Statistical Fluctuations in Convective Forcing Computed from Big-Domain Cloud-Resolving Model Simulations

Glenn Shutts November 2 2005

Acknowledgments

- Peter Bechtold, Tim Palmer
- Rachael Stratton, Tom Allen
- Roy Kershaw, Leon Hermanson

Why ?

- ‘Stochastic physics’ – lack of EPS spread associated with missing statistical fluctuations from parametrized sub-filter scale phenomena

- under forecasting of low frequency variability in the Tropics e.g. Madden-Julian oscillation

- realism of convection parametrization

- Lin and Neelin (2002) use a stochastic variant of a convective parametrization and find :

“substantial impact on atmospheric variabililty in the tropics, including intraseasonal and longer time scales”

Tropical convection and its parametrization

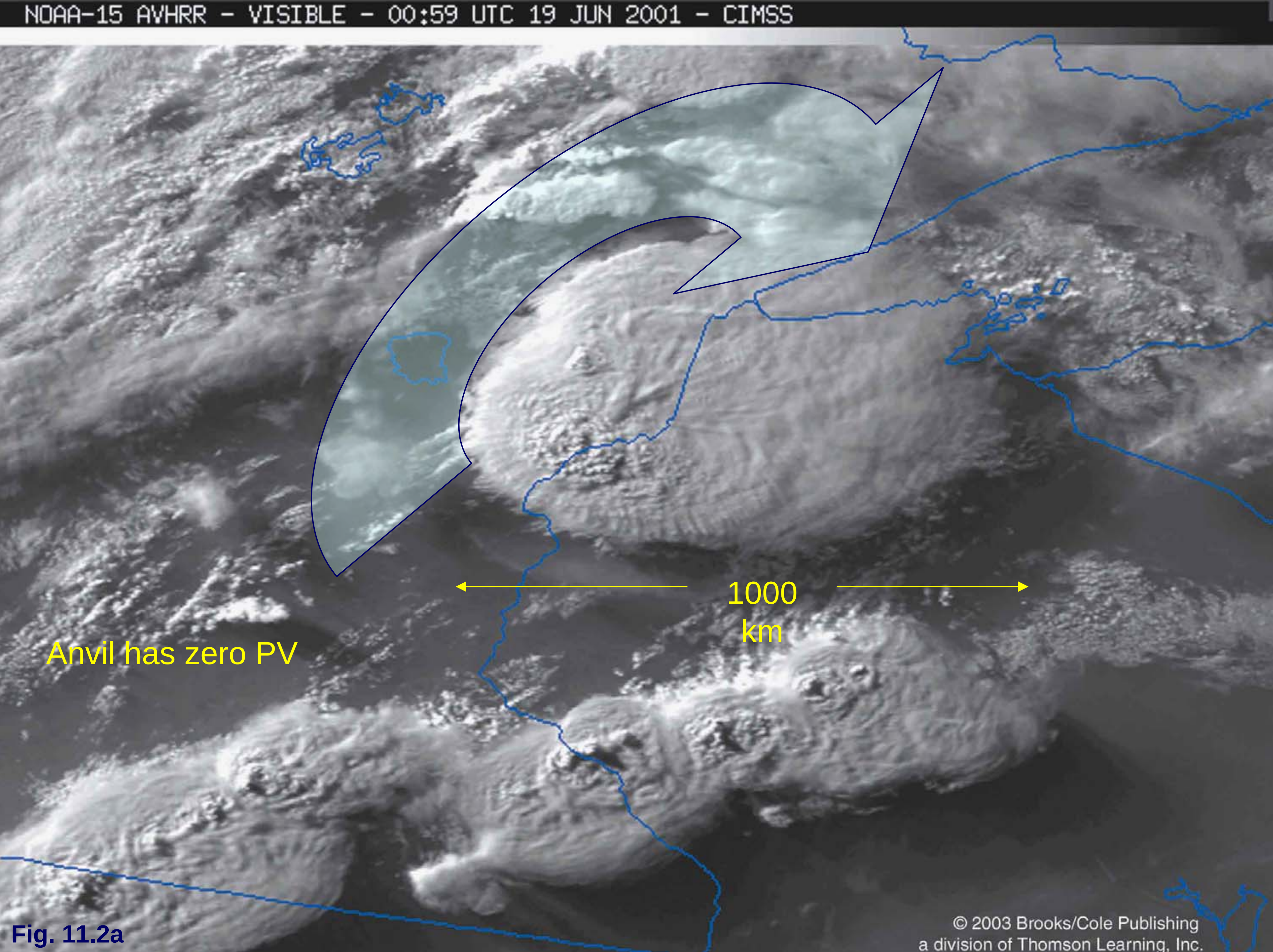
- Convection is a 'multi-scale phenomenon' (updraughts ~ 100 m to stratiform anvils of 100's kms)

- Horizontal autocorrelation length scale ~ 130 km; time scale~ 5.5 hours (Ricciardulli and Sardeshmukh, 2002)

- Global NWP models contain < 1 Cb per gridbox.

- This is no ensemble of deep clouds within each model grid column

- Parametrization assumes deterministic relationship between ensemble-average effect of convection and instantaneous vertical profile


NOAA-15 AVHRR - VISIBLE - 00:59 UTC 19 JUN 2001 - CIMSS
1000
km
Anvil has zero PV
Fig. 11.2a
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Statistical mechanics view (Craig and Cohen)

- Non-interacting ‘point clouds’
- Individual cloud mass fluxes (m) follow Boltzmann-like exponential pdf with mean <m>
- total mass flux (M) of a cloud ensemble the following pdf :

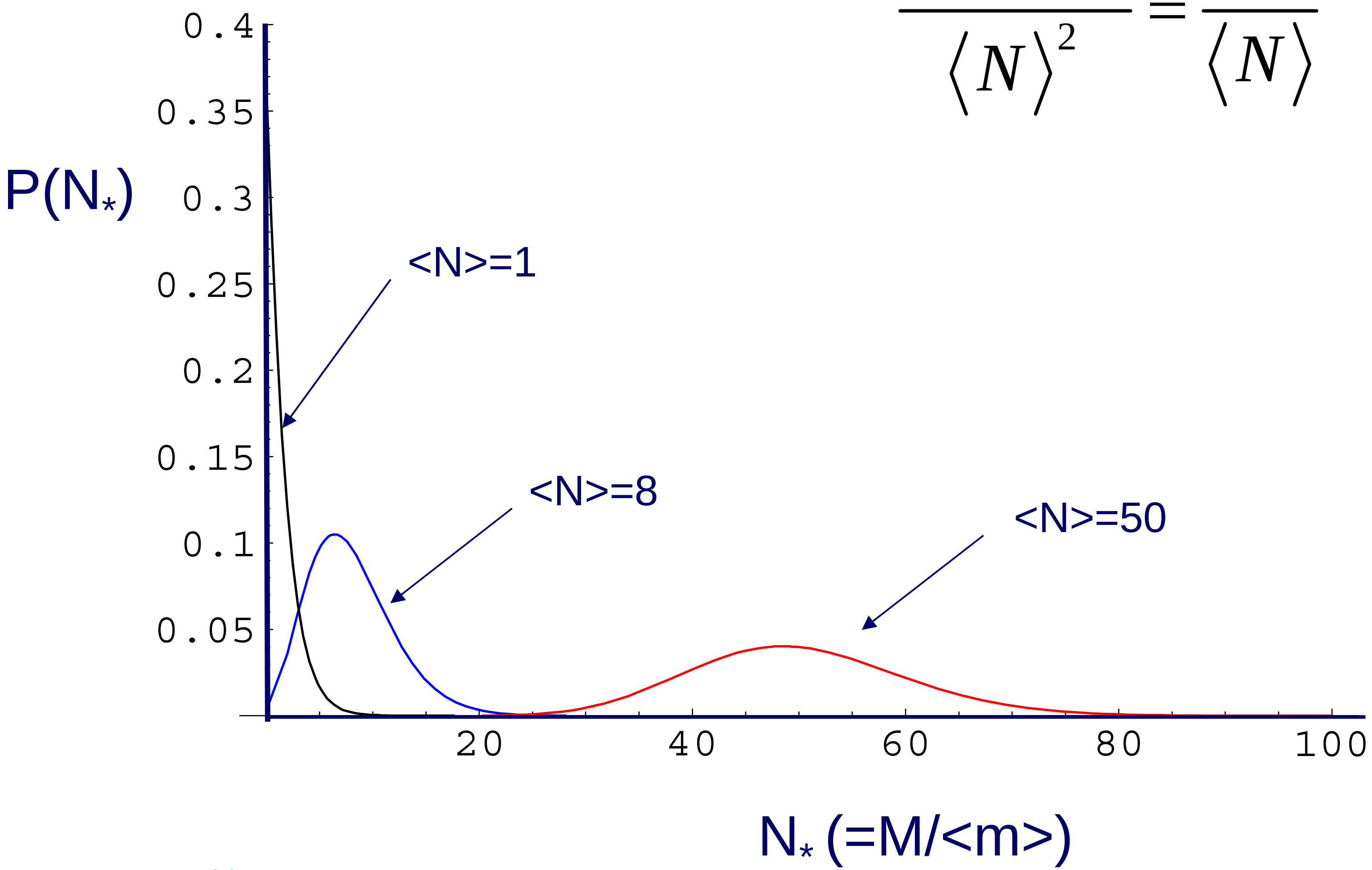
$$P(N_*) = \sqrt{\frac{\langle N \rangle}{N_*}} e^{-(\langle N \rangle + N_*)} \cdot \underbrace{I_1}\left[2\sqrt{\langle N \rangle N_*} \right] + \delta(N_*) e^{-\langle N \rangle}$$

Modified Bessel function

where $N_* = M / \langle m \rangle$ and $\langle N \rangle$ is the ensemble-mean number of clouds per finite area

Pdf of normalized convective mass flux $P(N_*)$

$$\frac{Var(N_*)}{\langle N \rangle^2} = \frac{2}{\langle N \rangle}$$



Low cloud areal density <N> < 1

$$P(N_*) = \langle N \rangle e^{-(\langle N \rangle + N_*)} + \underbrace{\delta(N_*) e^{-\langle N \rangle}}$$

Probability of no clouds $e^{-\langle N \rangle}$

Exponential mass flux PDF

Suggests that the convective precipitation rate should have exponential PDF

Cloud-resolving model to calibrate model error due to convection

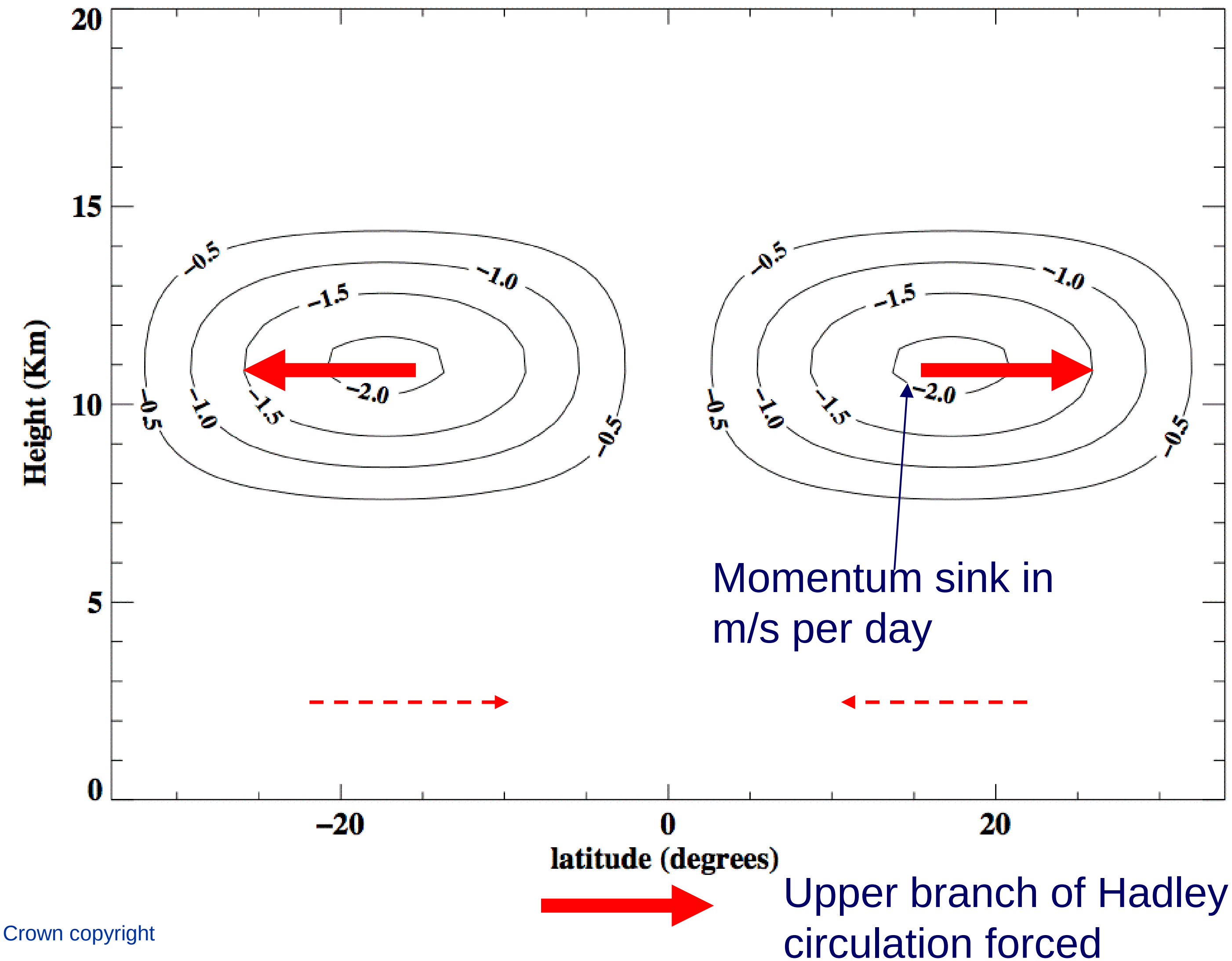
- Met Office LEM configured as an equatorial beta-plane with SST variation, imposed cooling and ‘Trade Wind forcing function’

- Domain 7680 x 7680 x 30 km. 50 levels dx= 2km dy=10 km. Latitude range +/- 35 degs

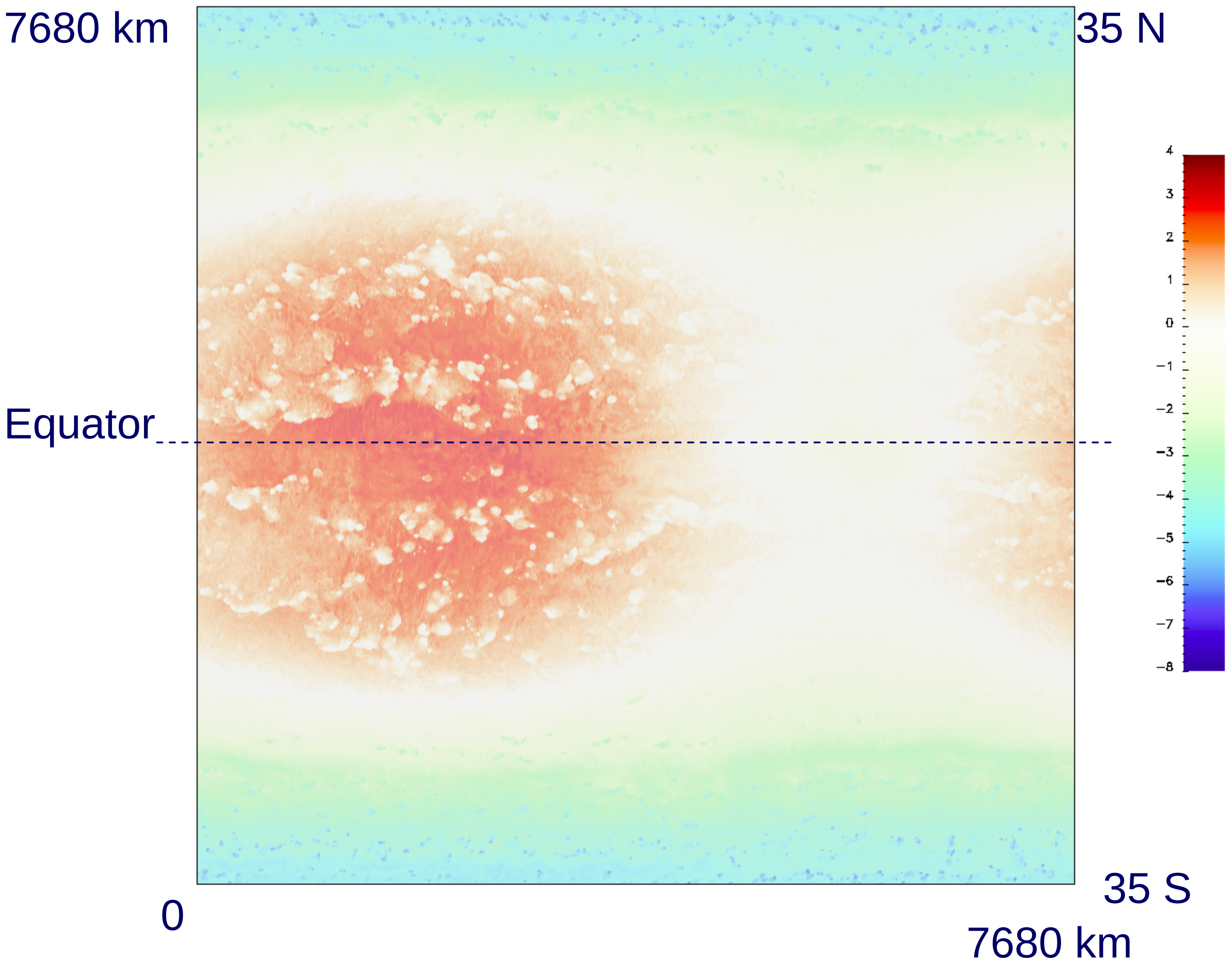
- Simulations produce cloud ‘super-clusters’,squall lines, double ITCZ and tropical cyclones

- Compute convective temperature and vorticity forcing seen by an NWP model grid and characterize its statistical properties

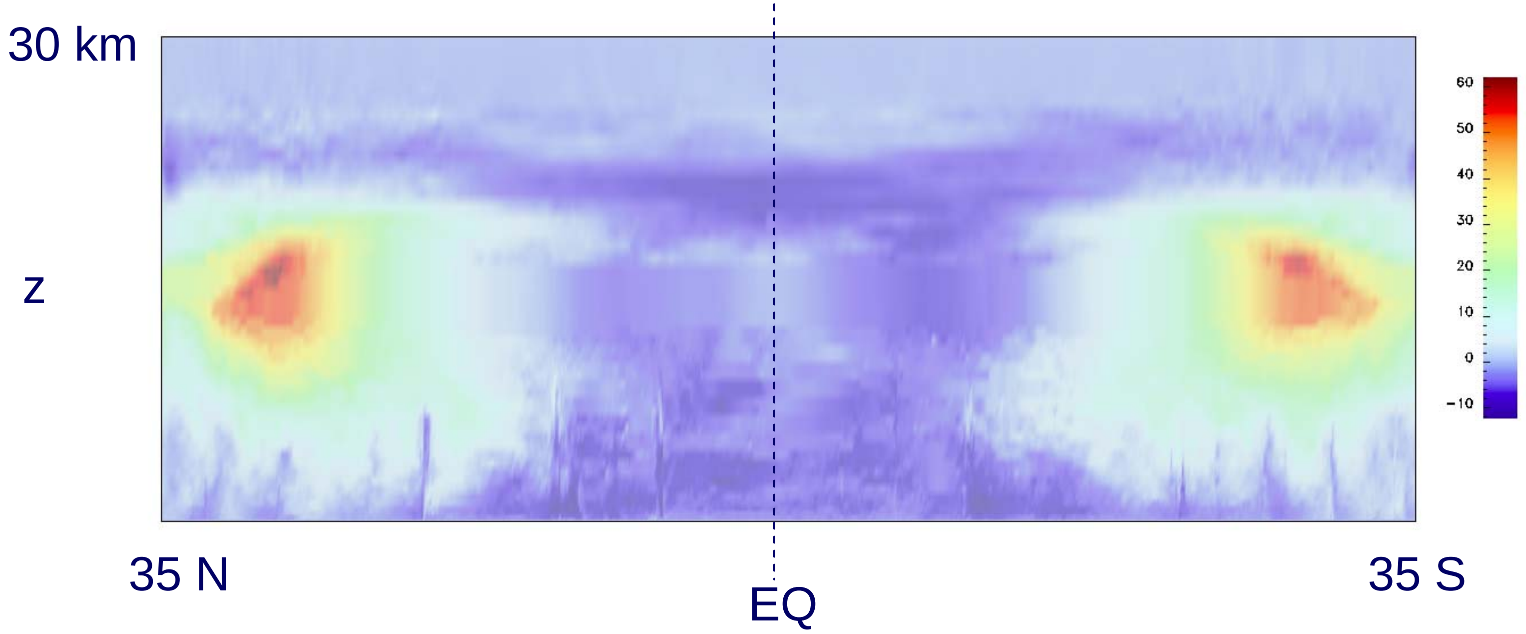
Driving the sub-tropical surface easterlies



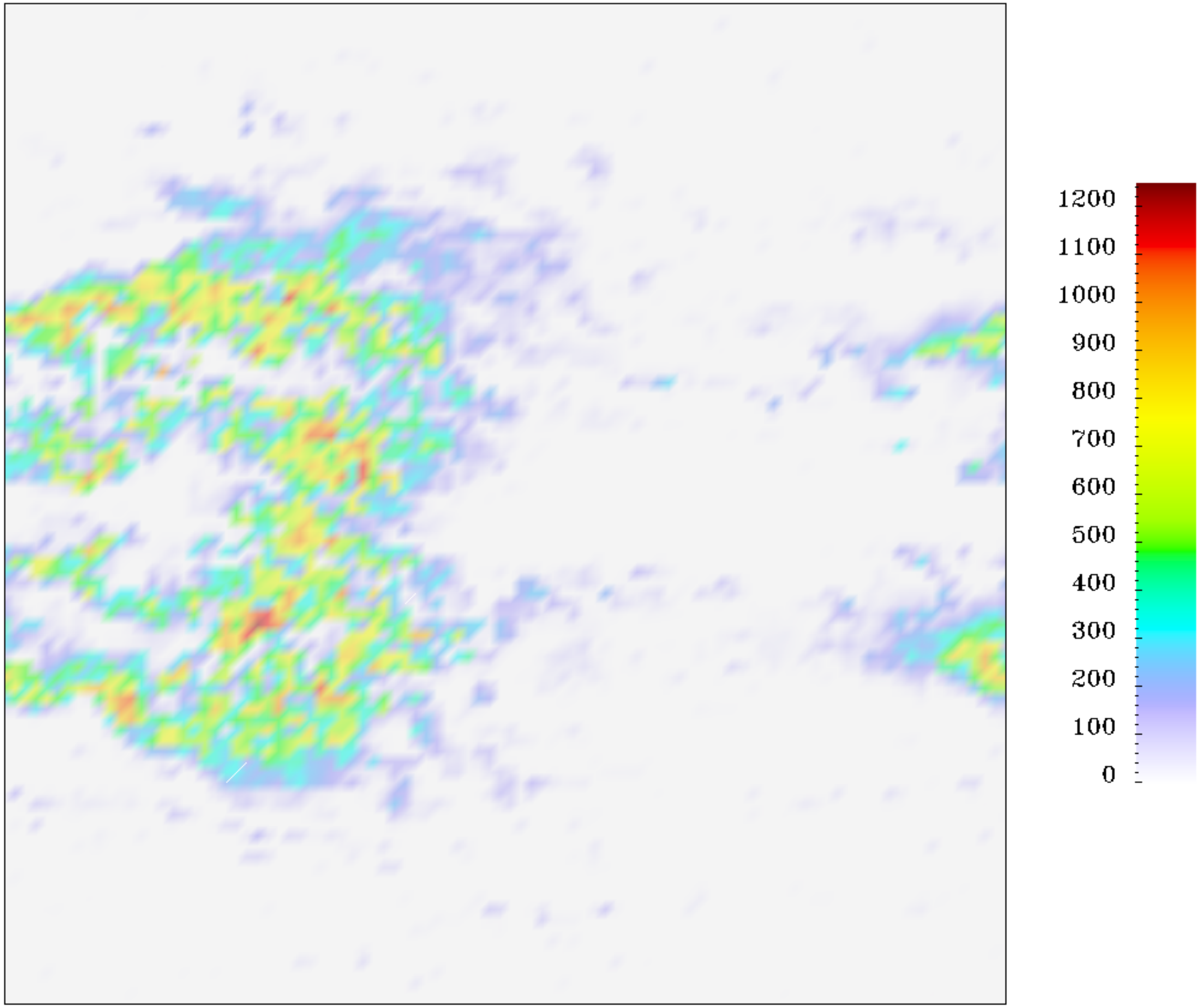
Surface Temperature (z=78 m) at day 4.5



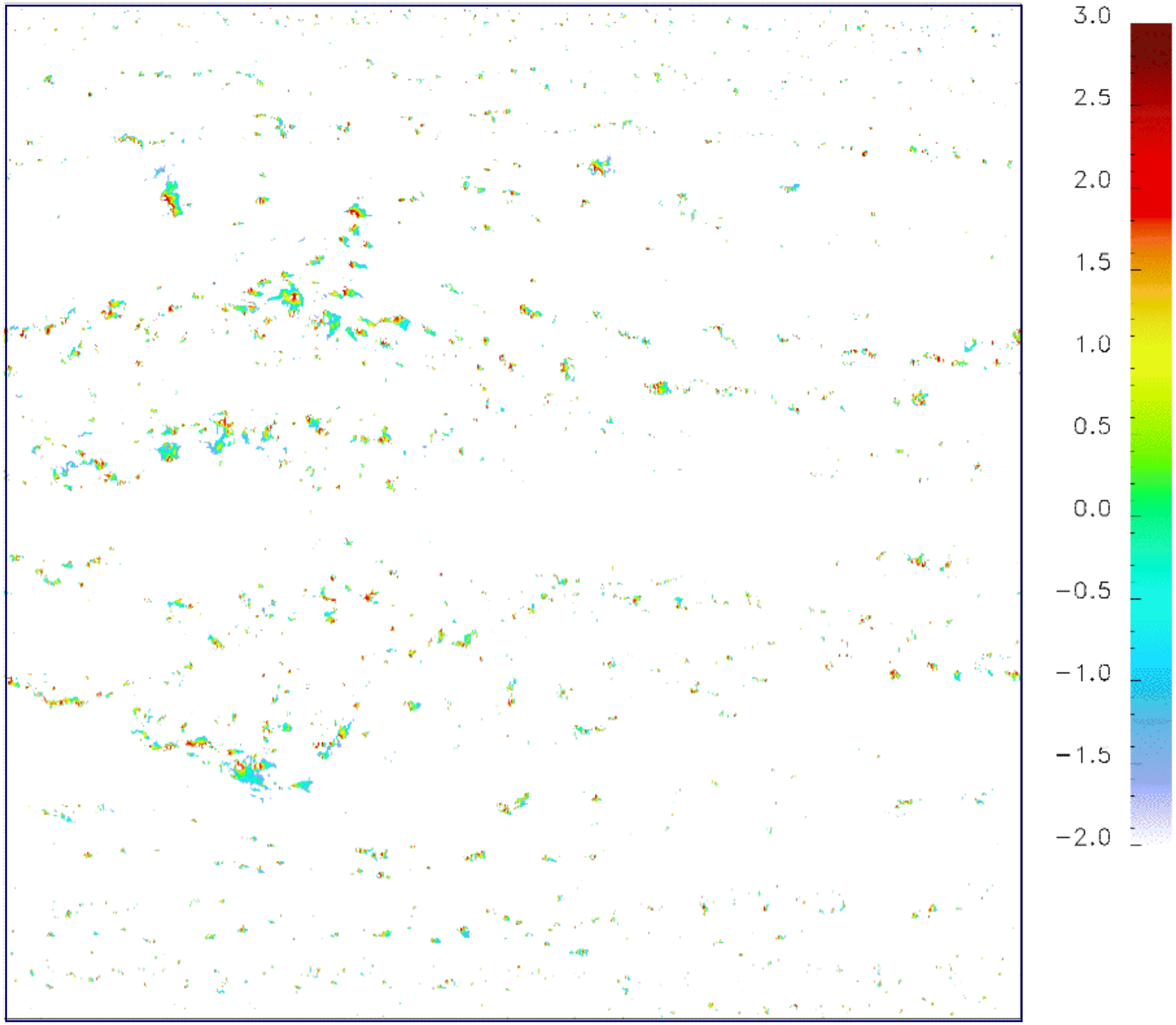
Latitude-height section of zonal wind



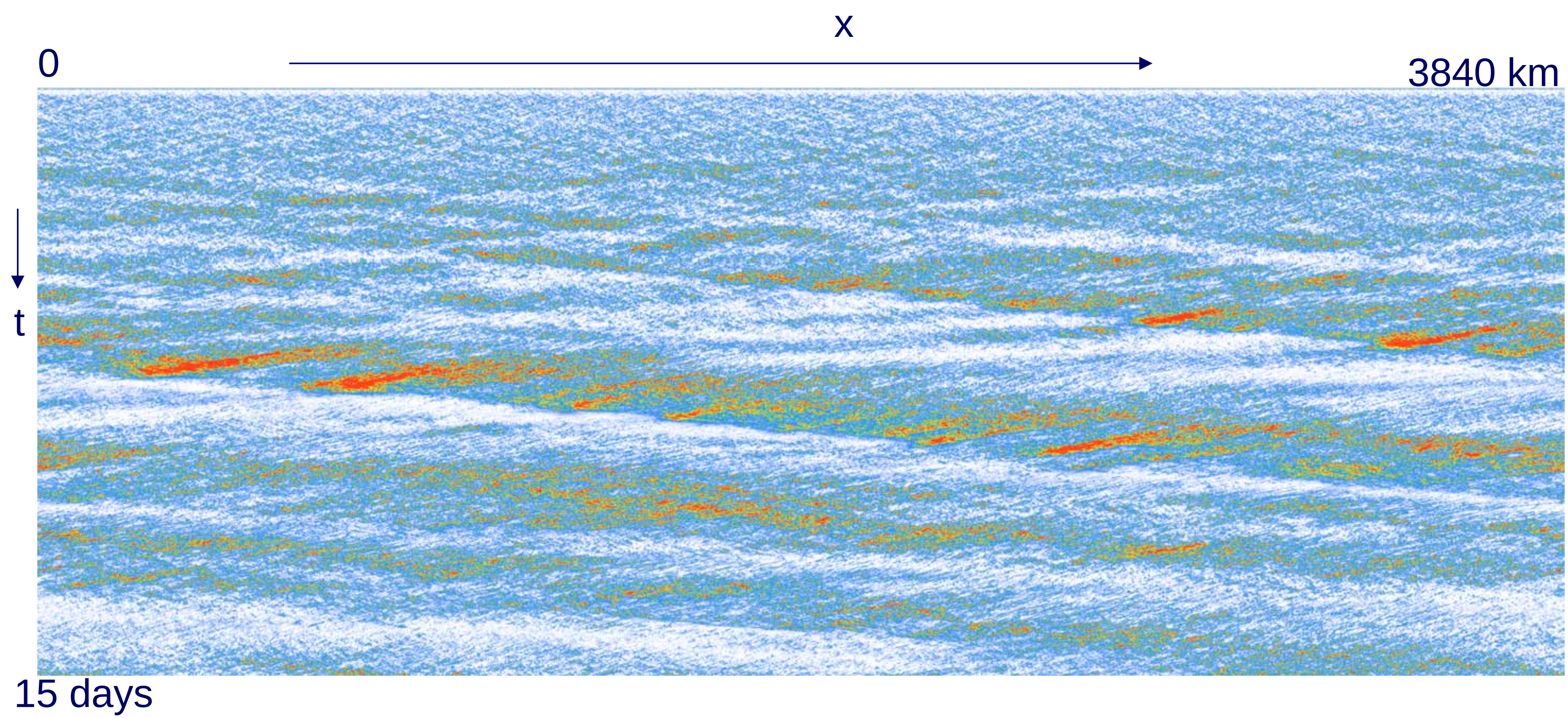
Convective Available Potential Energy



Surface rainfall rate at day 4.5

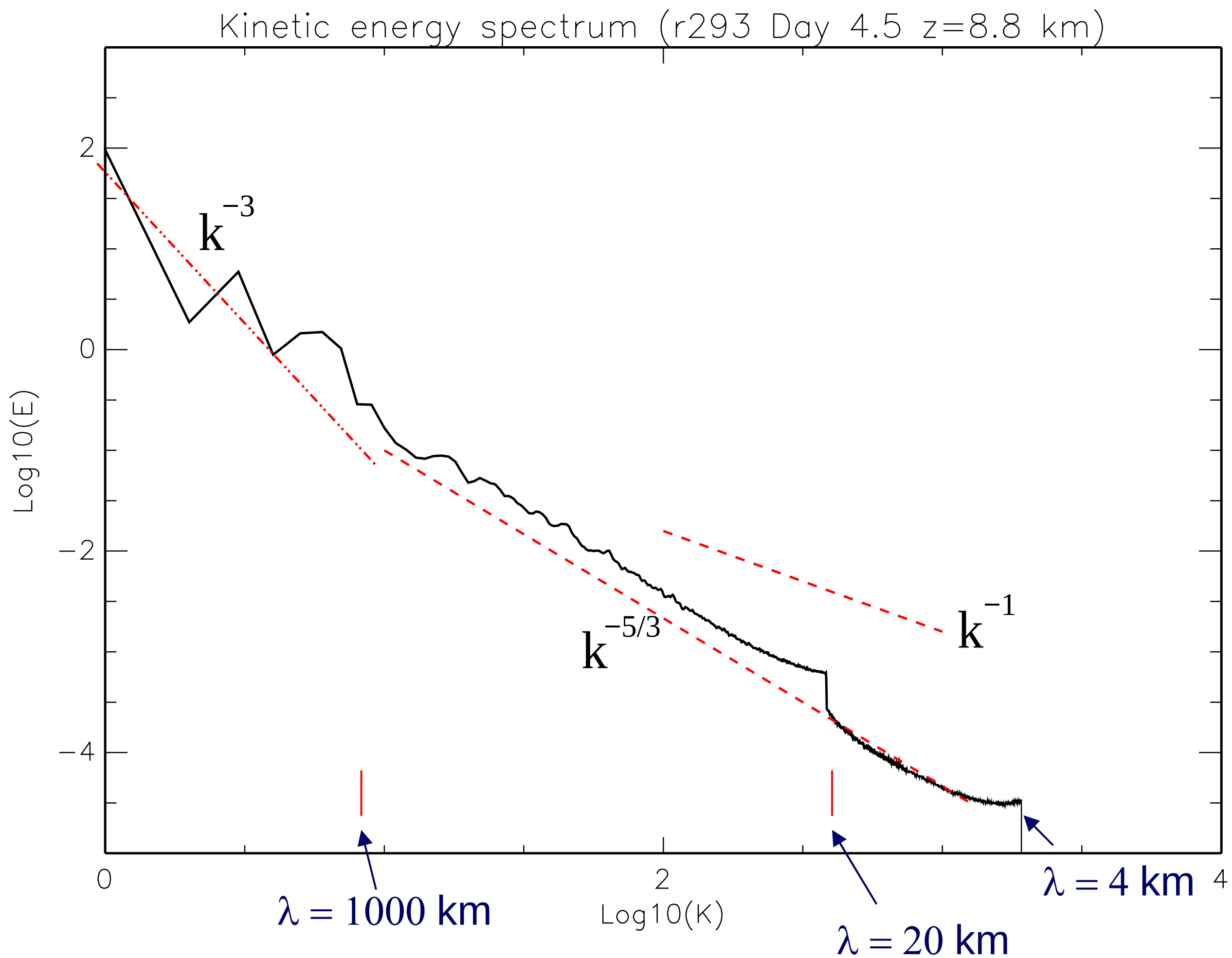


Hovmuller Diagram of rainfall rate from anisotropic grid run



Red is > 50 mm/day

Kinetic Energy spectrum at day 4.5



Coarse-grain effective temperature tendency

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

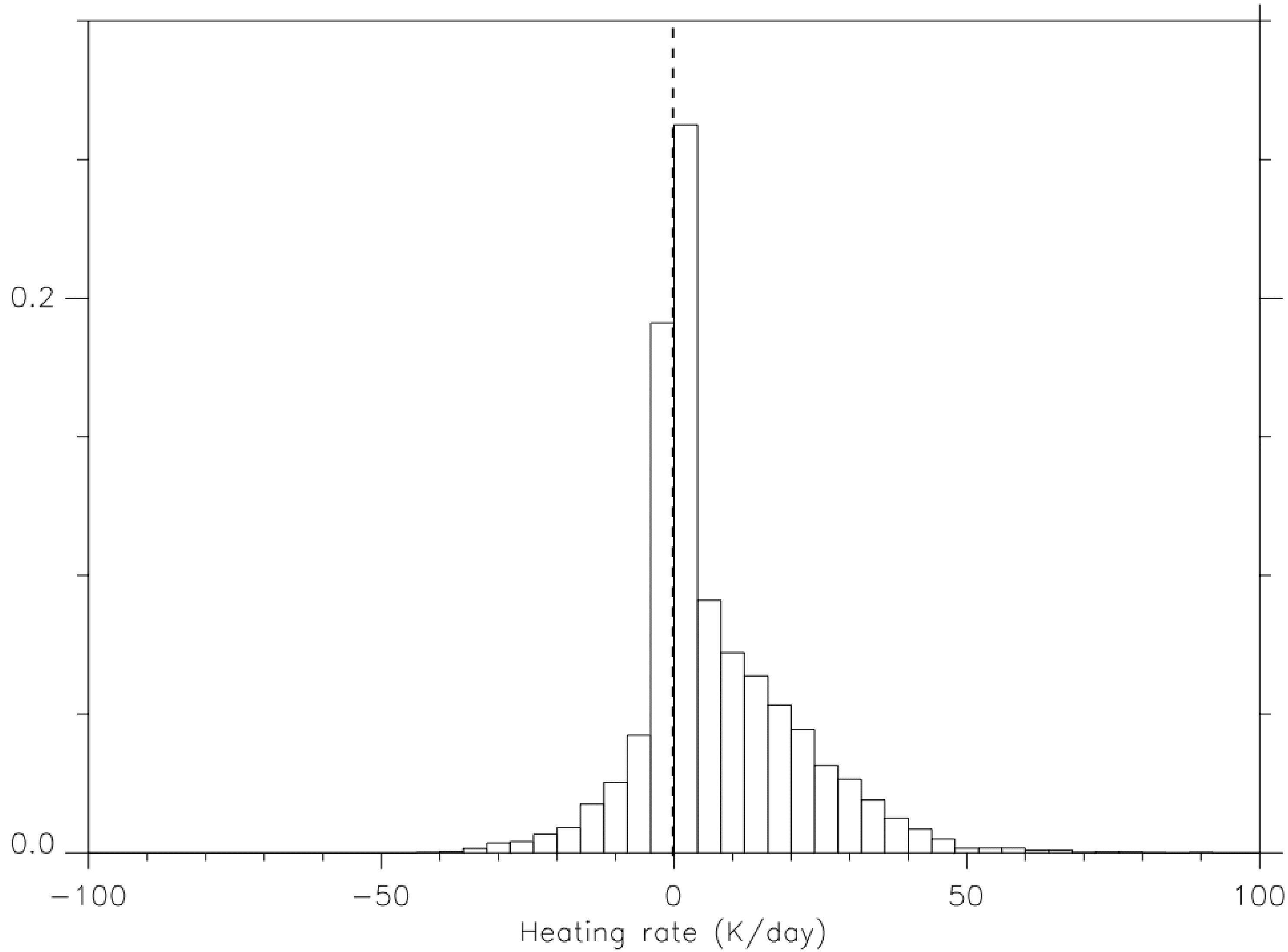
Let overbar denote average over a coarse grid box, then:

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

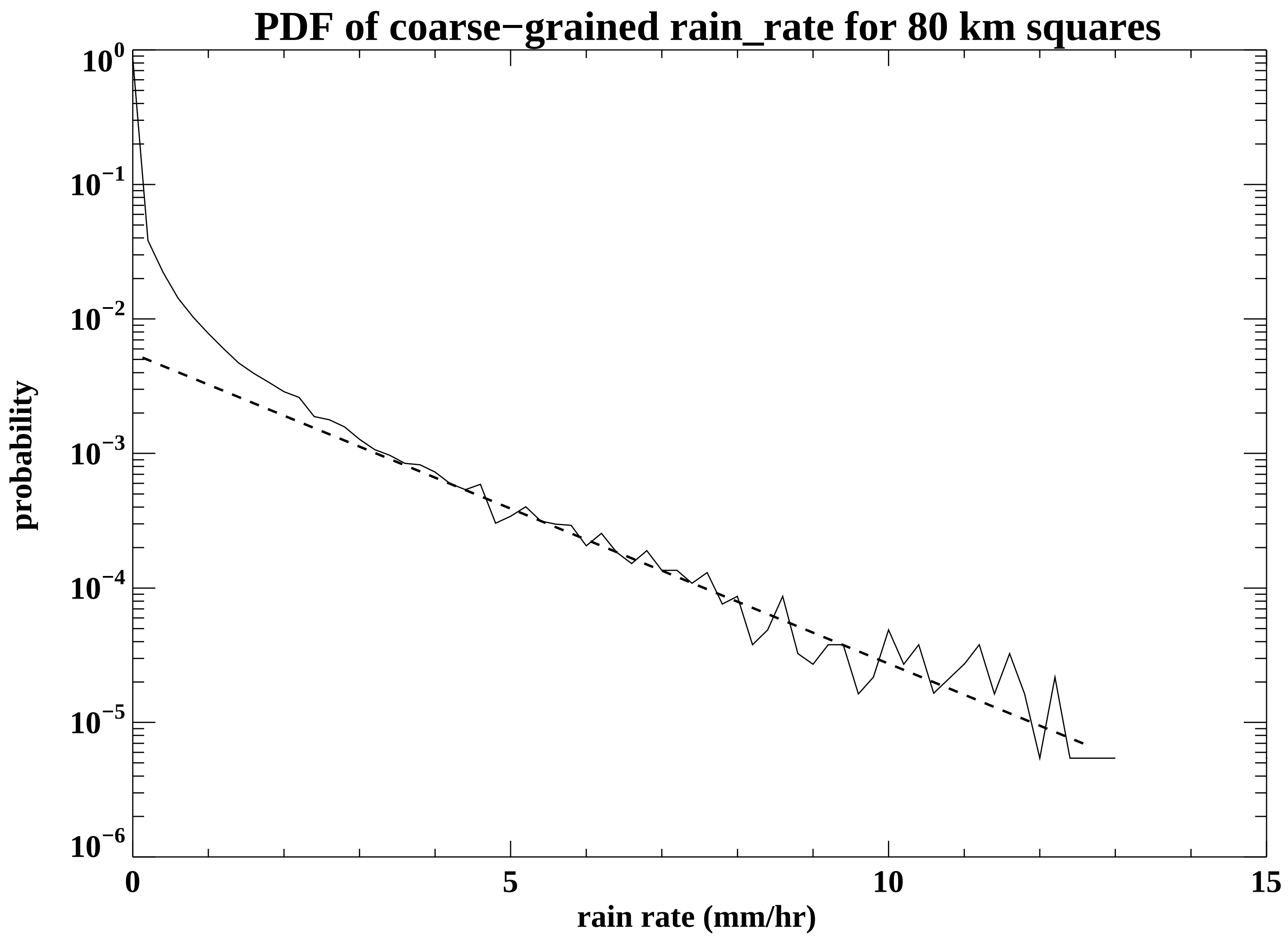
$$\frac{\partial \bar{\theta}}{\partial t} + \bar{\mathbf{V}} \cdot \nabla \bar{\theta} = \underbrace{\bar{\mathbf{V}} \cdot \nabla \bar{\theta} - \overline{\left(\mathbf{V} \cdot \nabla \theta\right)} + \bar{Q}} = \tilde{Q}$$

Parametrized + resolved heating

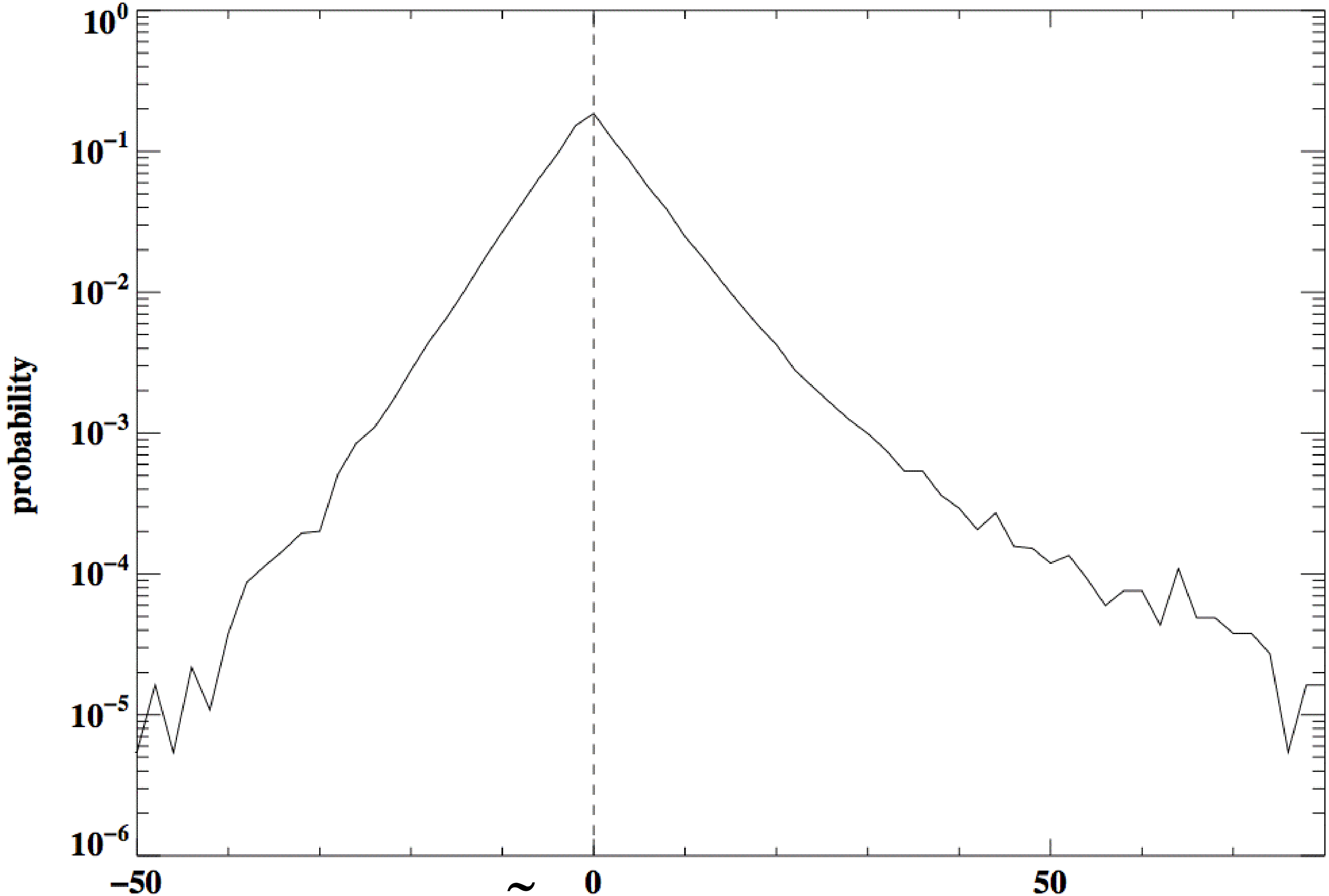
Histogram of diabatic heating coarse-grained to an 80 km grid at z=9.4 km



Pdf of surface rainfall rate coarse-grained to 80 km



PDF of effective T forcing as seen from an 80 km grid



$\tilde{Q}$ (K/day)

Pdfs conditioned on convective parametrization temperature tendencies

- take the coarse-grained CRM fields and feed them into a convective parametrization scheme (Bechtold et al, 2001) → Q1 - the convective warming rate

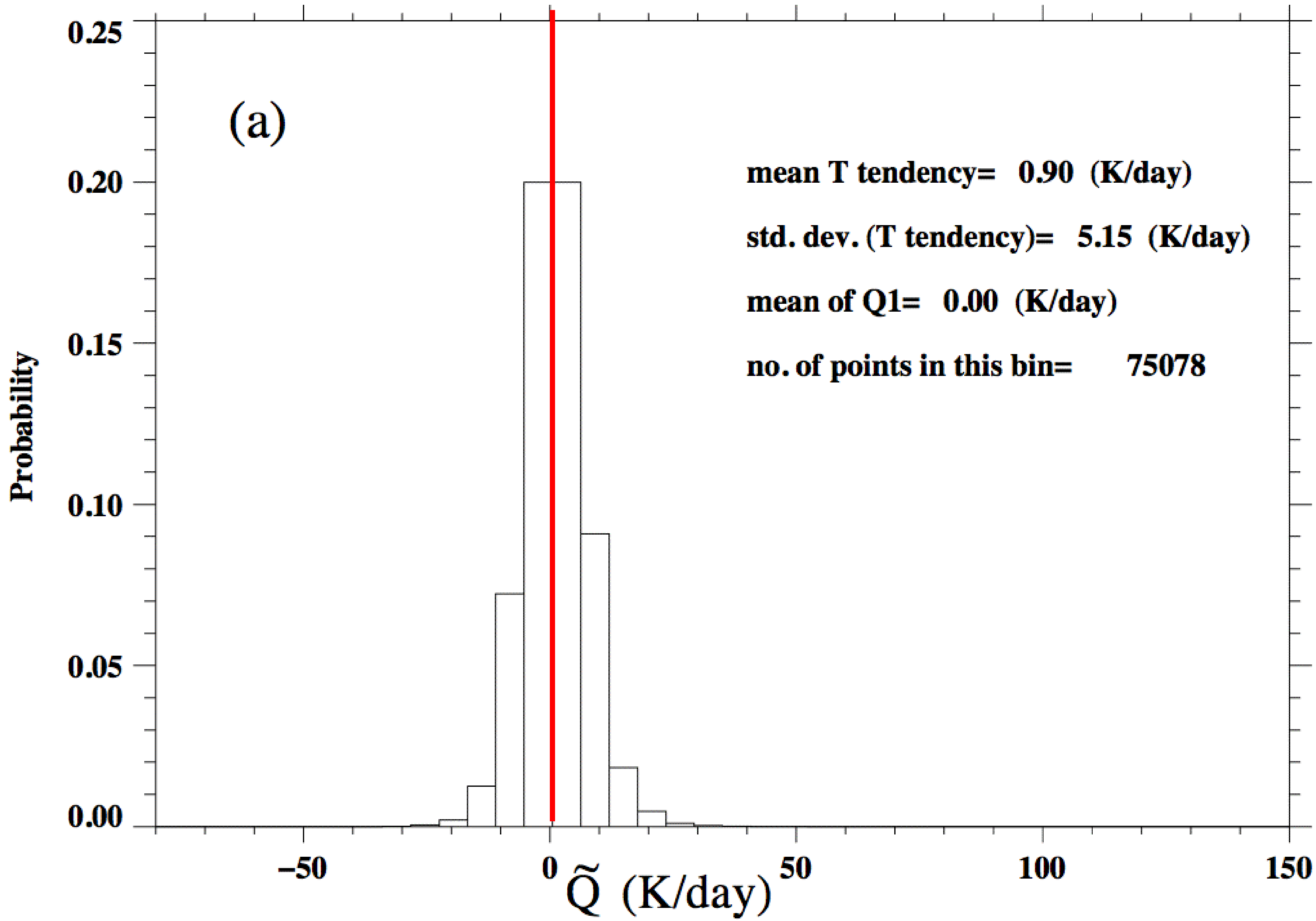
- at any model level, bin the effective temperature tendency $\tilde{Q}$ according to different ranges of Q1

- see how the variance of effective temperature tendency depends on Q1

- use knowledge of variance dependence to calibrate ‘stochastic physics’ schemes based on multiplicative noise

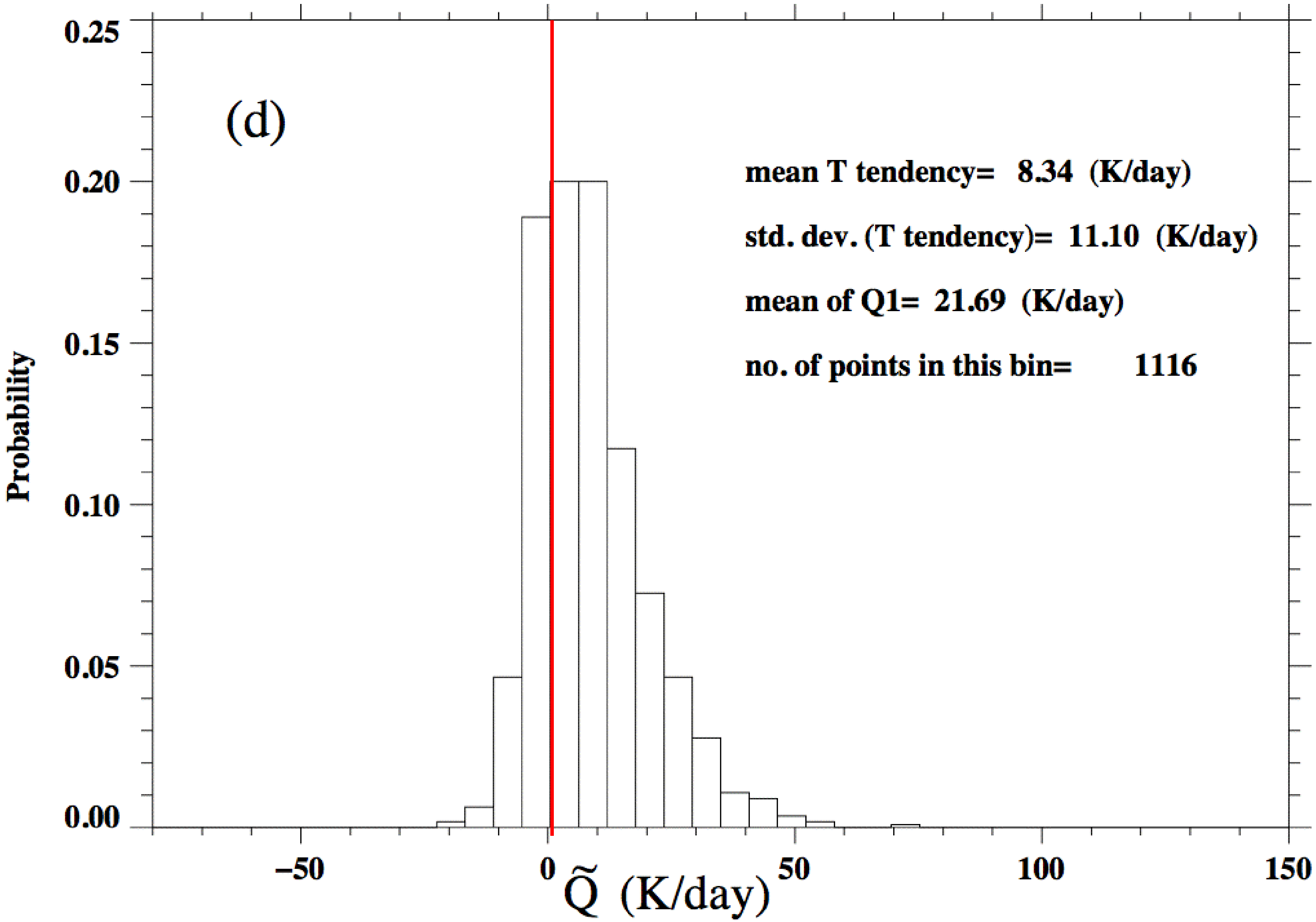
Pdf of effective CRM dT/dt for which -0.1< Q1< 0.1K/day

Coarse box size= 120 km



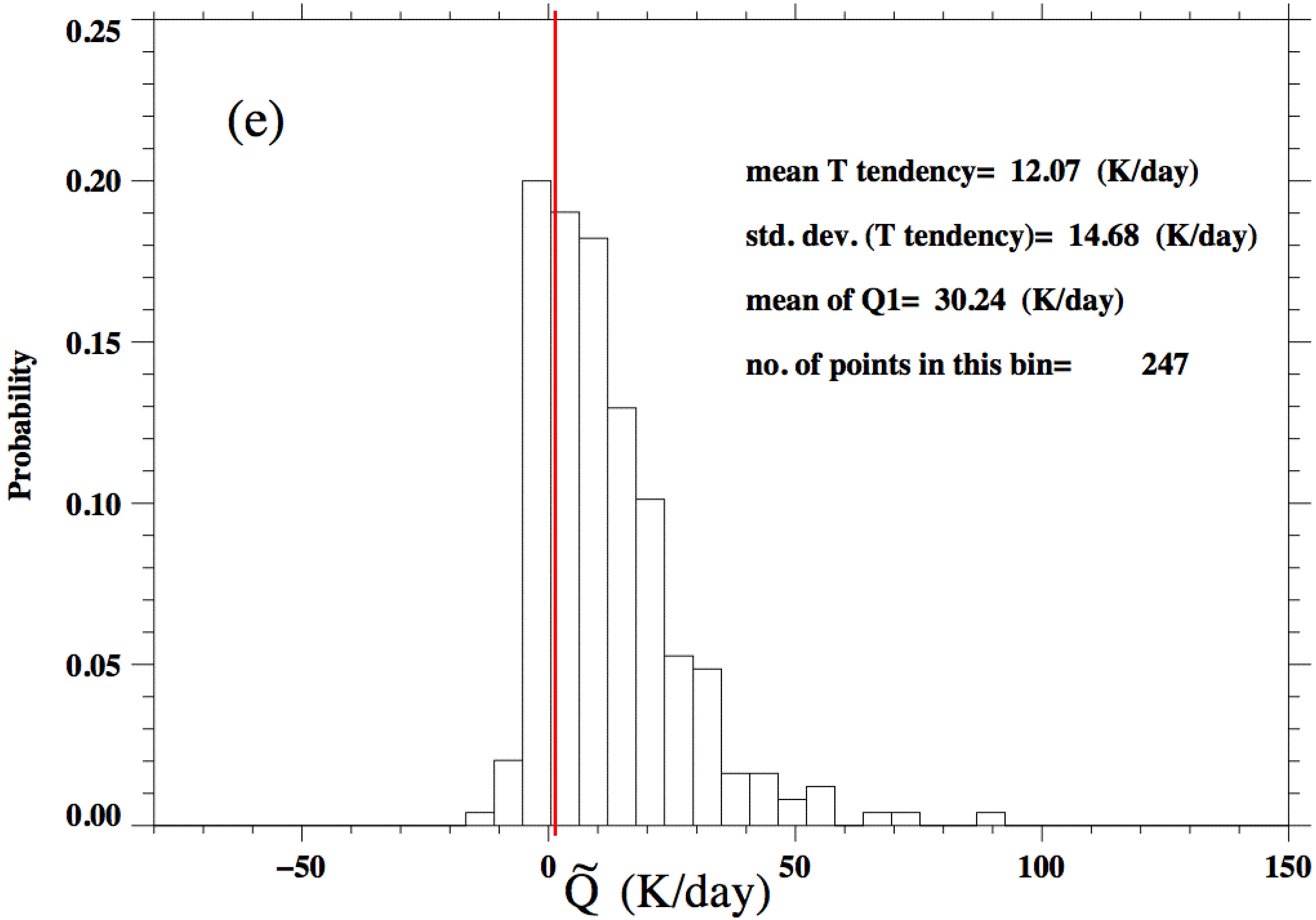
Pdf of effective CRM dT/dt for which 18 < Q1< 27 K/day

Coarse box size= 120 km



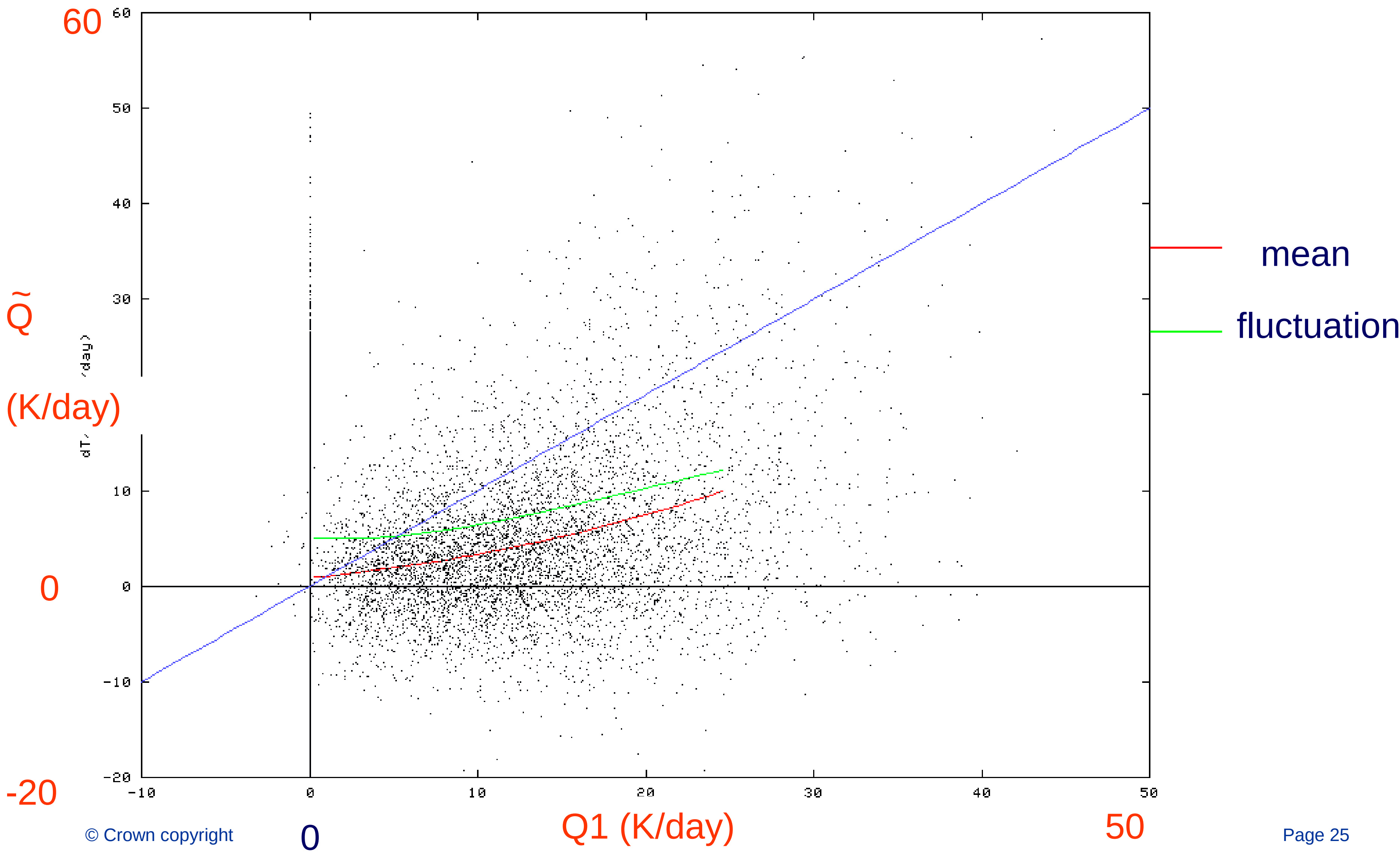
Pdf of effective CRM dT/dt for which 27 < Q1< 36 K/day

Coarse box size= 120 km



Scatter plot of effective T forcing computed from CRM versus Q1

Coarse box size= 120 km

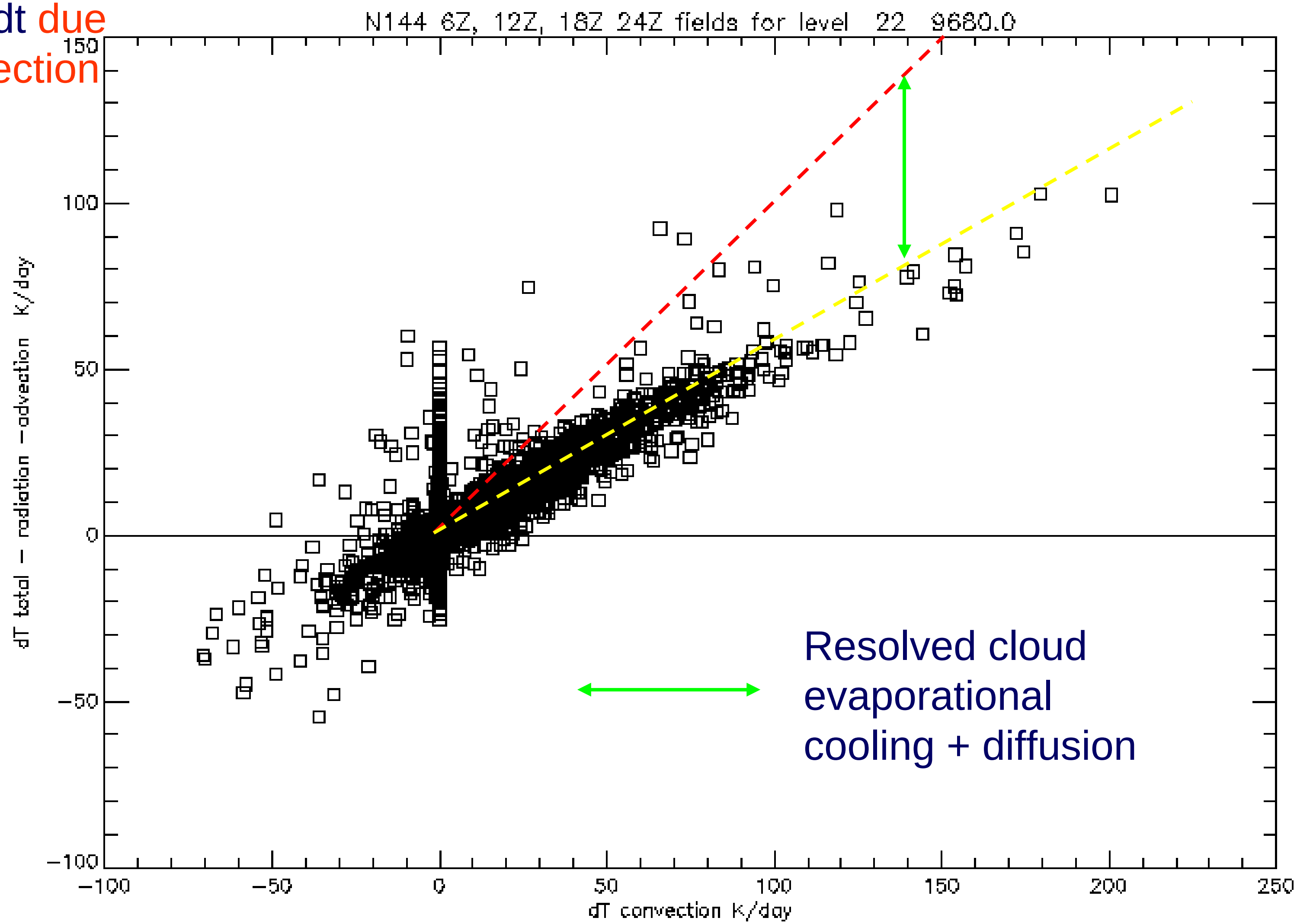


Scatter plot UM (dT/dt – radiation – advection) versus Q1 from aquaplanet run.

Provided by Rachel Stratton

Resolution= N144, z=9.68 km

Net dT/dt due to convection

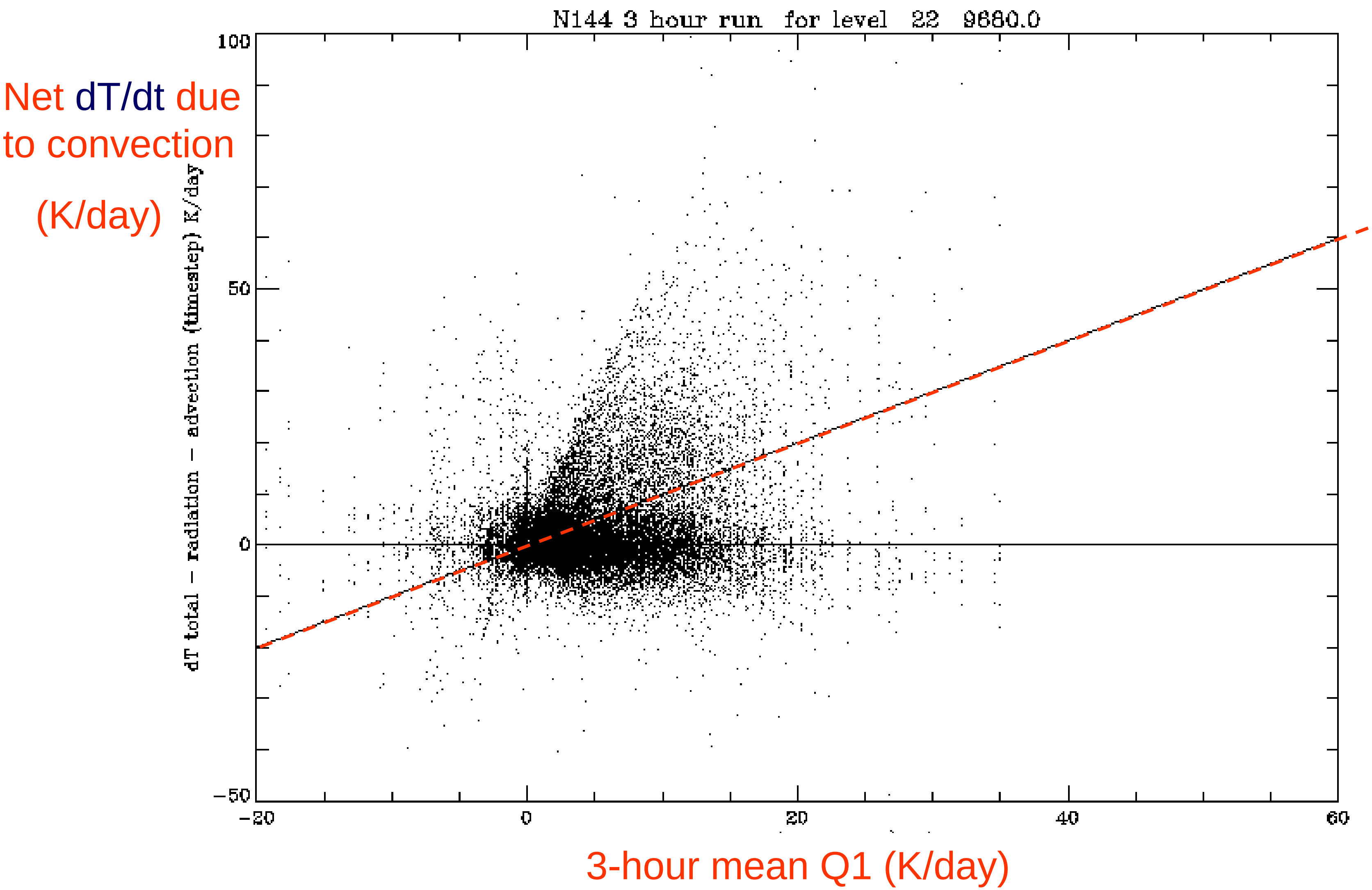


Q1 (K/day)

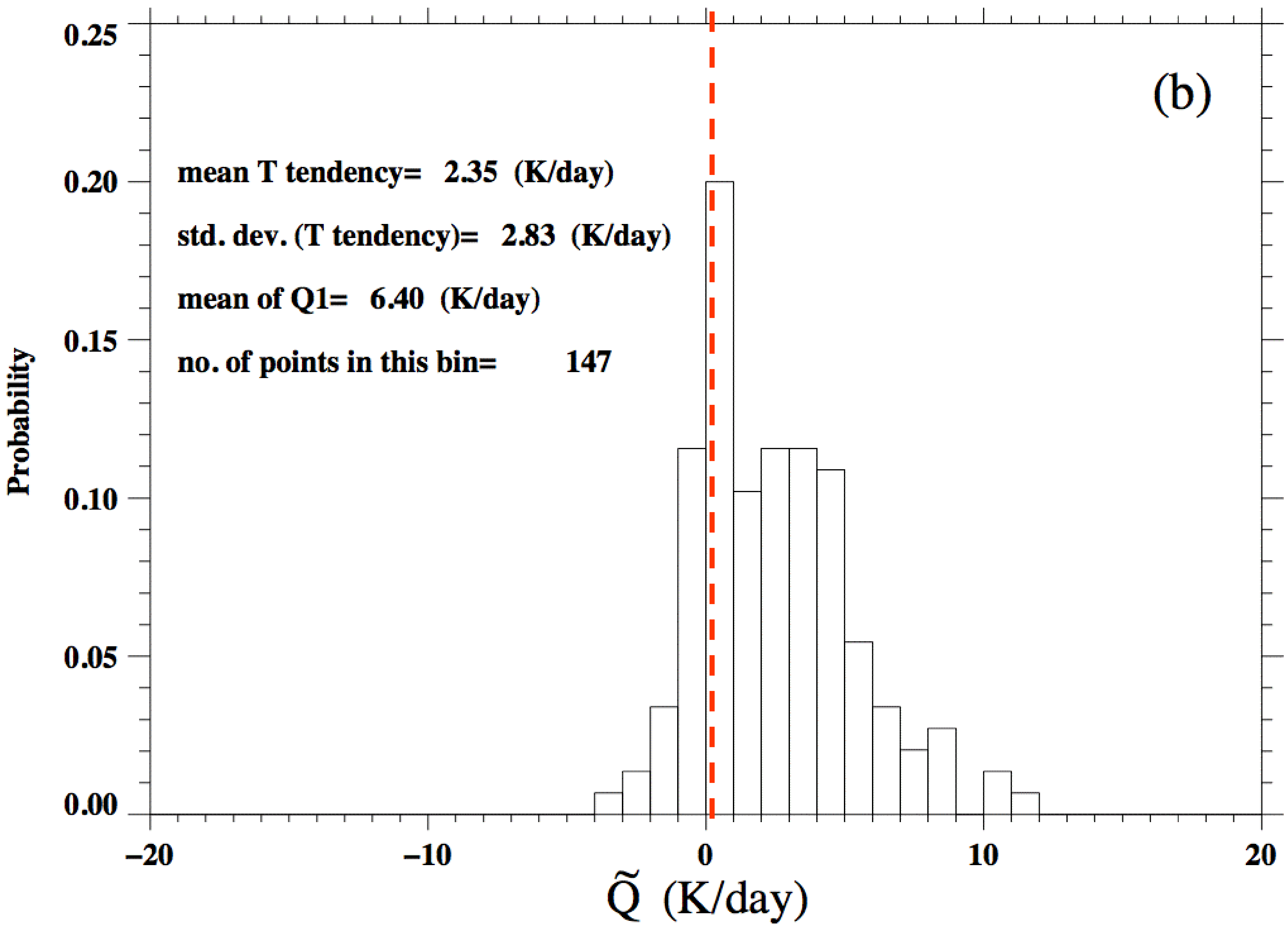
Scatter plot UM (dT/dt – radiation – advection) versus Q1 from aquaplanet run.

Provided by Rachel Stratton

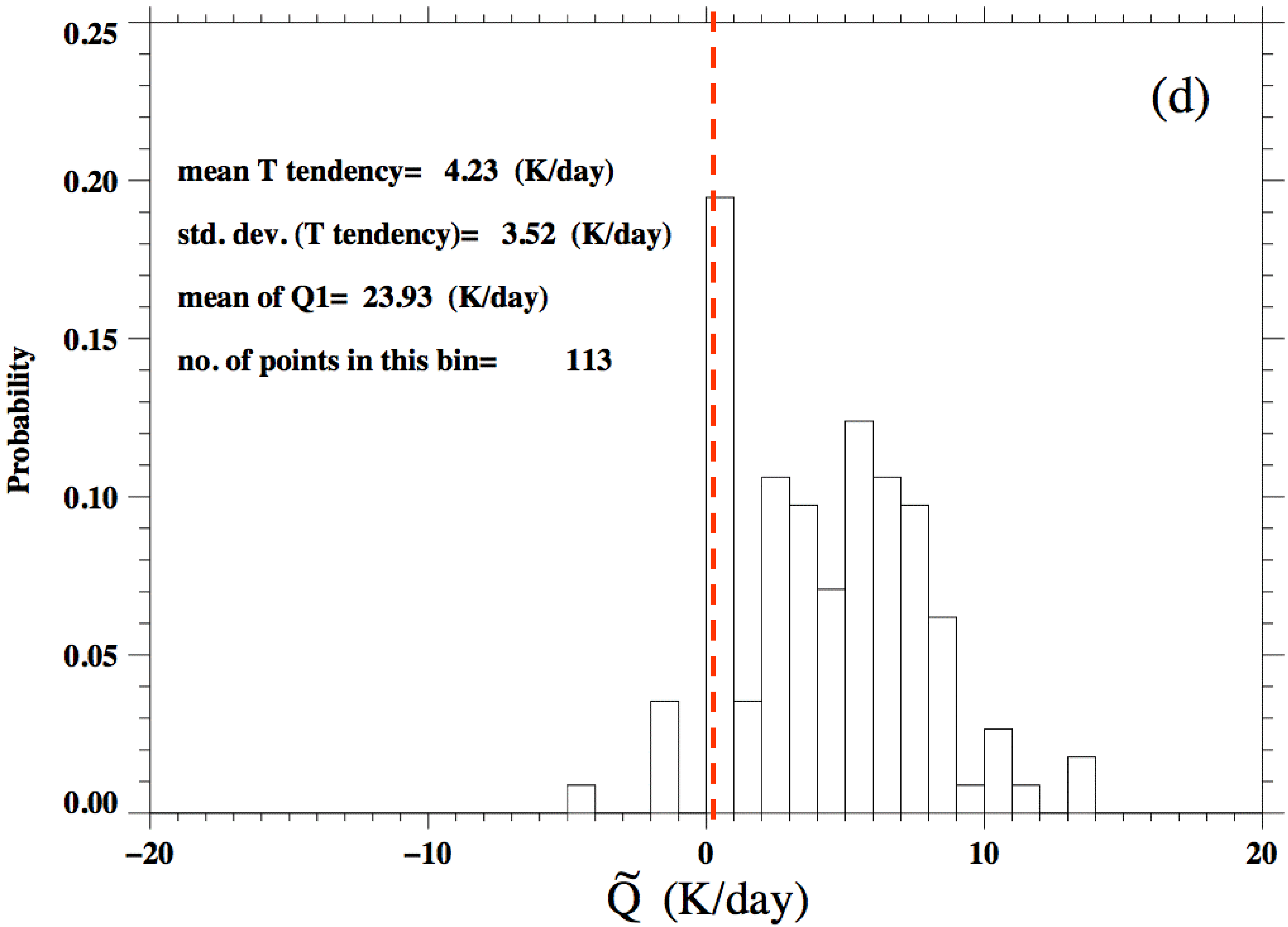
Resolution= N144, z=9.68 km



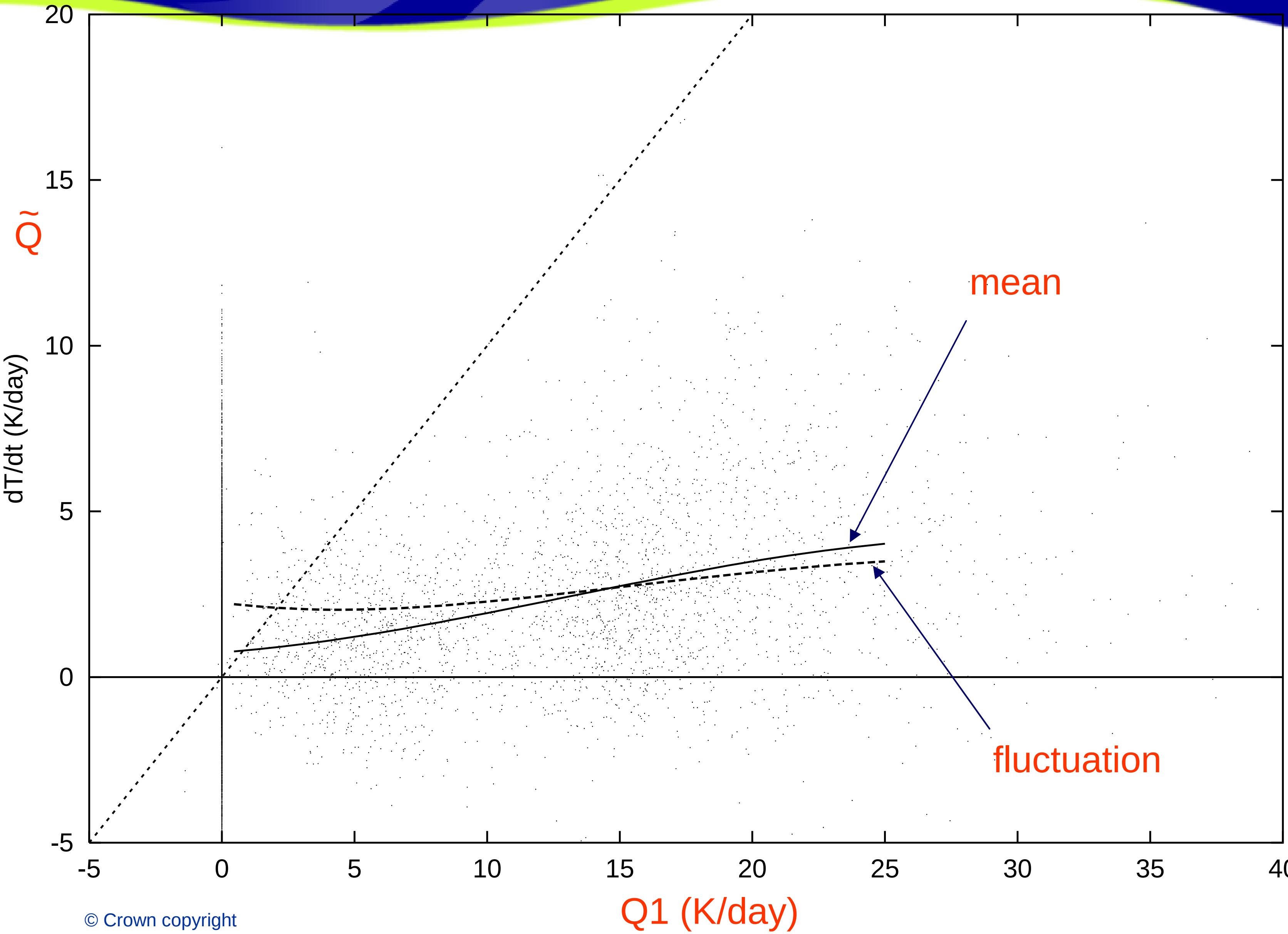
Pdf of effective CRM on 320 km grid dT/dt for which 0 < Q1< 10 K/day



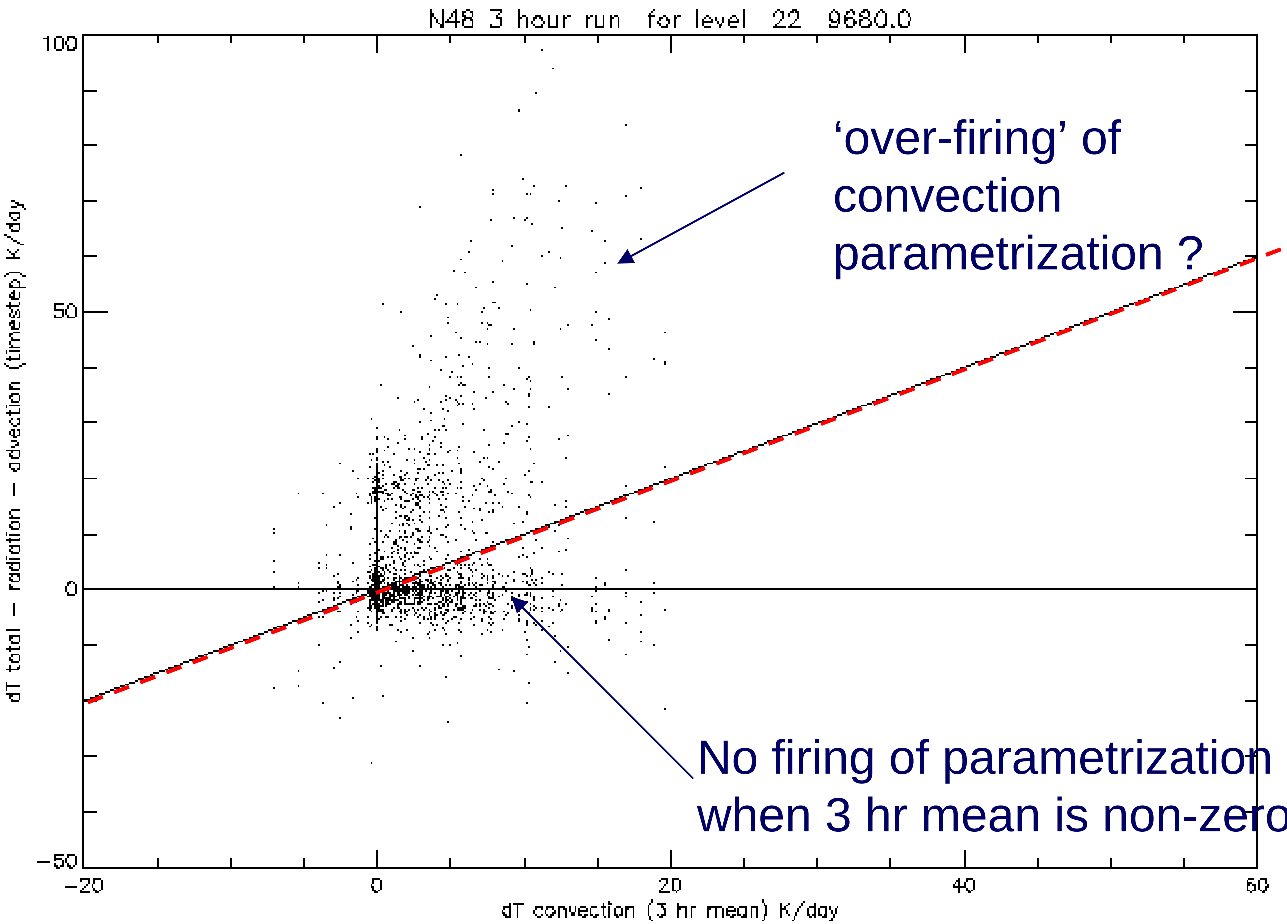
Pdf of effective CRM on 320 km grid dT/dt for which 20 < Q1< 40 K/day



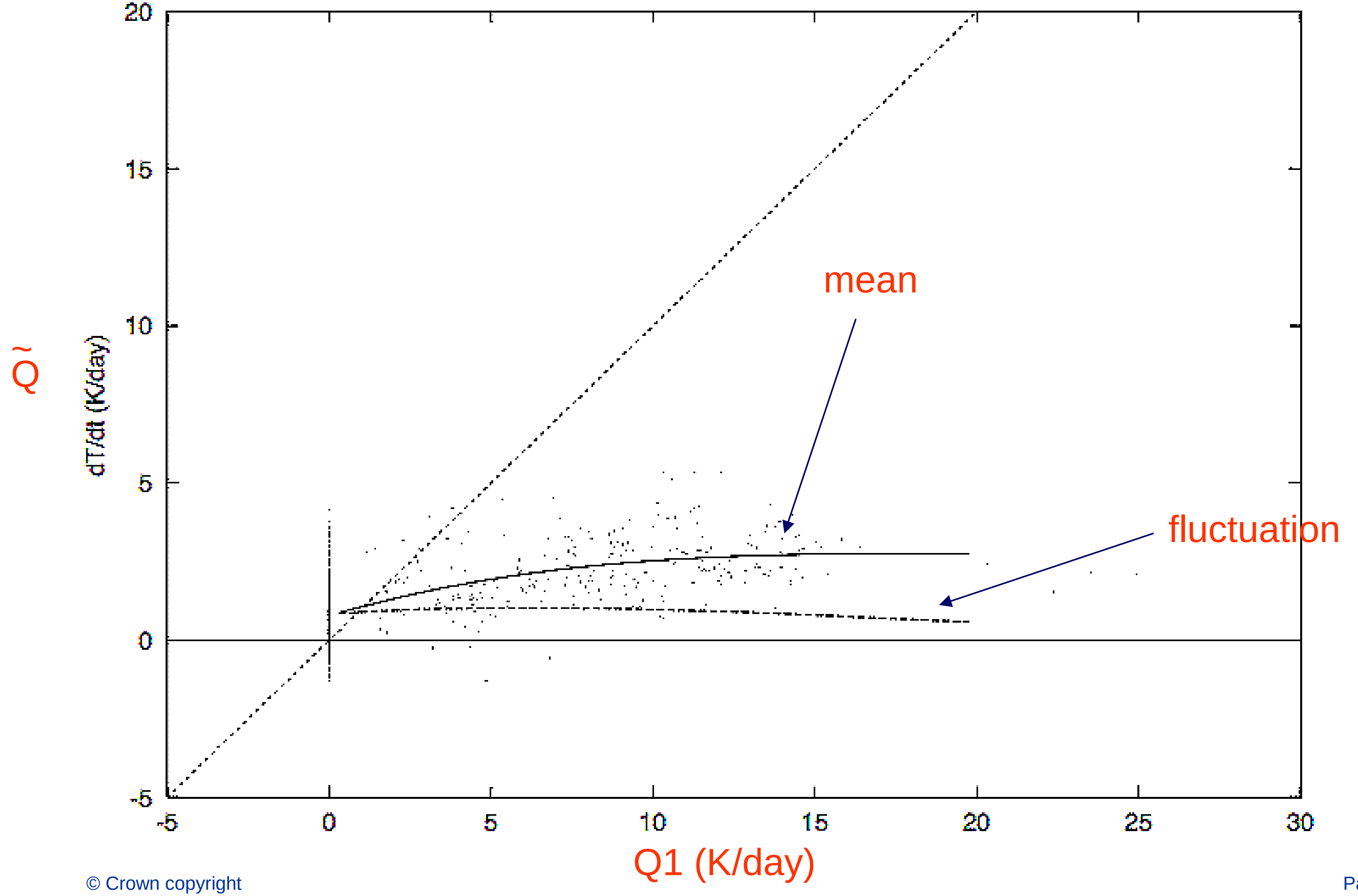
Scatter plot of effective dT/dt for 320 km grid versus Q1



Scatter plot UM (dT/dt – radiation – advection) versus 3-hr mean Q1 at N48



Scatter plot of effective dT/dt for 960 km grid versus Q1



Stochastic parametrization – cellular automaton backscatter

- use a cellular automaton to prescribe time-evolving patterns of convective forcing (Palmer, 1997)
- Cellular Automaton Stochastic Backscatter (CASB) scheme has been used in ECMWF EPS and climate runs to inject KE back into flow. (Shutts, 2005)
- CASB only concerned with convective momentum tendencies

Simple cellular automaton

Living cells are red

Dead cells are white

0	0	0	0	0	0
0	0	0	0	0	0
1	2	3	3	2	1
1	1	2	2	1	1
1	2	3	3	2	1
0	0	0	0	0	0

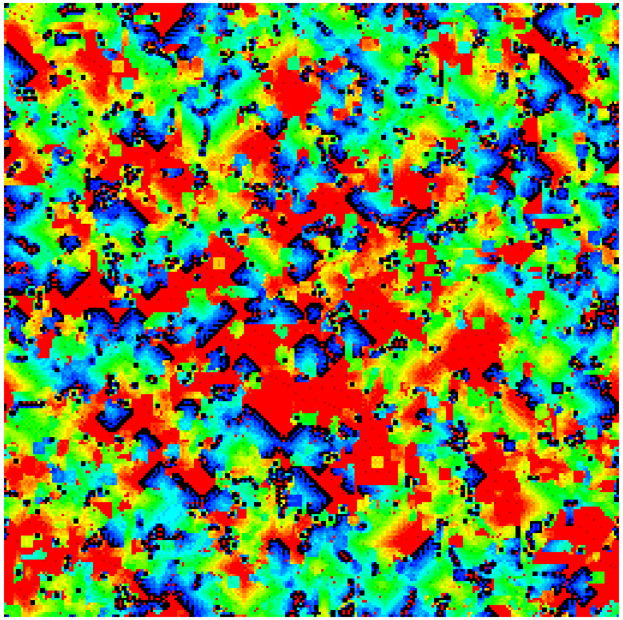
0	0	0	0	0	0
0	1	2	2	1	0
0	2	3	3	2	0
0	3	5	5	3	0
0	2	3	3	2	0
0	1	2	2	1	0

Rules:

Survival: 2 or 3 living neighbours

Birth: 3 living neighbours

animation of CA cell ages



- Blue cells are young
- Red cells are old or dead

Implementation of Cellular Automaton Stochastic Backscatter (CASB) in the ECMWF IFS

- estimate the total rate of generation of sub-grid scale kinetic energy due to numerical and physical sources (D)
- define time-evolving patterns with a cellular automaton (CA)
- compute a field of vorticity increments using the CA pattern and scaling the amplitude with $\sqrt{D}$
- streamfunction tendency due to upscale energy transfer given by:

$$\frac{\partial \psi}{\partial t} = \alpha \cdot \Delta s \cdot \Psi(\lambda, \phi, t) \sqrt{\Delta \tau \cdot D} / \Delta \tau$$

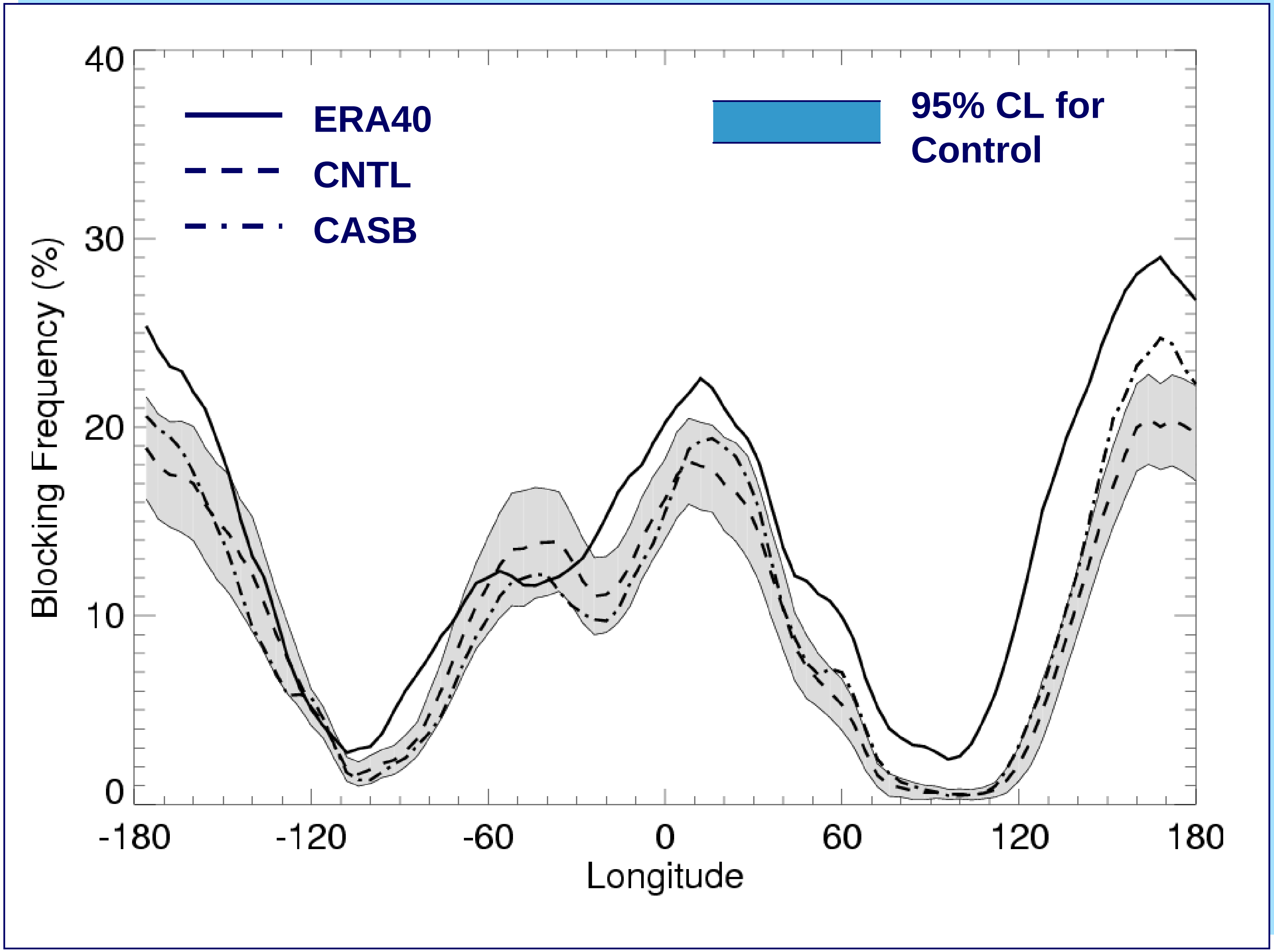
$\alpha =$ dimensionless parameter determining backscatter fraction

$\Delta s =$ CA gridlength $\Psi =$ CA pattern amplitude (function of lat. /lon.)

$\Delta \tau =$ time interval between CA states

Impact of Stochastic backscatter on Atmospheric Blocking (Dec-Mar 1962-2001)

Work by Thomas Jung

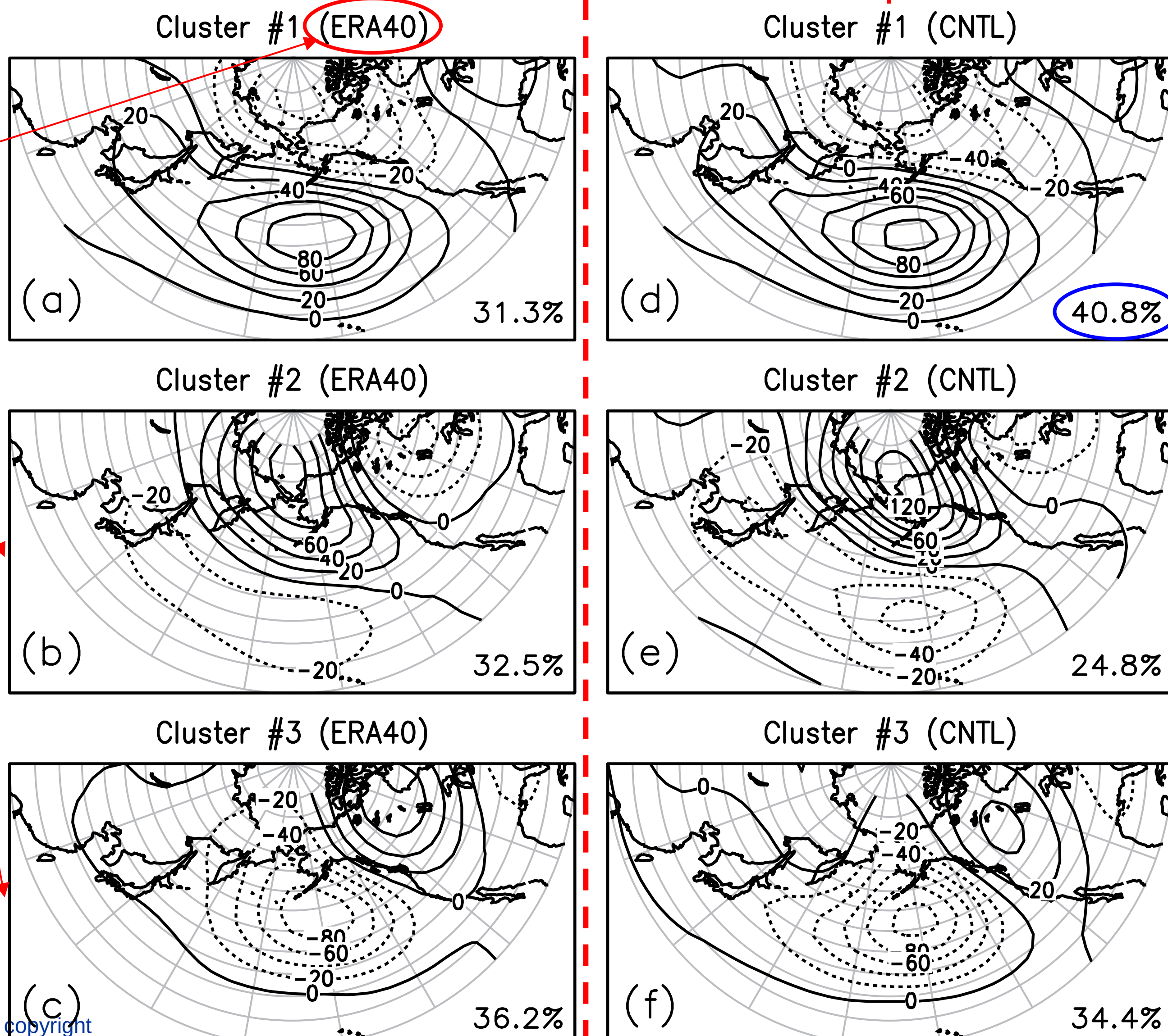


Cluster centroids of wintertime Z500 anomalies

From Jung, Shutts and Palmer (2005)

For winters in the period 1962-2001

ERA 40 'truth'



T95

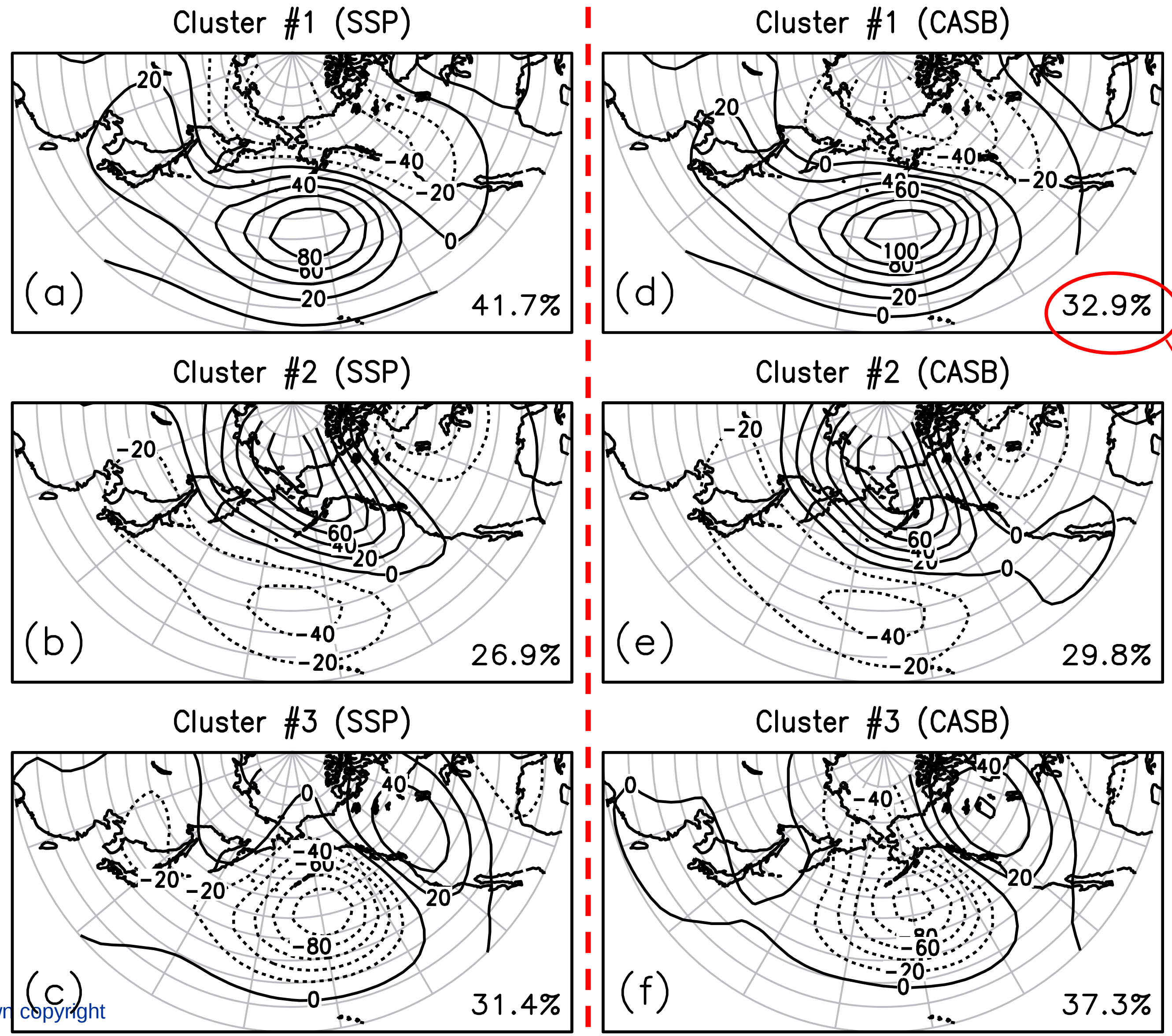
Units= m

frequency

control

Stochastically-perturbed cluster centroids

Op. stochastic physics (SSP)



CASB

Closer to ERA 40 than CNTL or SSP

Summary

- idealized tropical circulation can be numerically-simulated with a CRM
- using a coarse-graining approach the effective cloud forcing can be computed
- PDF of latent heating on an 80 km grid shows cooling as well as warming due to evaporation
- PDFs of Q can be conditioned on the parametrized convective tendency Q1
- Variance of Q increases with Q1 (although at 960 km apparently not !)
- Calibrate stochastic convective parametrizations with PDF info from cloud-resolving model simulations