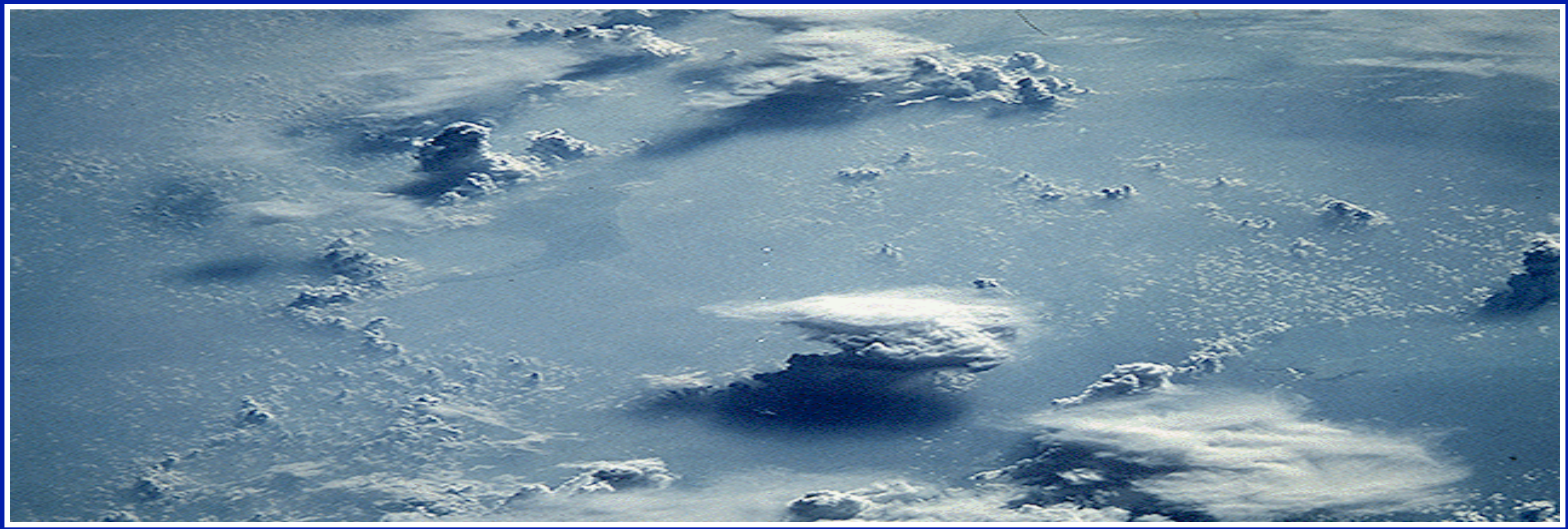
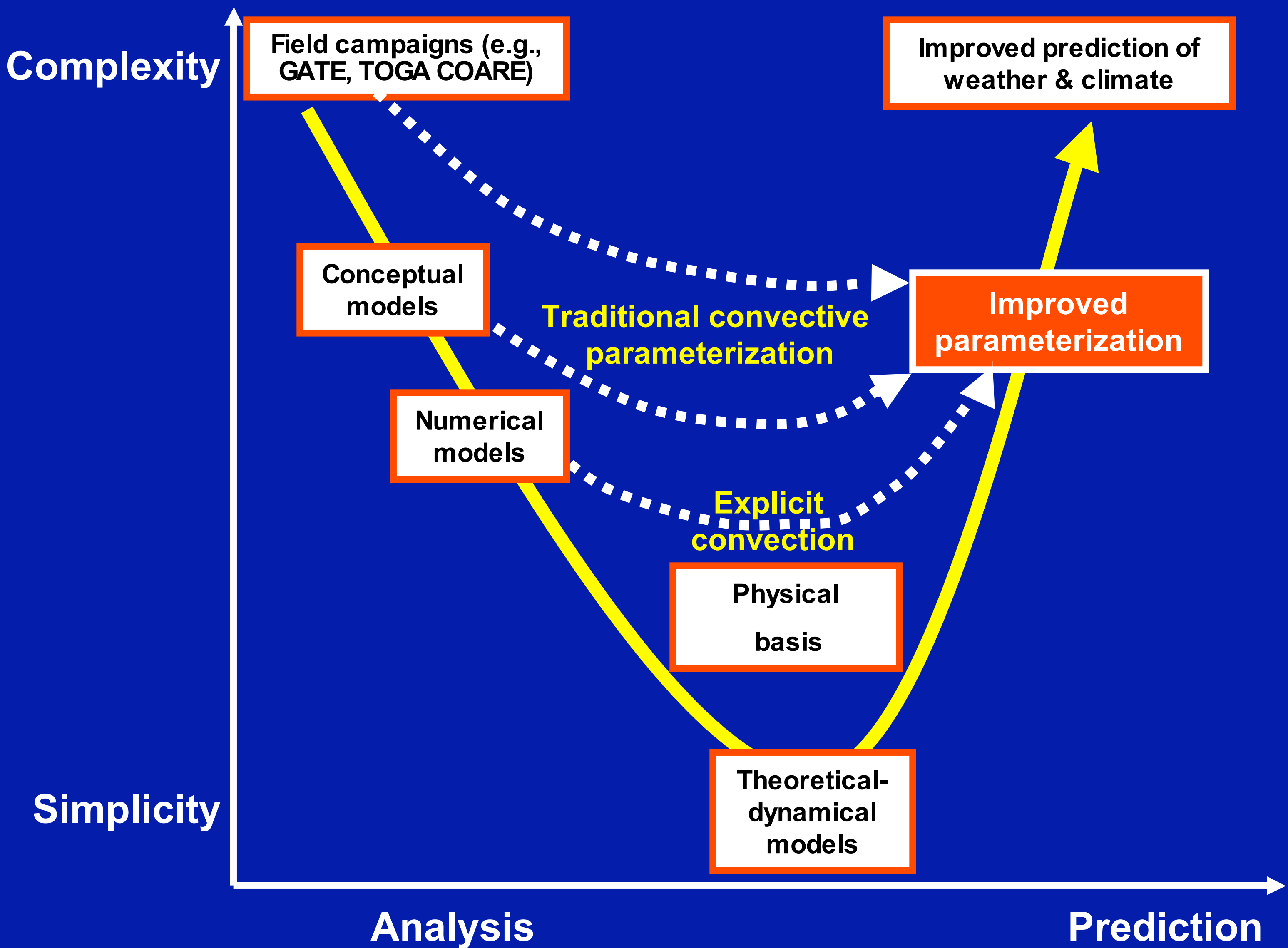
Representing Precipitating Convection in the 10-km-grid Grey Zone: The Organized Convection Issue



Mitchell W. Moncrieff
Cloud Systems Group, MMM
Earth Sun Systems Laboratory, NCAR

IMAGe Theme of the Year Workshop II: Multi-Scale Interactions in a GCM Grid Box: Mathematical Theory, Numerics and Parameterization, NCAR, Oct. 31-Nov. 4, 2005

The complete convection problem



Next-generation global NWP models will have 10-km grid spacing

- Parameterized convection and explicit convection may occur simultaneously
- Parameterization is ill-conditioned, explicit convection is under-resolved
- Dynamical structure, scale-selection, transport, scale-interaction are all compromised
- Positive factors, but pitfalls too, for NWP
- Next in line are seasonal prediction models and, ultimately, climate models

A sobering fact:

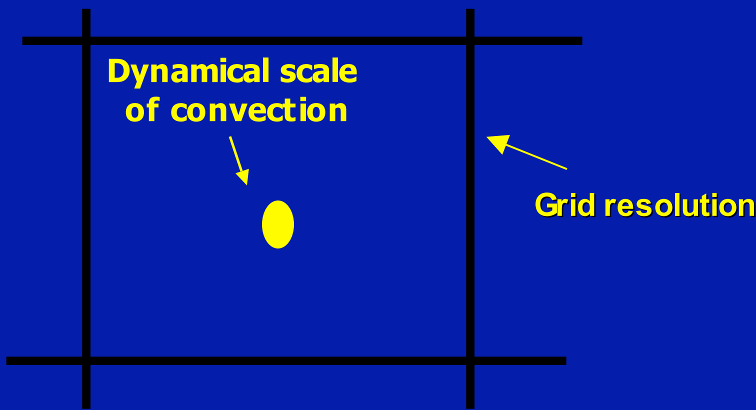
Physical resolution is 7-10 x grid spacing

… important implications for convection where fastest growth rates are on small scales

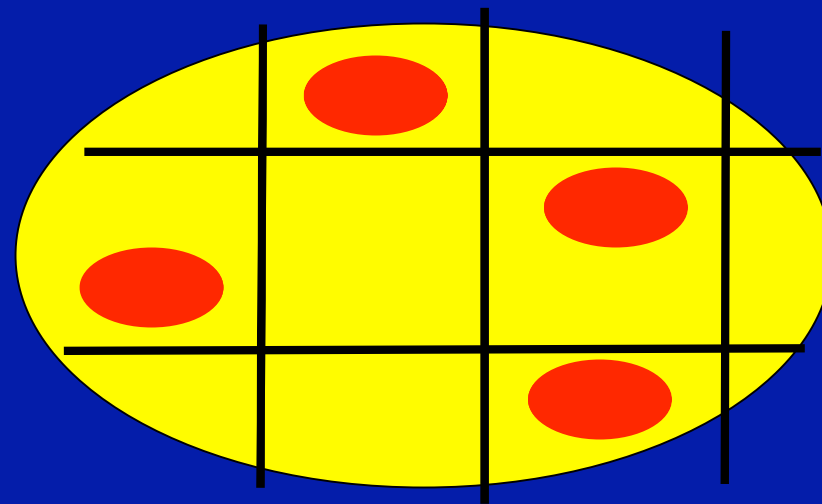
… mesoscale organization of convection may be surrogate at 10-km-grid spacing

… however, even under- resolved explicit convection is a vast improvement over convective parameterization

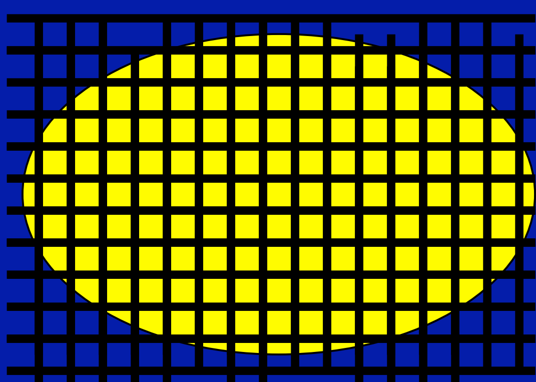
The under-resolved dynamics issue



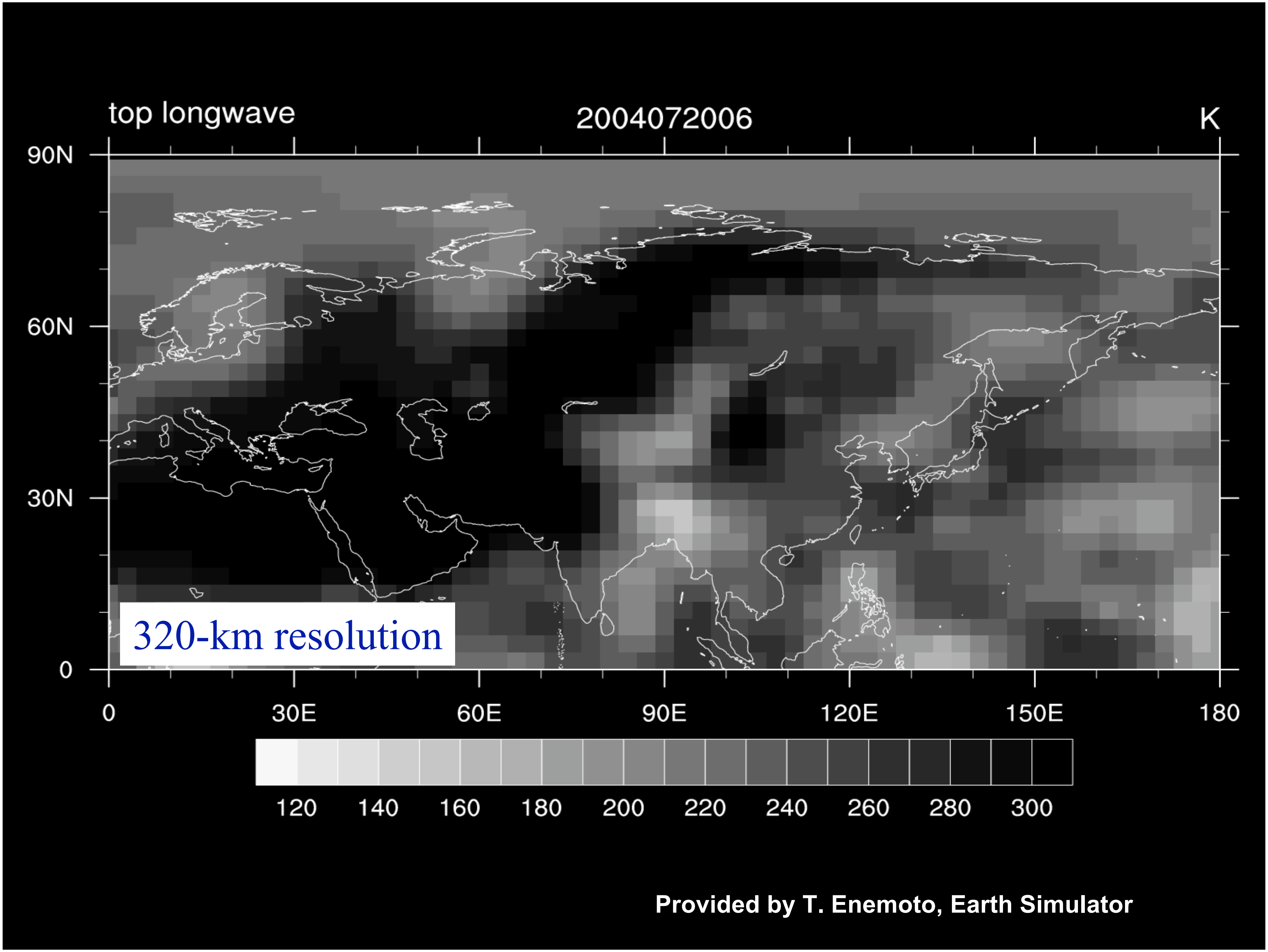
Traditional convective parameterization based on scale separation

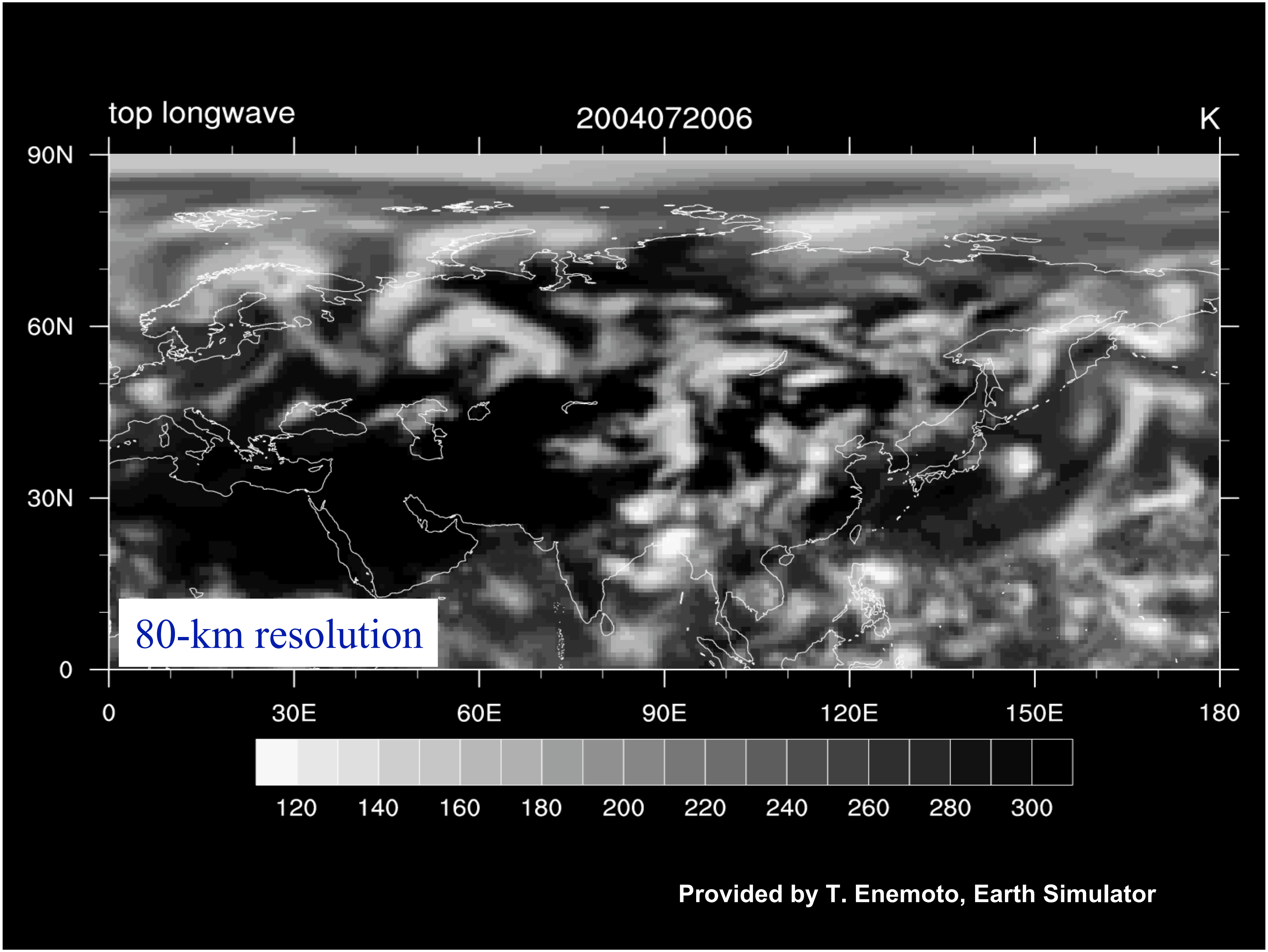


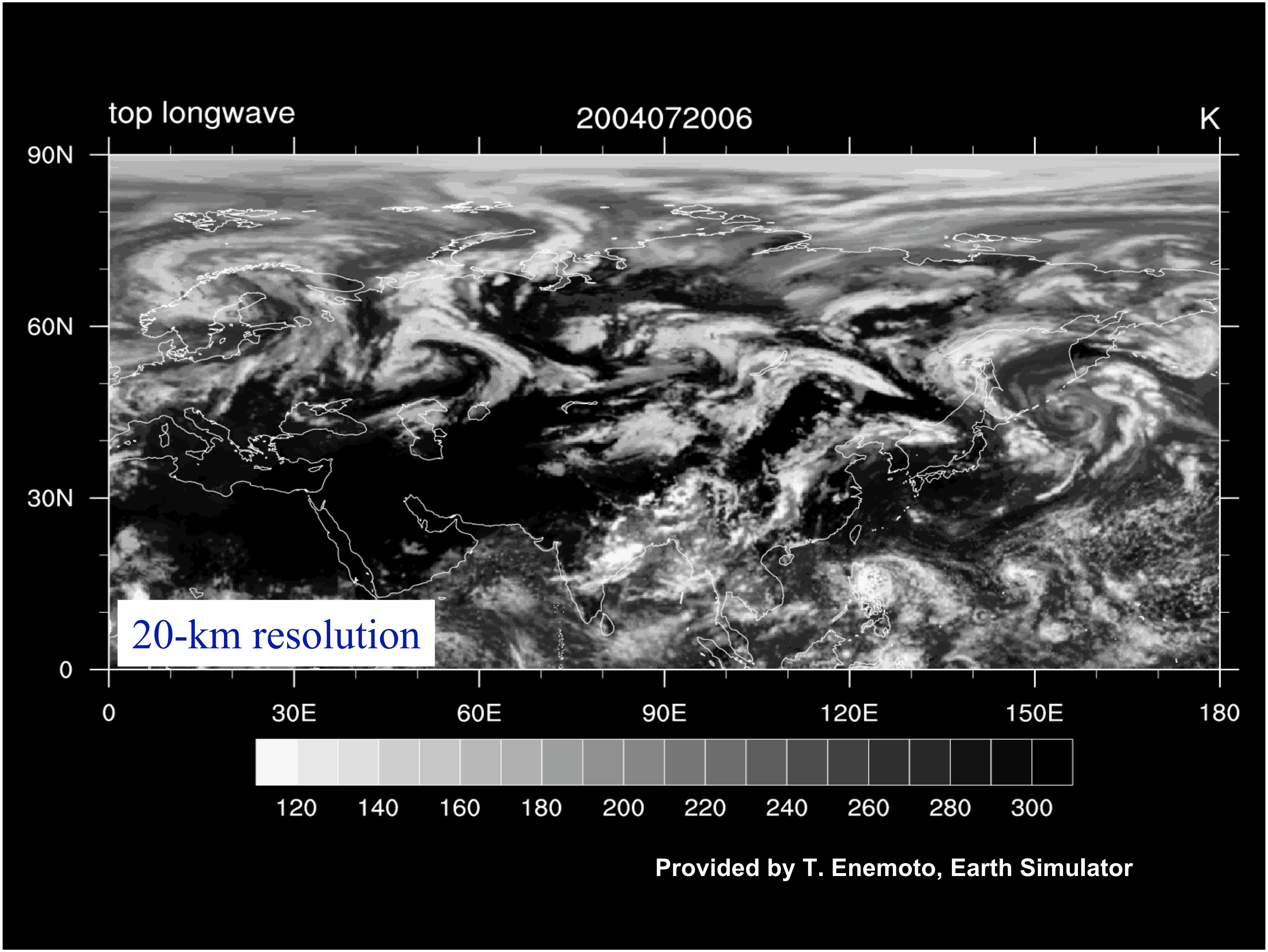
Under-resolved explicit dynamics



Cloud-system resolving models (CRM) at ~100 m grid-resolution


top longwave
2004072006
K
90N
60N
30N
0
0
30E
60E
90E
120E
150E
180
120
140
160
180
200
220
240
260
280
300
320-km resolution
Provided by T. Enemoto, Earth Simulator


top longwave
2004072006
K
90N
60N
30N
0
0
30E
60E
90E
120E
150E
180
80-km resolution
120
140
160
180
200
220
240
260
280
300
Provided by T. Enemoto, Earth Simulator


top longwave
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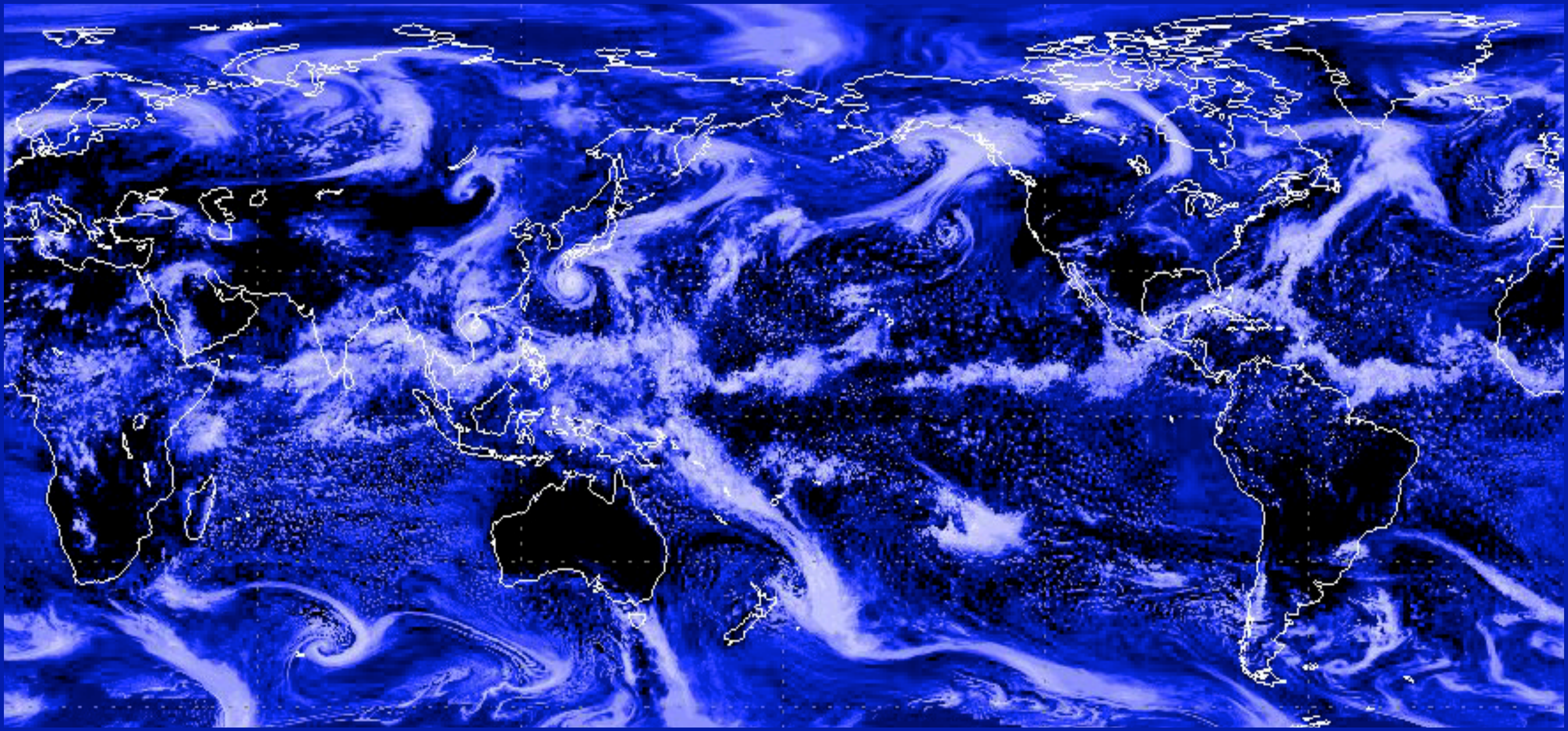
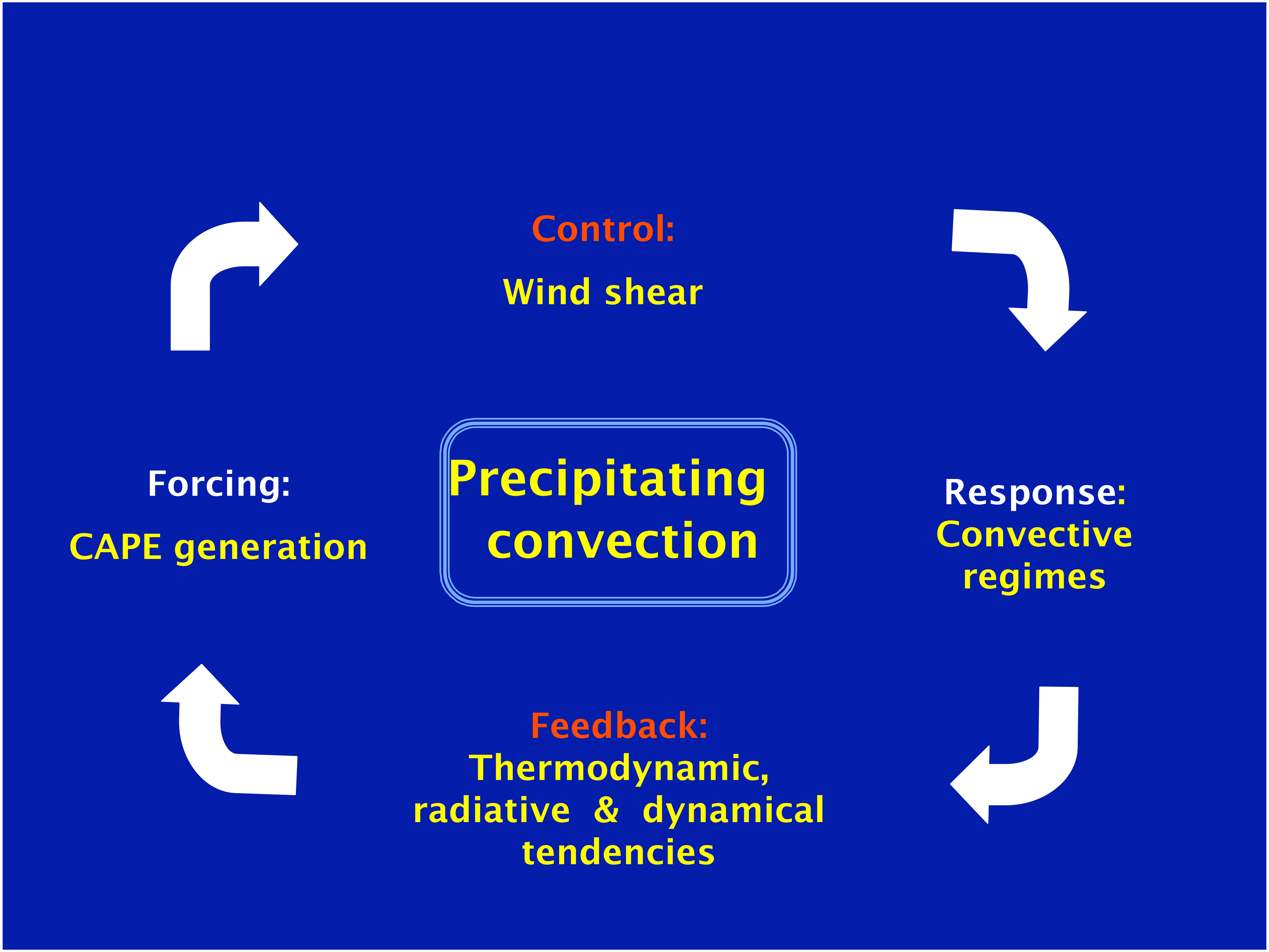
160
180
200
220
240
260
280
300
20-km resolution
Provided by T. Enemoto, Earth Simulator

T1279 L96 simulation on Japan's Earth Simulator:

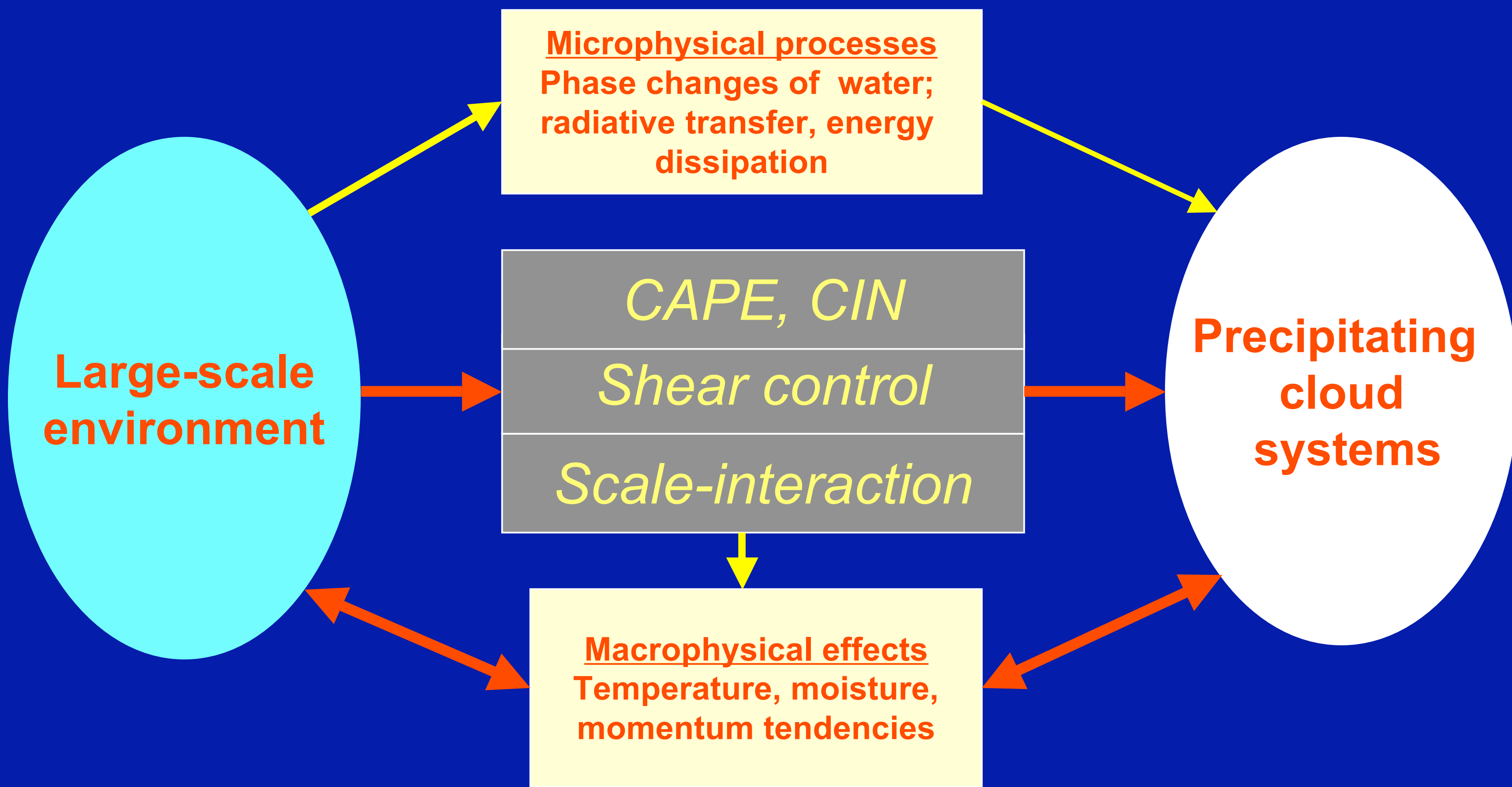
(15-km horizontal, 500 m vertical)



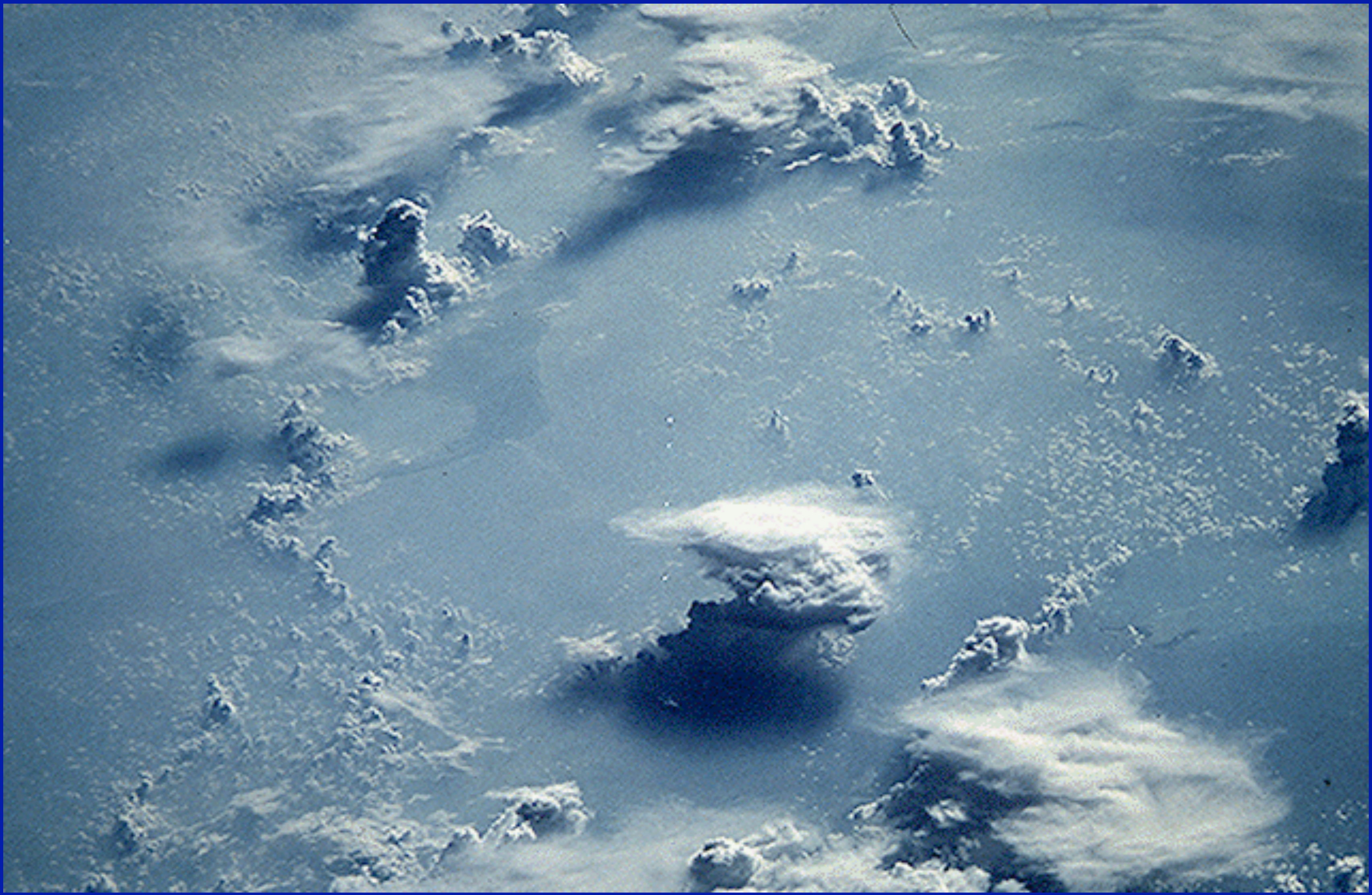
Ohfuchi et al. (2004)


Control:
Wind shear
Forcing:
CAPE generation
Precipitating convection
Response:
Convective regimes
Feedback:
Thermodynamic, radiative & dynamical tendencies

Macrophysics and convective organization

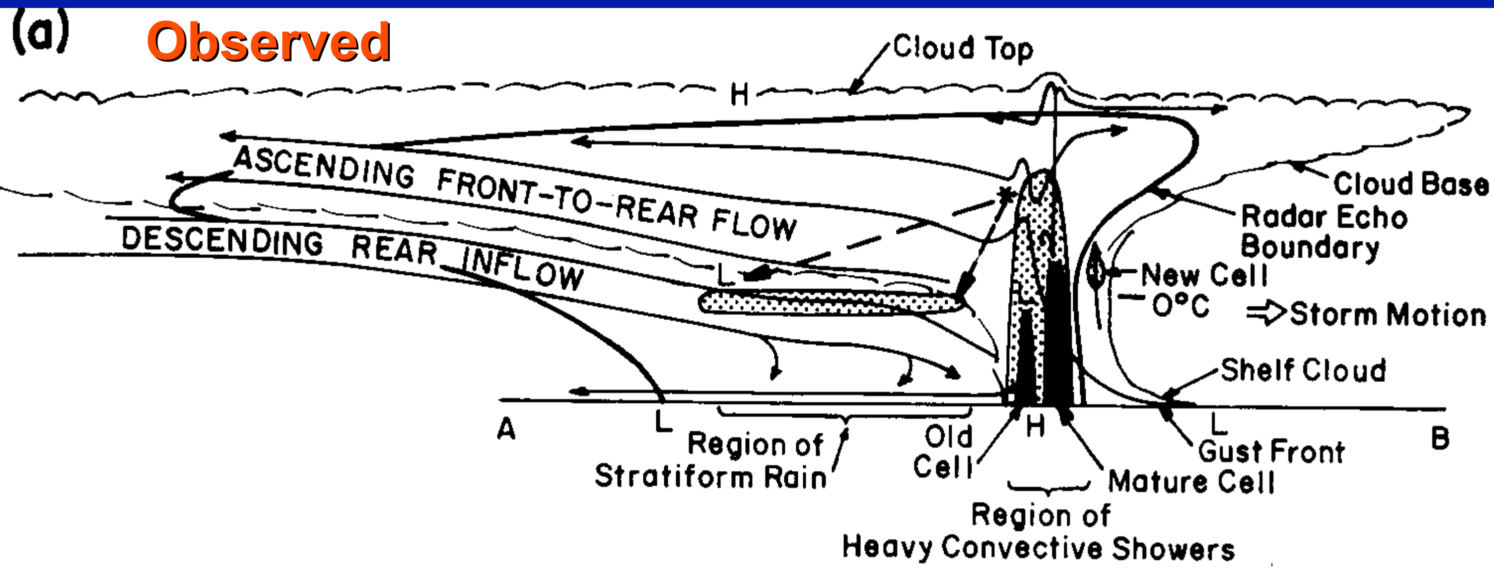


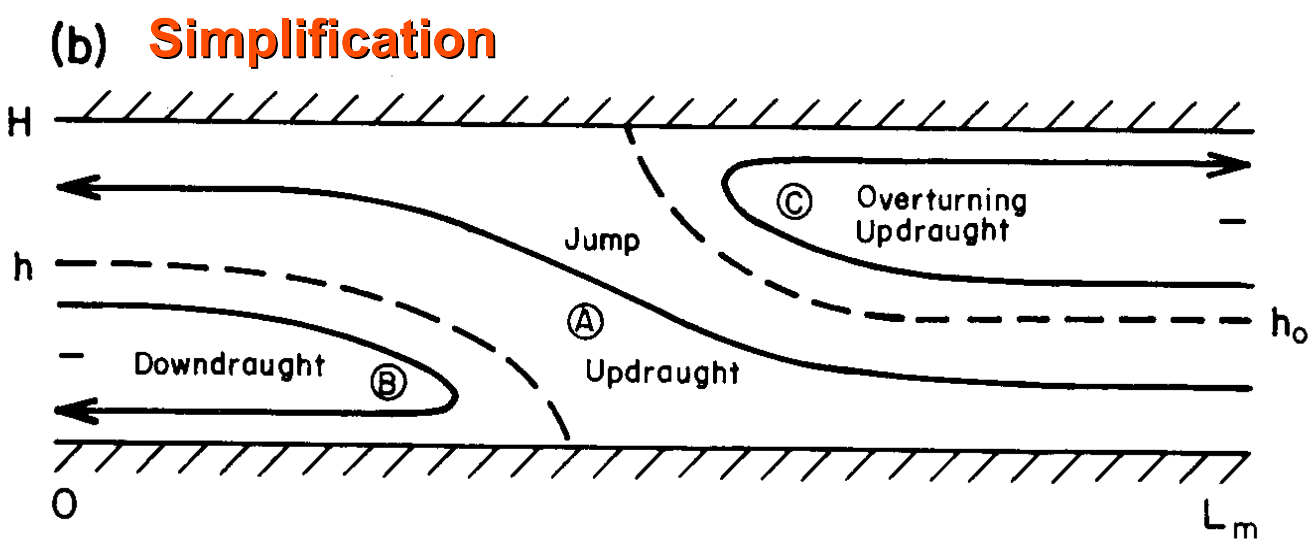
A 'field-theory' for atmospheric convection is the ultimate need



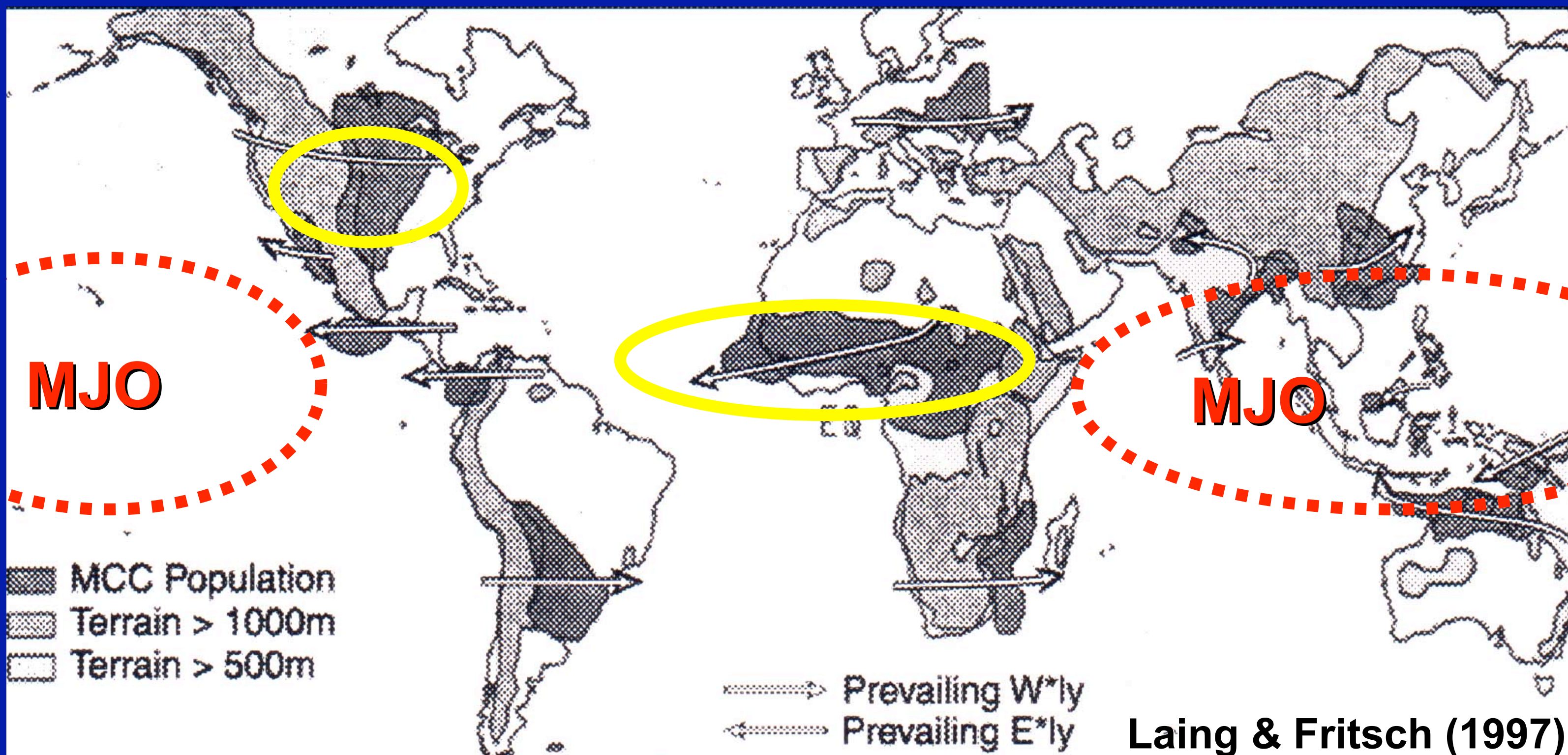
Organized traveling convection of the mesoscale convective system (MCS) kind

Conceptual MCS



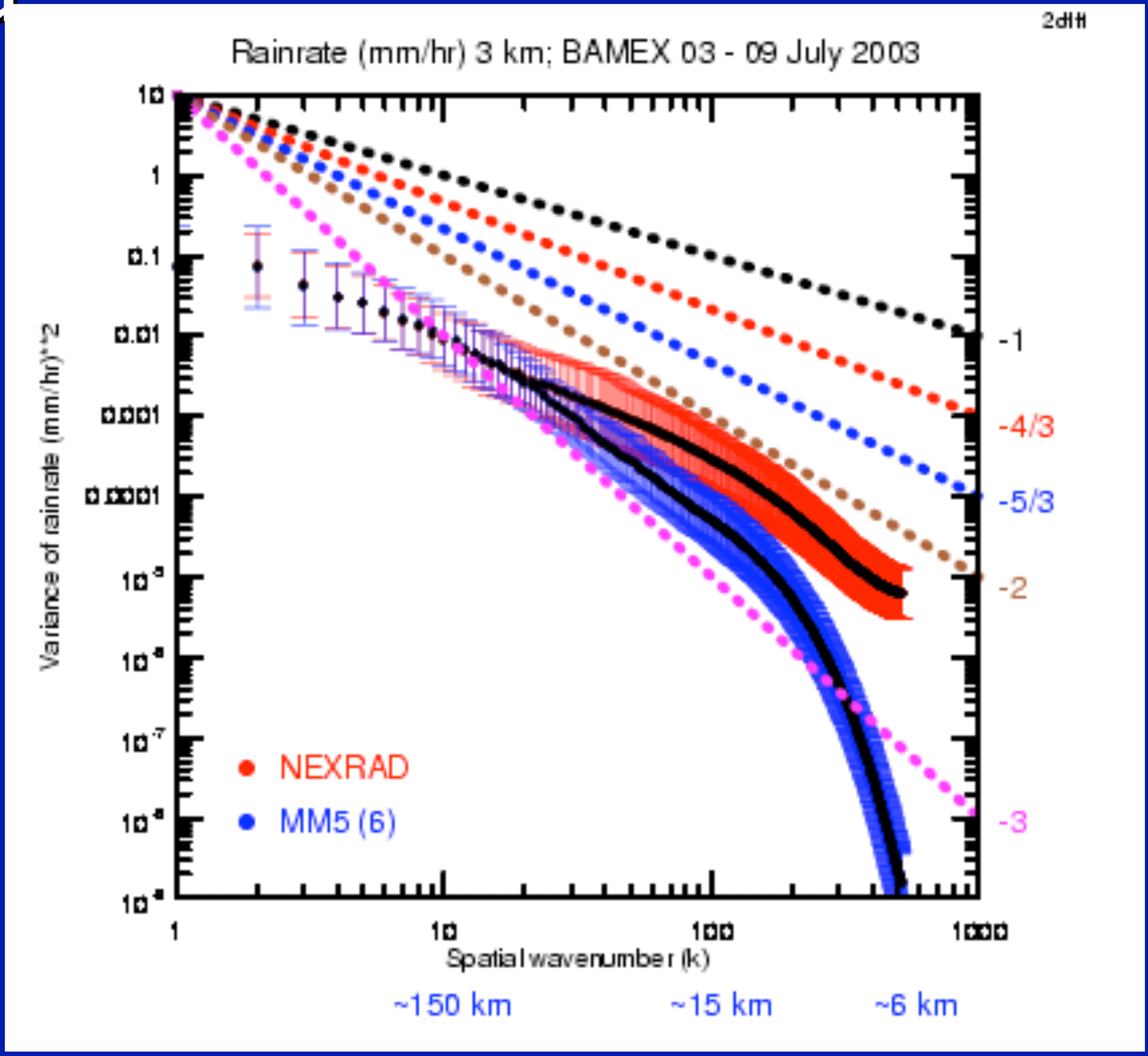


Large-scale convective organization

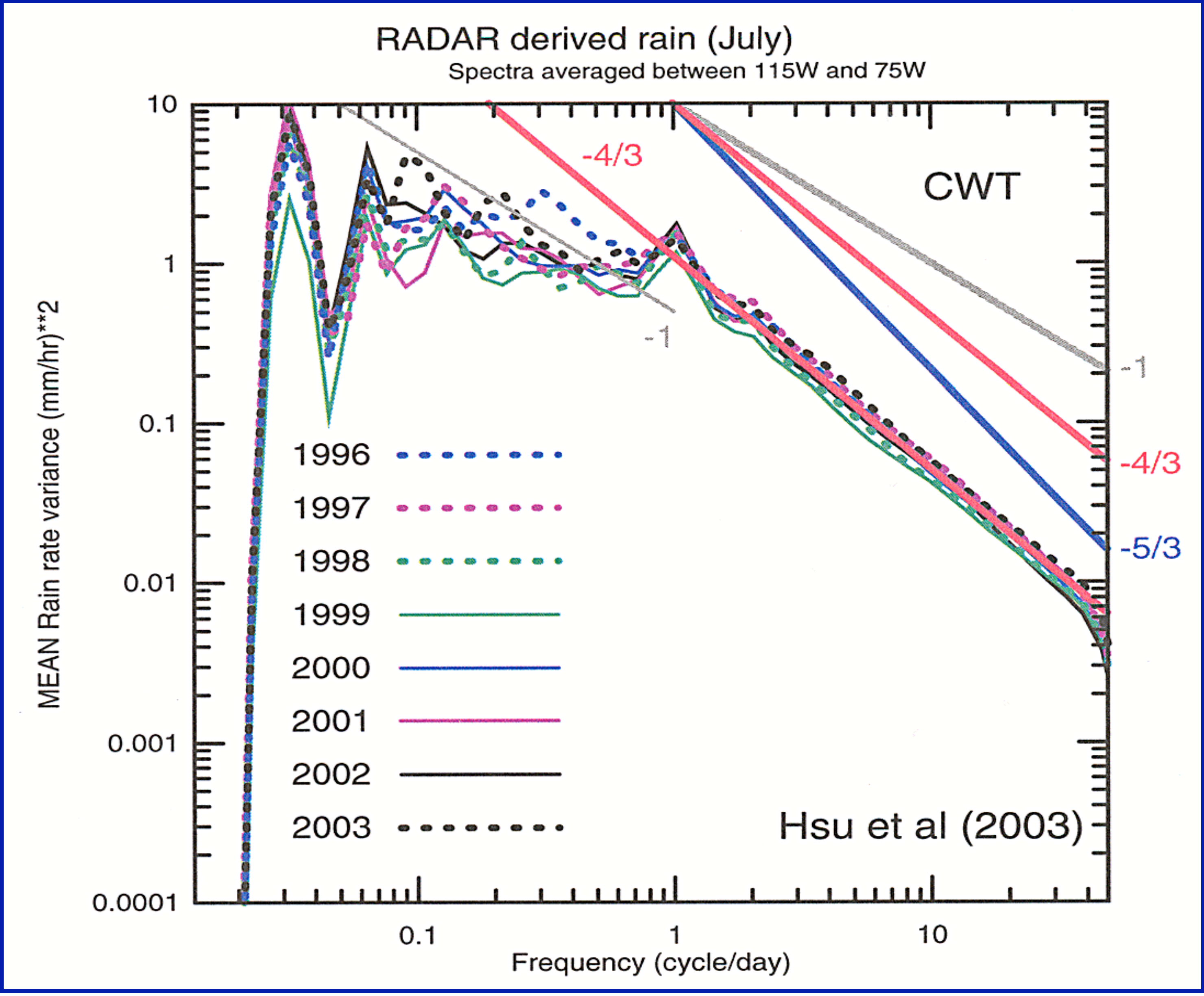


... correlated with shear zones & steep orography

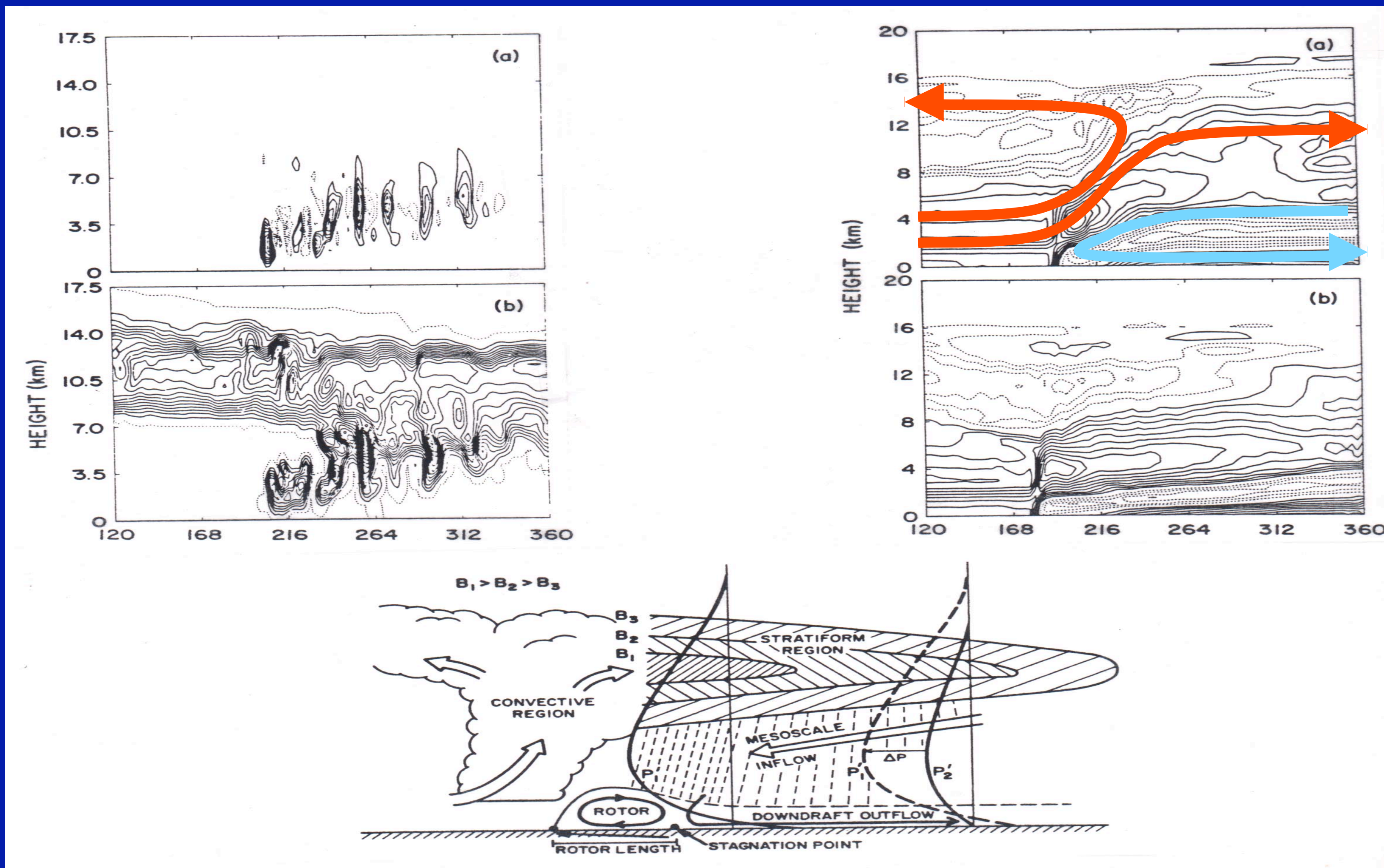
Coma


2dfft
Rainrate (mm/hr) 3 km; BAMEX 03 - 09 July 2003
Variance of rainrate (mm/hr)**2
Spatial wavenumber (k)
1
10
100
1000
-1
-4/3
-5/3
-2
-3
NEXRAD
MM5 (6)
~150 km
~15 km
~6 km

Convective precipitation: a scaling law?

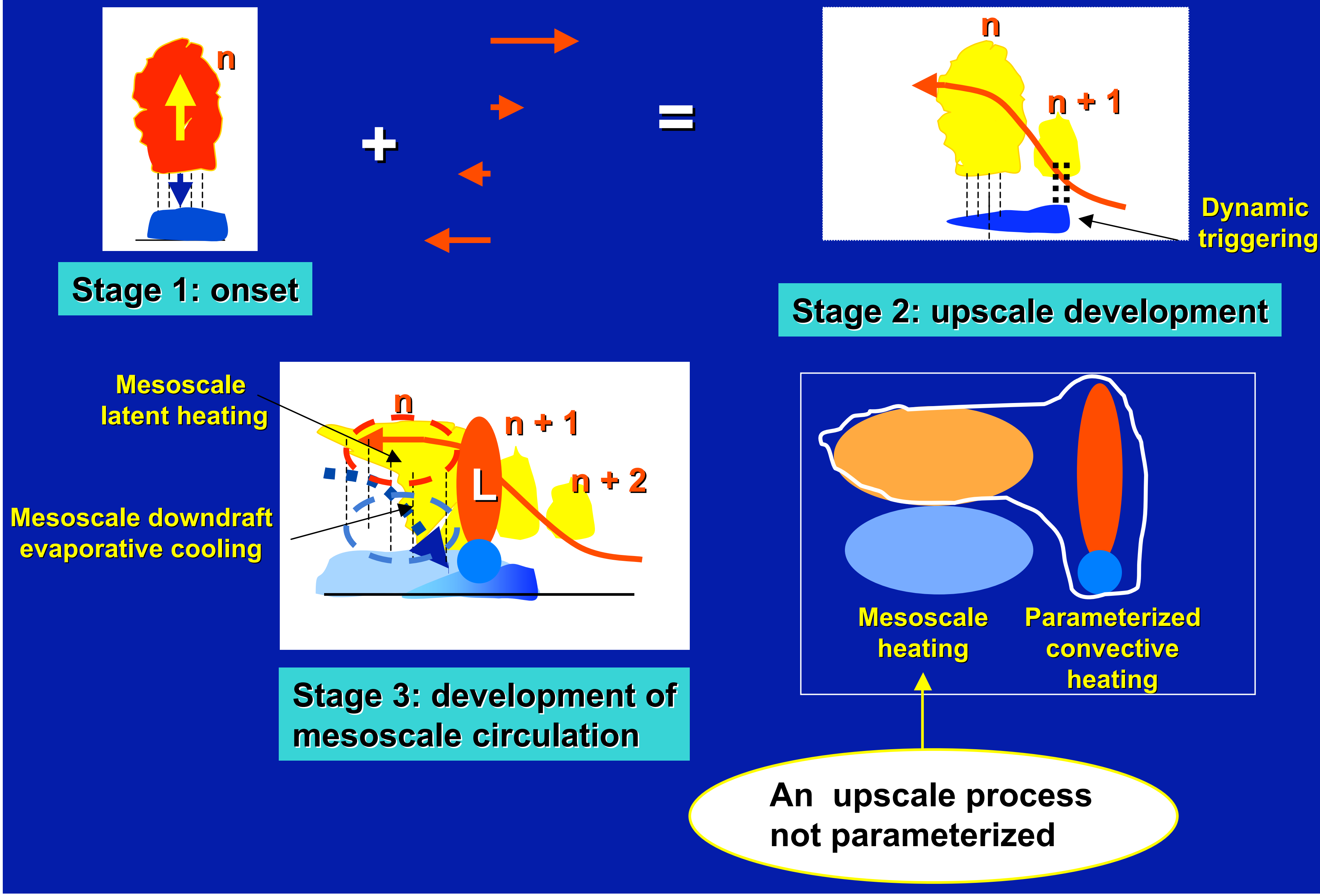


Convective-stratiform interaction



Lafore & Moncrieff (1989)

Physics of upscale evolution



Steady, finite-amplitude convective overturning

Lagrangian conservation properties

Fundamental Theorem of Calculus

applied to the total derivative:

$$\frac{D}{Dt}\int_{z_0}^{z} F(\psi, z')\; dz' \;=\; \frac{Dz}{Dt}F(\psi, z) \;-\; \frac{Dz_0}{Dt}F(\psi, z_0)$$

$$= wF(\psi, z) - \cancel{w_0 F(\psi, z_0)}$$

$$= w\,F(\psi, z)$$

Conserved quantities for 2D moist convection

$$\frac{D\eta}{Dt} = -g\frac{\partial\theta'}{\partial x} = -g\frac{\partial}{\partial\psi}\left(\frac{\partial\psi}{\partial x}\right) = w\frac{\partial F}{\partial\psi} = \frac{D}{Dt}\int_{z_0}^{z}\left(\frac{\partial F}{\partial\psi}\right)_{z'} dz'$$

$$\frac{D\phi_p}{Dt} = \dot{Q} = w\Gamma = \frac{D}{Dt}\int_{z_0}^{z}\Gamma_p\, dz \;,\; where\;\; \phi = c_p \ln\theta \;\; and$$

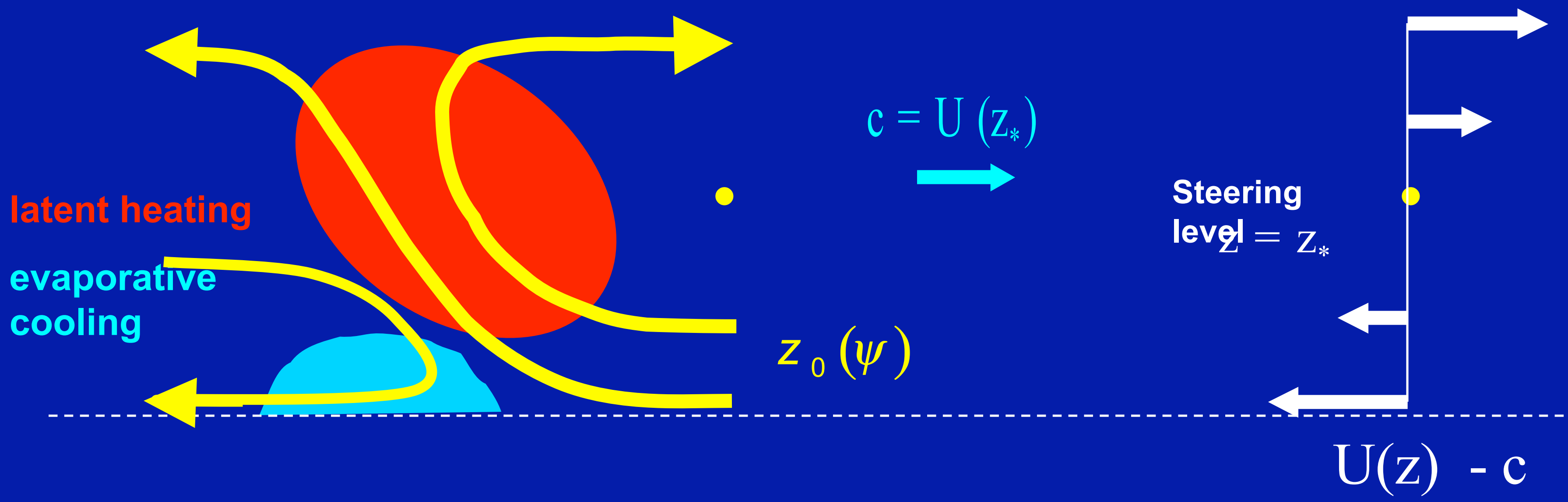
$$\Gamma_p = moist\;\; adiabat$$

Conserved quantities:

$$\eta = G_1(\psi) + \int_{z_0}^{z}\left(\frac{\partial F}{\partial\psi}\right)_{z'} dz' \quad - \quad vorticity$$

$$\phi_p = G_2(\psi) + \int_{z_0}^{z}\Gamma\, dz \quad - \quad entropy$$

Generalized nonlinear eigen-value / free-boundary theory of organized convection



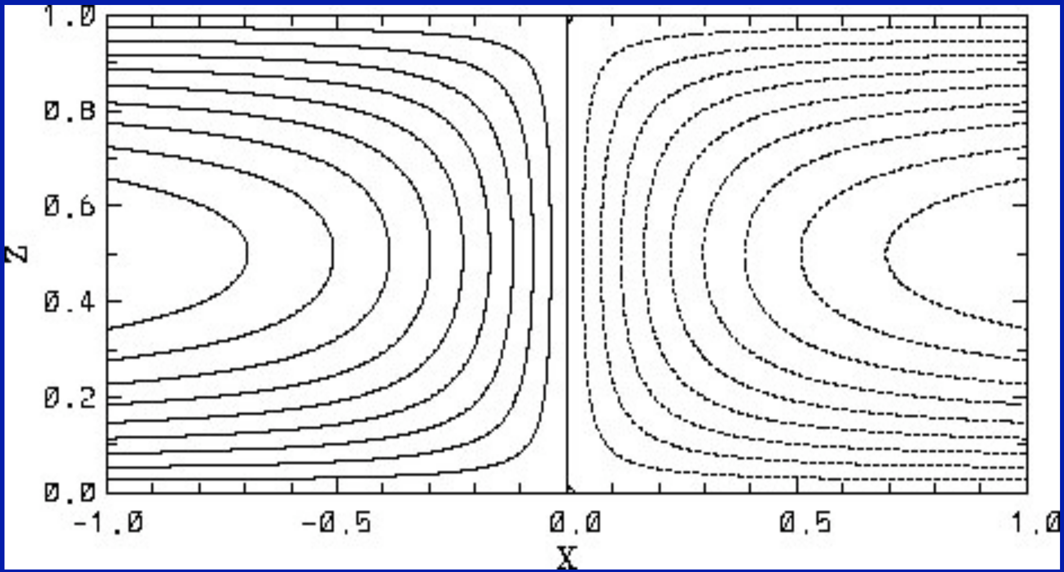
Formally represented by Moncrieff & Green's equation:

$$\nabla^2\psi = G(\psi) + \int_{z_0}^{z}\left(\frac{\partial F}{\partial \psi}\right)dz$$

vorticity along trajectories — inflow vorticity — vorticity generated by latent heating

$F(\psi, z, c)$: parcel buoyancy

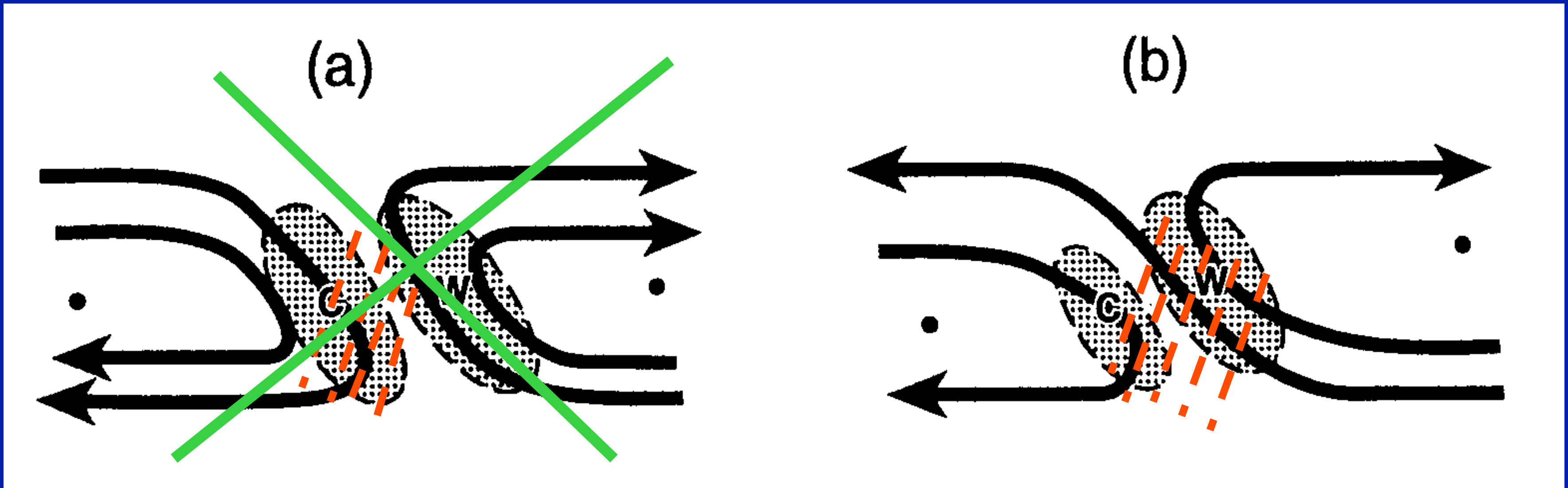
A complete analytic solution for unsheared environments



$$\psi(x,z) = \frac{Uz}{H}(z-H) + \frac{8UH}{\pi^3}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^3} sin[(2n+1)\frac{\pi z}{H} exp[-(2n+1)\frac{\pi|x|}{H}$$

$$L\overline{w}(z) = 2Uz\big(1 - \frac{2Uz}{H}\big)$$

What's what the simplest possible (archetypal) model of steady traveling convection in shear?



Two-branch steady model

Convective overturning in constant shear (A):

$$\psi = A(z_0 - z_*)^2 \quad \text{inflow} \quad (z_0 < z_*)$$

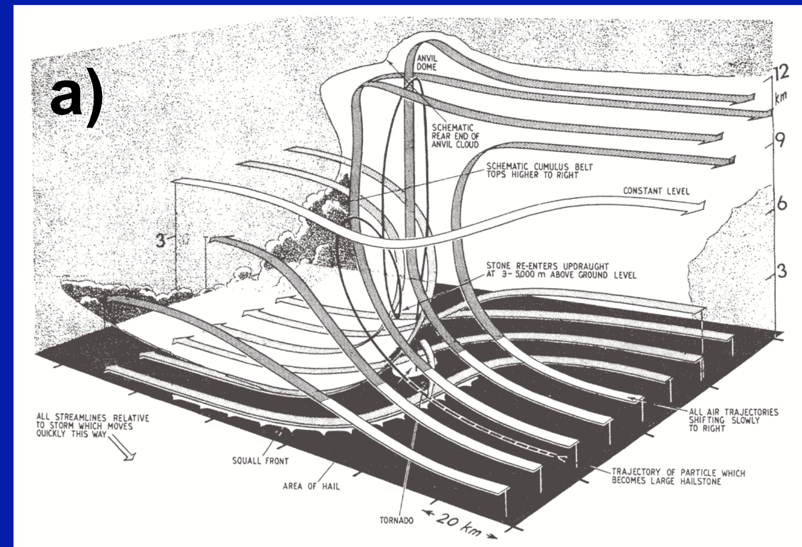
$$\psi = A\beta^2 (z_1 - z_*)^2 \quad \text{outflow} \quad (z_* < z_1)$$

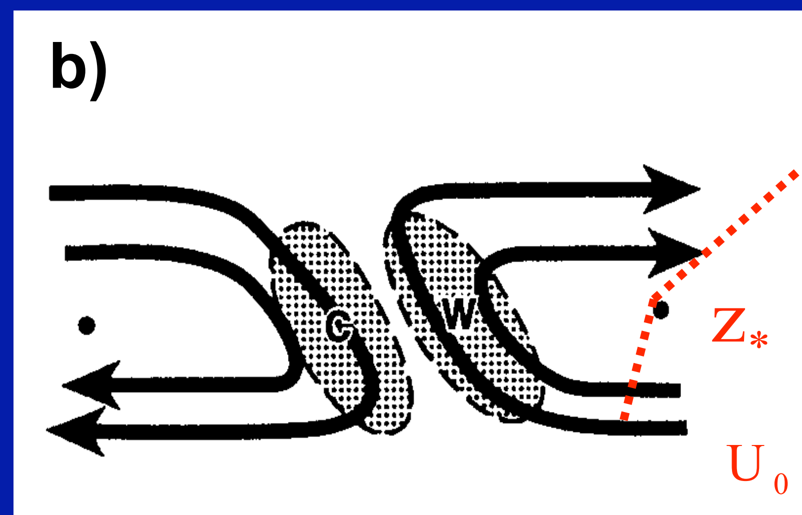
$$z_* = \beta H / (1 + \beta)$$

$$\beta = \tfrac{1}{2}\left(1 + \sqrt{1 + 4Ri}\right)$$

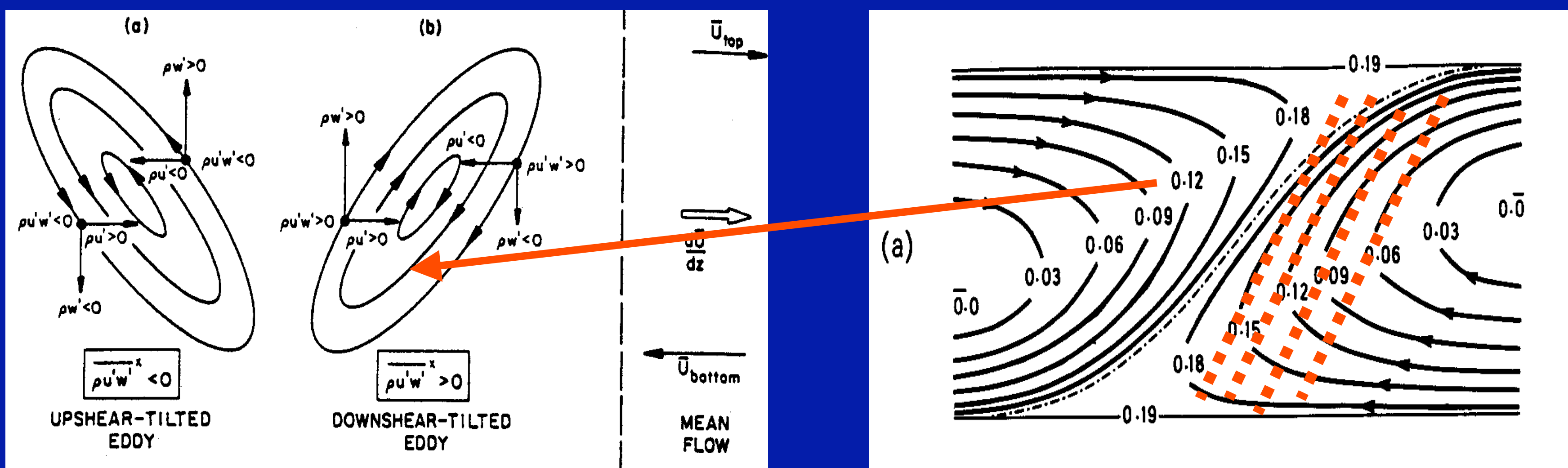
$$Ri = \frac{CAPE}{\frac{1}{2} U_0^2} \quad \text{Convective Richardson number}$$

$$CAPE > 0 \quad \text{so} \quad 1 < \beta^2 = \frac{\text{outflow shear}}{\text{inflow shear}}$$

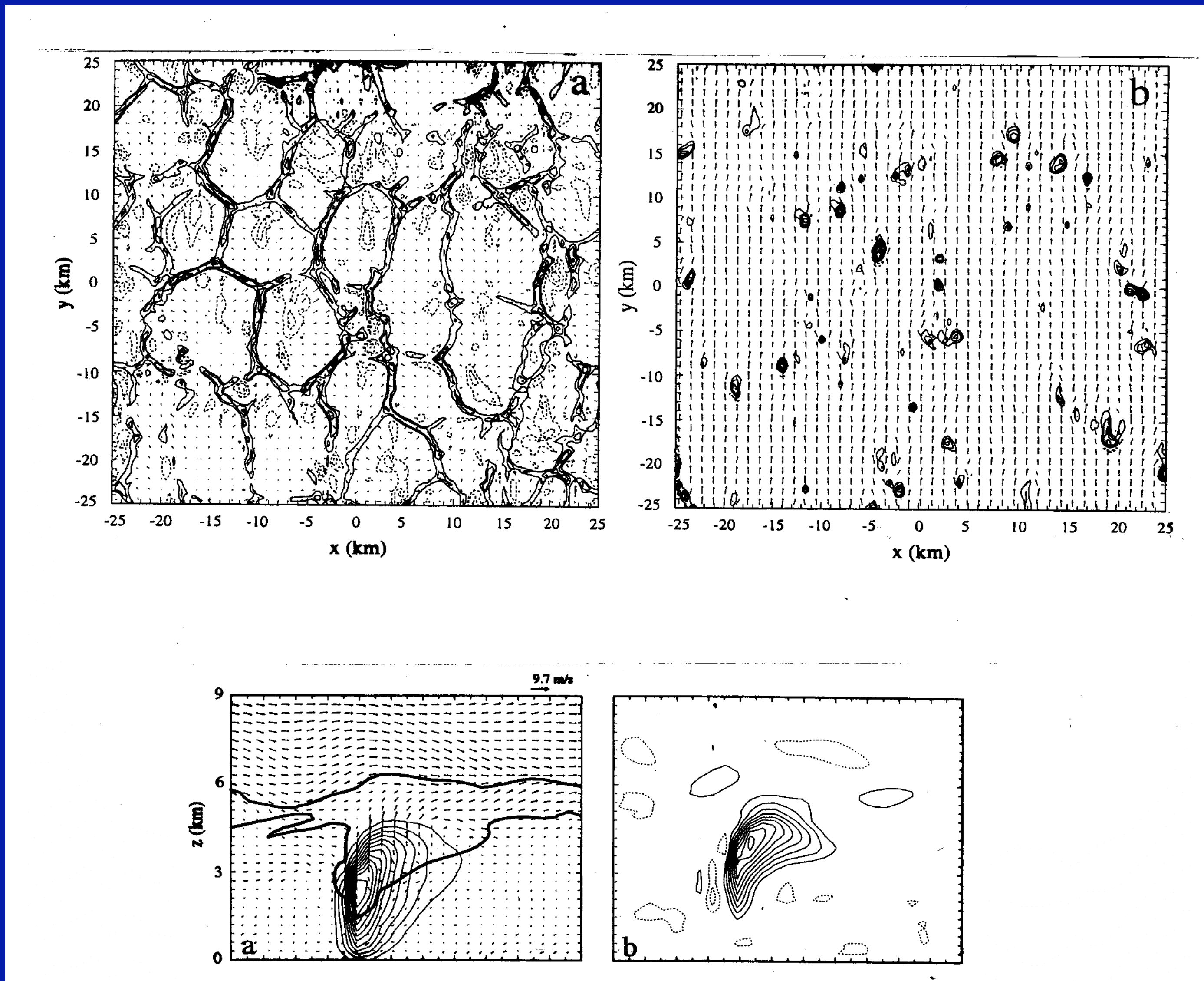




…free-boundary solution tilts downshear - two-branch model is physically unrealistic



Showers in polar outbreaks over oceans triggered by cellular organization in the boundary layer

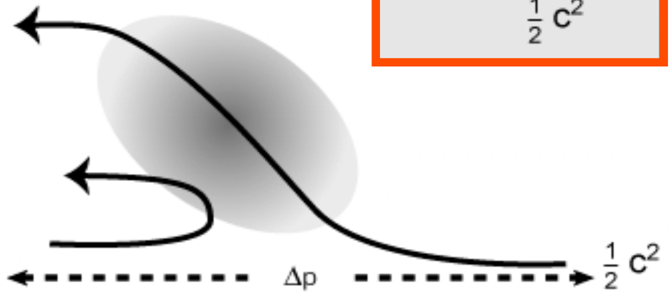


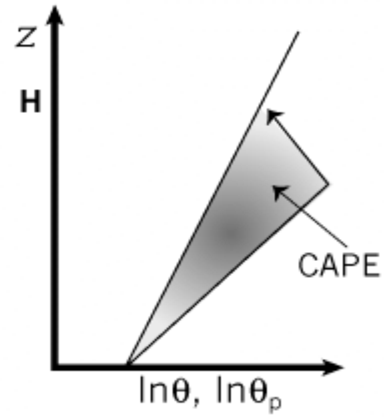
Grubisic & Moncrieff (1995)

MCS-like convective organization: two key dimensionless quantities

Convective Richardson number:

$$R = \frac{CAPE}{\frac{1}{2}c^2}$$





Bernoulli number:

$$E = \frac{\Delta p}{\frac{1}{2}\rho c^2}$$

Density-current-like (hydraulic) behavior

Formal definition of convective organization

- **Integrating the horizontal momentum equation along trajectories gives a dimensionless quantity D, the ratio of the eddy Reynolds number to dynamical quantities**

- **Organized convection characterized by *D* << 1**

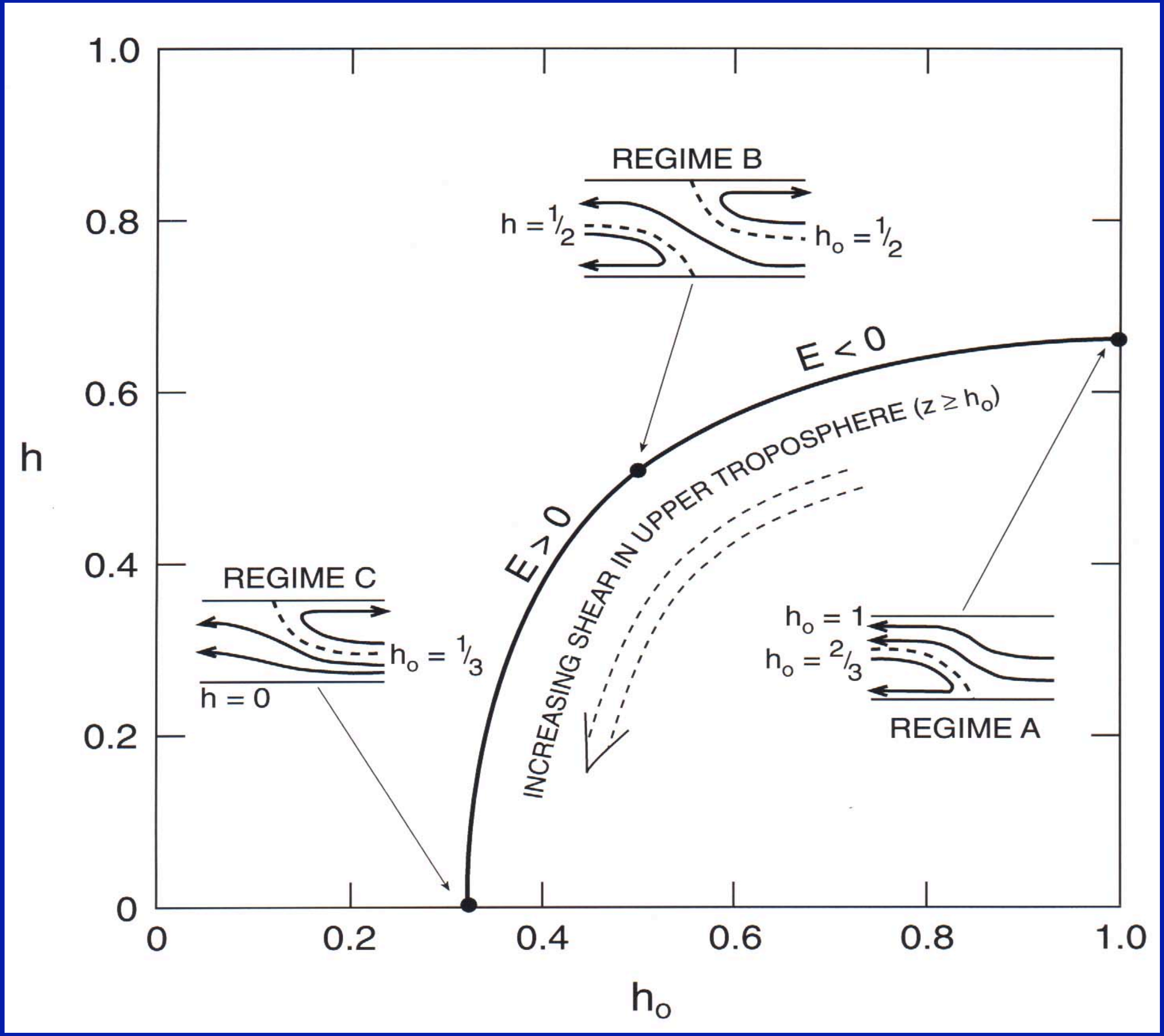
$$\frac{u_c}{u_\psi}(\underset{\sim}{x},t) = 1 + \int_\psi [\left(\frac{K_E}{u_\psi L}\right)\left(\frac{L}{u_c}\right)\nabla^2 u_c - \left(\frac{u_\psi}{u_c}\right)\frac{\partial}{\partial x}\frac{p}{\rho u_\psi^2}]dx$$

$$\boxed{D = \frac{\frac{K_E}{U L}}{\frac{\Delta p}{\rho u_\psi{}^2}\left(\frac{H}{L}\right)^2}}$$

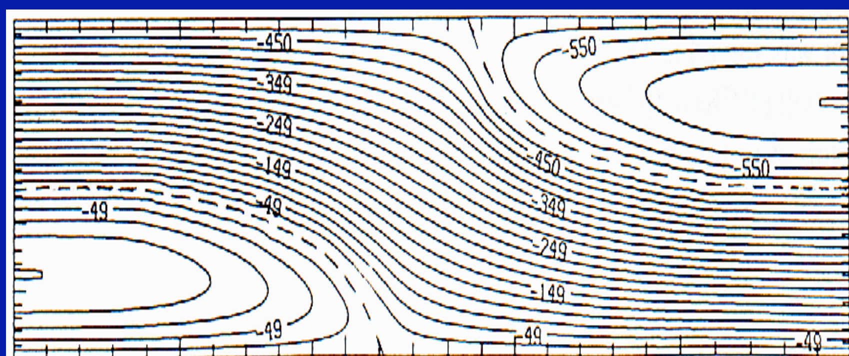
u_c and u_ψ **--- in-cloud & inflow horizontal velocities, respectively**

The simplest possible three-branch set of solutions: The archetypal regimes

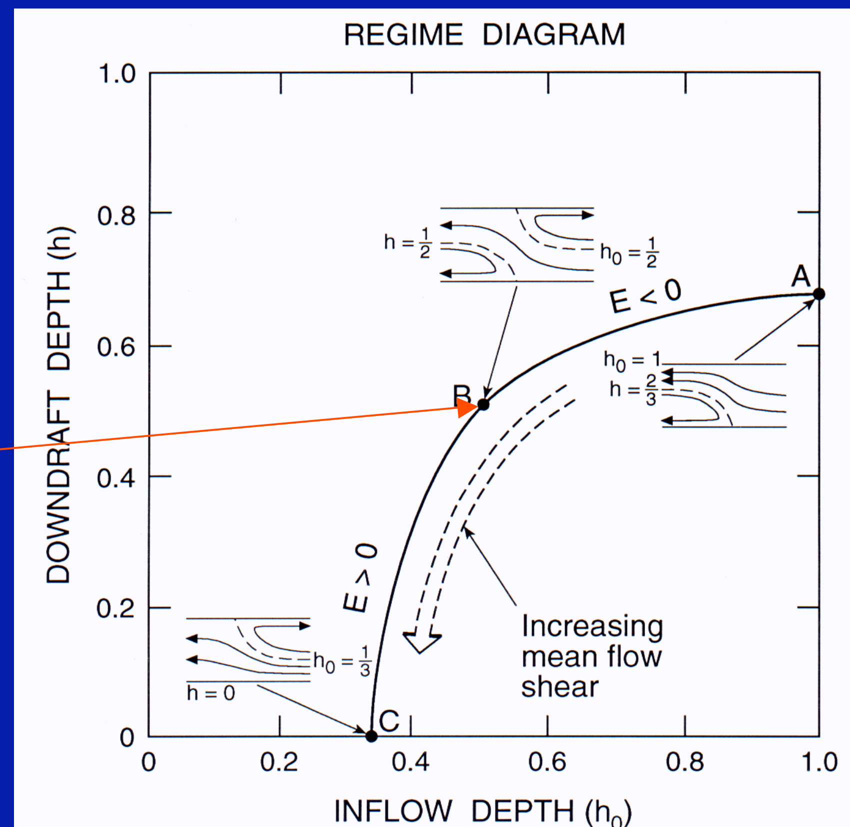
$$E = \frac{\Delta p}{\frac{1}{2}\rho c^2}$$



The simplest possible three-branch set of solutions: The archetypal regimes

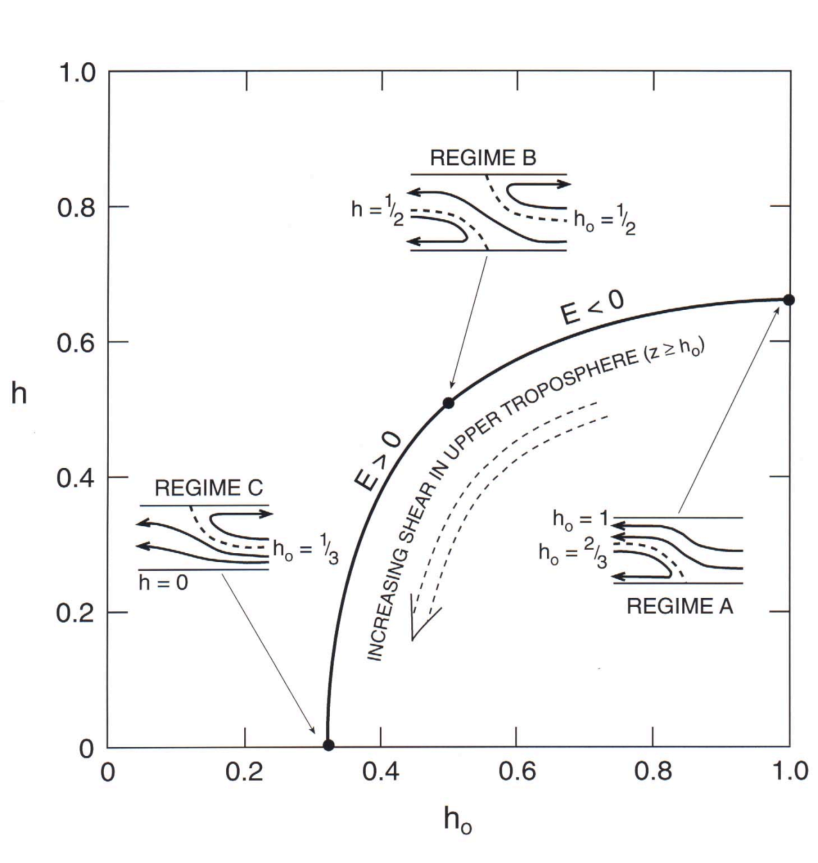


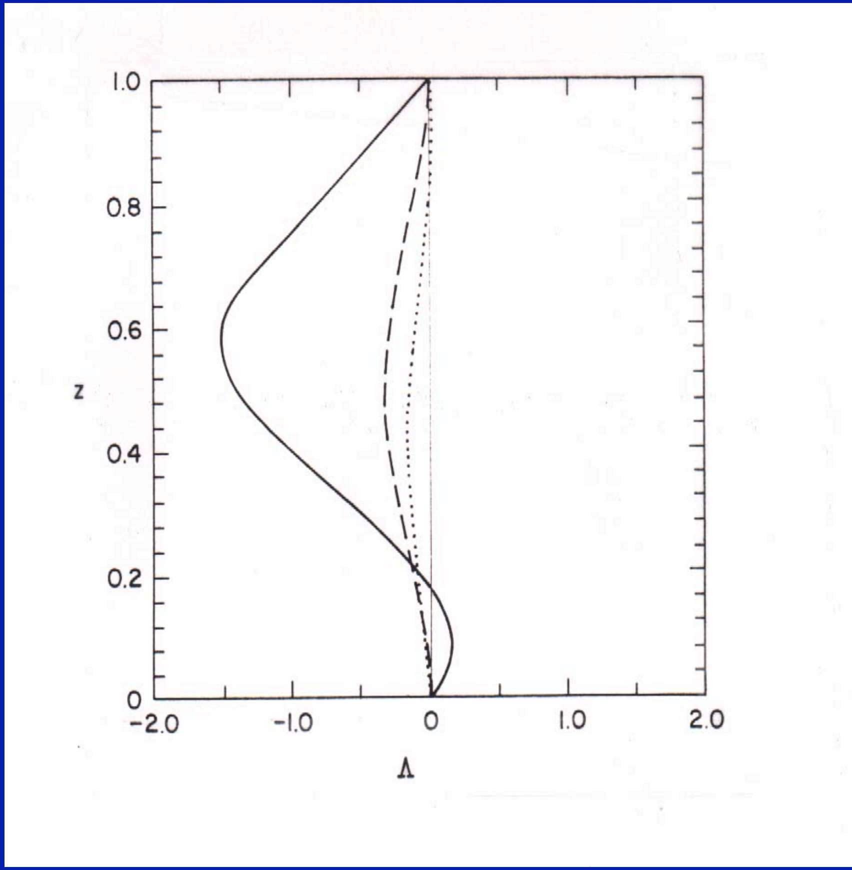
Free-boundary solution for E = 0



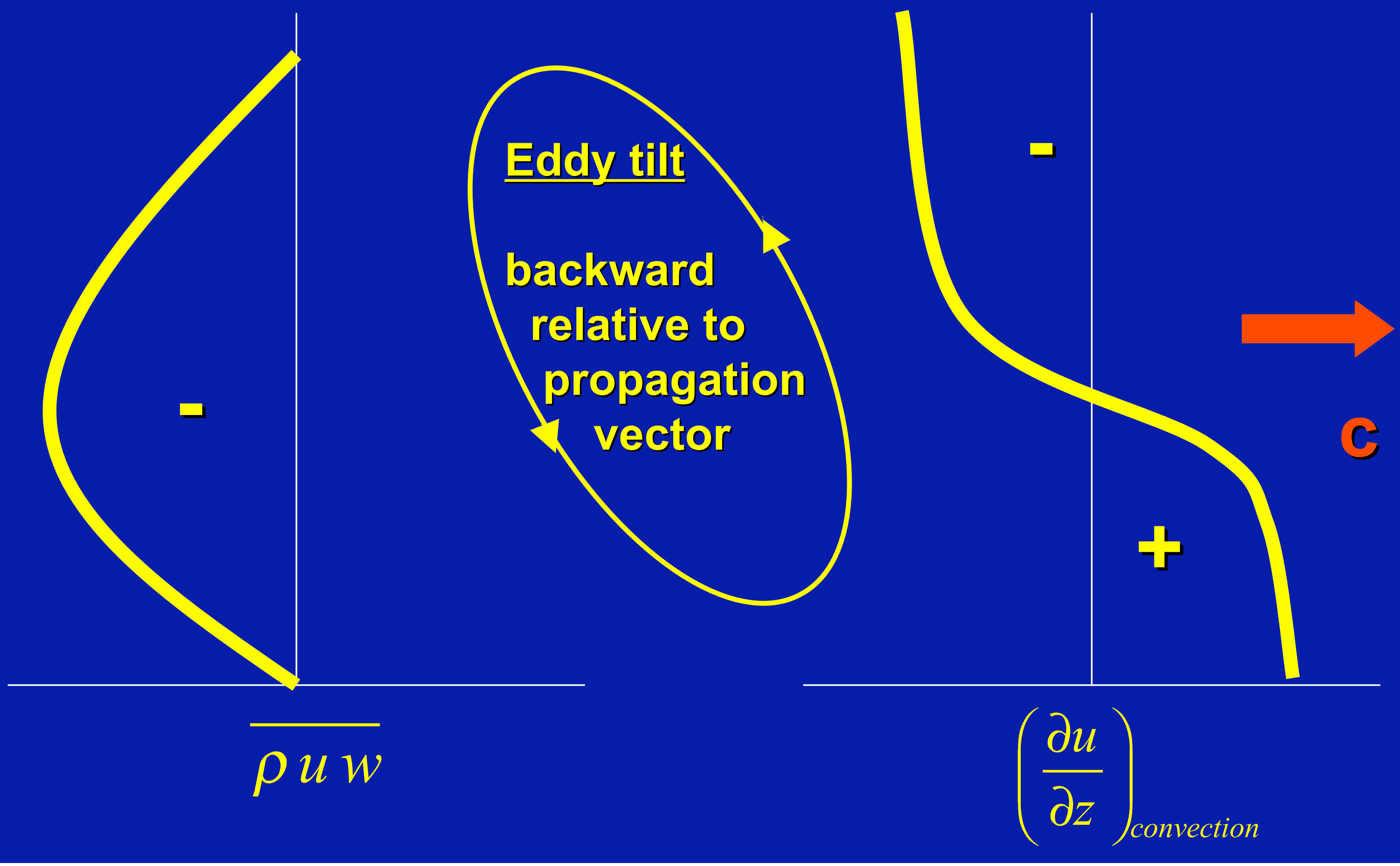
Moncrieff (1992)

Vertical transport of horizontal momentum

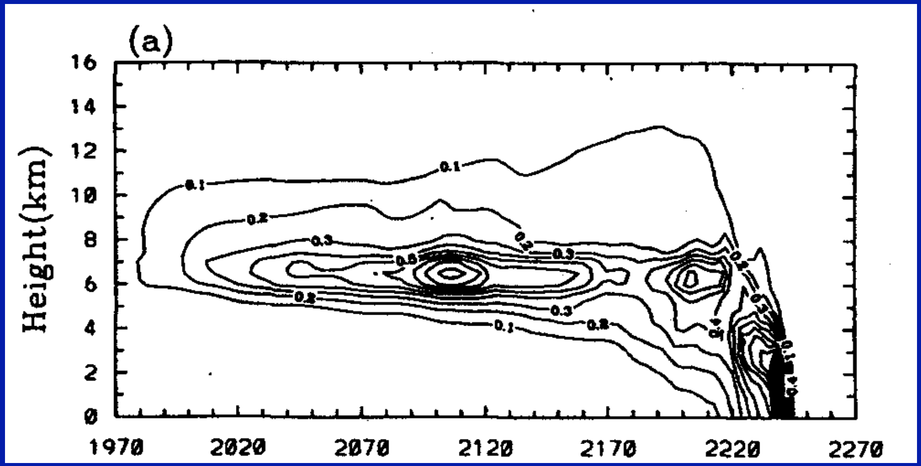


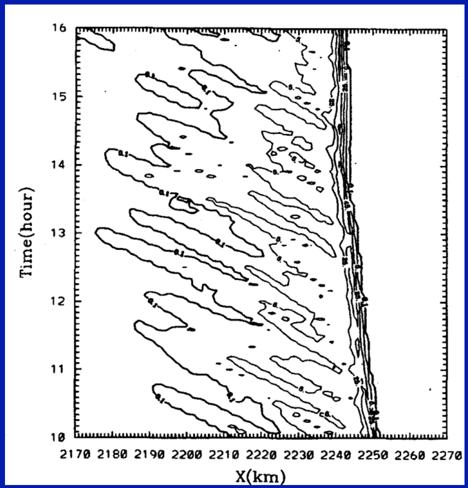


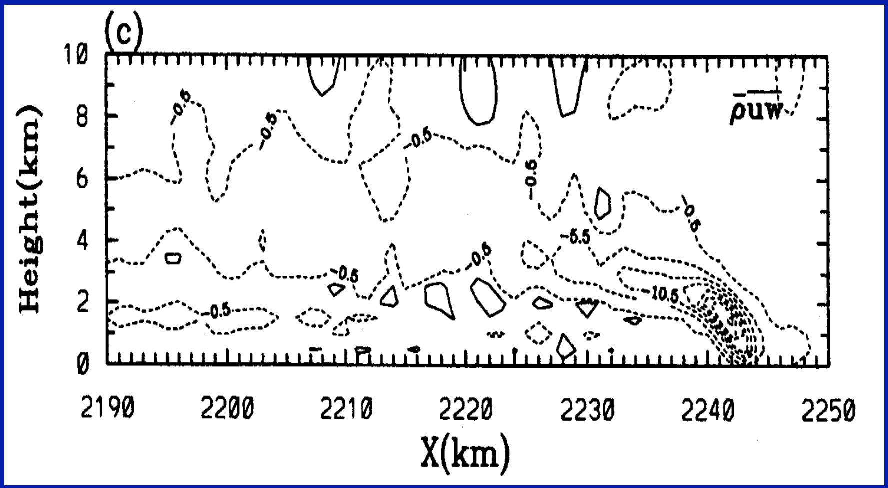
Conceptualization of momentum transport

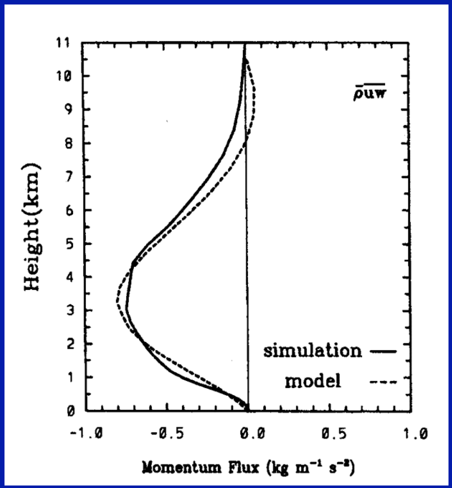


Validation against numerical simulation





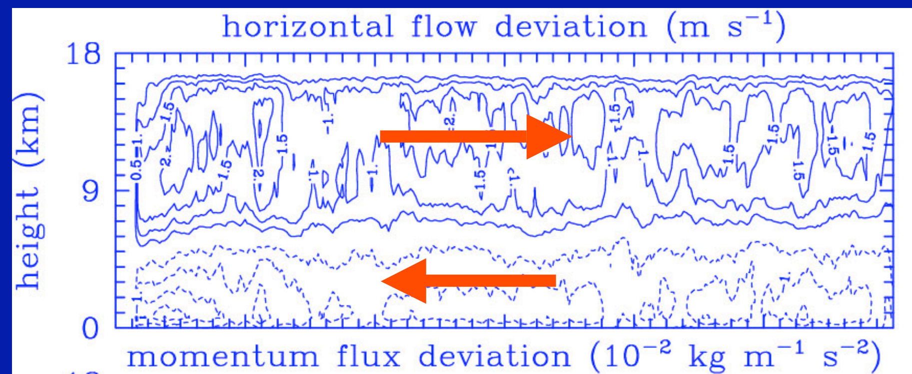


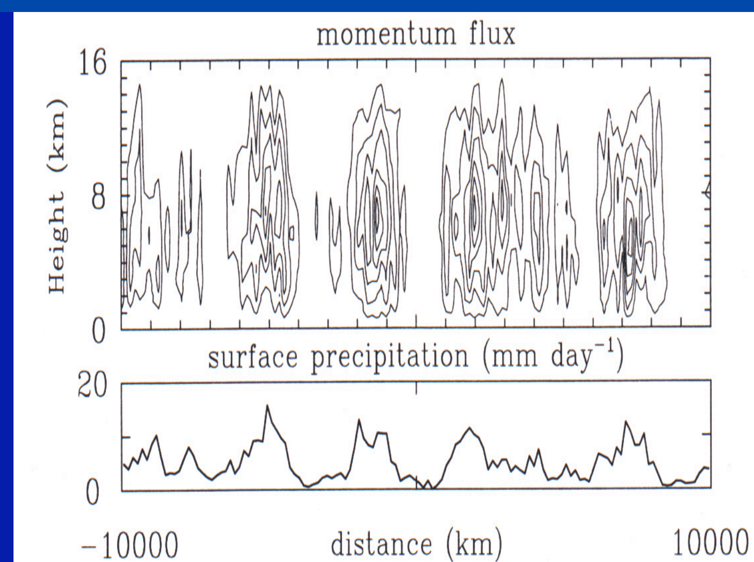


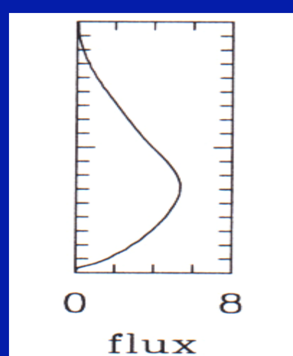
Wu and Moncrieff (1996)

Shear generation from a resting initial state

Mesoscale convective systems generate shear -- redistribute horizontal momentum in the vertical: a positive dynamical feedback recalling that MCS live on shear flow

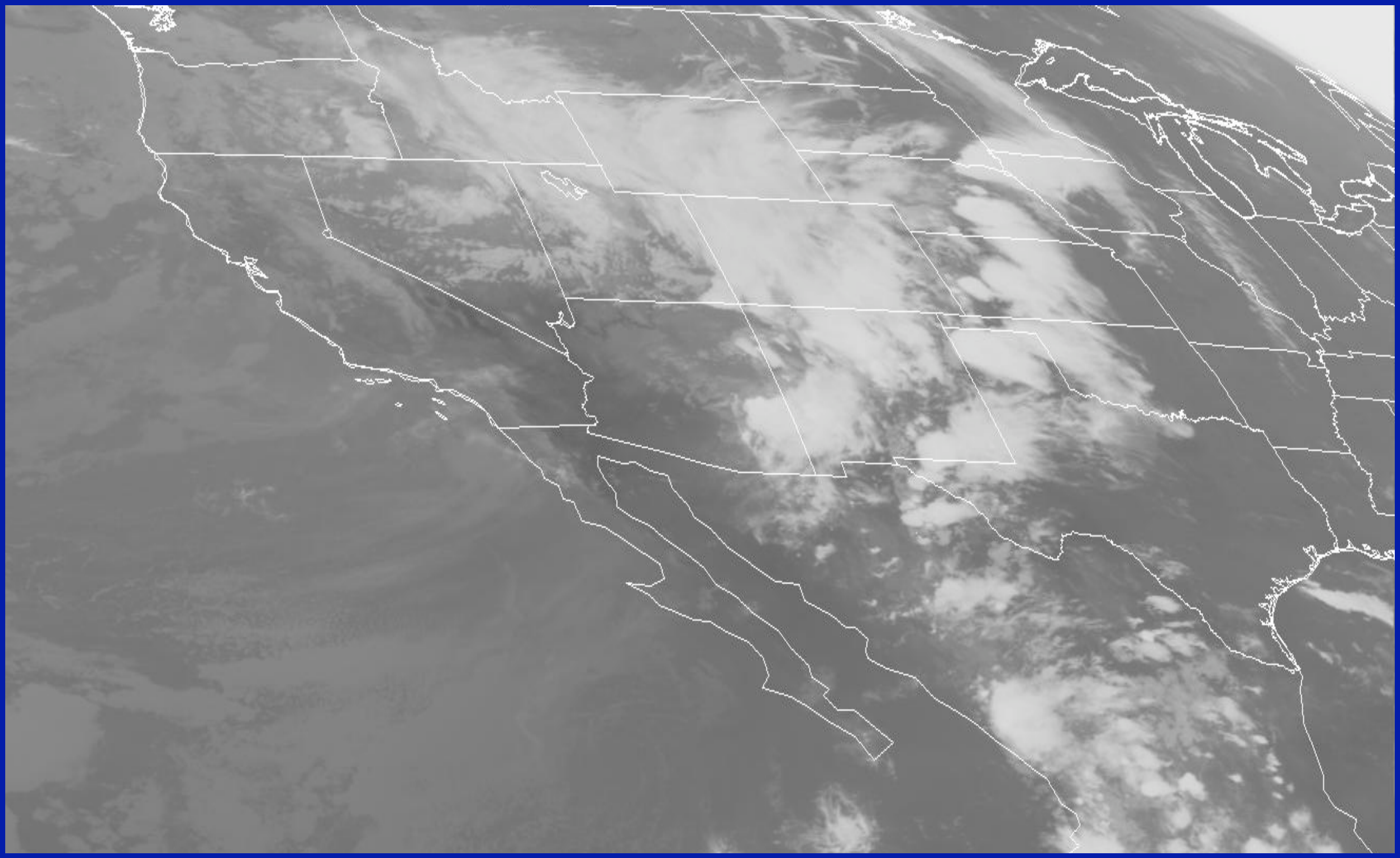




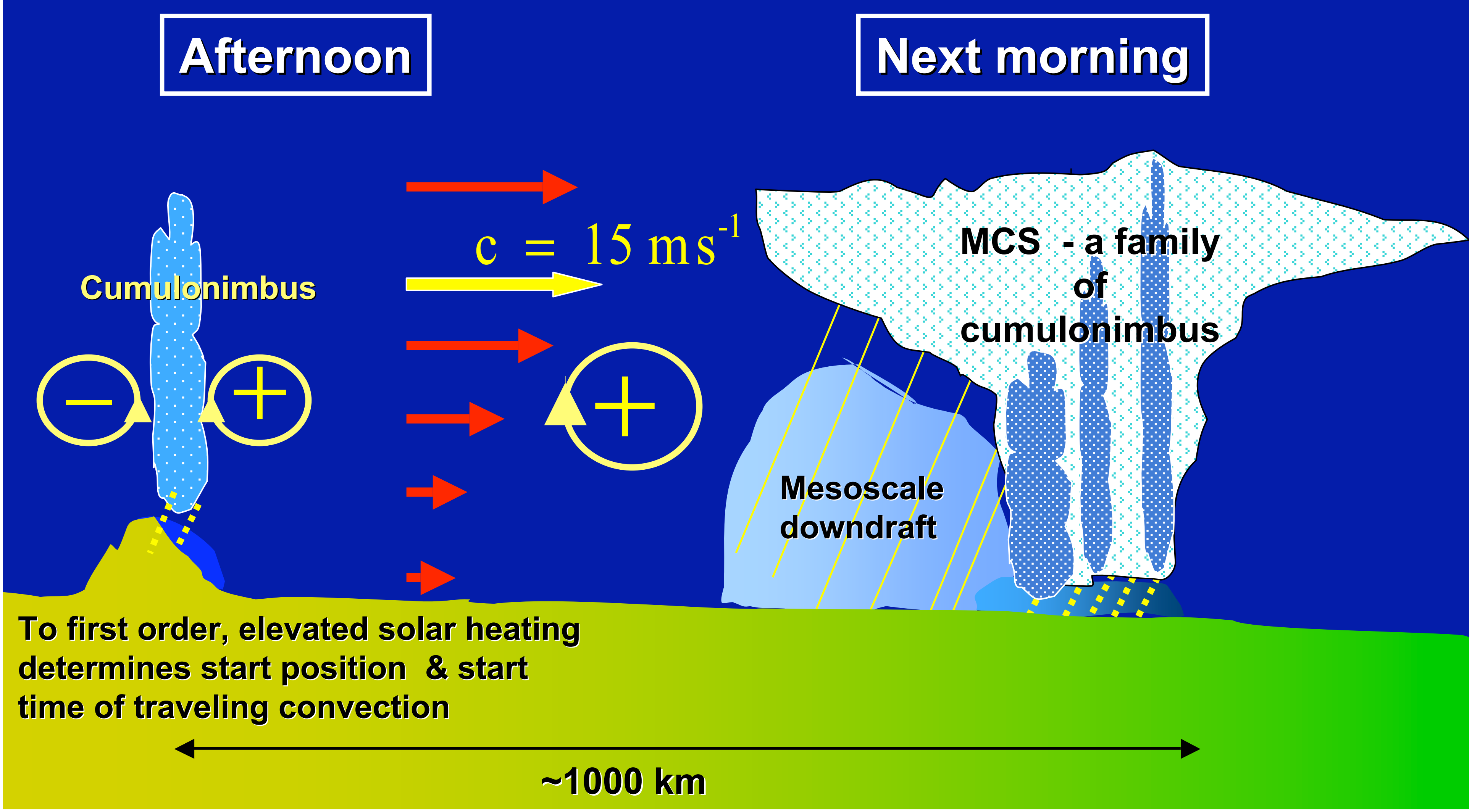


Grabowski & Moncrieff (2001)

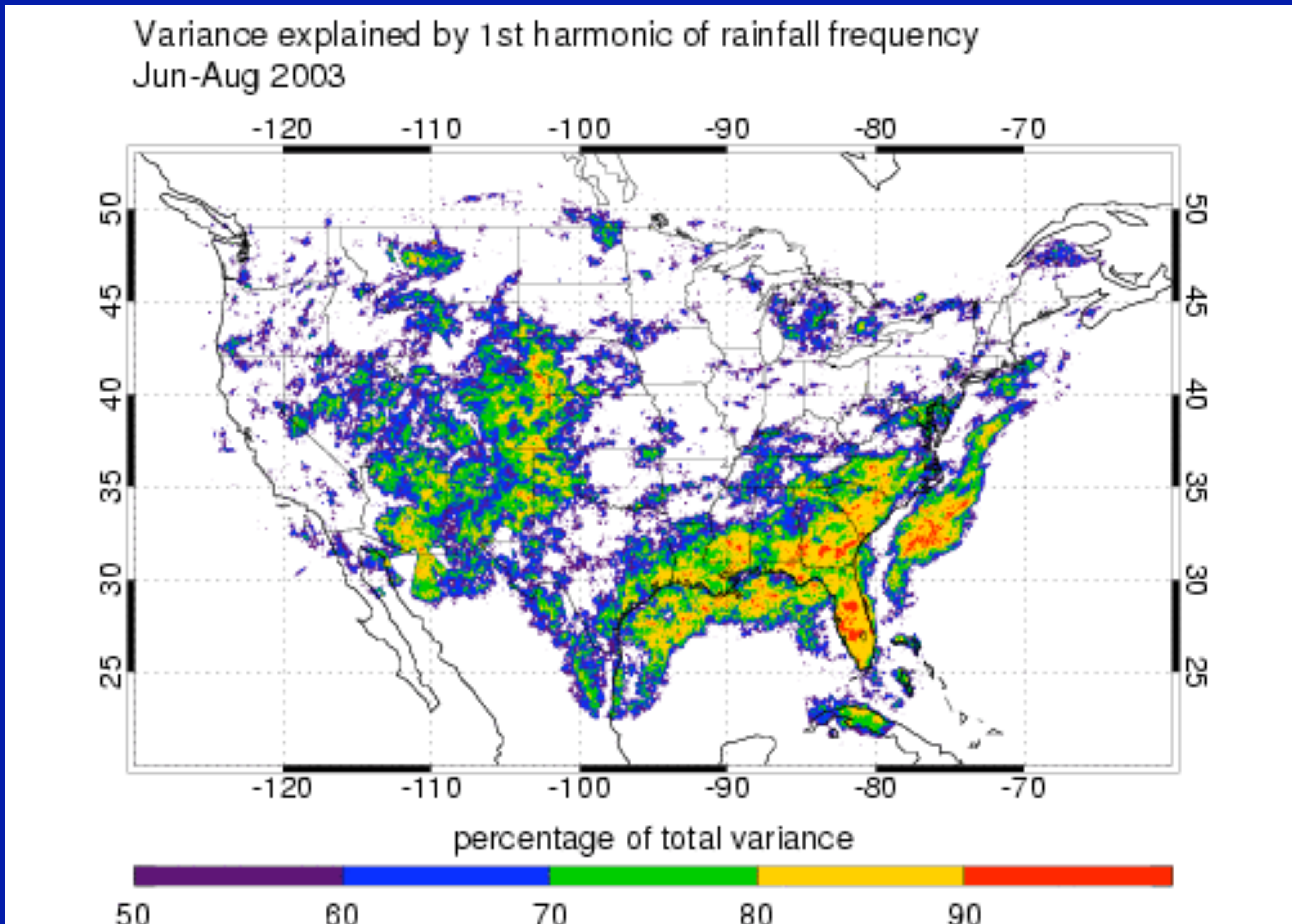
Traveling organized convection over the continental US



A problem of elevated heating, shear flow, traveling organized convection and the diurnal cycle

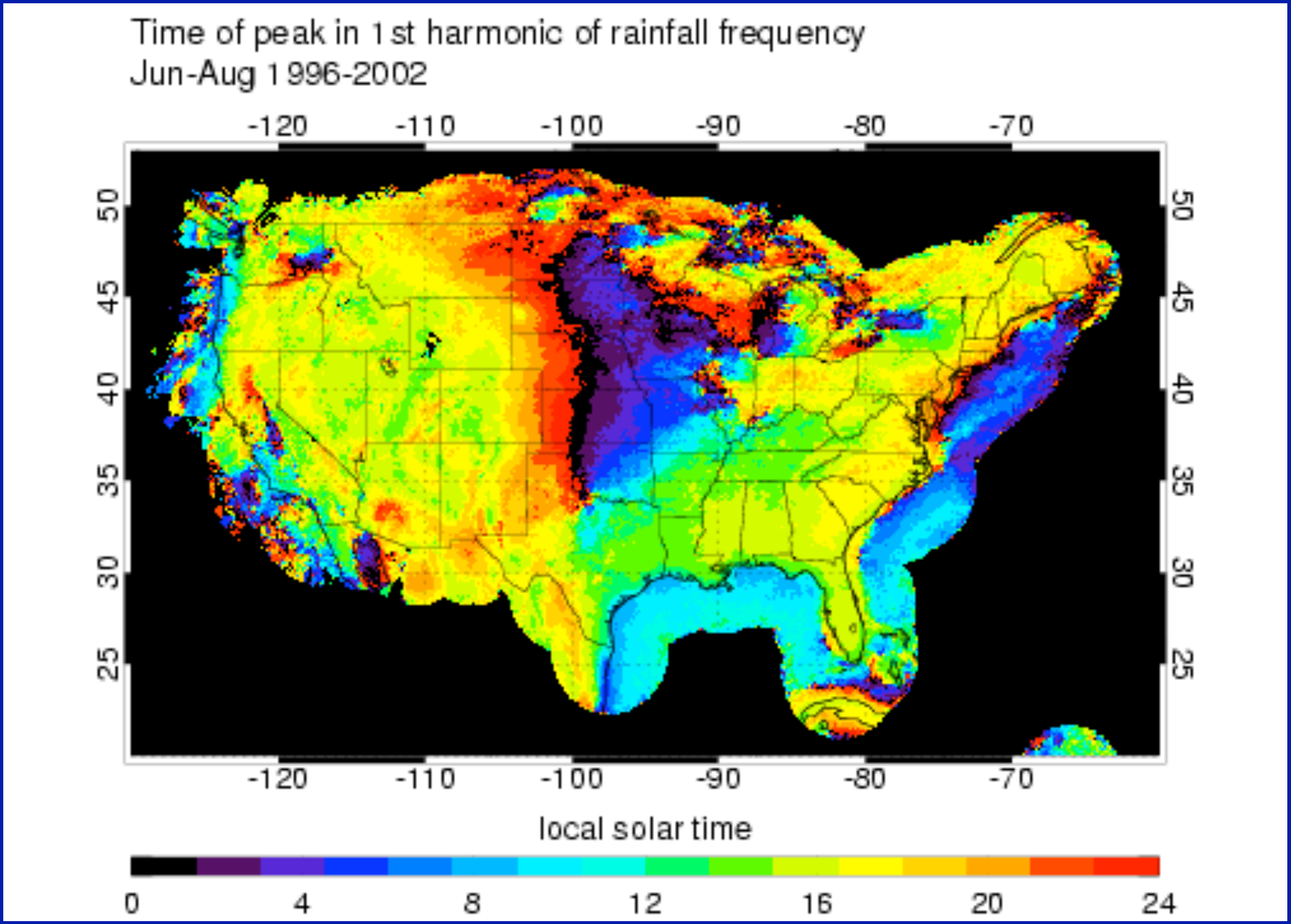


Amplitude of diurnal cycle:



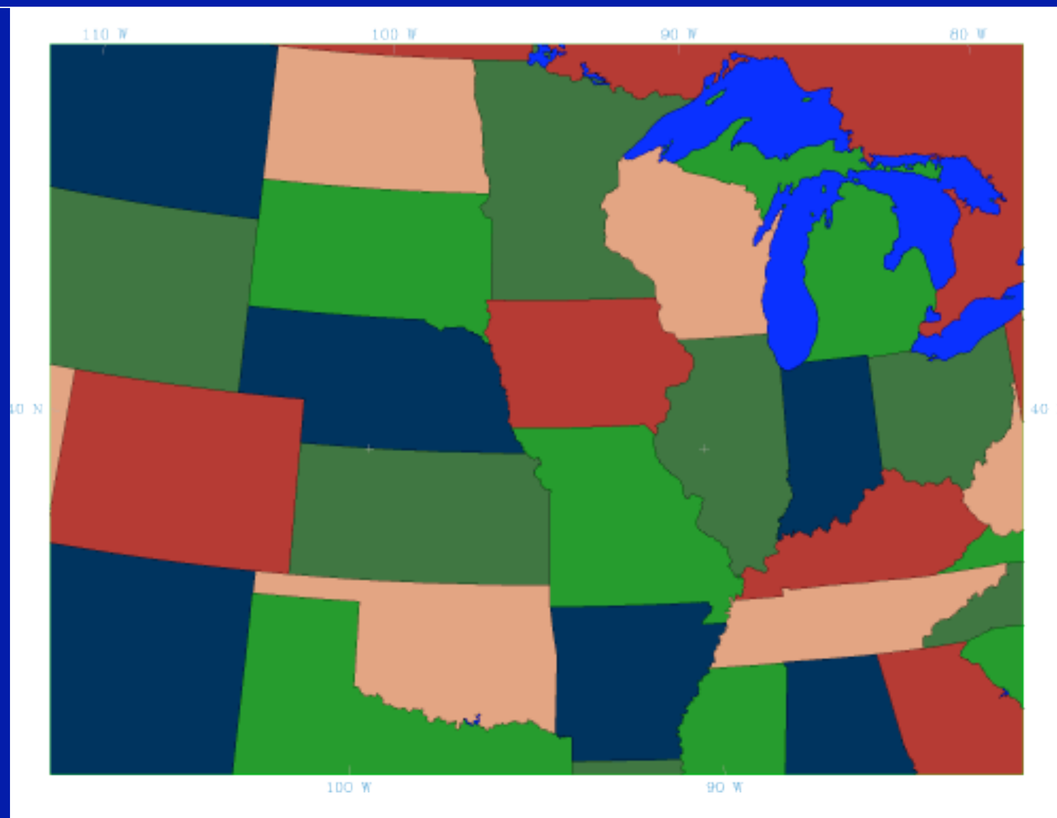
Knievel et al. (2004)

Phase of diurnal cycle: getting it right means getting traveling convective systems right …



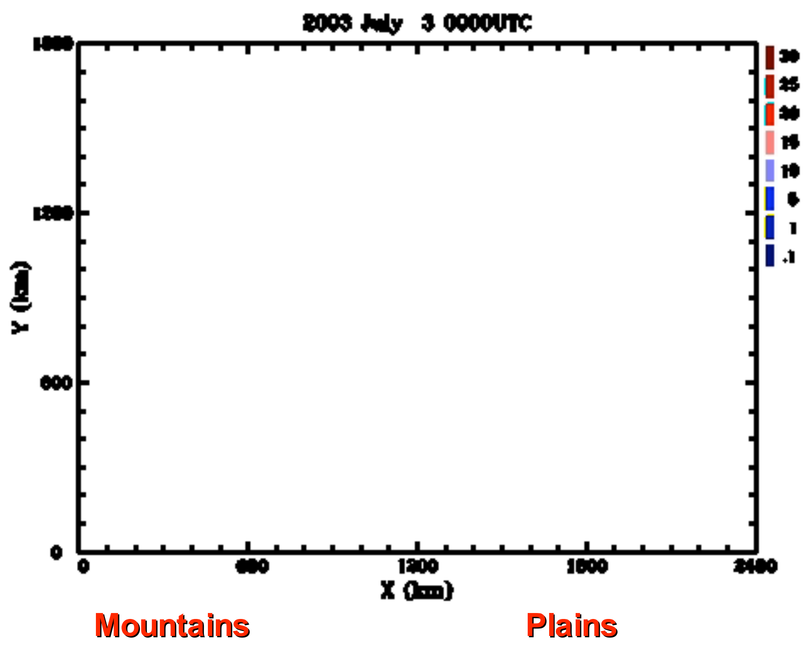
Knievel et al. (2004)

MM5 incorporating NCEP MRF boundary layer & surface exchange schemes, Noah LSM, GSFC microphysics, Betts-Miller convective parameterization, 40-km ETA model analysis for lateral boundary conditions and large-scale forcing. Simulate 3-10 July 2003 at 3-km, 10-km, 30-km, 60-km grid-resolution

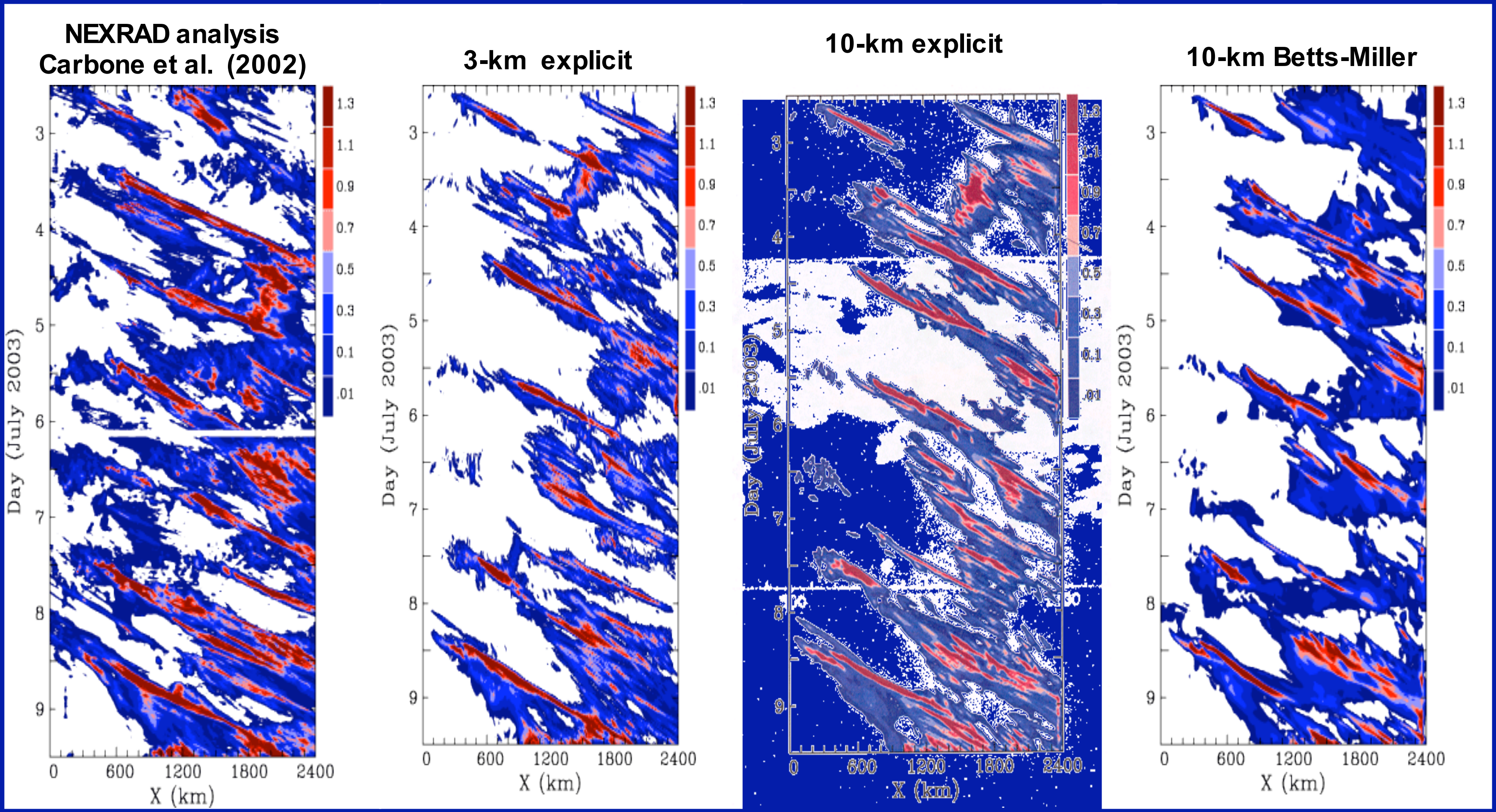


Moncrieff and Liu (2005)

Precipitation: 3-km grid resolution

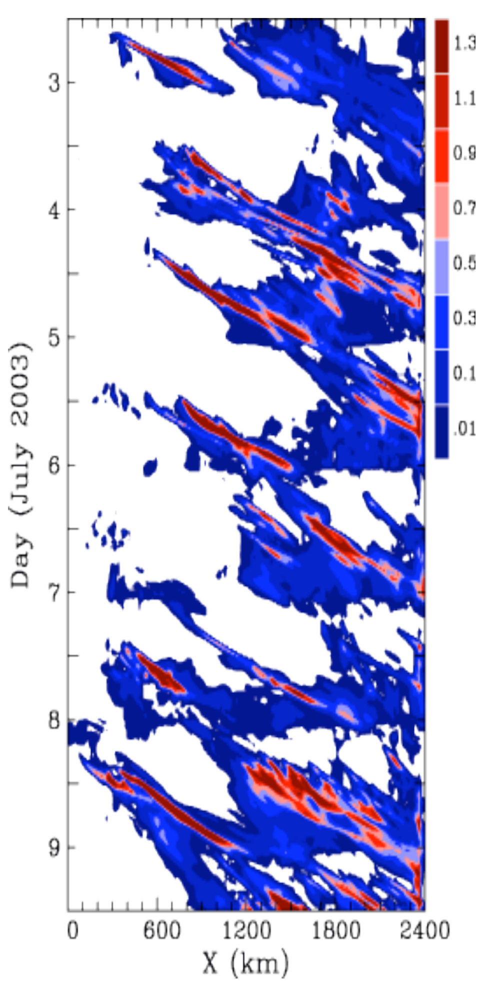


Meridionally averaged rain-rate

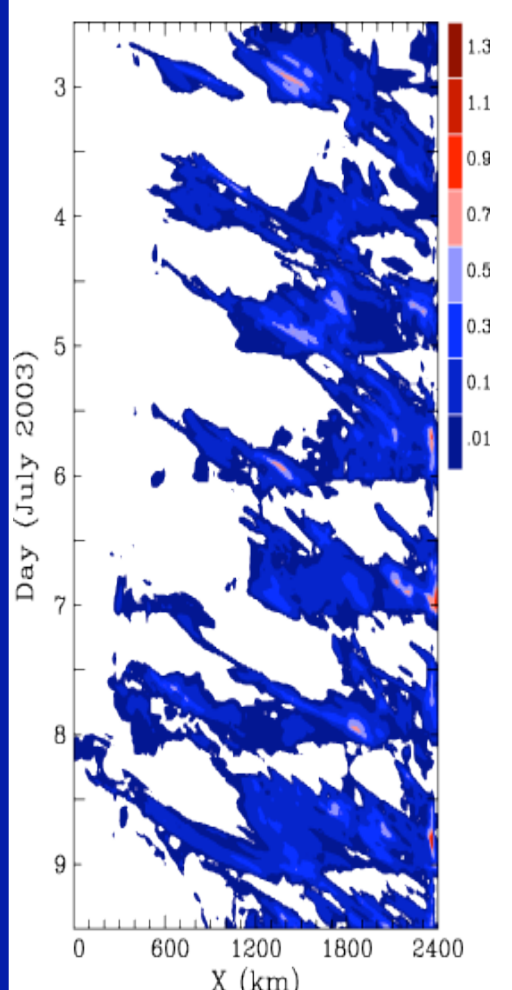


Parameterized vs. explicit precipitation

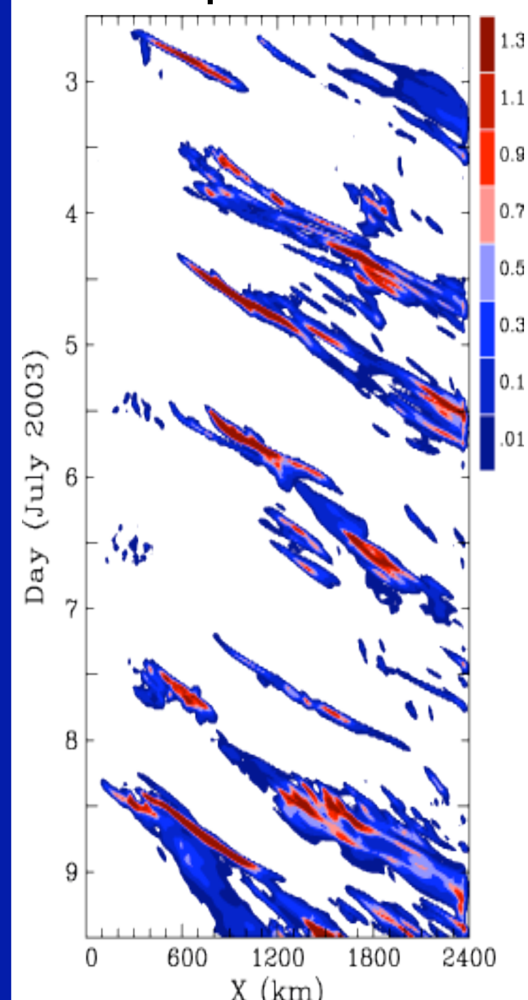
Total



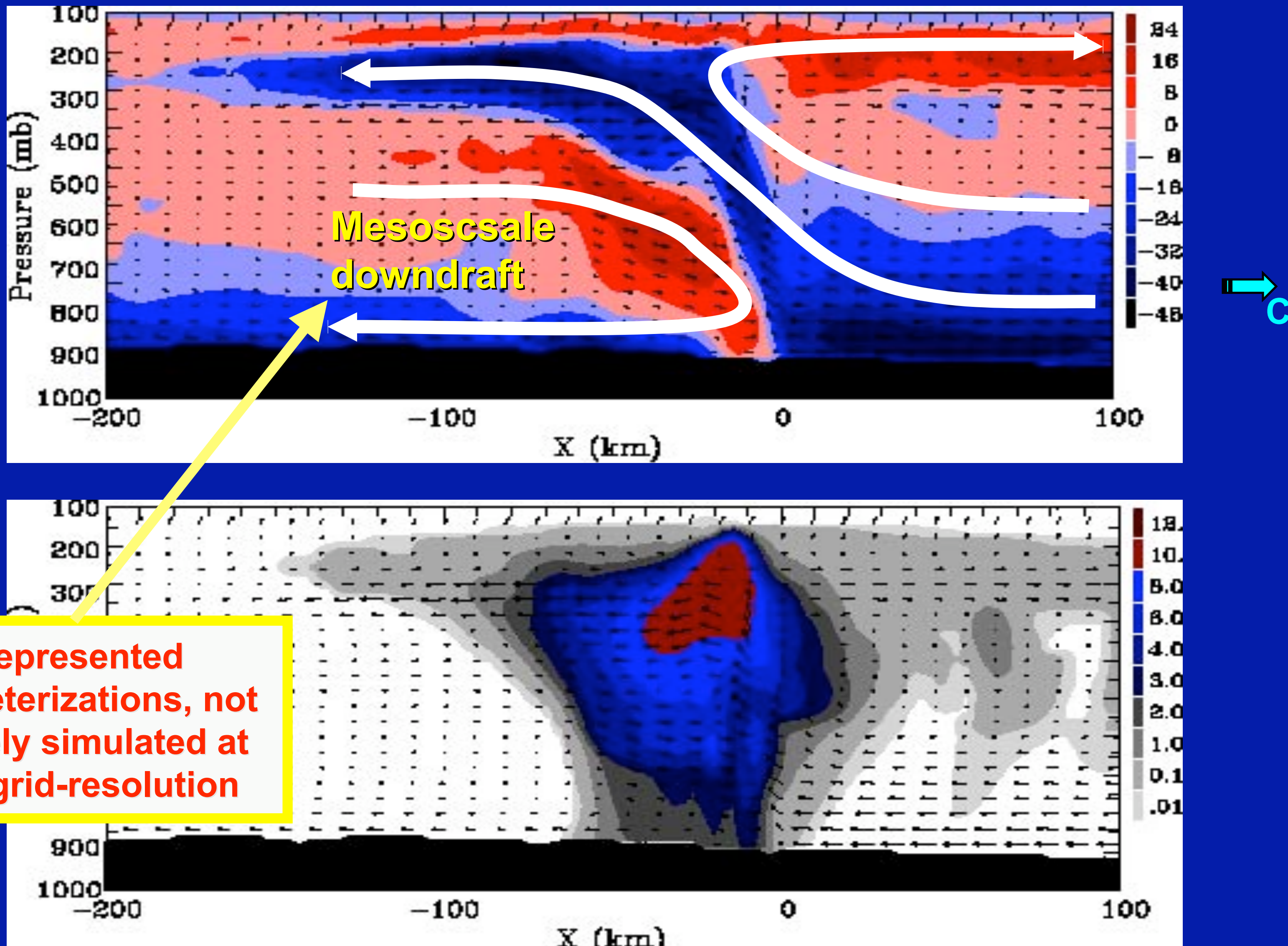
Parameterized



Explicit

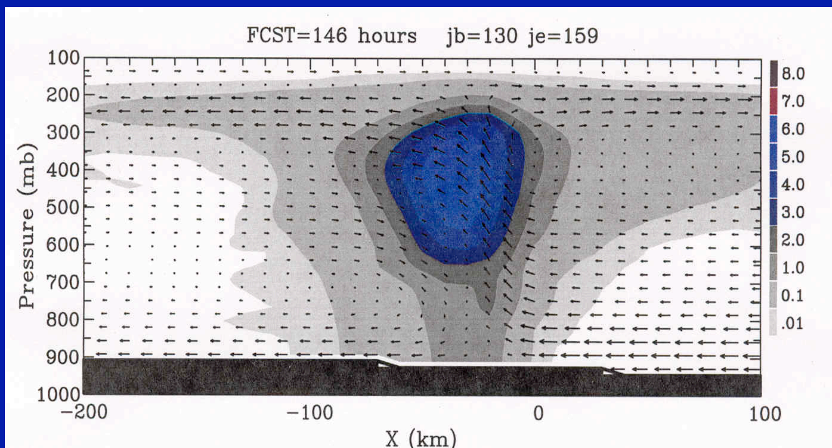


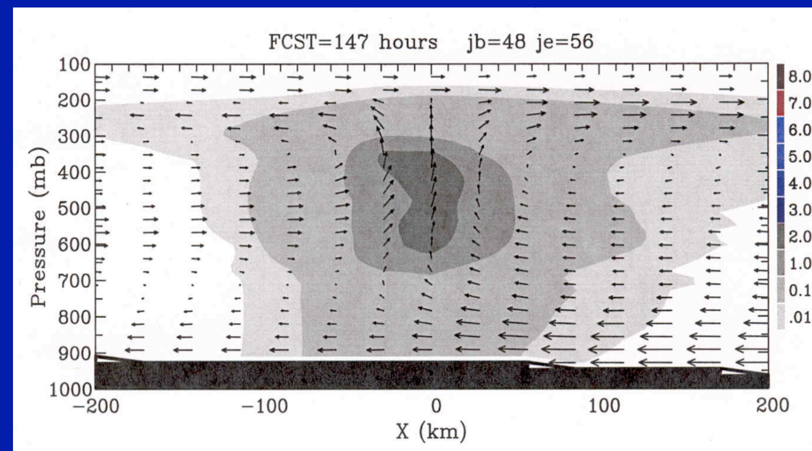
3-km grid resolution

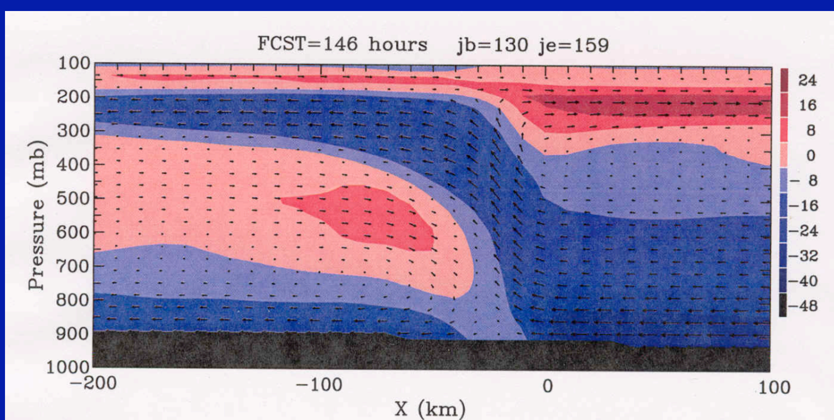


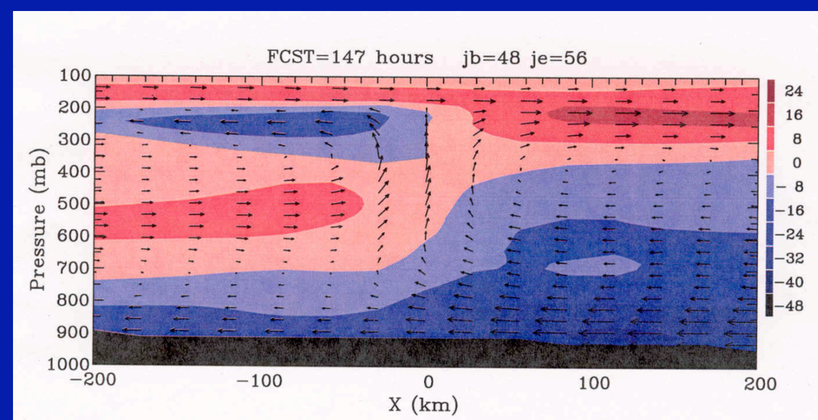
Not represented
in parameterizations, not
adequately simulated at
~10-km grid-resolution

Under-resolution distorts airflow









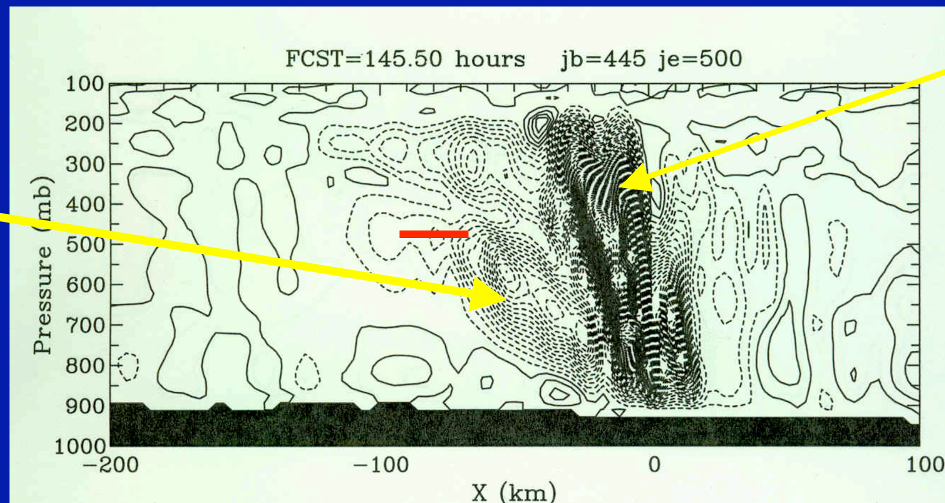
Ä =10 km

Ä =30 km

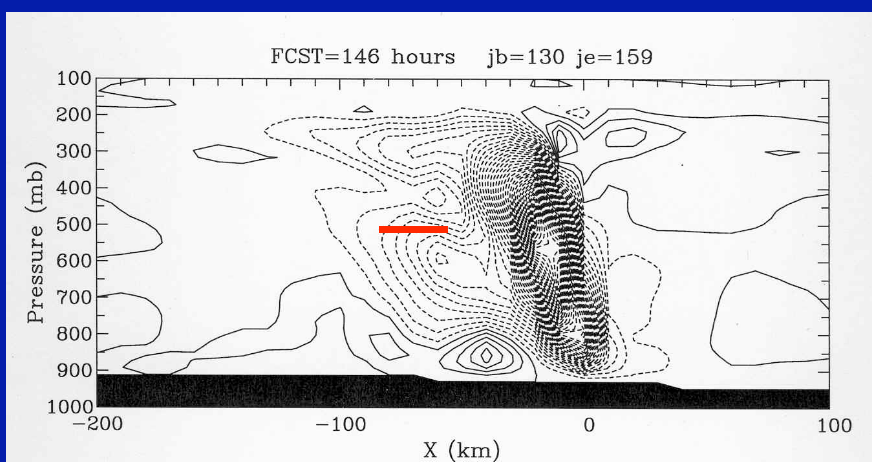
Momentum transport:

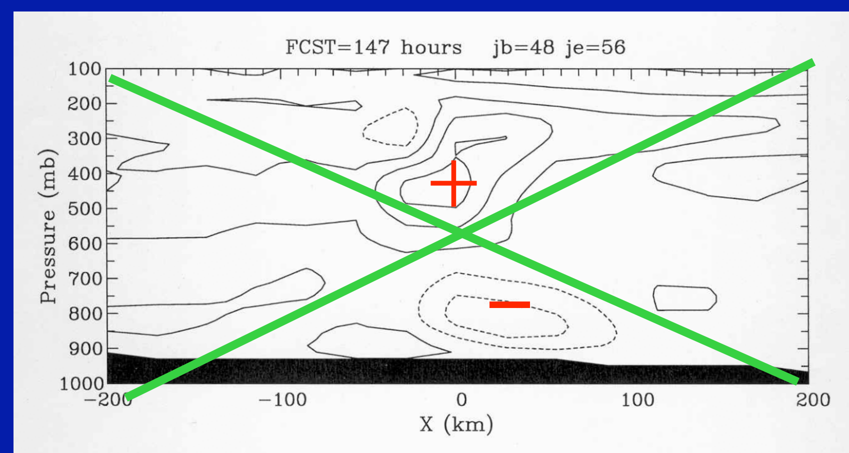
convective

mesoscale



Ä = 3km

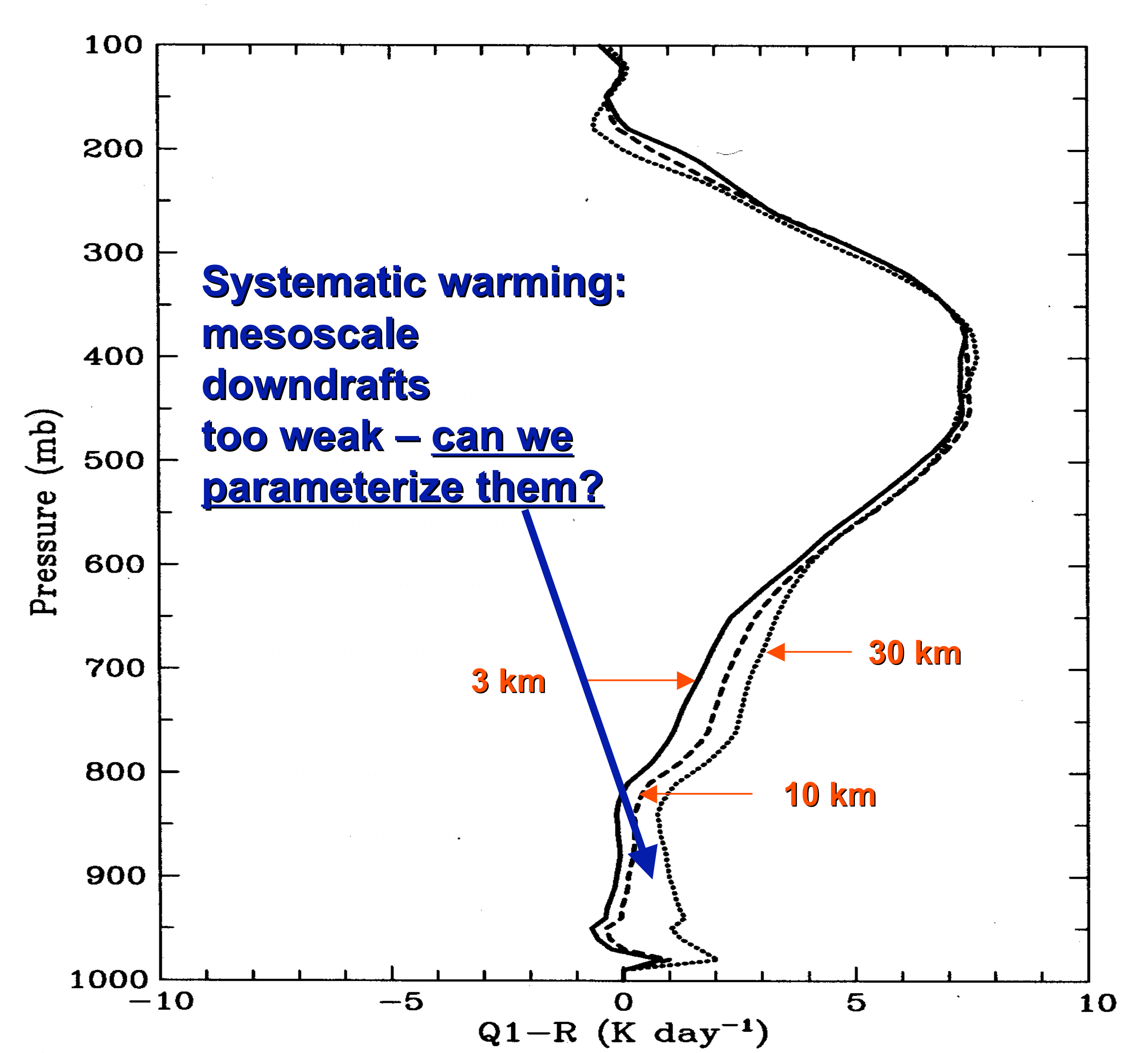




Ä = 10km

Ä = 30 km

Resolution dependence of convective heating

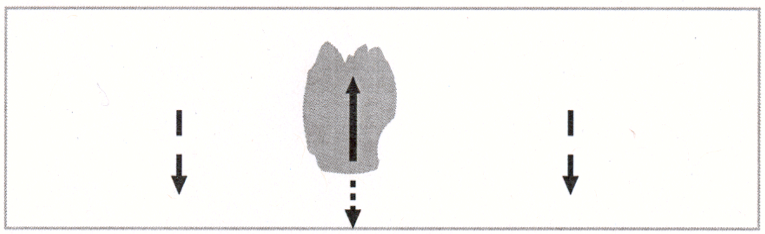


Parameterizing convective organization

Organized convection: a parameterization challenge

Ordinary

a)

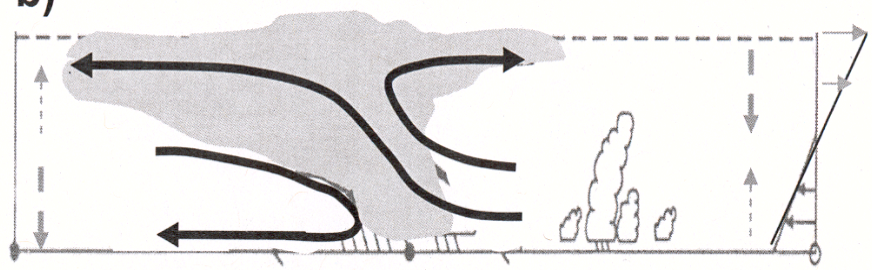


Isolated system, single grid volume

- Entraining plume (small-scale mixing)
- Environmental shear omitted
- Local response
- Closed system (confined subsidence)
- Weak scale-interaction
- Gravity waves not involved

Organized

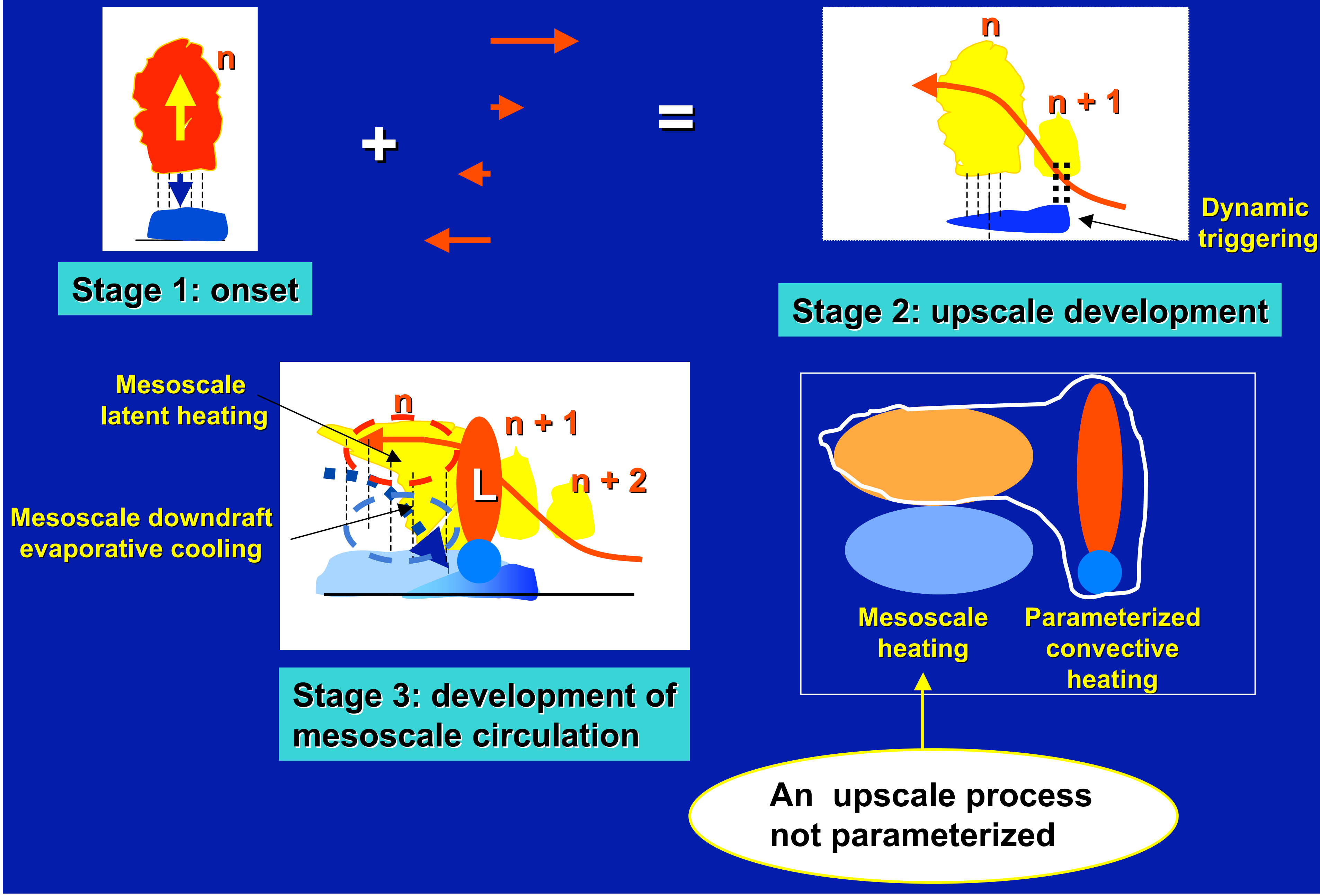
b)



Propagating system, many grid volumes

- Organized flow (mesoscale dynamics)
- Environmental shear important
- Local and remote response
- Open system (wave response)
- Strong scale-interaction
- Convectively-generated gravity waves

Upscale evolution

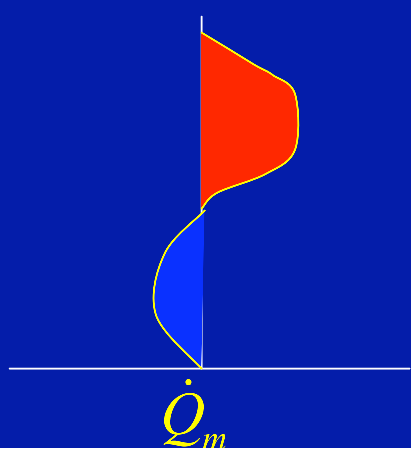


Simple parameterization of stratiform heating / mesoscale evaporation

$$\dot{Q}_m(p,t) = \alpha_1 \dot{Q}_c(t) \sin \partial \frac{p - p_s}{p_s - p_*} \qquad p_* \le p \le p_s$$

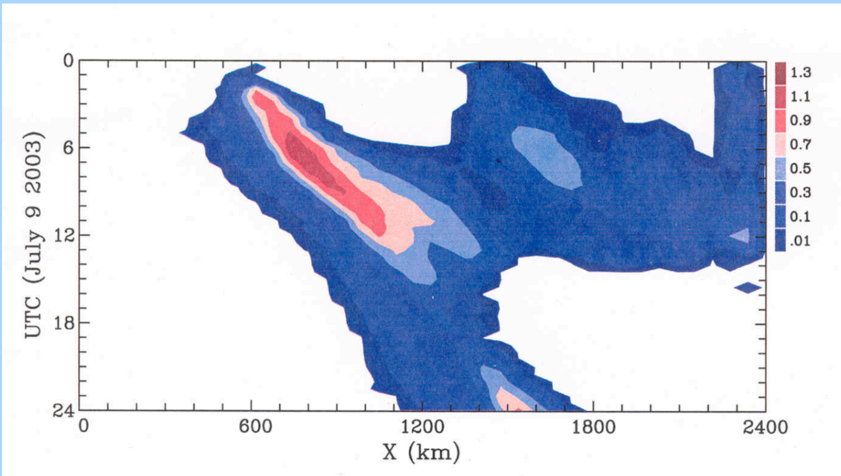
$$\dot{Q}_m(p,t) = \alpha_2 \dot{Q}_c(t) \sin \partial \frac{p_s - p}{p_* - p_t} \qquad p_t \le p \le p_*$$

Q_c = parameterized *convective* heating

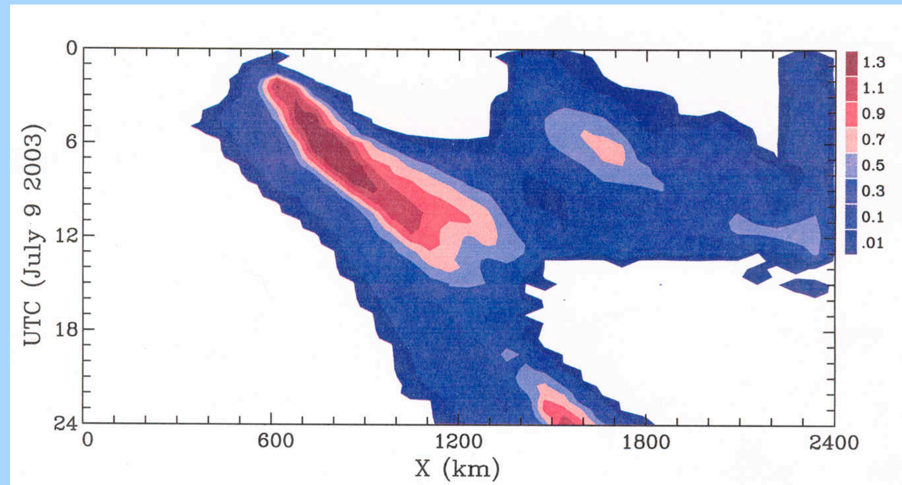


Moncrieff (1992), Johnson (1993), Betts (1997)

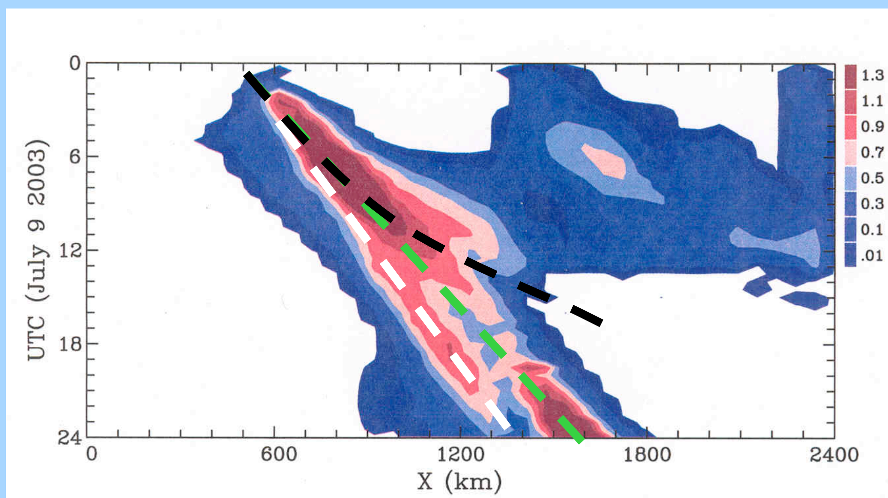
Ä = 60 km



Parameterization



Parameterization + mesoscale heating



Parameterization + mesoscale heating + grid-scale heating

Decomposition of convective tendency

$$\frac{\delta\bar{\phi}}{\delta t} = \frac{\partial}{\partial z}\left[(M_c - \varepsilon_c \bar{M})(\bar{\phi} - \bar{\phi}_c)\right] + \frac{\partial}{\partial z}\left[(M_m - \varepsilon_m \bar{M})(\bar{\phi} - \bar{\phi}_m)\right]$$

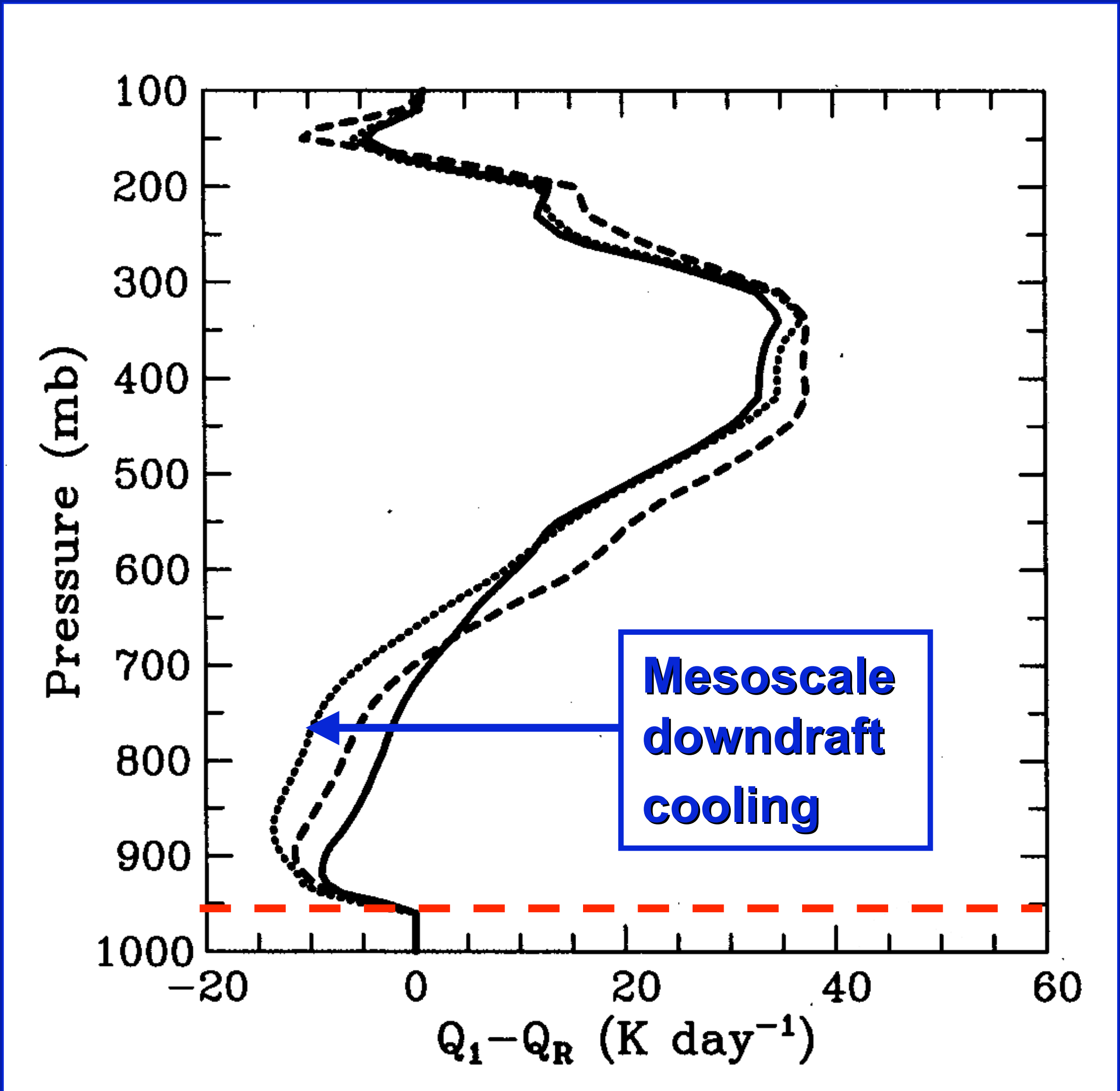
M_c, M_m and $\bar{M}$ are convective−scale, mesoscale and resolved−scale mass fluxes; ε_c and ε_m are the fractional areas of convective−scale and mesoscale updrafts, respectively.

For organized convection $\varepsilon_c << \varepsilon_m$ and $\varepsilon_m = 1$, approximately.

So the grid−scale term in the mesoscale parameterization is equivalent to $(\bar{\phi} - \bar{\phi}^{m})\frac{\partial \bar{M}}{\partial z}$

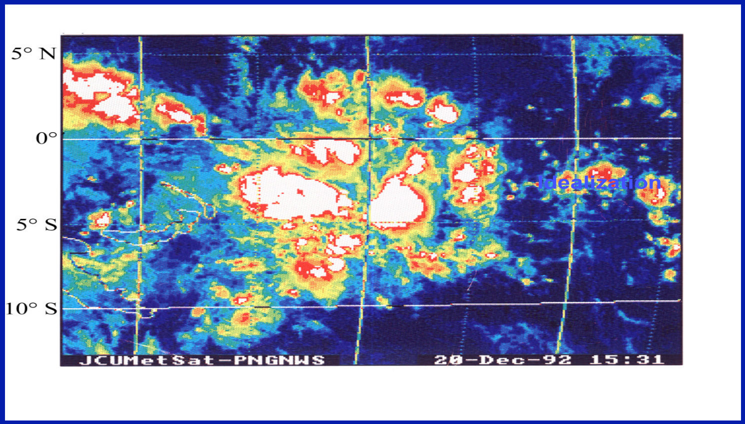
Cheng & Yanai (1989)

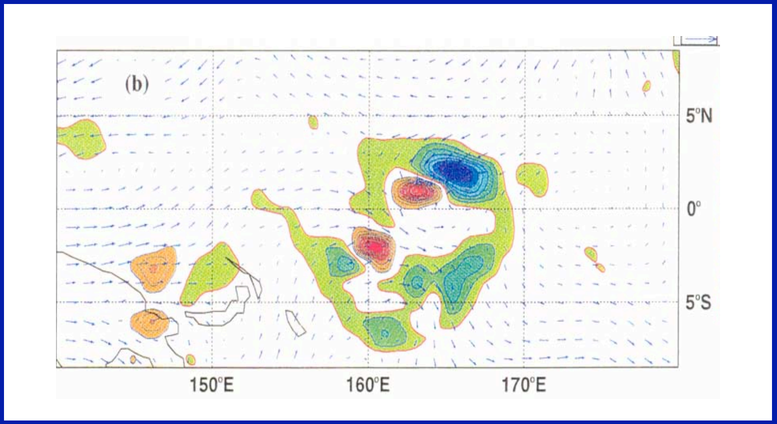
Effect of mesoscale parameterization on convective heating

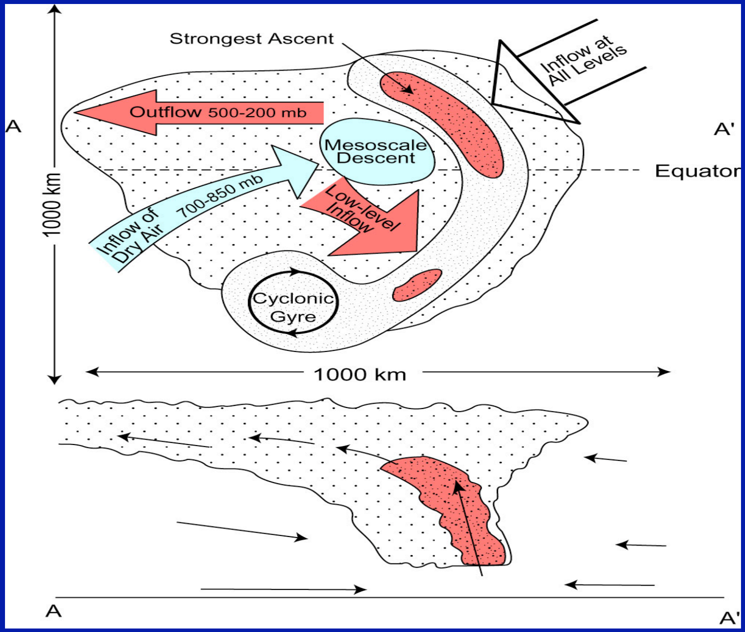


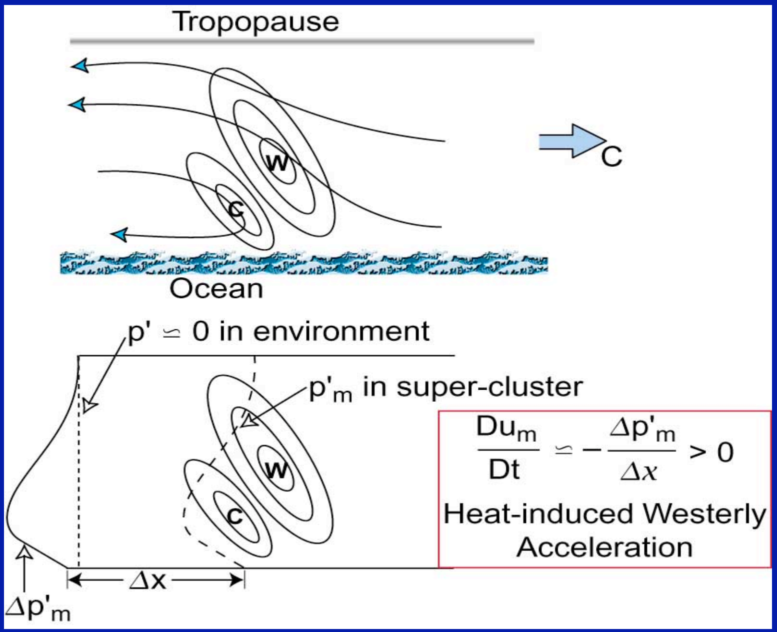
Remarkably similar results for tropical super-clusters suggests a degree of universality …

Superclusters resemble huge mesoscale convective systems (in a GCM)









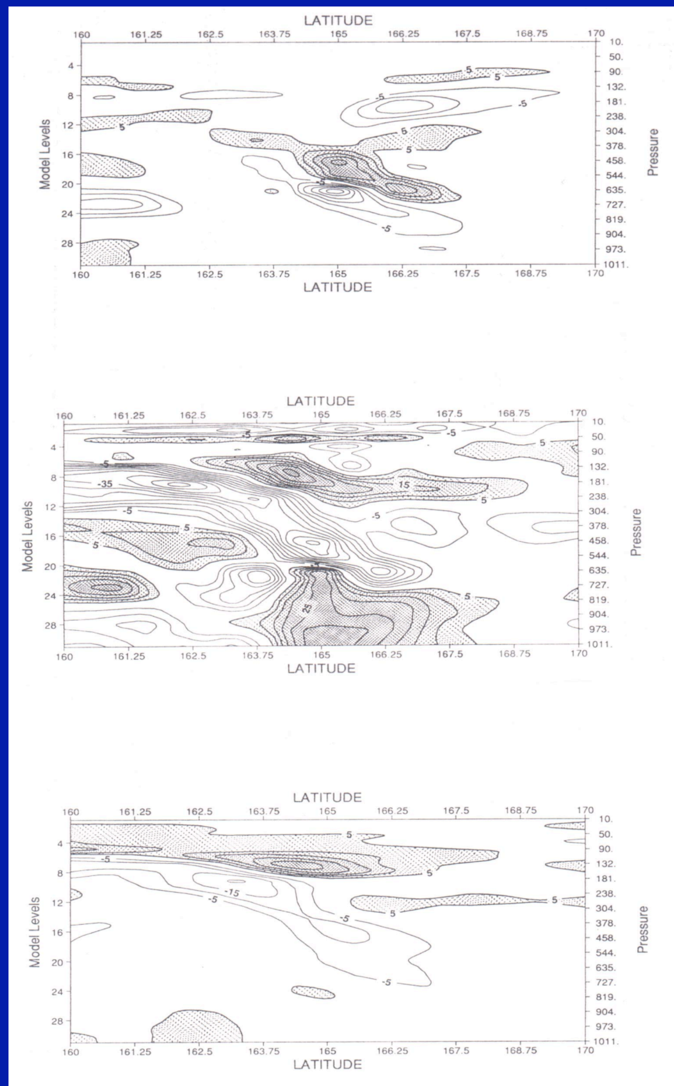
Moncrieff and Klinker (1997)

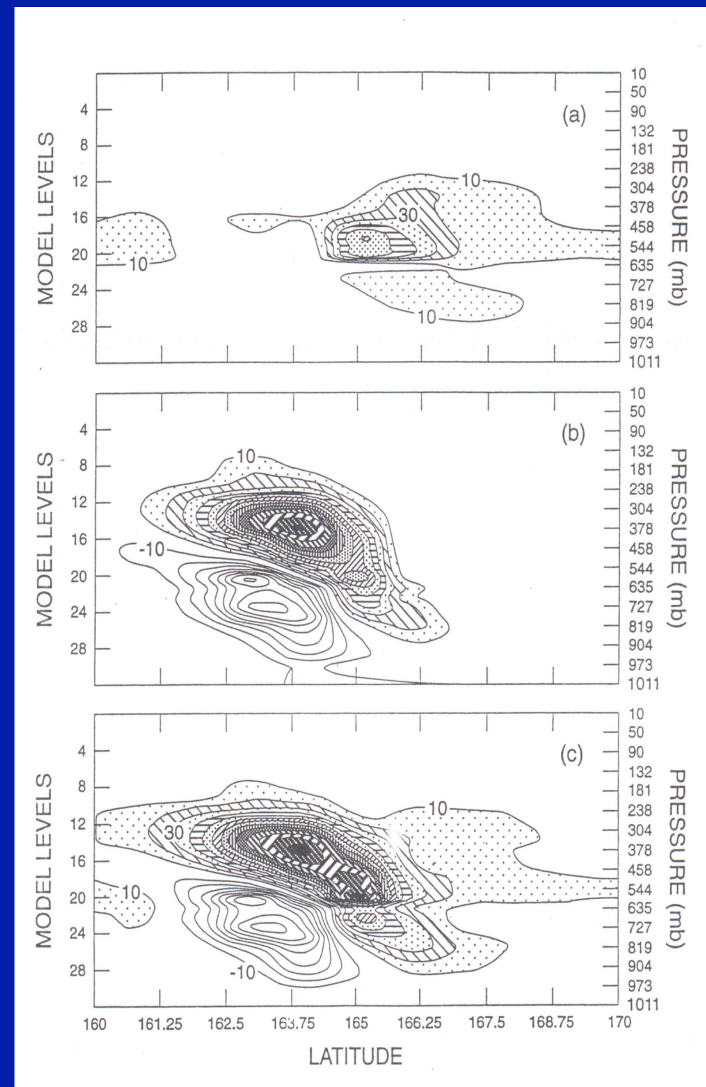
Total, parameterized (under-resolved) grid-scale tendencies of predicted superclusters

Parameterized

Grid-scale

Total





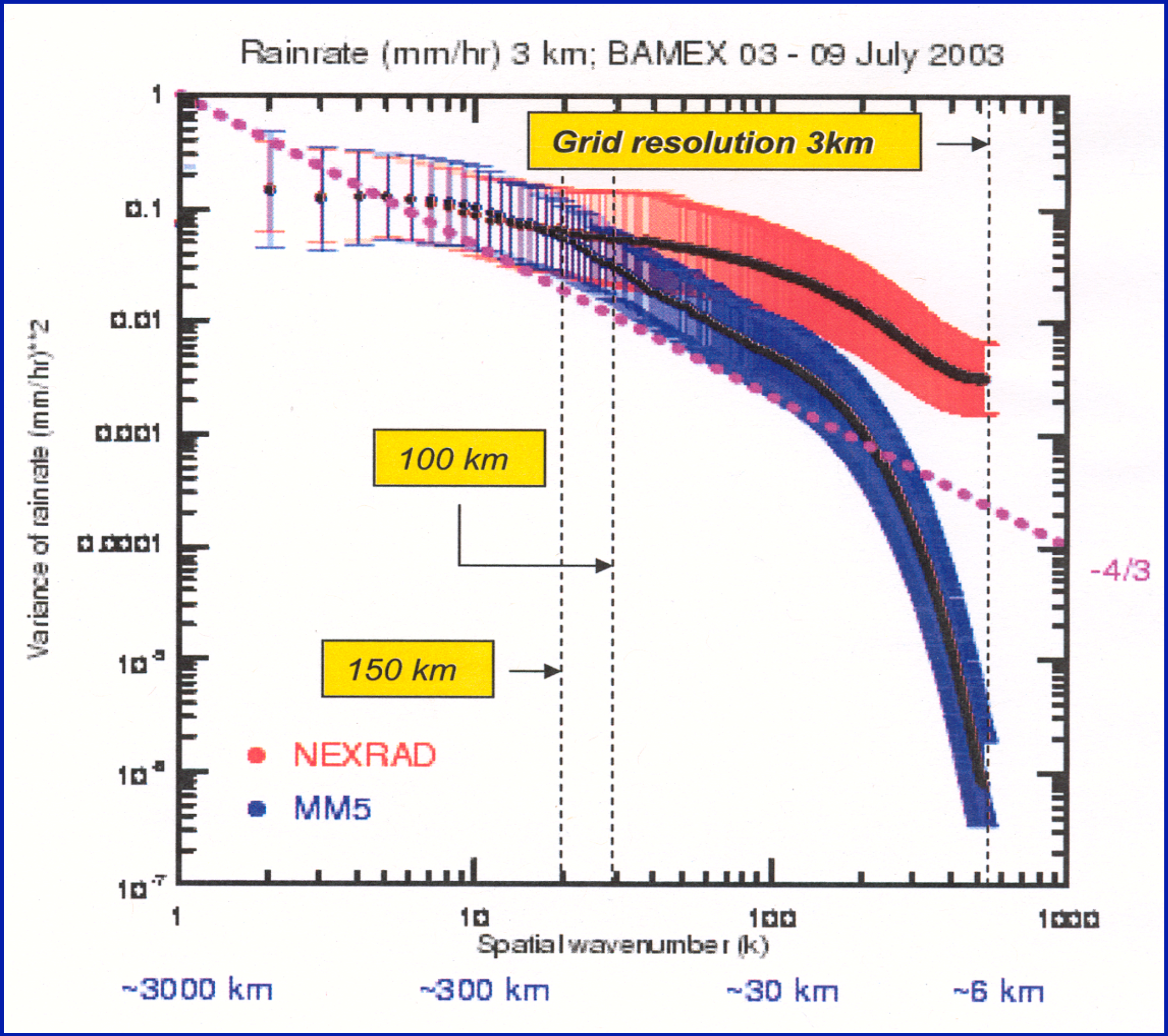
Momentum

Temperature

MCS-like dynamical structure is remarkably ubiquitous: widely seen in large-domain explicit convection simulations and ‘super-parameterized’ simulations

To some degree this evinces physical aliasing (‘surrogacy’)

Rain-rate spectra: Observed and simulated



Moncrieff, Liu and Hsu (2005)

Summary

- Universal convective organization ubiquitous in many regions of the world
- Dynamical models of MCS- like organization have stood the test of time, new application -- represent organized convection structures in modern explicit models
- At ~10-km grid-resolution, the representation of convection is markedly different from conventional parameterization
- Mesoscale downdrafts represented by a simple parameterization, promtes propagation, work continues
- Under-resolved explicit circulations have practical advantages, care is needed but points to ways forward
- Resuts for the U.S. continent apply to other regions of the world where steep orography, organized convection and shear-flow exist
- Convective parameterization is being redefined, should help break the vexing bottleneck in convective parameterization – dynamics are to the fore