Stochastic parameterization in NWP and climate models

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Acknowledgements:

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Parameterization of unrepresented processes

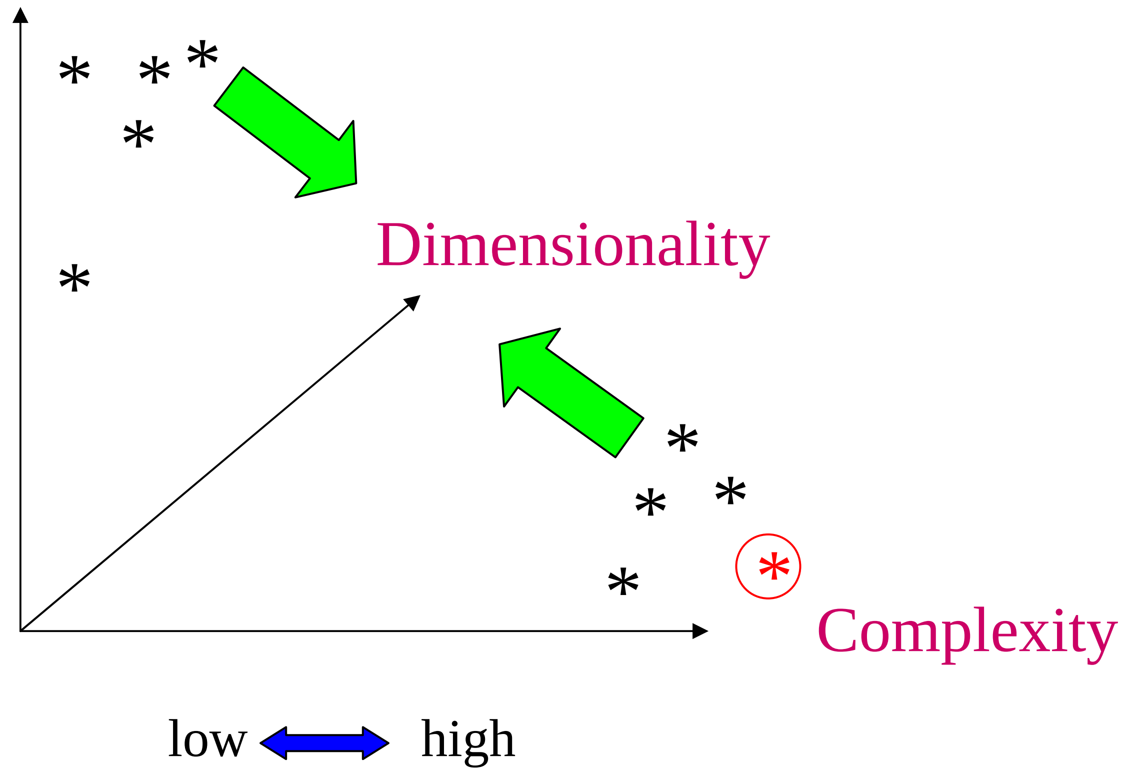
- Motivation: unresolved and unrepresented processes lead to model error
- Unresolved sub-gridscale processes
  - Example: Stochastic backscatter of dissipated energy on resolved flow (CABS)
- Unrepresented super-gridscale processes
  - Example: Stochastic cloud clusters (SSC) as part of organized tropical convection (scales of several thousand kilometers)

Stochastic parameterization: Closing the Gap?!

Sophistication of methods for stochastic parameterization

Mathematically vigorous

“Ad hoc” ; capturing essential physically nature



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:

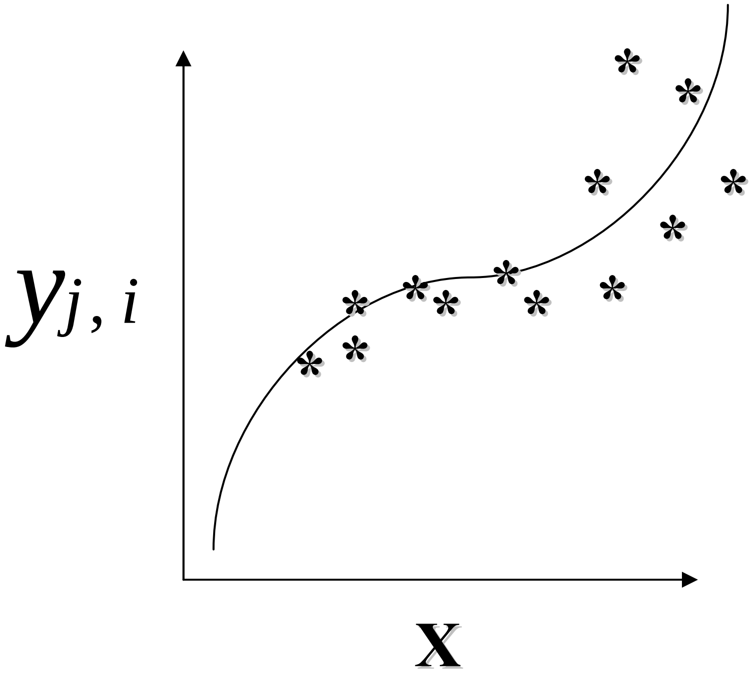
Stochastic-dynamic parameterization:

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

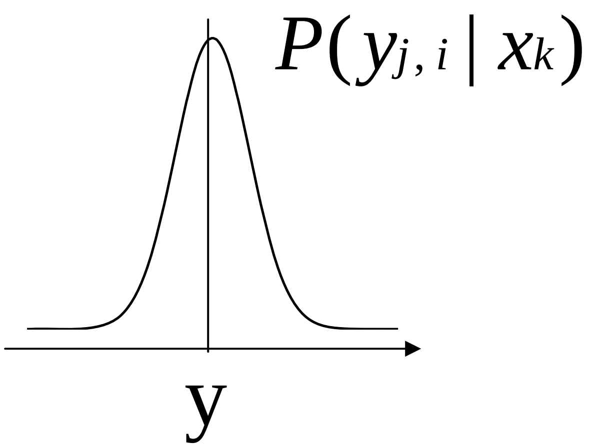
local and deterministic: each large scale state is in equilibrium with ensemble of subgrid-states

nonlocal and random: particular realization of subgrid-scale state

Shortcomings of classical bulk-parameterization



There are several realizations of the subgrid-state for a given large-scale state



Conventional vs stochastic-dynamic parameterization

<u>Conventional parameterization in NWP:</u>

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

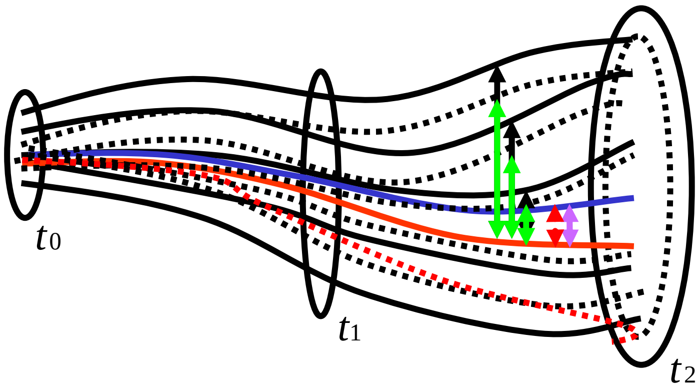
<u>Stochastic-parameterization:</u>

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

Here: Cellular Automaton

Model Error of NWP models

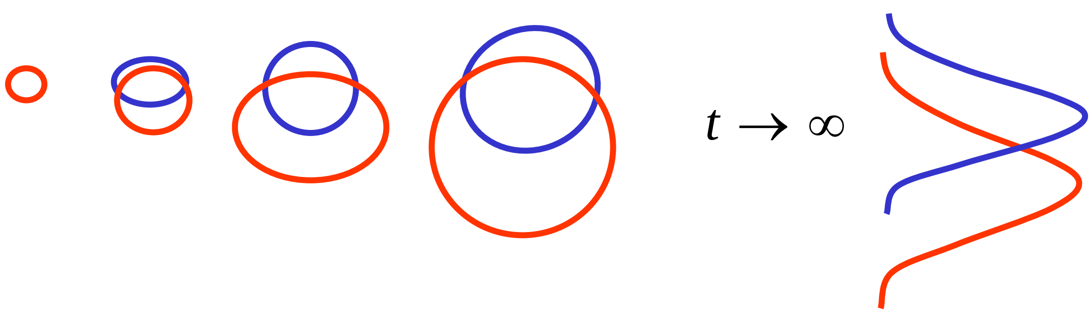
❖ NWP: Model is under-dispersive on medium-range



Insufficient representation of subgrid-scale processes?

Missing physical processes on super-grid scale (e.g., cloud super-clusters for OC)

❖ Systematic error



Potential benefits of stochastic-dynamic parameterizations

- Additional degrees of freedom
  - Increase spread without degradation of the forecast error
  - Improve skill
- Noise-induced drift and transition
  - Reduce systematic error

Stochastic Parameterization for Organized Convection

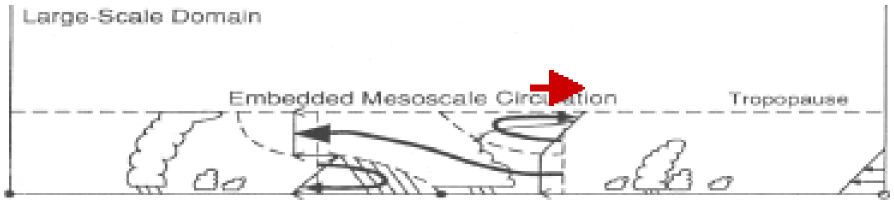
Rationale: Develop a stochastic representation of cloud-clusters currently not captured by conventional parameterizations, but play an important role in organized convection in the tropics

- Super-gridscale!

Is stochastic approach valid or should this be the goal for deterministic physical parameterization?

SSC – Stochastic superclusters

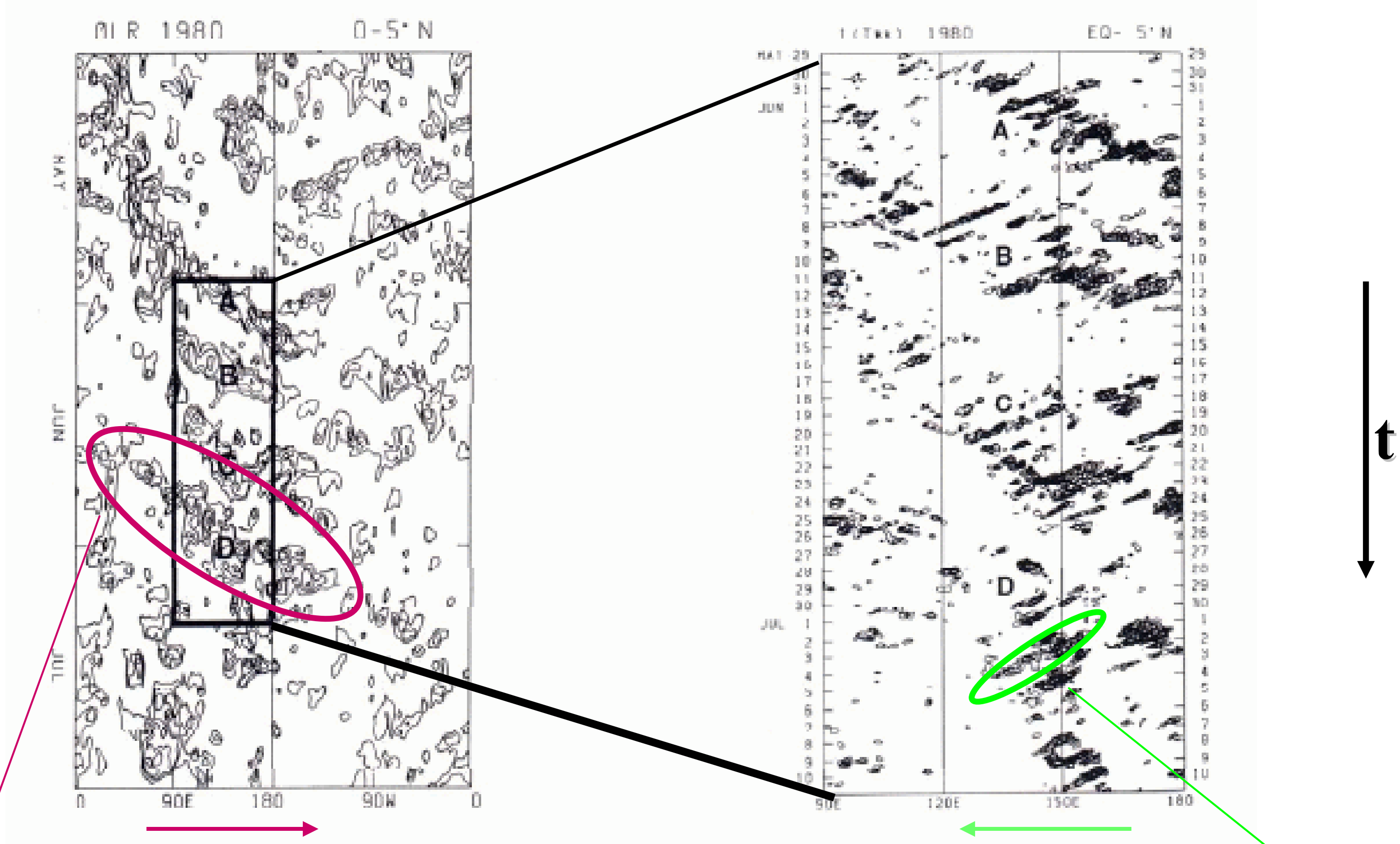
Develop of a multi-scale cellular automaton (MSCA) for organized convection that captures the subgrid-scale forcing not represented by conventional parameterizations.



- Potential to reduce systematic error by better representation of MJO (connect to ENSO)

- 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

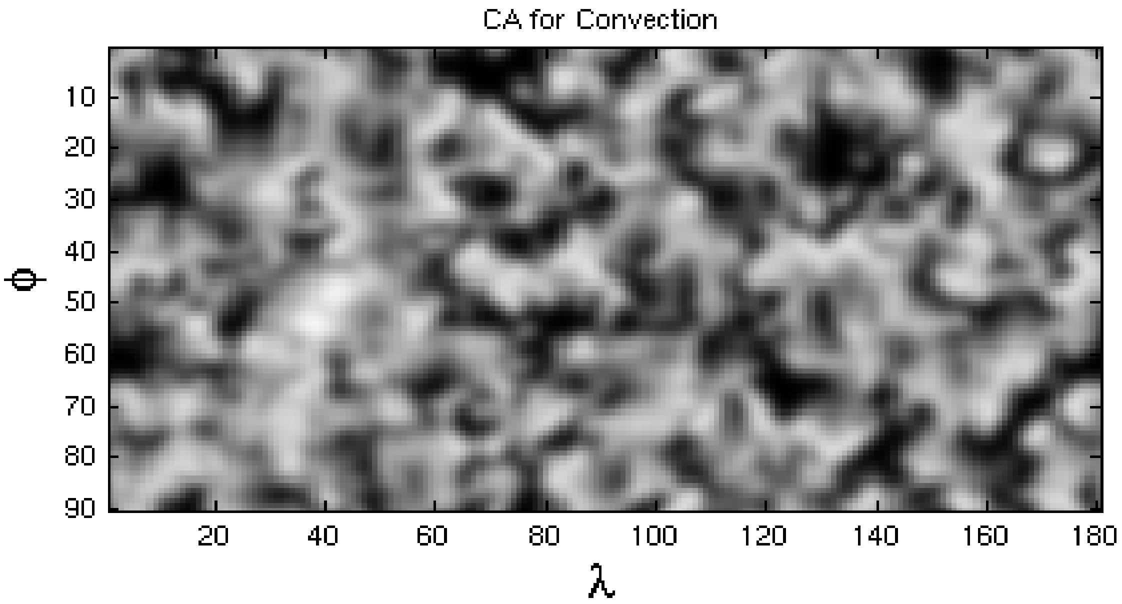
Nakazawa, 1988

Organized convection ~1000km

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

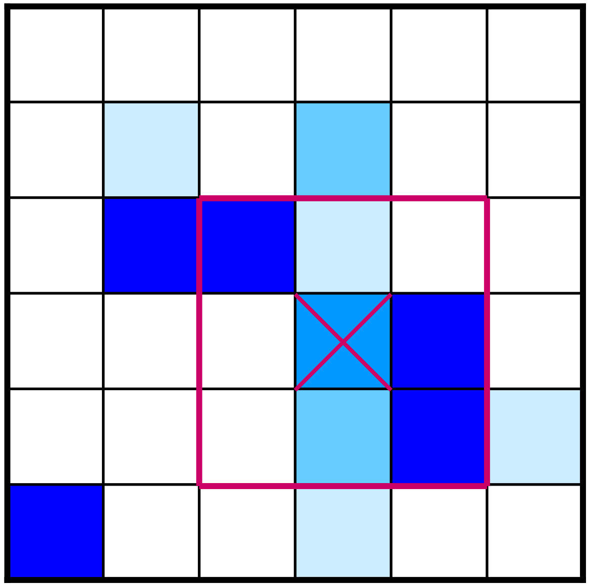
- Small-scale CA models convective cells advecting westwards
- Large-scale CA models envelope of convective cells (cloud-clusters) propagating eastward

Small-scale CA for convection



Shutts and Palmer, 2003

Rules for small-scale CA



- Fertile cell (N lives)
- Living cell (n lives)
- Dead cells

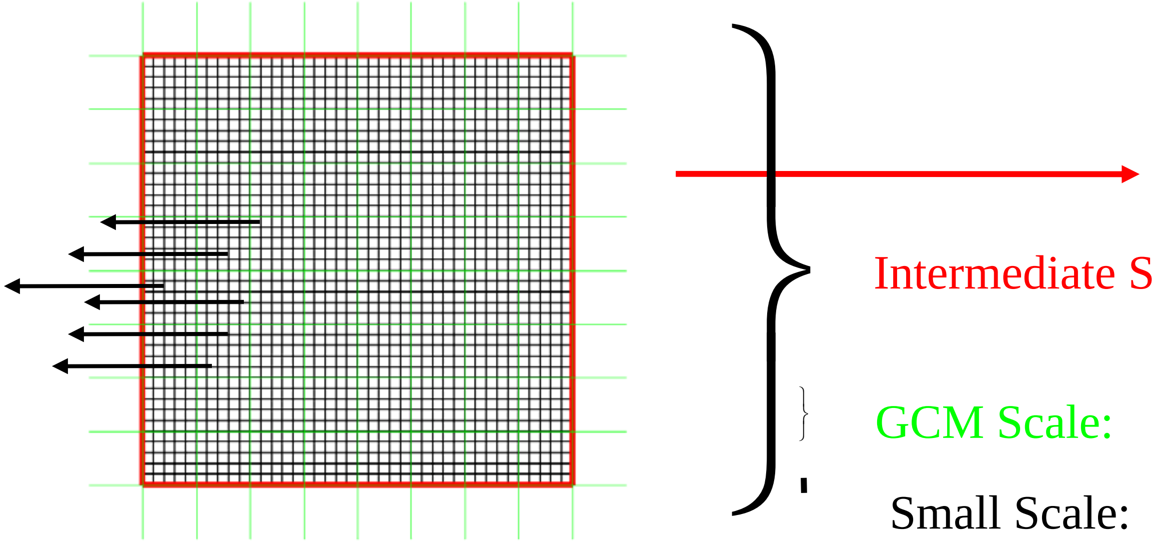
- ❖ Variant of the ‘Game of Life’
- ❖ Find the number of fertile cells in immediate neighbourhood: S
- ❖ If cell dead and S=2 or 3 => create fertile cell
- ❖ If cell alive and S=3, 4 or 5 => cell survives with same number of lives
- ❖ If cell alive and S≠3, 4 or 5=> cell loses one life
- ❖ One Parameter: Number of lives N

System has memory (=> temporal correlation)

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

Multi-scale-Cellular Automaton

- Small-scale cells evolve according to rules and propagate to the west
- Large-scale cells can be on/off (depending on CAPE) and propagate to the east
- Fertile cells in small-scale CA can only be born if large-scale cell is ‘on’

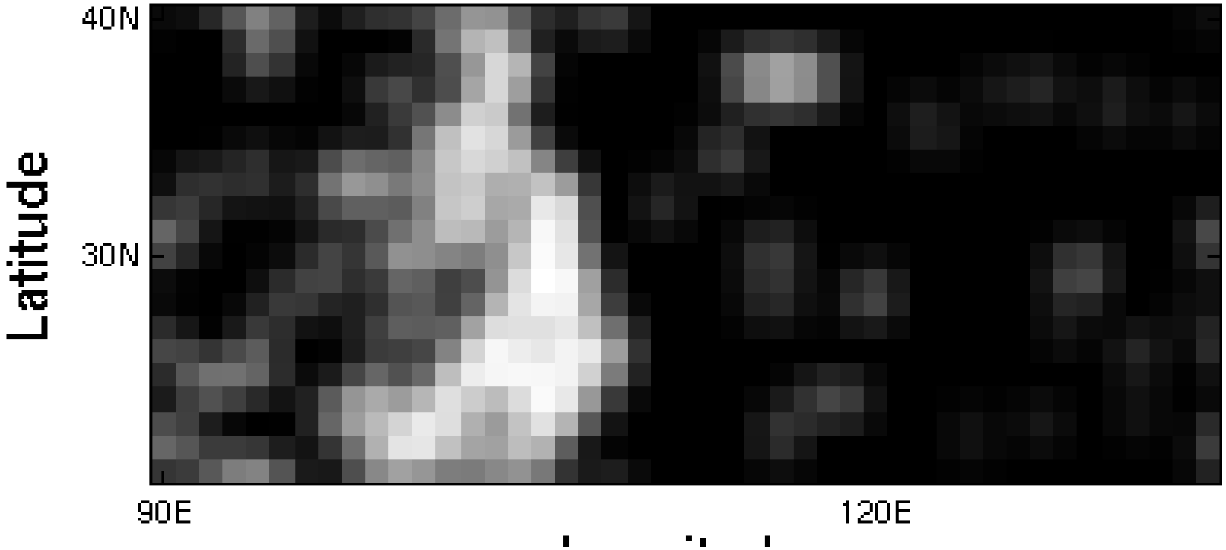


Intermediate Scale: 40° ≈ 4444 km

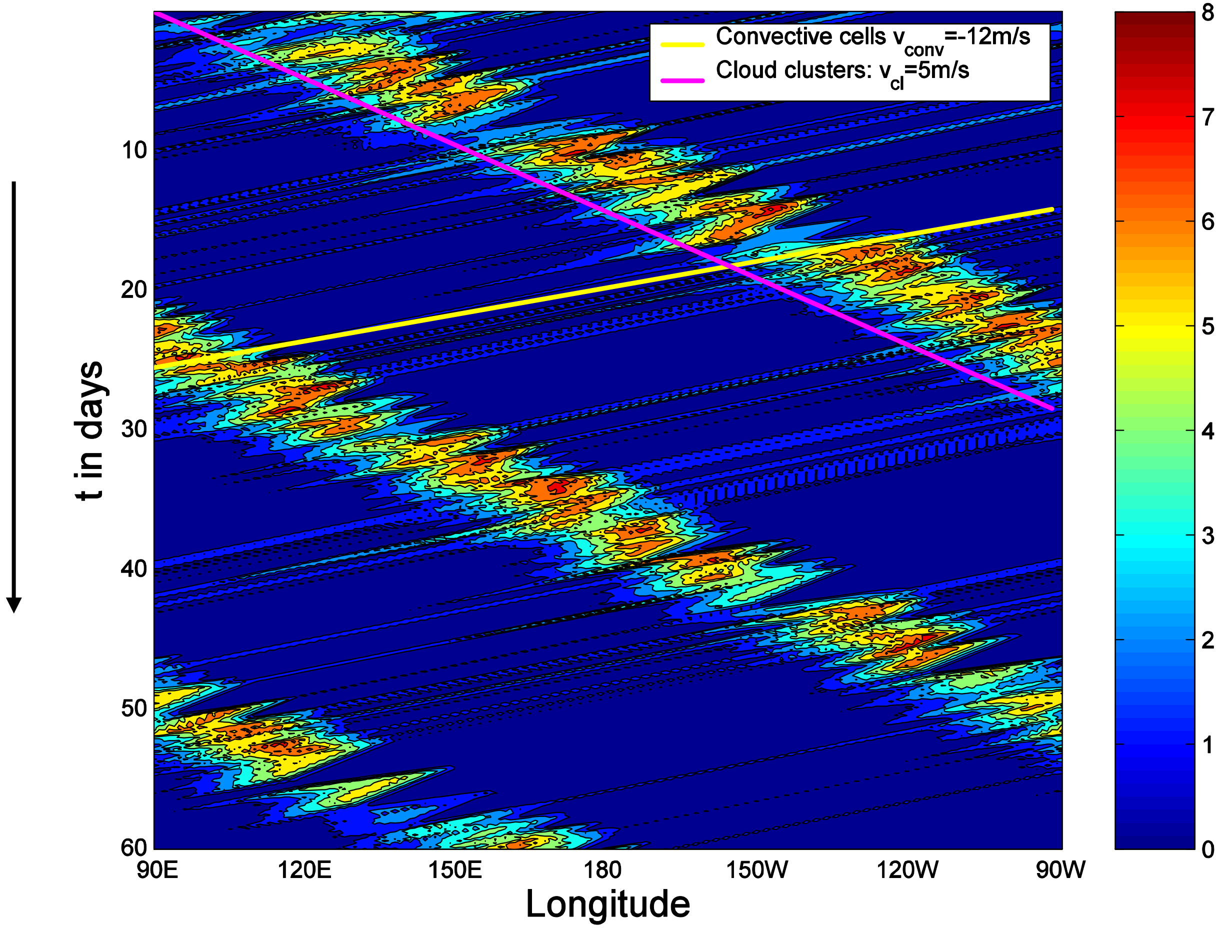
GCM Scale: 5° ≈ 560 km

Small Scale: 1° ≈ 111 km

Multi-scale-CA for Convective Organization

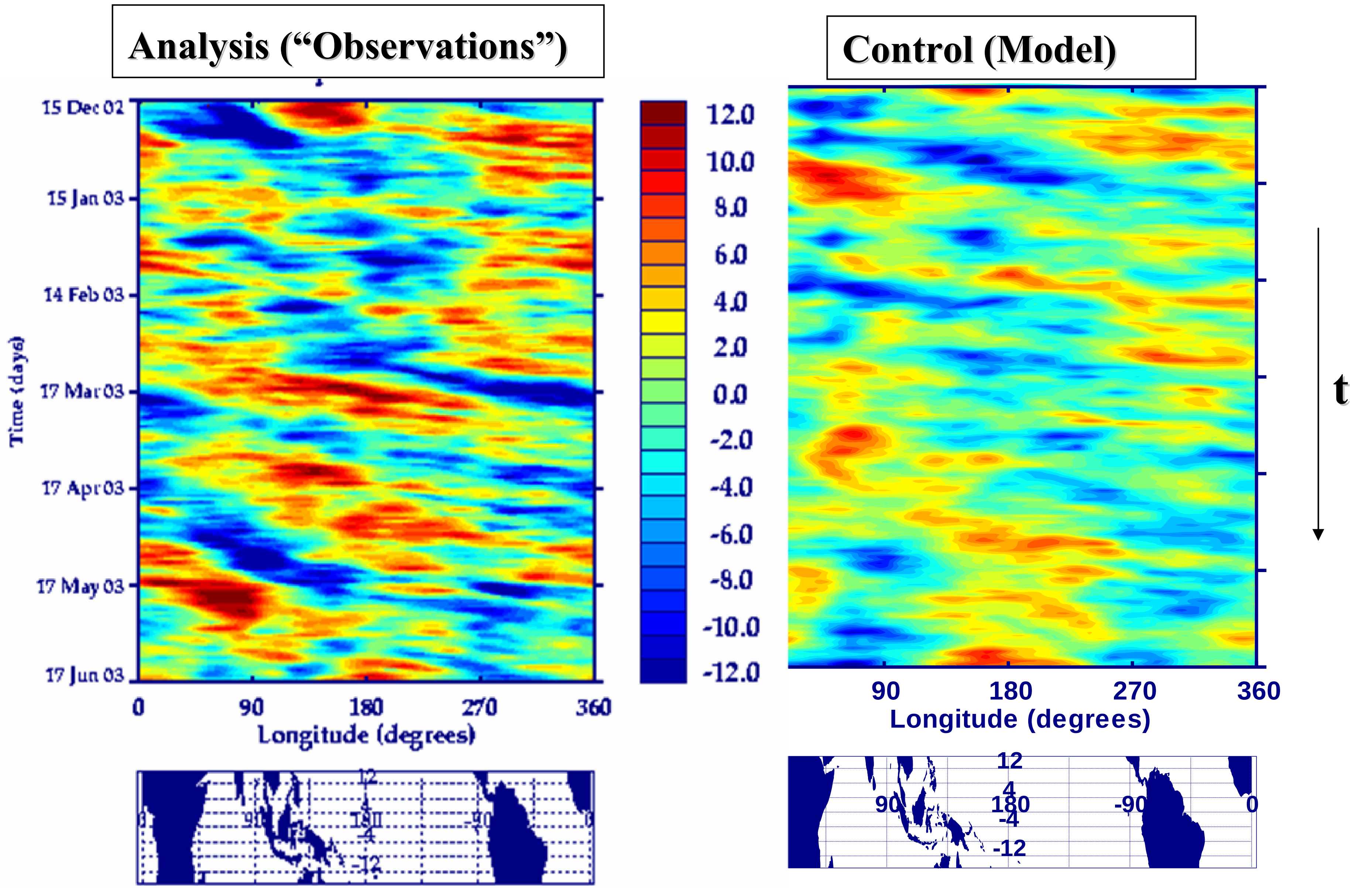


Hovmöller diagram

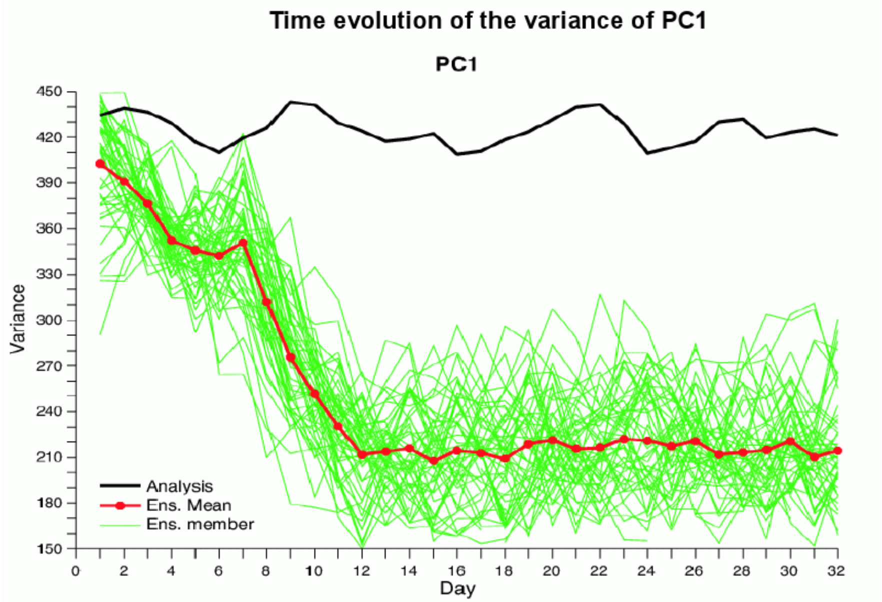


Towards a MSCA-representation of organized convection in the ECMWF model

Velocity potential (200hPa)



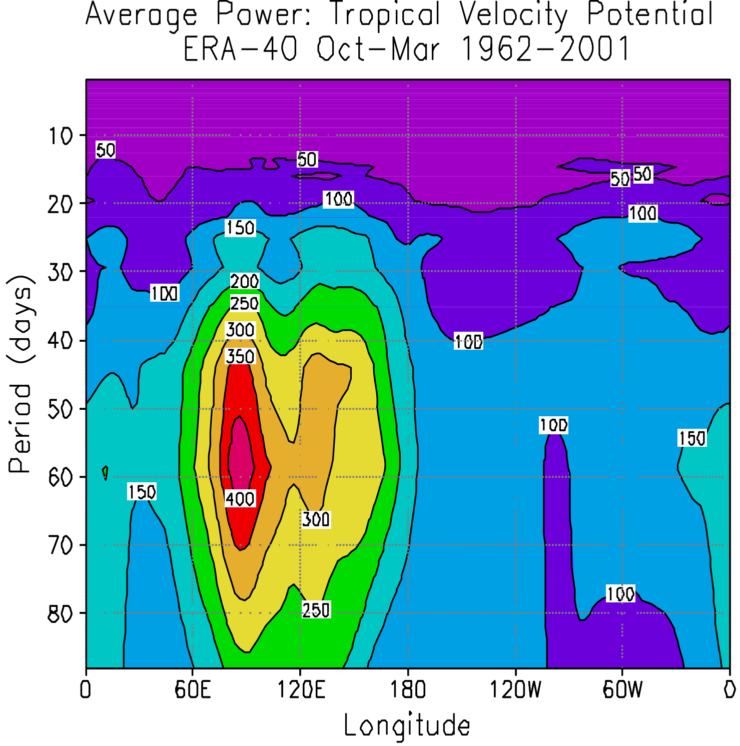
MJO in coupled ECMWF model

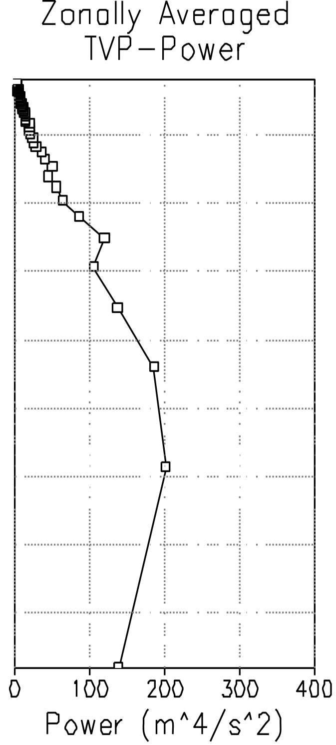


Vitart et al. 2003:

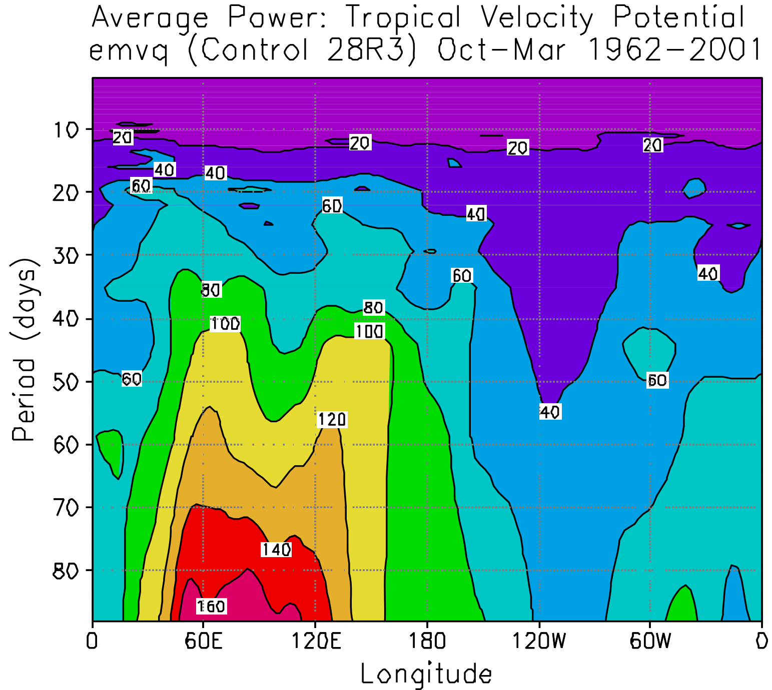
MJO variance decreases during the first 10d by as much as 50%

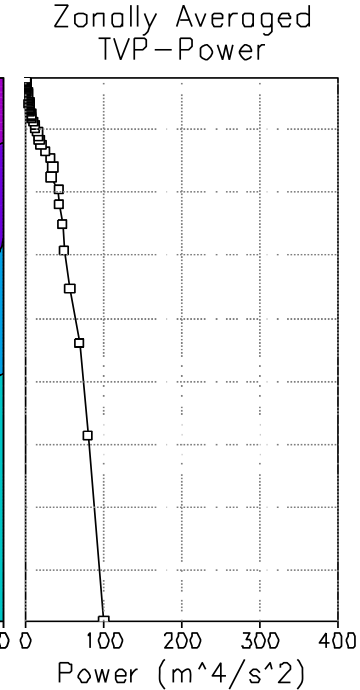
Vitart and Anderson, 2004





ERA40-Reanalysis





Model: IFS CY28R3

Stochastic superclusters

Parameterization of organized convection is introduced as streamfunction pertubation:

$$\frac{\partial \psi}{\partial t} \propto f(\Psi(\boldsymbol{\lambda}, \boldsymbol{\varphi}, t), z) * CAPE\ (\lambda, \phi, t)$$

Streamfunction forcing

Horizontal and vertical structure function

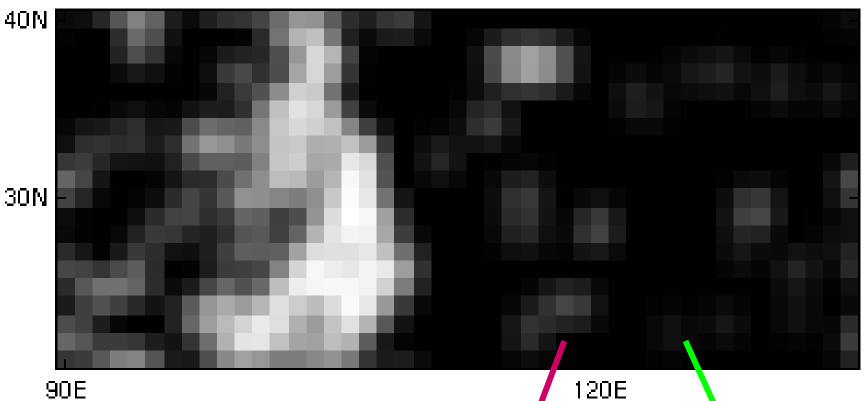
Quasi-random noise from CA (smoothed, coarse-grained)

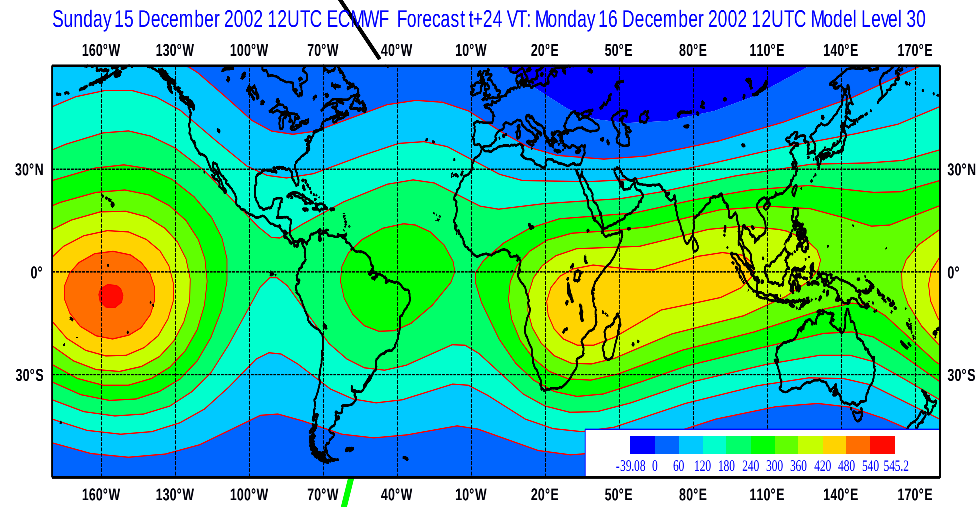
Convective available potential energy

Stochastic super clusters as part of organized convection (super-gridscale)

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

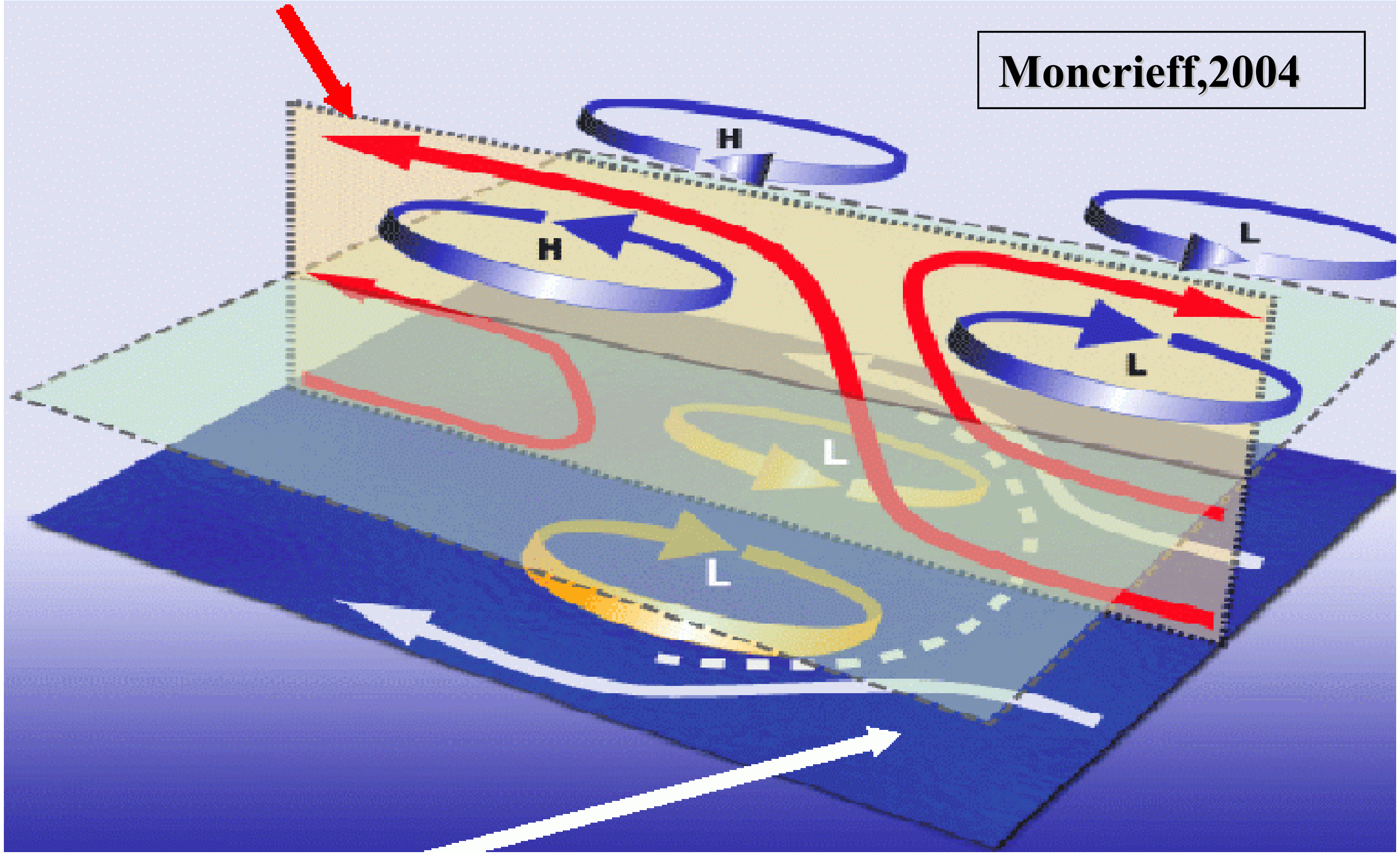
Cartoon





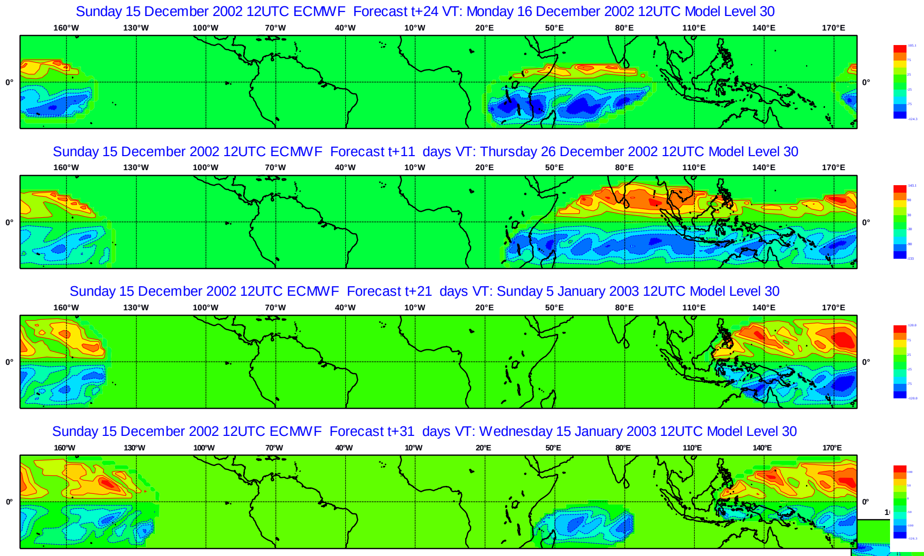
Non-local, quasi-random, state-dependent

Archetype for organized convection



Horizontal and vertical tilt!

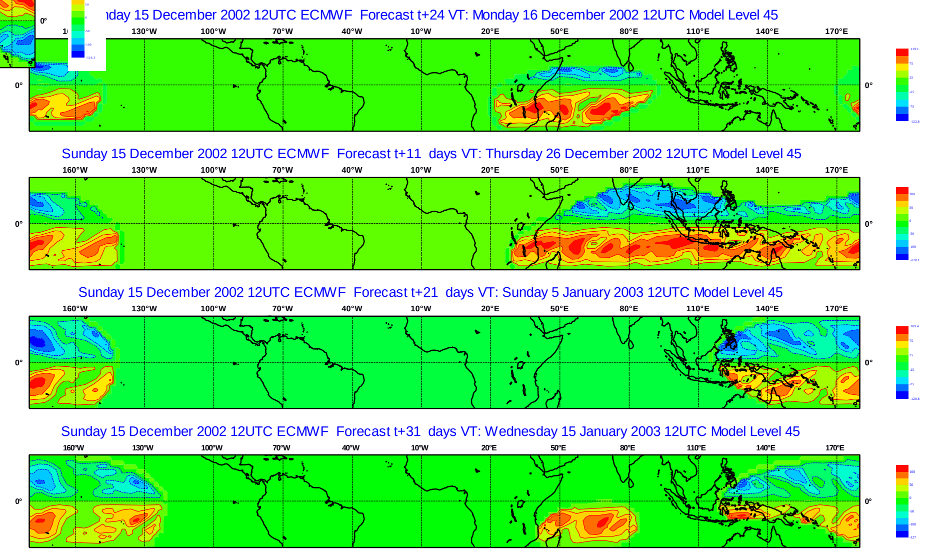
Streamfunction forcing



250hPa

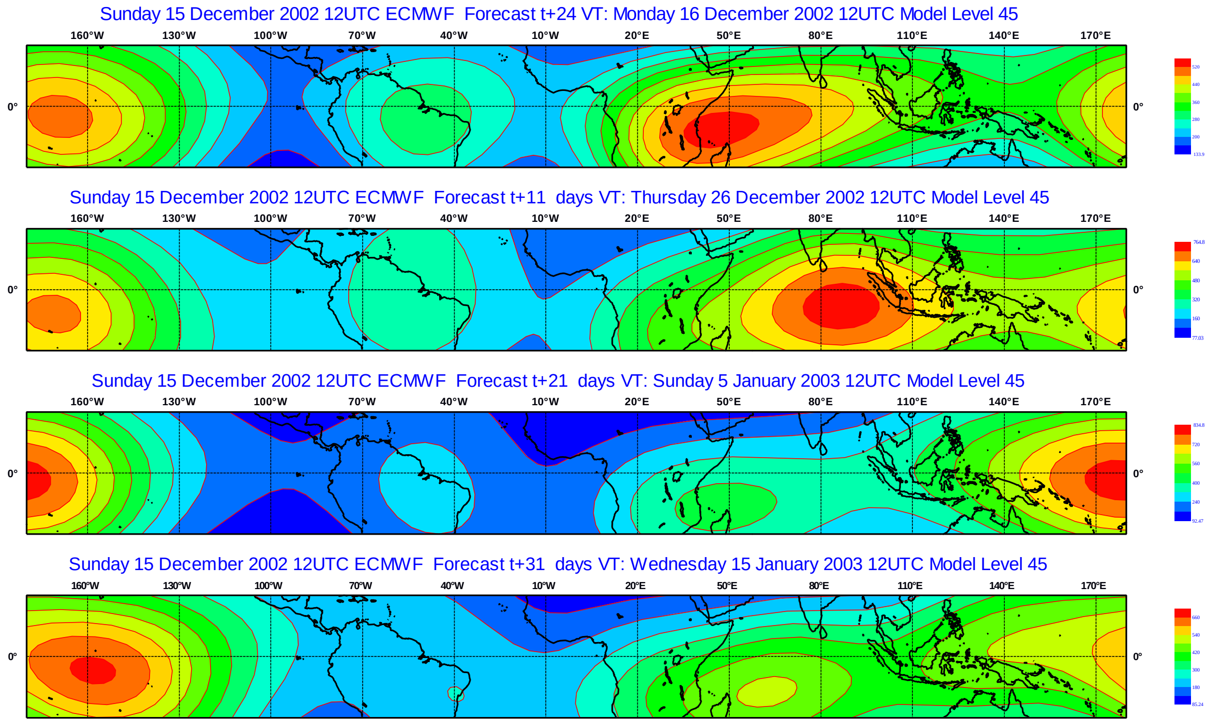
30d

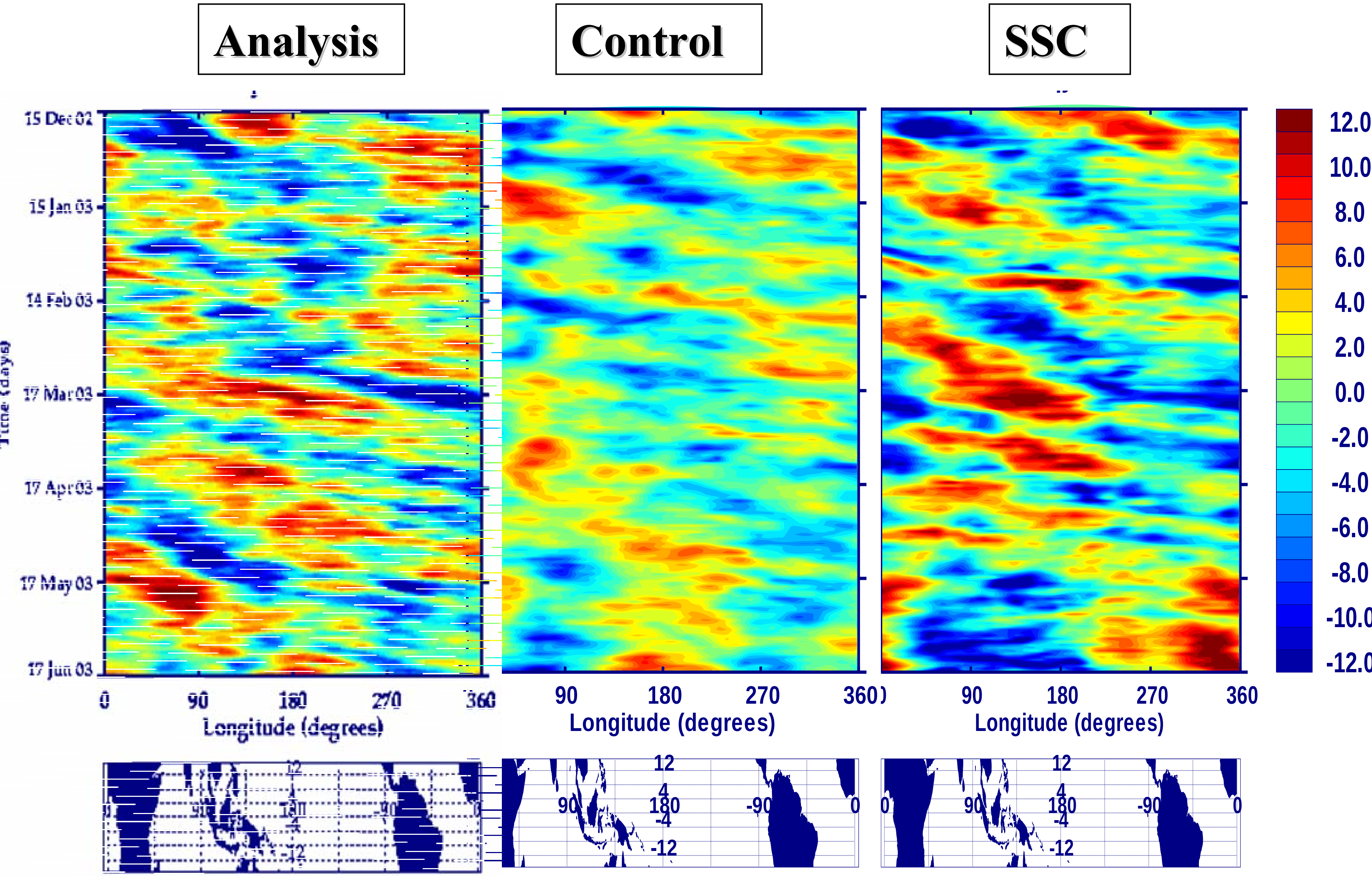
750hPa

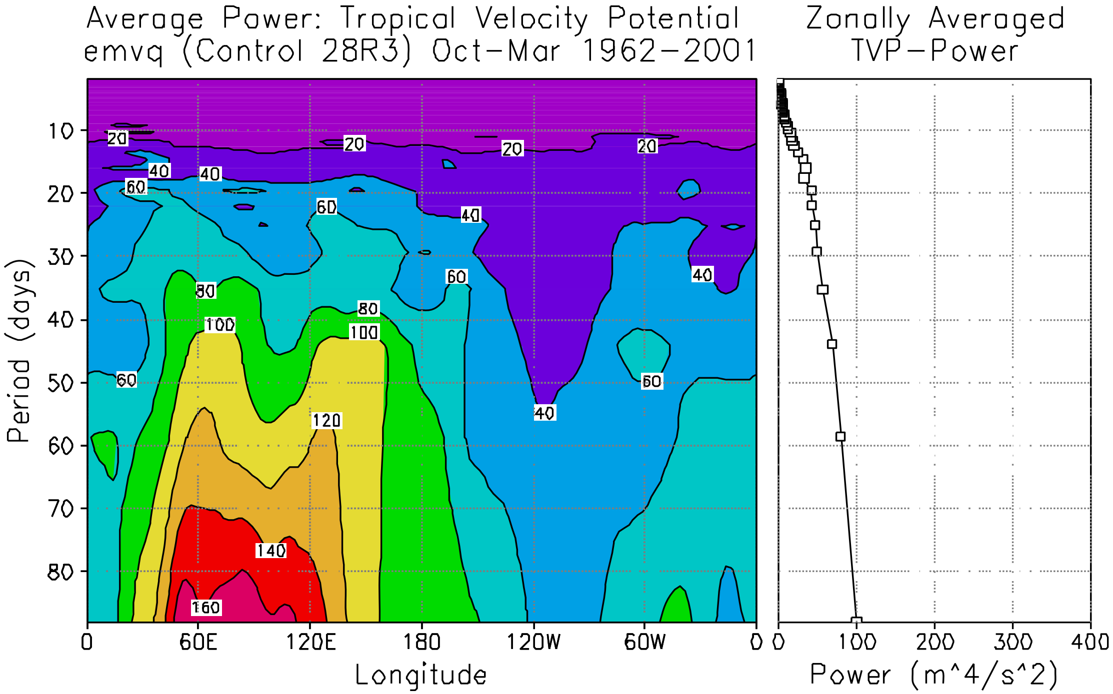


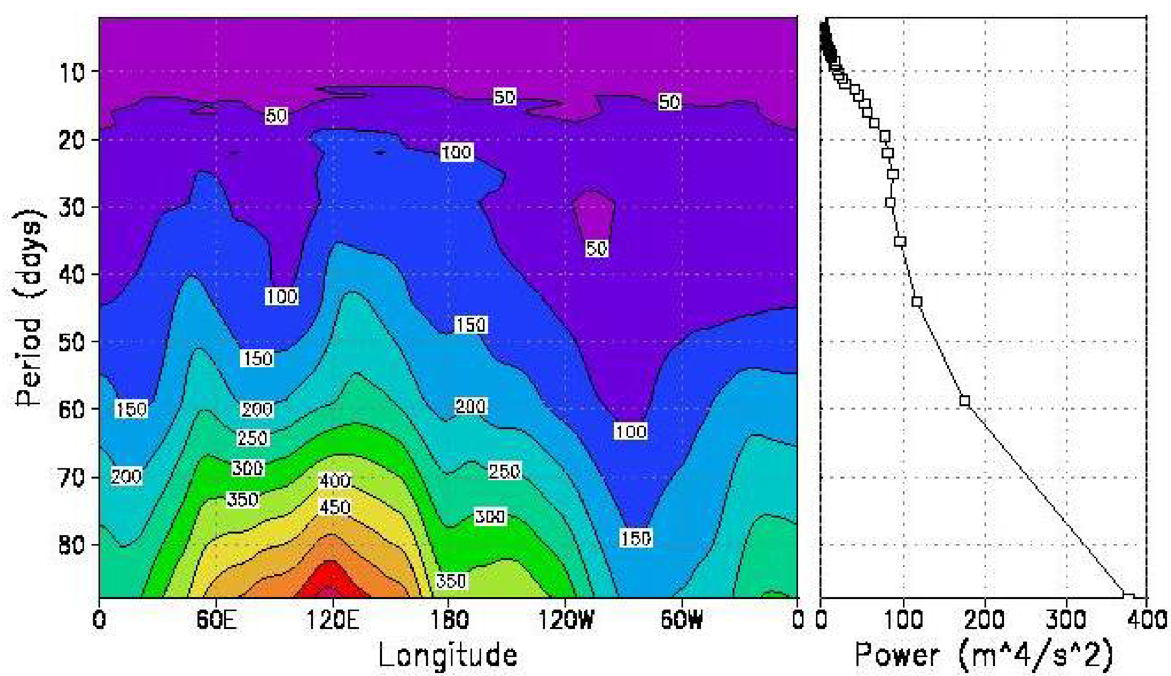
Smoothed divergence

SSC

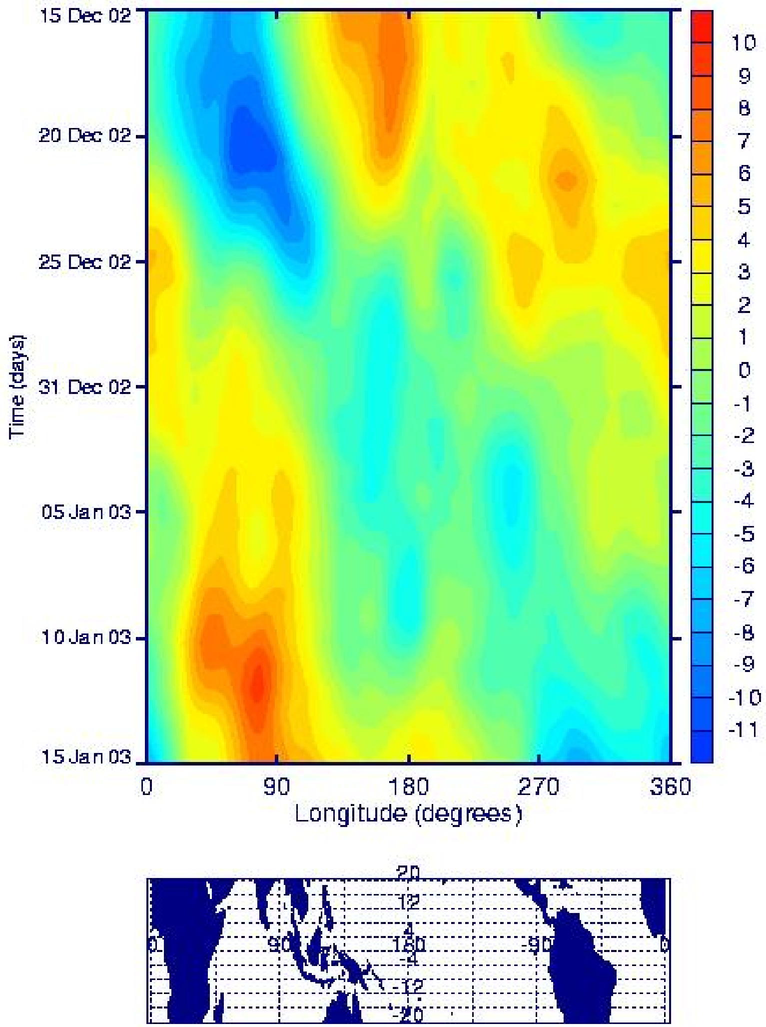


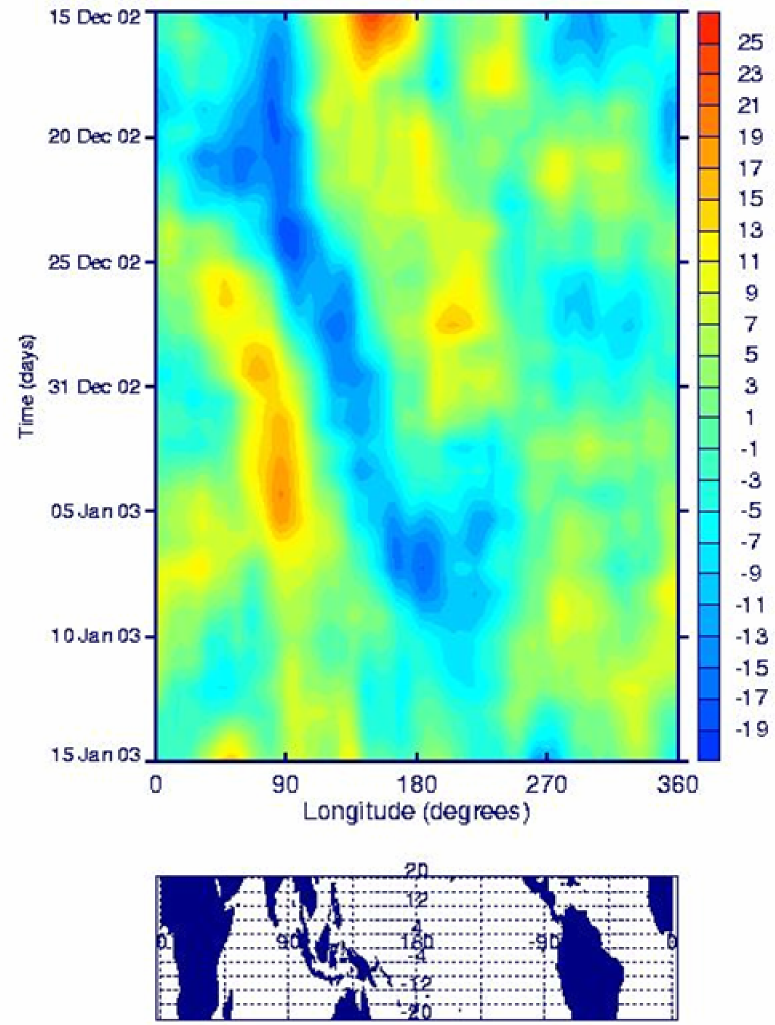

Analysis
Control
SSC
15 Dec 02
15 Jan 03
14 Feb 03
17 Mar 03
17 Apr 03
17 May 03
17 Jun 03
Time (days)
0
90
180
270
360
Longitude (degrees)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
12
4
-4
-12
-90

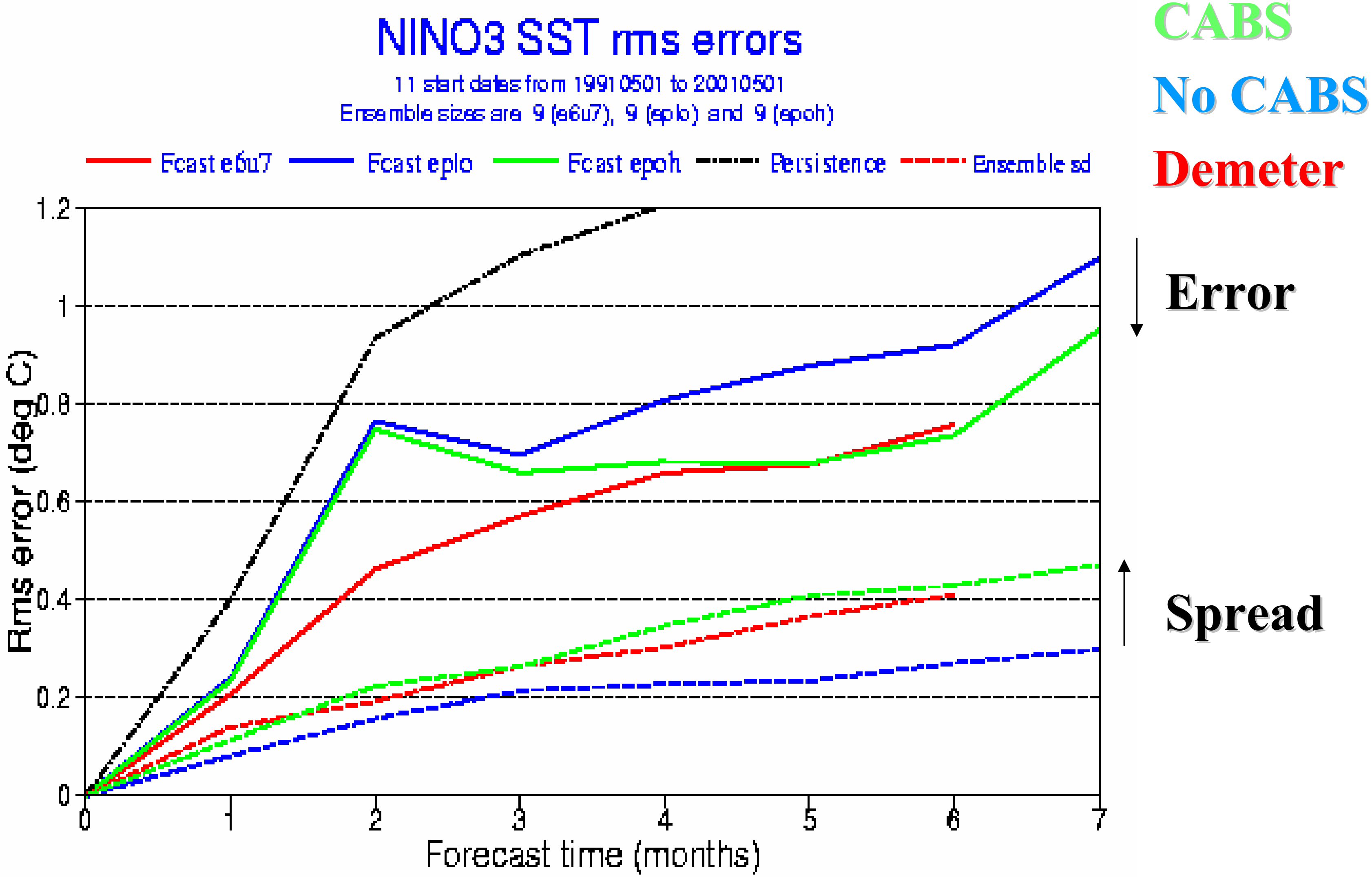

Average Power: Tropical Velocity Potential
emvq (Control 28R3) Oct–Mar 1962–2001
Zonally Averaged
TVP–Power
Period (days)
Longitude
Power (m^4/s^2)
0
60E
120E
180
120W
60W
0
100
200
300
400


Period (days)
Longitude
Power (m^4/s^2)
0
60E
120E
180
120W
60W
0
100
200
300
400

Day-5 forecasts

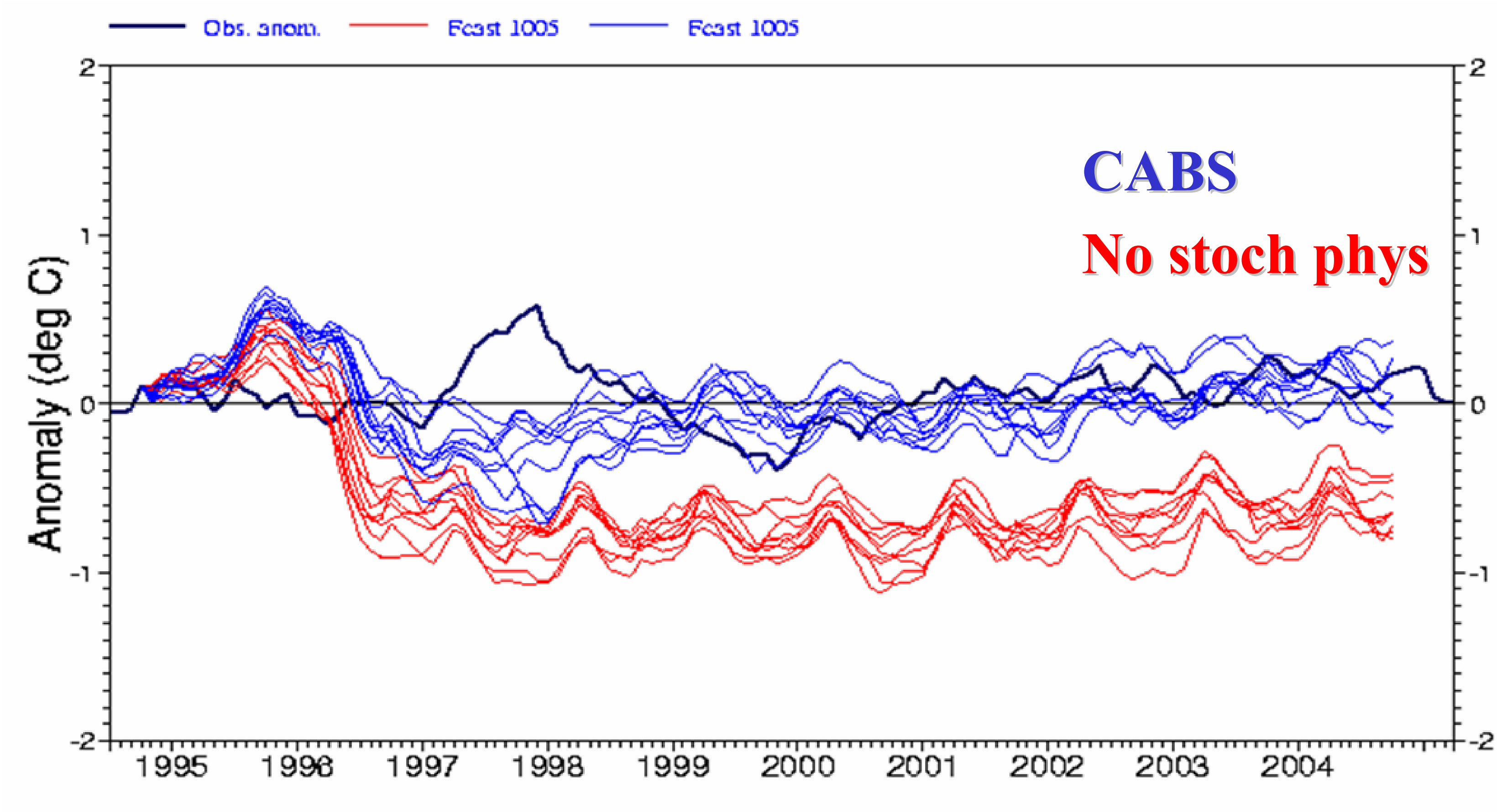






Courtesy Antje Weisheimer, Paco Doblas-Reyes

CABS improves SST anomalies in tropical Pacific



Courtesy Antje Weisheimer, Paco Doblas-Reyes

Open questions

- Can organized convection be fully represented by local parameterizations?
- Should super-clusters be resolved explicitely rather than represented stochastically?
- System self-organizing on the subgrid-scale or is organization coming through the large-scales?