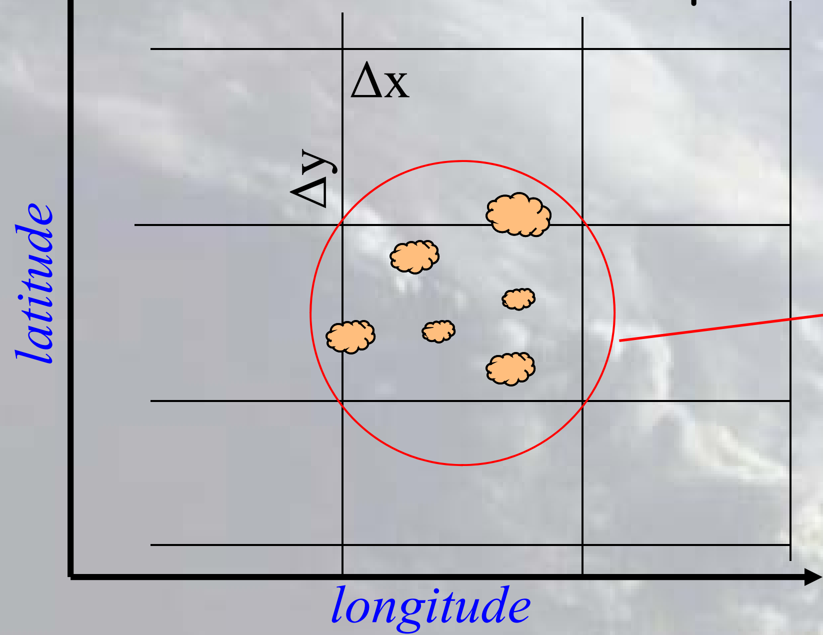
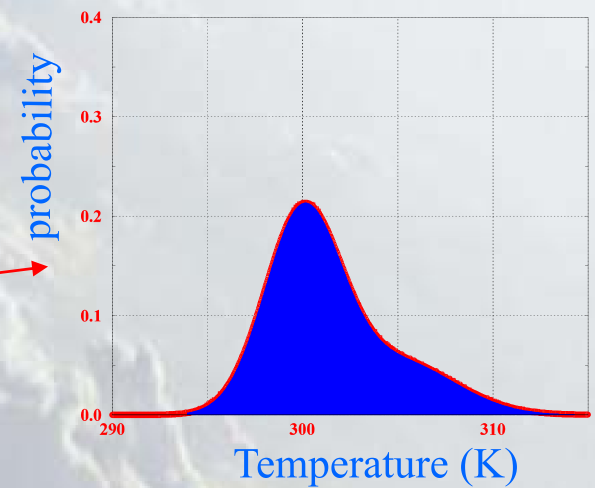
What is the physical parameterization problem in Climate models?

It is related to the classic turbulence closure problem with additional complexity: buoyancy, phase-transitions, radiation, precipitation, gravity waves, wide range of scales (from 10^{-3} to 10^{6} m)

Resolution of climate prediction models: Δx=Δy~100 km





PDF of temperature in model grid-box

Essence of parameterization problem is the estimation of joint PDFs of climate model variables (u, v, w, T, q) -> e.g. co-variance $\overline{w'\phi'}$

Parameterization problem in climate models

Atmospheric/oceanic model equation for a generic variable can be written as:

$$\frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial x}(u\varphi) - \frac{\partial}{\partial y}(v\varphi) - \frac{\partial}{\partial z}(w\varphi) + S,$$

Using Reynolds decomposition and averaging $\varphi = \overline{\varphi} + \varphi'$ to get an equation for the mean:

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

vertical sub-grid flux needs to be <u>parameterized</u>

It is assumed that S is linear and the horizontal divergence terms of the sub-grid fluxes can be neglected

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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

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

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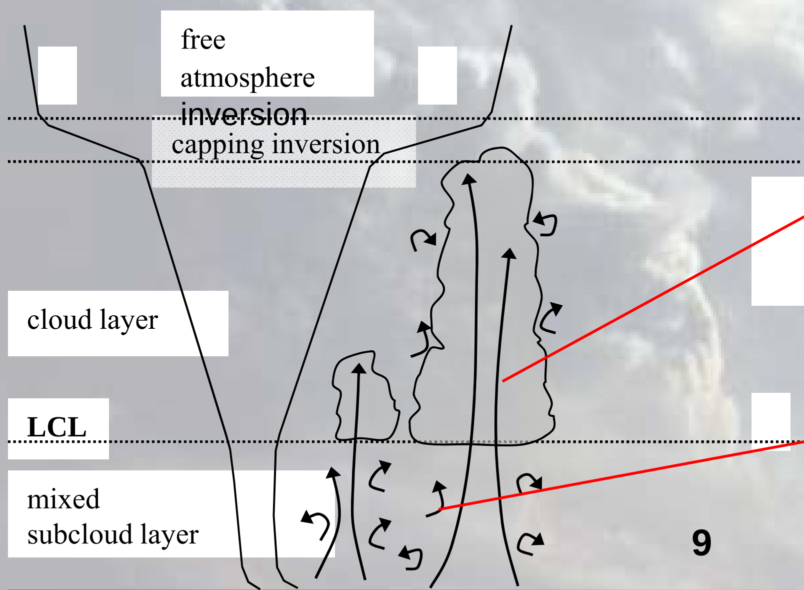
Mass-Flux (MF) approach

MF closure is based on parcel ideas (e.g. Stommel 1947) and attempts to represent strong upward/downward convection:

$$\overline{w'\varphi'} = a\, w_{u/d}(\varphi_{u/d} - \bar{\varphi})$$

a - updraft/downdraft area
$w_{u/d}$ - upward/downward vertical velocity in a
$\varphi_{u/d}$ - variable value in a.

MF is typically used for parameterization of moist convection



Mass-flux (MF) represents large-scale eddies

Eddy-Diffusivity (ED) represents small-scale eddies

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Moist conserved variables

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

Traditional dry 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 practical advantages of using conserved variables:

1) The cloud/condensation term disappears from the equations

2) The ED and MF approaches are able to represent the correct cloud fluxes

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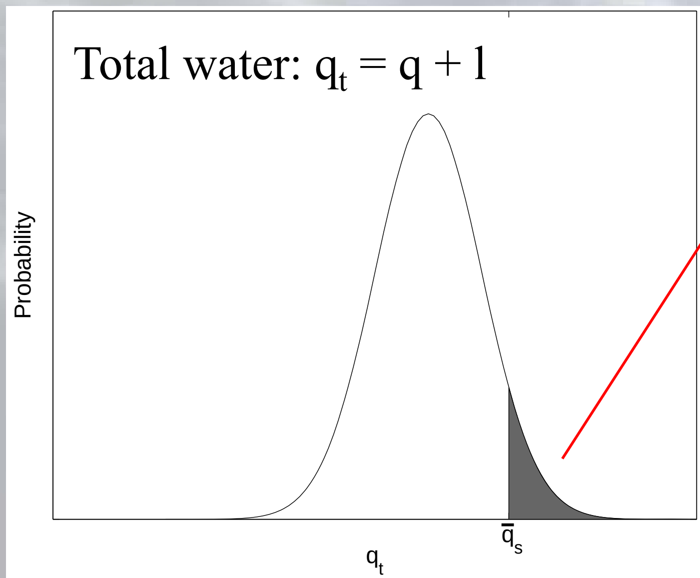
PDF-based Cloud Parameterizations

PDF-based 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

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

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

With Gaussian distribution we obtain cloud fraction and liquid water as a function of Q:

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

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

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

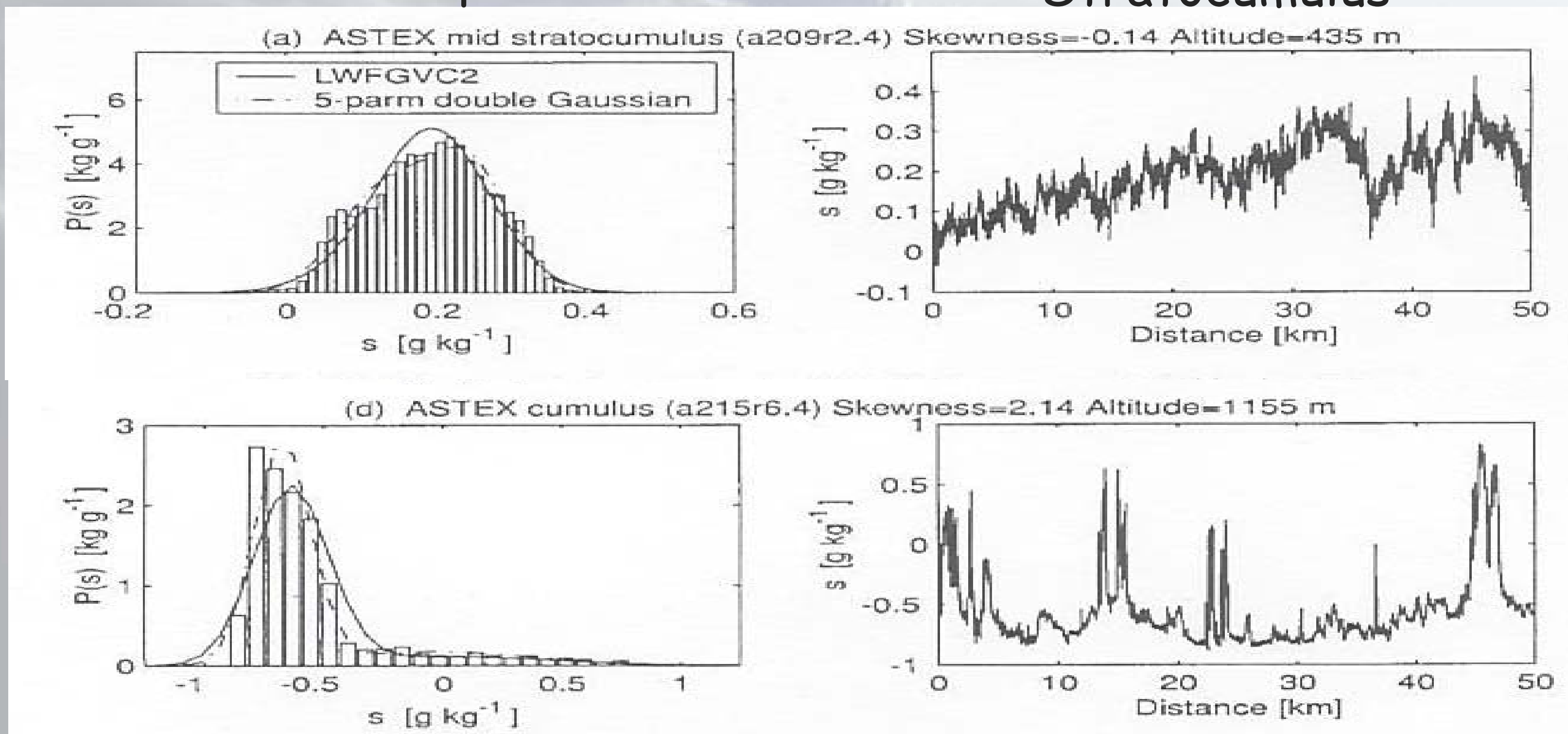
Characterizing the variance of thermodynamic properties is essential for cloud parameterization development

PDF-based approaches and observations

Aircraft observations of variable Q

Gaussian pdf

Stratocumulus



Skewed pdf

Cumulus

How realistic is a Gaussian approximation?

Larson et al 2002

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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

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

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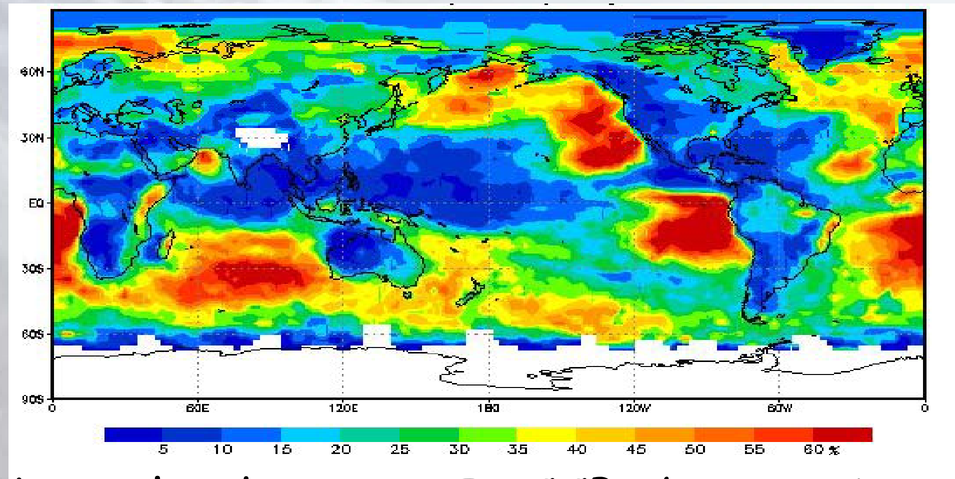
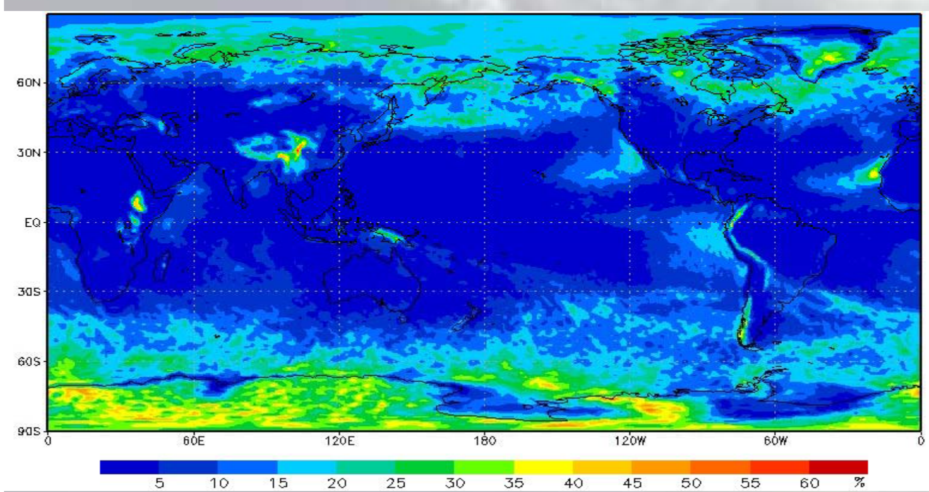
PDF-based stratocumulus cloud parameterization in a coupled model

Models and observations for Aug. 2004

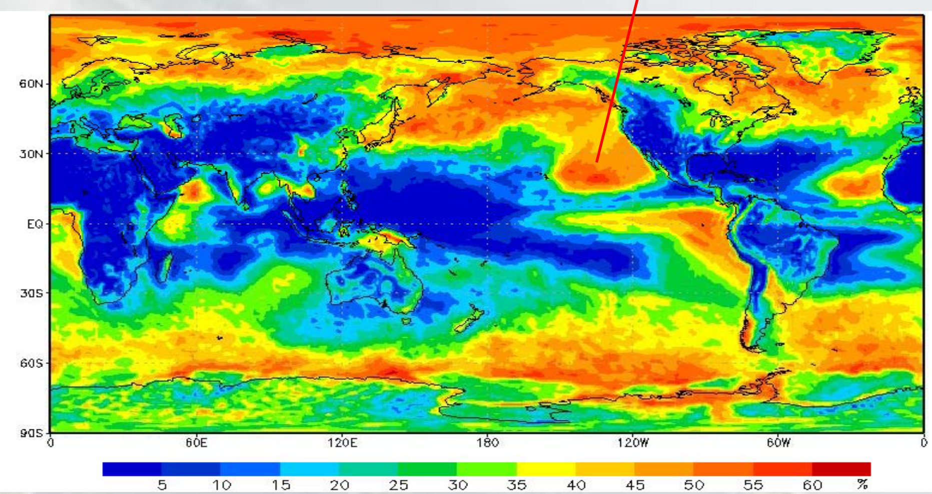


Low cloud cover - ISCCP observations

New model much closer to observations



Low cloud cover – old model



Low cloud cover – new model

Teixeira et al. 2008

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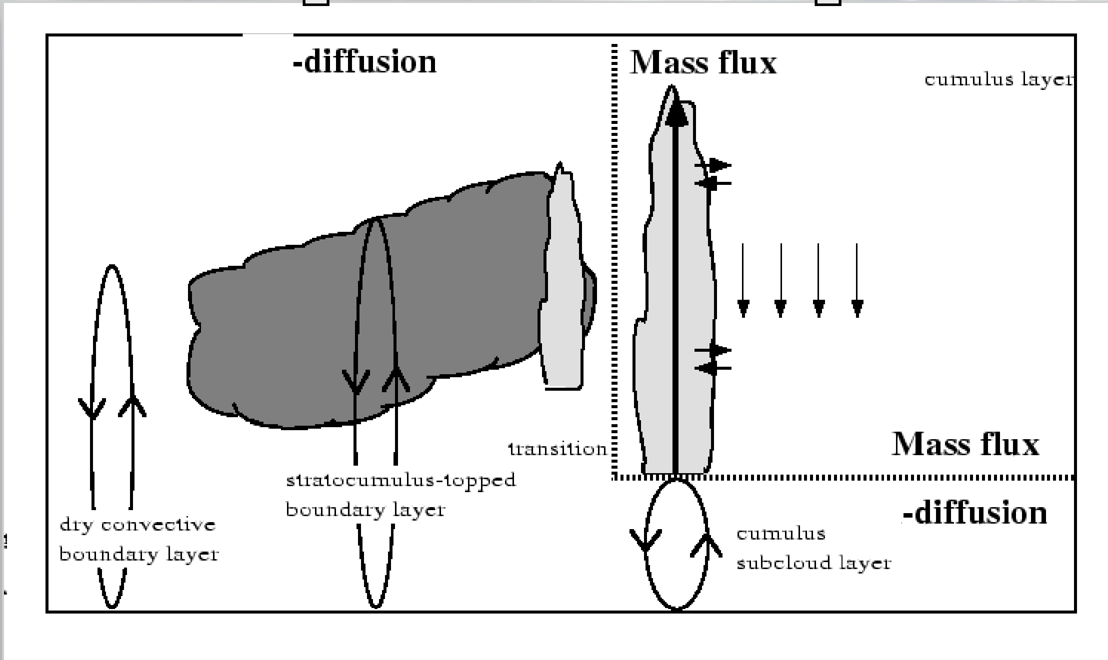
Trying to unify boundary layer convective transport in clear, sub-cloud and cloud layer

Standard climate model approach:

$$\overline{w'\phi'} \cong -K\frac{\partial\overline{\phi}}{\partial z}$$

$$\overline{w'\phi'} \cong M(\phi_u - \overline{\phi})$$

$$\frac{\partial\overline{\phi}}{\partial t} \cong -\frac{\partial}{\partial z}\left(\overline{w'\phi'}\right) + \overline{S}$$



This modularity leads to problems:

- Possibility of "double counting" of processes
- Interface problems
- Problems with transitions between different regimes

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Eddy-Diffusivity/Mass-Flux parameterization

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<<1 and w_e~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: $$\overline{w'\varphi'} = -k\frac{\partial\bar{\varphi}}{\partial z} + M(\varphi_u - \bar{\varphi})$$

Siebesma and Teixeira 2000

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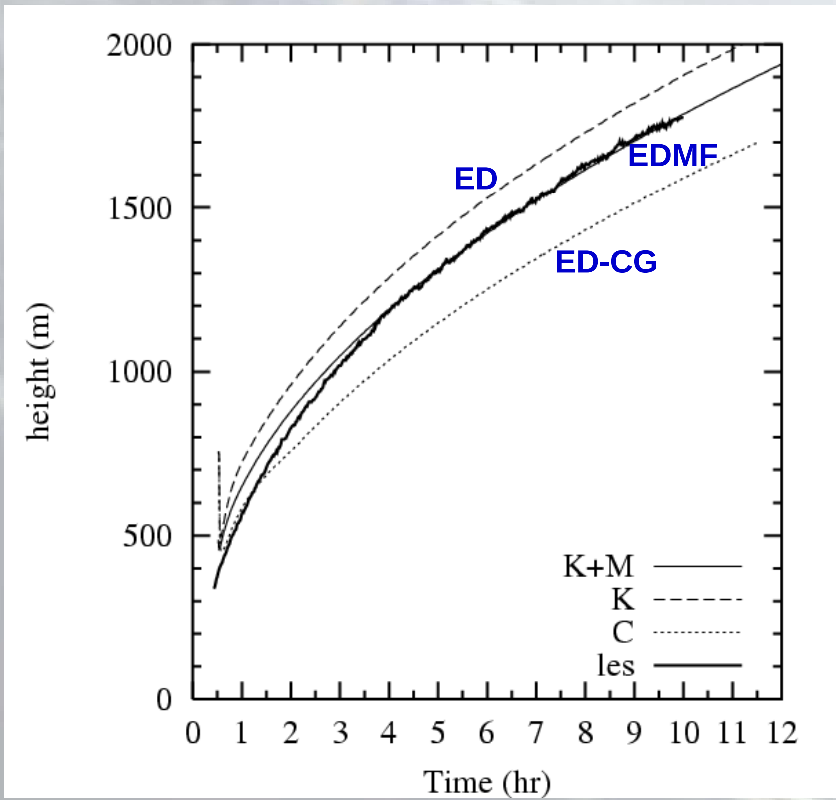
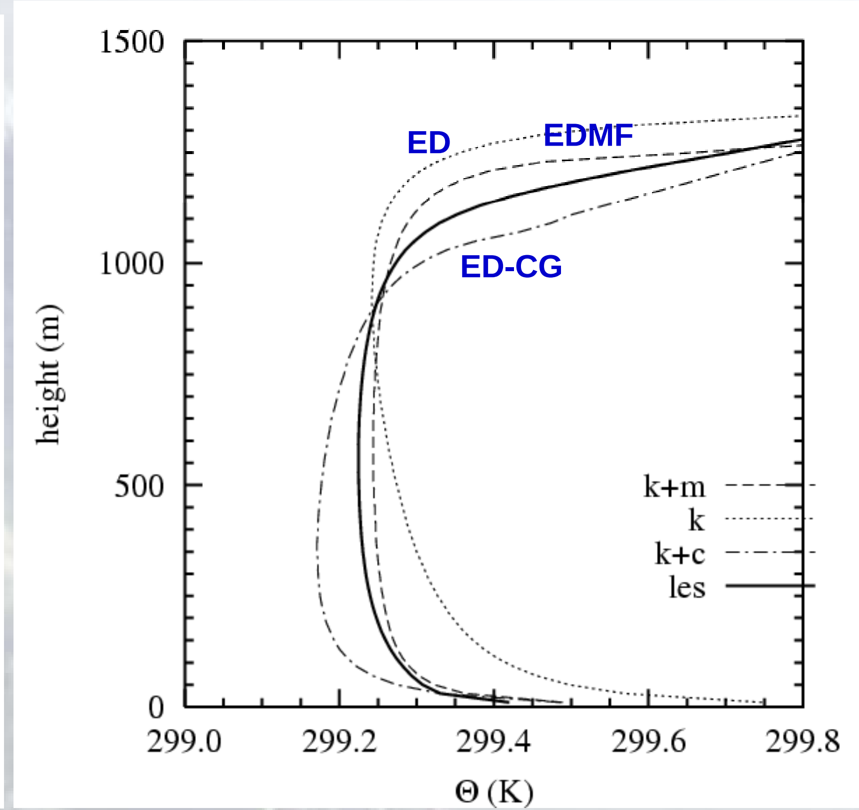
A dry convective boundary layer case study



PBL height growth



Mean profiles after 10 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 et al, JAS, 2007

ARM shallow convection over land case

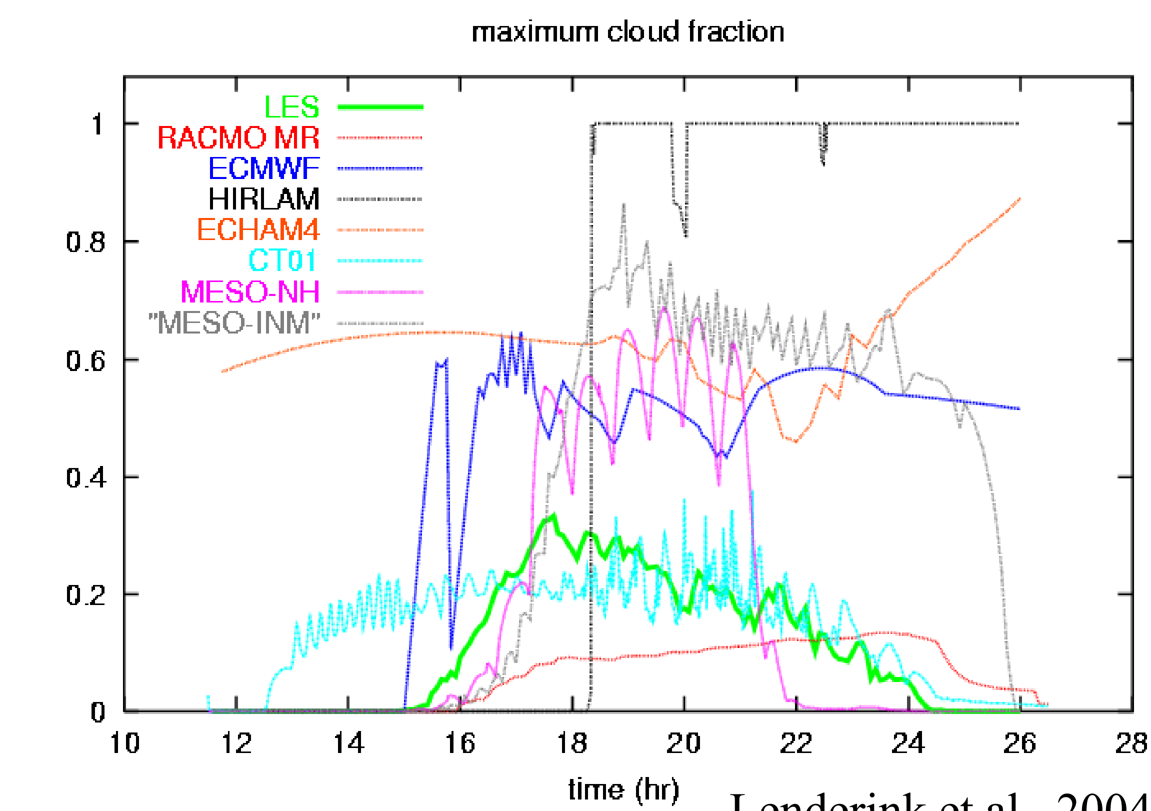
1) Oklahoma ARM site

2) 21 June 1997

3) Several single-column models (SCM) versus LES

Start: 10 am (local time)
End: 3 am (next day)

4) Shallow convection develops at around 3 pm (in LES and in observations)



Lenderink et al., 2004

No model is able to capture the diurnal cycle of convection

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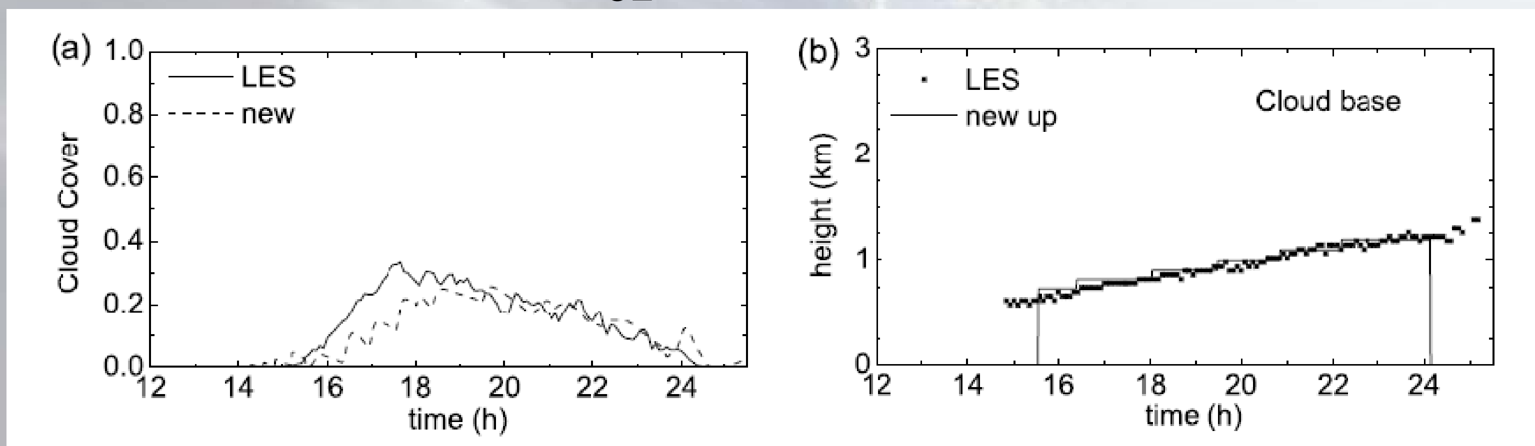
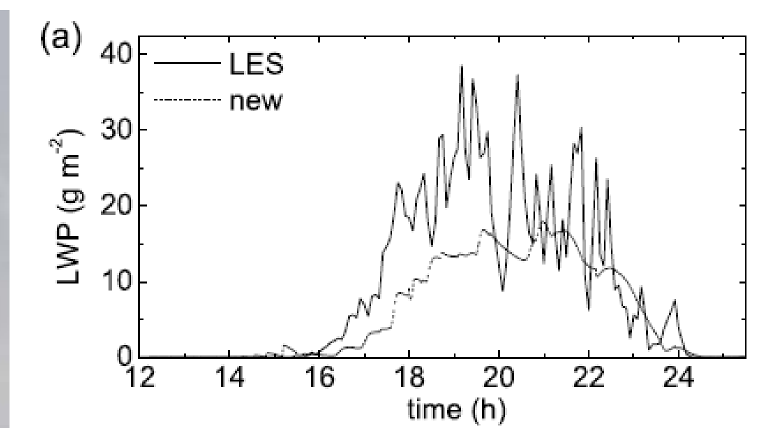
EDMF approach and the ARM case

1) ED coefficient is based on prognostic turbulent kinetic energy (TKE);

2) MF is based on updraft vertical velocity equation;

3) Updraft values estimated as $\frac{\partial \phi_u}{\partial z} = -\varepsilon\left(\phi_u - \bar{\phi}\right)$ (ε is the lateral entrainment)





Soares et al, QJRMS; 2004

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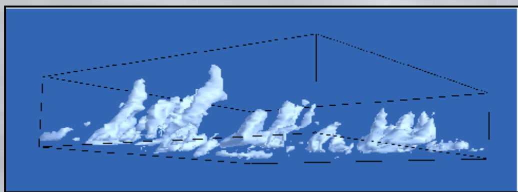
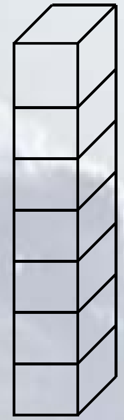
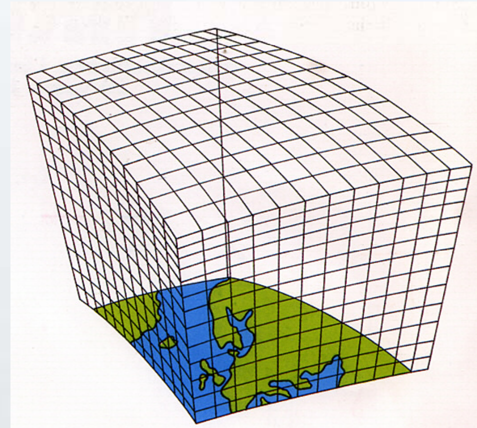
What is the strategy for parameterization development in climate models?







High-resolution data:

Large Eddy Simulation (LES) Models

Cloud Resolving Models (CRMs)

Testing in Single Column Models:

Versions of Climate Models

3D Climate/Weather Models:

Evaluation and diagnostics for a variety situations

Field experiment observations to build case-studies and for model evaluation

Global satellite observations for 3D model evaluation

It has been a fairly (but not fully) successful strategy for the past 10 yrs

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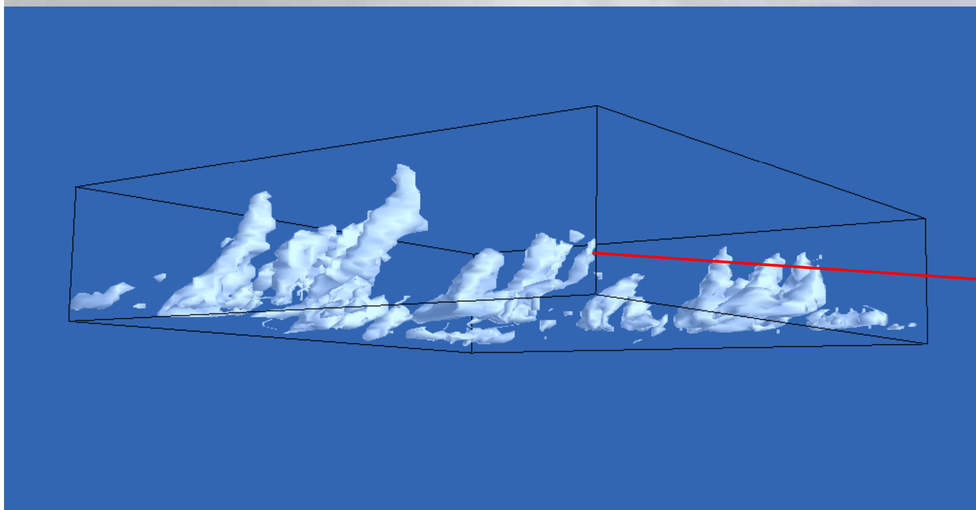
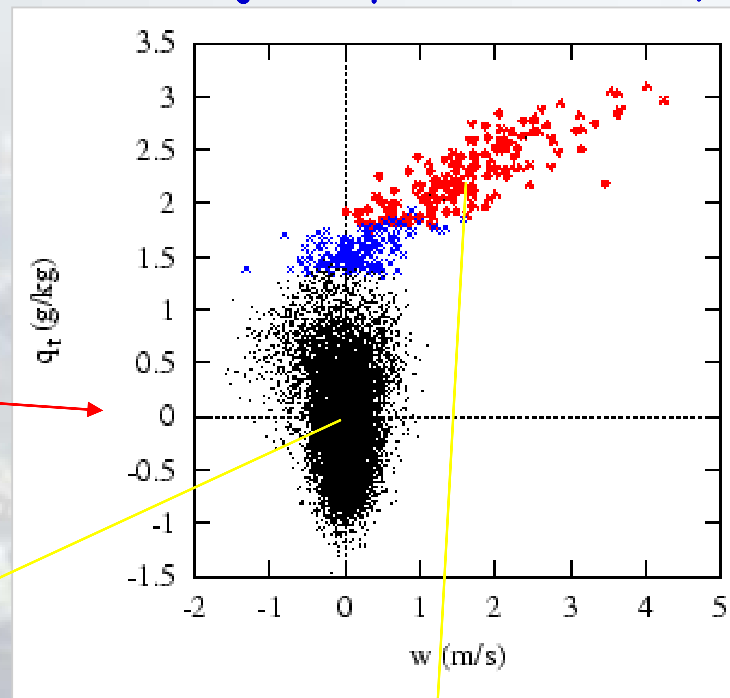
Large Eddy Simulation models and cumulus convection

Large Eddy Simulation (LES) model – BOMEX shallow cumulus case



Bimodal joint pdf of w and qt



Siebesma et al

Clear environment:
Eddy-Diffusivity (ED) mixing

Cloud core updrafts:
Mass-Flux (MF) transport

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Summary

- Cloud-climate feedbacks are a major issue in climate prediction
- Climate prediction models still have serious difficulties in representing small-scale processes such as turbulence, clouds and convection
- Recent satellite data is able to characterize vertical structure of cloud regime transitions (e.g. subtropics to tropics transition) – but not in boundary layer
- Large Eddy Simulation (LES) models are essential tools for boundary layer cloud and convection parameterization development
- New parameterization approaches that lead to more realistic results:

1) PDF-based cloud parameterizations are based on a solid theoretical framework and have solid connection to observations
2) Eddy-Diffusivity/Mass-Flux (EDMF) approach successfully combines boundary layer and convection parameterizations

<u>What satellite observations are needed to help improve the representation of boundary layer clouds in climate models?</u>

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Pdf-based parameterization and observations

Aircraft observations of variable Q

Stratocumulus

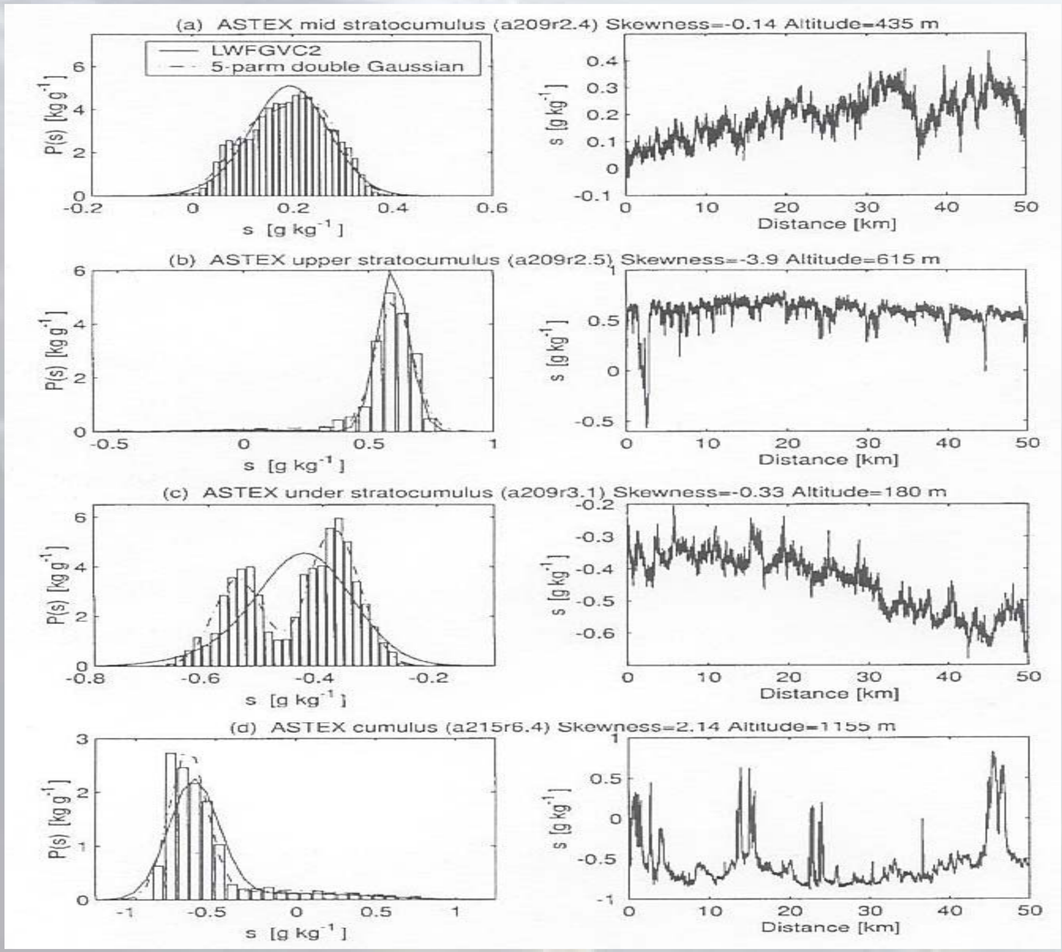
Gaussian pdf

Cumulus and Stratocumulus

Double Gaussian

Cumulus

Skewed pdf



In many situations clouds "are" Gaussian

Larson et al 2002

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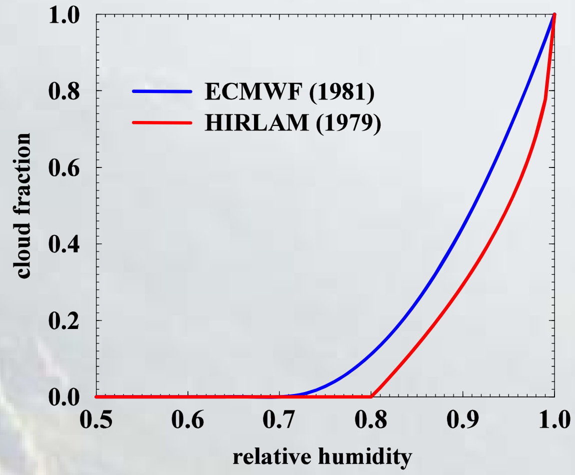
Cloud parameterization : A brief history until 1980s

1960s: Cloud properties - artificially prescribed

1970s: Cloud fraction - empirical function of relative humidity (RH)
Cloud water - prescribed

1980s (Slingo, 1987):
Cloud fraction - function of RH, inversion strength (Sc) and convective rain (Cumulus)
Cloud water – prescribed or function of qs

1980s (Sundqvist, 1989):
Cloud water - prognostic (but empirical)
Cloud fraction - empirical function of RH



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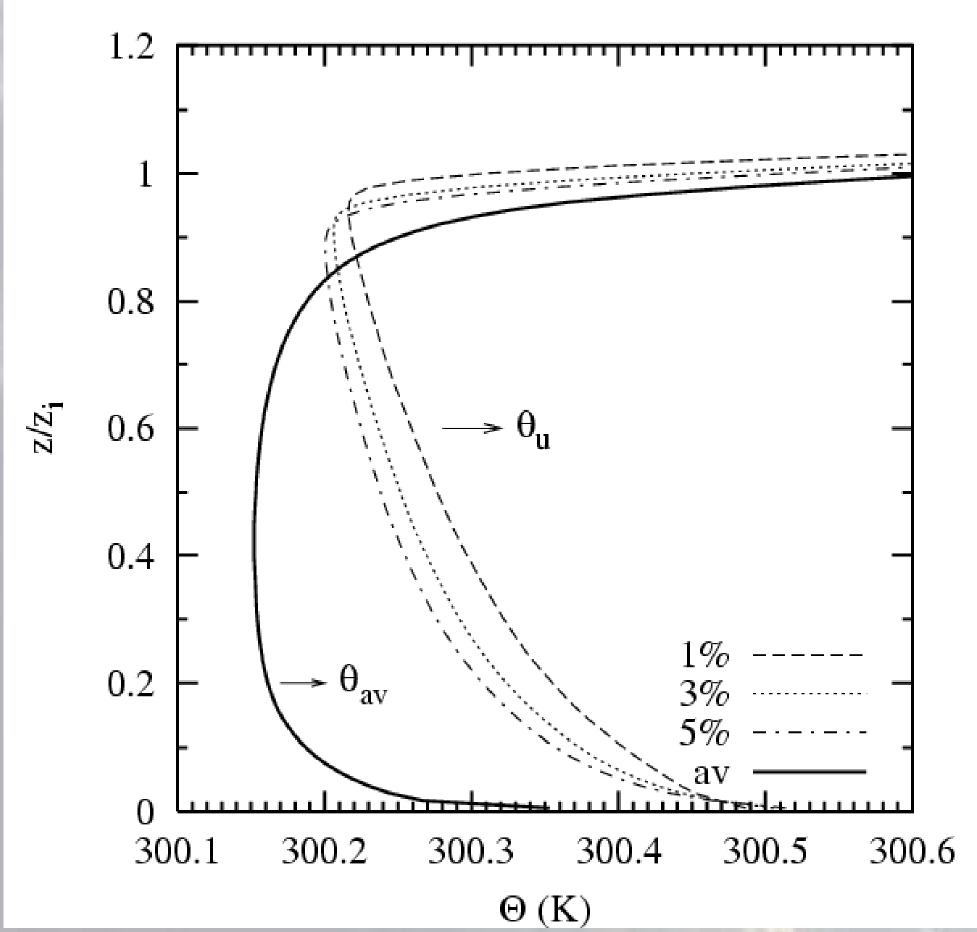
Using LES to derive updraft model in dry convective boundary layer.



Updraft at height z composed

of those grid points

that contain the highest p%

of the vertical velocities:

p=1%,3%,5%:

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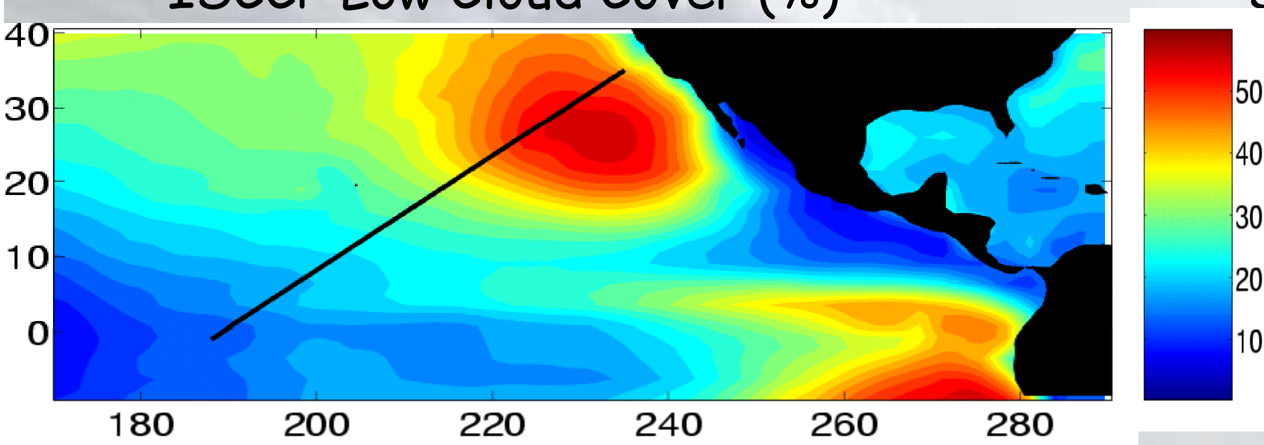
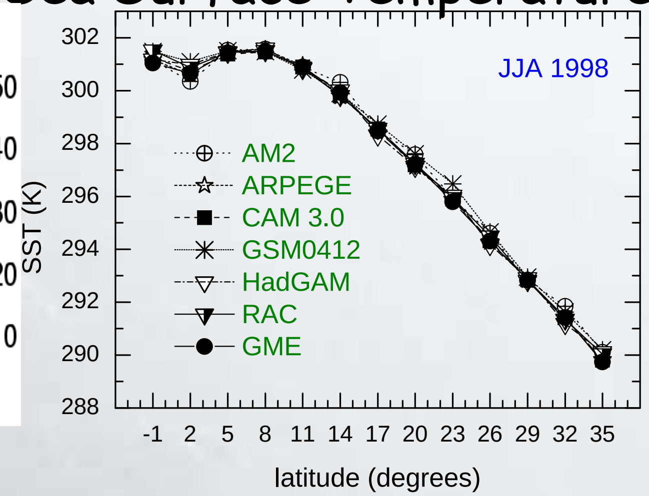
GCSS Pacific Cross-section Intercomparison (GPCI): Tropical and subtropical cloud regime transitions

ISCCP Low Cloud Cover (%)



Sea Surface Temperature



Courtesy C. Hannay

GCSS/WGNE Pacific Cross-section Intercomparison (GPCI) is a working group of the GEWEX Cloud System Study (GCSS)

Models and observations are analyzed along a transect from stratocumulus, across shallow cumulus, to deep convection

Models: GFDL, NCAR, UKMO, JMA, MF, KNMI, DWD, NCEP, MPI, ECMWF, BMRC, NASA/GISS, UCSD, UQM, LMD, CMC, CSU, GKSS

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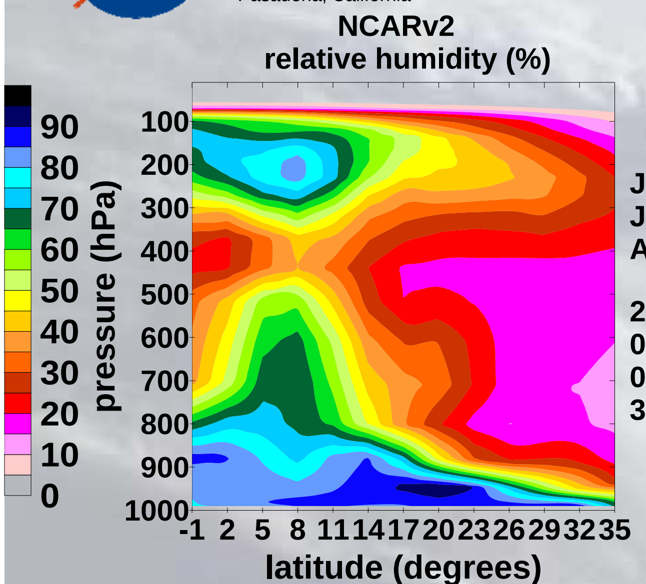
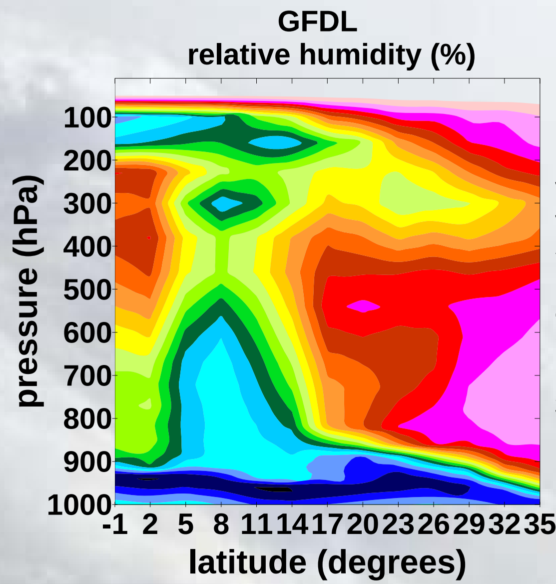
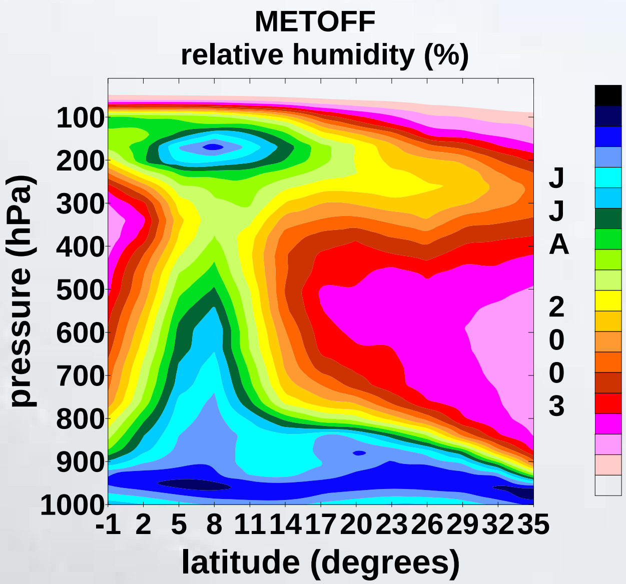
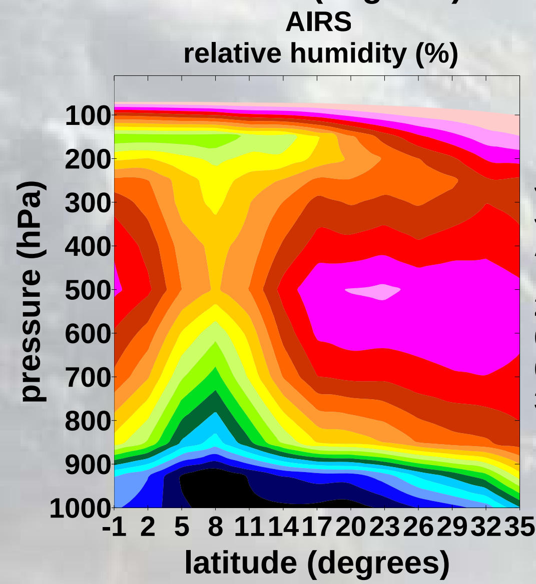
GPCI mean relative humidity – JJA 2003







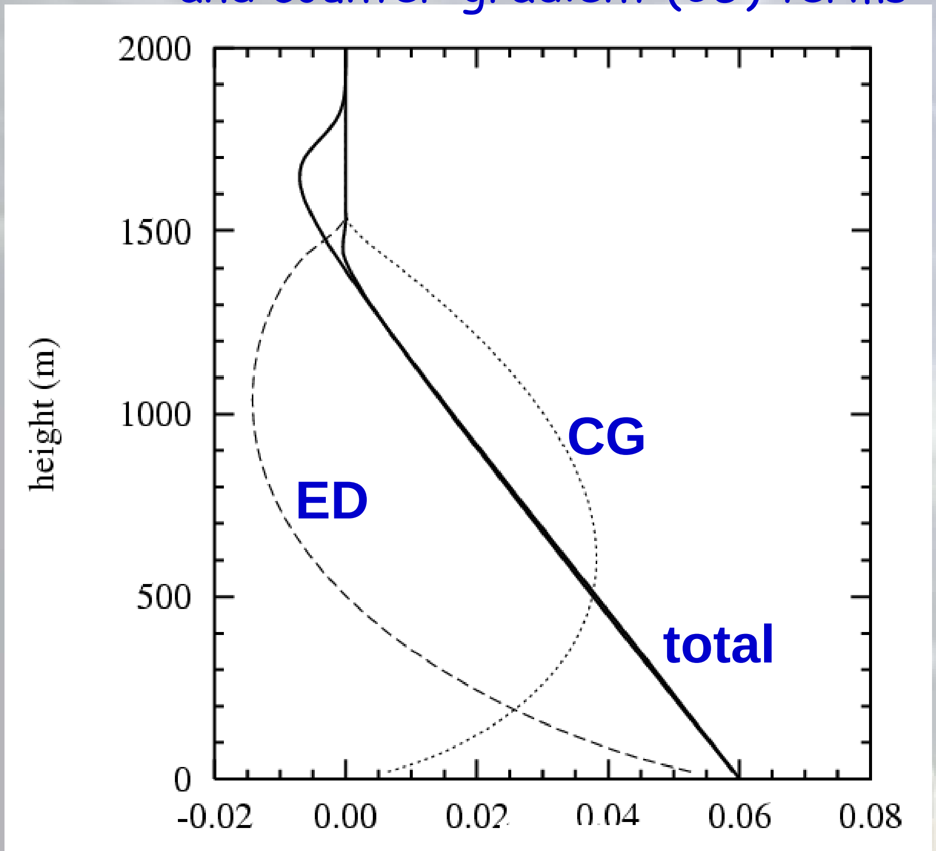
General RH pattern from models and AIRS observations is similar …



… But there are substantial and problematic differences between models and AIRS

What is the problem with the eddy-diffusivity + counter-gradient approach?

Decomposing the eddy-diffusivity (ED) and counter-gradient (CG) terms



$\overline{w'\theta'}$

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

Very small entrainment flux because counter-gradient (CG) term cancels ED-term

Siebesma et al, JAS, 2007

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Pasadena, California

GPCI – 23 participating models

Model Results		
Organization	***Model***	***Type***
BMRC (Aus)	BAM 4.0.21	Global
CCC (Can)	CCCma	Global
CMC (Can)	GEM	Regional
CSU/BUGS (US)	BUGS	Global
CSU/MMF (US)	MMF	Global/MMF
DWD (Ger)	GME	Global
ECMWF (UK)	ECMWF	Global
ETH / MPI (Ger)	ECHAM5	Global
GFDL (US)	AM2p12b	Global
GKSS (Ger)	CLM	Regional
JAMSTEC (Jap)	AFES2	Global
JMA (Jap)	GSM0412	Global
KNMI (Ned)	RAC	Regional
LMD (Fra)	LMDZ4	Global
MeteoFrance (Fra)	ARPEGE	Global
NASA/GISS (US)	GISS III 3.3	Global
NCAR (US)	CAM 3.0	Global
NCEP (US)	GFS&MOM3	Global Coupled
NCEP (US)	GFS	Global
UCLA (US)	UCLAtm7.3	Global
UCSD (US)	RSM	Regional
UKMO (UK)	HadGAM	Global
UQM (Can)	CRCM	Regional

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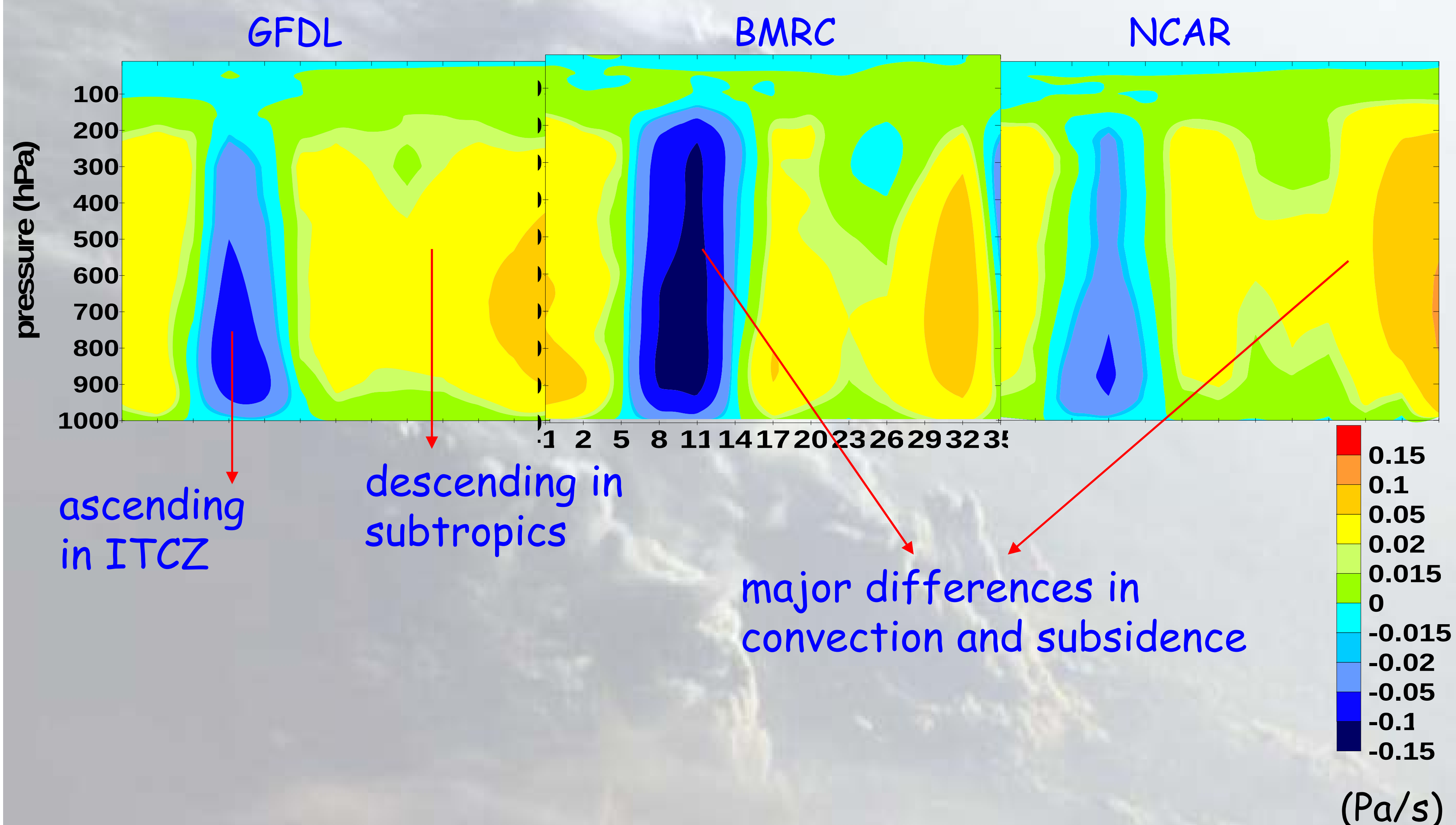
GPCI: JJA98 mean vertical velocity

All models exhibit Hadley-circulation-like features…



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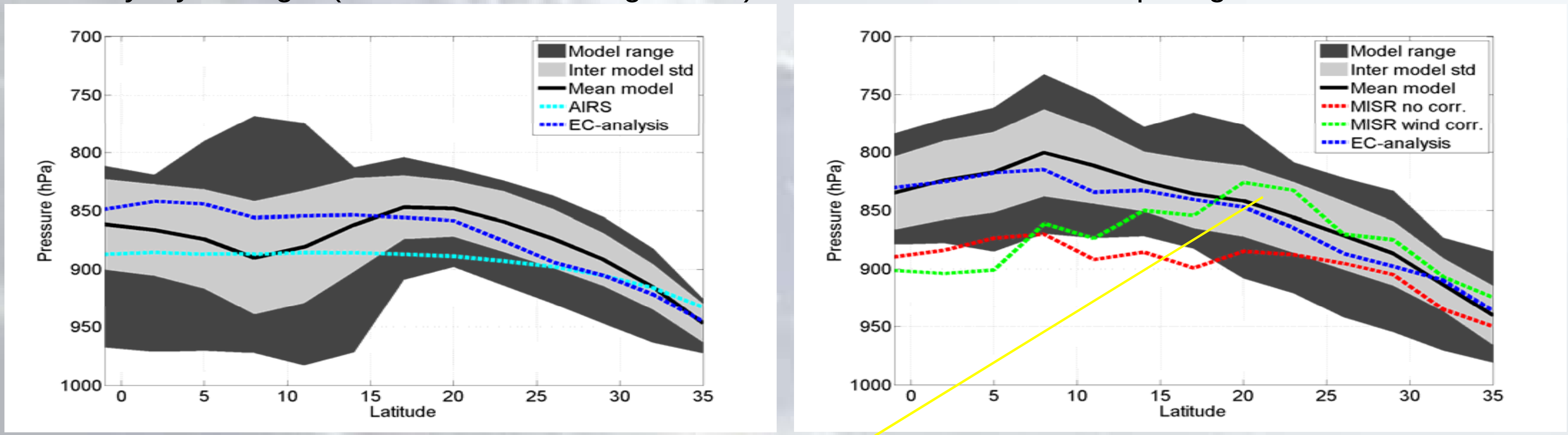
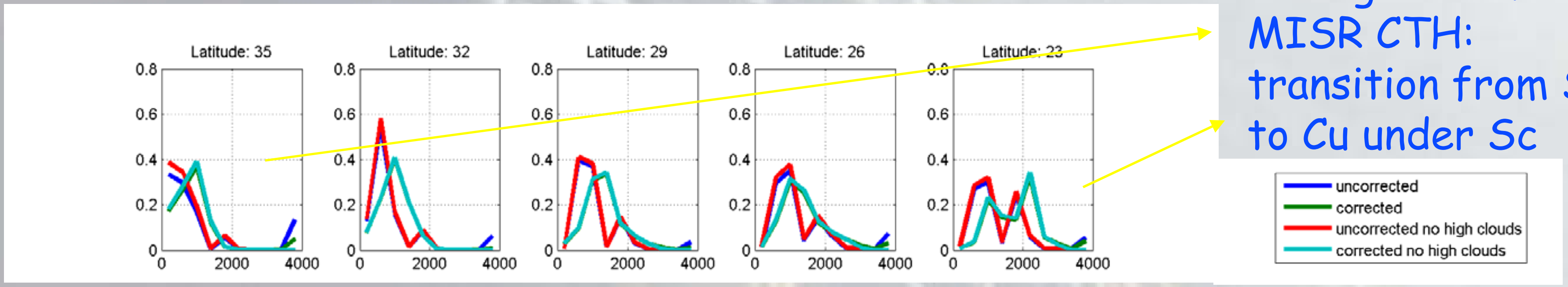
Characterizing the transition: evolution of boundary layer and cloud top height

Boundary layer height (altitude of max RH gradient)

Cloud top height



MISR tracks EC while there are stratocumulus



Histograms of MISR CTH: transition from Sc to Cu under Sc

Satellite observations can characterize well PBL and cloud top height

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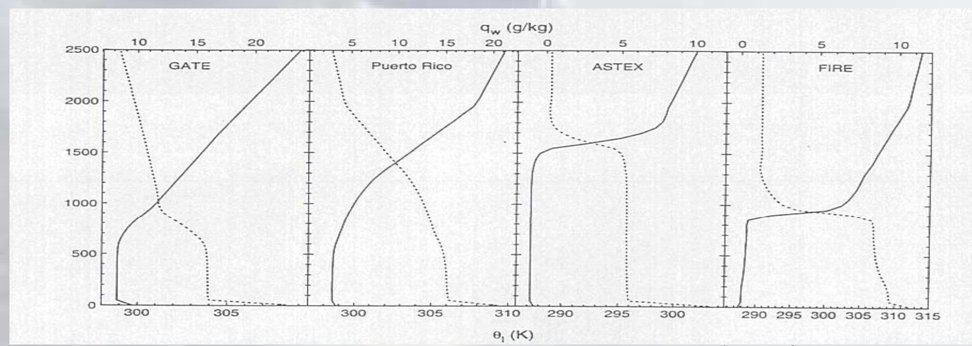
Large-Eddy Simulation (LES) studies for cloud parameterization development

LES models (high-resolution models Δx ~ 10-100 m that partially resolve turbulent/convective flow) are used to study the cloudy boundary layer

two cumulus cases:1) GATE, 2) Puerto Rico

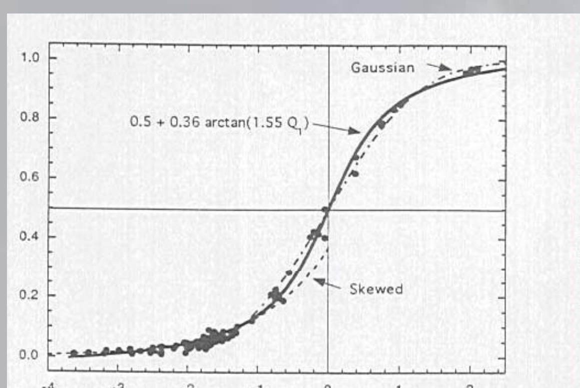


two stratocumulus cases:1) ASTEX, 2) FIRE

Cuijpers and Bechtold, 1995

LES is used to obtain cloud fraction and liquid water parameterizations as a function of $Q = \frac{q_t - q_s}{\sigma}$

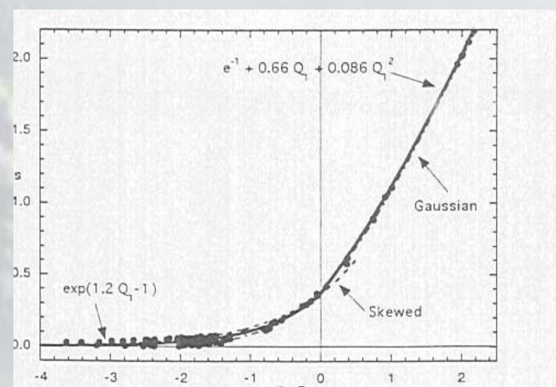
Cloud fraction



Q

$$a = 0.5 + \alpha \arctan\left(\gamma \frac{q_t - q_s}{\sigma}\right)$$

l/σ



Q

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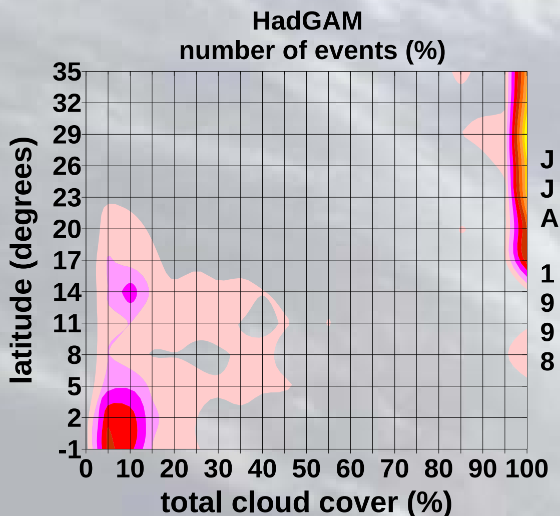
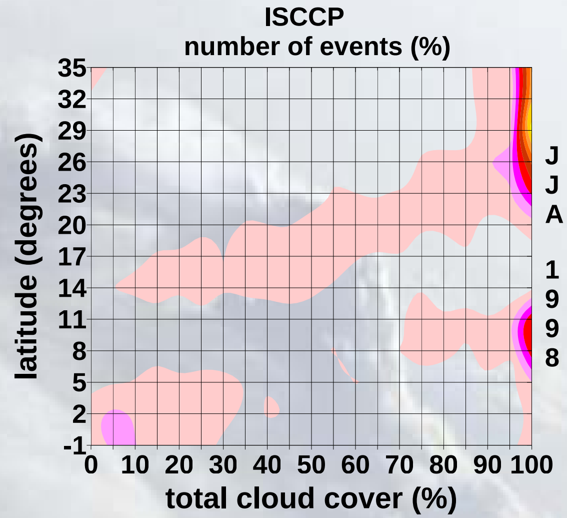
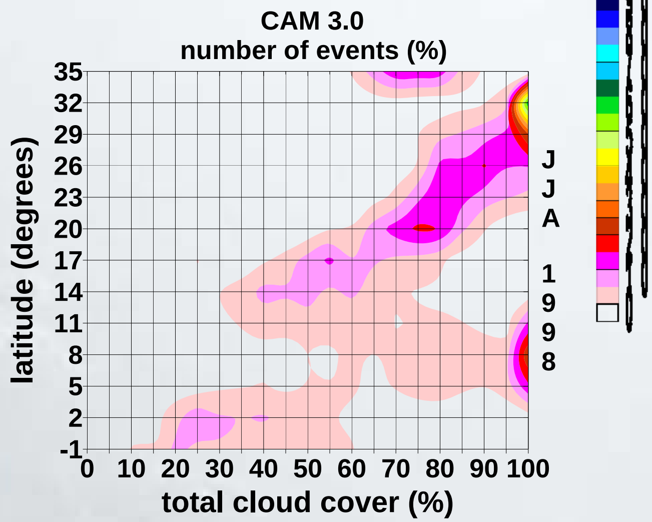
Characterizing the transition: histograms of cloud cover

UKMO





NCAR



ISCCP is between continuous and bimodal

- NCAR low cloud parameterization is partly based on "climatology" => continuous transition
- UKMO (and partly GFDL) cloudy-PBL parameterizations are based on the idea of distinct-regimes => discontinuous transition
- ISCCP suggests that none of these two "extreme" concepts is fully valid => relevant for parameterization development

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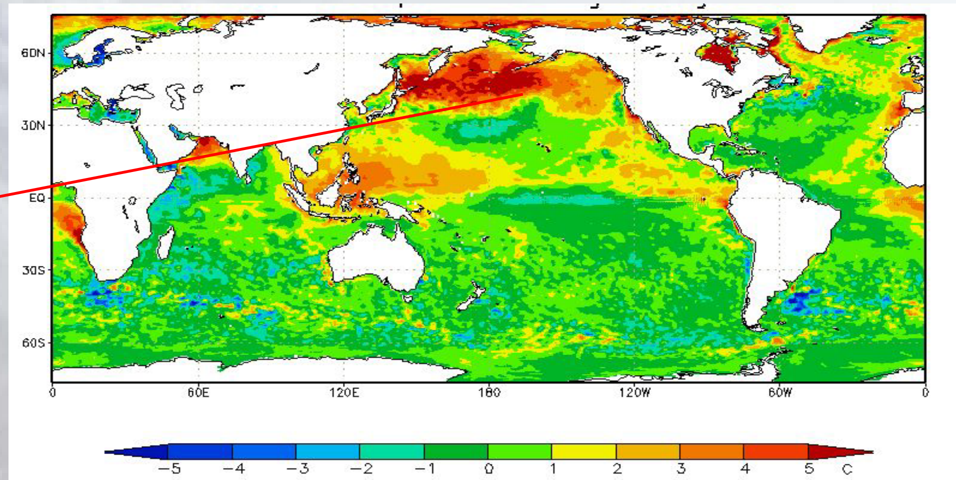
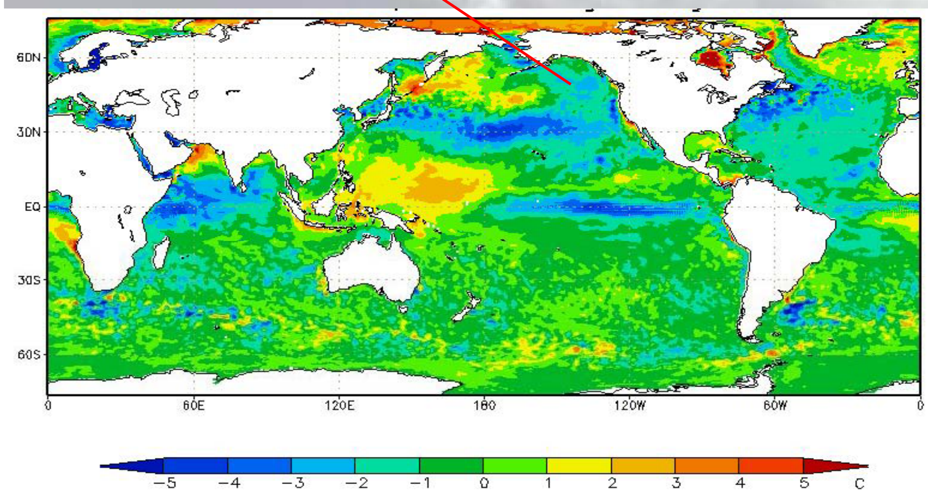
SST sensitivity to cloud parameterization

Models and observations for Aug. 2004

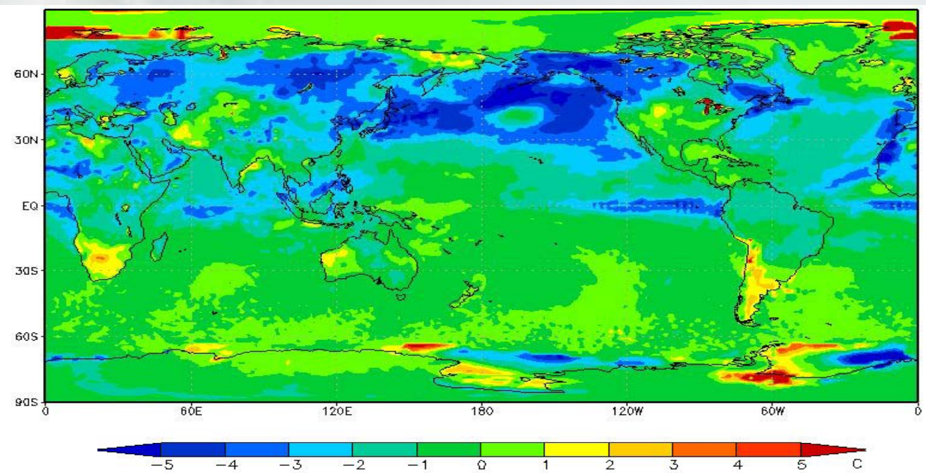
Large SST warm biases reduced by new model



SST: old_model - analysis



SST: new_model - analysis



SST: new_model – old_model

Teixeira et al. 2008