Blurring the boundary between dynamics and physics in weather and climate models

Tim Palmer
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$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}.\nabla\right)\mathbf{u}=\rho\mathbf{g}-\nabla p+\nu\,\nabla^2\mathbf{u}$$

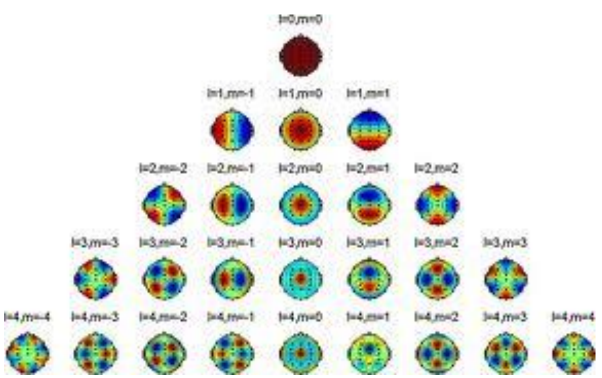
The Canonical Numerical Ansatz

Resolved scales ←

→ Unresolved scales

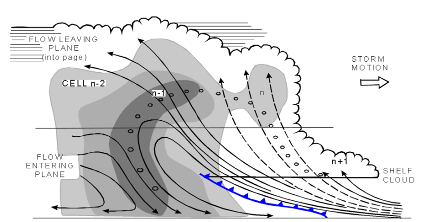
Dynamical Core

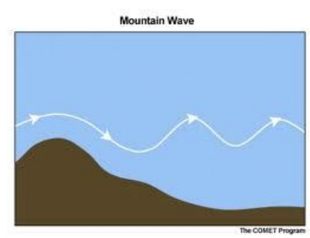
$$z=\sum_{m}^{\infty}\sum_{l} z_{ml}e^{im\lambda}P_l^m(\phi)$$



Parametrisations

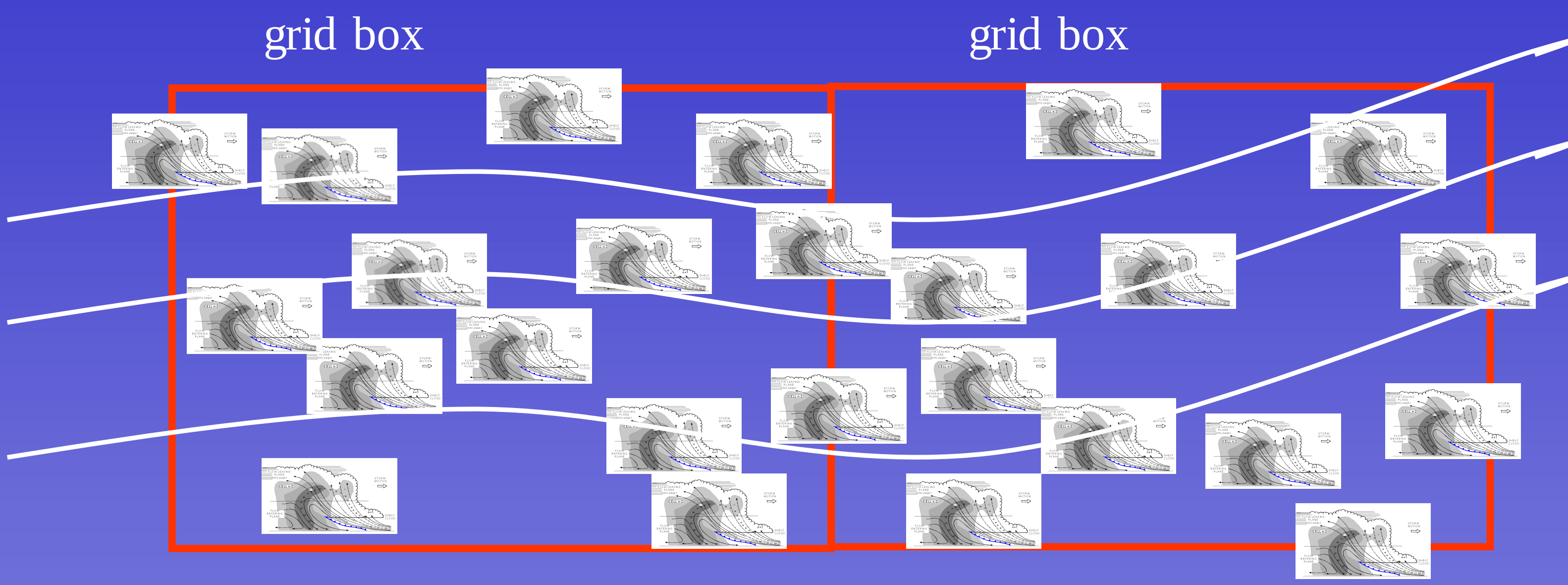
$$P\left(X_{\mathrm{Tr}};a\right)$$



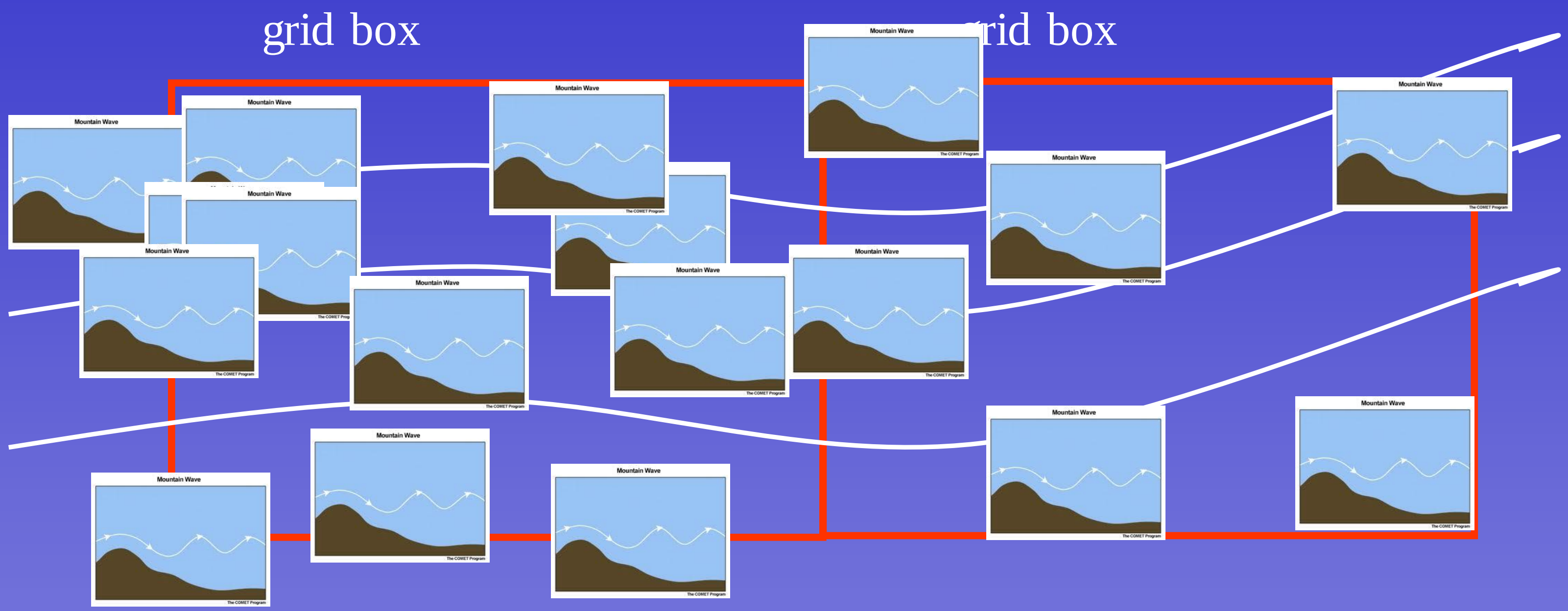


$$D=P$$

… ie the world looks like this

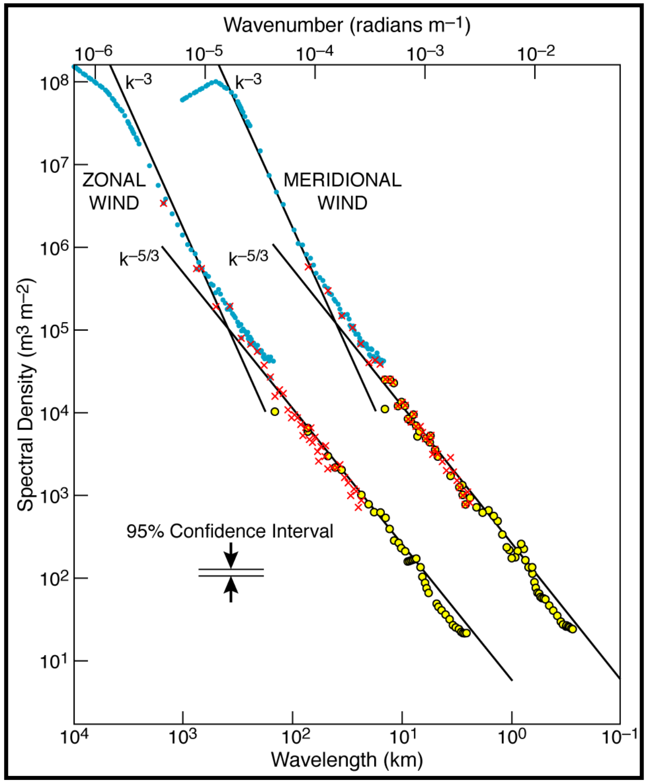


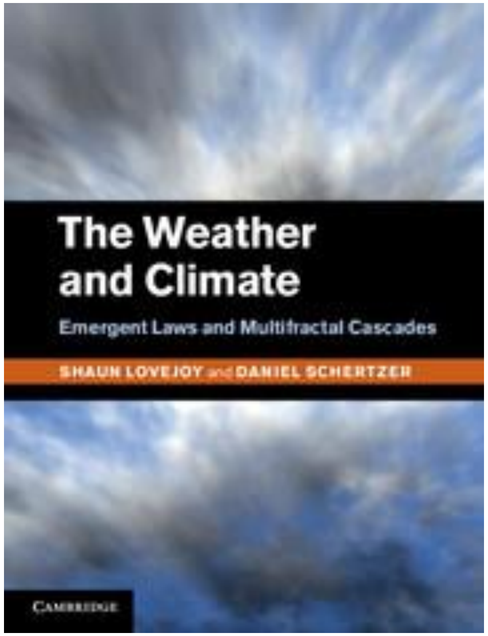
… or this



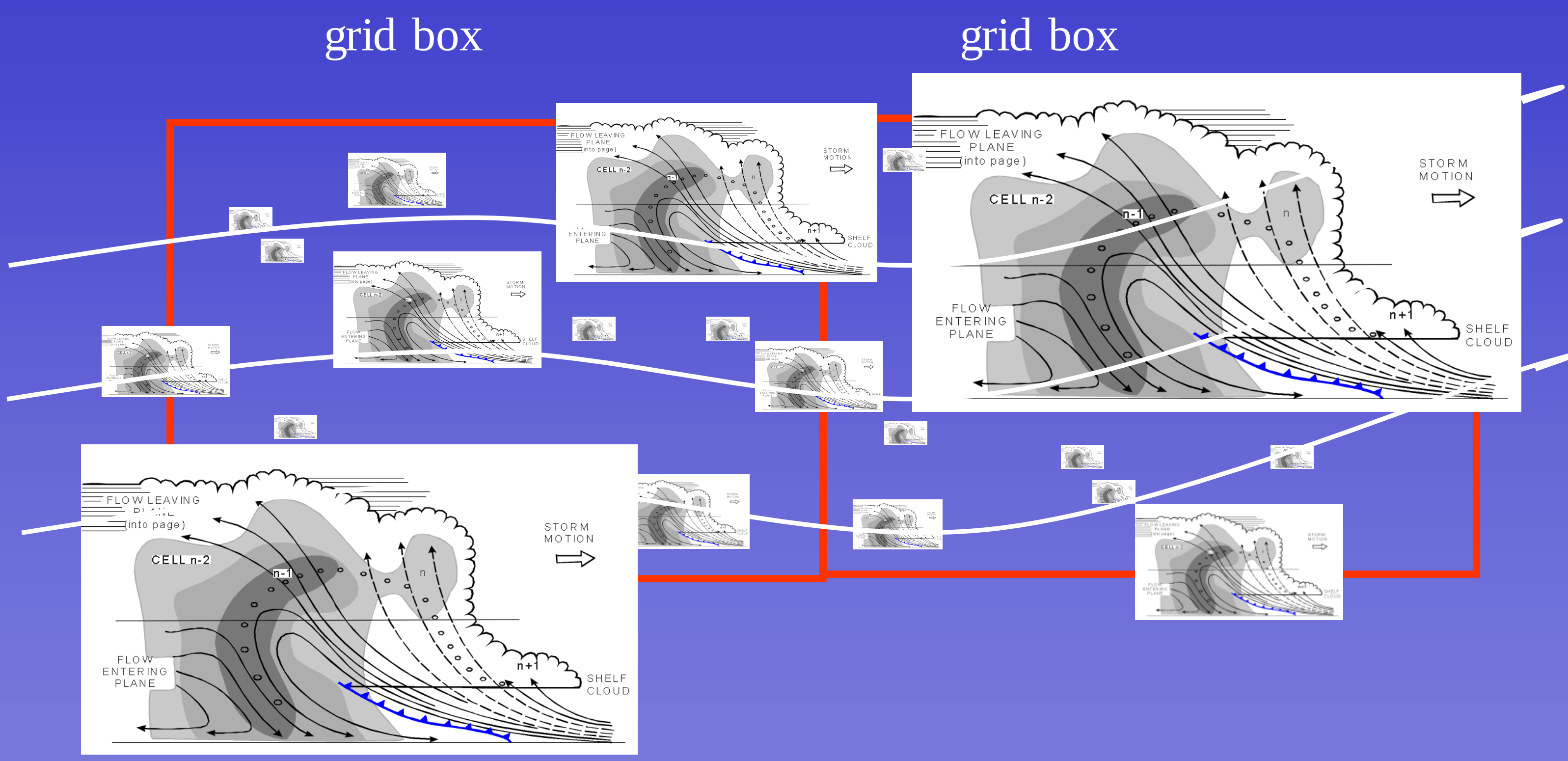
… then the Canonical Numerical Ansatz for solving the underlying PDEs would be well posed

But reality is more like this… (Nastrom and Gage, 1985)!





The reality of the situation

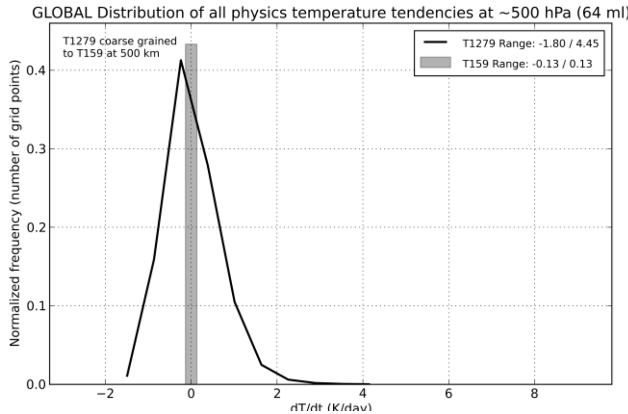


cannot be described by a simple deterministic formula

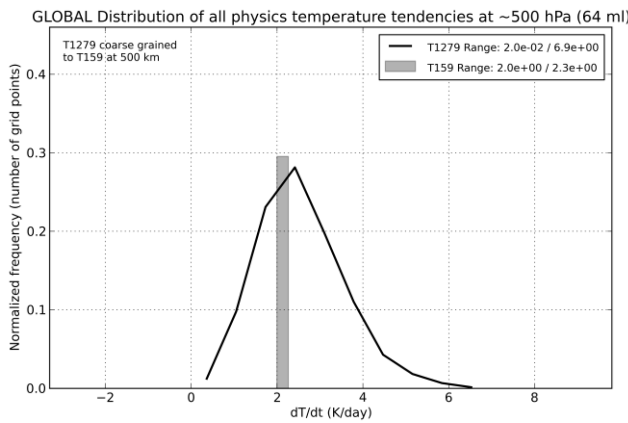
Coarse-graining

(Shutts and Palmer, 2007)

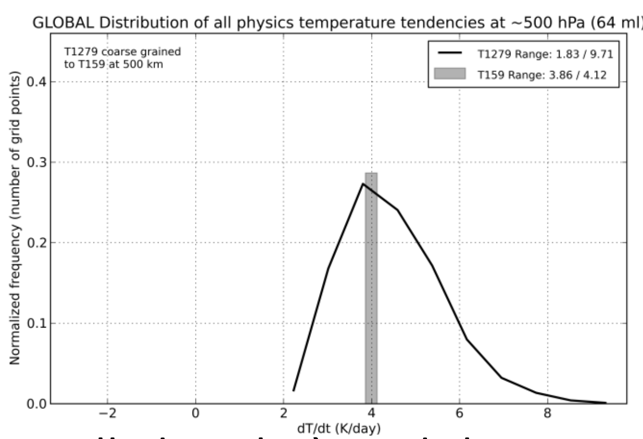
Small tendency



Medium tendency



Large tendency



Callado-Palarès and Shutts, 2013.

Assume T1279 (16km) model = "truth".

Assume T159 coarse-grain "model" grid.

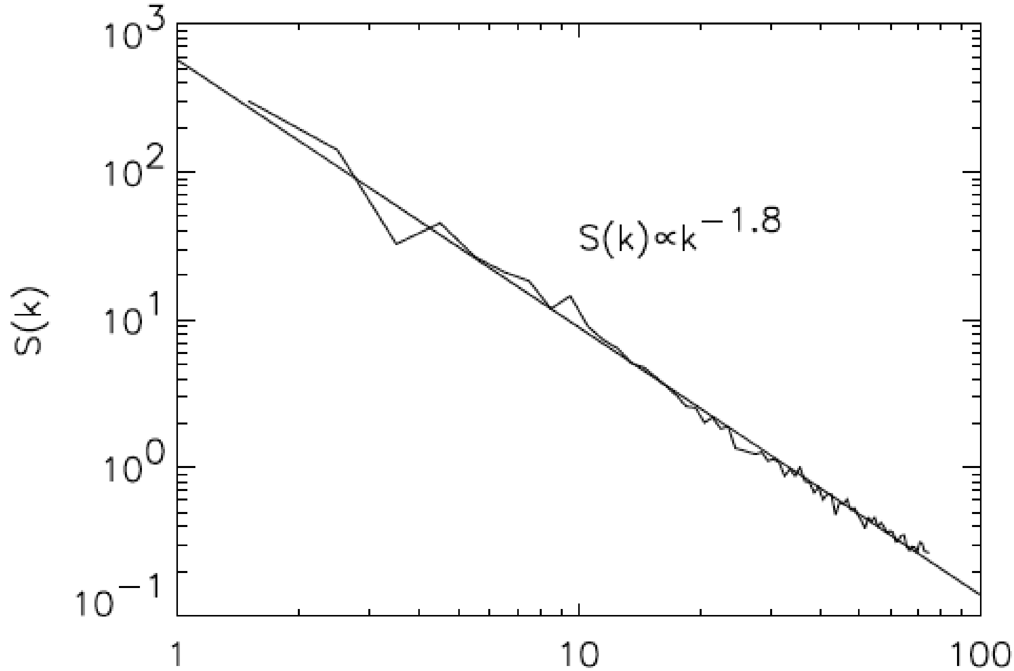
Bar= Subset of T159 total temperature parametrisation tendencies driven by T1279 coarse-grain fields.

Curve= Corresponding "true" sub-T159-scale tendency conditioned on T1279 coarse-grain averaged fields.

Ie when the parametrisations think the sub-grid pdf is a thin hat function, the reality is a much broader pdf.

The standard deviation increases with parametrised tendency – consistent with multiplicative noise stochastic schemes.

Earth’s Topography has Power Law Structure Too



Why is topography fractal?

Jon D. Pelletier
Department of Geological Sciences, Snee Hall, Cornell University, Ithaca, New York

Figure 4. Average power spectrum S as a function of wave number k for one dimensional transects of the surface generated with the BSOS model. A least square fit to the logarithms of the ordinate and abscissa yield a slope of -1.81 indicating that $S(k) \propto k^{-1.81}$.

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}.\nabla\right)\mathbf{u} = \rho\mathbf{g} - \nabla p + \nu\,\nabla^2\mathbf{u}$$

← Resolved scales

Unresolved scales →

Dynamical Core

$$\zeta = \sum_{m}\sum_{l}^{\infty} \zeta_{ml} e^{im\lambda} P_l^m(\phi)$$

- Discretisation errors
- Convergence errors
- Round-off errors

Parametrisations

$$P\left(X_{\mathrm{Tr}};\alpha\right)$$

- Errors in the functional form of P
- Errors in the assumed values of α

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}.\nabla\right)\mathbf{u}=\rho\mathbf{g}-\nabla p+\nu\ \nabla^2\mathbf{u}$$

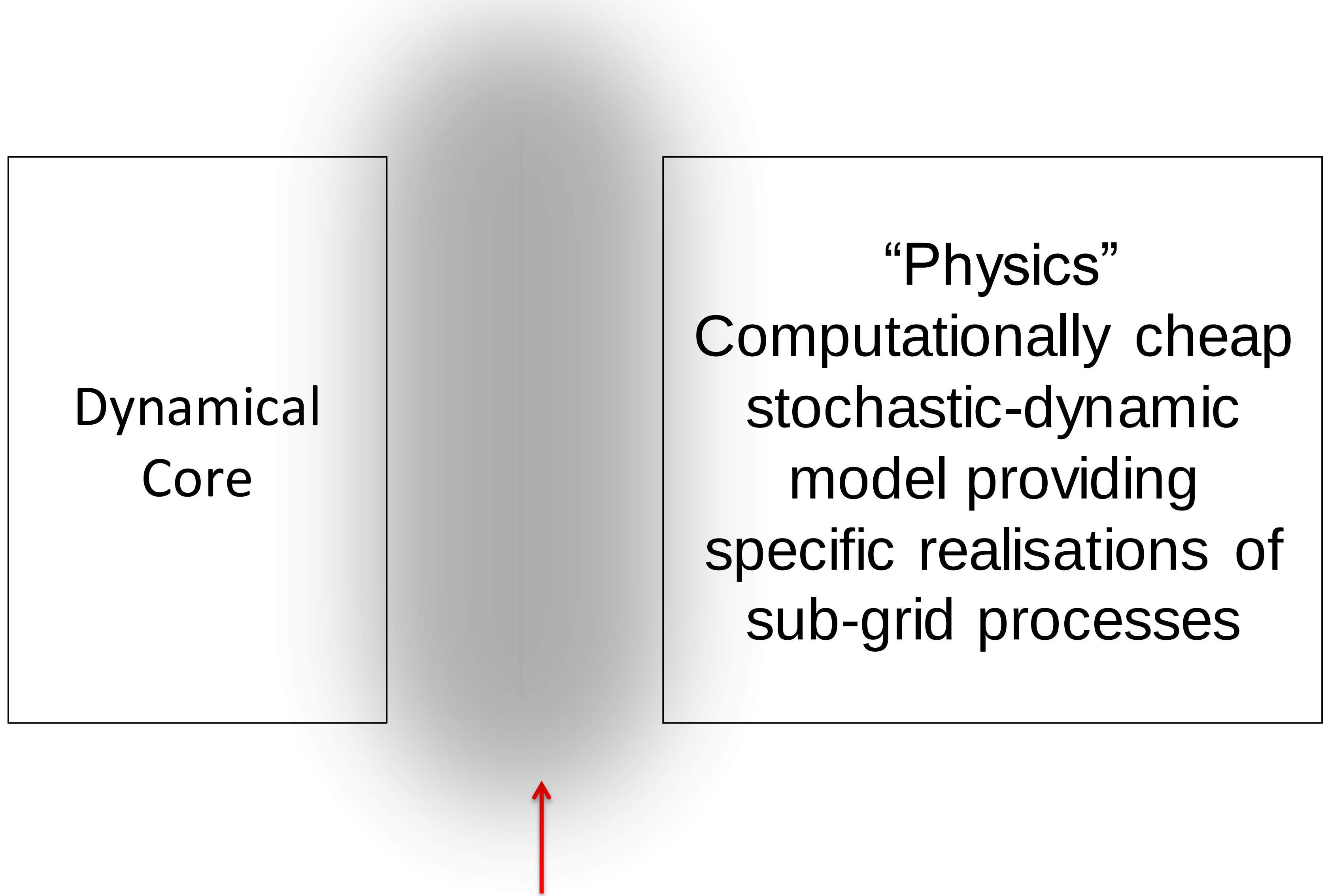
← Resolved scales

Truncation Scale (7 to 8 orders of magnitude above viscous scale!)

Unresolved scales →

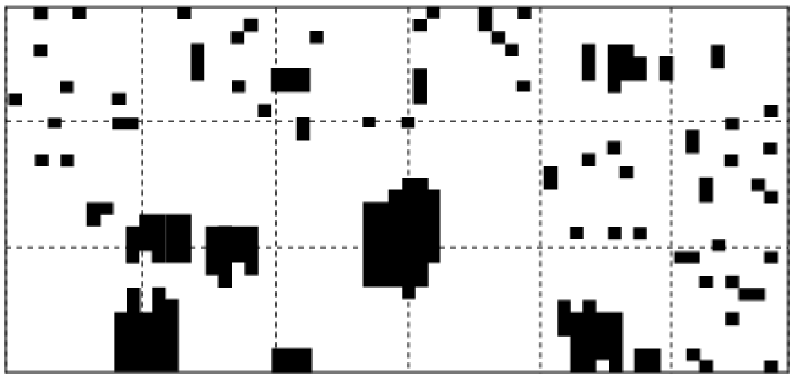
Dynamical Core

Parametrisations



Not such a "brick wall" interface. Only makes sense in an ensemble context. But forecasts should only made in an ensemble context in any case!

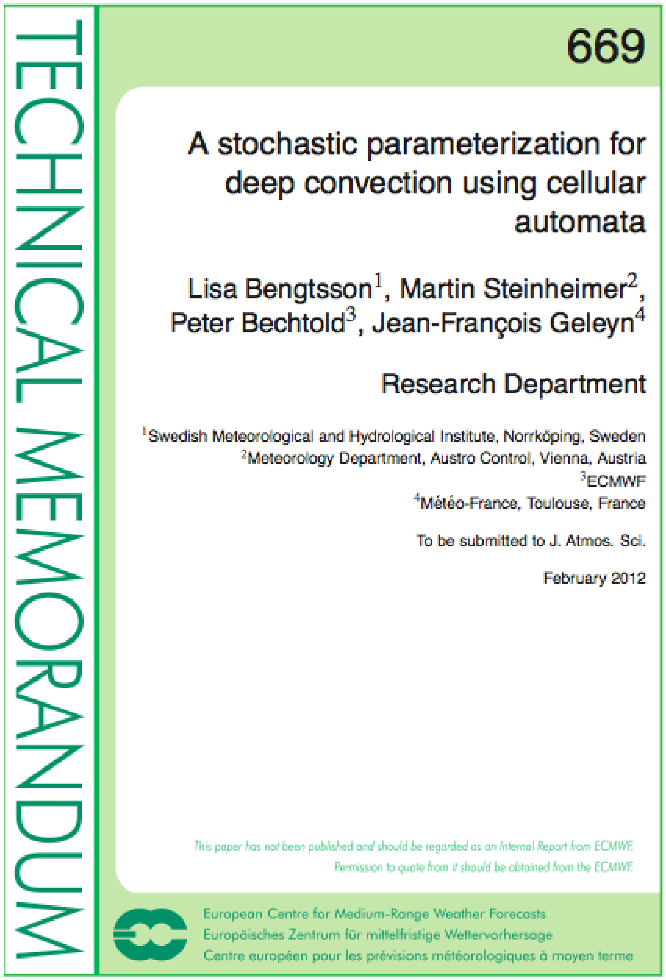
Stochastic Cellular Automaton for Convection



Palmer 1997

Probability of an "on" cell proportional to CAPE and number of adjacent "on" cells – "on" cells feedback to the resolved flow

Stochastic Cellular Automata



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A stochastic parameterization for deep convection using cellular automata

Lisa Bengtsson[1], Martin Steinheimer[2], Peter Bechtold[3], Jean-François Geleyn[4]

Research Department

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[2]Meteorology Department, Austro Control, Vienna, Austria
[3]ECMWF
[4]Météo-France, Toulouse, France

To be submitted to J. Atmos. Sci.

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European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

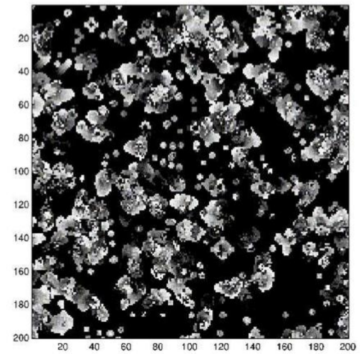


Figure 1: Example of a Cellular Automaton following the rules of Conway's game of life

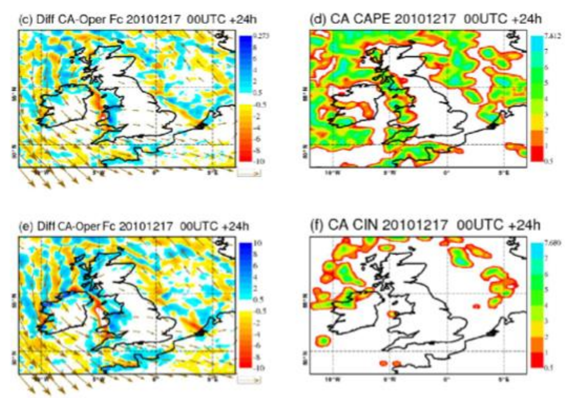
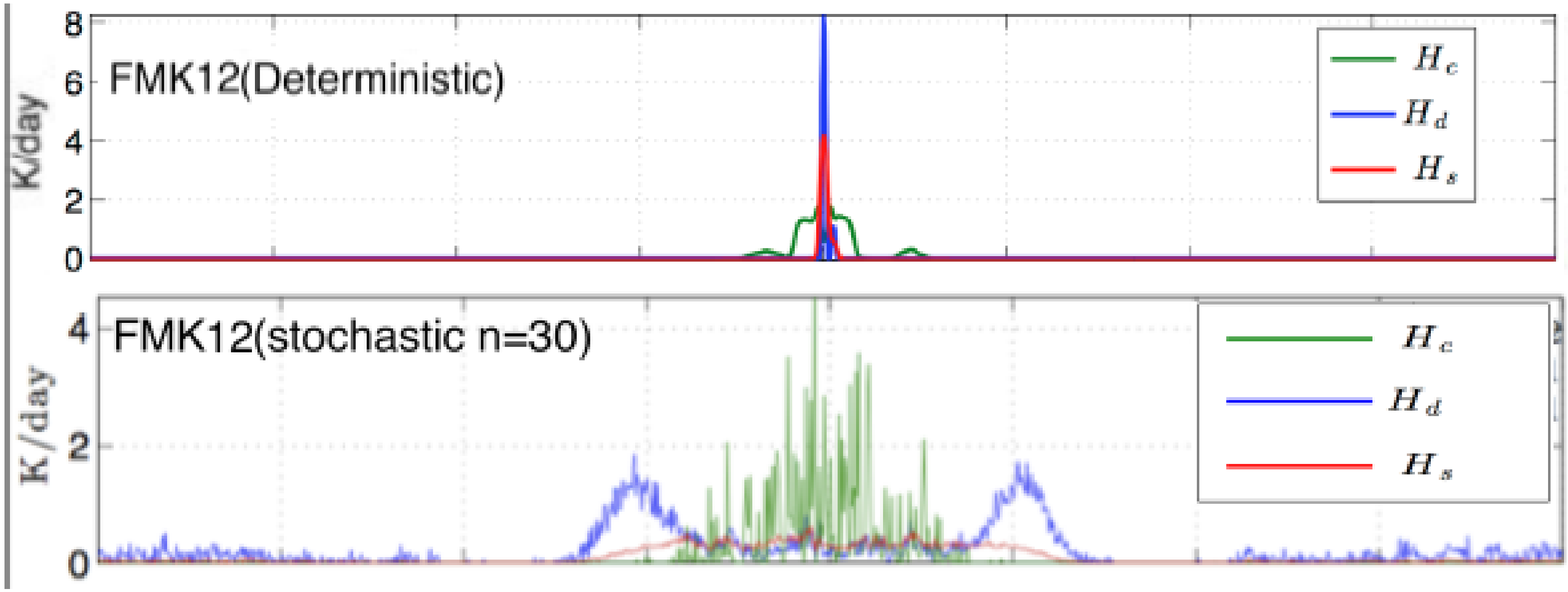


Figure 5: 24 hour accumulated precipitation (mm) on 17 December 2010 over the British Isles and Western Europe as observed by the OPERA radar network (a), the operational 24 hour deterministic IFS forecast at spectral resolution T1279=16 km (b), difference (mm) between the operational forecast and forecast using CA with CAPE seeding (c), the corresponding CA pattern for CAPE seeding (number of lives) (d), difference (mm) between the operational forecast and forecast using CA with CIN seeding (e), and corresponding CA pattern for CIN seeding (number of lives) (f)

Stochastic and Deterministic Multicloud parameterizations for tropical convection

Yevgeniy Frenkel · Andrew J. Majda · Boulalem Khouider



Stochastic multicloud model based on a Markov chain lattice model. An extension of an Ising-type spin-flip model used for phase transitions in material science

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Stochastic Parametrization and Model Uncertainty

Palmer, T.N., R. Buizza, F. Doblas-Reyes, T. Jung, M. Leutbecher, G.J. Shutts, M. Steinheimer, A. Weisheimer

Research Department

October 8, 2009

This paper has not been published and should be regarded as an Internal Report from ECMWF. Permission to quote from it should be obtained from the ECMWF.

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

- Multiplicative Noise – (1+ε)P
- Operational since 1999
- Improved forecast reliability
- Reduced systematic error

Originally based on CA pattern generators, now spectral.

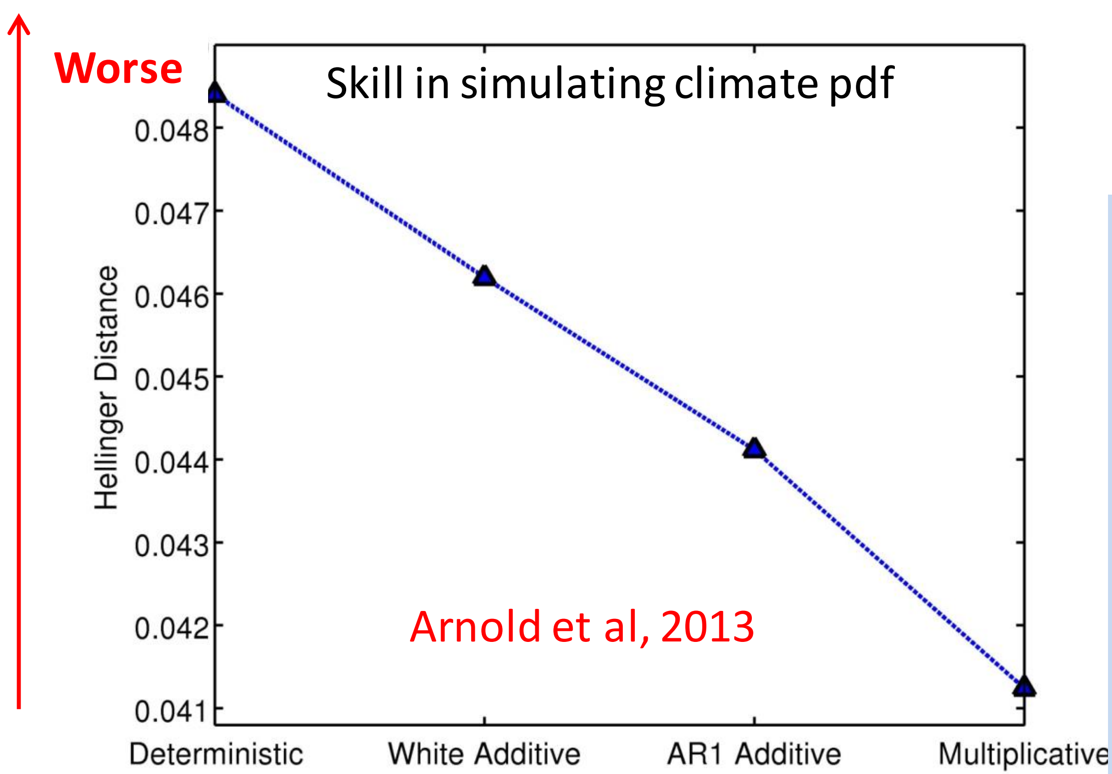
Experiments with the Lorenz '96 System (i)

$$\frac{dX_k}{dt} = -X_{k-1}\left(X_{k-2} - X_{k+1}\right) - X_k + F - \cancel{\frac{hc}{b}\sum_{j=J(k-1)+k}^{kJ} Y_j}$$

$$\frac{dY_j}{dt} = -cbY_{j+1}\left(Y_{j+2} - Y_{j-1}\right) - cY_j + \frac{hc}{b} X_{\text{int}[(j-1)/J+1]}$$

Assume Y unresolved

Approximate sub-grid tendency by U



Deterministic: $U = U_{det}$

Additive: $U = U_{det} + e_{w,r}$

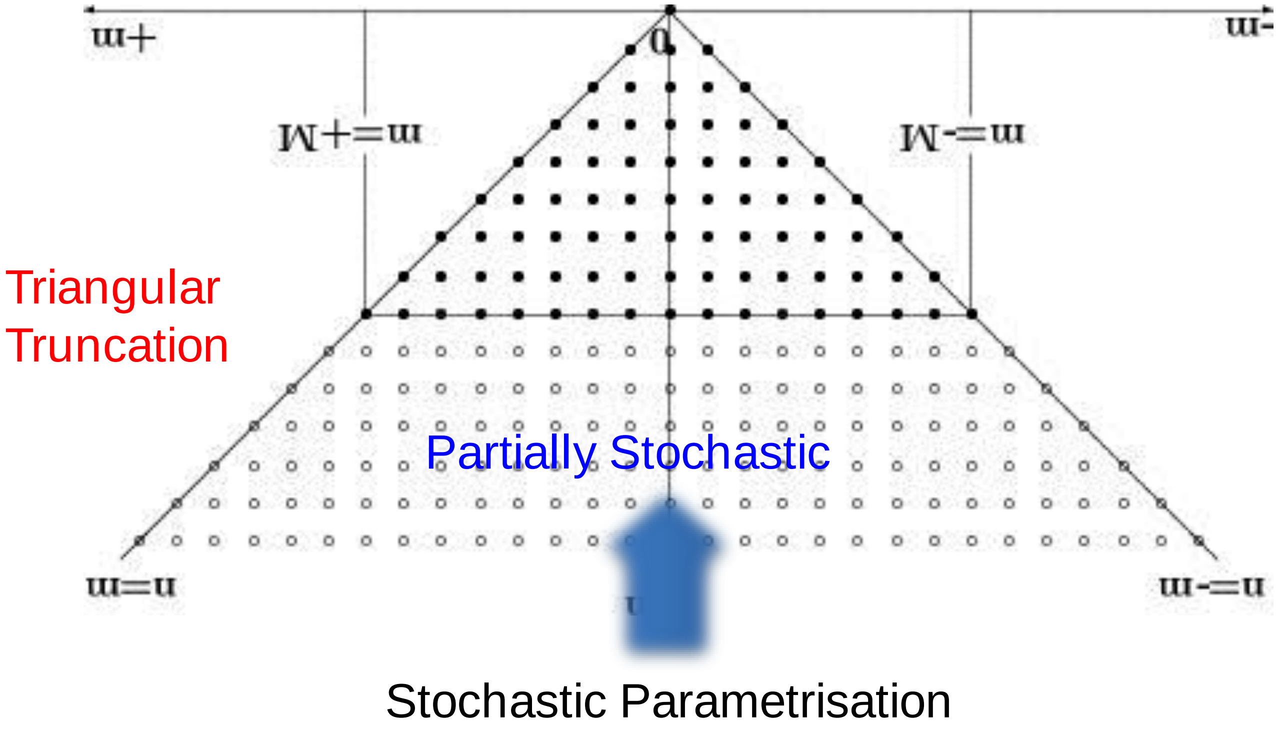
Multiplicative: $U = (1+e_r)\, U_{det}$

Where:

U_{det} = cubic polynomial in X

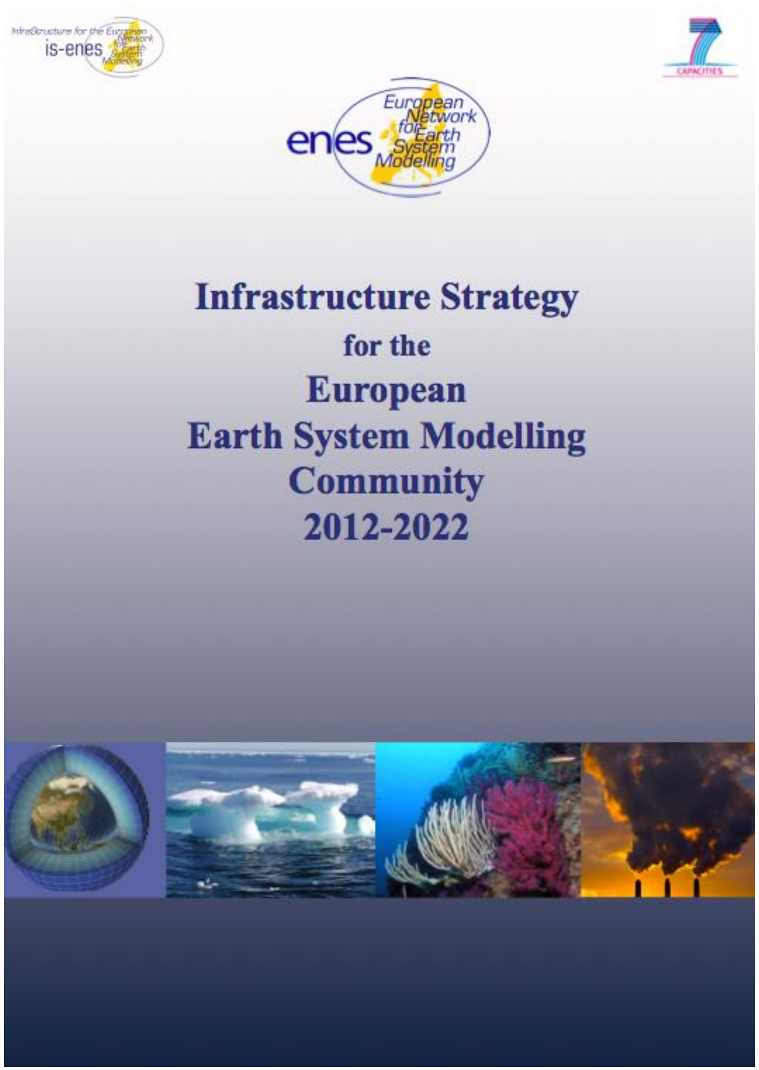
$e_{w,r}$ = white / red noise

Fit parameters from full model



Are we “over-engineering” our dynamical cores by using double-precision bit-reproducible computations for high wavenumbers?

iv Towards the cloud-resolved model



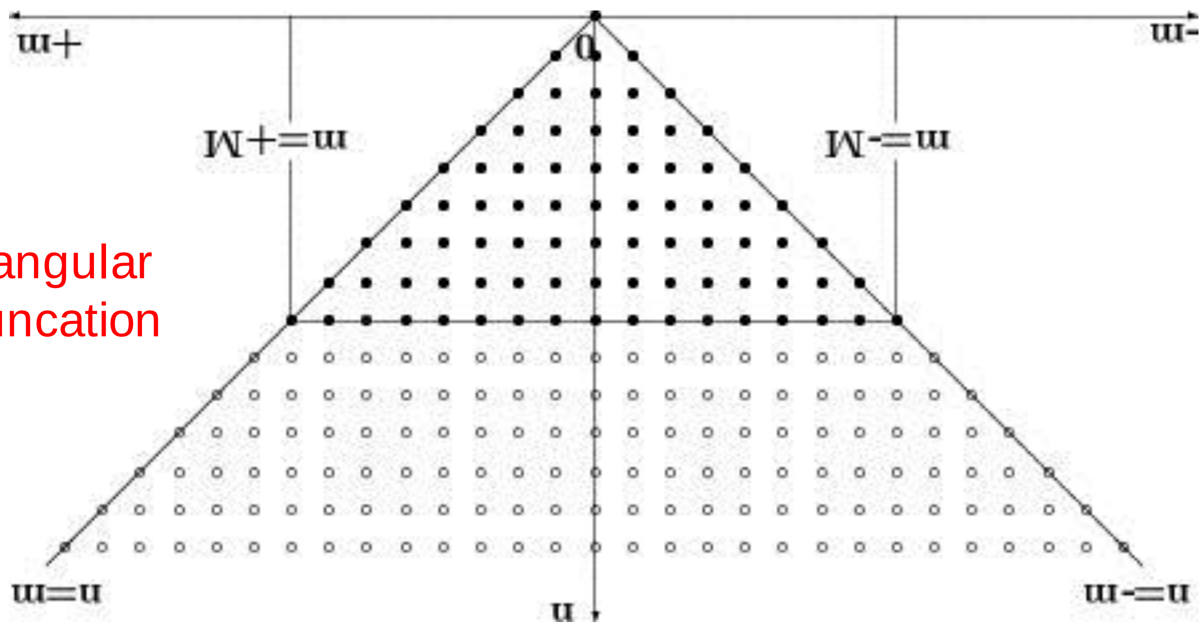
4.1 A grand challenge:
Towards 1 km global resolution

A "grand challenge" for the longer term is to develop global climate models which resolve convective scale motions (nominally around 1km horizontal resolution). Although ostensibly this challenge is only about resolution, ENES believes that addressing this challenge will also support nearly all of the other scientific goals outlined earlier.

Problem:

Models make inefficient use of available HPC capability (elapsed time < 10% of peak time) and HPC is itself becoming increasingly energy intensive and hence expensive (100MWs for a bit reproducible exaflop machine?!)

Triangular Truncation



Reduced Precision arithmetic

Oliver Fuhrer - Met Swisse

Motivation

- Move less information

```
real(kind=8) :: a     ! I am 8 Bytes
real(kind=4) :: b     ! I am 4 Bytes
```

- Fit more information into cache

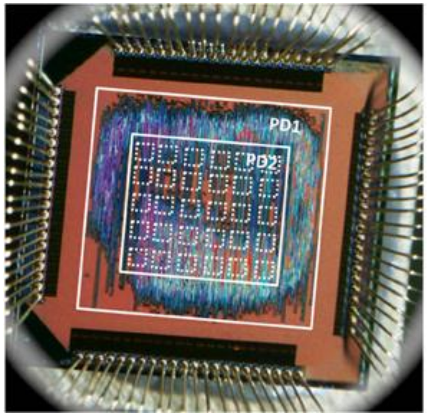
- Lower precision arithmetic is faster

```
a = a+a-a*a*a    ! Wow, time flies!
b = b+b-b*b*b    ! That was fast!
```

Superefficient inexact chips

http://news.rice.edu/2012/05/17/computing-experts-unveil-superefficient-inexact-chip/

Krishna Palem.
Rice, NTU
Singapore

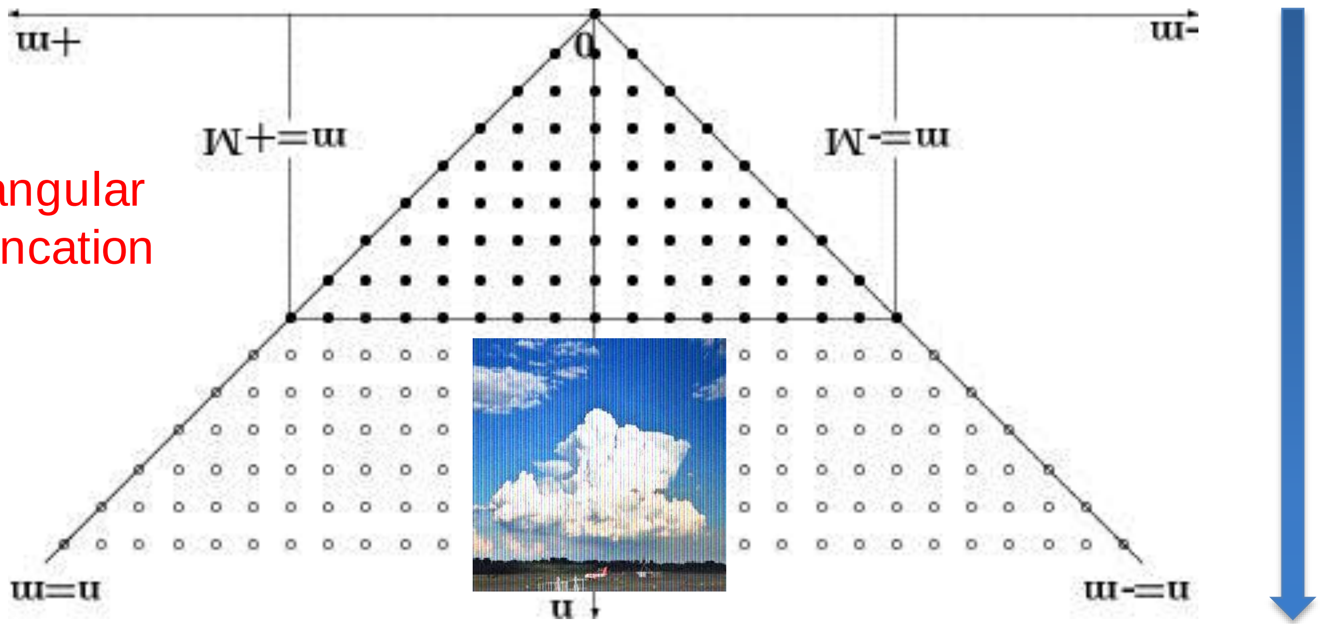


In terms of speed, energy consumption and size, inexact computer chips like this prototype, are about 15 times more efficient than today's microchips.

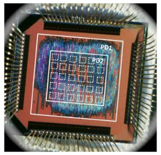
This comparison shows frames produced with video-processing software on traditional processing elements (left), inexact processing hardware with a relative error of 0.54 percent (middle) and with a relative error of 7.58 percent (right). The inexact chips are smaller, faster and consume less energy. The chip that produced the frame with the most errors (right) is about 15 times more efficient in terms of speed, space and energy than the chip that produced the pristine image (left).

Towards the Stochastic Dynamical Core?

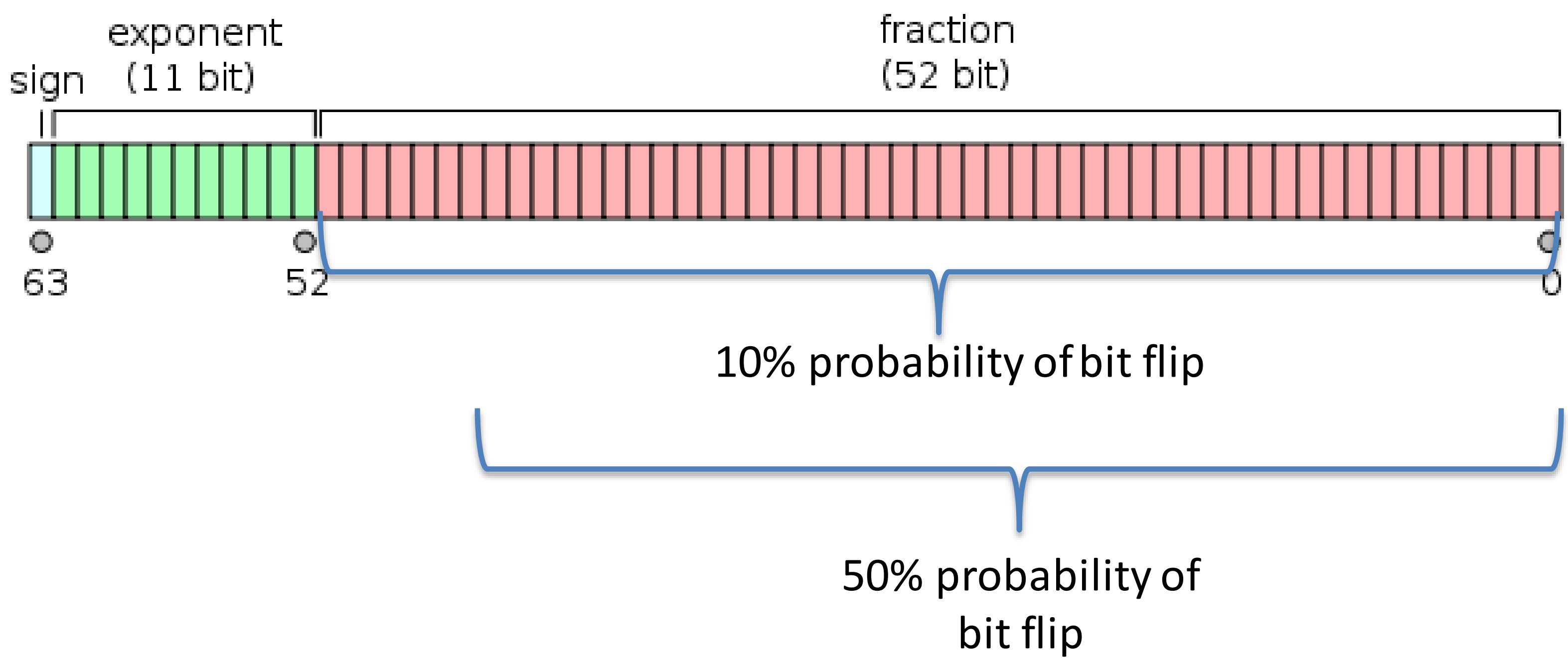
Triangular Truncation



Inexactness of chip



Emulator of Stochastic Chip/Reduced Precision



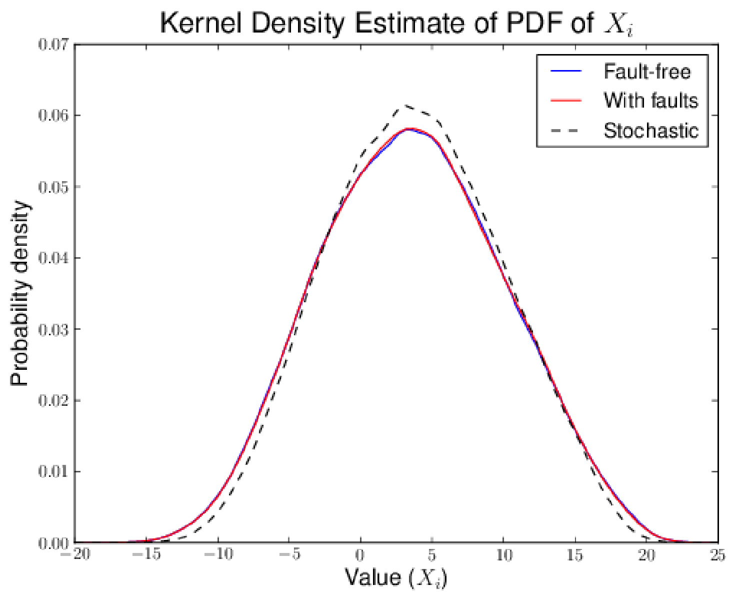
The emulator is used on 50% of numerical workload:

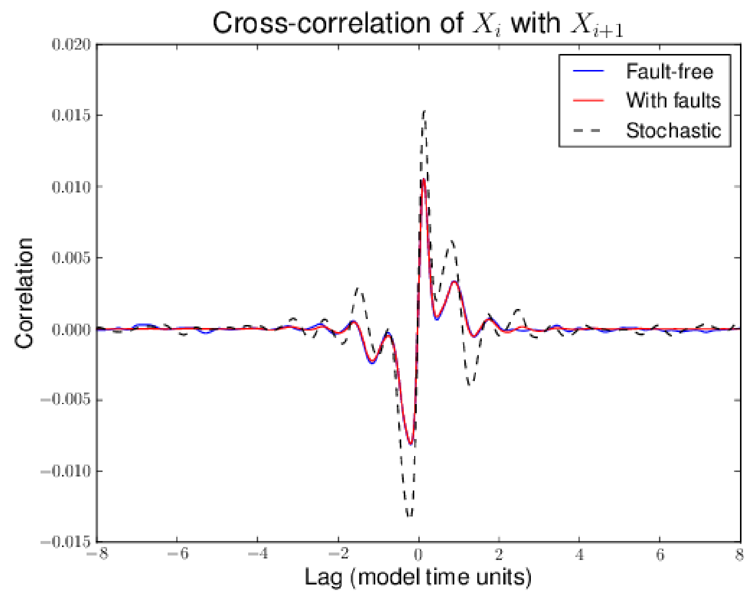
All floating point operations in grid point space

All floating point operations in the Legendre transforms between wavenumbers 31 and 85.

Cost approx that of T73

20% fault rate on Y variables

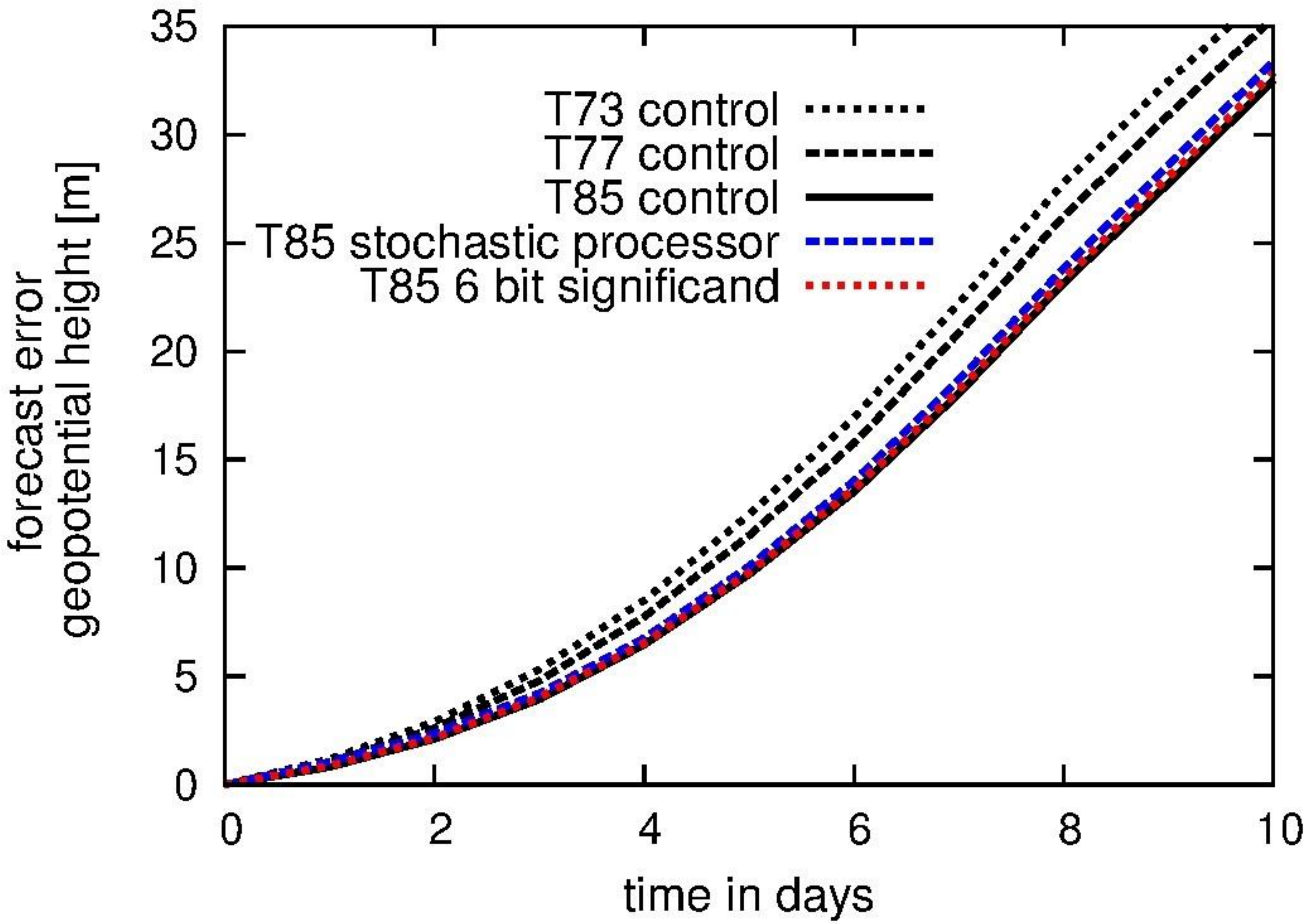




Imprecise L96 is more accurate than parametrised L96

Hugh McNamara personal communication

Weather forecasts with imprecise processing



Peter Düben, Personal Communication

20 Years Ago

Dynamics

Parametrisation

O(100km
)

Now

Dynamics

Parametrisation

O(10km)

In 10 years?

Dynamics

Parametrisation

O(1km)