Physics-Dynamics Interplay III:

Physics Parameterizations in Global Atmospheric Models

DCMIP 2012

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Outline

- What are “GCM Physics”?
- Explicit physics vs. sub-grid physics
- Parameterization
- Examples
  - Mass-flux Convection scheme
  - Gravity wave drag
  - Clouds (an interaction between real and sub-grid physics)
- Issues at high horizontal resolution
- Future directions

Hydrostatic Primitive Equations

Where do the "physics" appear?

Horizontal scales >> vertical scales

Vertical acceleration << gravity

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \boxed{\mathbf{F},}$$ F_V *(horizontal momentum)*

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = \boxed{Q}/c_p,$$ F_T *(thermodynamic energy)*

$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0,$$ *(mass continuity)*

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$$ *(hydrostatic equilibrium)*

$$d\overline{q}/dt = \boxed{S_q.}$$

F_{QV}, $F_{QL,}$ F_{QI} …? ***(water substance evolution equations)***

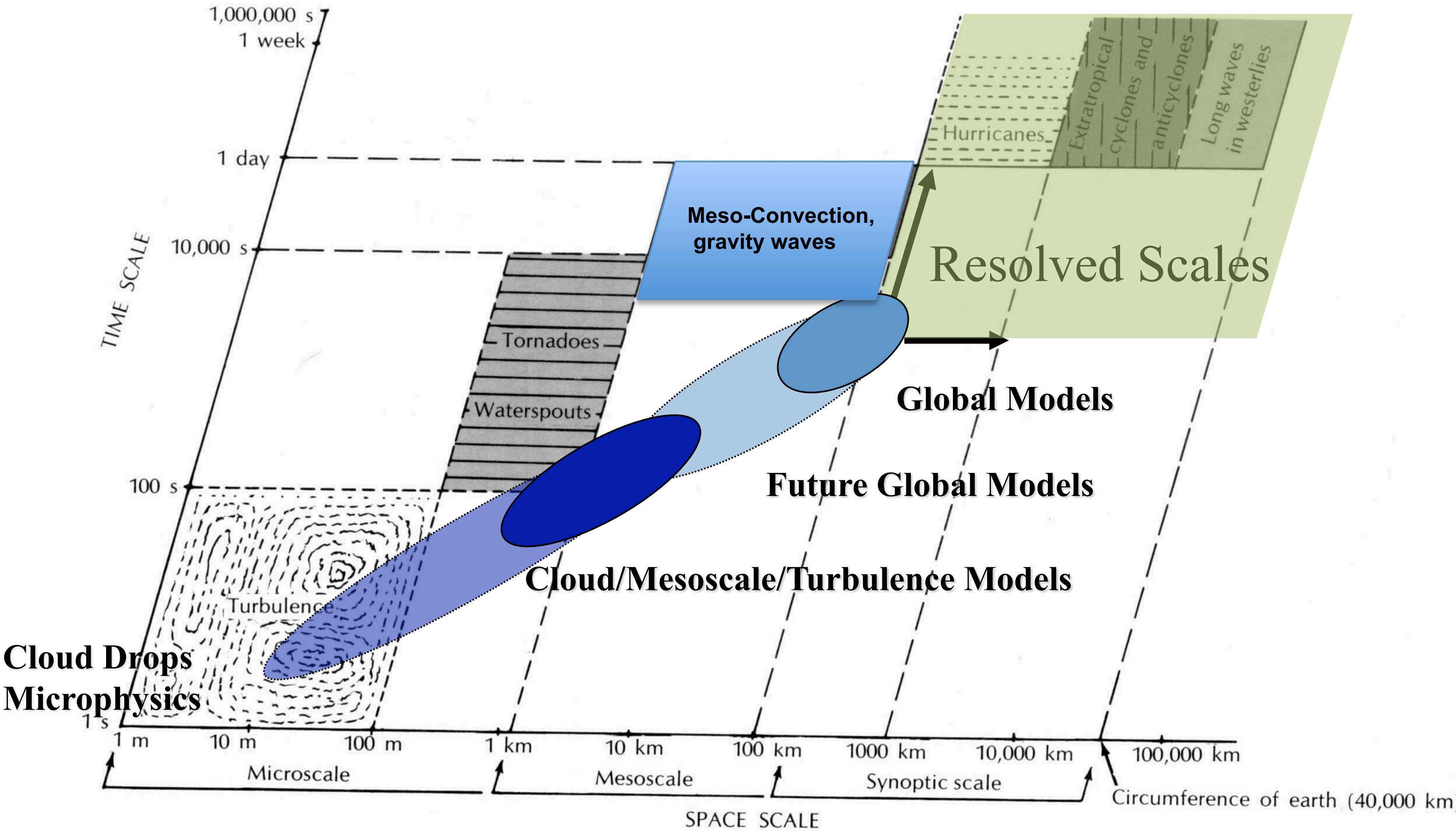
Harmless looking terms F, Q, and $S_q \Longrightarrow$ "physics"

Explicit physics versus sub-grid scale physics

- Explicit physics don't *necessarily* rely on a picture of what is occurring at unresolved scales
  - Clear-sky radiation
  - Condensation, micro-physics (…but more later)
- Sub-grid physics attempt to calculate tendencies produced by processes that occur at smaller scales than explicitly resolved
  - Convection
  - Boundary layer turbulence and surface fluxes
  - Gravity wave drag
  - Cloud radiative effects
  - Cloud micro-physics

Scales of Atmospheric Processes

Determines the formulation of the model



What is a 'Parameterization'?

- Algorithm to obtain ostensible sub-grid quantities and/or tendencies using grid mean quantities as inputs
- Can be based on
  - Basic physics
  - Empirical formulations from observations
  - Some simple conceptual model – "cartoon"

Mass flux convection schemes in climate models

Convective cloud conceptualized as simple entraining/detraining plume(s)

Thermodynamic Equation

$$\partial_t \rho s + \nabla \cdot \rho \mathbf{u} s + \partial_z \rho w s = \boxed{Q} + \ldots$$

Latent heating

Plume/cloud cont. equation

$$\partial_t \rho \boxed{a} + \partial_z \rho \boxed{a} w_c = \boxed{E} - \boxed{D}$$

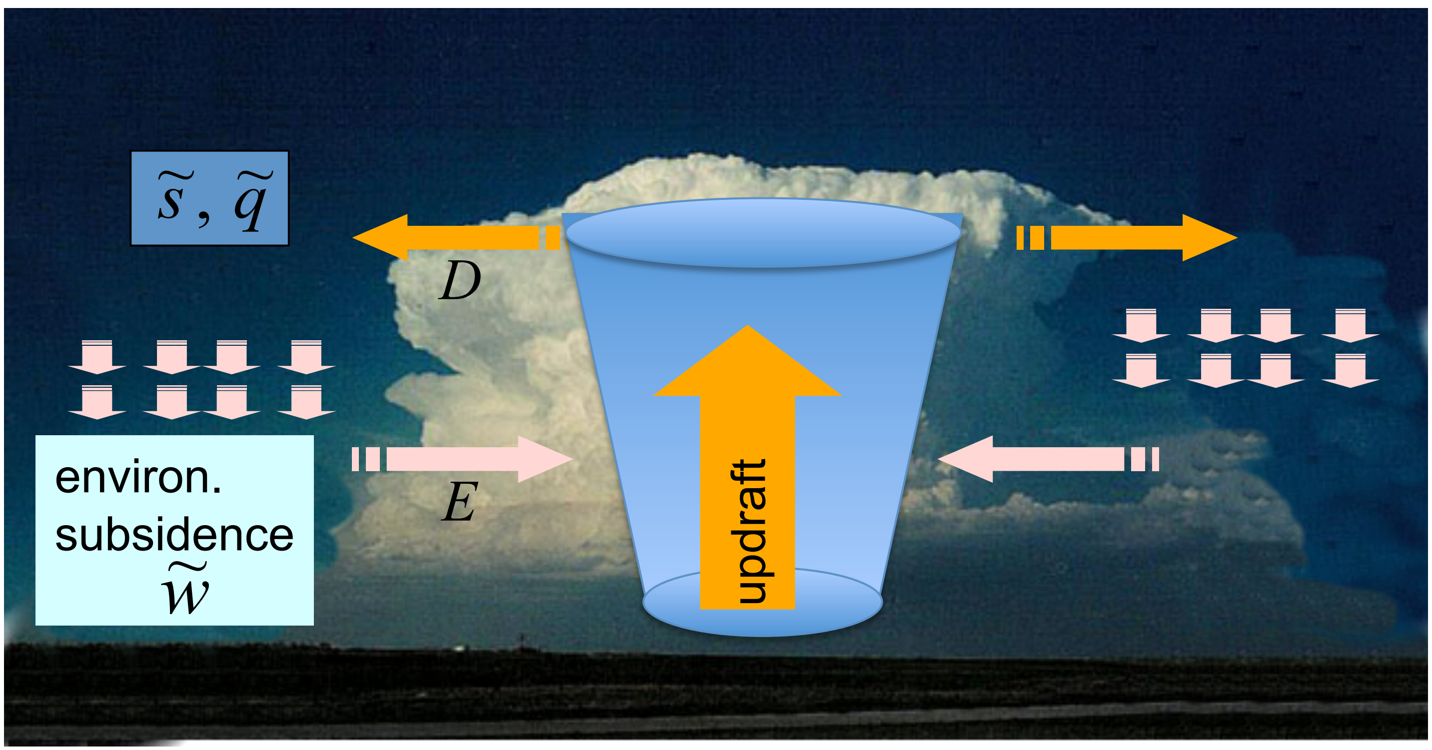
Cloud areal fraction Entrainment Detrainment

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = \overline{Q} - \partial_z \overline{\rho w' s'} + \ldots$$

Plume therm. equation

$$\partial_t \rho a s_c + \partial_z \rho a w_c s_c = E\tilde{s} - D s_c + a Q_c$$



Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \overline{\rho w' s'} + \ldots$$

Sub-grid fluxes re-written

$$\partial_z \overline{\rho w' s'} = \partial_z \rho a w_c s_c + \partial_z \rho (1-a) \tilde{w} \tilde{s}$$

compensating subsidence*

$$\Leftrightarrow \rho a w_c = -\rho (1-a) \tilde{w}$$

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \rho a w_c s_c - \partial_z \rho (1-a) \tilde{w} \tilde{s} + \ldots$$

$$\partial_z \rho a w_c s_c = E\tilde{s} - D s_c + aQ_c - \partial_t \rho a s_c$$

Plume therm. equation

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \overline{\rho w' s'} + \ldots$$

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$$\partial_z \rho a w_c s_c = E\tilde{s} - D s_c + \cancel{aQ_c} - \partial_t \rho a s_c$$

Plume therm. equation

Explicit in-cloud latent heating term drops out

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = -E\tilde{s} + D s_c + \partial_t \rho a s_c - \partial_z \rho (1-a) \tilde{w} \tilde{s} + \ldots$$

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = -E\tilde{s} + Ds_c + \partial_t \rho a s_c - \partial_z \rho(1-a)\tilde{w}\tilde{s} + \ldots$$

$$-\rho(1-a)\tilde{w} = \rho a w_c \equiv M_c$$

$$a \to 0 \;\Leftrightarrow\; \tilde{s} \to \bar{s}$$

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = \underbrace{-E\bar{s} + Ds_c + \partial_z M_c \bar{s}} + \ldots$$

In final form, cumulus forcing is determined entirely by profiles of E, D, and M_c. Key assumptions up to here:

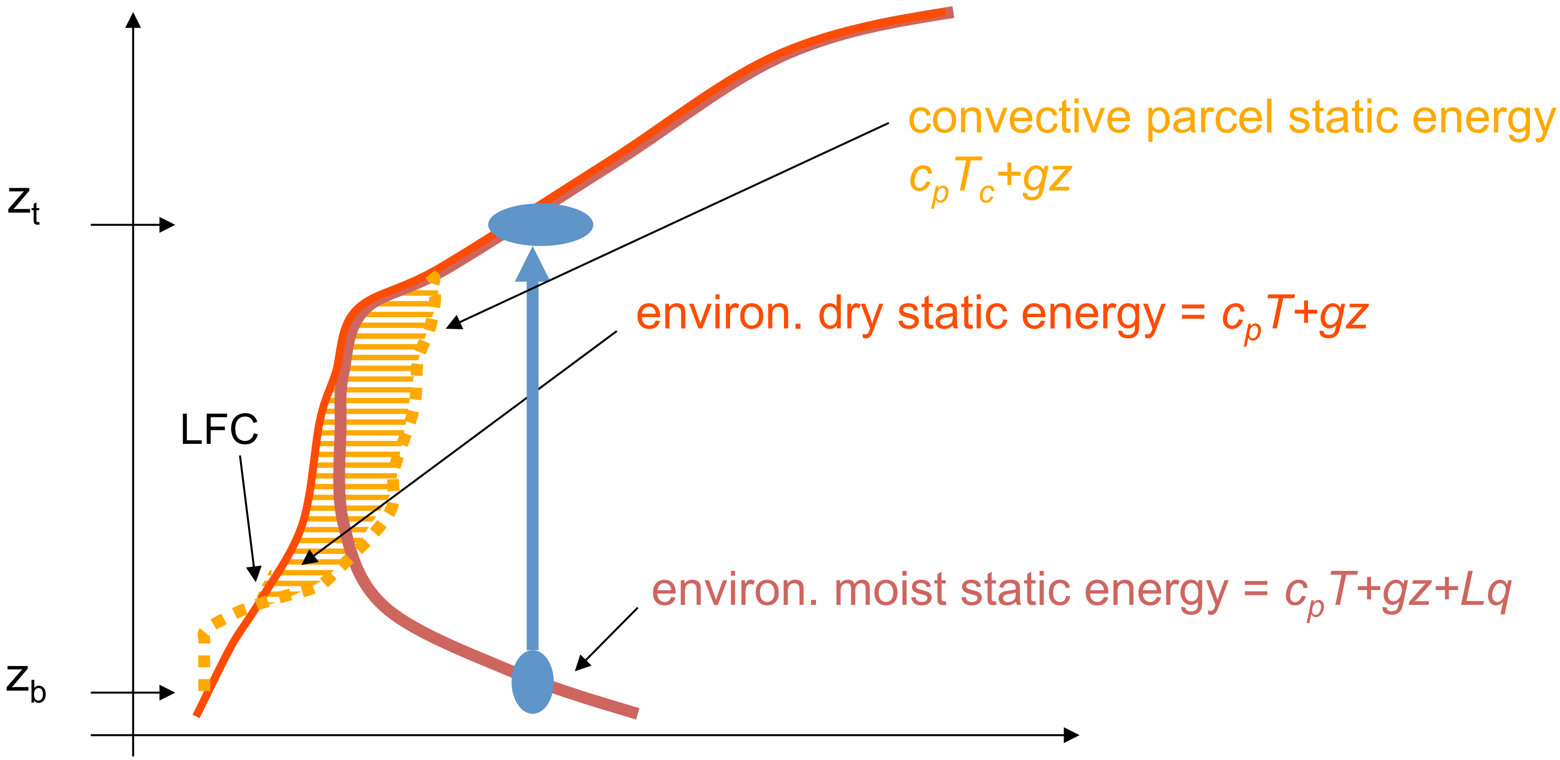
$-\rho(1-a)\tilde{w} = \rho a w_c$ (compensating subsidence);

$a \to 0$ (small areal fraction/negligible storage)

Mass-flux convective parameterizations determine profiles E, D, and M_c based on grid mean quantities and ***assumed plume models***.

Convective Available Potential Energy is a common control for parameterized convective mass flux in climate models

$$\sim CAPE = g\int_{z_B}^{z_T} \frac{T_c - T}{T}\, dz \qquad M_c(z_b) \sim f(CAPE, \partial_t CAPE)$$



Mountain wave drag in climate models

Affects mean sea-level pressure patterns, planetary wave patterns (esp. NH winter)

Momentum Equation

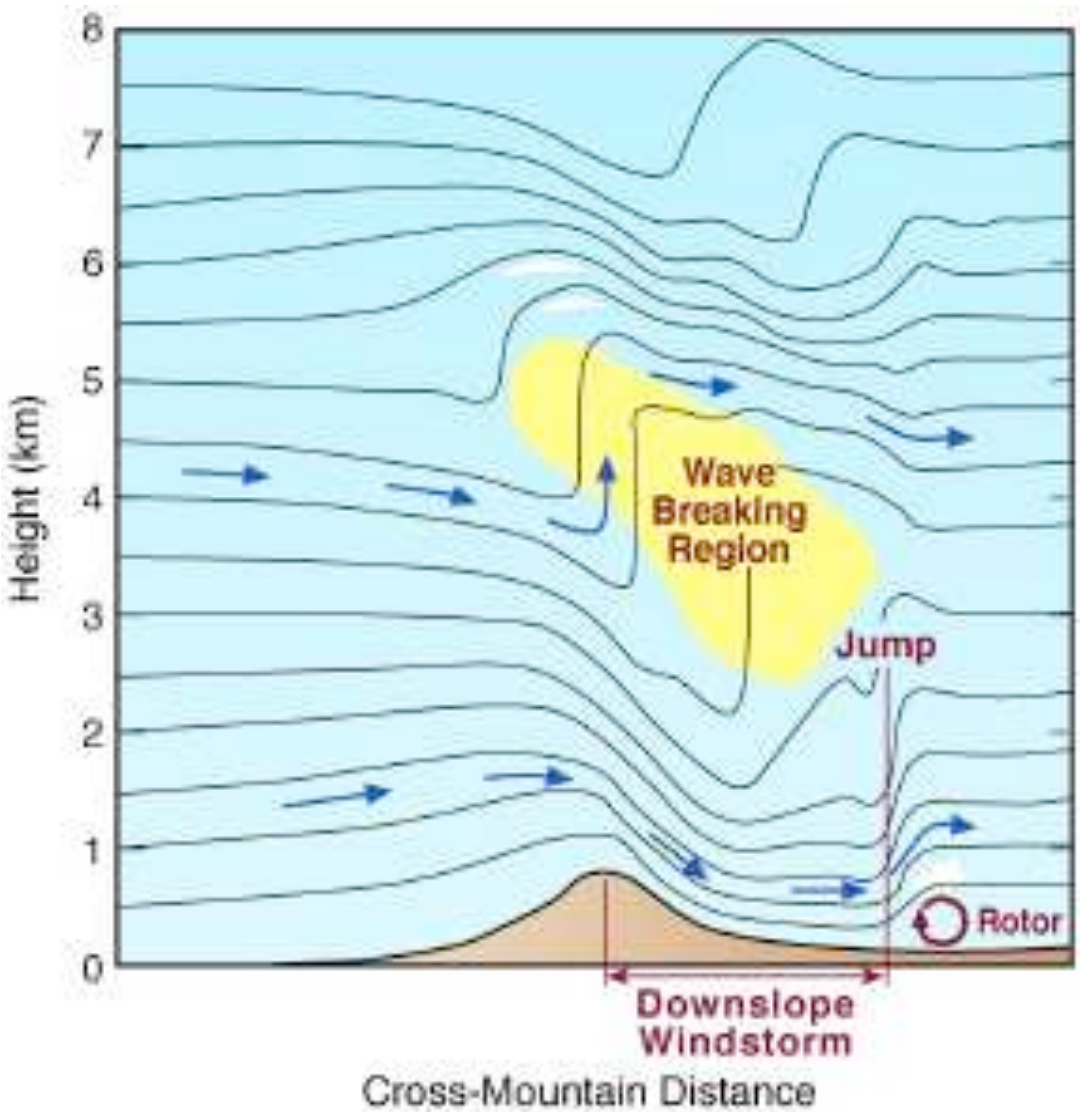
$$\partial_t \rho \mathbf{u} + \ldots + \partial_z \rho w \mathbf{u} = -\nabla p - \rho \nabla \phi + \mathbf{F} + \ldots$$

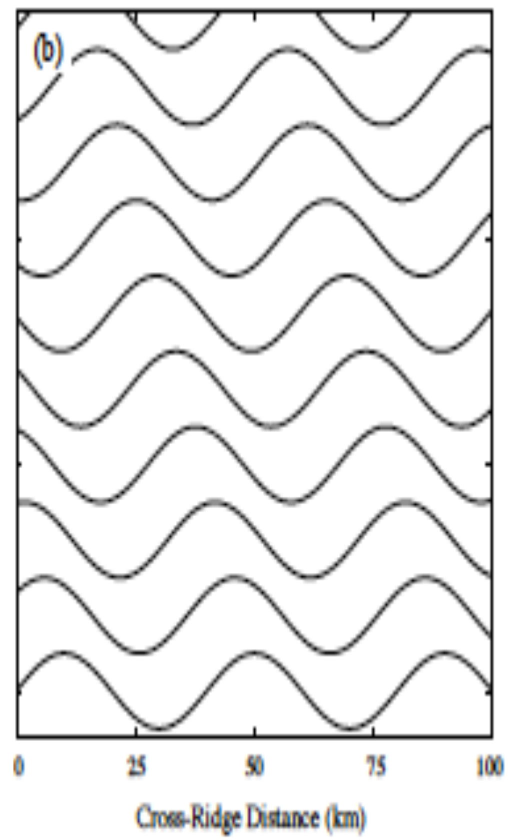
Grid box average momentum equation

$$\partial_t \overline{\rho}\,\overline{\mathbf{u}} + \ldots + \partial_z \overline{\rho}\,\overline{w}\,\overline{\mathbf{u}} = -\nabla \overline{p} - \overline{\rho} \nabla \overline{\phi} - \boxed{\partial_z \overline{\rho w' u'} \mathbf{i}} - \boxed{\partial_z \overline{\rho w' v'} \mathbf{j}.} + \overline{\mathbf{F}}.$$

Zonal and meridional subgrid vertical momentum fluxes

Complex mountain wave pattern conceptualized as steady, hydrostatic, 2D monochromatic wave





$$N = \sqrt{g\frac{\theta_z}{\theta}}$$ Brunt Vaisalla Freq

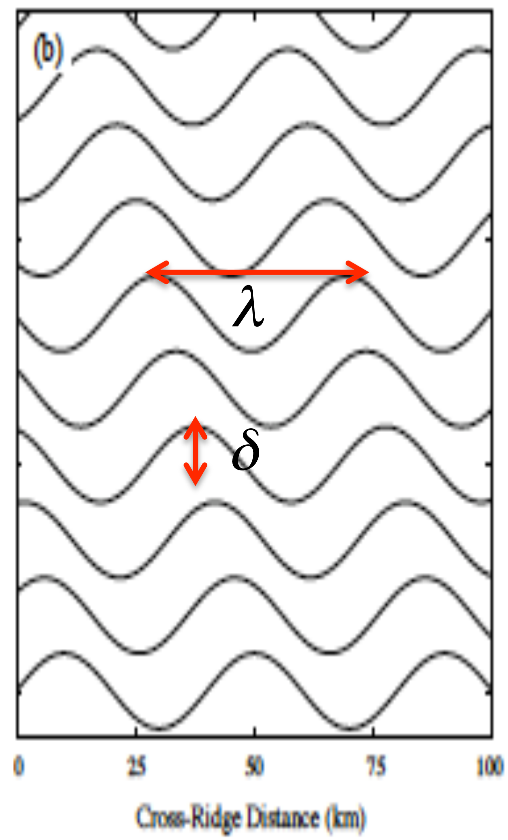
U Mean wind

δ Vertical displacement

λ Horizontal scale/wavelength

$$u' \sim N\delta \quad w' \sim U\frac{\delta}{\lambda}$$ Gravity wave dispersion relations

$$\overline{\rho w'u'} \sim \rho N U \frac{\delta^2}{\lambda}$$ Momentum flux



$$\overline{\rho w' u'} \sim \rho N U \frac{\delta^2}{\lambda}$$

Gravity wave theory → Momentum flux constant in the vertical in the absence of dissipation

$$\rho_l N_l U_l \frac{\delta_l^2}{\lambda} = \rho_{l+1} N_{l+1} U_{l+1} \frac{\delta_{l+1}^2}{\lambda}$$

Conceptual model → dissipation begins when saturation amplitude $\delta = U/N$ is reached (wave breaking) and maintains amplitude exactly at $\delta = U/N$

$$\delta_l = MIN\left(\frac{U_l}{N_l} \,,\; \delta_{l+1} \sqrt{\frac{\rho_{l+1} N_{l+1} U_{l+1}}{\rho_l N_l U_l}} \right)$$

Decreasing momentum flux in the vertical induces drag

Initial vertical displacement at z=0 is determined by topographic variance.

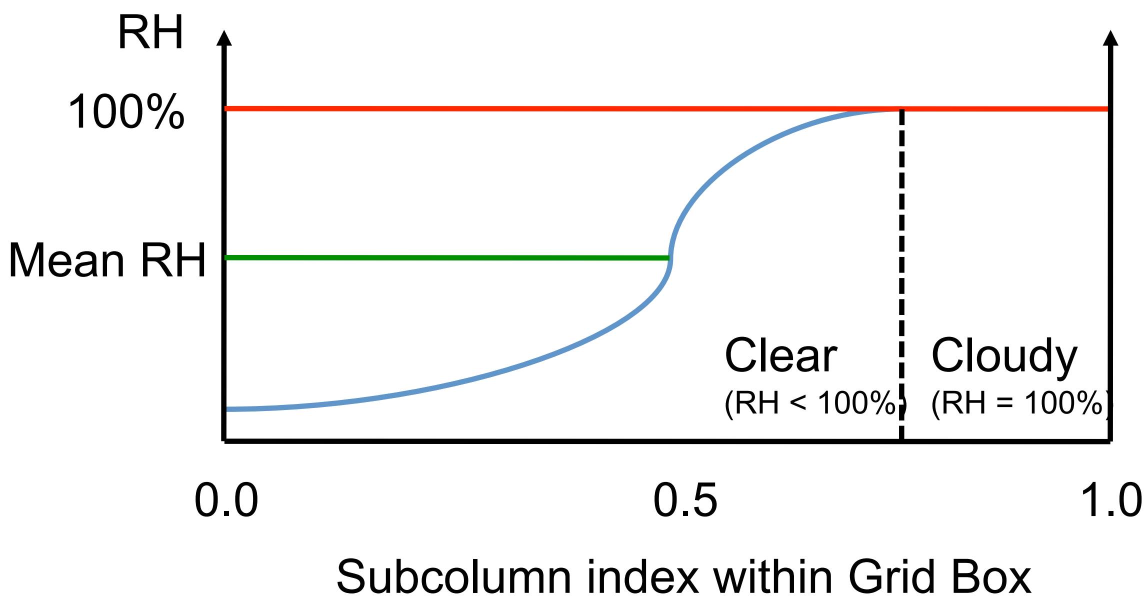
Clouds

Stratiform Clouds

Sub-Grid Humidity and Clouds

Liquid clouds form when RH = 100% ($q=q_{sat}$)

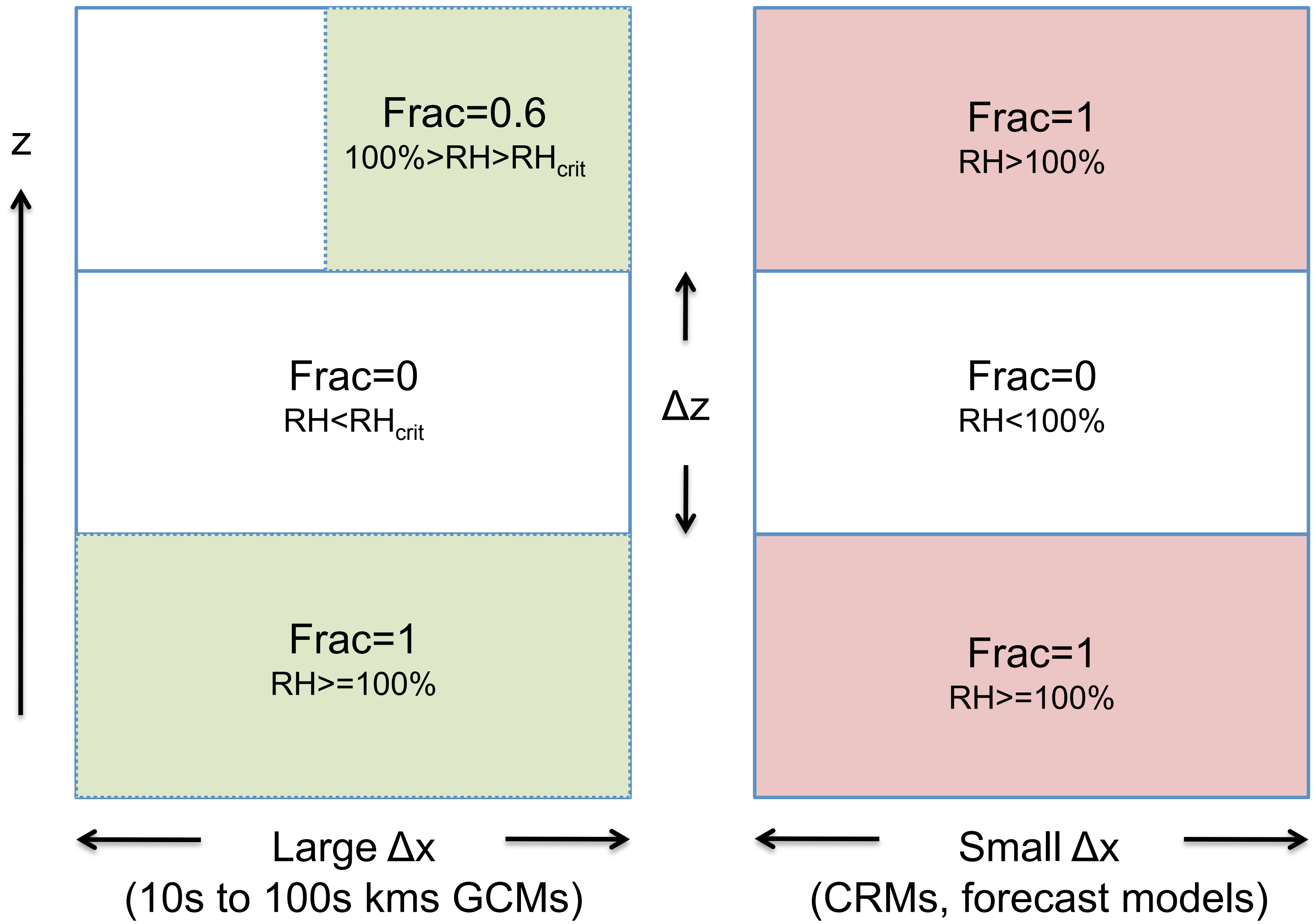
But if there is variation in RH in space, some clouds will form before *mean* RH = 100%



Assumed Distribution function of Humidity in a grid box with sub-grid variation

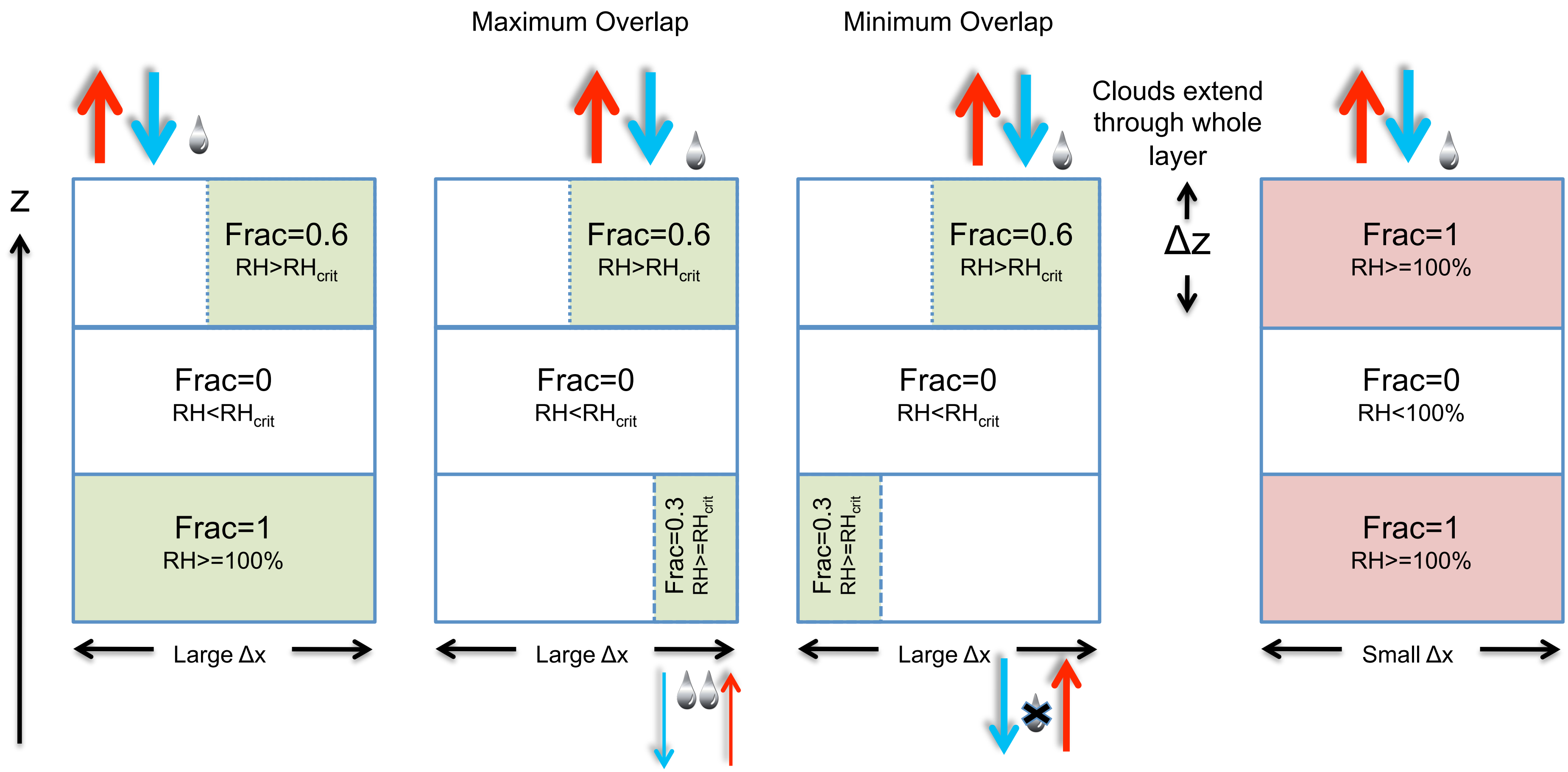
The Cloud Fraction Challenge

Cloud_Frac=f(RH,w,water,aerosols,time,…)



The Cloud Overlap Challenge

Radiation and micro/macro-physics impact

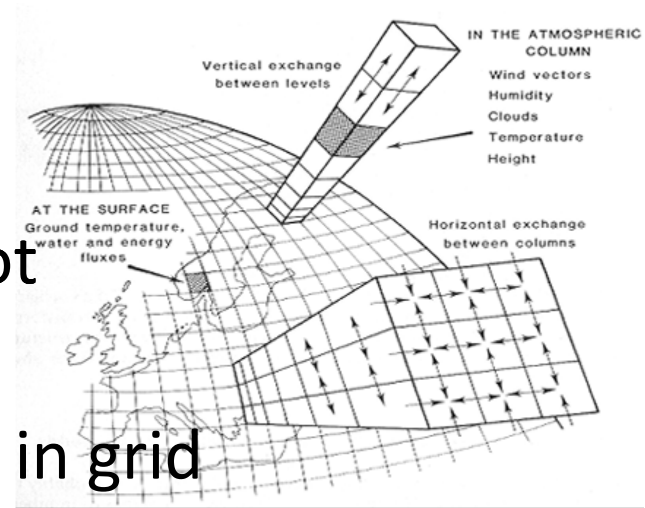


- Contiguous cloudy layers maximally overlapped in CAM
- Non-contiguous layers randomly overlapped

Parameterizations

High level design

1. Inputs and effects totally contained within single columns
   – Single grid point structures are believed
2. Most (many common) schemes do not possess a "memory"
3. Assume sufficient space-time volume in grid means for "good" statistics
4. For climate should be mass, momentum and energy conserving (limiters and fixers)



1,2 and 3 begin to cause trouble as resolution increases and time-steps decrease

Parameterizations

High level design

Process splitting versus time splitting (CAM)

Process splitting:

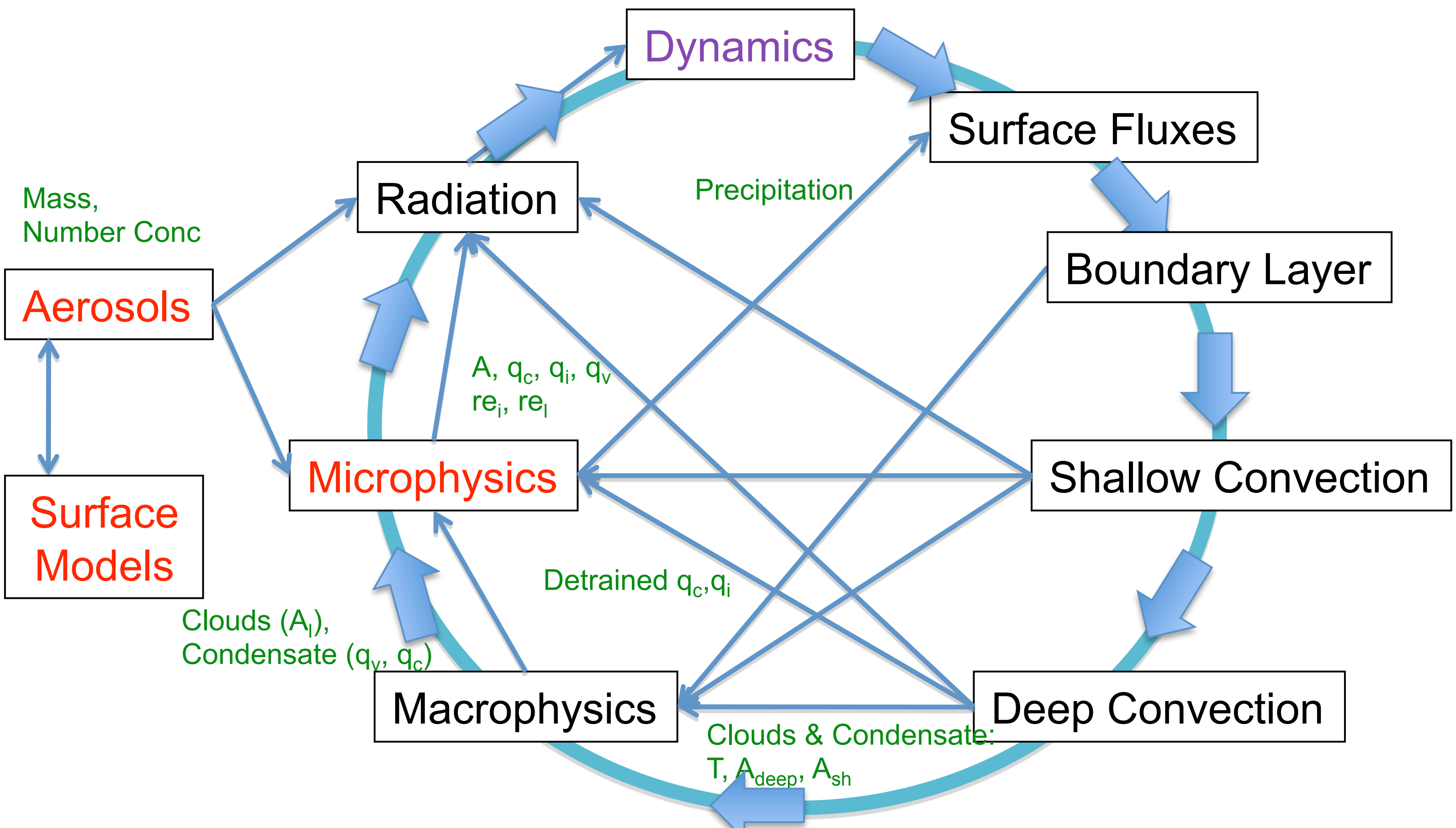
- All parameterizations work on same state. Provide tendencies for unified update

Time splitting

- Parameterizations update state as they work and pass updated state to next param.

CAM time-step

Community Atmosphere Model (CAM) Version 5



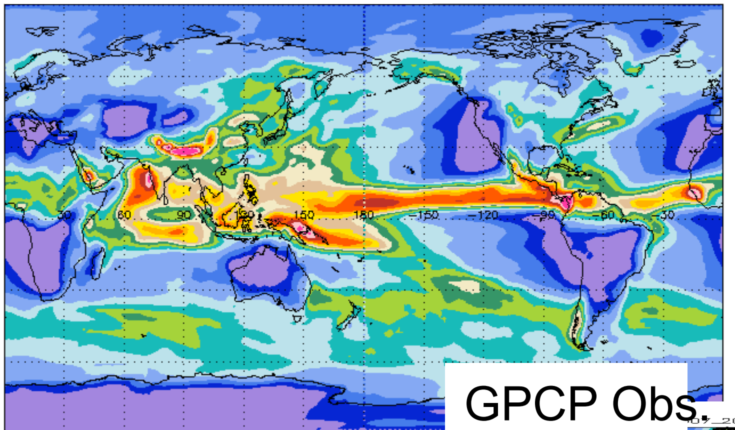
A = cloud fraction, q=H_2O, re=effective radius (size), T=temperature
(i)ce, (l)iquid, (v)apor

High horizontal resolution

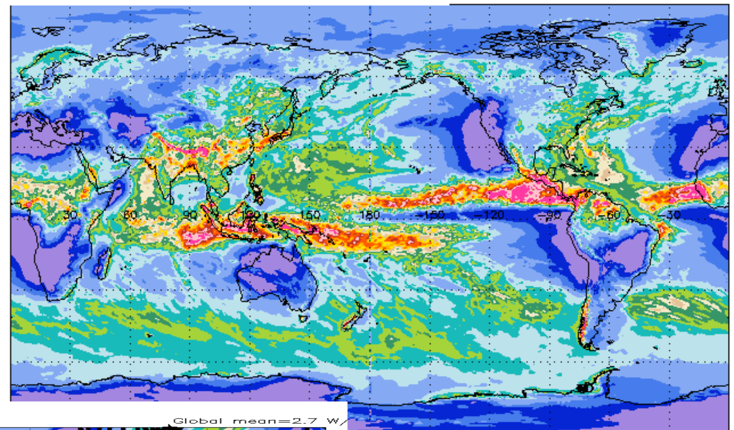
Many key aspects of climate simulations don't improve

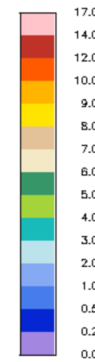
JJA precipitation

Total Prec. 2 degree

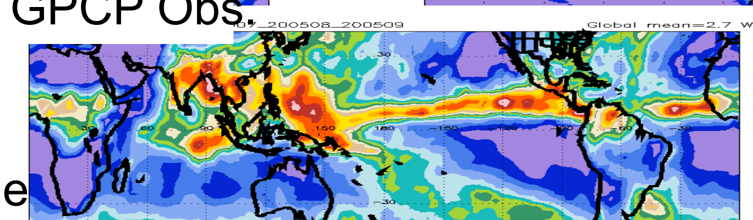


Total Prec. ¼ degree

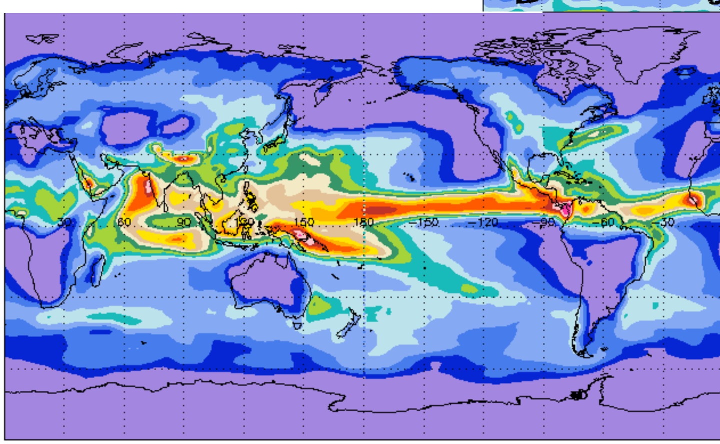




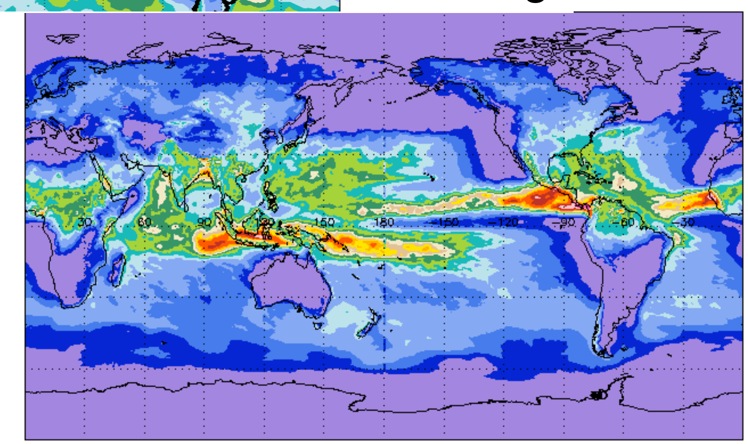
GPCP Obs.

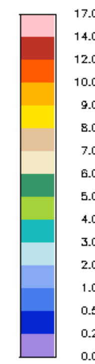


Convective Prec. 2 de

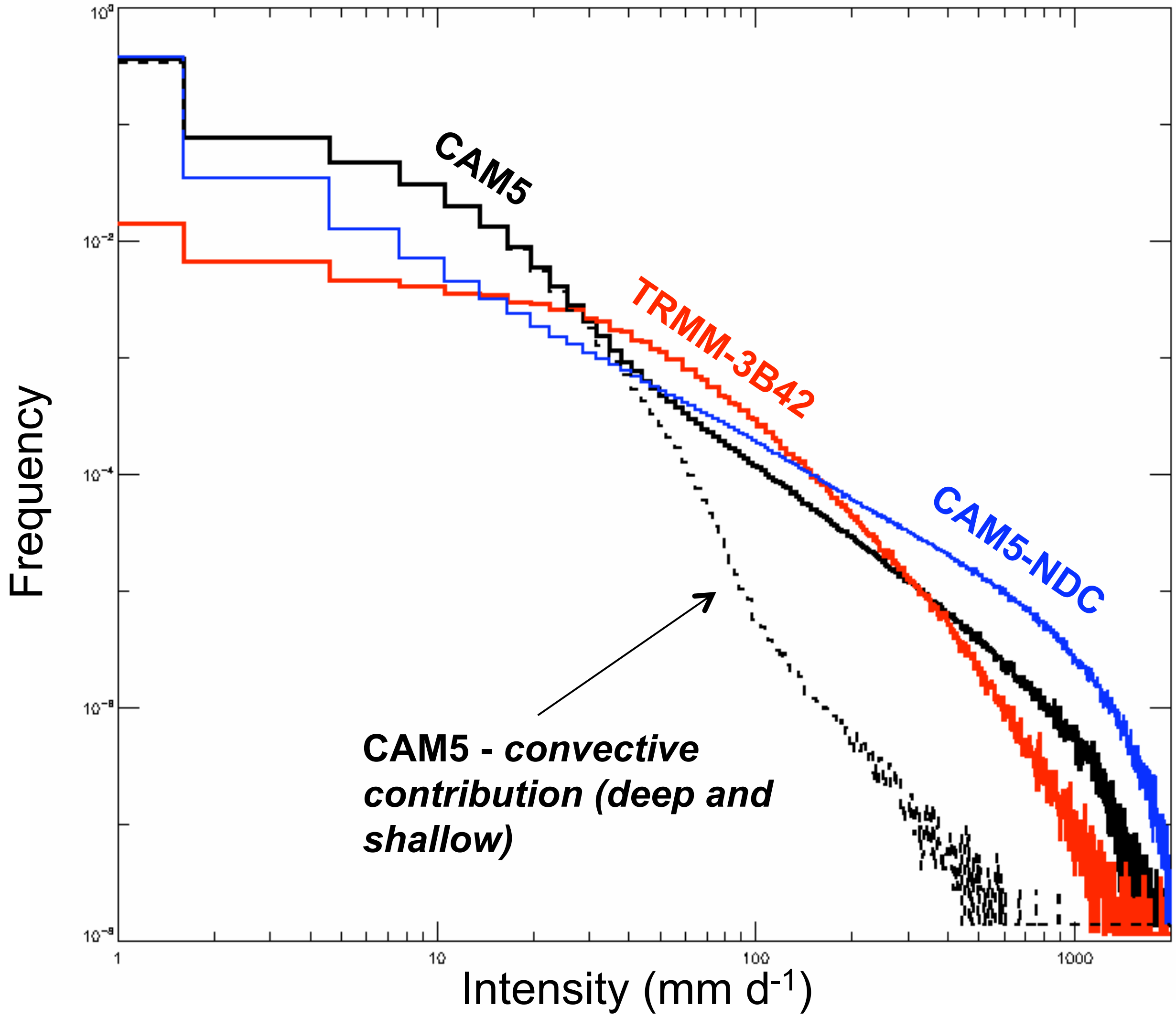


c. ¼ degree

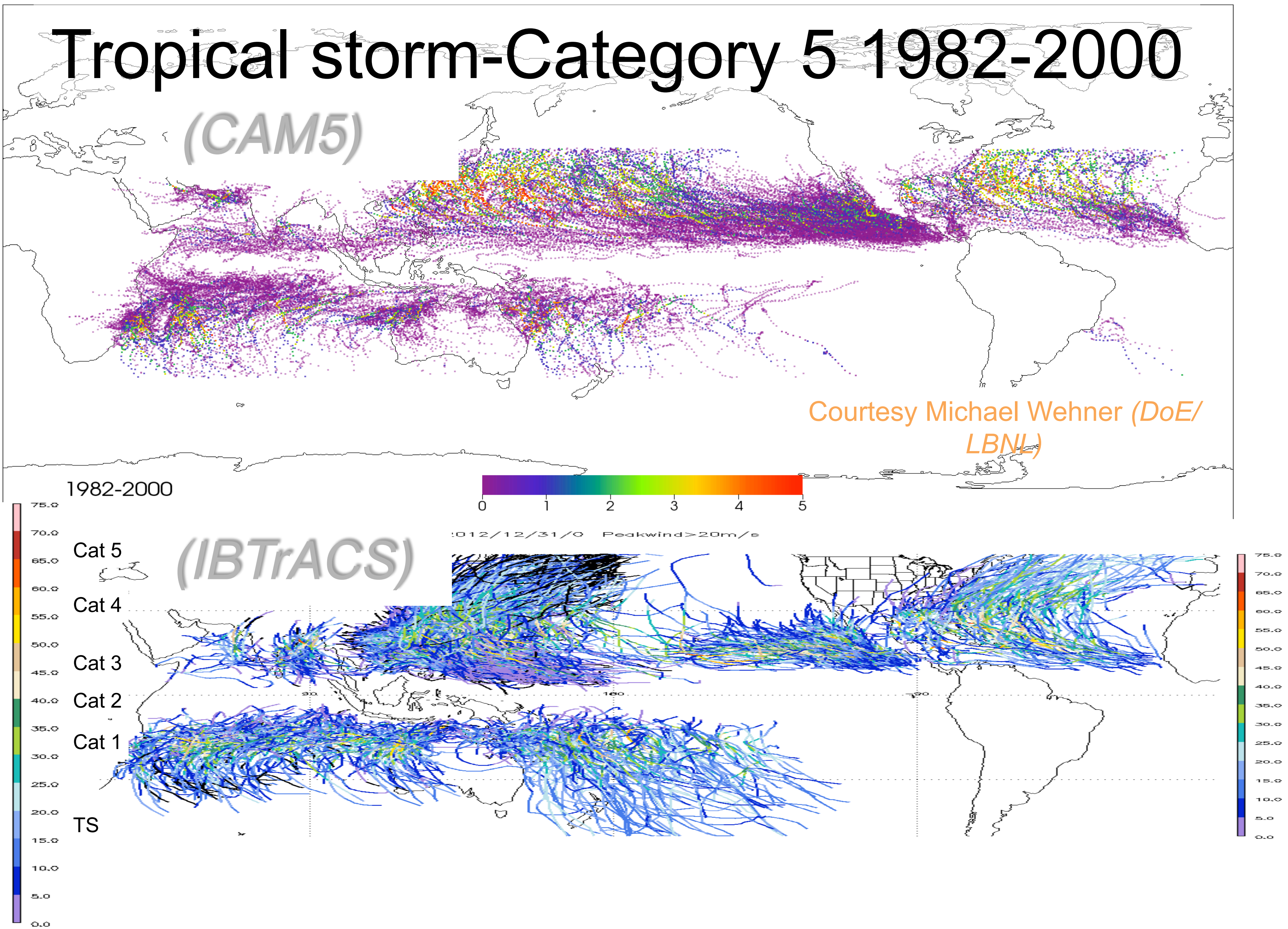




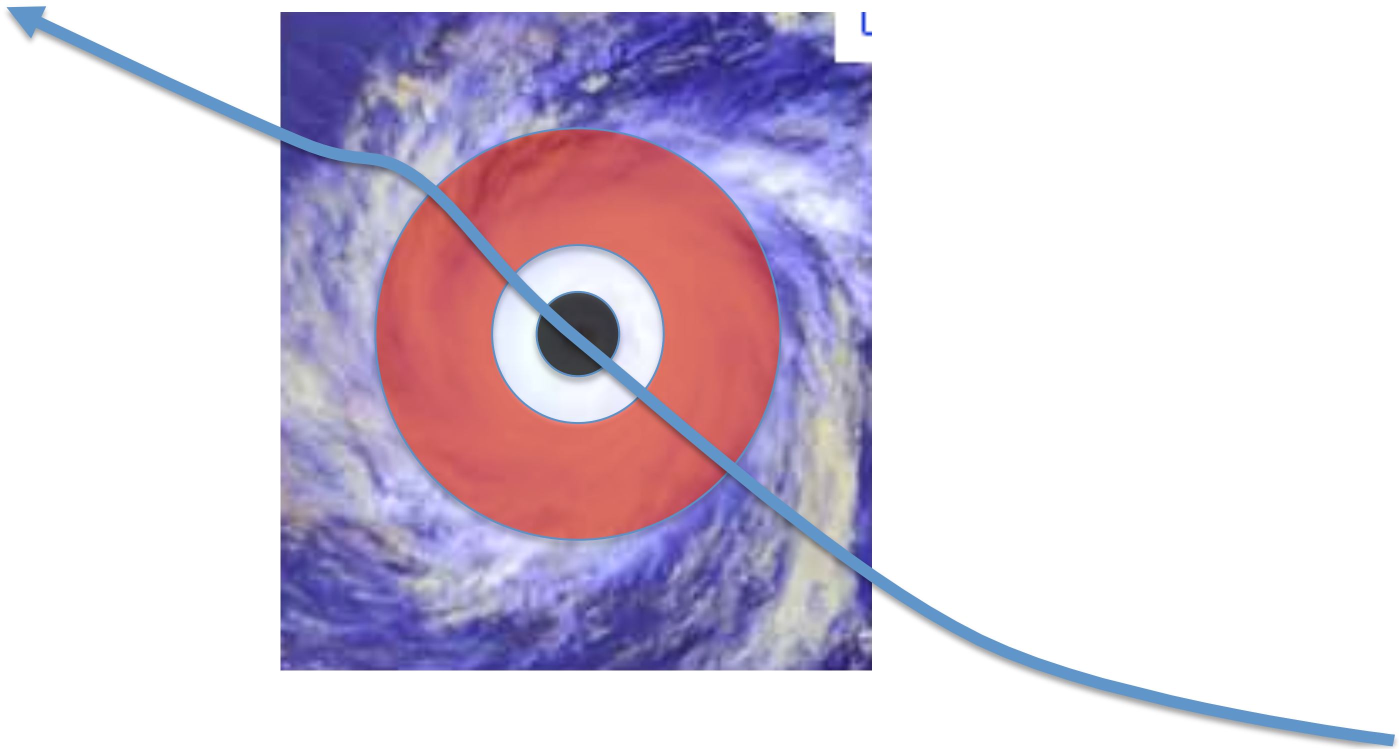
PDFs of tropical precipitation (30S-30N) rates Aug 2005
model –***instantaneous*** *3hrly* , TRMM *3-hrly*



Tropical storm-Category 5 1982-2000



Time series of precipitation following storms in CAM5;
core r<50km (black) and ***storm exterior*** 500km>r>250km

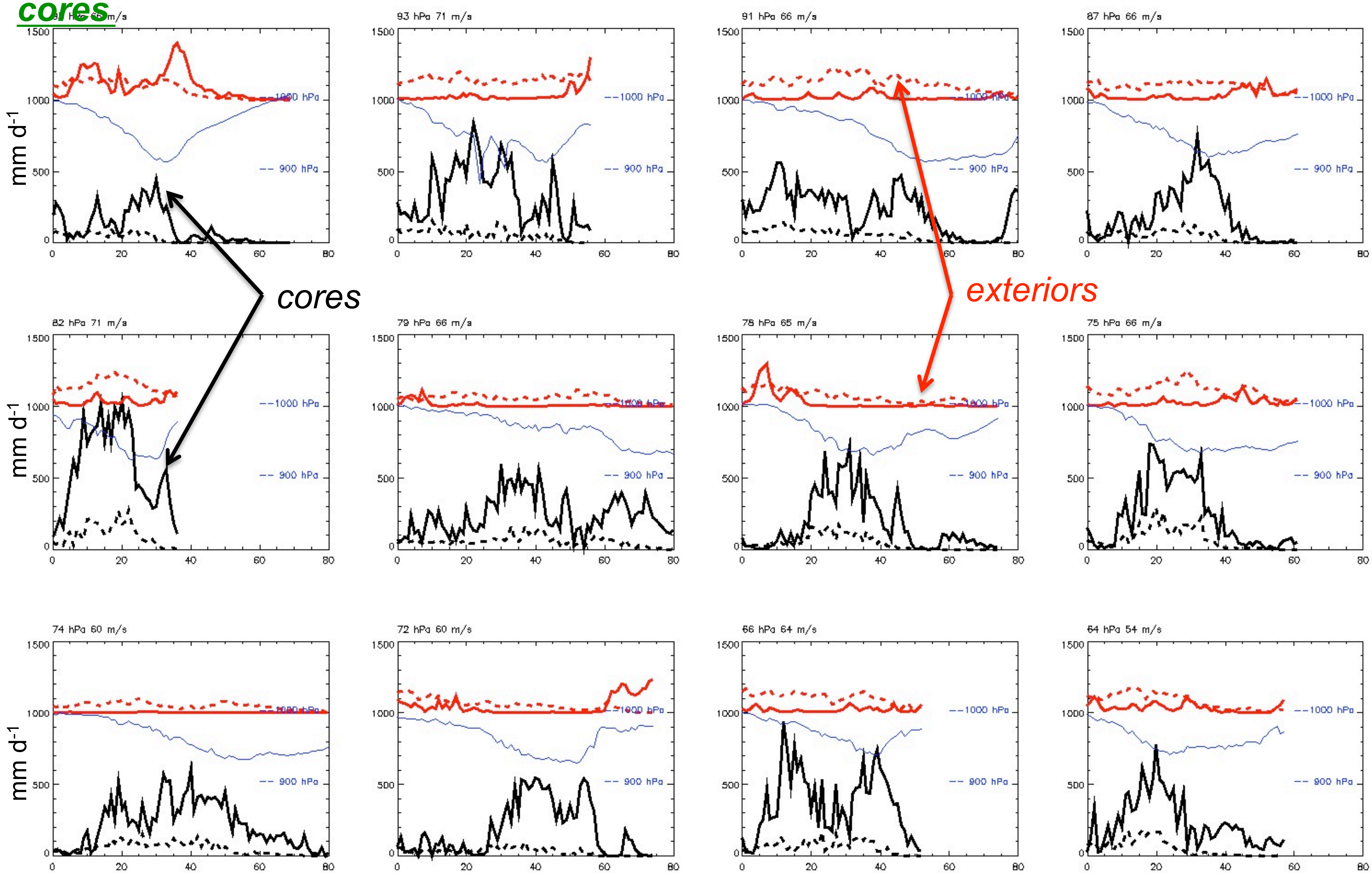


Convective and large-scale precipitation separated

Precipitation time series in ***storm cores*** ***(black)****,* ***storm exteriors*** ***(red)****.*

Convective precip (dashed), ***Large-scale precip (solid).***

Thin ***blue*** *lines show surface pressure.* ***Note overwhelming dominance of LS in cores***



Future Directions for Physics in Models

What do we need to consider?

As grid-sizes and time steps decrease, parameterizations may need to communicate across space and time

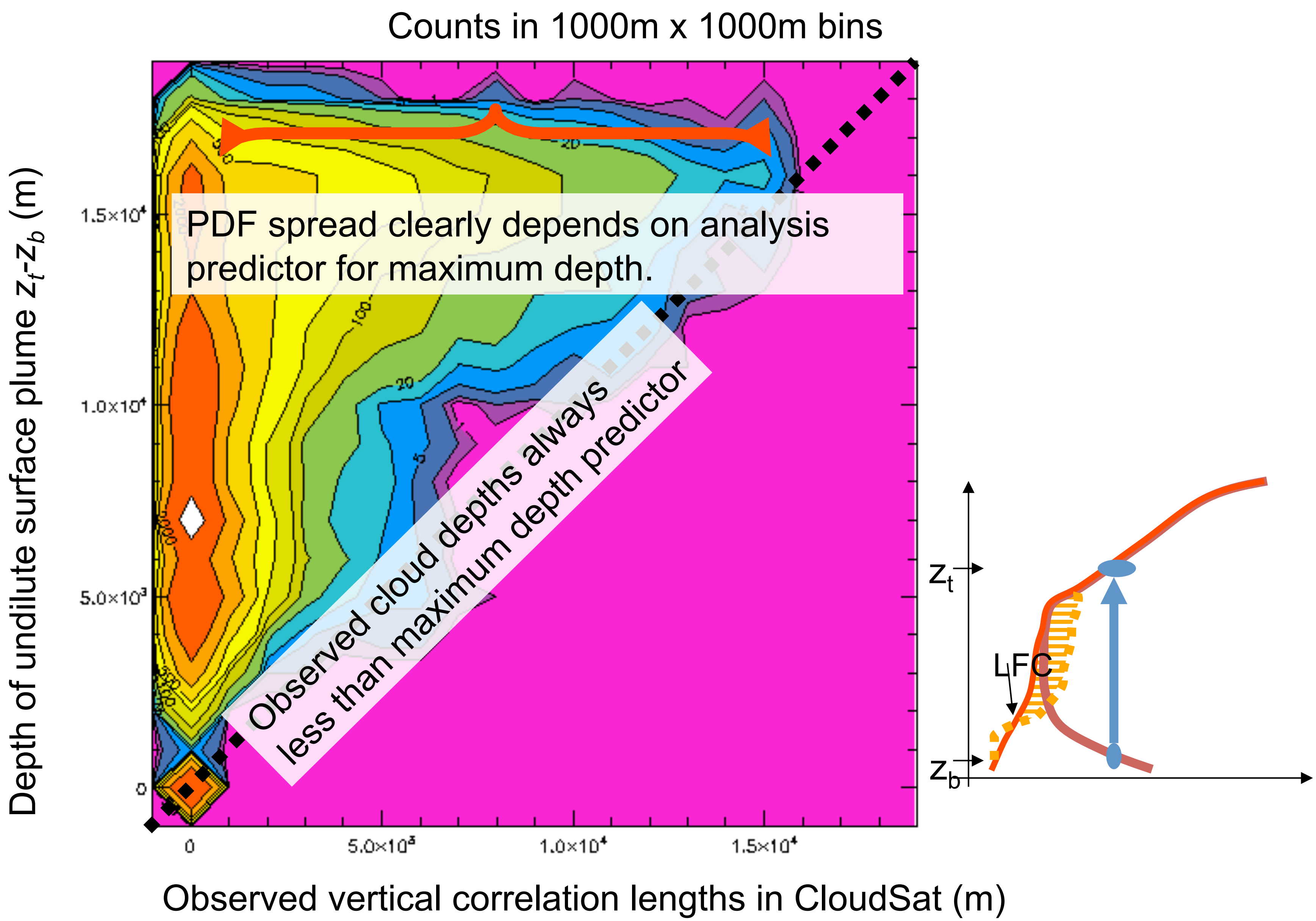
As grid-sizes and time steps decrease, resolved scales may not contain enough information to close parameterizations

- Stochastic elements?
- Life-cycles of processes?

At any resolution, better sub-grid representations are needed

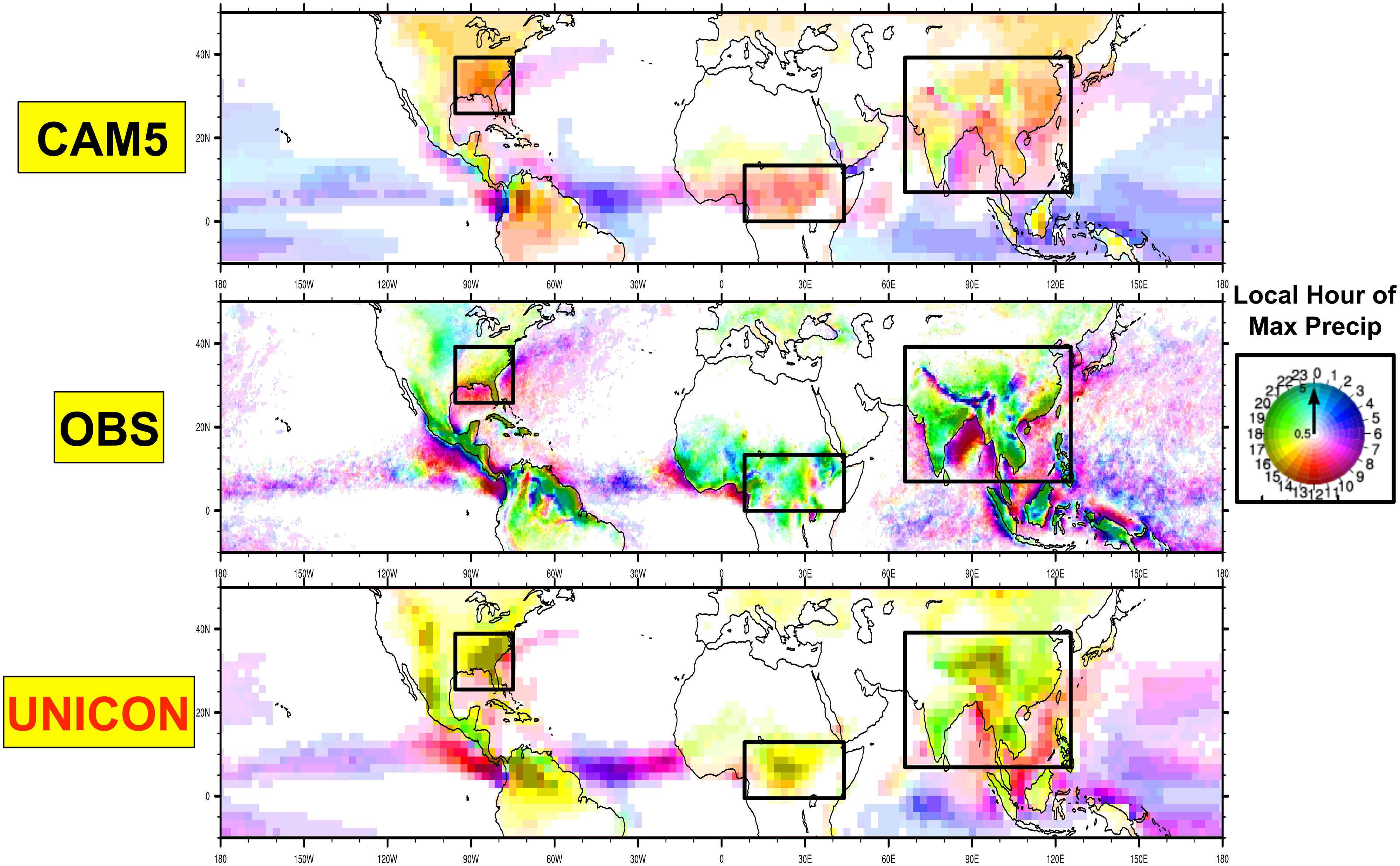
- Subcolumns?

Joint PDF of *observed* cloud vertical scales (CloudSat) vs *predicted* maximum cloud heights in GEOS-5 reanalysis. **Tropical Oceans**, July 2006.



Diurnal Cycle of Precipitation. JJA.

(Sungsu Park, NCAR/CGD)



Thank you