A multi-scale cellular automaton for organized tropical convection

J. Berner and T. Palmer

With special thanks to:

G. Shutts, T. Jung, A. Tompkins, L. Ferranti, M.Leutbecher, P. Bechthold

Outline

- Stochastic parameterizations in NWP
- Organized convection (OC)
  - Multi-scale structure
  - Representation of OC in the ECMWF model
  - Fundamental limitations of conventional parameterizations
- A simple multi-scale cellular automaton (MSCA) for organized convection
- Towards a MSCA-representation of organized convection in the ECMWF model

Parameterization of subgrid-scale processes

Coupled system of grid-scale and subgrid-scale processes (Lorenz, 1996)

$$\dot{x}_k = -x_{k-1}(x_{k-2} - x_{k+1}) - x_k - (hc/b) + F + \sum_{j=1}^{J} y_{j,k}$$

$$\dot{y}_{j,k} = -cb\, y_{j+1,k}(y_{j+2,k} - y_{j-1,k}) - c\, y_{j,k} + (hc/b)x_k$$

Equation for grid-scale process with parameterized subgrid-scale processes :

$$\dot{x}_k = -x_{k-1}(x_{k-2} - x_{k+1}) - x_k - (hc/b) + F + P_k(\vec{x})$$

Classical bulk-parameterization:

$$P_k(\vec{x}) = f(x_k)$$

local and deterministic: each large scale state is in equilibrium with ensemble of subgrid-states

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Equation for grid-scale process with parameterized subgrid-scale processes :

$$\dot{x}_k = -x_{k-1}(x_{k-2} - x_{k+1}) - x_k - (hc/b) + F + P_k(\vec{x})$$

Stochastic-dynamic parameterization:

$$P_k(\vec{x}) = f(\vec{x}, \varepsilon)$$

nonlocal and random: particular realization of subgrid-scale state

Conventional vs stochastic-dynamic parameterization

Conventional parameterization:

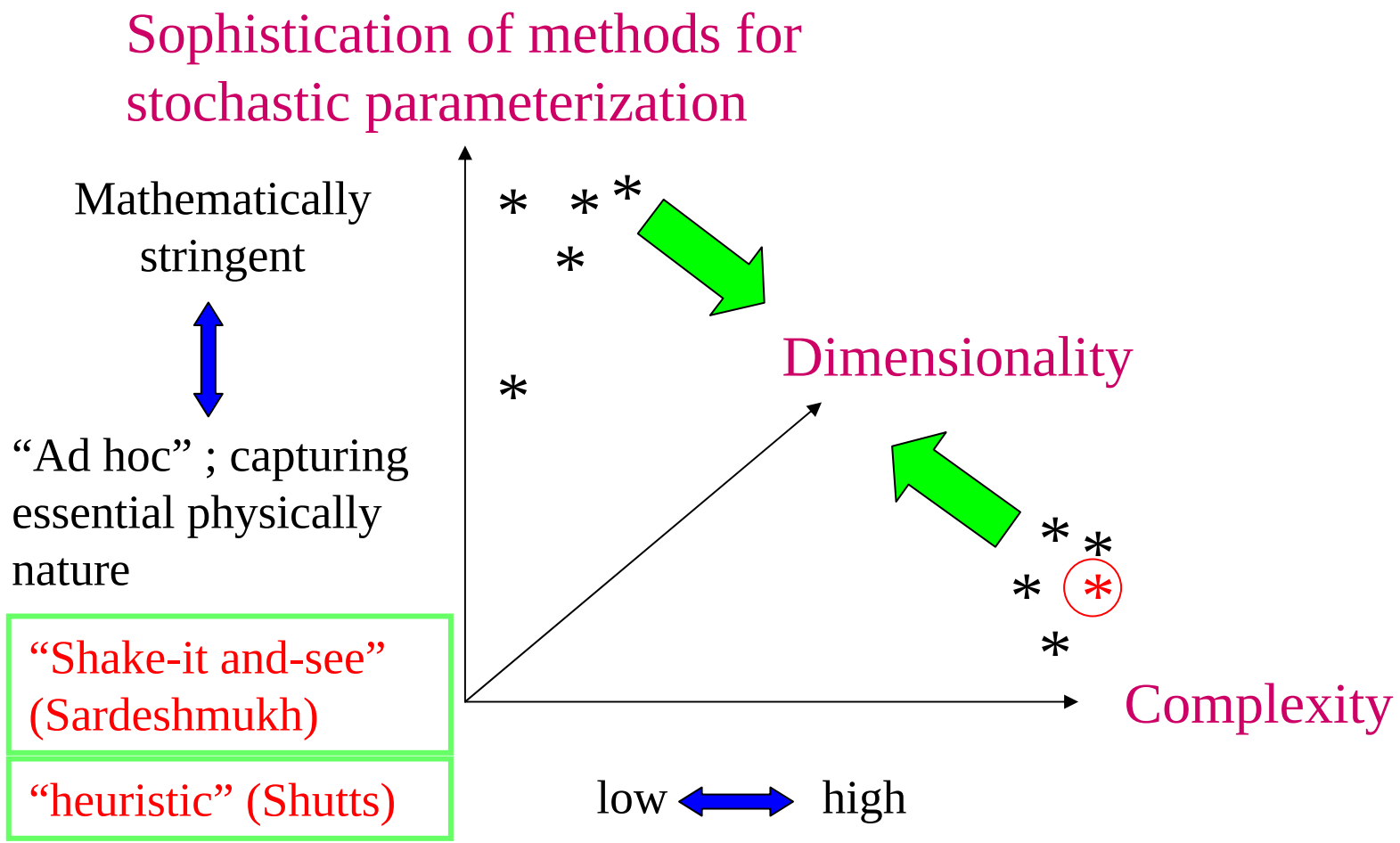
- Local: determined by state in one gridbox
- Deterministic
- State-dependent, i.e., flow-dependent

Stochastic-parameterization:

- Non-local: coherent structure spanning several gridboxes
- Stochastic or quasi-random
- State-dependent, i.e., flow-dependent

Here: Cellular Automaton (proposed by Palmer 1999, 2001 developed by Shutts and Palmer, 2003)

Stochastic parameterization: Closing the Gap?!

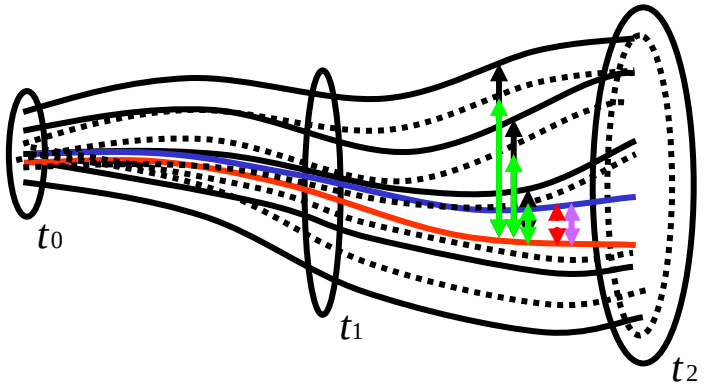


Empirical approach

- Physical intuition
- Shake-it-and-see
- If impact positive, Go-and-understand
  - Missing process inherently stochastic?
  - Change in deterministic formulation?

Model Error of NWP models

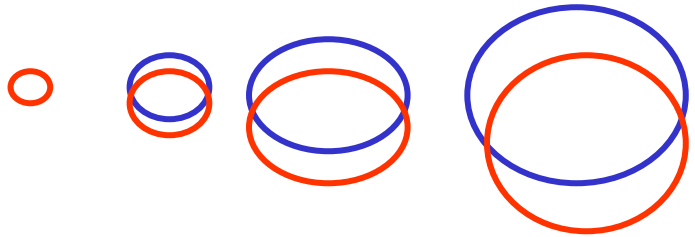
- Model is under-dispersive on medium-range



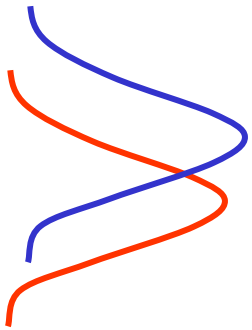
Insufficient representation of subgrid-scale processes?

Missing physical processes on near-gridcsale and gridscale (e.g., OC)

- Systematic error (climatic scale)

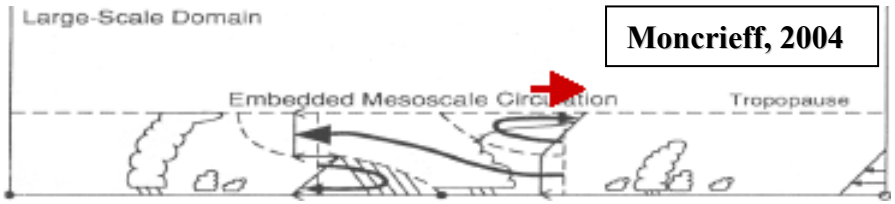


$t \rightarrow \infty$



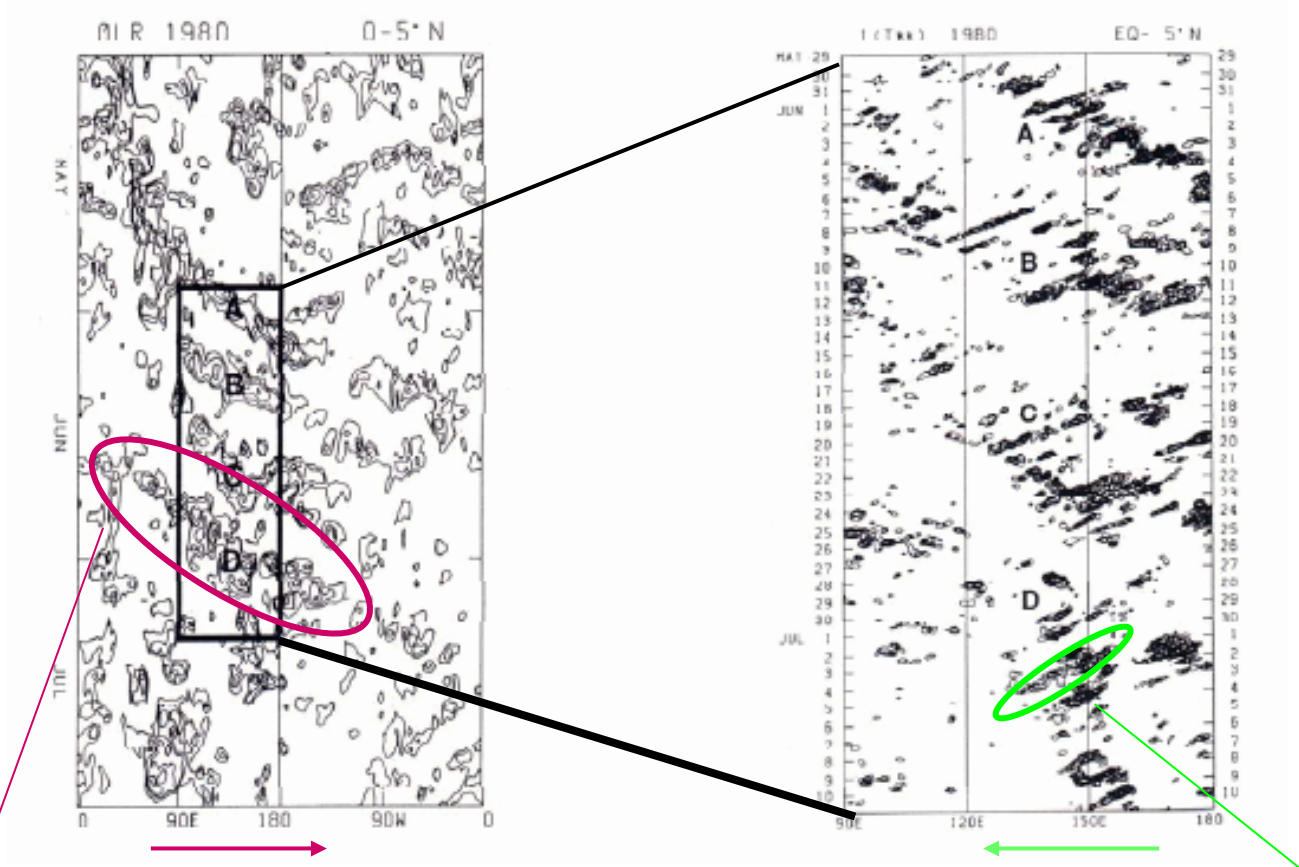
Aim of study

Develop of a multi-scale cellular automaton (MSCA) for organized convection that captures the subgrid-scale forcing not represented by conventional parameterizations.



- Potential to reduce systematic error by better representation of MJO
- Potential of improved skill of medium- to extended-range weather forecasts by better representation of tropical variability (Ferranti et al.,1990)

Multi-scale character of organized convection



Superclusters ~20000km

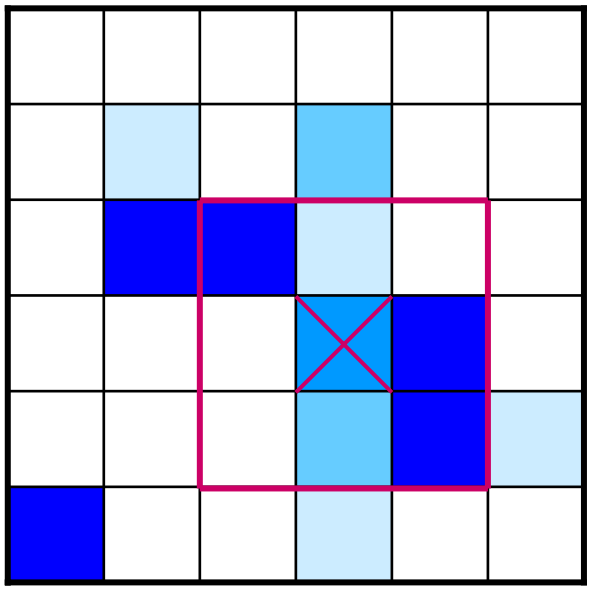
Nakazawa, 1988

Organized convection ~1000km

Multi-scale Cellular Automaton (MSCA) for convective organization (Palmer)

- Small-scale CA models convective cells advecting westwards with the trade winds
- Intermediate-scale CA models envelope of convective cells (cloud-clusters) propagating eastward

Rules for small-scale CA



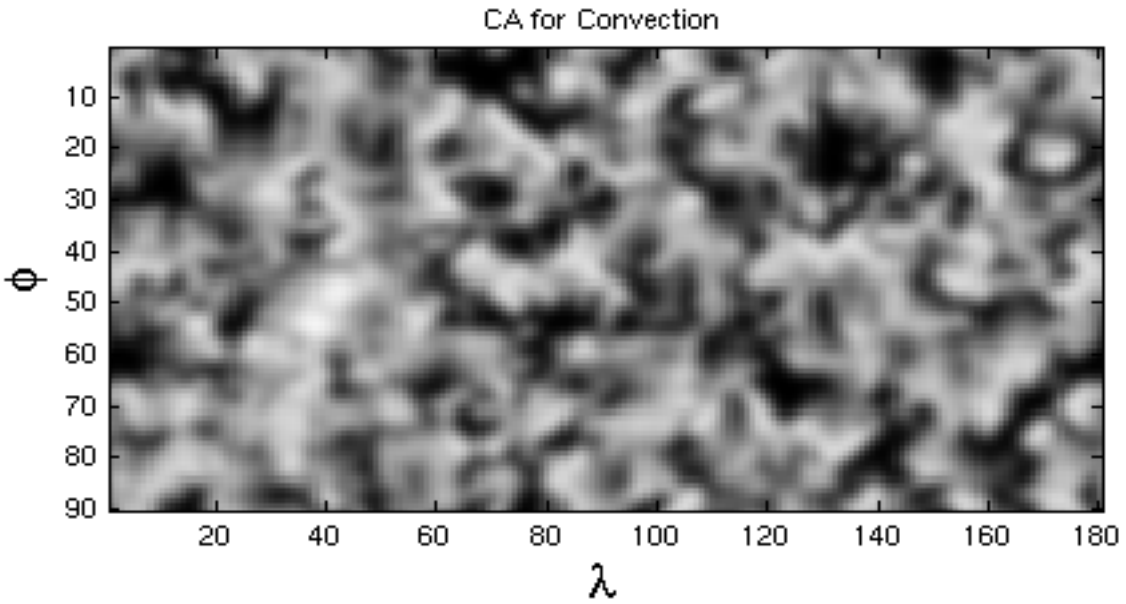
- Developed and used by Shutts (2005)
- Find the number of fertile cells in immediate neighbourhood: S
- If cell dead and S={2,3} => create fertile cell
- If cell alive and S={3,4,5} => cell survives with same number of lives
- If cell alive and S≠{3,4,5}=> cell loses one life
- One Parameter: Number of lives N

	Fertile cell
	Living cell with n lifes
	Dead cells

System has memory (=> temporal correlation)

Evolution depends on immediate neighbours (=> Coherent structures span several gridpoints)

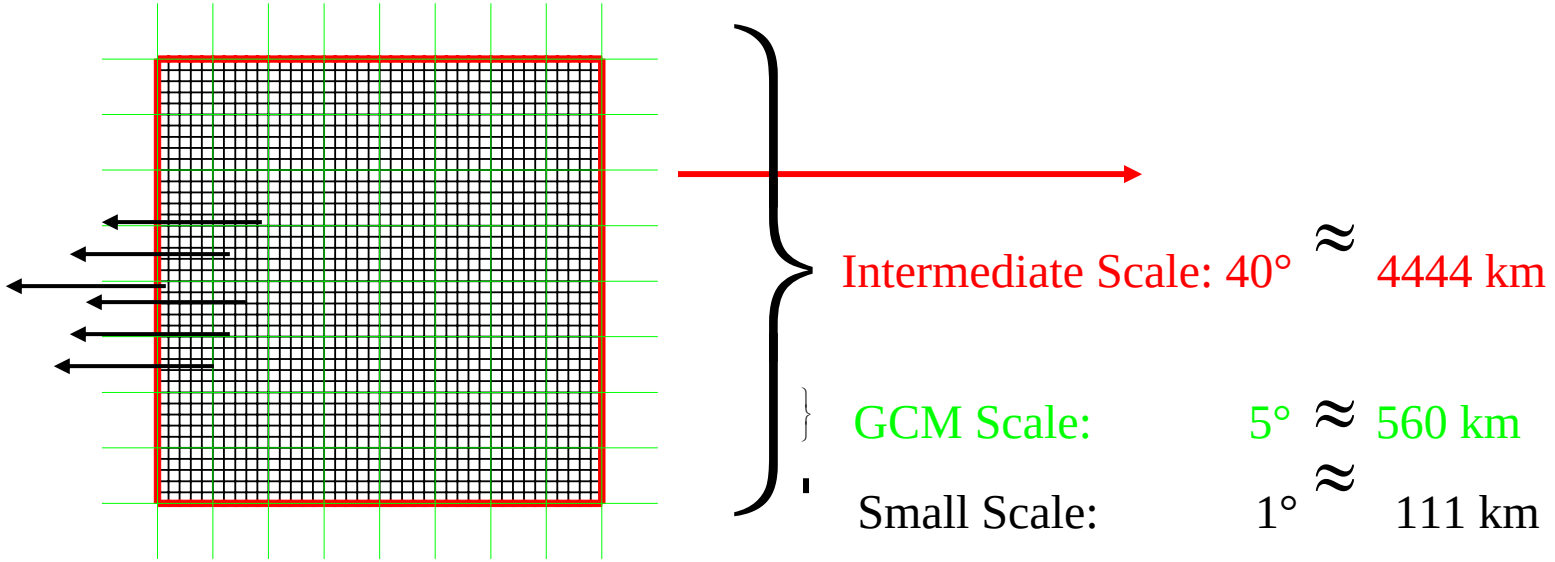
Small-scale CA for convection



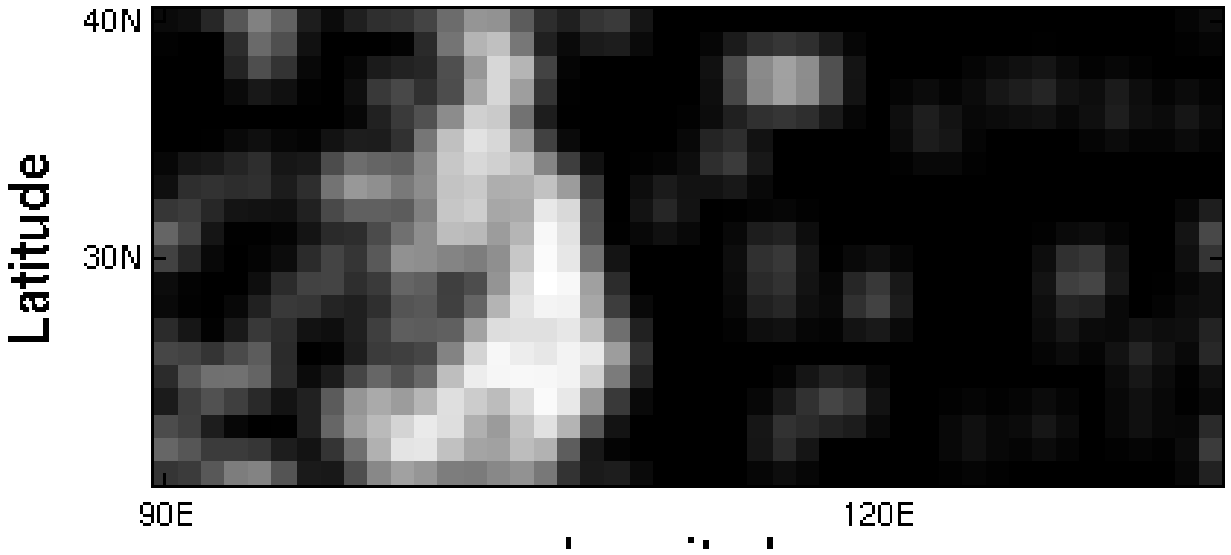
After Shutts and Palmer, 2003

Multi-scale-Cellular Automaton

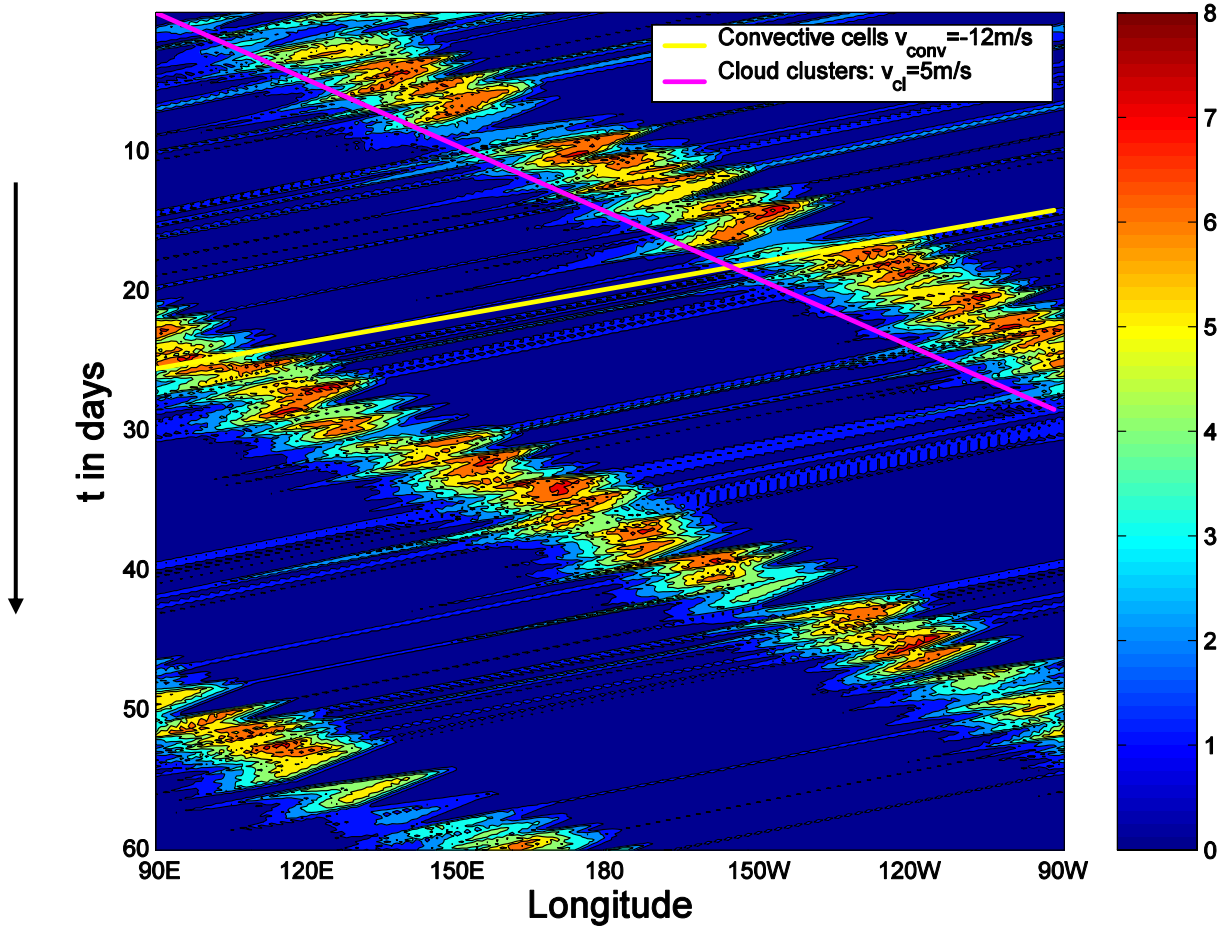
- Small-scale cells evolve according to rules and propagate to the west
- Intermediate-scale cells can be on/off and propagate to the east
- Fertile cells in small-scale CA can only be born if intermediate-scale cell is 'on'



Multi-scale-CA for Convective Organization

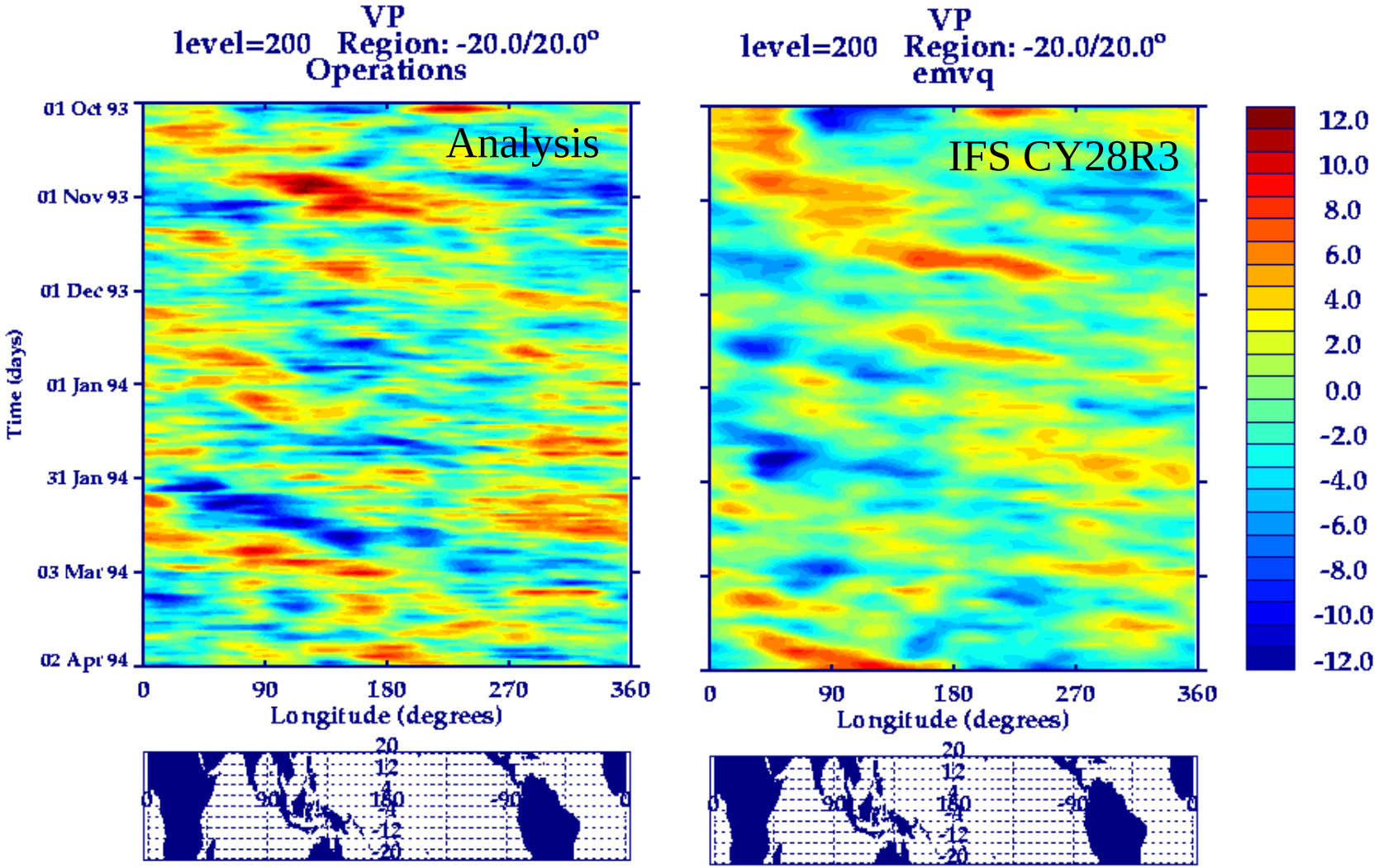


Hovmöller diagram



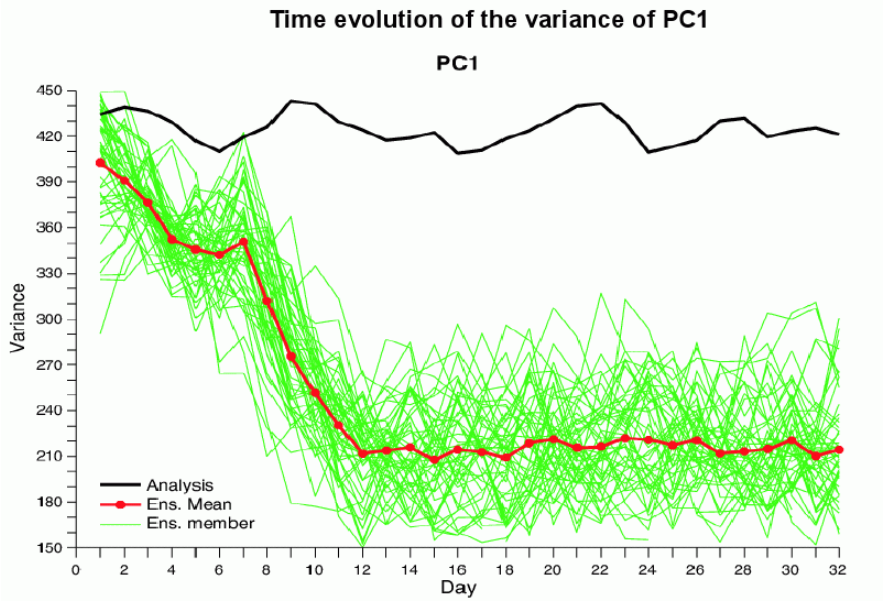
ECMWF

Towards a MSCA-representation of organized convection in the ECMWF model



- Not enough fine-scale structure
- Amplitude too small
- Problems with propagation after ~10d

MJO in coupled ECMWF model



Vitart et al. 2003:

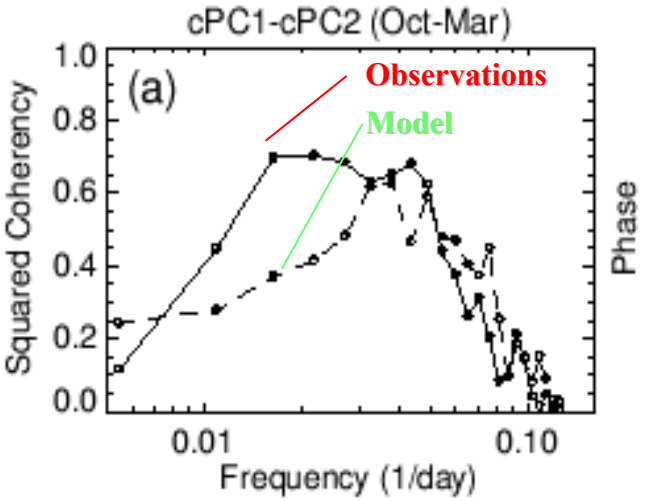
MJO variance decreases during the first 10d by as much as 50%

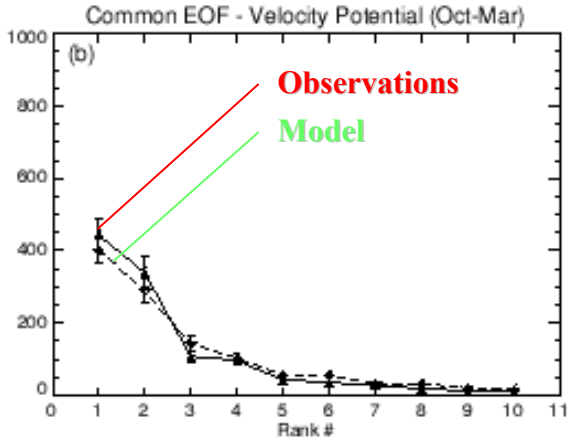
Vitart and Anderson, 2004

MJO in ECMWF model (uncoupled)

Jung and Tompkins, 2003
Tompkins and Jung, 2004:

- **Leading two EOFs are significantly less coherent than observations on timescales longer than 30d**
- **MJO activity is underestimated by about 10% in ECMWF model (T95L90, resolution dependent)**





Tompkins and Jung=2004

Explicit Representation of organized convection in the IFS

- Climate runs forced with observed SST
- Integrated for 6 months: Oct-Mar
- T95L60 with version CY28R3
- Two experimenal setups:
  - Forcing from CA only (state-independent)
  - forcing function of CA and CAPE (state-dependent)

Parameterization organized convection

Parameterization of organized convection is represented as additional streamfunction forcing and added to the relative vorticity in spectral space

$$\frac{\partial \psi}{\partial t} = f(\Psi(\lambda, \varphi, t), z) * CAPE\ (\lambda, \phi, t) / \Delta\tau$$

Sreamfunction forcing

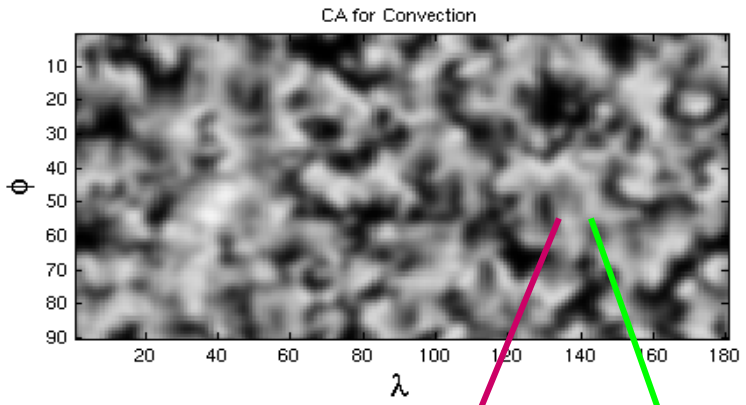
Horizontal and vertical structure function

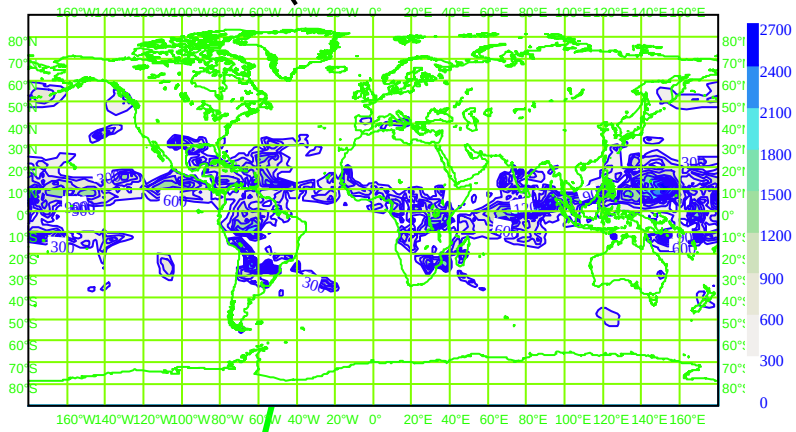
CA structure function (smoothed, coarse-grained)

Convective available potential energy

Parameterization organized convection

$$\Delta\psi = f(\Psi(\boldsymbol{\lambda}, \boldsymbol{\varphi}, t), z) * CAPE\ (\lambda, \phi, t)$$





Non-local, quasi-random, state-dependent

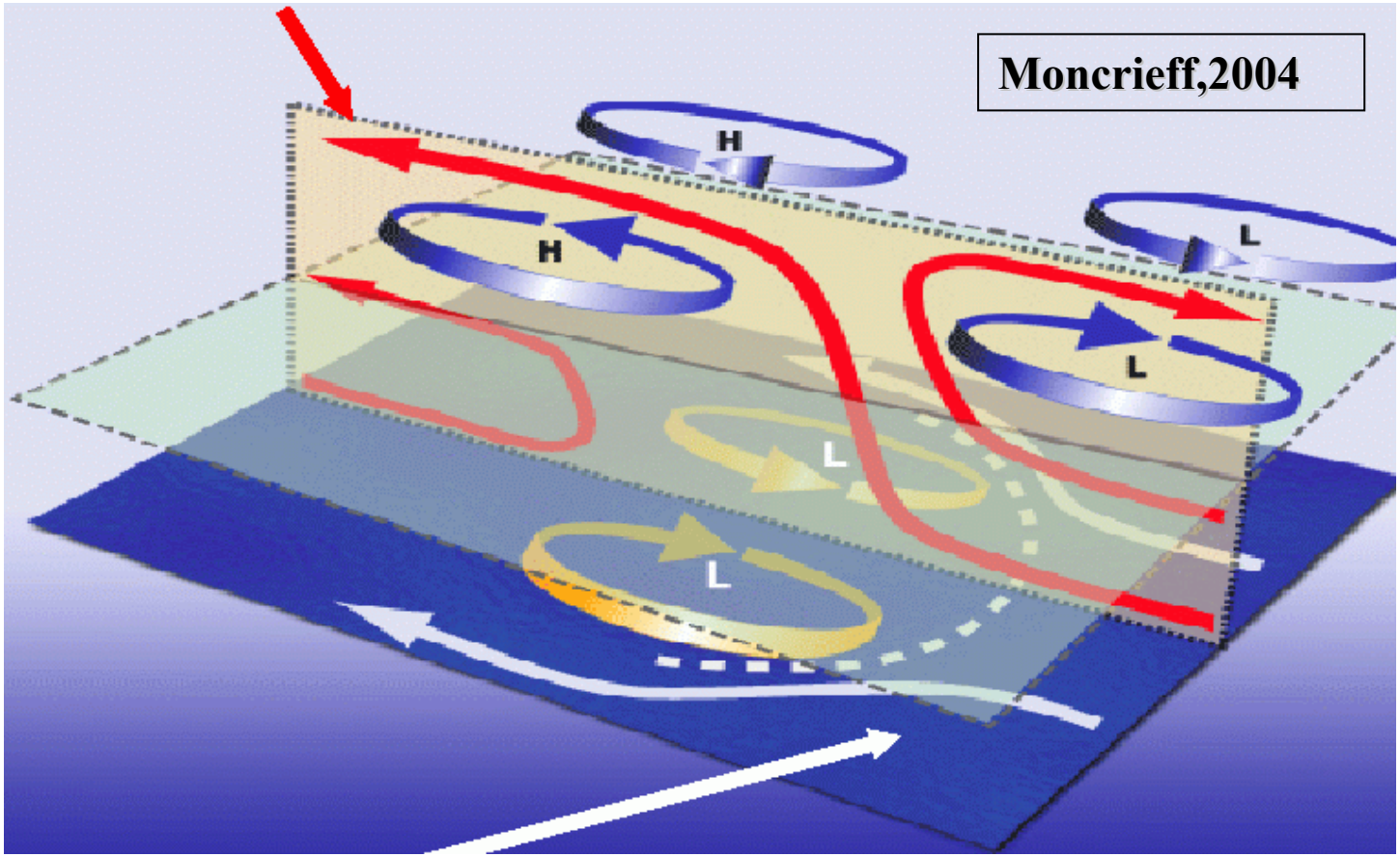
- Formulation almost identical to stochastic backscattering scheme of Shutts, 2005 (except vertical and horizontal structure)

But: different motivation

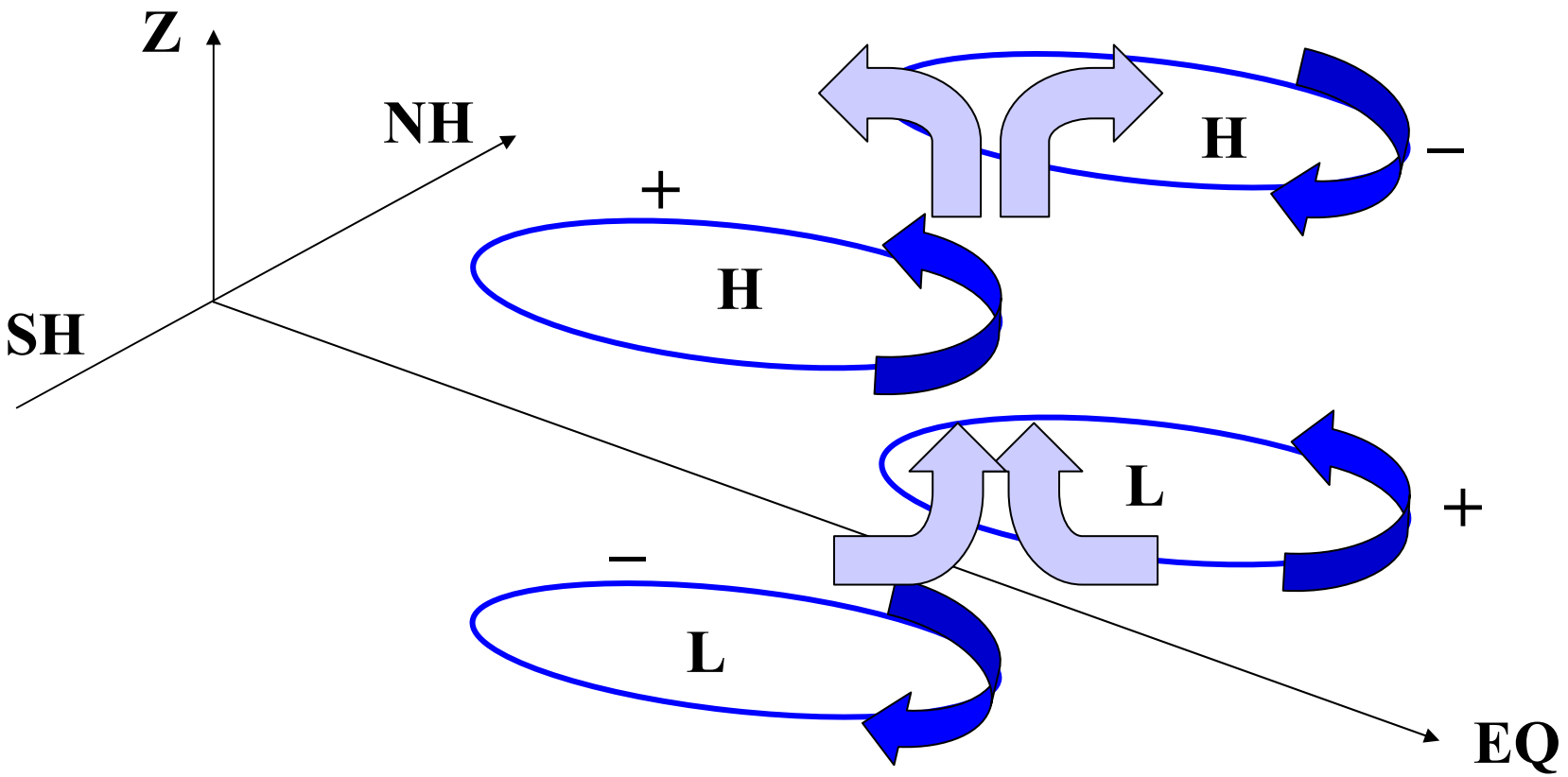
- Shutts: Backscatter of kinetic energy of processes represented by conventional parameterizations
- This work: adding (arguably) a missing nonlocal process, not representable by conventional parameterizations

- Can organized convection be fully represented by local parameterizations?
- System self-organizing on the subgrid-scale or is organization coming through the large-scales?

Archetype for organized convection (Moncrieff, 2004)



Horizontal and Vertical structure

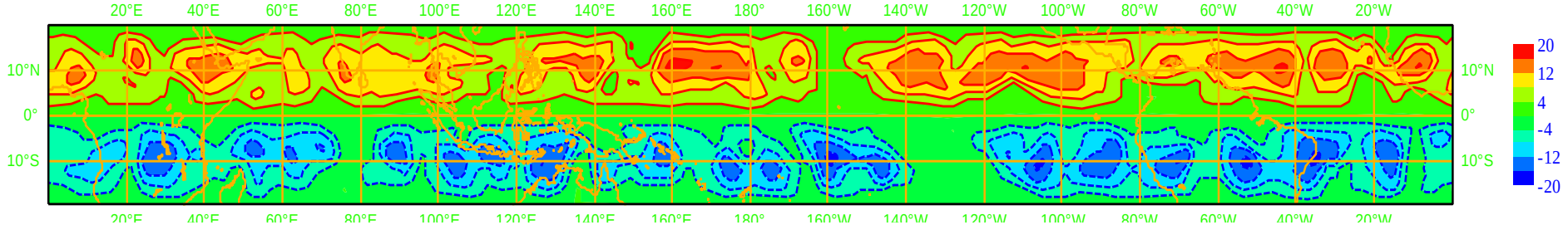


Horizontal and vertical structure
-- forcing from CA only (state-independent) –

Upper Troposphere ~15hPa

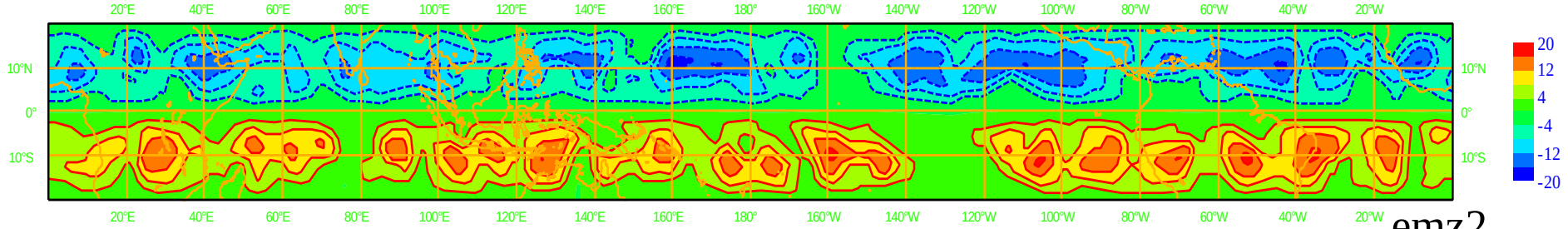
Problem with vertical structure

Tuesday 1 October 1991 12UTC ECMWF Forecast t+240 VT: Friday 11 October 1991 12UTC Model Level 15



Lower Troposphere ~750hPa

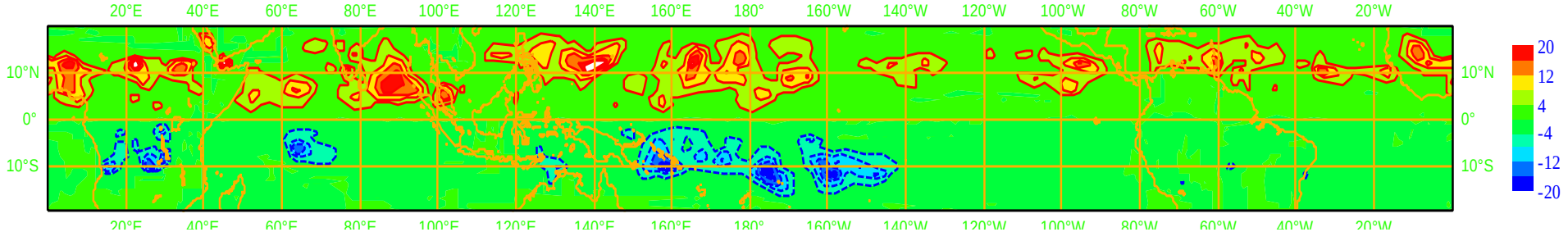
Tuesday 1 October 1991 12UTC ECMWF Forecast t+240 VT: Friday 11 October 1991 12UTC Model Level 45



emz2

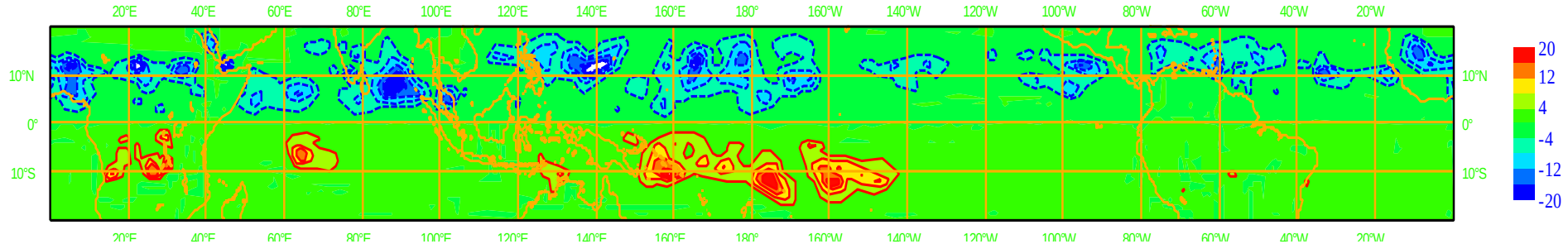
Horizontal and vertical structure
- forcing is function of CAPE (state-dependent)-

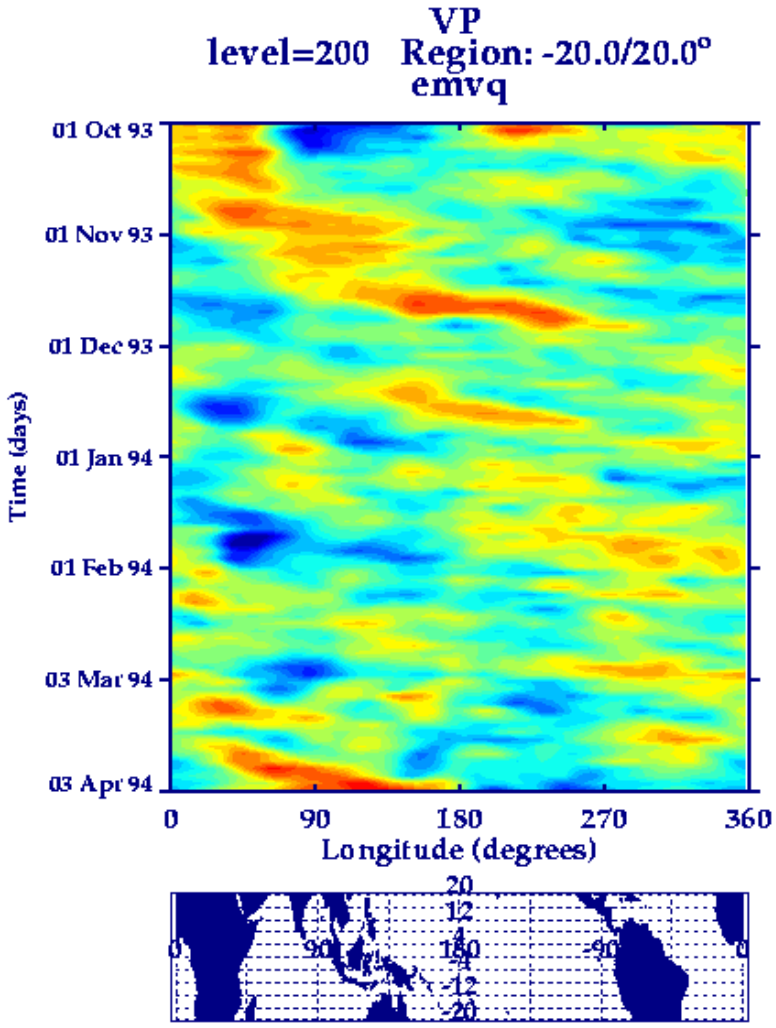
Tuesday 1 October 1991 12UTC ECMWF Forecast t+240 VT: Friday 11 October 1991 12UTC Model Level 15

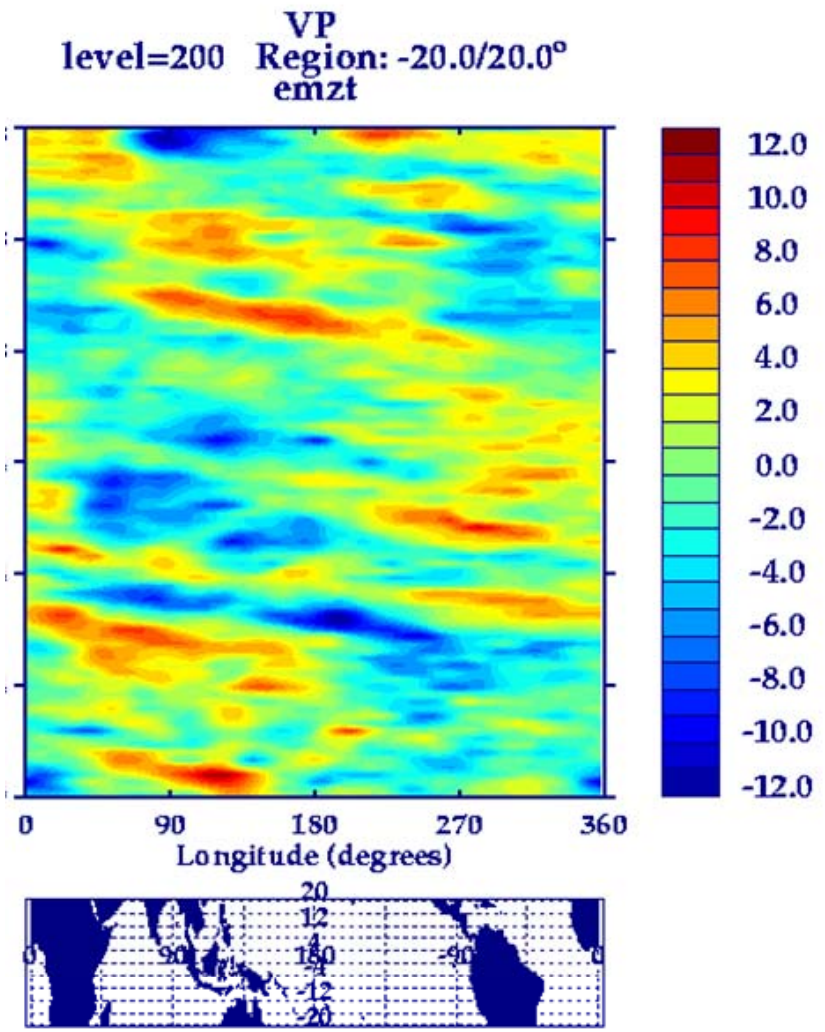


emzt

Tuesday 1 October 1991 12UTC ECMWF Forecast t+240 VT: Friday 11 October 1991 12UTC Model Level 45

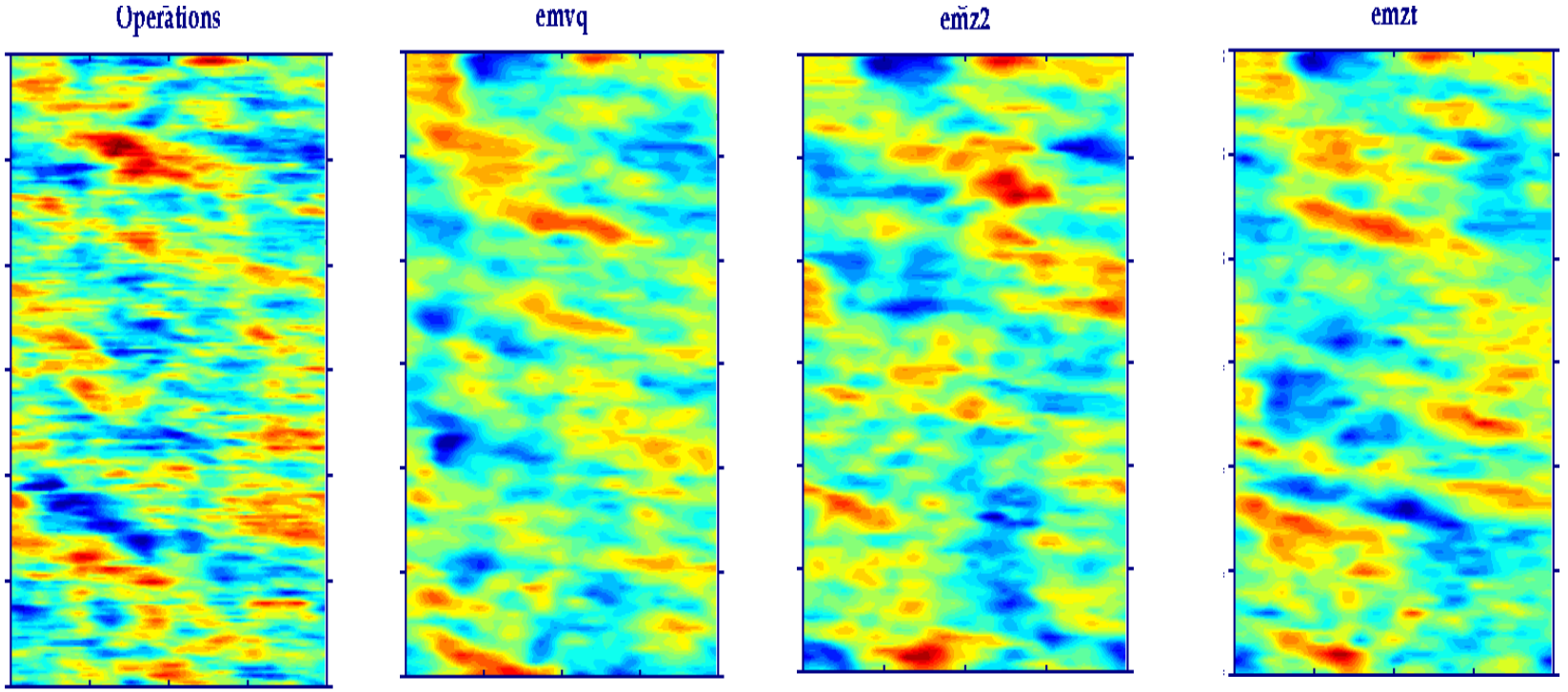




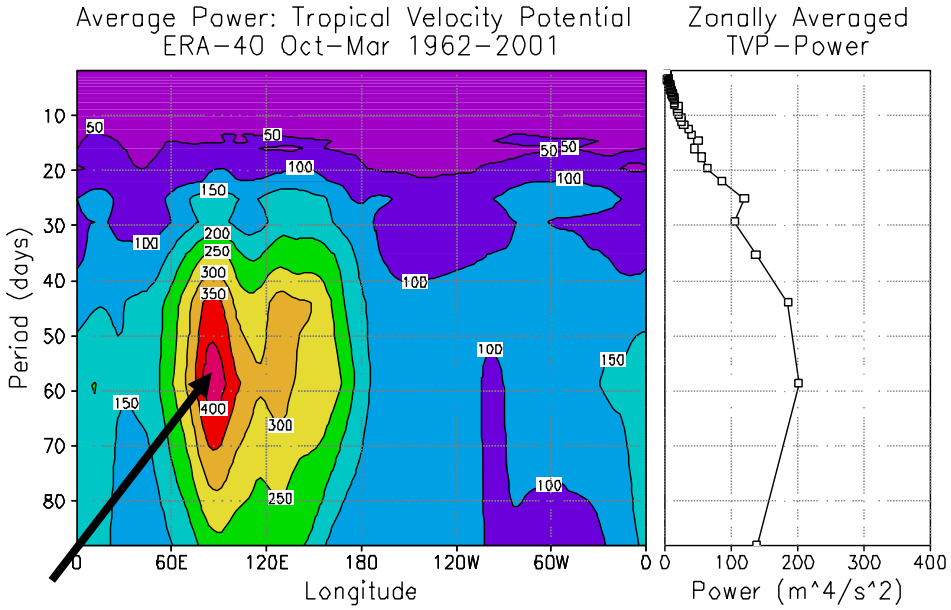


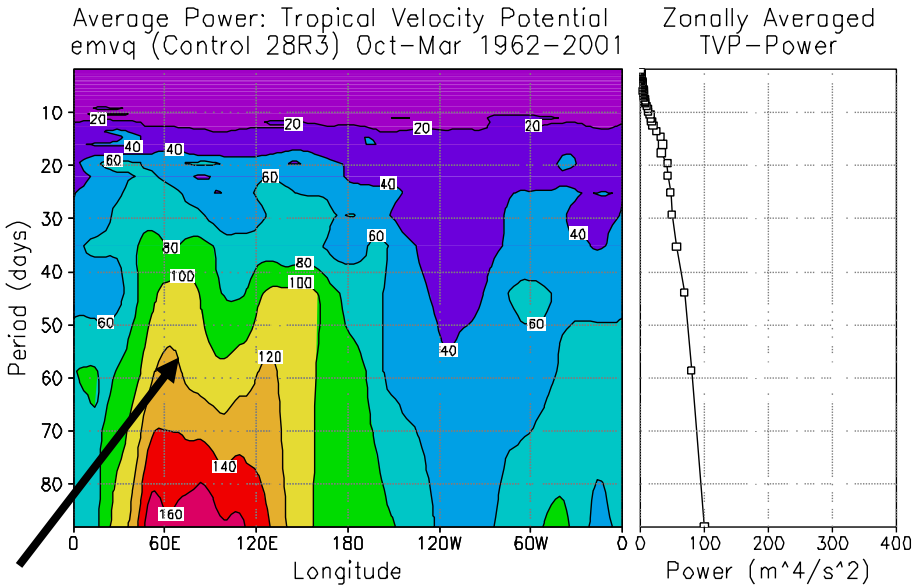
- More fine-scale structure
- Slightly larger amplitude
- More propagating features

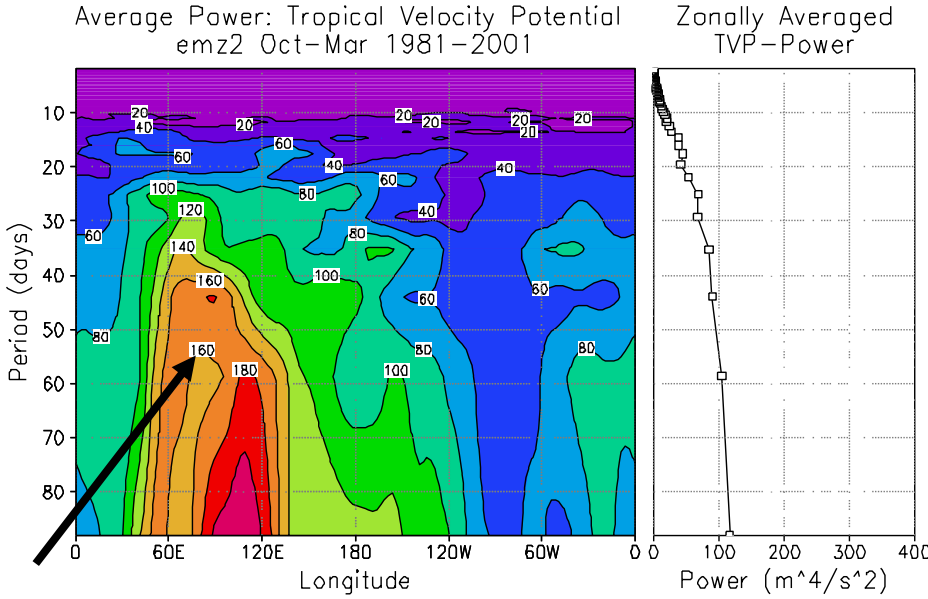
Analysis	IFS CY28R3	CA only	CA ,CAPE

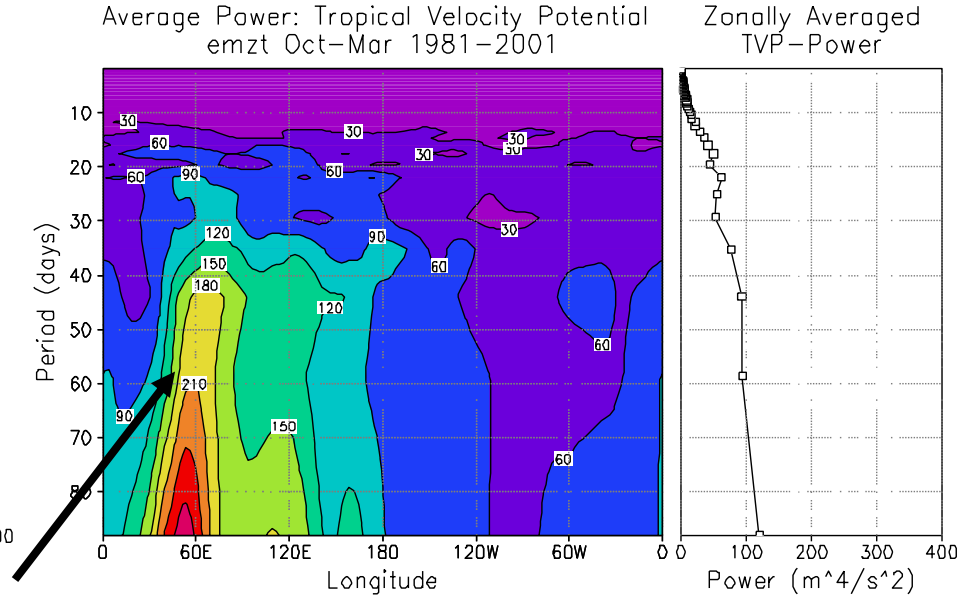


- Impact positive, but not sufficient small-scale structure
- More objective analysis needed!









Compare to Jung, Tompkins and Rodwell, 2005

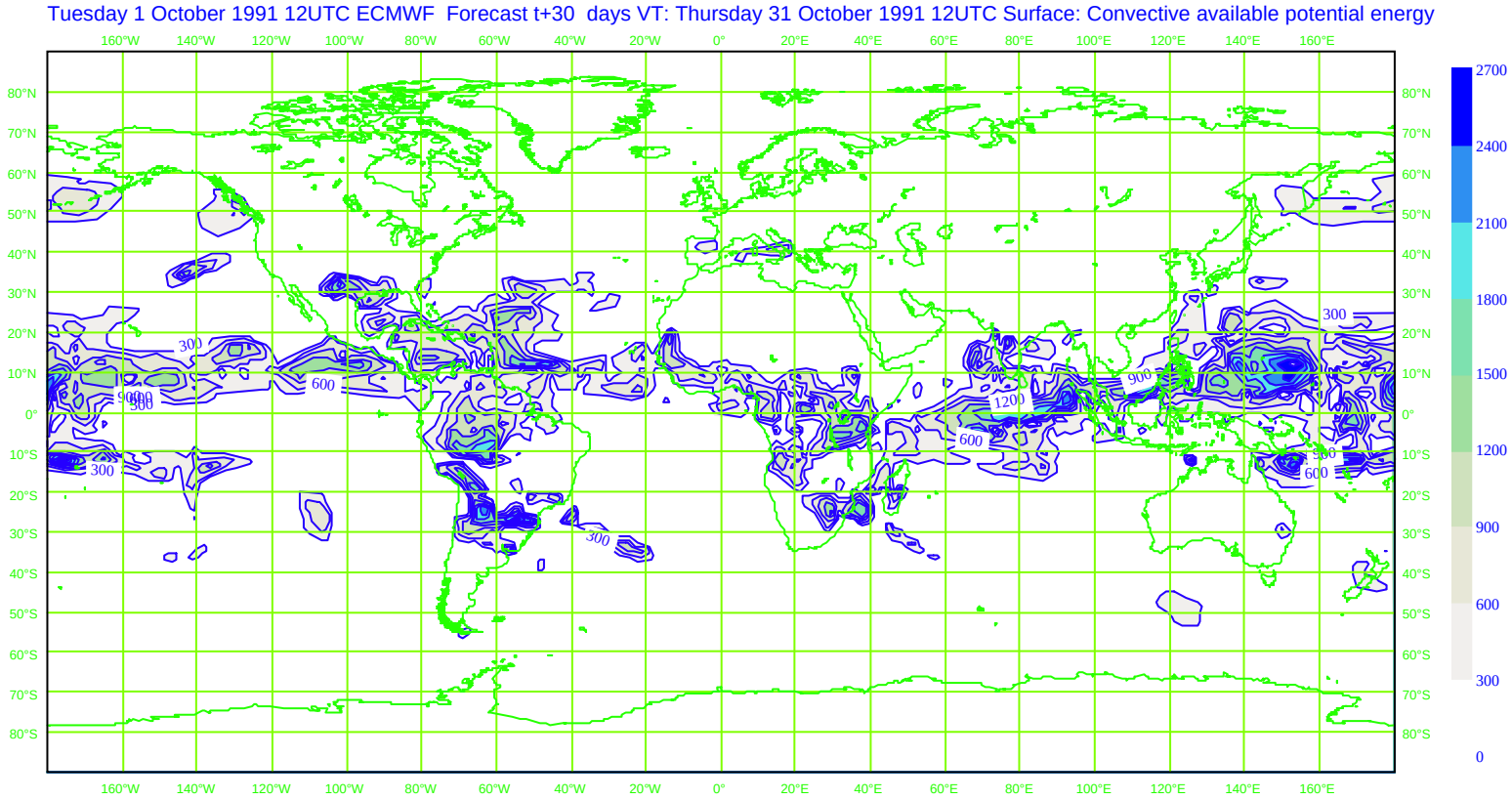
Future work I: Development

- Add stochastic forcing as
  - Divergence increment (spectral space)
  - Temperature increment (gridpoint space)
- Use physical insight to adjust
  - spatio-temporal scales (spectra)
  - vertical structure
- How is MSCA best linked to large-scale state?

Future work II: Impact

- Look at u850, OLR, rainfall, gridpoint storms
- Assess impact on skill and spread for medium-range and monthly and seasonal forecasts
- Assess impact on systematic error
- Test scheme in coupled model

CAPE


Tuesday 1 October 1991 12UTC ECMWF Forecast t+30 days VT: Thursday 31 October 1991 12UTC Surface: Convective available potential energy
160°W 140°W 120°W 100°W 80°W 60°W 40°W 20°W 0° 20°E 40°E 60°E 80°E 100°E 120°E 140°E 160°E
80°N 70°N 60°N 50°N 40°N 30°N 20°N 10°N 0° 10°S 20°S 30°S 40°S 50°S 60°S 70°S 80°S
2700
2400
2100
1800
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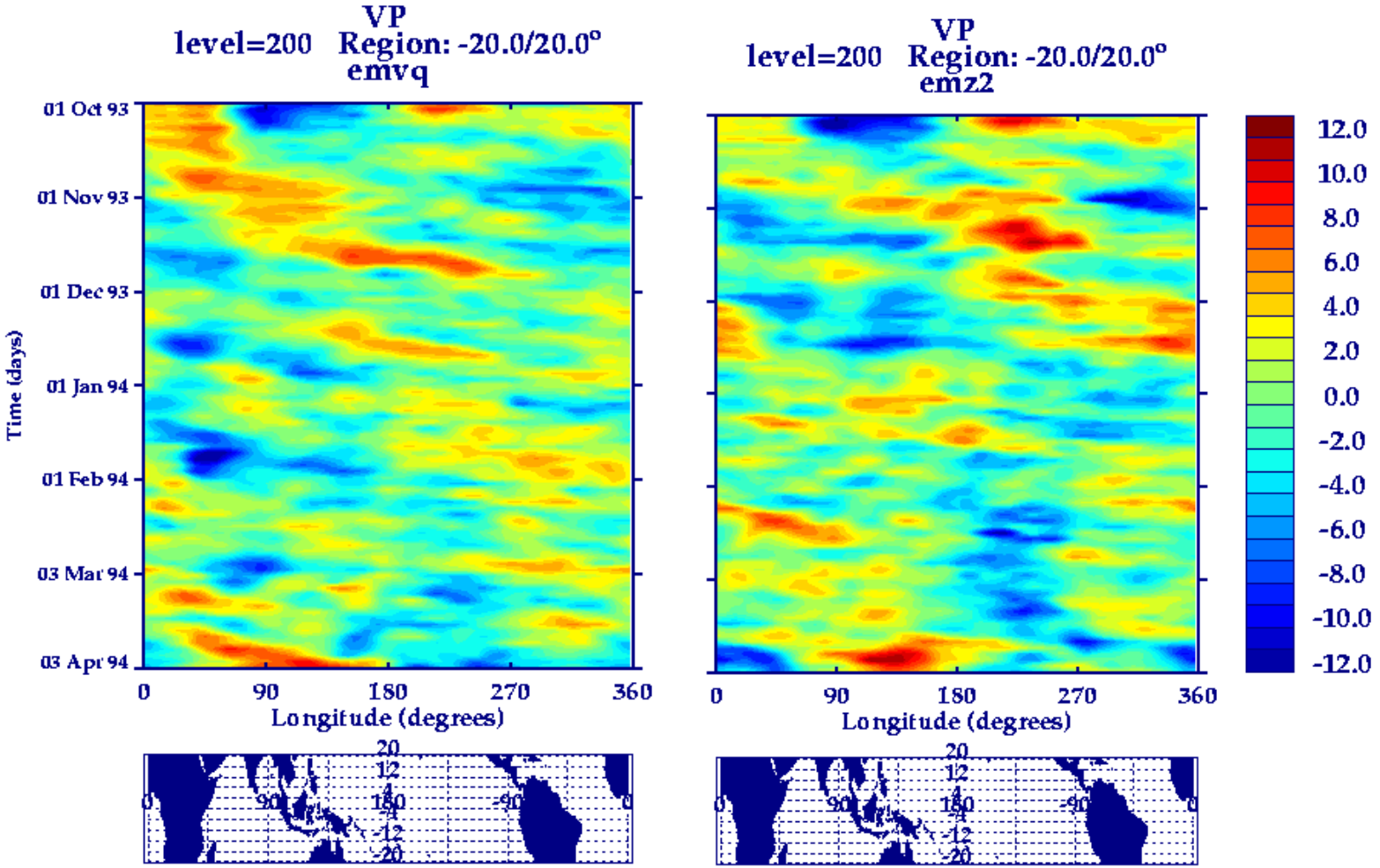
1200
900
600
300
0

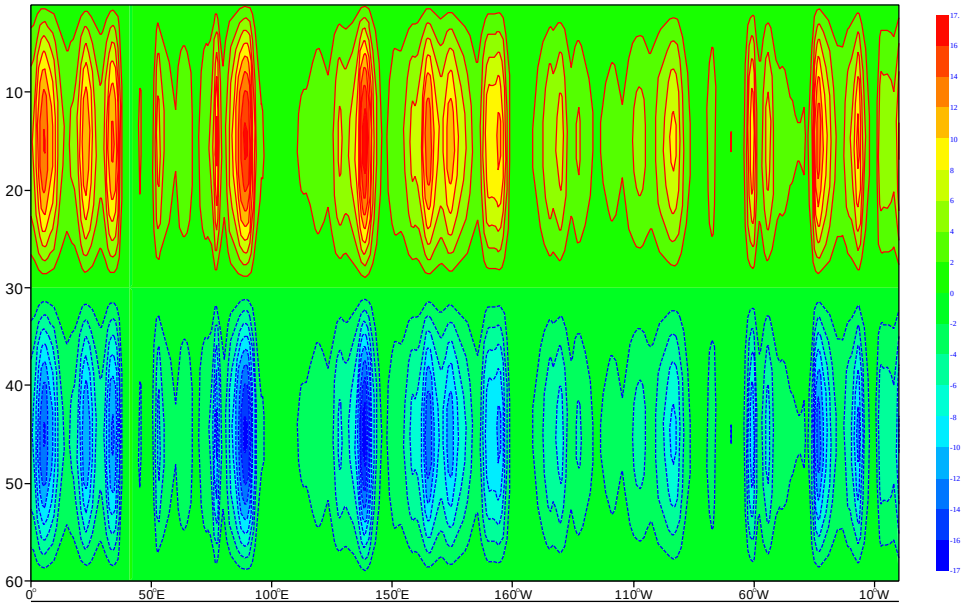
ECMWF



- More fine-scale structure
- slightly larger amplitude
- No obvious impact on propagation

Vertical structure of forcing

Cross section of p103/t128 19911001 1200 step 240 Expver emzt

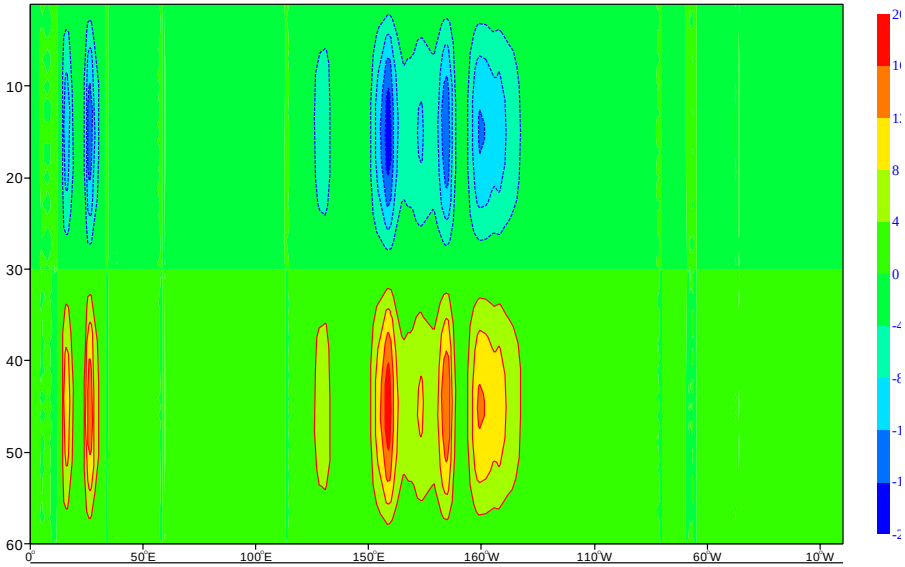


10.0N

Latitude: 10N

Latitude: 10S

Cross section of p103/t128 19911001 1200 step 240 Expver emzt



-10.0S