Dynamical Impacts of convection and stochastic approaches

by

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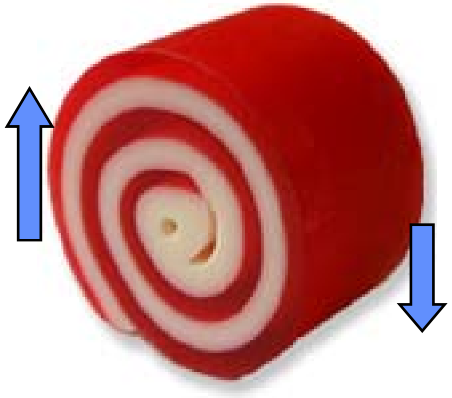
ECMWF/Met Office

Outline

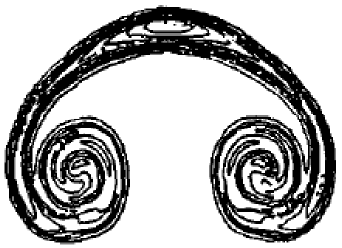
- **Dynamical processes in clouds and interactions with the rotating, stratified environment**
- **Generalized parcel model and balanced flow adjustment – PV generation and NWP impacts**
- **'Big-domain' tropical convection simulation – convectively-coupled tropical waves and statistical properties of convective forcing**
- **Stochastic parametrization and kinetic energy backscatter**

Convection conceptions



Mixing at cloud boundaries

- **Horizontal gradients of buoyancy cause the baroclinic generation of vorticity to be concentrated in cloud boundaries making them unstable.**
- **Cloud droplet evaporation causes internal downdraughts**



from Tripoli (1992)

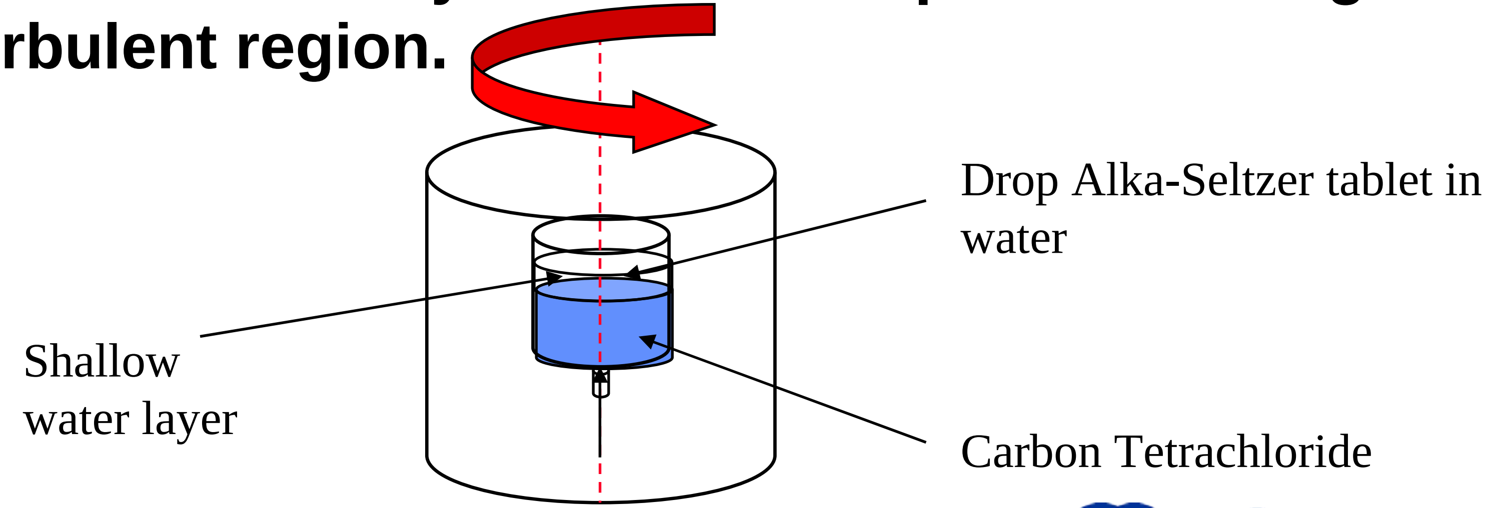
→ **Turbulent clouds**

Vorticity production at thermal boundaries winds up into a double Swiss Roll

Interplay between background rotation and convection - the Alka-Seltzer experiment

- **Richard Scorer's angular momentum mixing hypothesis. J. Science (1965). Hurricane formation by convective stirring**

- **vorticity expulsion hypothesis, Gough and Lyndon-Bell, JFM (1968). Turbulence scrambles vortex lines and drives mean vorticity to zero and expels to the edge of the turbulent region.**



Drop Alka-Seltzer tablet in water

Shallow water layer

Carbon Tetrachloride

Convective overturning and potential vorticity (PV) conservation – a thought experiment

- **Consider initial rest state in a rotating system where M =Ar^2 and $\theta = \theta_0 + Bz$ where A>0 and B<0**

$$\mathrm{PV} = \frac{1}{r}\frac{\partial M}{\partial r}\frac{\partial \theta}{\partial z} < 0$$

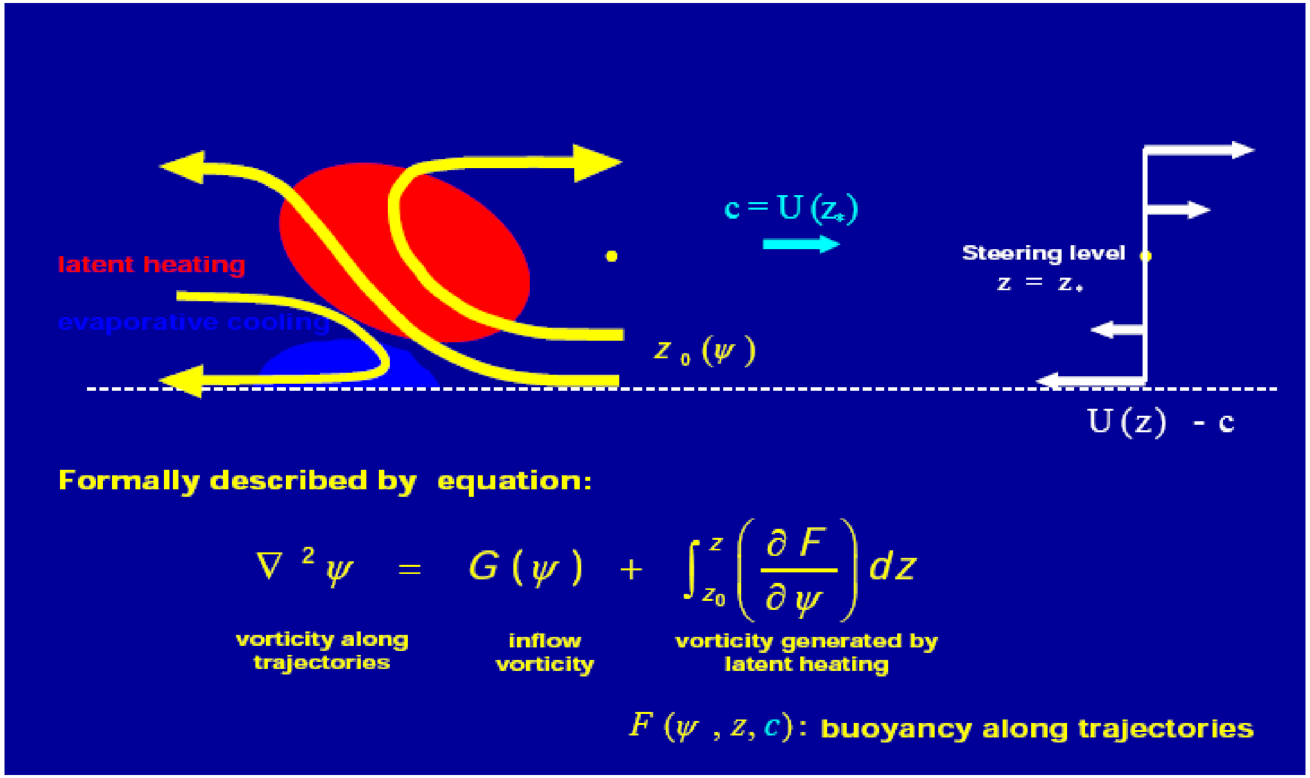
Overturning whilst conserving PV and global angular momentum would imply reversed radial gradient of M

e.g. $M = M_0 - A\,r^2$ ⟶ Vortex !

Energetically impossible unless we exclude a cylinder of fluid at the origin

Cloud momentum transport

- **Momentum not conserved on air parcels but vertical parcel exchange still causes downgradient transport**
- **Upgradient transport possible in squall line systems (Moncrieff and Green, 1972; Moncrieff, 1982 and 1991)**



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

$F(\psi, z, c)$: buoyancy along trajectories

Upscale energy cascade

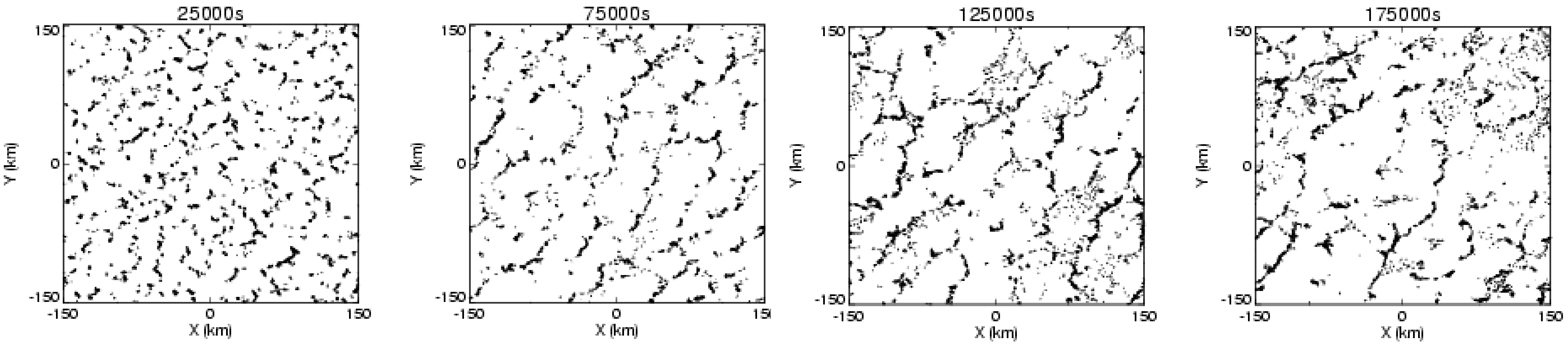
- **Deep convective systems leave a mesoscale potential vorticity (PV) 'footprint'**
- **PV anomalies have associated balanced flow fields**
- **Upscale energy transfer is caused by straining PV anomalies by large-scale flow**

from Shutts and Gray (1999)

7 hrs

time

2 days



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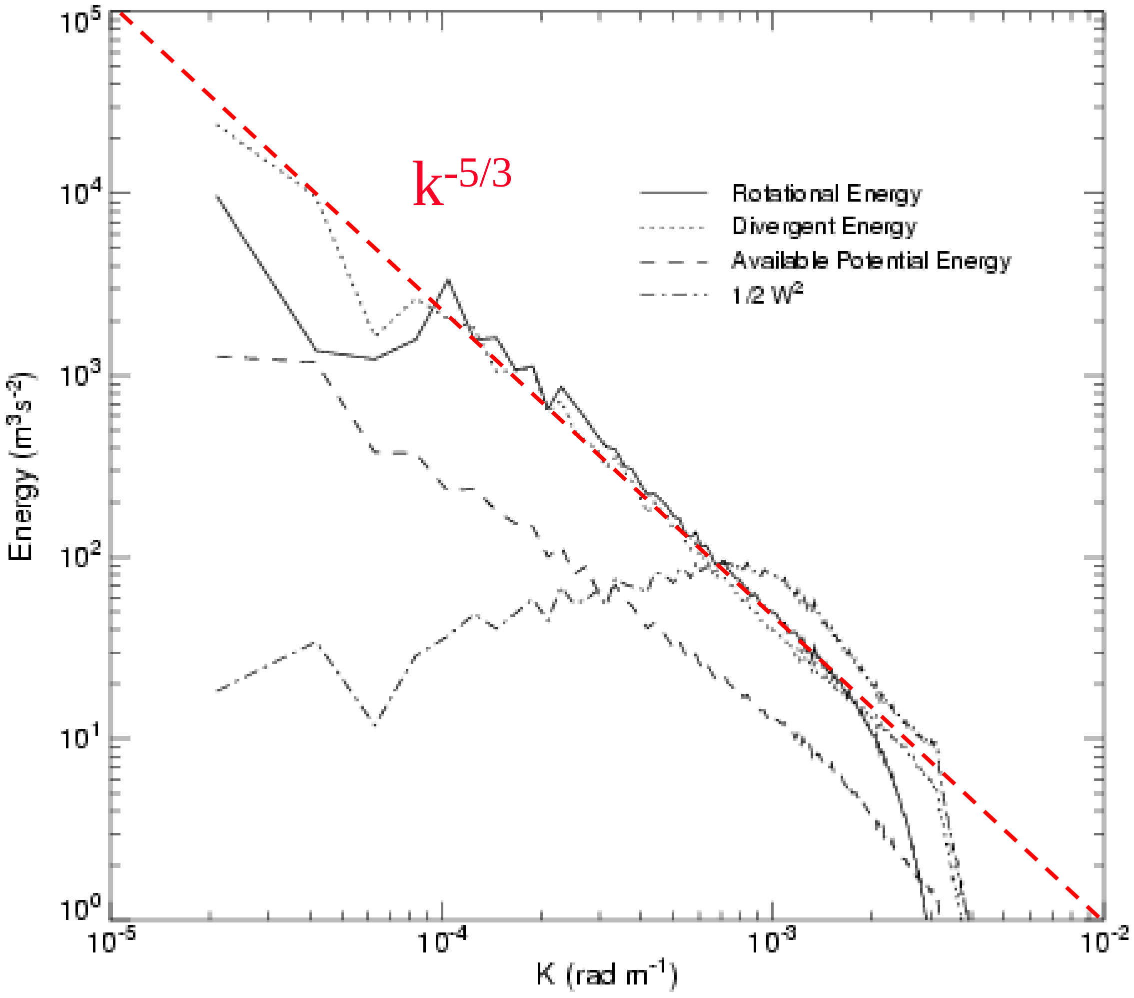
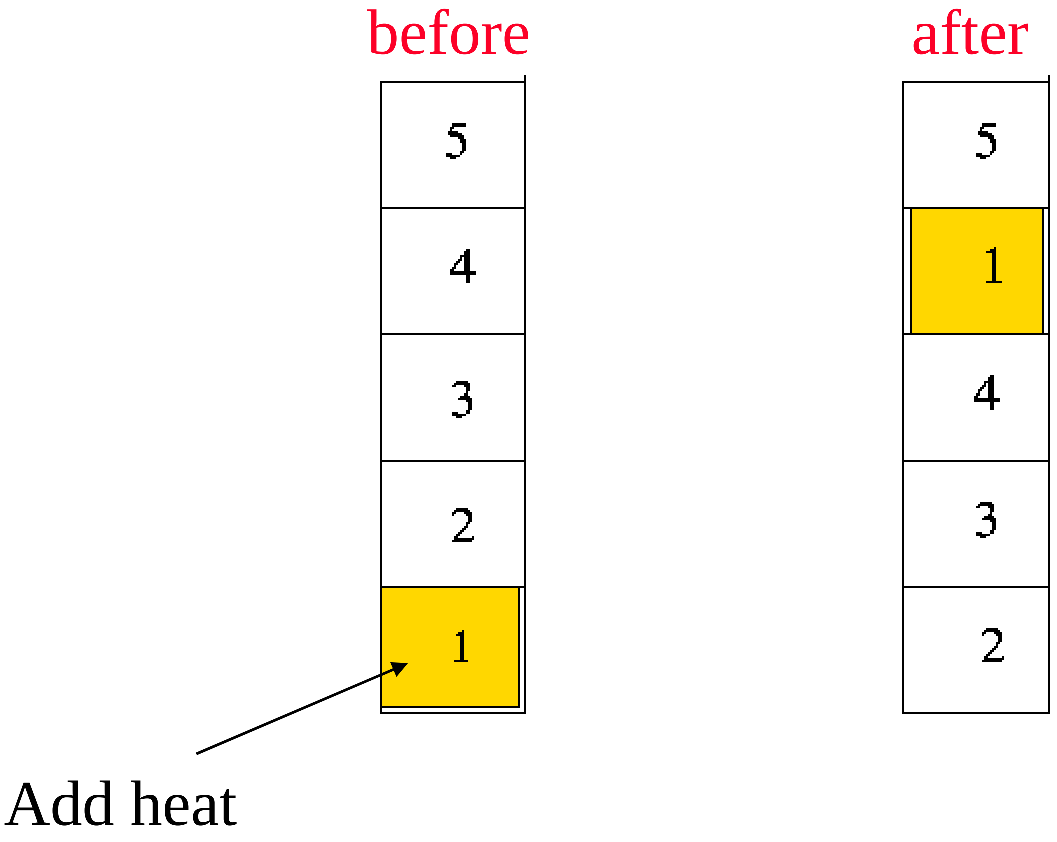
Deep convection / thunderstorm cloud - a view from space

CRM simulation of upscale energy cascade (Vallis et al, 1997)



Parcel models of convective adjustment

- **Simplest model – constant volume and potential temperature lumps in a column**



discrete model yet exact solution !

2D parcel model in rotating system

- **Air parcels conserved absolute momentum M= fx + v as well as potential temperature**
- **Inertial stability requires M increases monotonically with x**
- **Unlike 1D case we don't know parcel shapes *a priori* - only that they will be convex polygons**
- **the boundaries will be straight lines whose slope satisfies Margules's formula:**

$$\frac{dz}{dx} = -\frac{f\theta_0[M]}{[g\theta]}$$

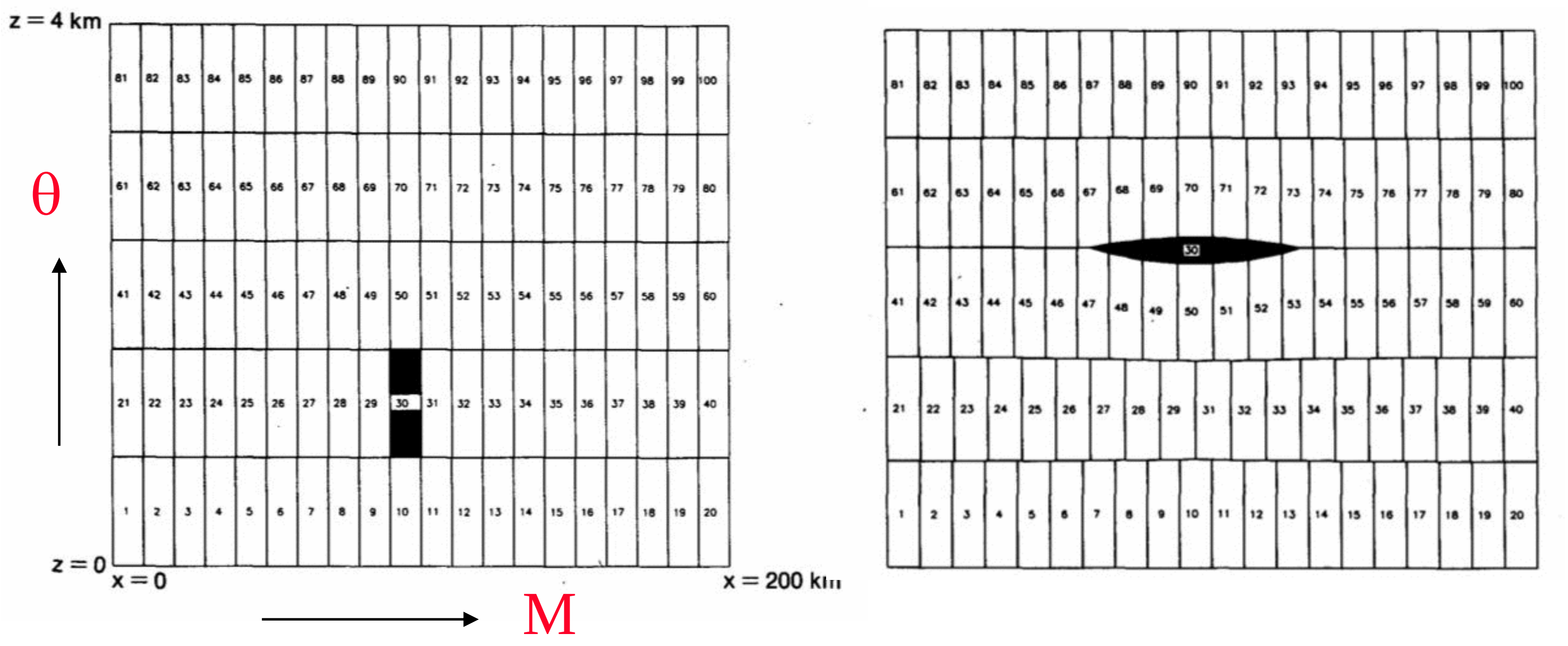
where [ ] indicates the jump in value between parcels

2D parcel jump in rotating environment

uses Jim Purser's element code

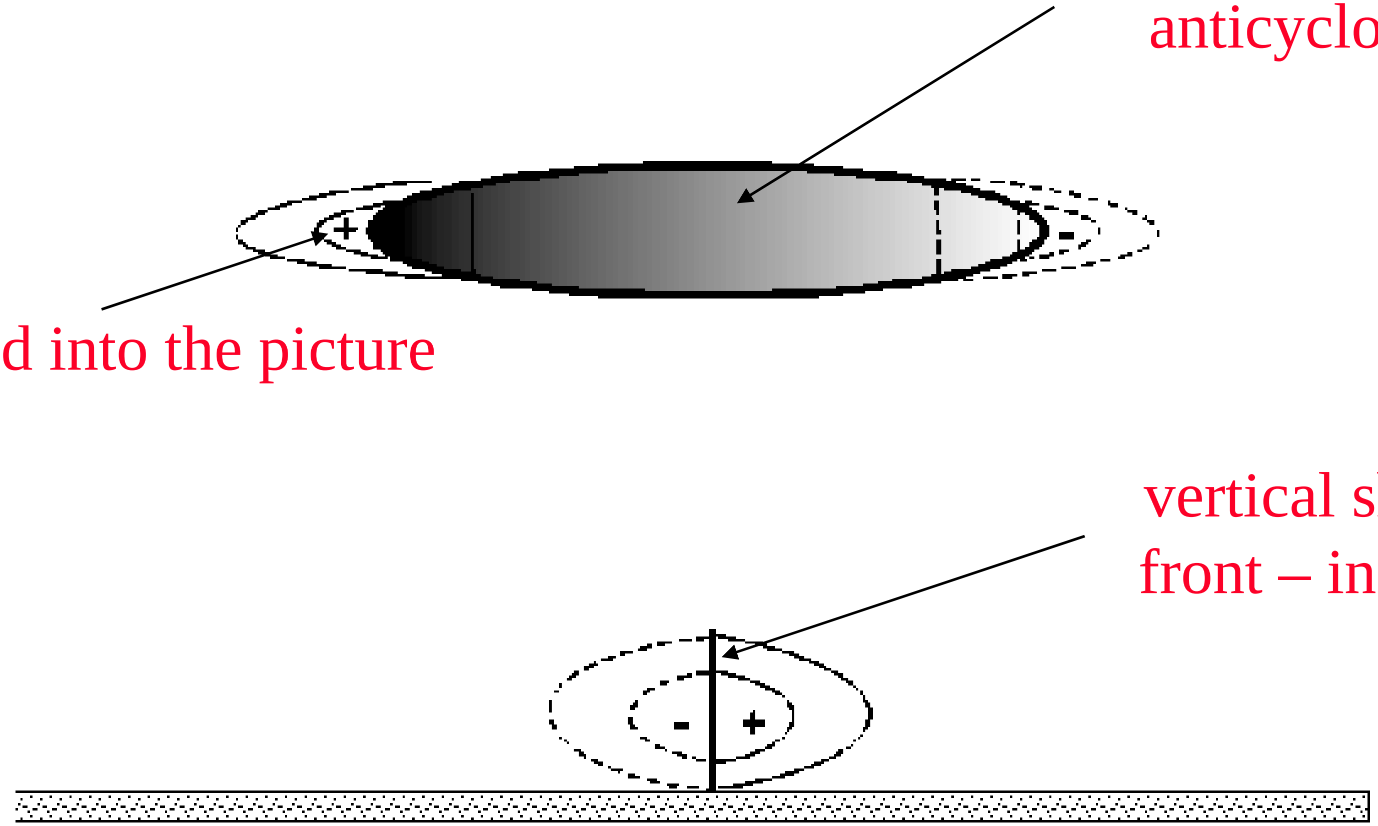
before

after



Note that rotation prevents the parcel from spreading into a thin block spanning the domain

convective jump end-state



anticyclonic lens

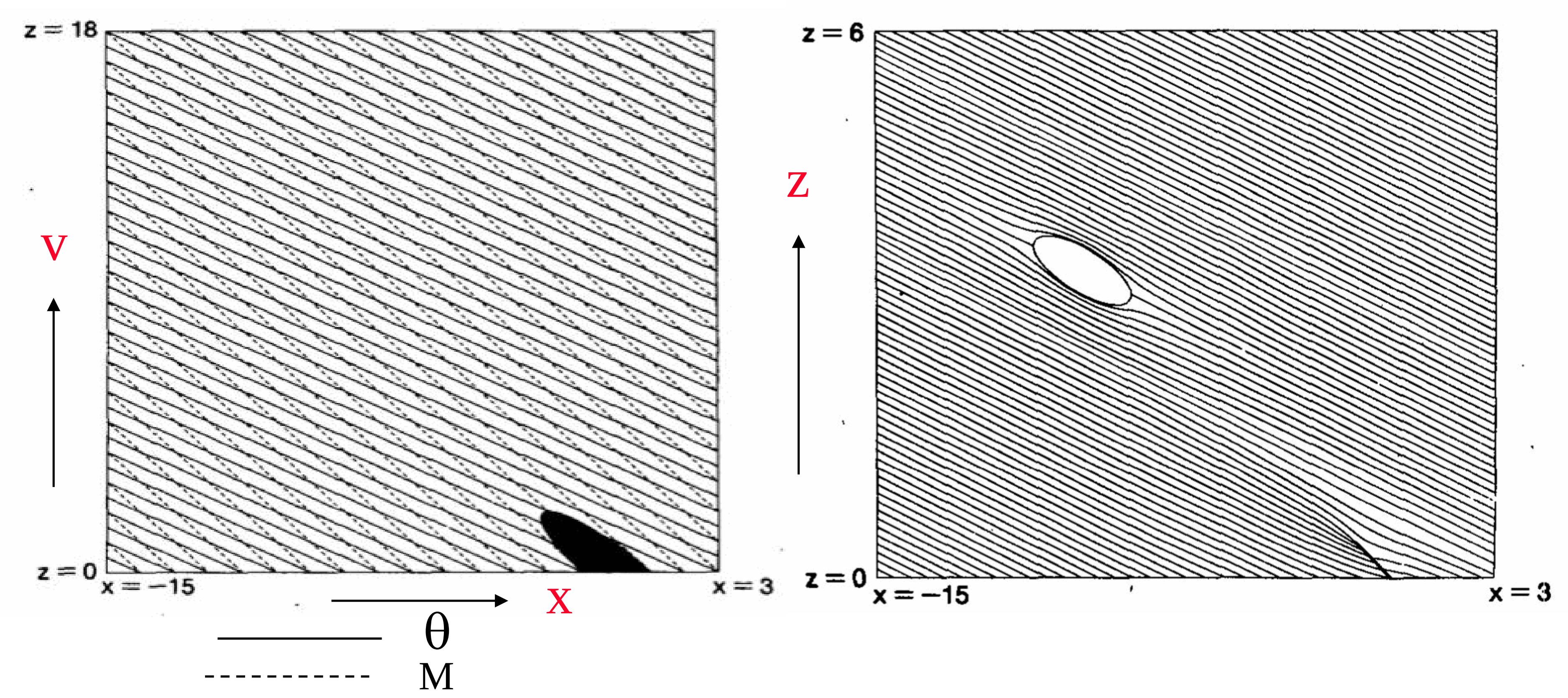
wind into the picture

vertical shear-line
front – infinite PV

Slantwise convection parcel jumps

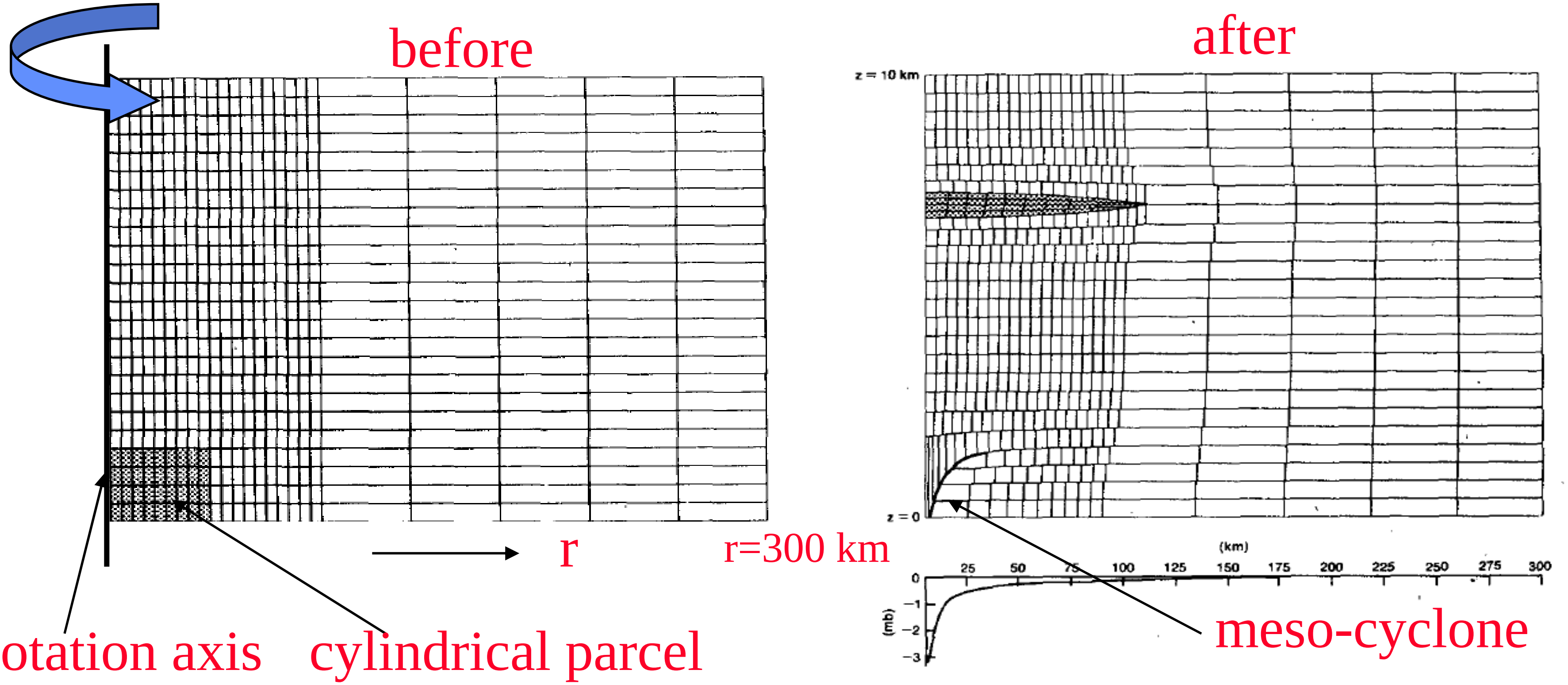
- **2D convection conserving M in an atmosphere initially with constant vertical wind shear in thermal wind balance**
- **Linear increase in θ with height.**

from Shutts (1987)

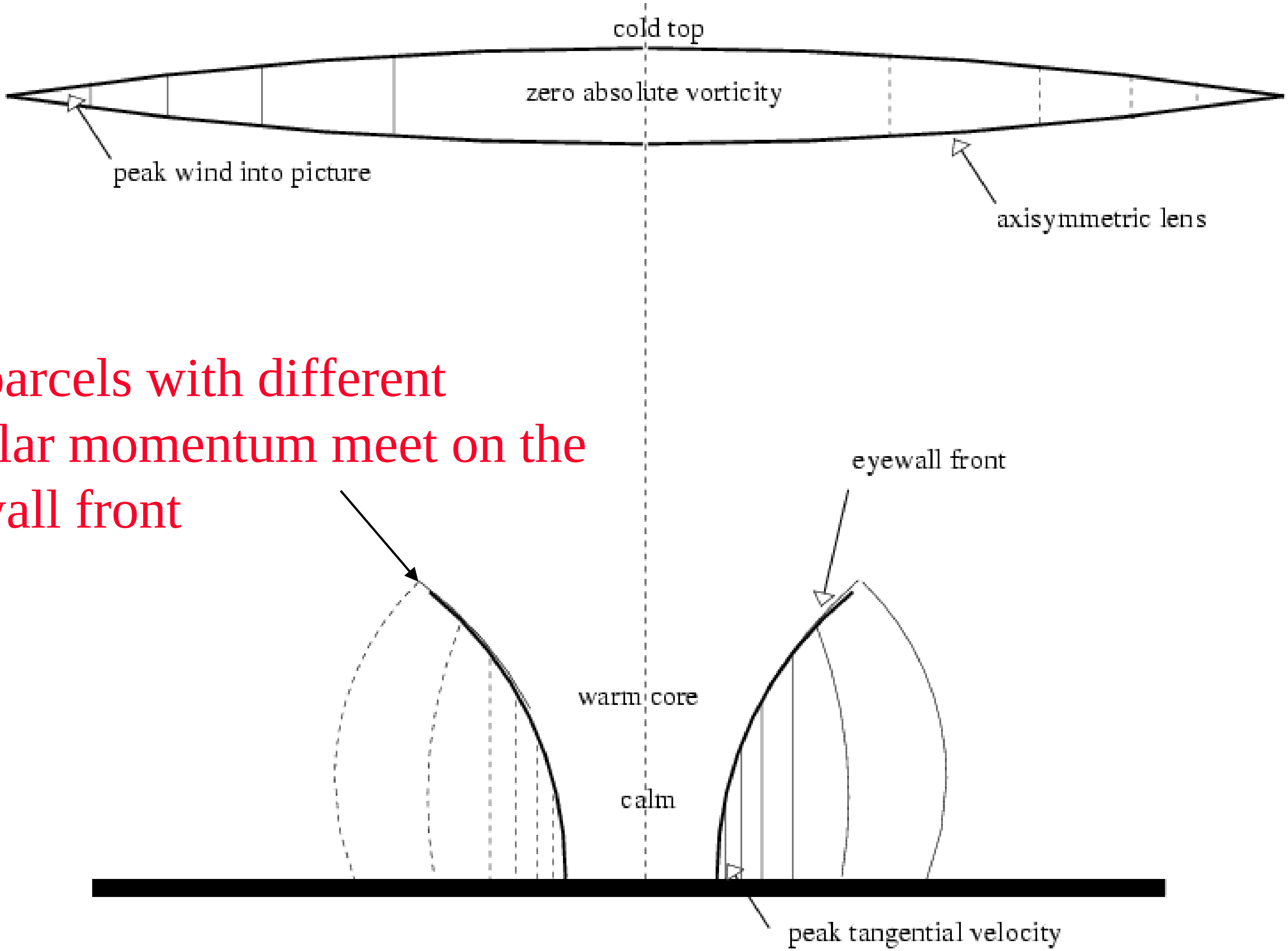


Axisymmetric parcel model

- **Use** **angular** **momentum instead of absolute momentum**
- **Transform to ‘bath plughole vortex’ coordinates (makes parcel boundaries straight lines)**
- **Variable parcel sizes but conserve torus volumes**



schematic picture of the end-state for a cylindrical convective parcel jump



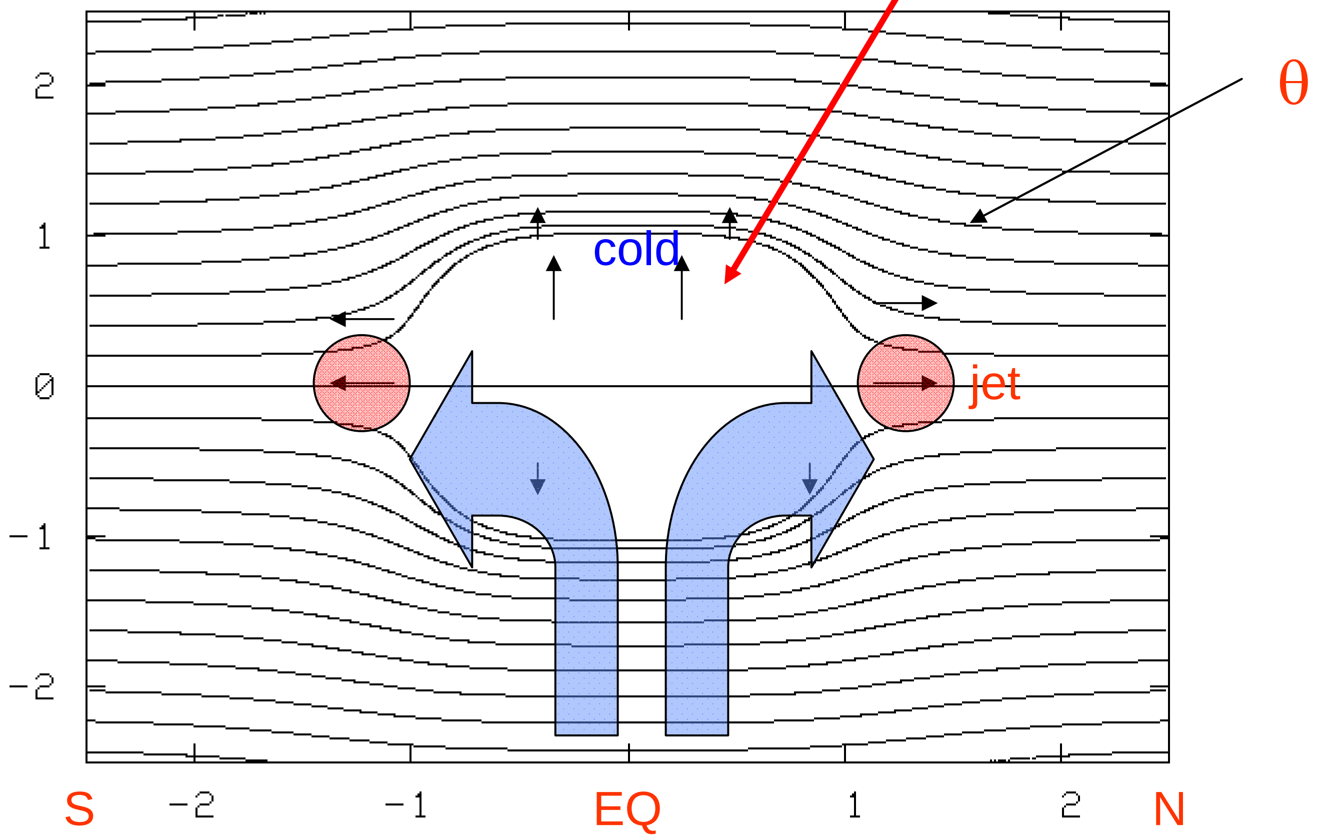
Air parcels with different angular momentum meet on the eyewall front

Convective mass flux – “pumping up the lens”

Homogeneous intrusion solution of Gill(1981) adapted for equatorial beta-plane i.e. $f = \beta y$

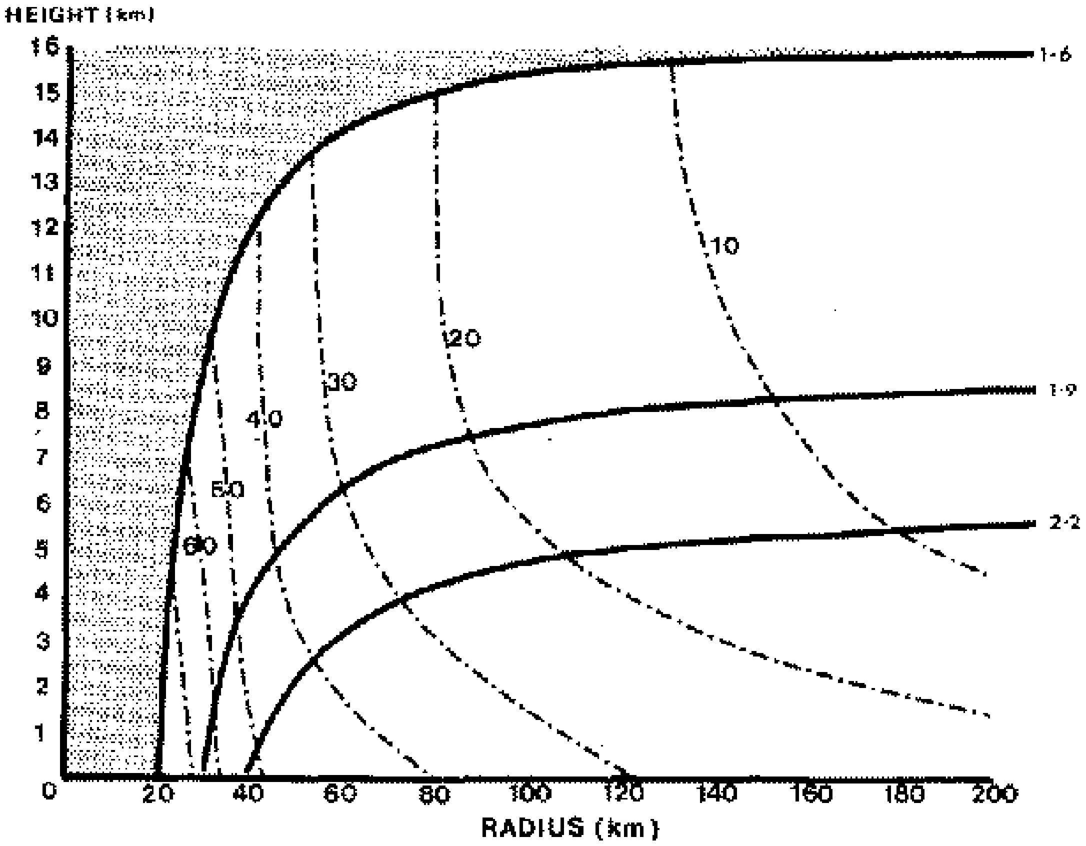
Zero PV region embedded in background linear meridional PV variation

Meridional-height section through the tropics



Hurricane structure – zero PV assumption

- M and θ surfaces coincide
- Shape of surfaces fixed by dθ/dM and θ at z=0

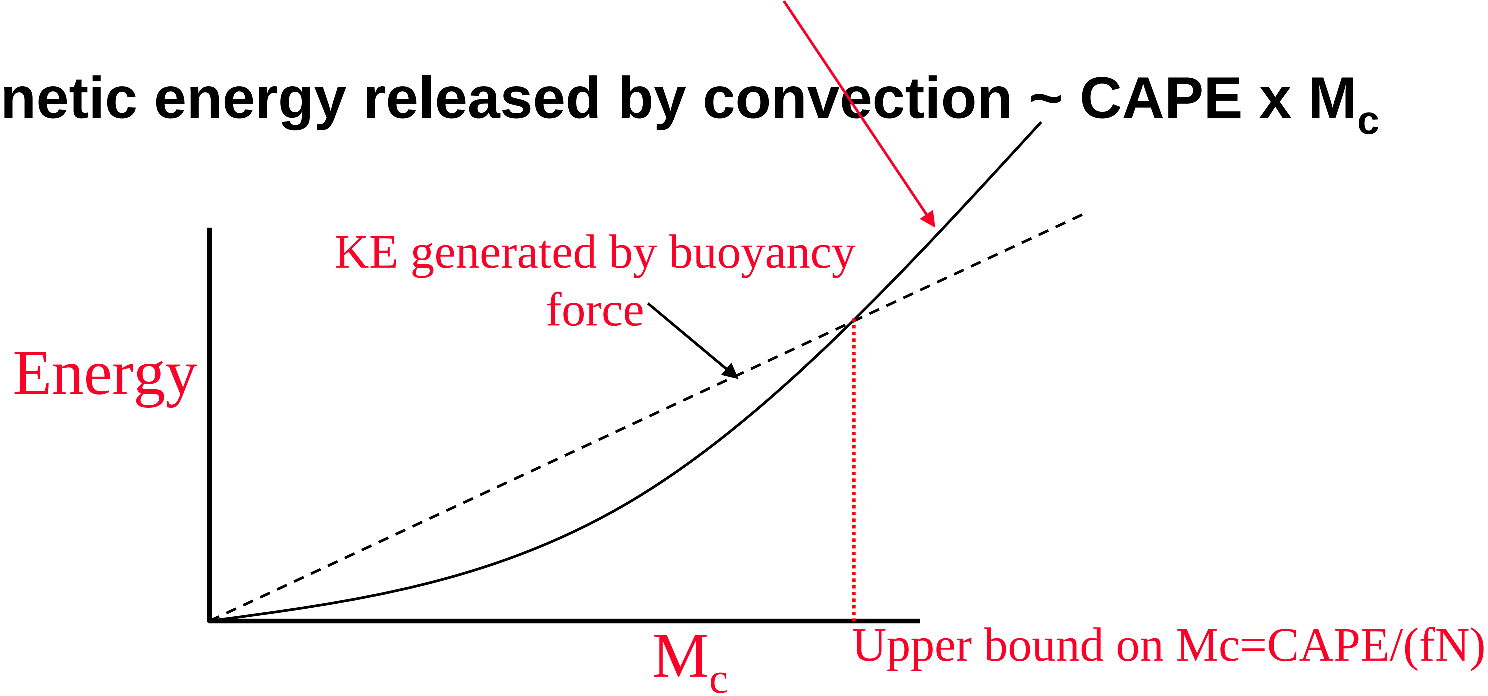


Mesoscale PV anomaly generation

- **if lens has radius r, the thickness is ~ (f/N)r**
- **Velocity at lens rim ~ fr and so KE~ $(fr)^2 \times M_c$**

where M_c $(\sim(f/N)r^2$ is the mass convected
therefore the lens energy E ~ fN M_c^2

- **kinetic energy released by convection ~ CAPE x M_c**



Convective length scales

max lens radius r_* $$r_* = \frac{\sqrt{(CAPE)}}{f}$$

CAPE=1000 $J.kg^{-1}$ and $f=10^{-4}\,s^{-1}$ → $r_*=300$ km

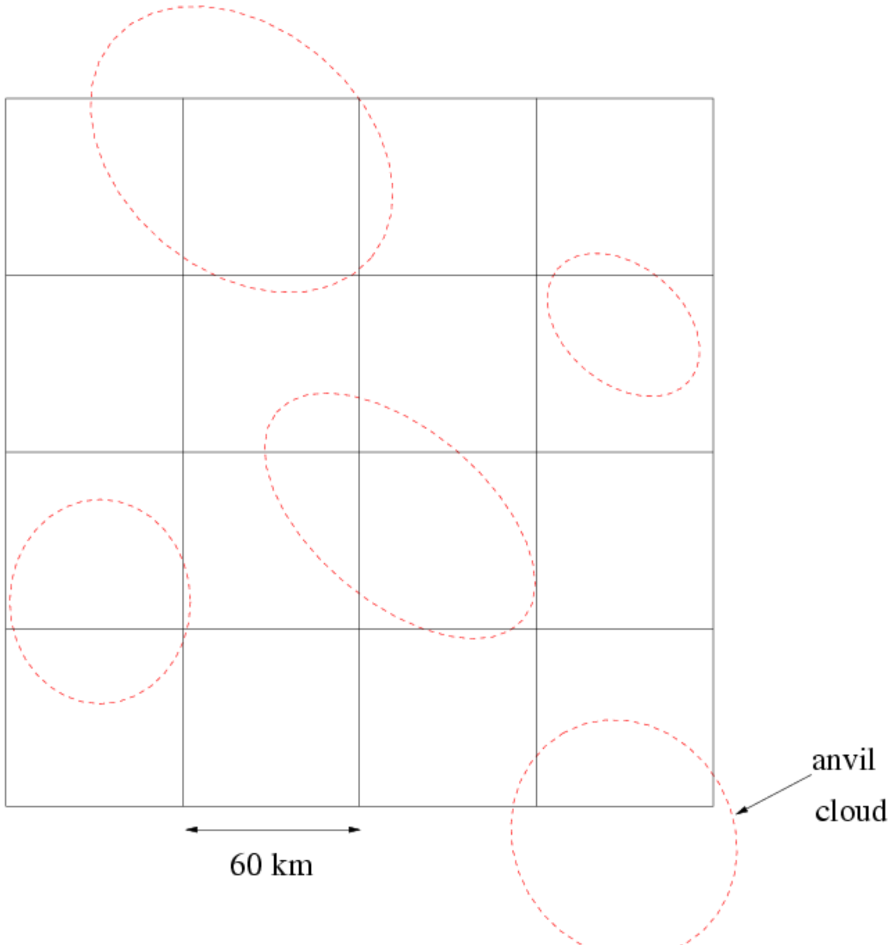
- Mesoscale convective system scale

Rossby radius of deformation (L_R) based on depth of convection ($H_{c)}$ gives:

$$L_R = \frac{NH_c}{f} \quad \sim 1000 \text{ km}$$

Convection parametrization issues

- **Low deep convective cloud density relative to ‘gridpoint density**



Convection parametrization issues (continued)

- **At the gridscale, are convective parametrization increments just noise ?**

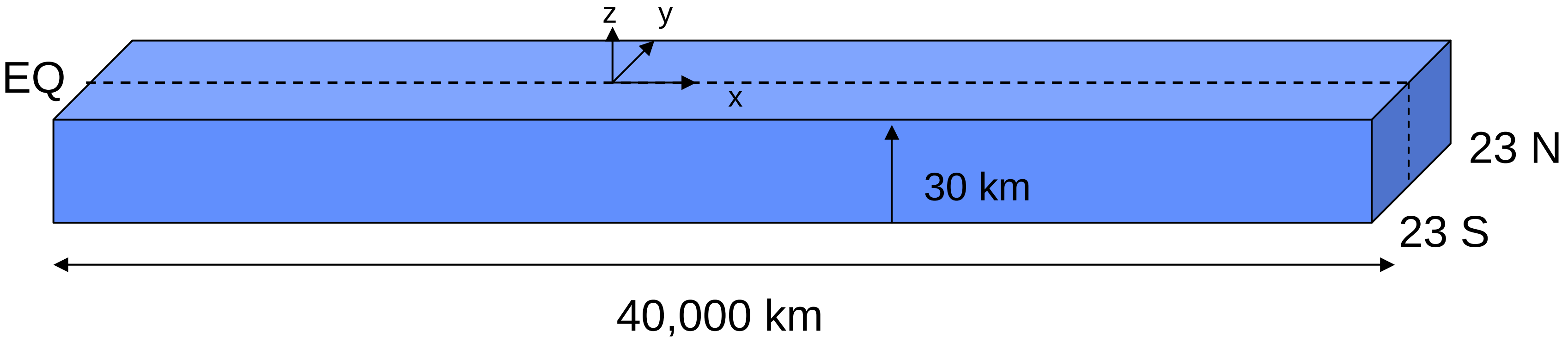
- **Can current convective parametrization provide the correct upscale energy transports ?**

Use big-domain convection simulation to provide answers !

Big-domain simulation of tropical convection

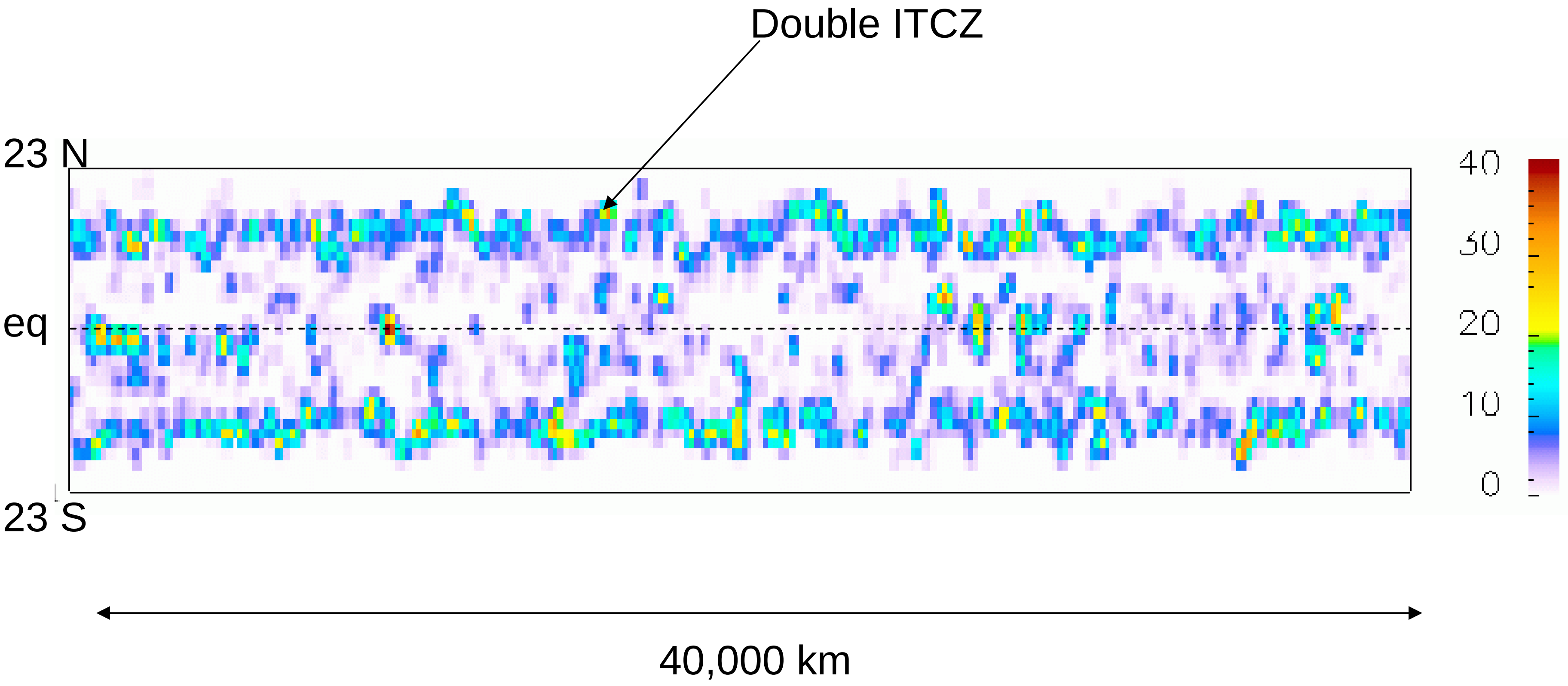
- attempt to simulate the interaction of deep tropical convection with large-scale flow with horizontal gridlengths > 1 km and domain sizes > 5000 km (in x & y)
- use O(1 km) resolution in x and O(10 km) in y
- run for at least 5 days but with short timestep (5 secs)
- coarse-grain fields *and* tendencies (i.e. source terms)
- compute PDFs, energy spectra, Fourier amp/phase plots

‘circum-equatorial’ model configuration

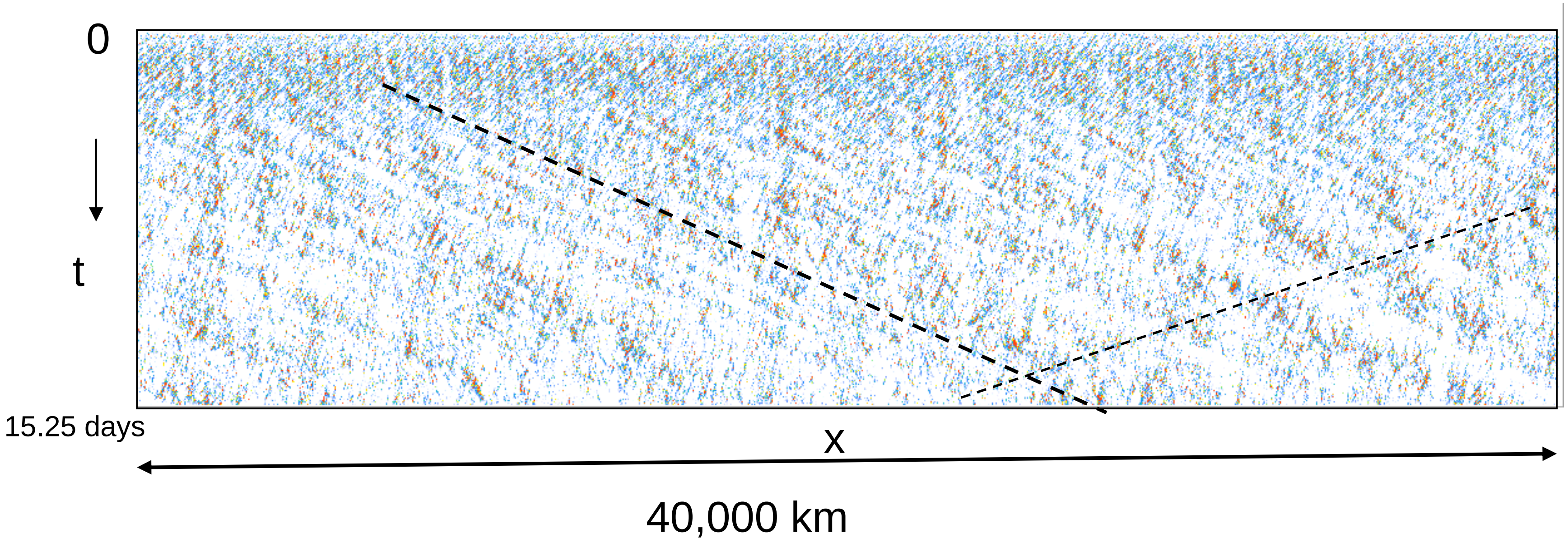


- dx= 2.44 km dy= 40 km   50 vertical levels
- 16384 x 128 x 50 gridpoints
- Coriolis parameter= β y
- impose 5 m/s easterly geostrophic wind
- fixed SST = (28 – *a* y$^{2)}$ degs C (*a* chosen so that N/S limits are 1.56 C cooler)
- no radiation , just imposed profile of cooling (-1.5 K/day up to 11 km)
- 3-phase cloud microphysics

Total rainfall over the 15.3 day CRM simulation

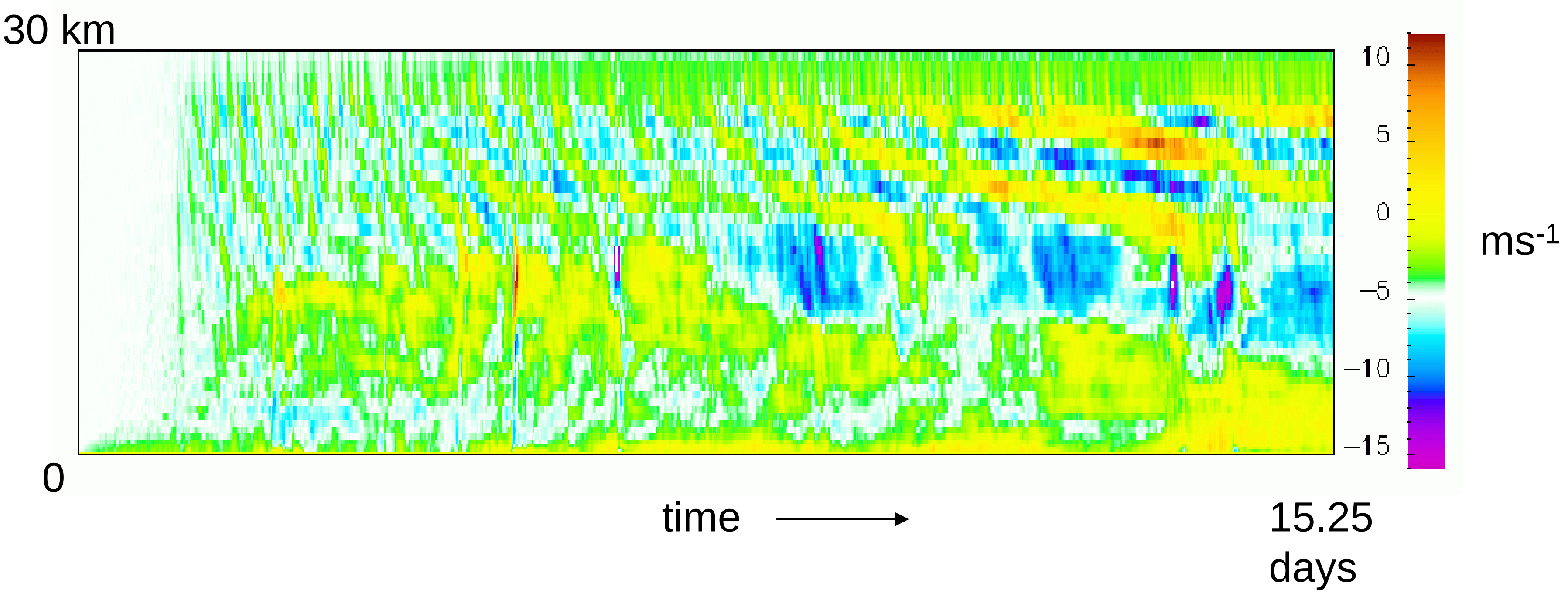


Hovmuller diagram of rainfall rate averaged over 10N-10S zone



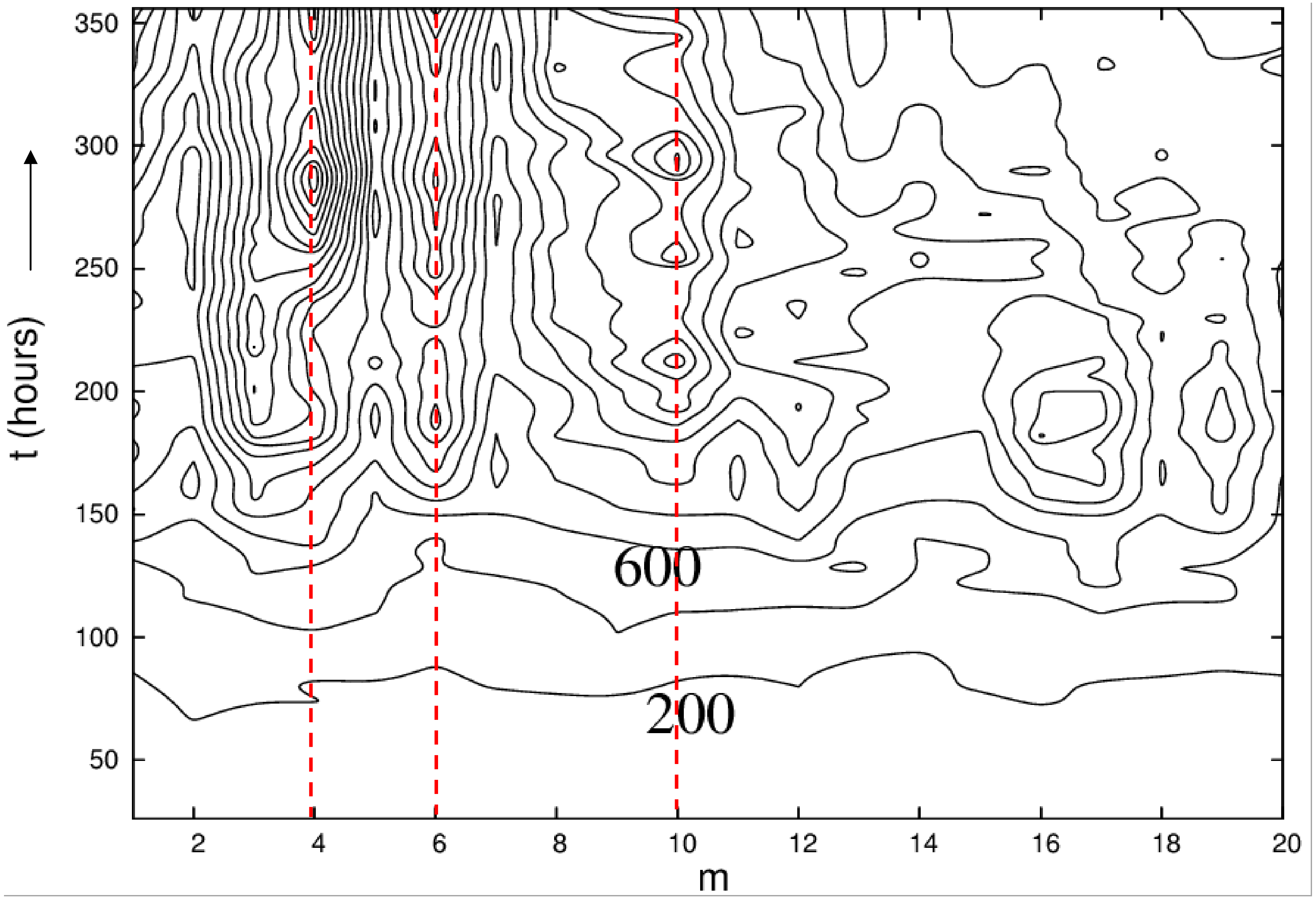
--------- equivalent to 18 m/s propagation speed

Time-height section of zonal wind at a point on the equator



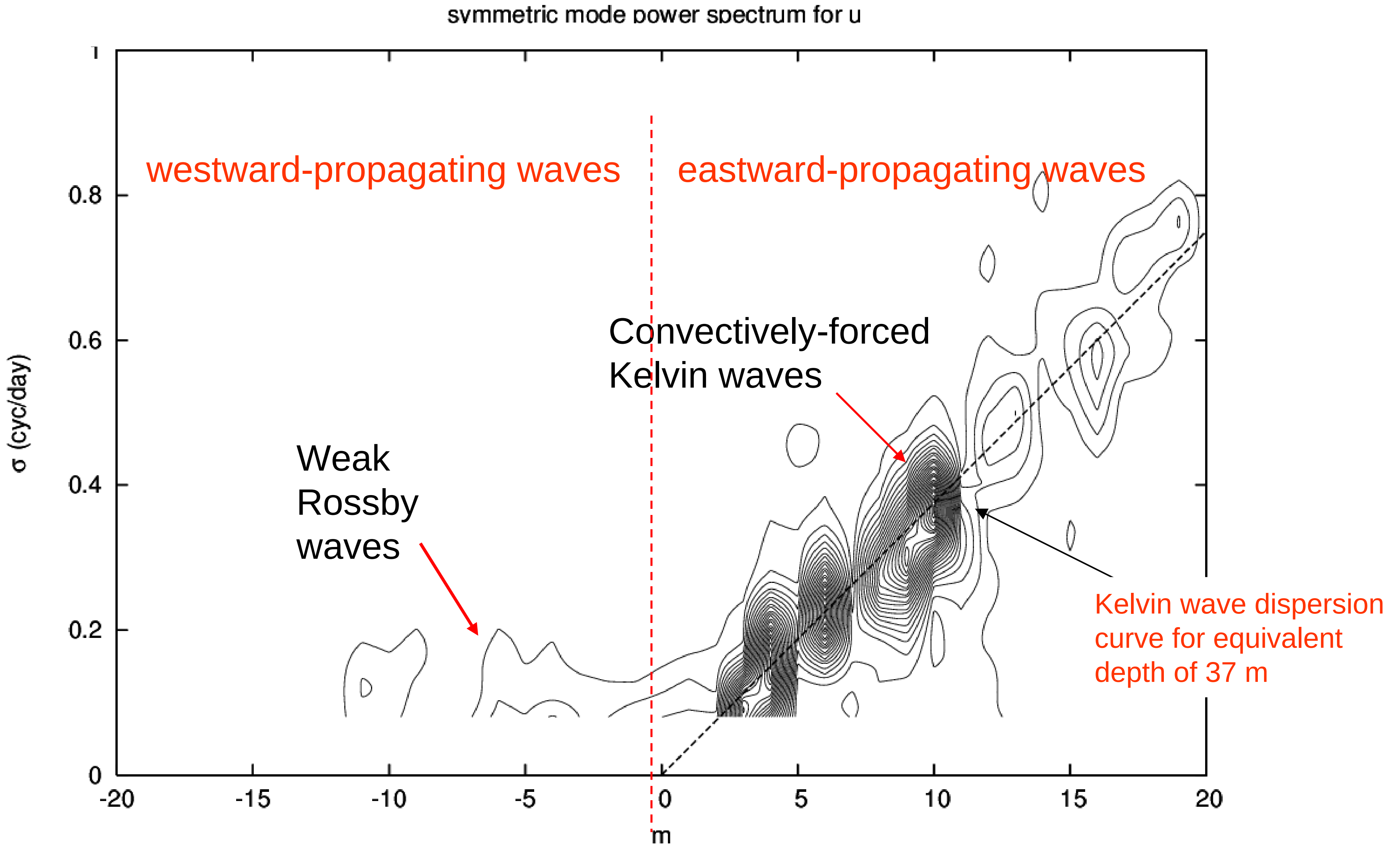
Growth of depth-integrated kinetic energy as a function of zonal wavenumber (m)

cont. int. 200 Jm^{-2}



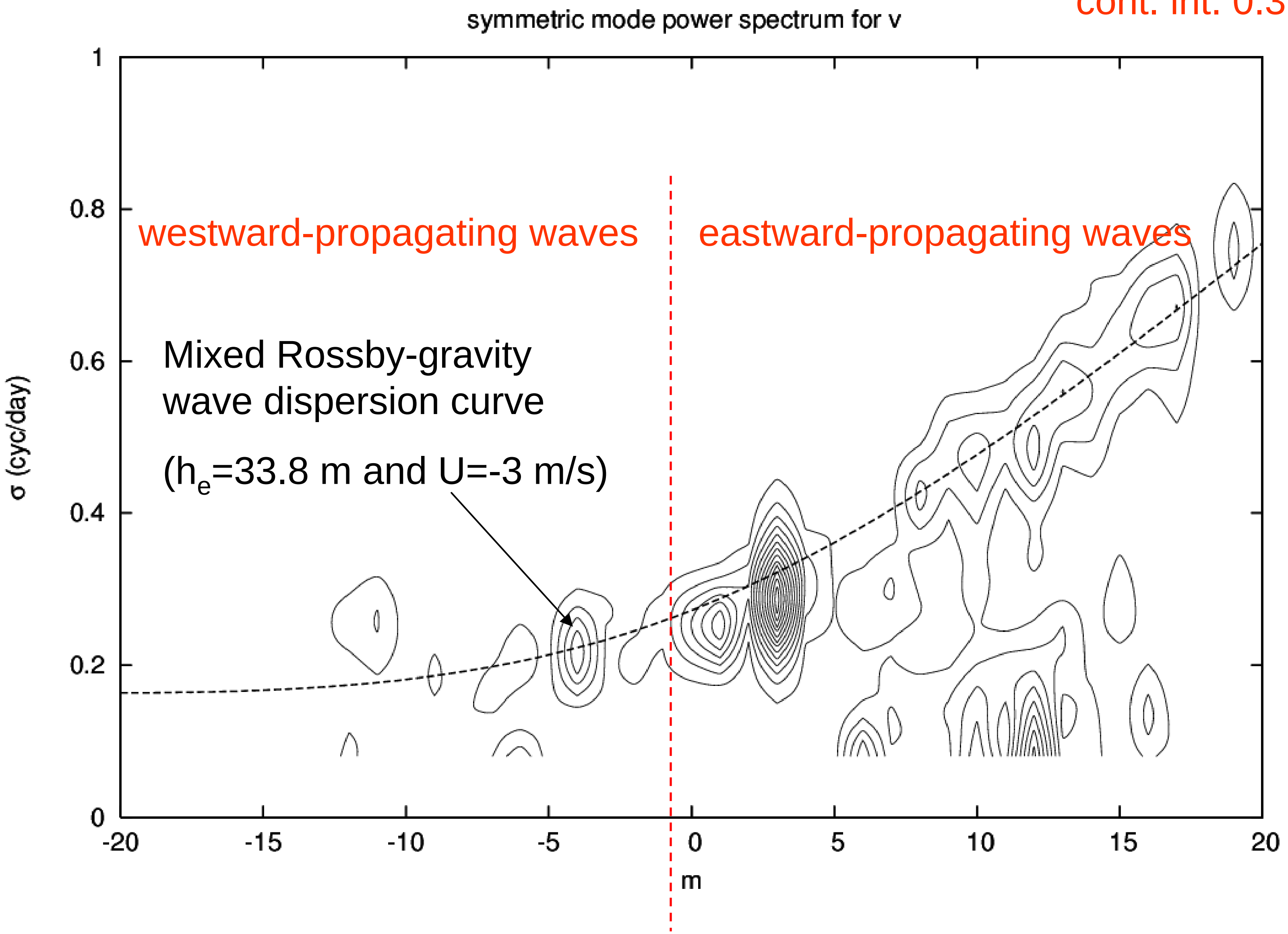
Symmetric contribution to the variance in u (height-mean)

cont. int. 0.3 m^2s^{-2}



Symmetric contribution to the variance in v

cont. int. 0.3 $m^2 s^{-2}$



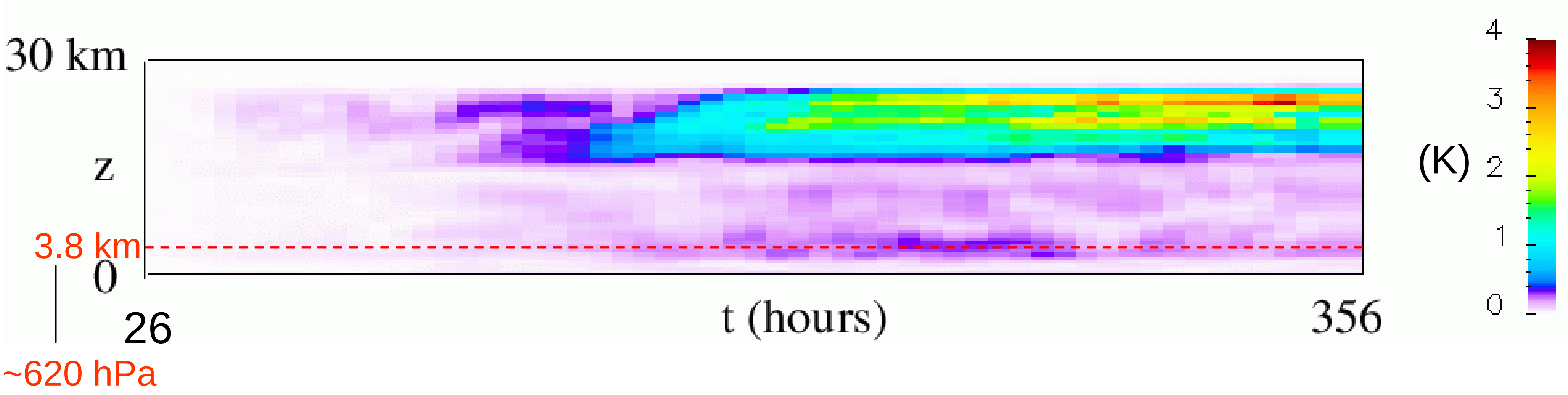
westward-propagating waves

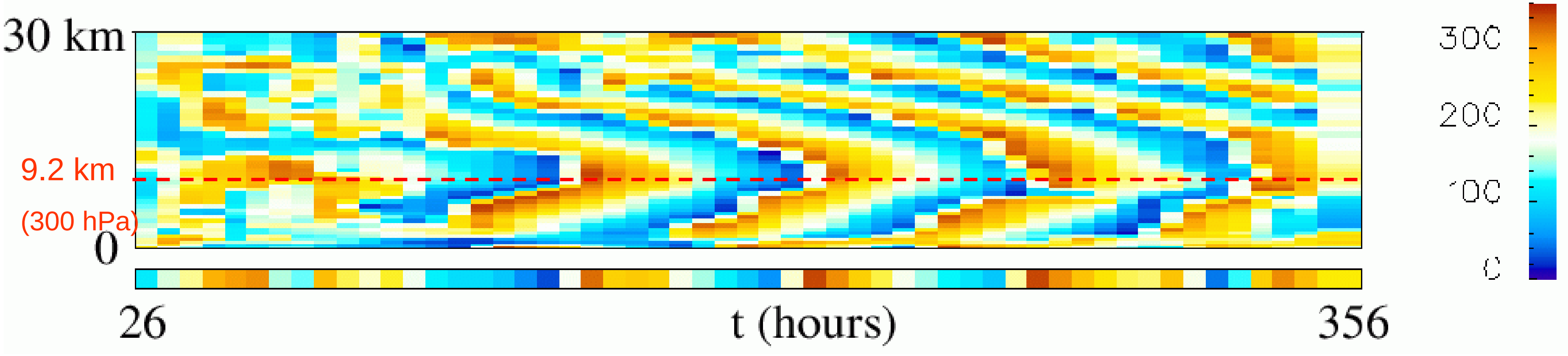
eastward-propagating waves

Mixed Rossby-gravity wave dispersion curve

(h_e=33.8 m and U=-3 m/s)

Time-height section of amplitude and phase of potential temperature perturbation. (m=10)

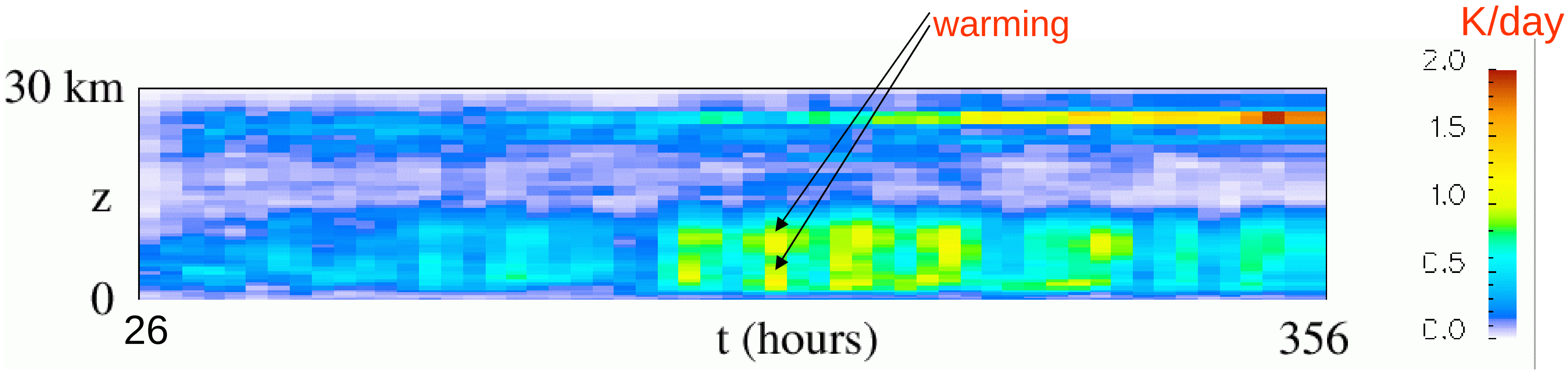




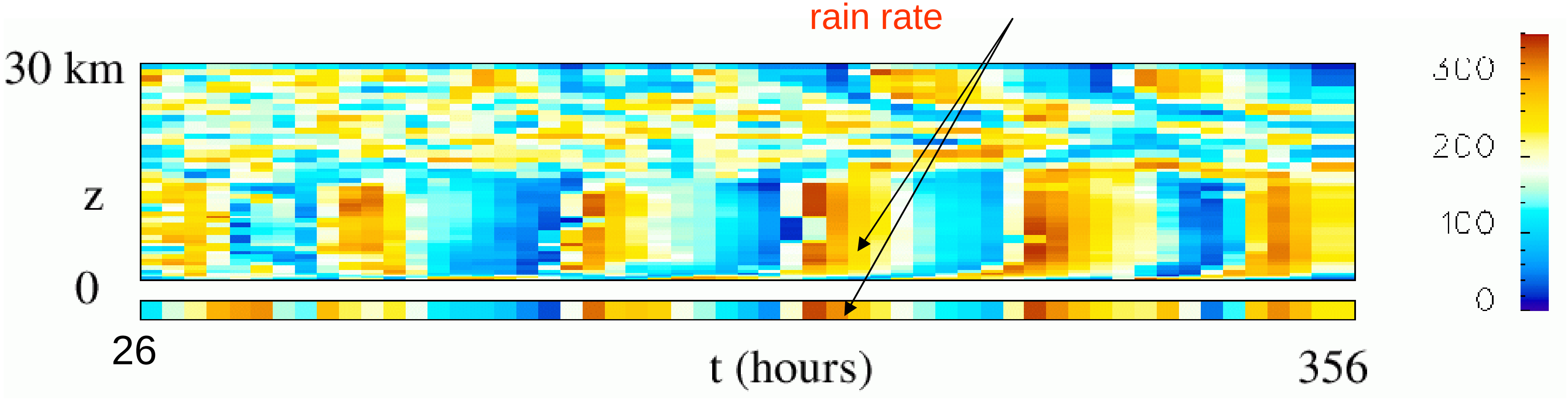
Time-height section of the amplitude and phase of Q

Zonal wavenumber 10

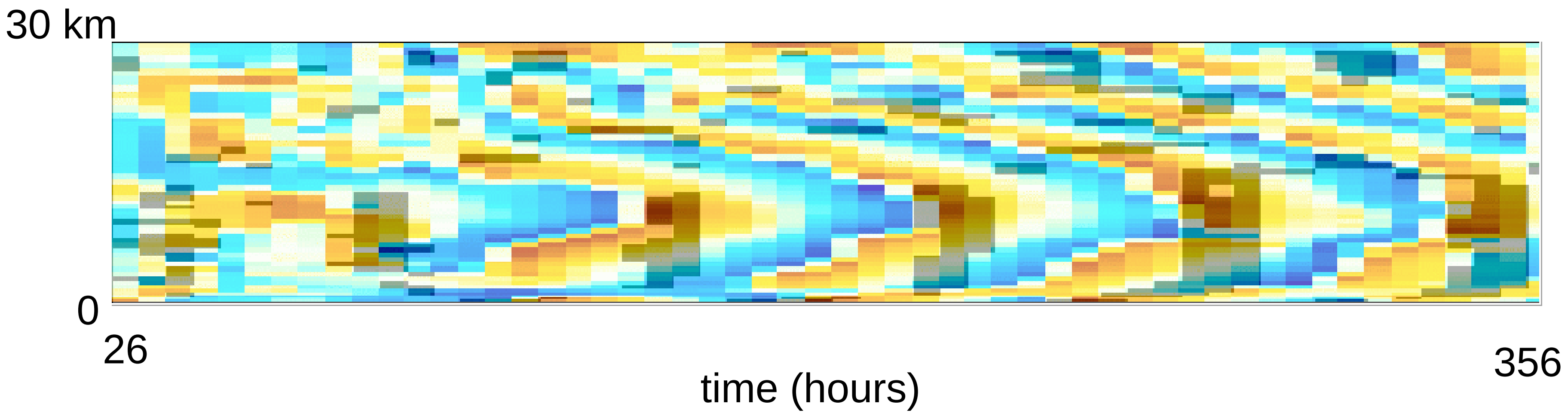
double peak in convective warming



Convective heating in phase with surface rain rate



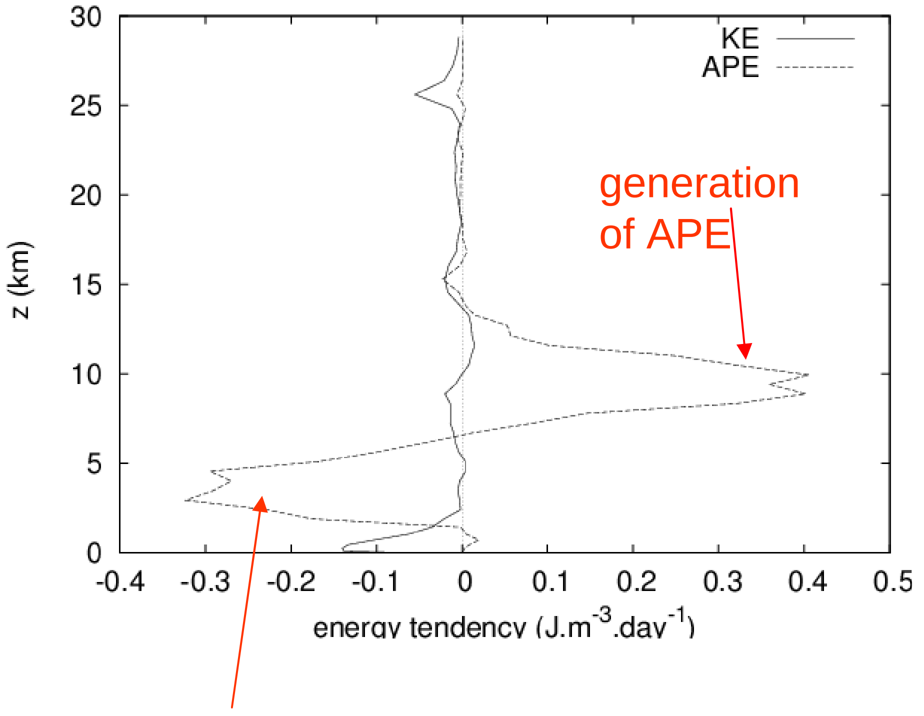
Composite of the time-height sections of wavenumber 10 phase for potential temperature perturbation and convective warming.



Think of red/orange as warm regions in m=10 wave

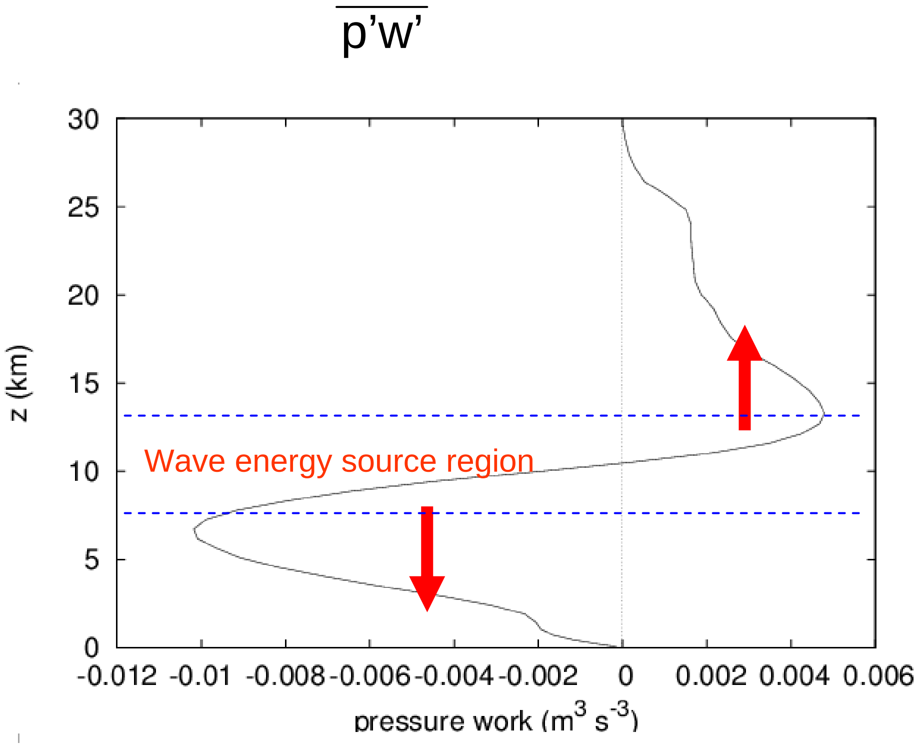
and dark shading represents convective warming

Vertical profiles of KE/APE production and pressure work at wavenumber 10



generation of APE

destruction of APE



Wave energy source region

Coarse-grain effective potential temperature tendency $(\tilde{Q})$

$$\frac{\partial \theta}{\partial t} = -\mathbf{V}\cdot\nabla\theta + Q$$

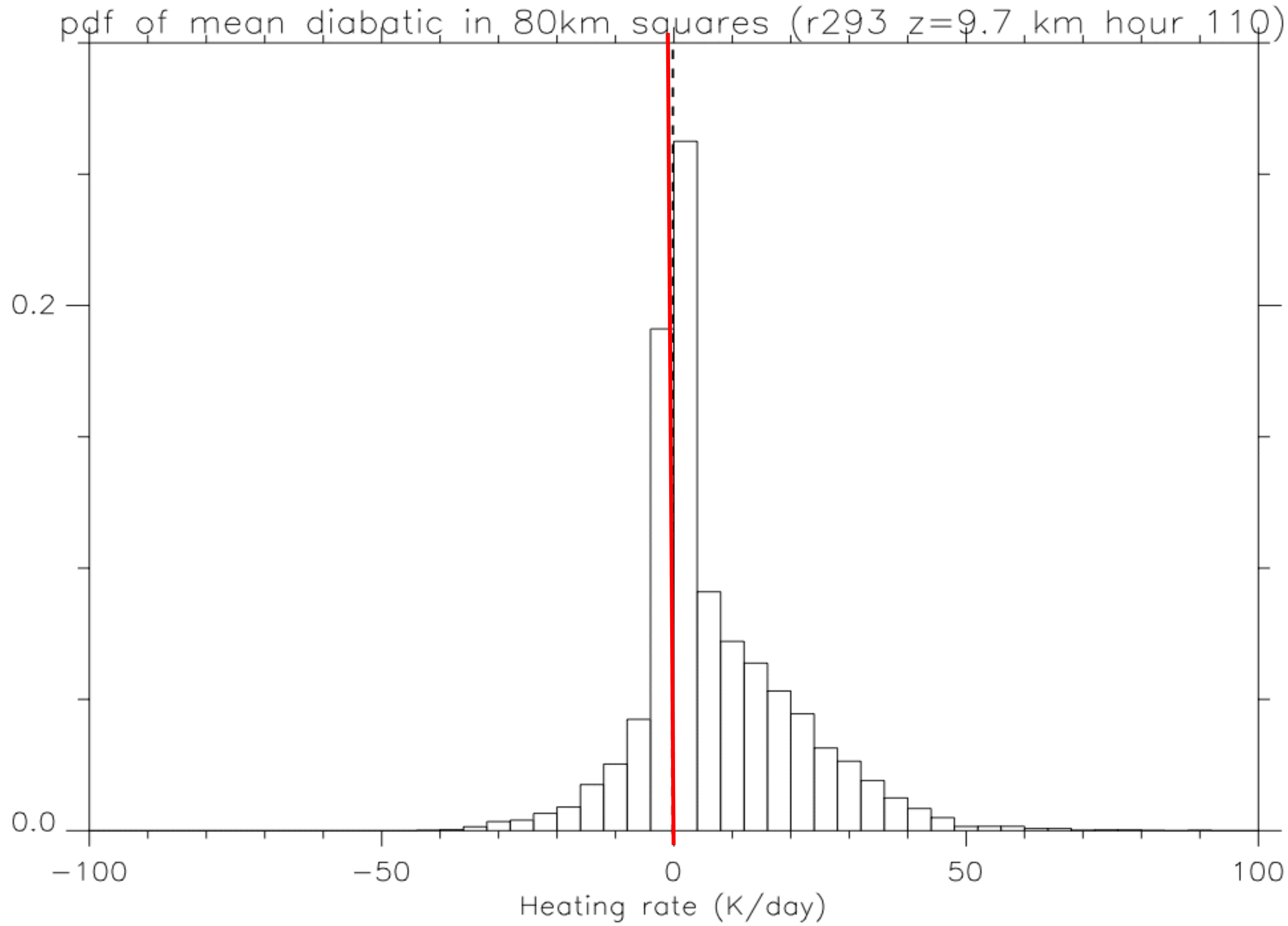
Let overbar denote average over a coarse grid box, then:

$$\frac{\partial \bar{\theta}}{\partial t} = -\overline{\left(\mathbf{V}\cdot\nabla\theta\right)} + \bar{Q}$$

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{\mathbf{V}}\cdot\nabla\bar{\theta} = \underbrace{\bar{\mathbf{V}}\cdot\nabla\bar{\theta} - \overline{\left(\mathbf{V}\cdot\nabla\theta\right)} + \bar{Q}} = \tilde{Q}$$

Parametrized + resolved heating

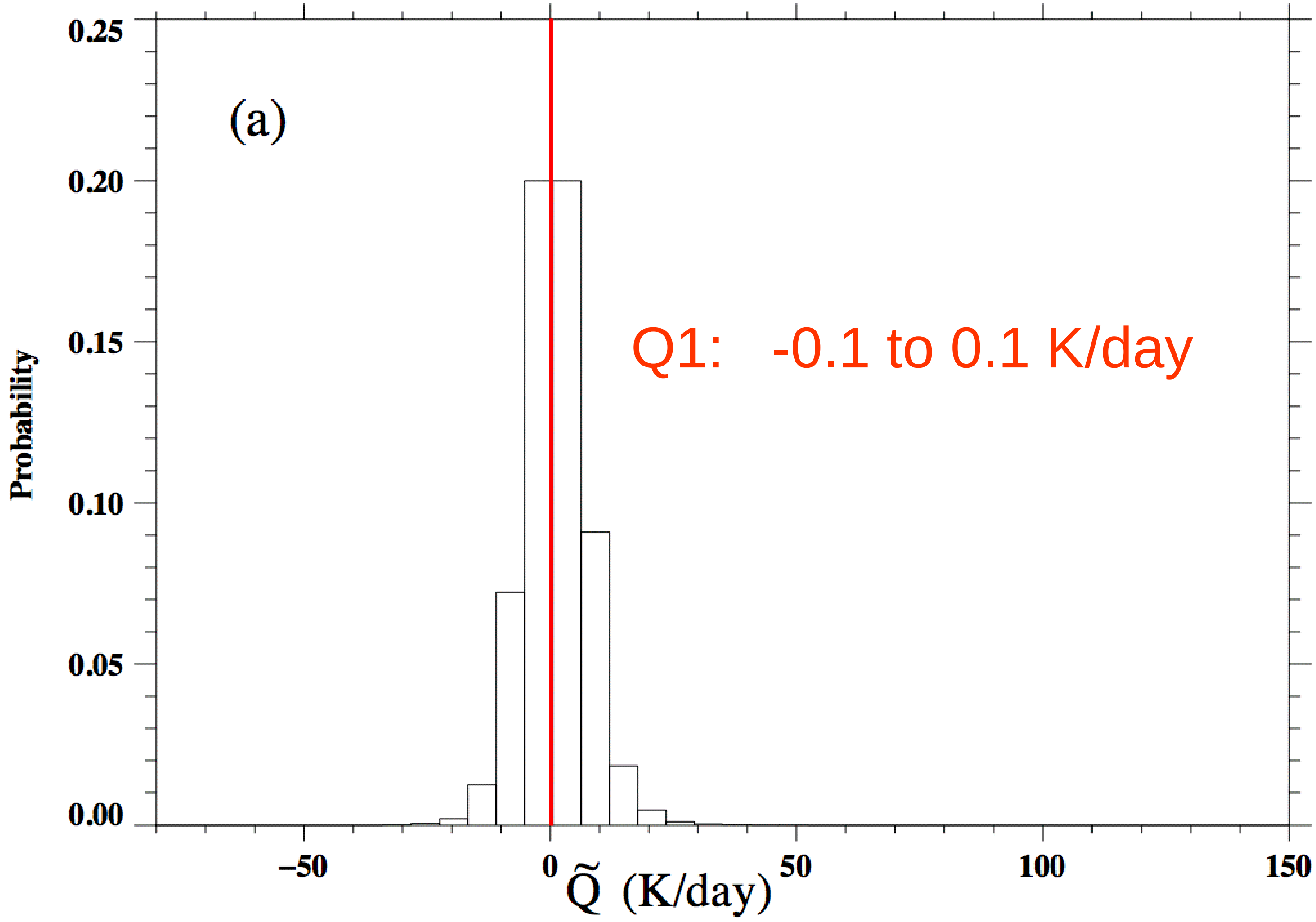
Histogram of diabatic heating (Q) coarse-grained to an 80 km grid at z=9.4 km



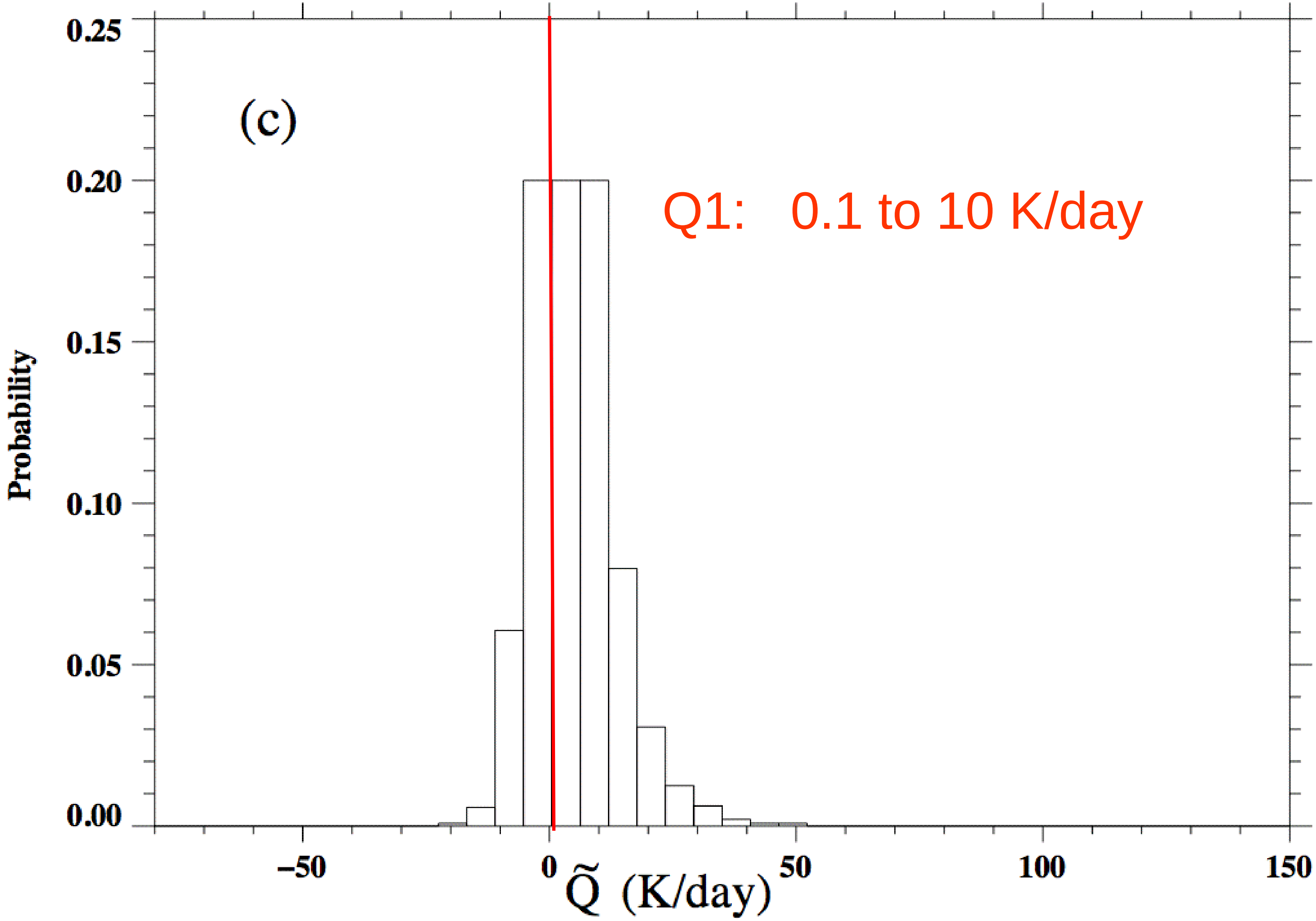
PDFs conditioned on convective parametrization temperature tendencies (Q1)

- take the coarse-grained CRM fields and feed them into a convective parametrization scheme (Bechtold et al, 2001) → Q1 - the convective warming rate
- at any model level, bin the diabatic tendency $\tilde{Q}$ according to different ranges of Q1
- See how the variance of $\tilde{Q}$ depends on Q1
- Use knowledge of variance dependence to calibrate 'stochastic physics' schemes based on multiplicative noise

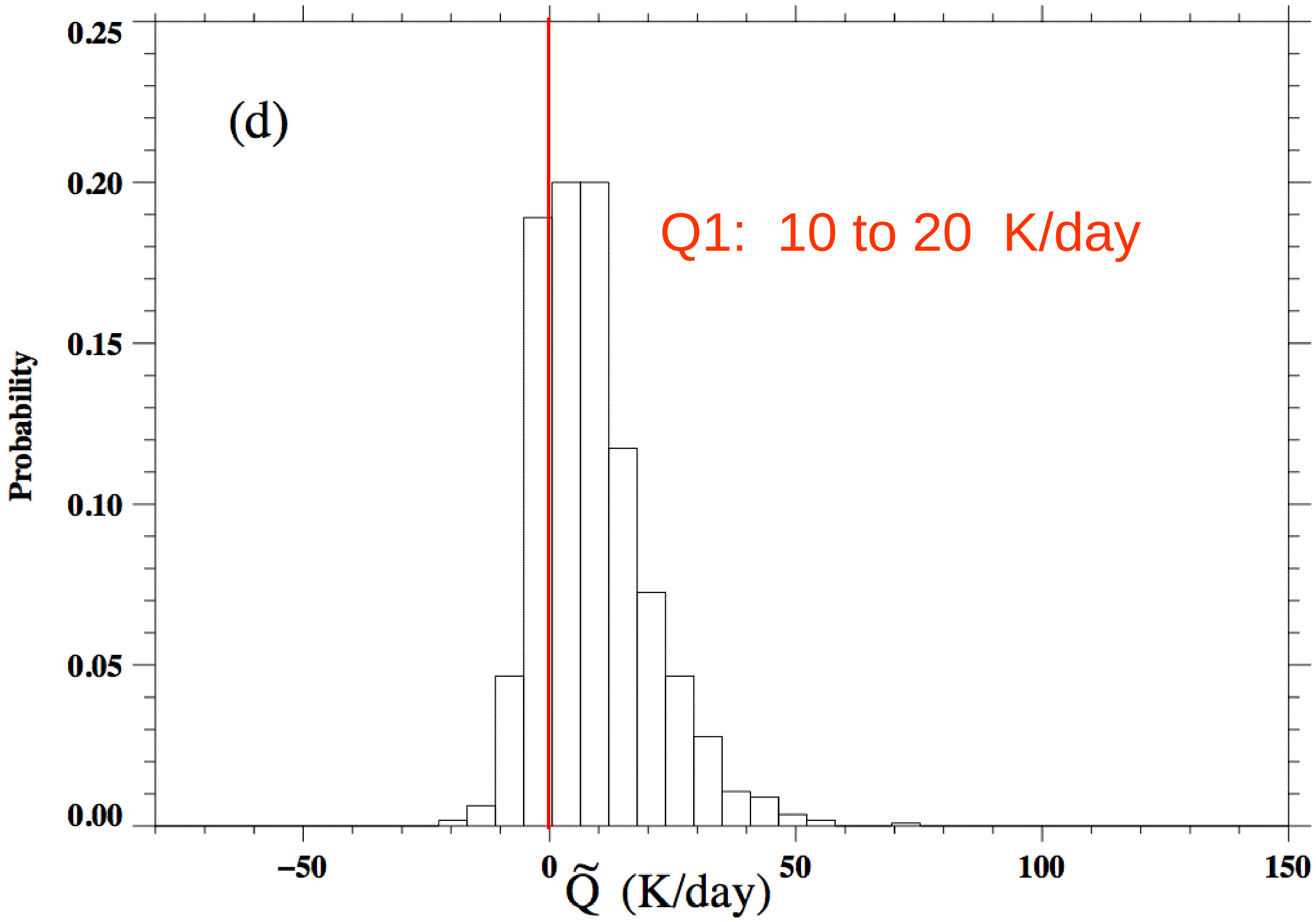
Pdfs of Q conditioned on different ranges of Q1



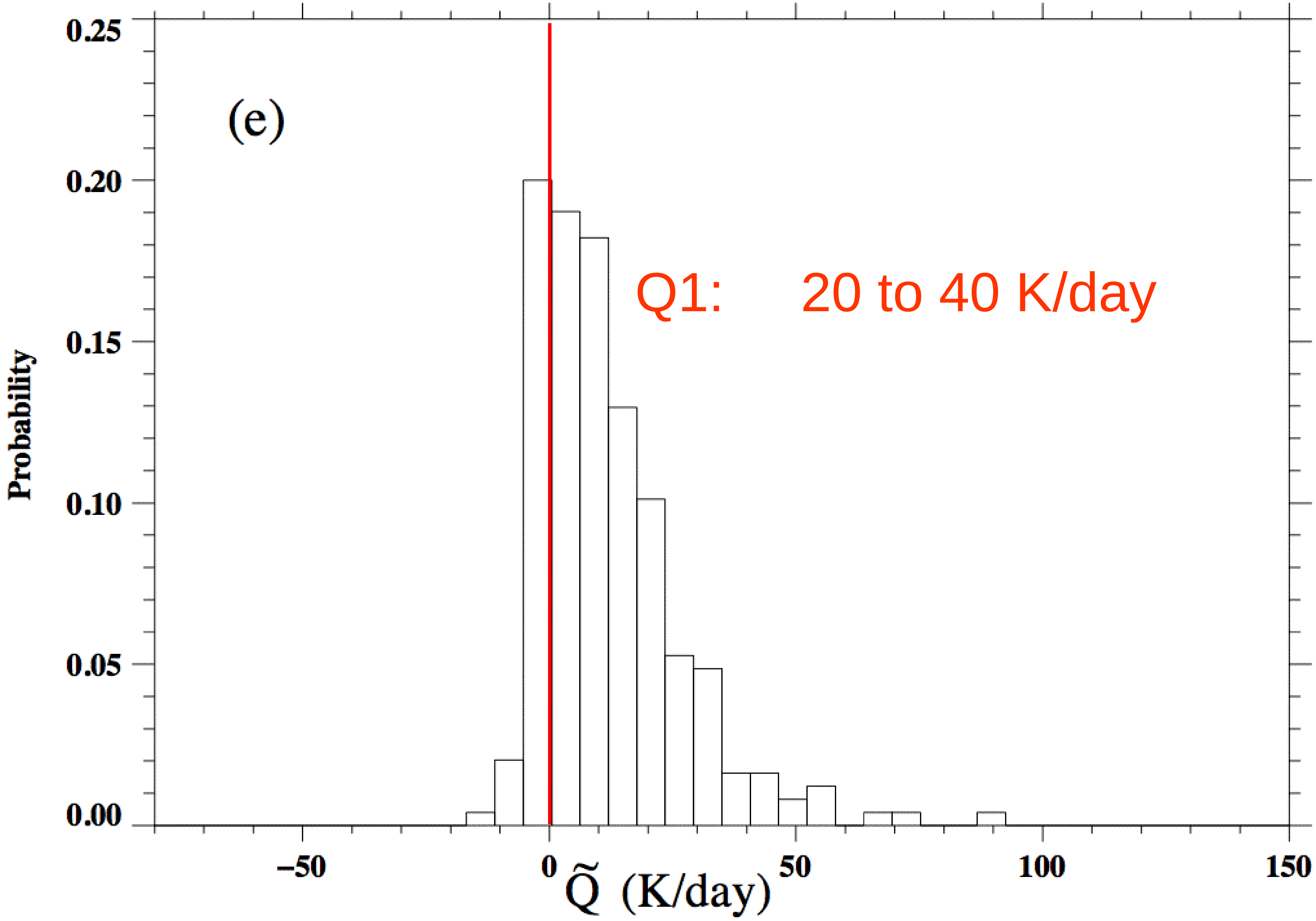
Q1: -0.1 to 0.1 K/day



Q1: 0.1 to 10 K/day

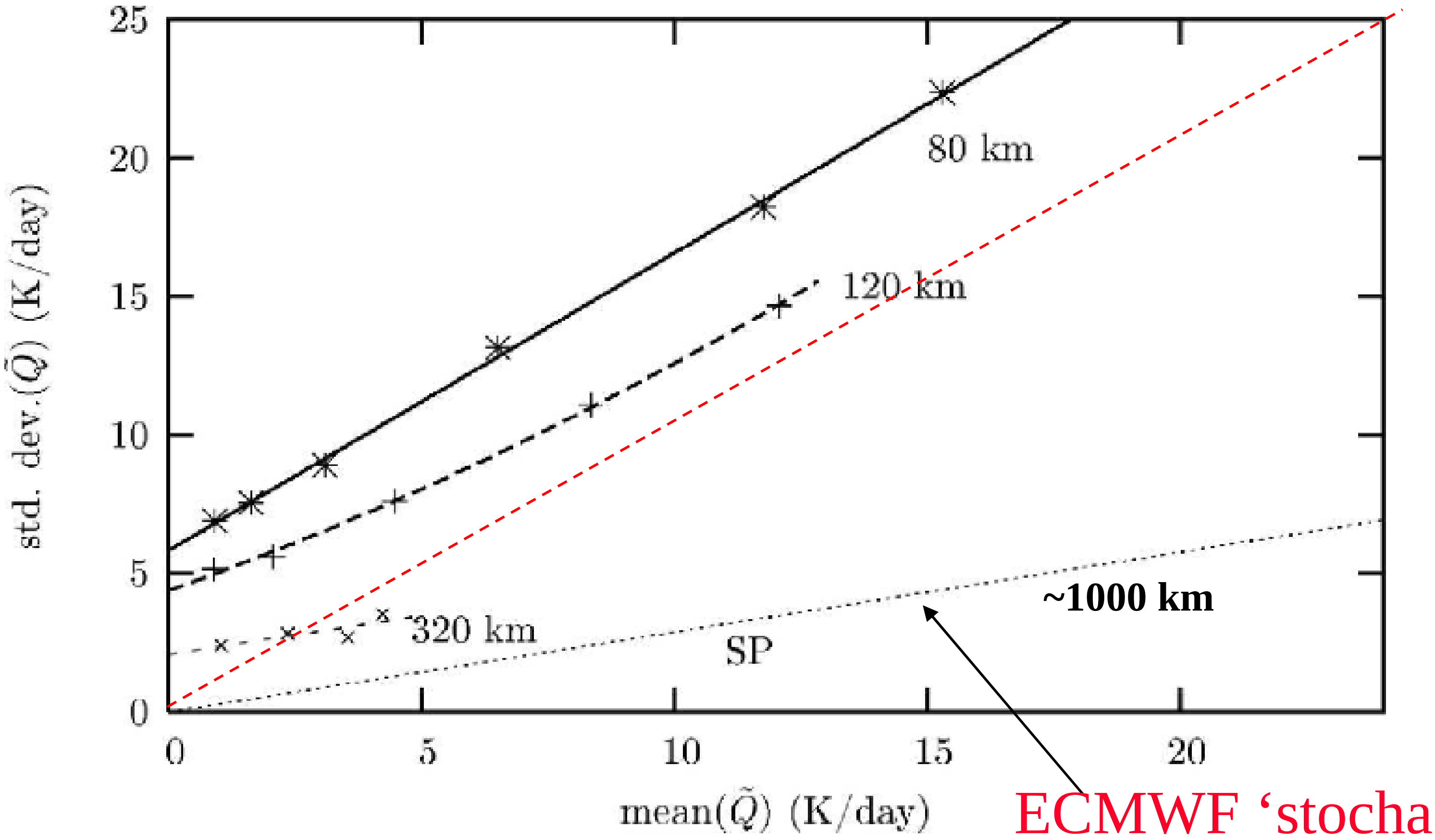


Q1: 10 to 20 K/day



Q1: 20 to 40 K/day

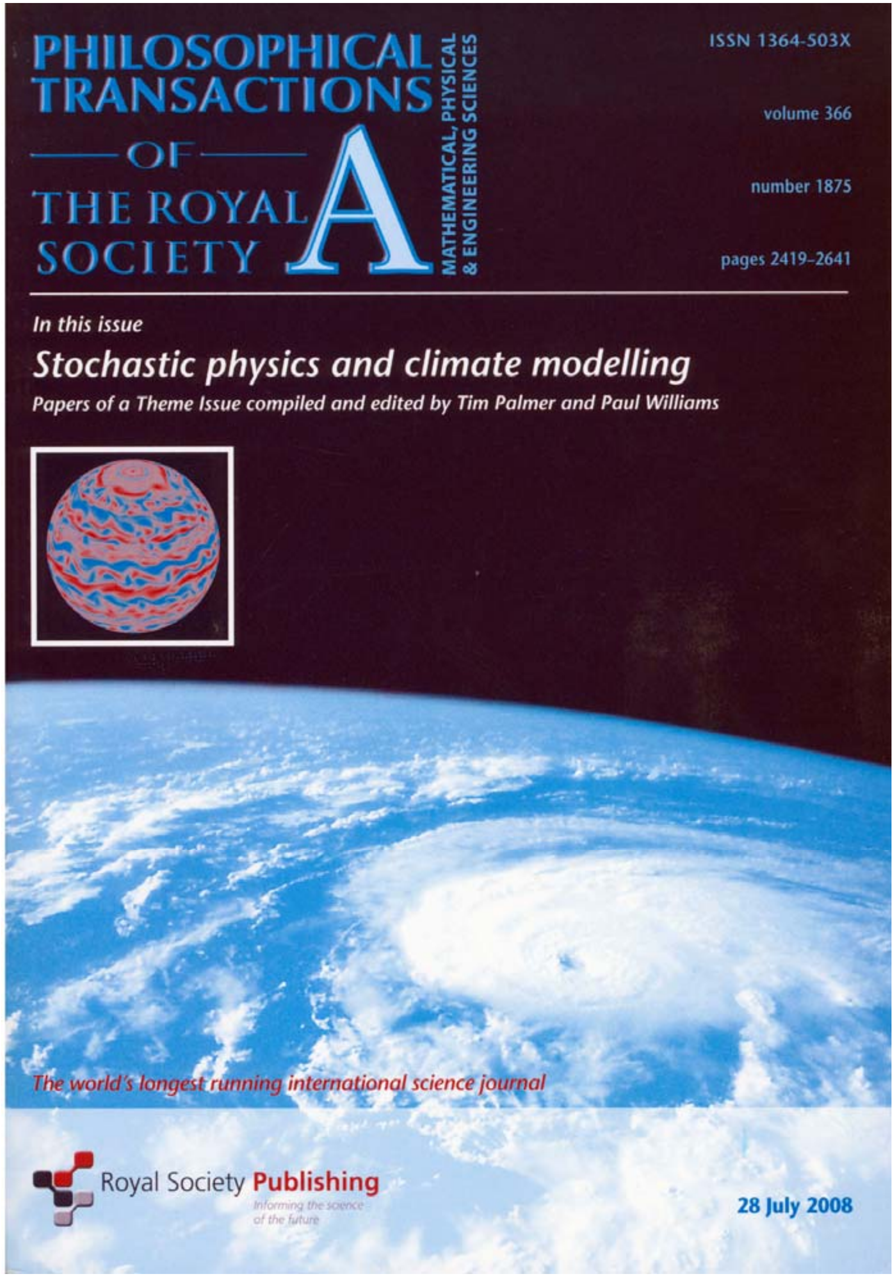
Variance of coarse-grained diabatic tendency



ECMWF ‘stochastic physics scheme’

Phil. Trans paper

Volume 366, Number 1875 / July 28, 2008 Theme Issue: “Stochastic physics and climate modelling” compiled by Tim Palmer and Paul Williams



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Stochastic physics and climate modelling

Papers of a Theme Issue compiled and edited by Tim Palmer and Paul Williams

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Stochastic convection parametrization

- **Buizza et al (1999) -- a component of the 'stochastic physics scheme'. Multiply tendencies by a number between 0.5 and 1.5, selected randomly with a uniform pdf. 10 degree lat/lon box correlation**
- **Lin and Neelin (2000) allow random CAPE fluctuations in the Betts-Miller convection parametrization. Lin and Neelin (2002) use observed rainfall pdf to adapt existing parametrization**
- **Plant and Craig (2008) – stochastic convection parametrization based on a mix of statistical mechanics theory and conventional equilibrium parametrization.**
- **Teixeira and Reynolds (2008) – perturbed wind and temperature tendencies. No temporal/horizontal spatial correlations.**

- Bowler et al (2008) (used in MOGREPS – the Met Office EPS system)

(i) Stochastic convective vorticity – based on anticyclonic lens/meso-vortex model of Gray and Shutts (2002)

(ii) Random parameters – vary entrainment rate and CAPE time scale as an autoregressive process in time

- Shutts (2005) Cellular Automaton Backscatter Scheme (CABS) – includes a convective component to return KE generated by buoyancy to larger scales
- Berner et al (2008) - spectral backscatter scheme (adaption of CABS)

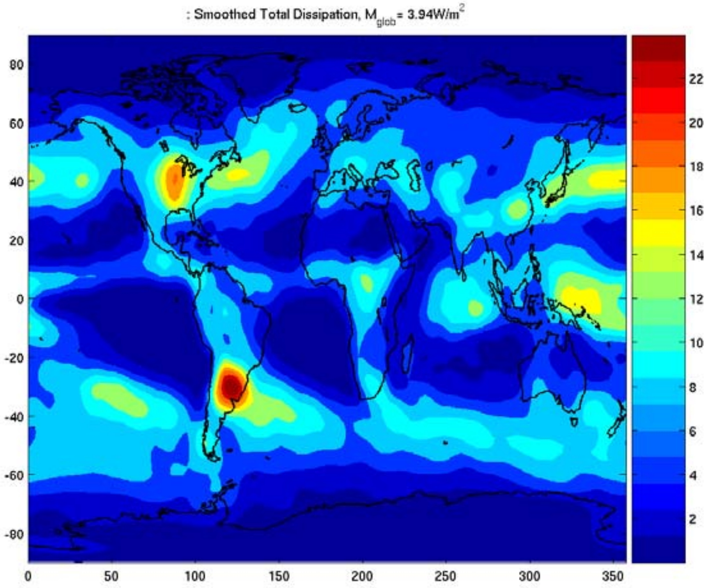
ECMWF Spectral Backscatter Scheme

Berner et al, 2008

Rationale: A fraction of the dissipated energy is scattered upscale and acts as streamfunction forcing for the resolved-scale flow (LES, CASBS: Shutts and Palmer 2004, Shutts 2005); New: spectral pattern generator

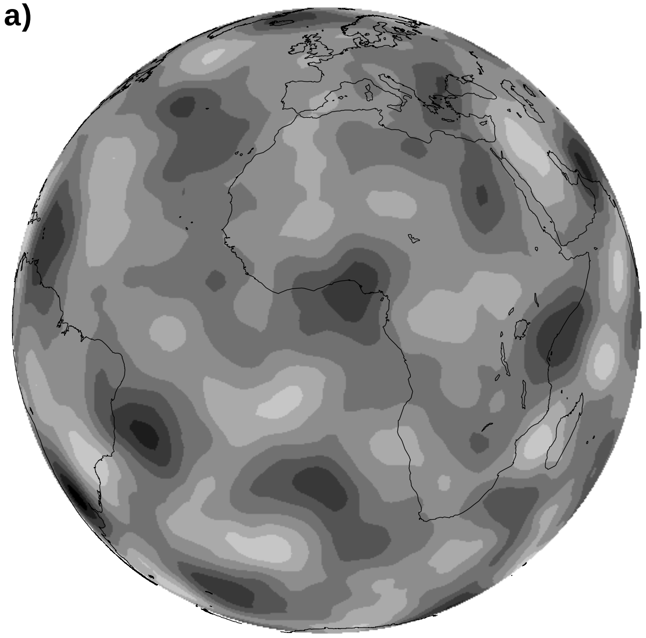
$$\boxed{\Delta\psi^* \propto \sqrt{D}\psi'}$$

$\boxed{D}$



Total Dissipation rate from numerical dissipation, convection, gravity/mountain wave drag.

$\boxed{\psi'}$



Spectral Markov chain: temporal and spatial correlations prescribed

Spectral Backscatter scheme

Assume a streamfunction perturbation in ***spherical harmonics*** representation

$$\psi'(\phi,\lambda) = \sum_{n=0}^{N} \sum_{m=-n}^{n} \psi_n'^m(t) P_{n,m}(\mu) e^{im\lambda}$$

Assume furthermore that each coefficient evolves according to the ***spectral Markov process***

$$\psi_n'^m(t+1) = (1-\alpha)\psi_n'^m(t) + g_n\sqrt{\alpha}\,\epsilon(t)$$

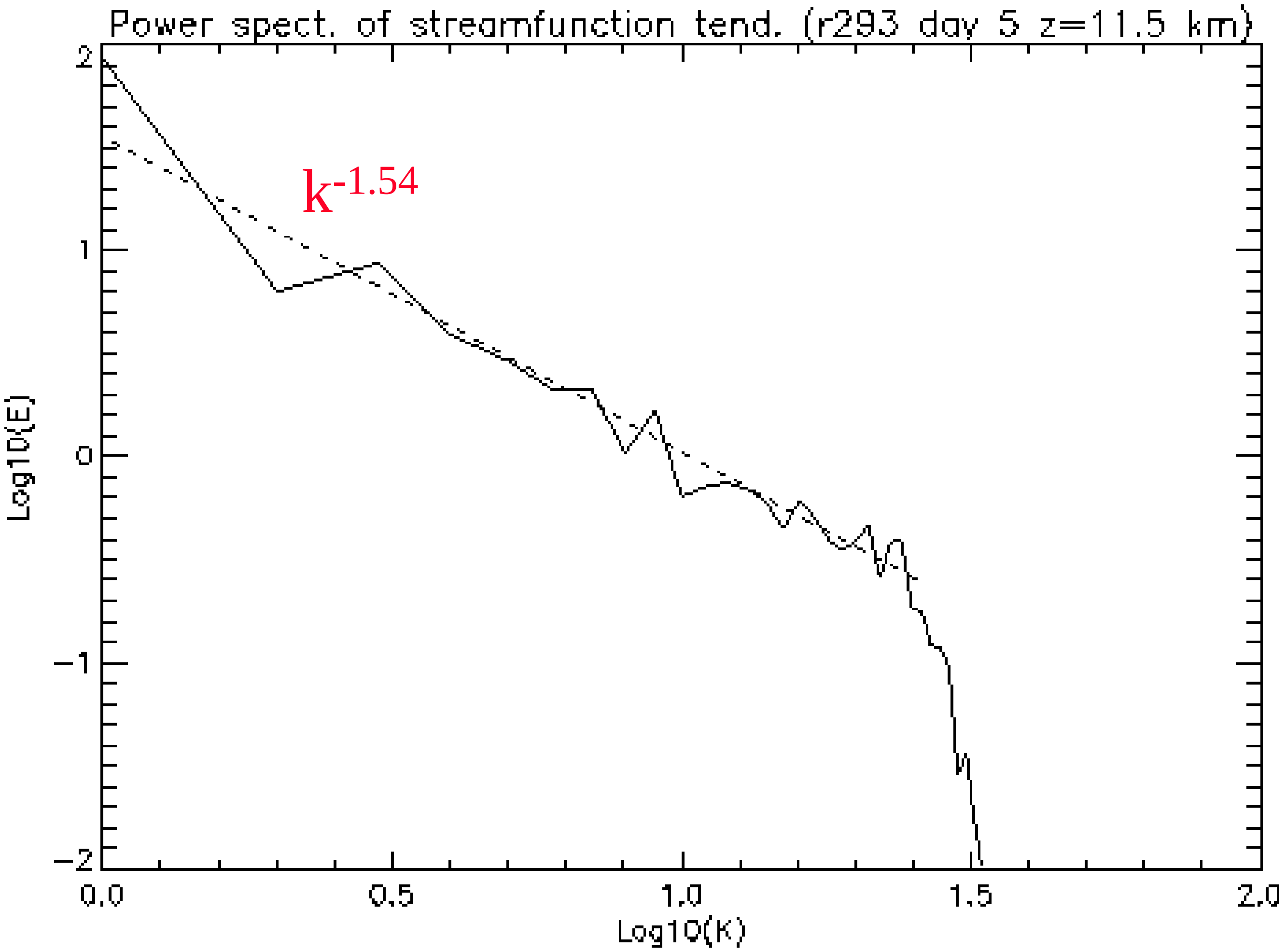
Find the wavenumber dependent noise amplitudes $g_n = b \;\; n^p$

so that prescribed kinetic energy dE is injected into the flow

$$b \; = \left(\frac{4\pi a^2\alpha}{\sigma_z\Gamma}\, dE'\right)^{\frac{1}{2}}$$

with $\Gamma = \sum_{n=n_1}^{n_2} n(n+1)(2n+1)n^{2p}$

Power spectrum of coarse-grained streamfunction forcing

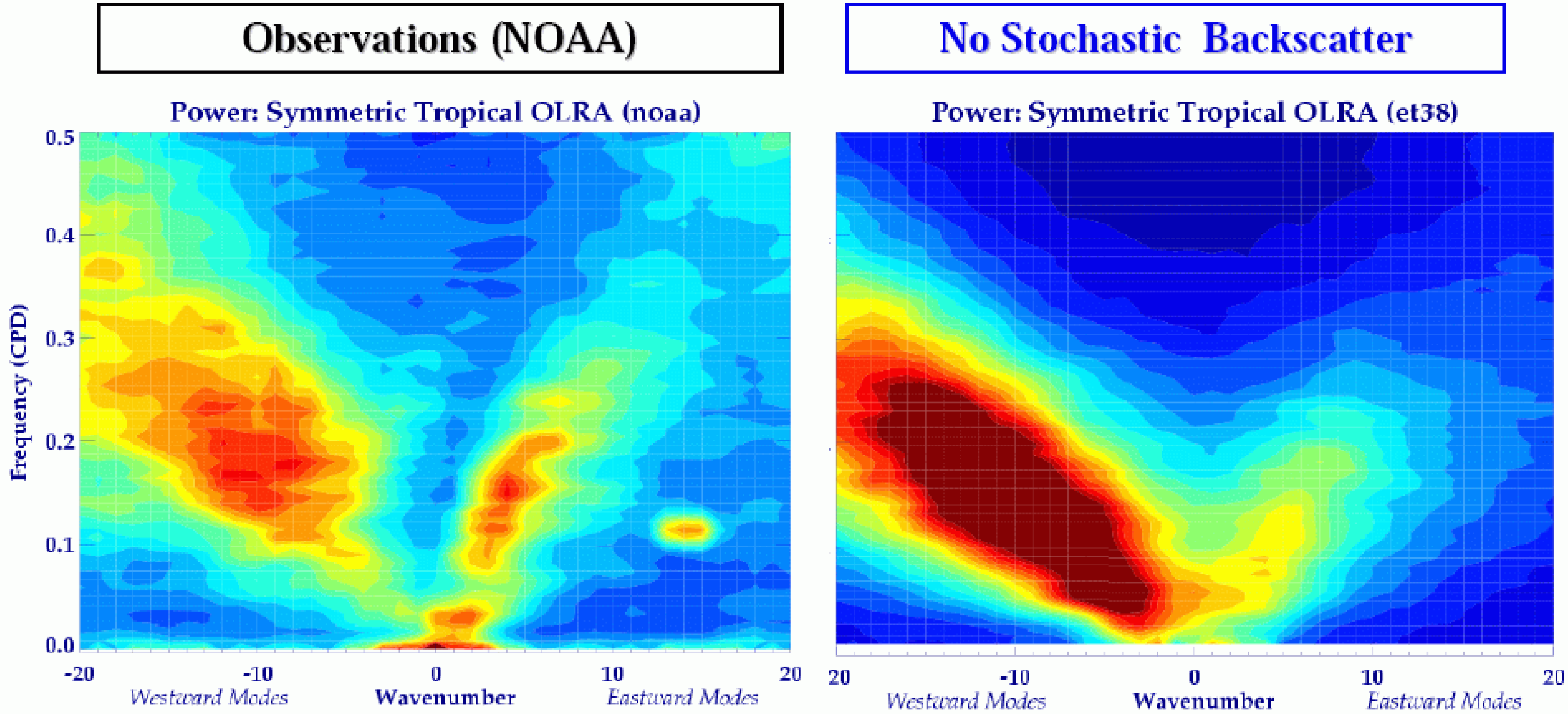


Wavenumber-Frequency Spectrum

Slide from Judith Berner

Symmetric part, background removed
(after Wheeler and Kiladis, 1999)

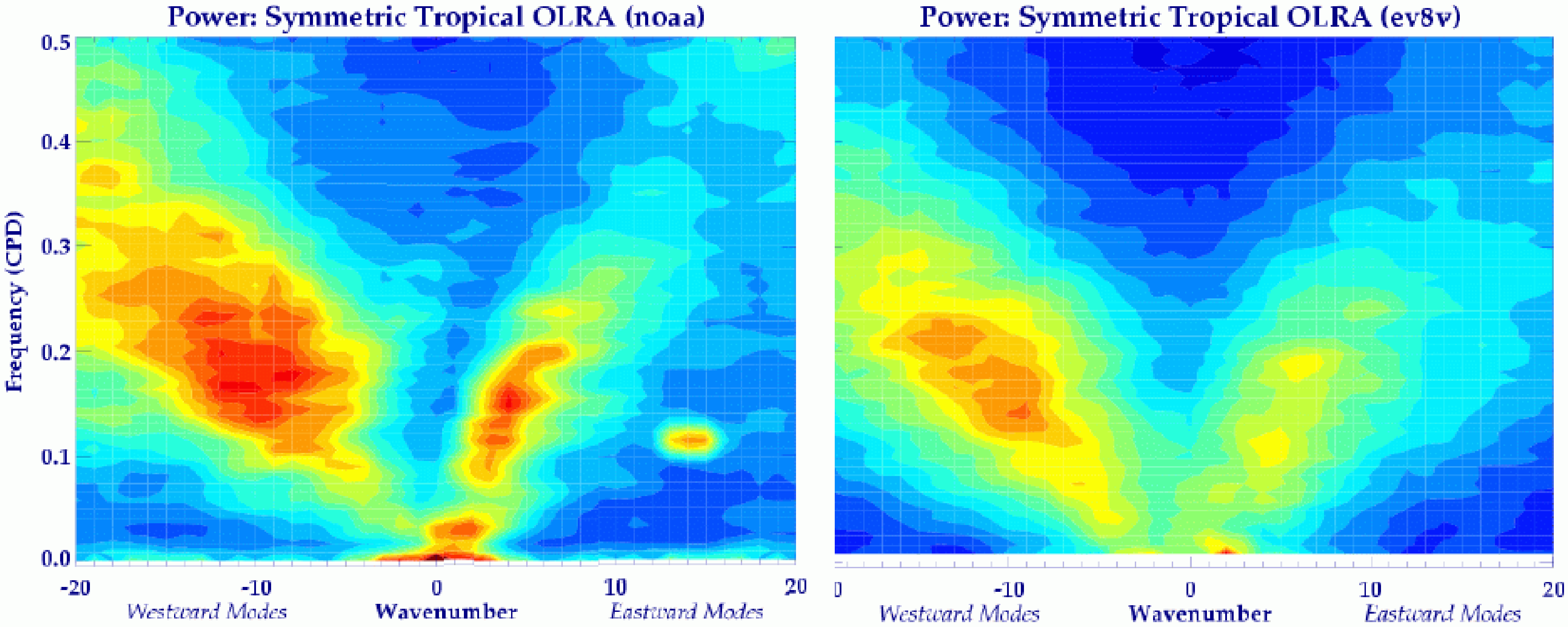
cy31r1



Improvement in Wavenumber-Frequency Spectrum

Observations (NOAA)

Stochastic Backscatter



- ❖ Backscatter scheme reduces erroneous westward propagating modes

Summary

- **Convection is a multi-scale phenomenon**

- **Convective mass fluxes may generate mesoscale PV anomalies and associated balanced flow structures (e.g. lens and front)**

- **Convective forcing at the near-gridscale is a non-equilibrium phenomenon**

- **Stochastic methods are desirable**

- **Must calibrate these methods using CRMs**

e.g. CASCADE project