Blurring the boundary between dynamics and physics

Tim Palmer, Peter Düben, Hugh McNamara

University of Oxford

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

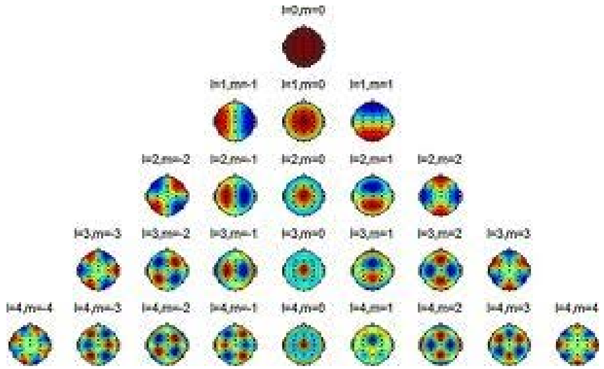
Resolved scales

The Canonical Numerical Ansatz

Unresolved scales

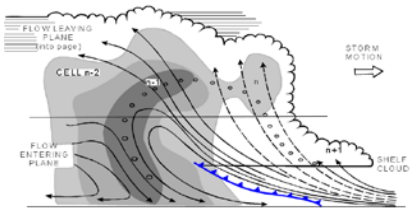
Dynamical Core

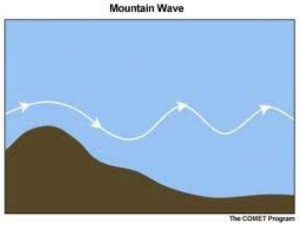
$$\zeta=\sum_{m\ l}^{\infty}\zeta_{ml}e^{im\lambda}P_{l}^{m}(\phi)$$



Parametrisations

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





$$D=P$$

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

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

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

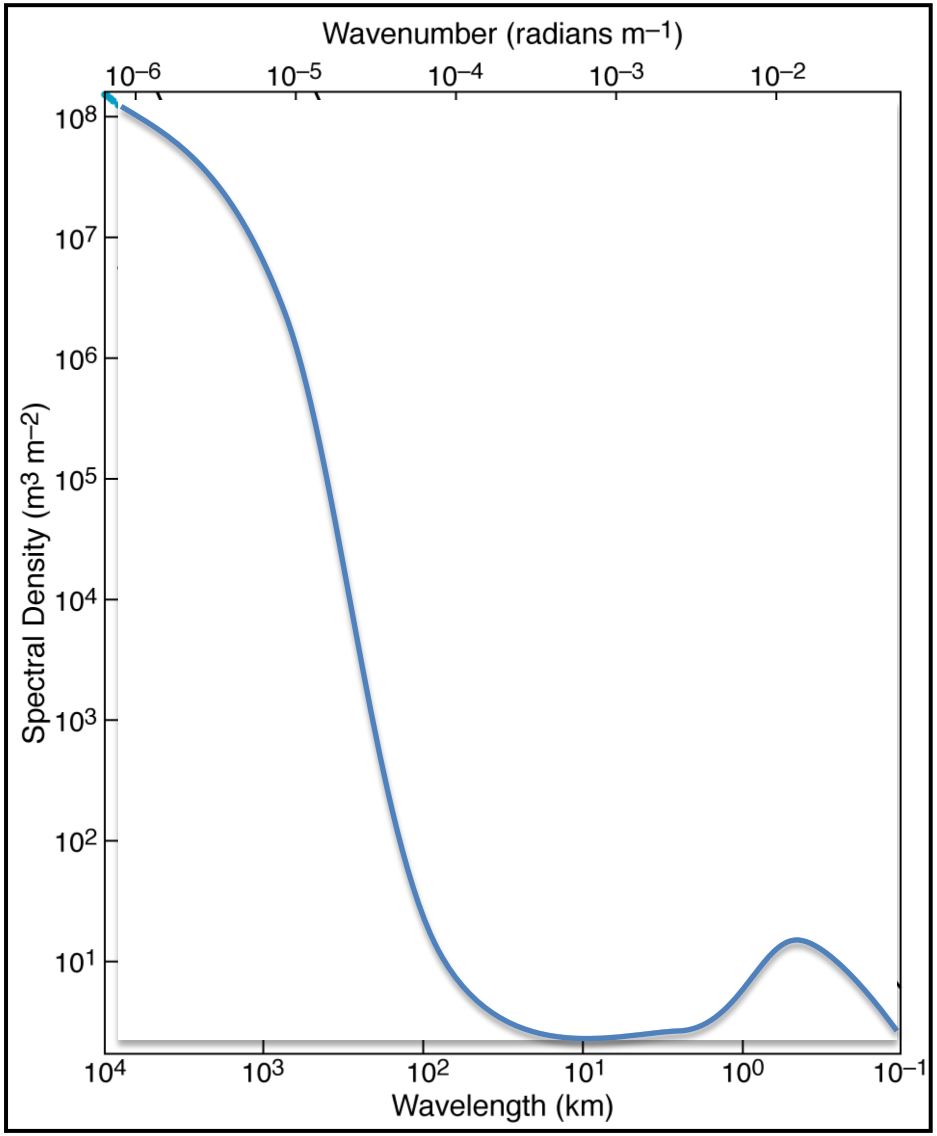
← Resolved scales

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

Unresolved scales →

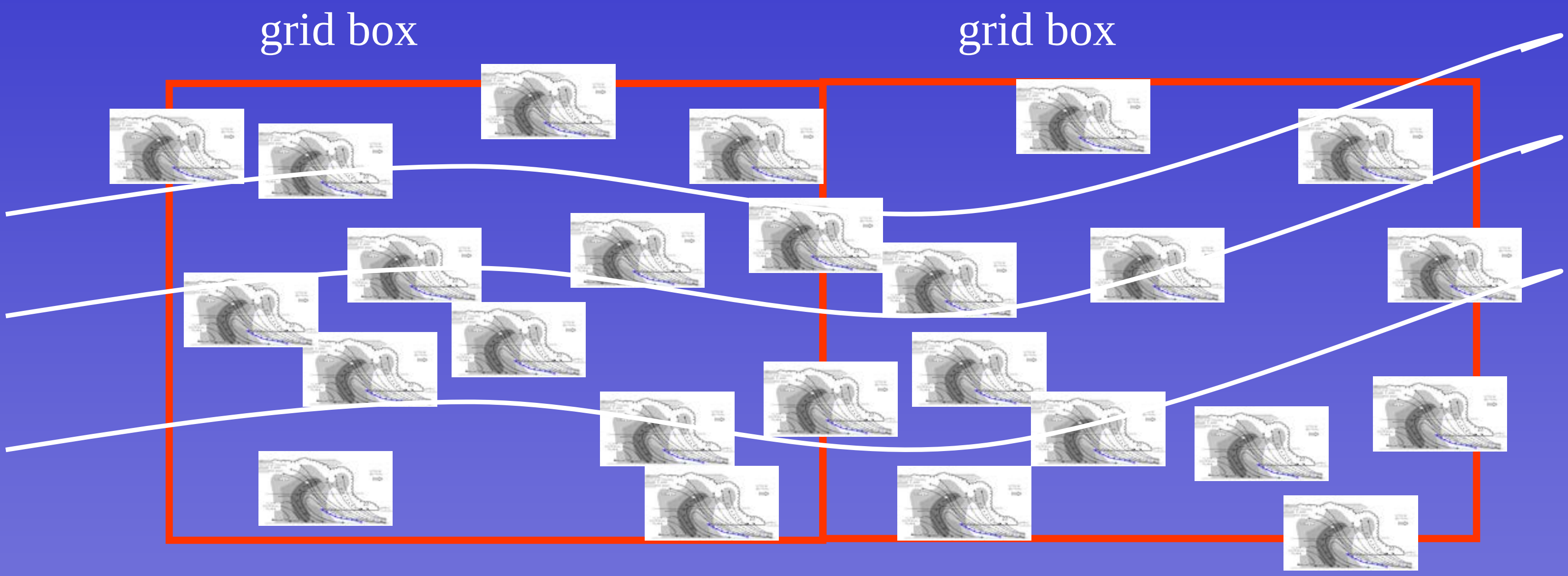
Dynamical Core

Parametrisations



If the energy spectrum in the atmosphere was like this……

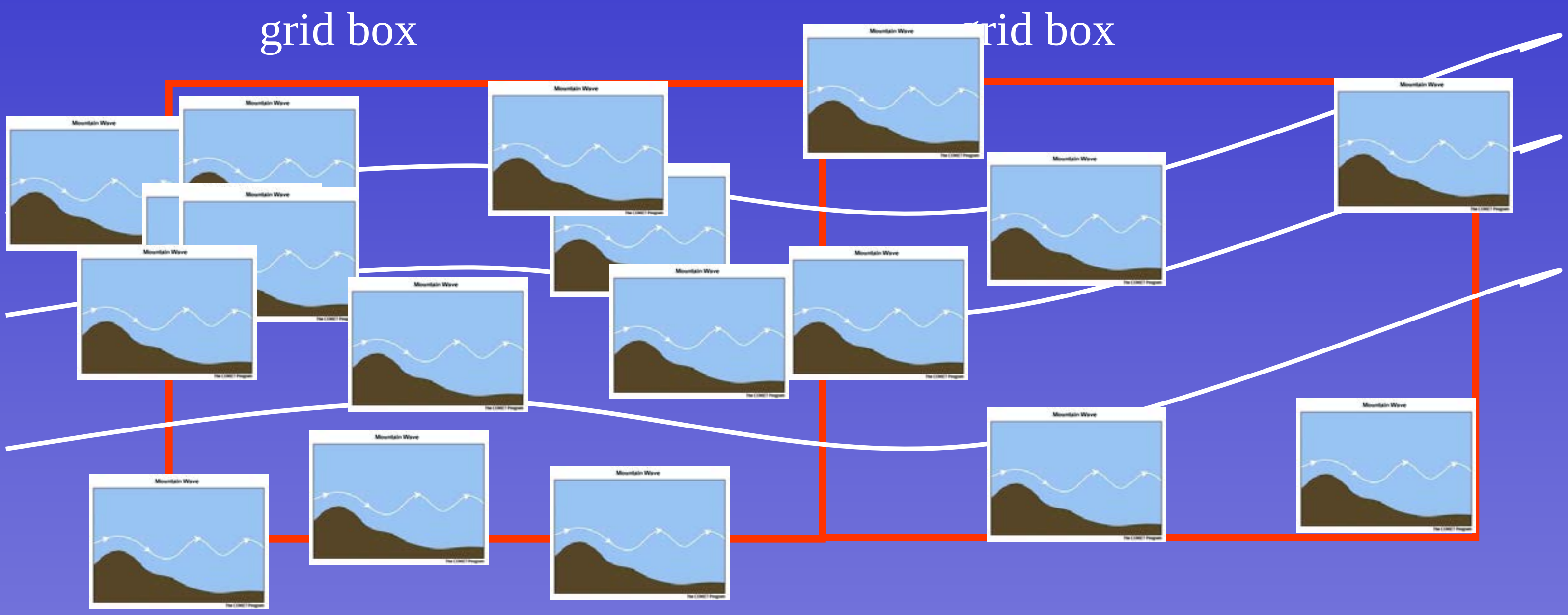
… ie the world looks like this



grid box

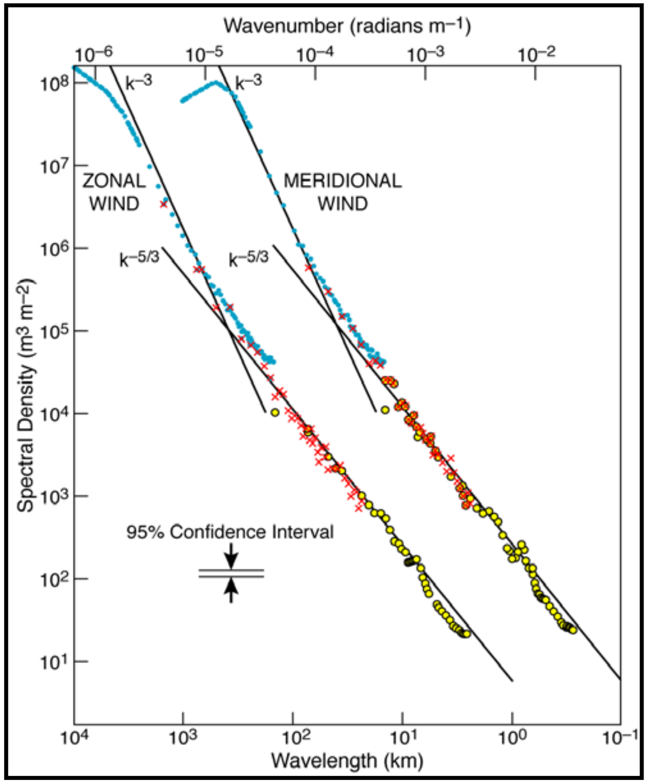
grid box

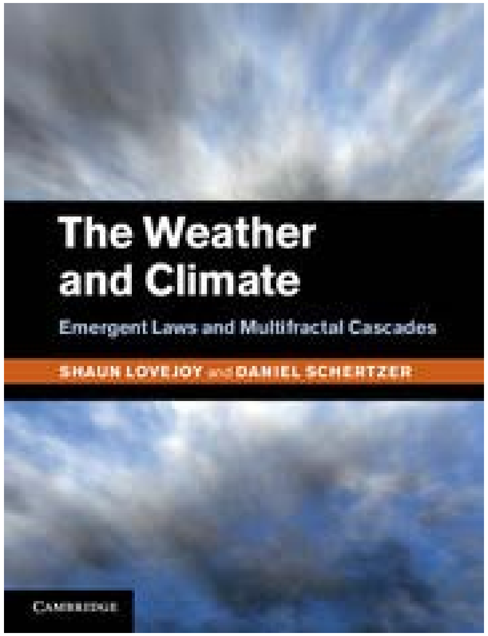
… or this



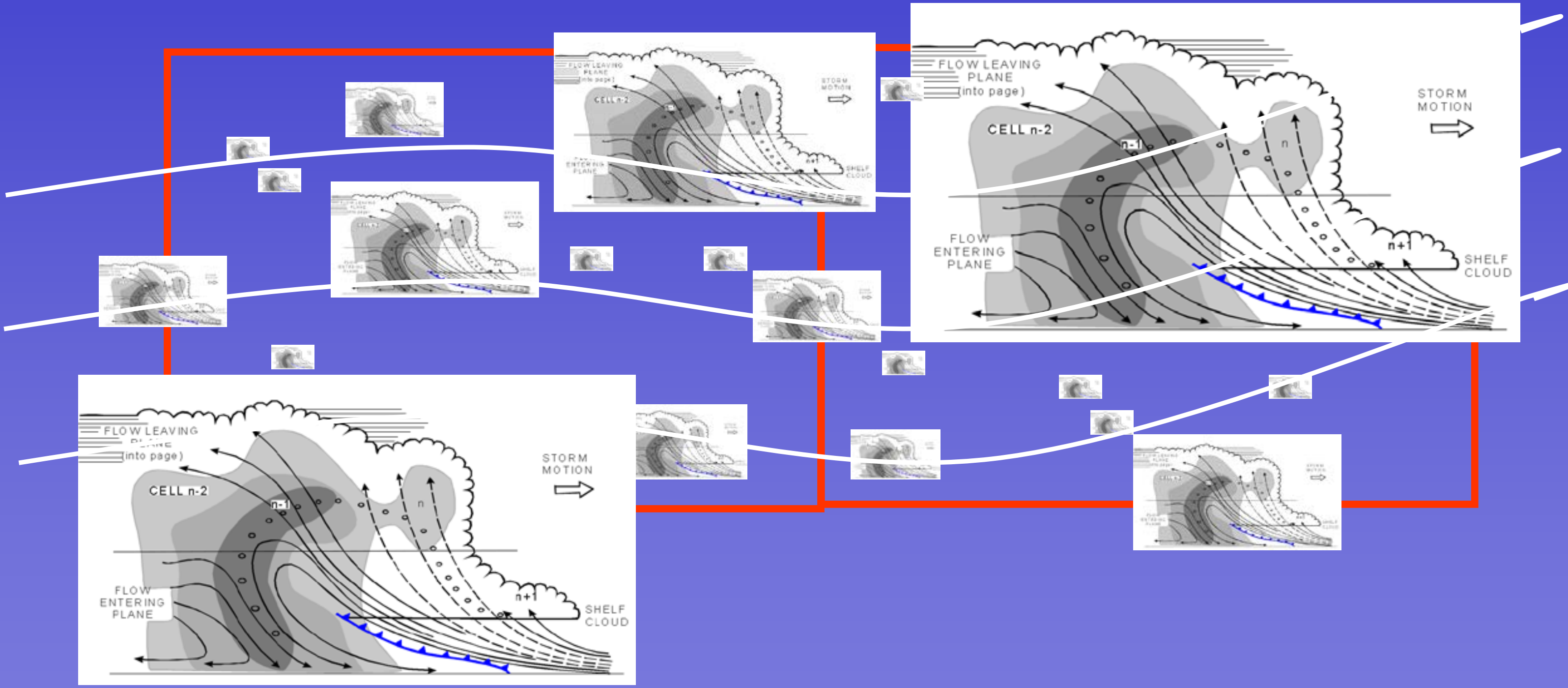
… then the Canonical Numerical Ansatz for solving the underlying PDEs would be well posed

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





The reality of the situation



grid box

grid box

cannot be described by a simple deterministic formula

Coarse-graining

(Shutts and Palmer, 2007)

Assume T1279 (16km) model = “truth”.

Assume T159 coarse-grain “model” grid.

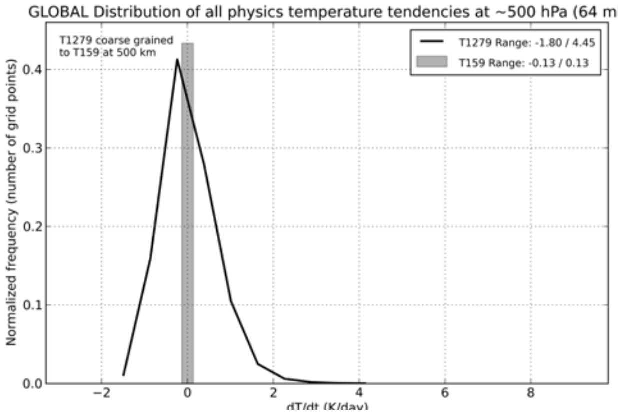
Bar= Subset of T159 total temperature parametrisation tendencies driven by T1279 coarse-grain fields.

Curve= Corresponding “true” sub-T159-scale tendency based on T1279 truth model.

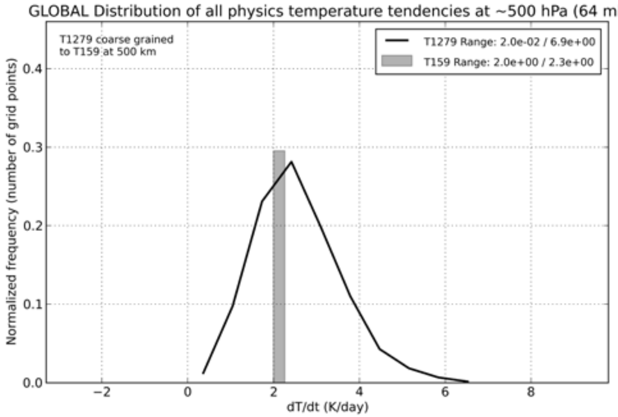
Ie when the parametrisations think the sub-grid pdf is a thin hat function, the reality is a much broader pdf.

The standard deviation increases with parametrised tendency – consistent with multiplicative stochasticity.

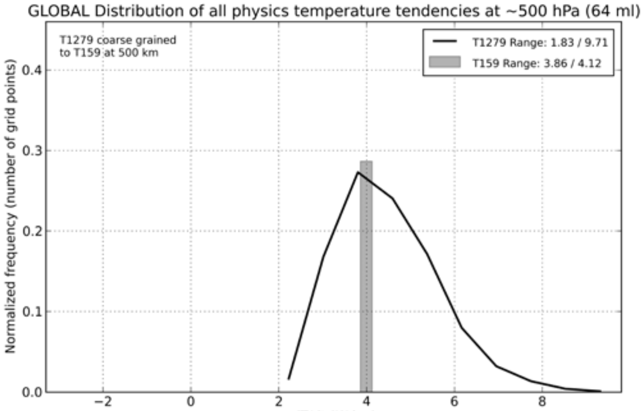
Small tendency



Medium tendency

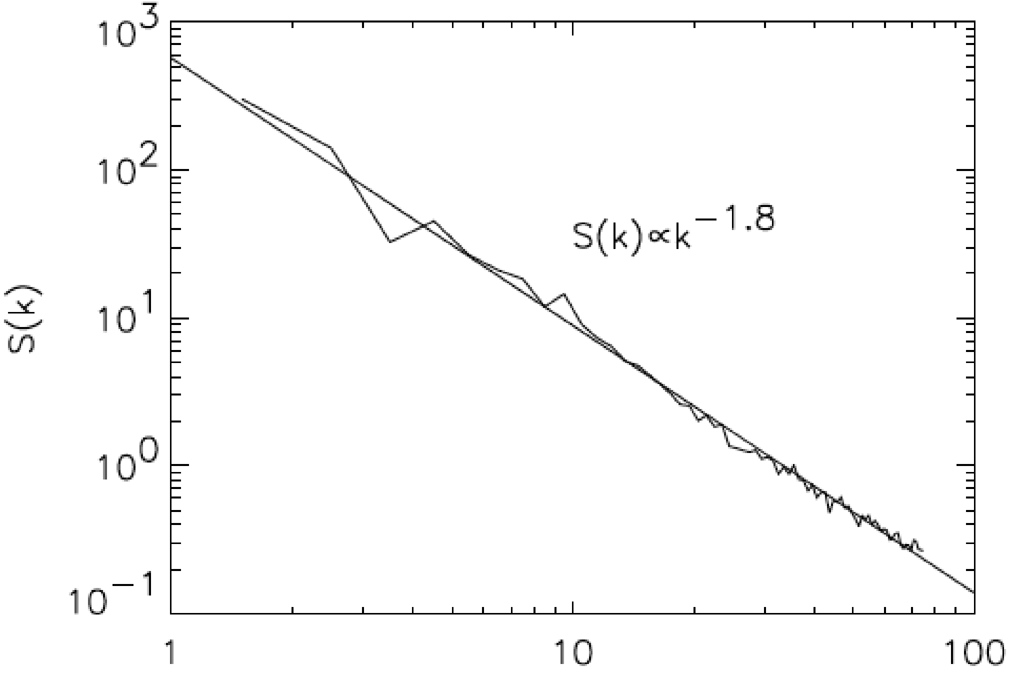


Large tendency



Callado-Palarès and Shutts, 2013.

Earth’s Topography has Power Law Structure Too

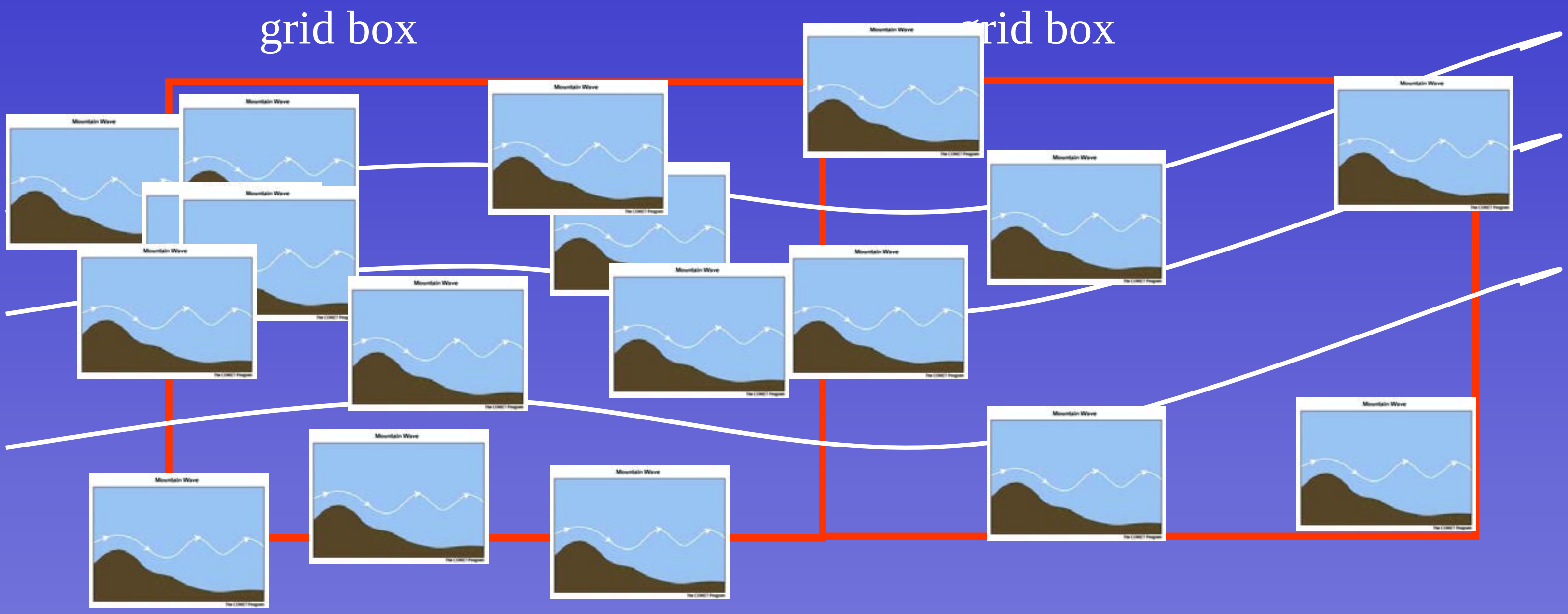


Why is topography fractal?

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 RSOS model. A least square fit to the logarithms of the ordinate and abscissa yield a slope of -1.81 indicating that $S(k) \propto k^{-1.81}$.

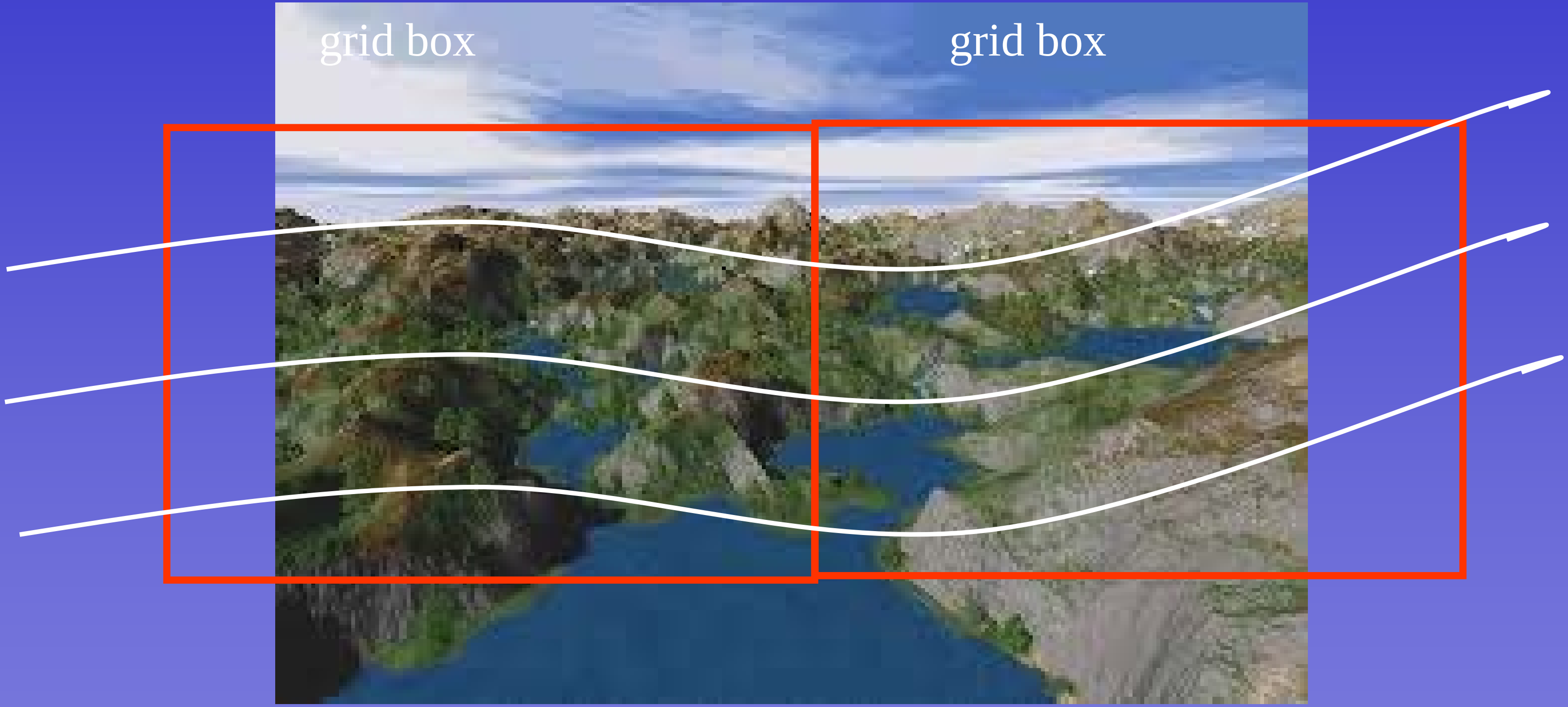
… ie not like this

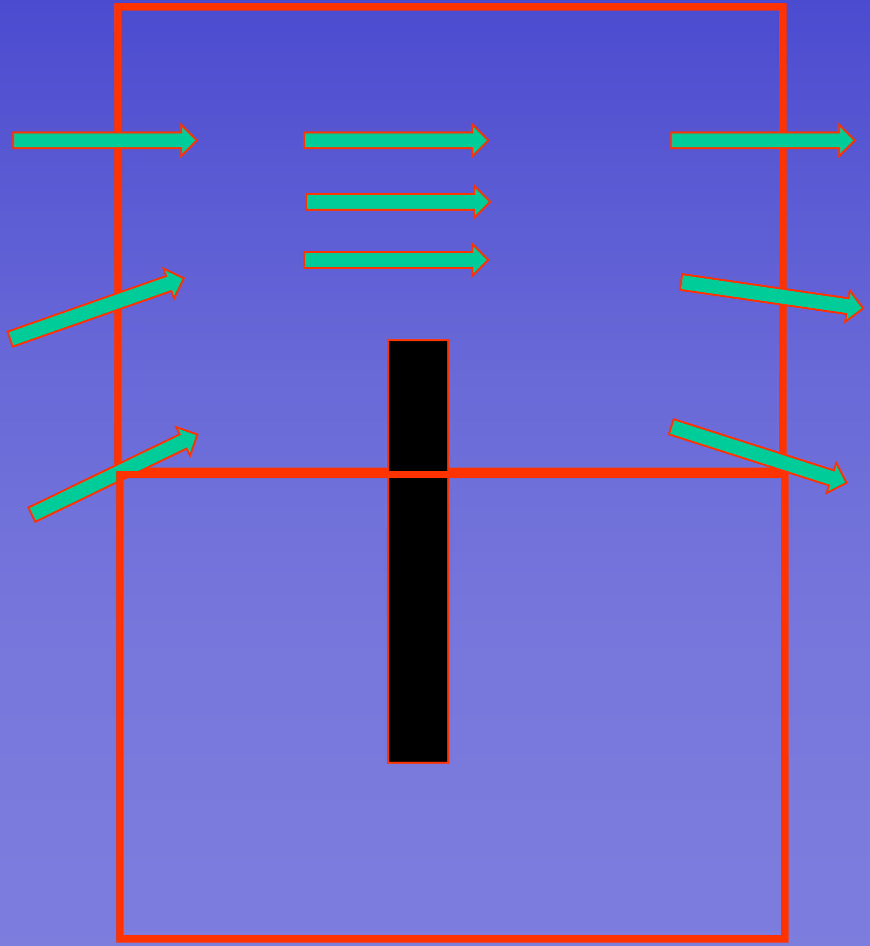


grid box

grid box

… but this





grid box

From Schertzer and Lovejoy, 1993

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

← Resolved scales

Unresolved scales →

Dynamical Core

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

Parametrisations

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

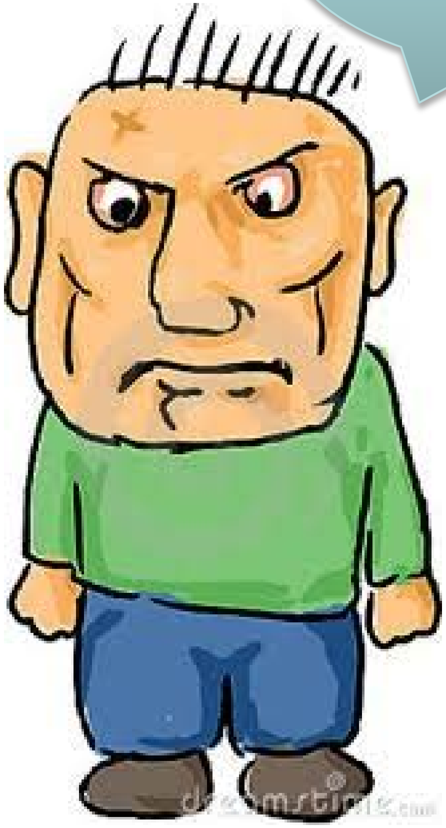
The Canonical Numerical Ansatz – ie the deterministic delineation into “resolved” and “parametrised” scales - is itself a (the?) major source of model error.

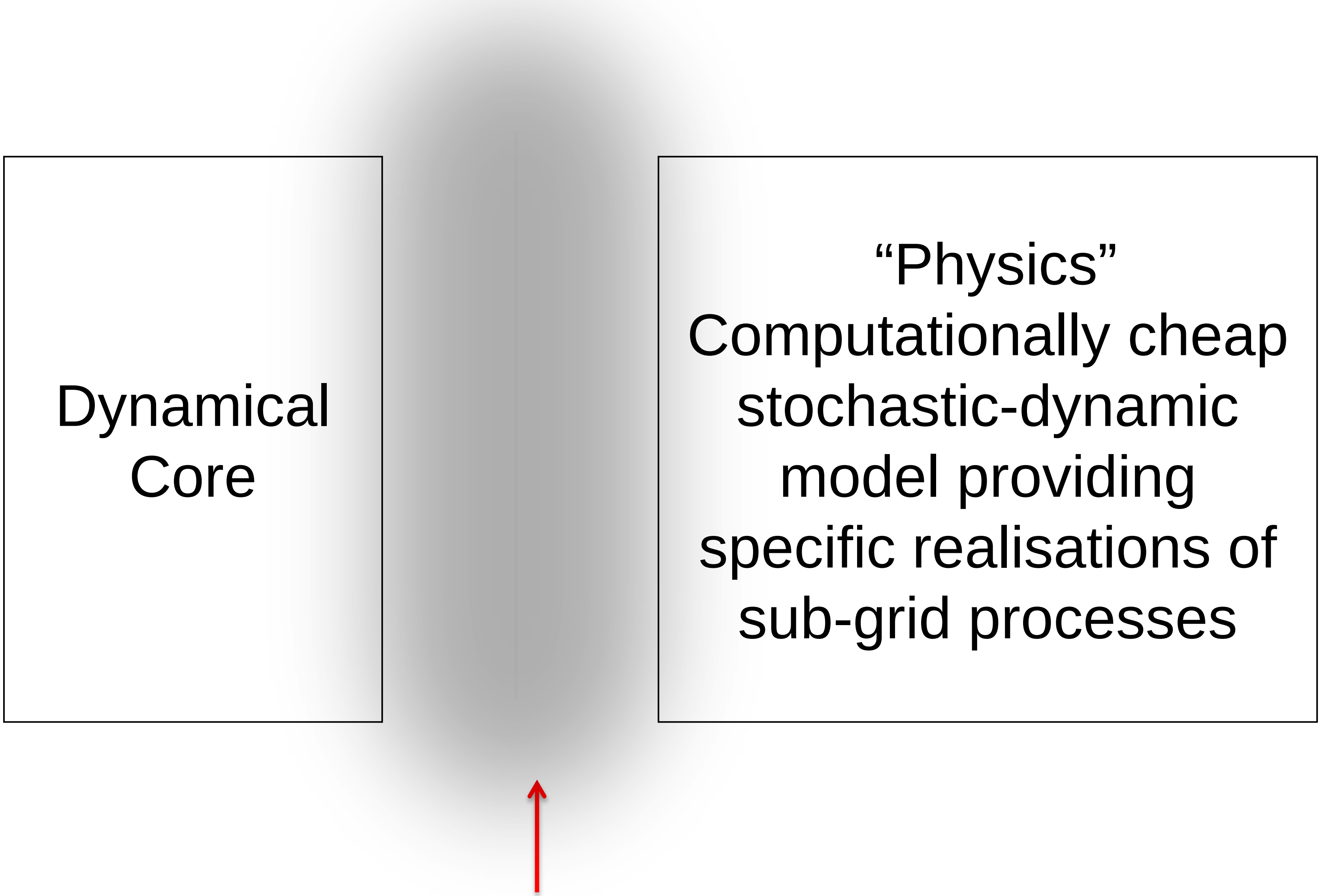
Numerics Group

Not my problem!

Physics Group

Not my problem!



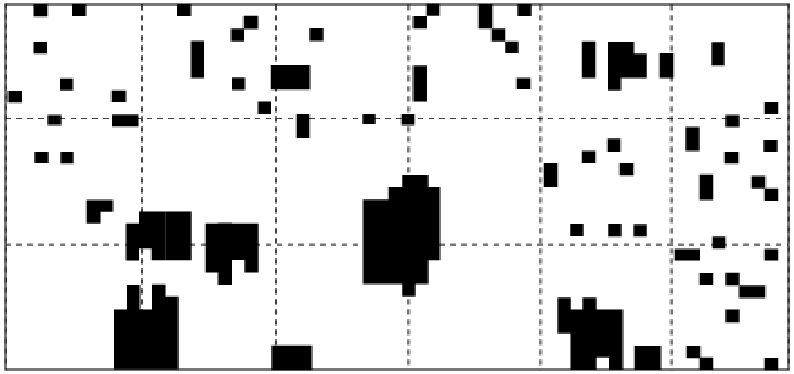


Dynamical Core

"Physics"
Computationally cheap stochastic-dynamic model providing specific realisations of sub-grid processes

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!

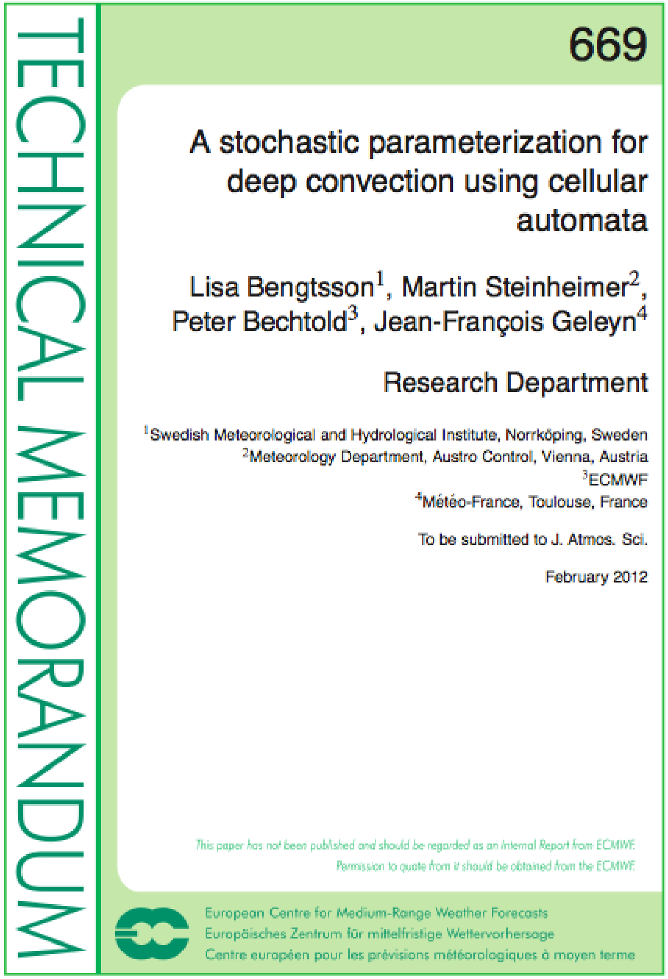
Stochastic Cellular Automaton for Convection



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



TECHNICAL MEMORANDUM

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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

[1]Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
[2]Meteorology Department, Austro Control, Vienna, Austria
[3]ECMWF
[4]Météo-France, Toulouse, France

To be submitted to J. Atmos. Sci.

February 2012

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

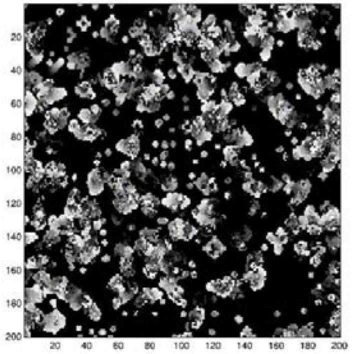


Figure 1: Example of a Cellular Automaton following the rules of Conway's game of life

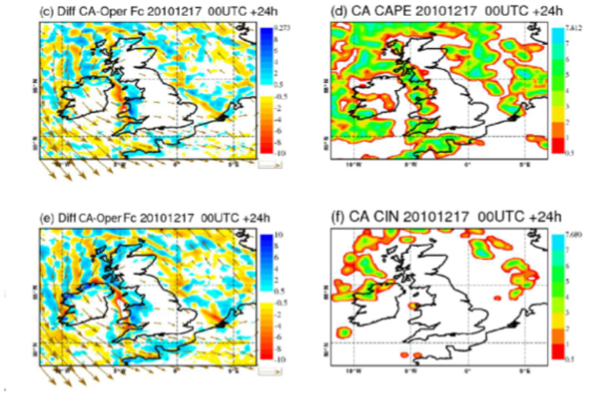
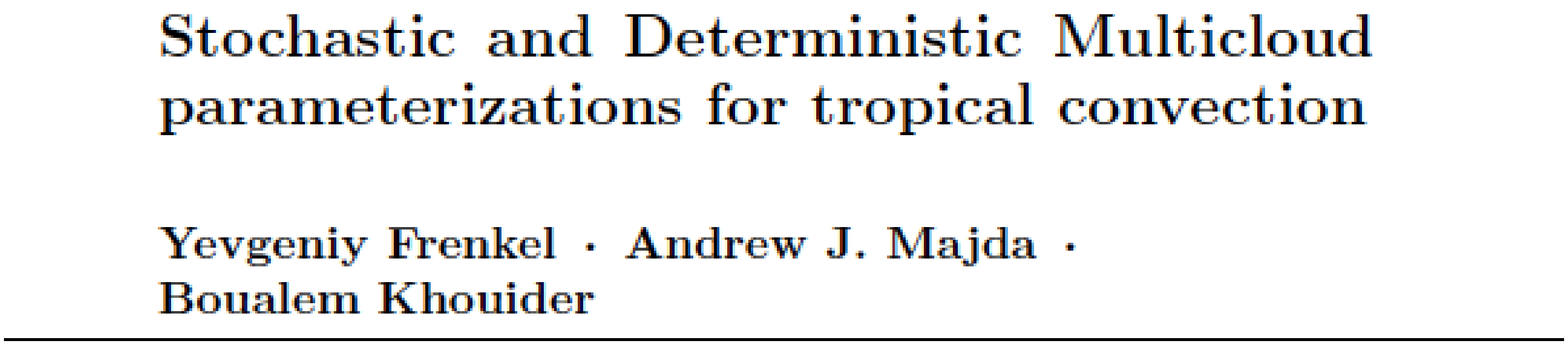
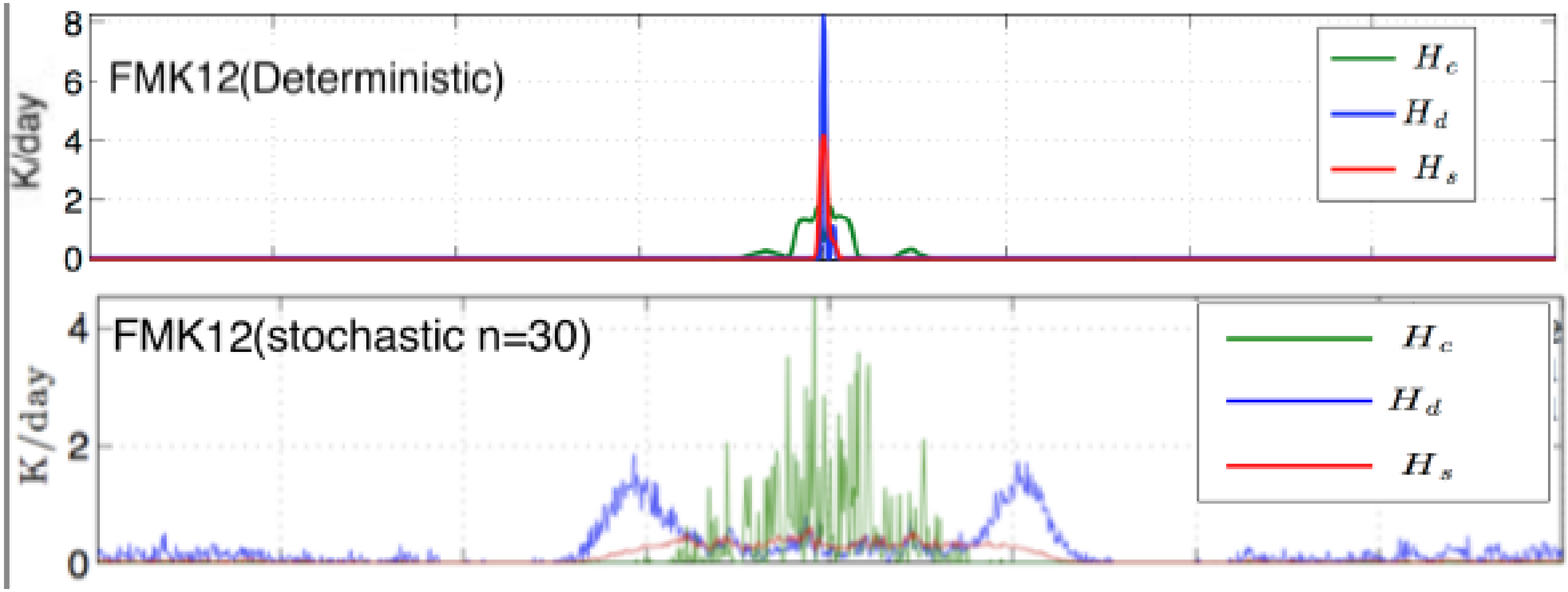


Figure 5: 24 hour accumulated precipitation (mm) on 17 December 2010 over the British Isles and Western Europe as observed by the OPERA radar network (a), the operational 24 hour deterministic IFS forecast at spectral resolution T1279=16 km (b), difference (mm) between the operational forecast and forecast 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)



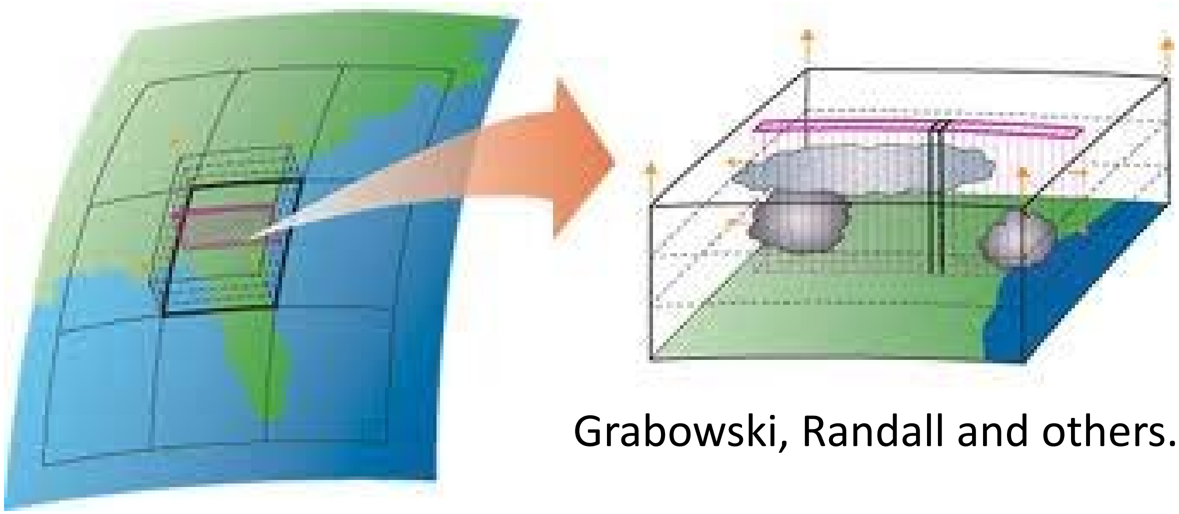
Stochastic and Deterministic Multicloud parameterizations for tropical convection

Yevgeniy Frenkel · Andrew J. Majda · Boualem Khouider

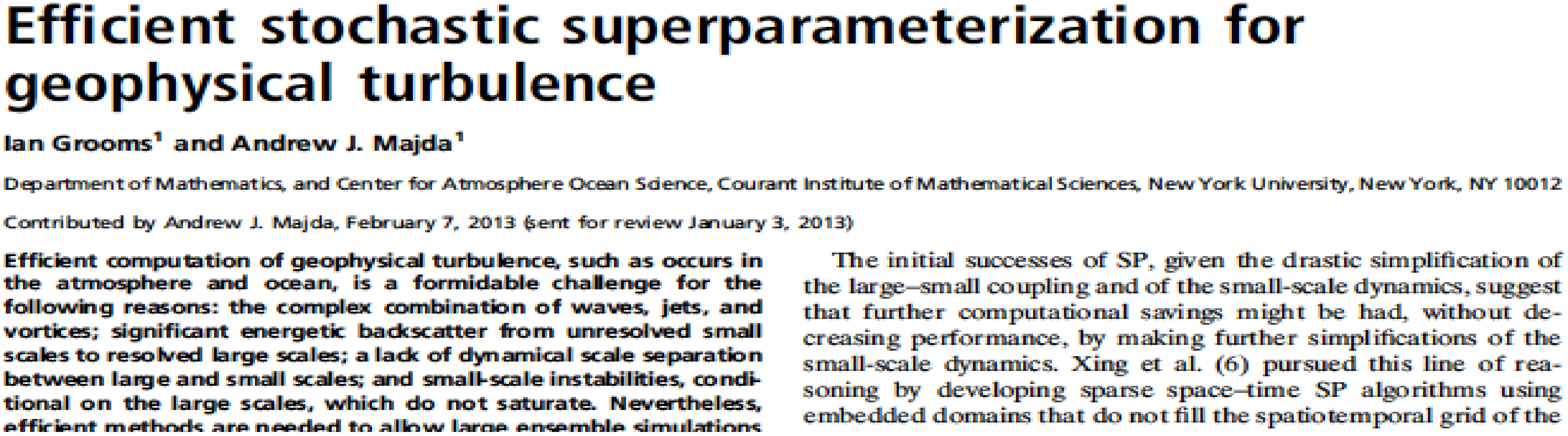


Stochastic multicloud model based on a Markov chain lattice model. An extension of an Ising-type spin-flip model used for phase transitions in material science

Superparameterization



Grabowski, Randall and others.



Efficient stochastic superparameterization for geophysical turbulence

Ian Grooms[1] **and Andrew J. Majda**[1]

[1] Department of Mathematics, and Center for Atmosphere Ocean Science, Courant Institute of Mathematical Sciences, New York University, New York, NY 10012

Contributed by Andrew J. Majda, February 7, 2013 (sent for review January 3, 2013)

Efficient computation of geophysical turbulence, such as occurs in the atmosphere and ocean, is a formidable challenge for the following reasons: the complex combination of waves, jets, and vortices; significant energetic backscatter from unresolved small scales to resolved large scales; a lack of dynamical scale separation between large and small scales; and small-scale instabilities, conditional on the large scales, which do not saturate. Nevertheless, efficient methods are needed to allow large ensemble simulations

The initial successes of SP, given the drastic simplification of the large–small coupling and of the small-scale dynamics, suggest that further computational savings might be had, without decreasing performance, by making further simplifications of the small-scale dynamics. Xing et al. (6) pursued this line of reasoning by developing sparse space–time SP algorithms using embedded domains that do not fill the spatiotemporal grid of the

TECHNICAL MEMORANDUM

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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

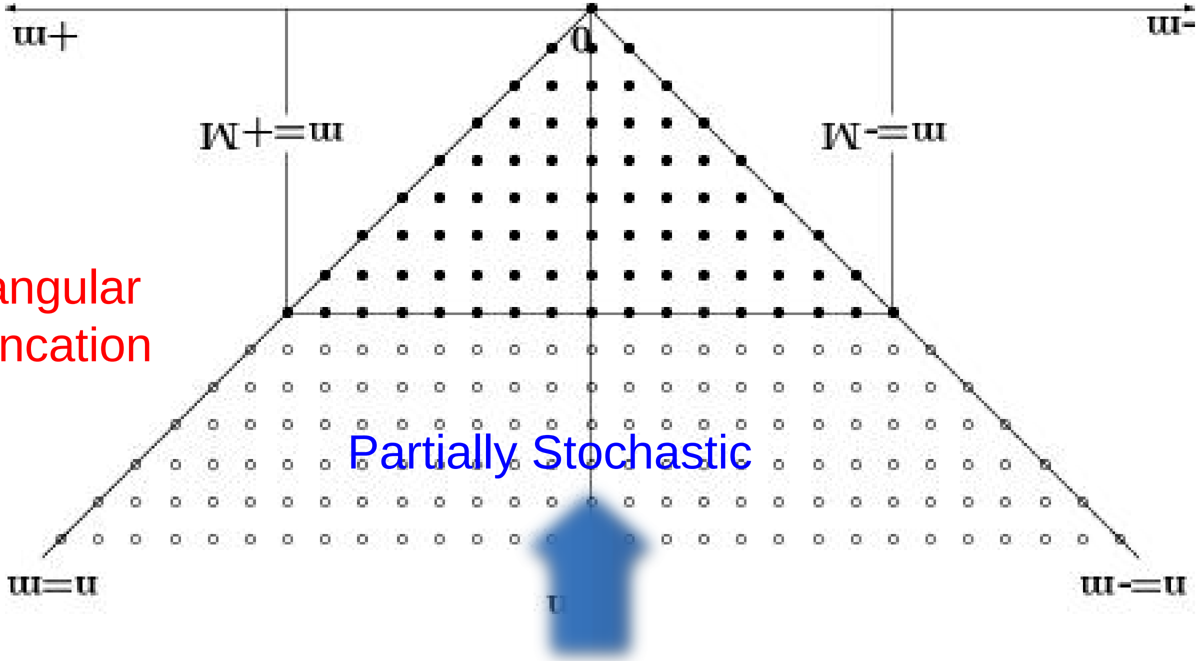
October 8, 2009

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

- Improved forecast reliability
- Reduced systematic error

Originally based on CA pattern generators, now spectral.



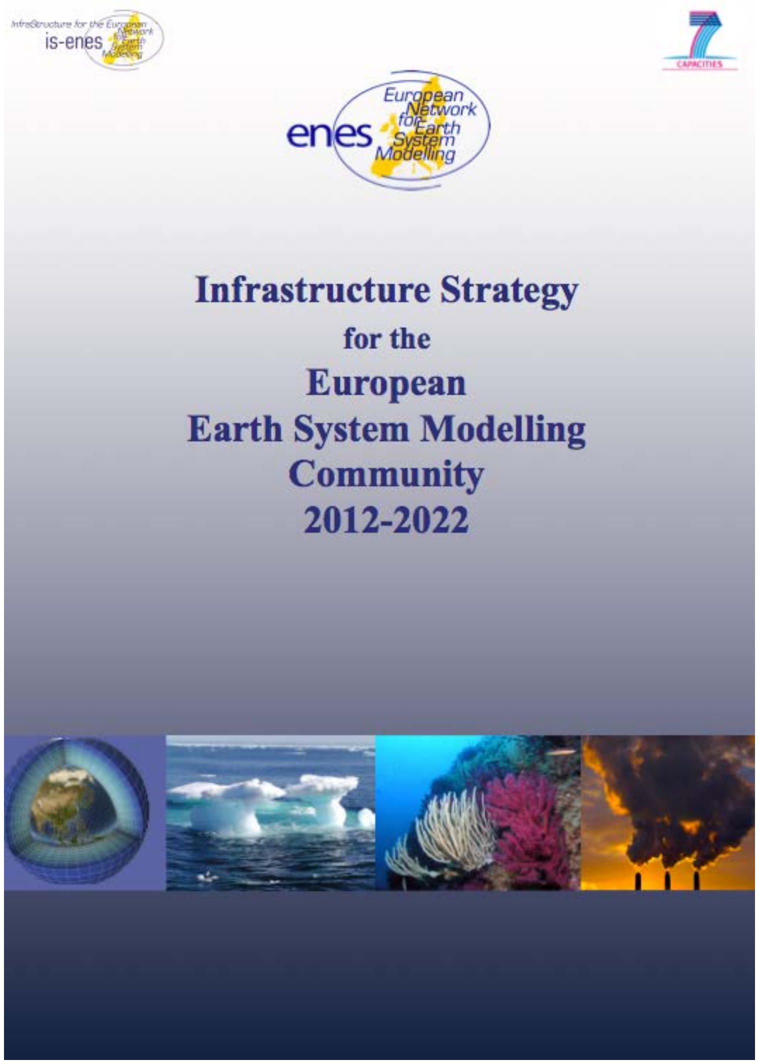
Triangular Truncation

Partially Stochastic

Stochastic Parametrisation

Are we “over-engineering” our dynamical cores by using double-precision bit-reproducible computations for high wavenumbers, thereby making them inefficient for evolution to high resolution?

Towards the cloud-resolved model

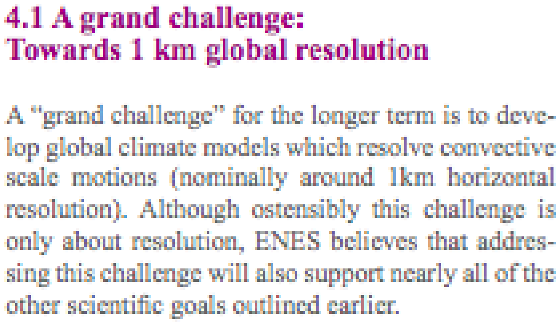


InfraStructure for the European Network for Earth System Modelling
is-enes

enes European Network for Earth System Modelling

CAPACITIES

Infrastructure Strategy
for the
European
Earth System Modelling
Community
2012-2022



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.

Possible for NWP by 2030? For climate change predictions, we cannot not wait that long!

Is degrading the dynamical core as we approach the truncation scale a credible route to global cloud resolution (< 1km) by 2020?

Less precise numerics, more reliable forecasts!

Floating point numbers

- Most computers follow the IEEE 754 standard

$$x = (-1)^s \cdot c \cdot b^q$$

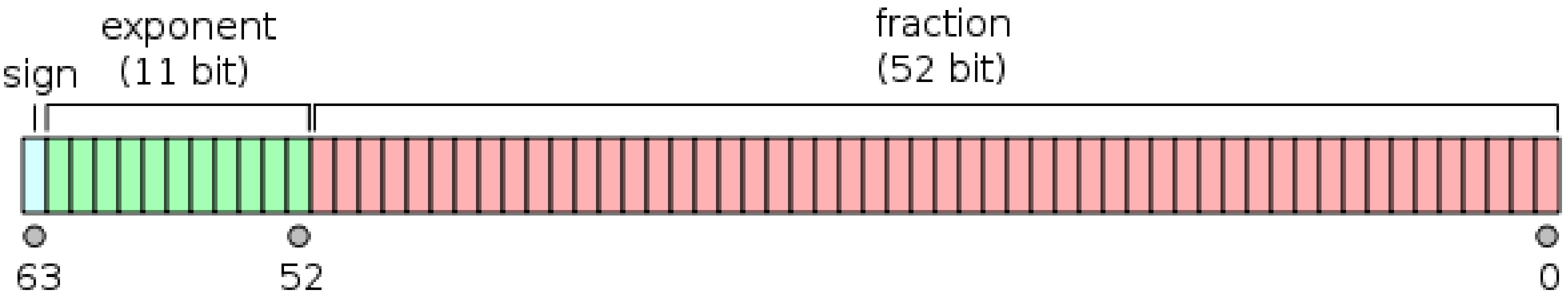
$$-12.345 = (-1)^1 \cdot 12345 \cdot 10^{-3}$$

s	sign
c	significand (coefficient)
b	base
q	exponent

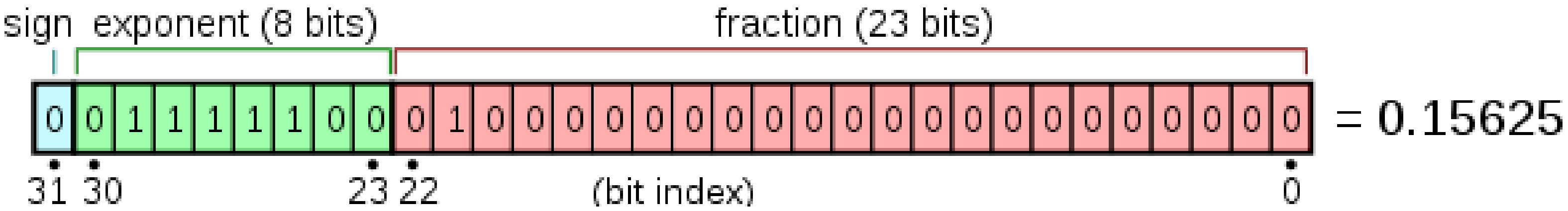
- Examples

Name	**Size**	**Decimal digits**	**Minimum number**	**Maximum number**
half precision	2 Bytes	3.3	10^{-5}	10^{4}
single precision	4 Bytes	7.2	10^{-38}	10^{38}
double precision	8 Bytes	16.0	10^{-308}	10^{308}
quadruple precision	16 Bytes	34.0	10^{-4932}	10^{4932}

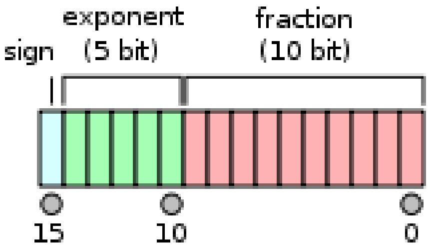
NB. 1/32 precision = 1 bit = on/off (a cellular automaton)!!



Double Precision

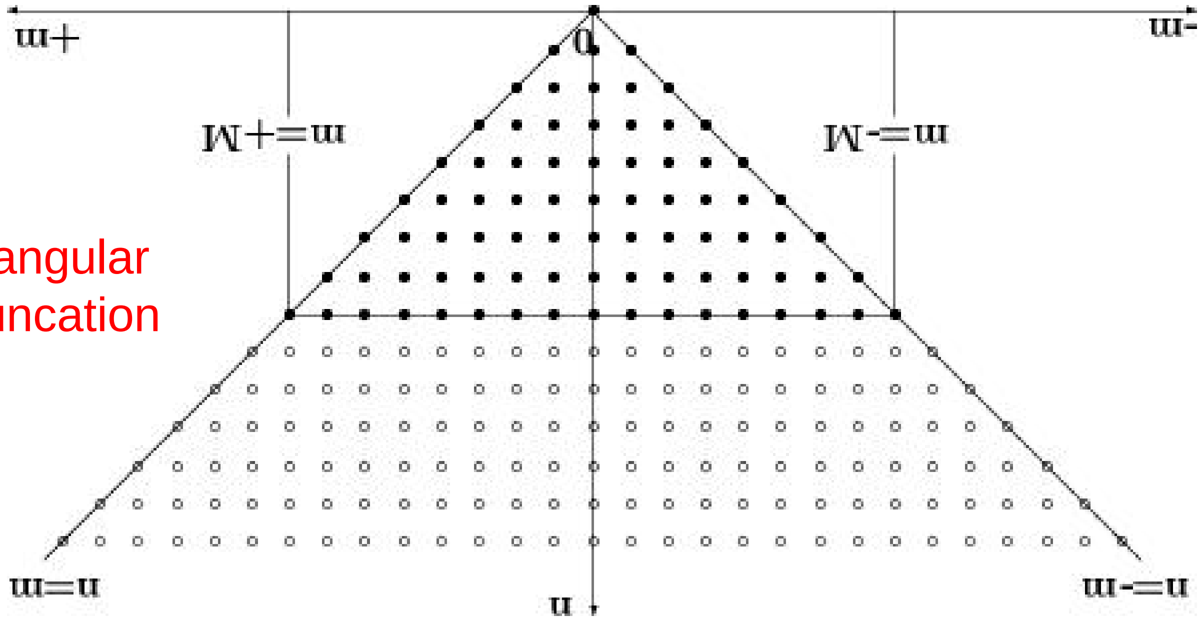


Single Precision



Half Precision

Triangular Truncation



parametrisation

Reduced Precision arithmetic

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

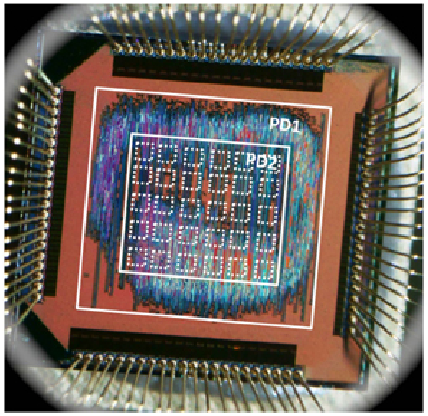
- Lower precision arithmetic is faster

```
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

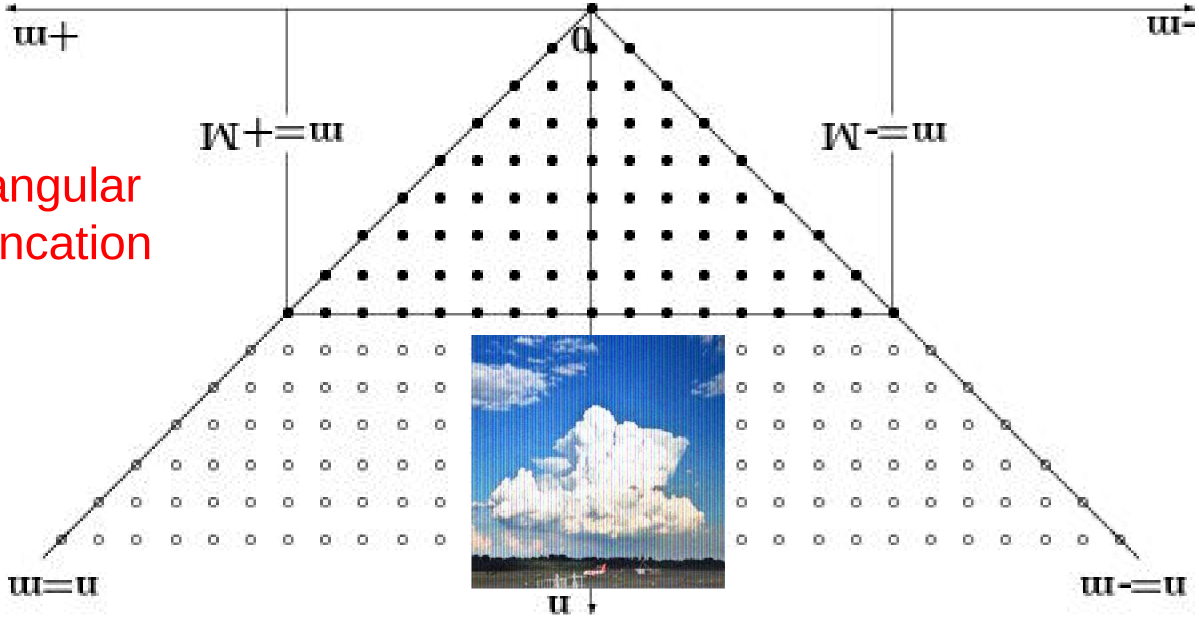


In terms of speed, energy consumption and size, inexact computer chips like this prototype, are about 15 times more efficient than today's microchips.

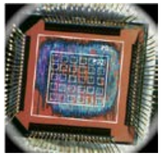
This comparison shows frames produced with video-processing software on traditional processing elements (left), inexact processing hardware with a relative error of 0.54 percent (middle) and with a relative error of 7.58 percent (right). The inexact chips are smaller, faster and consume less energy. 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?

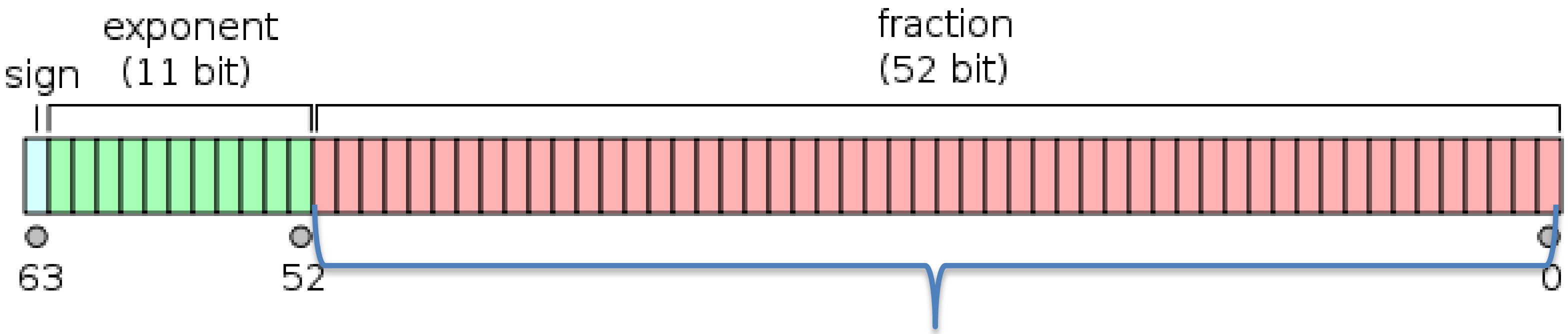
Triangular Truncation



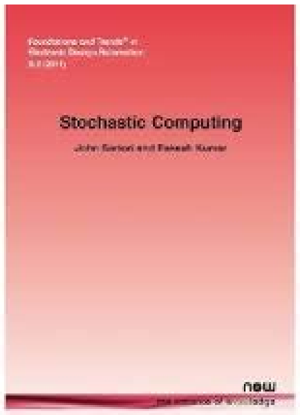
Inexactness of chip



Emulator of Stochastic Chip



10% probability of bit flip = 90% reduction in power consumption by chips



Stochastic Computing

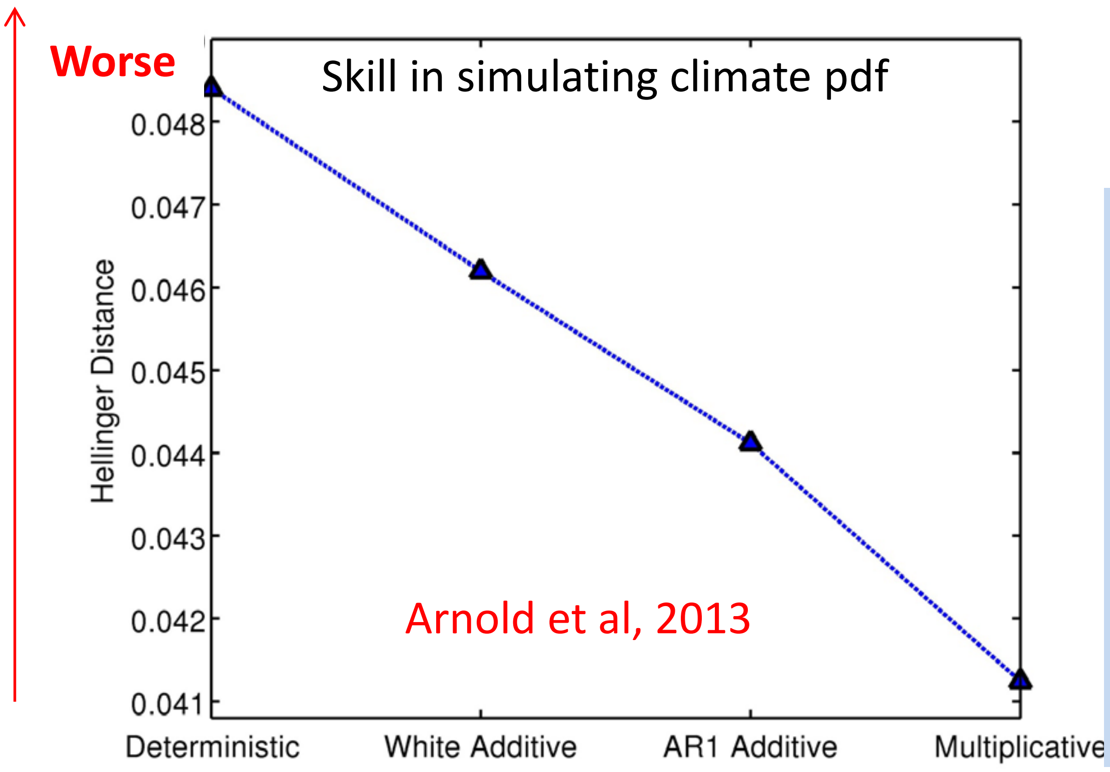
Experiments with the Lorenz '96 System (i)

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

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

Assume Y unresolved

Approximate sub-grid tendency by U



Deterministic: $U = U_{det}$

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

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

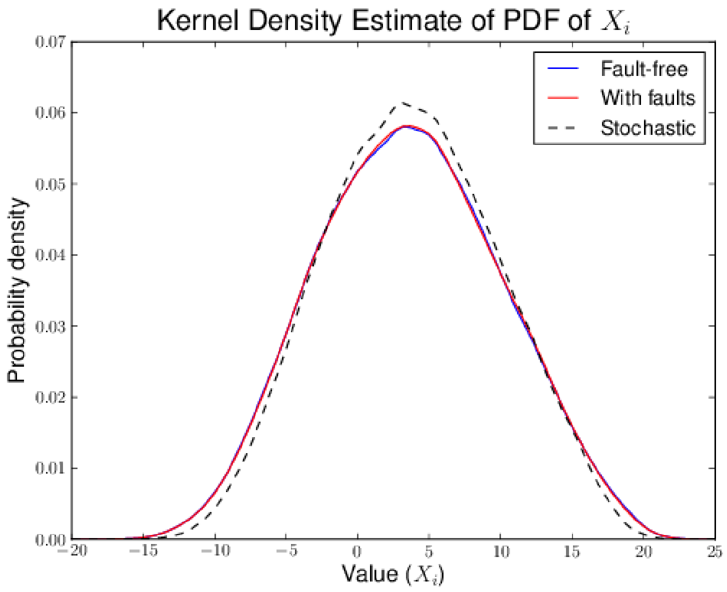
Where:

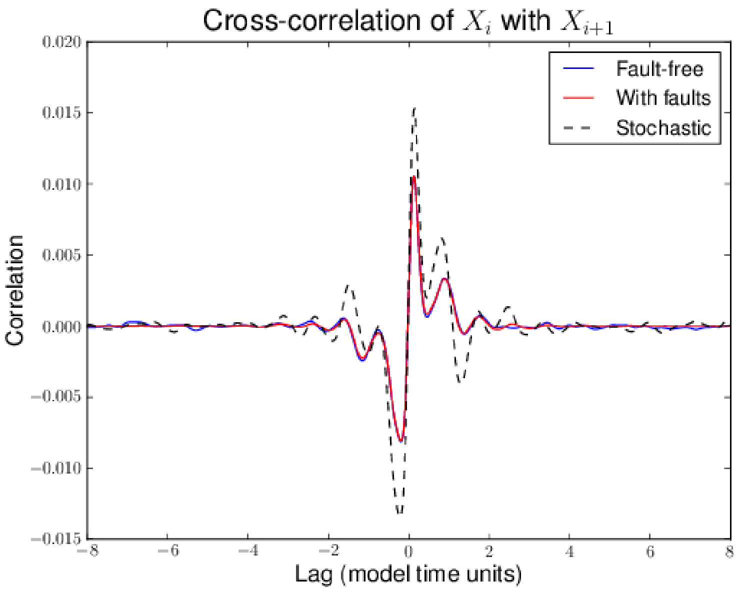
U_{det} = cubic polynomial in X

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

Fit parameters from full model

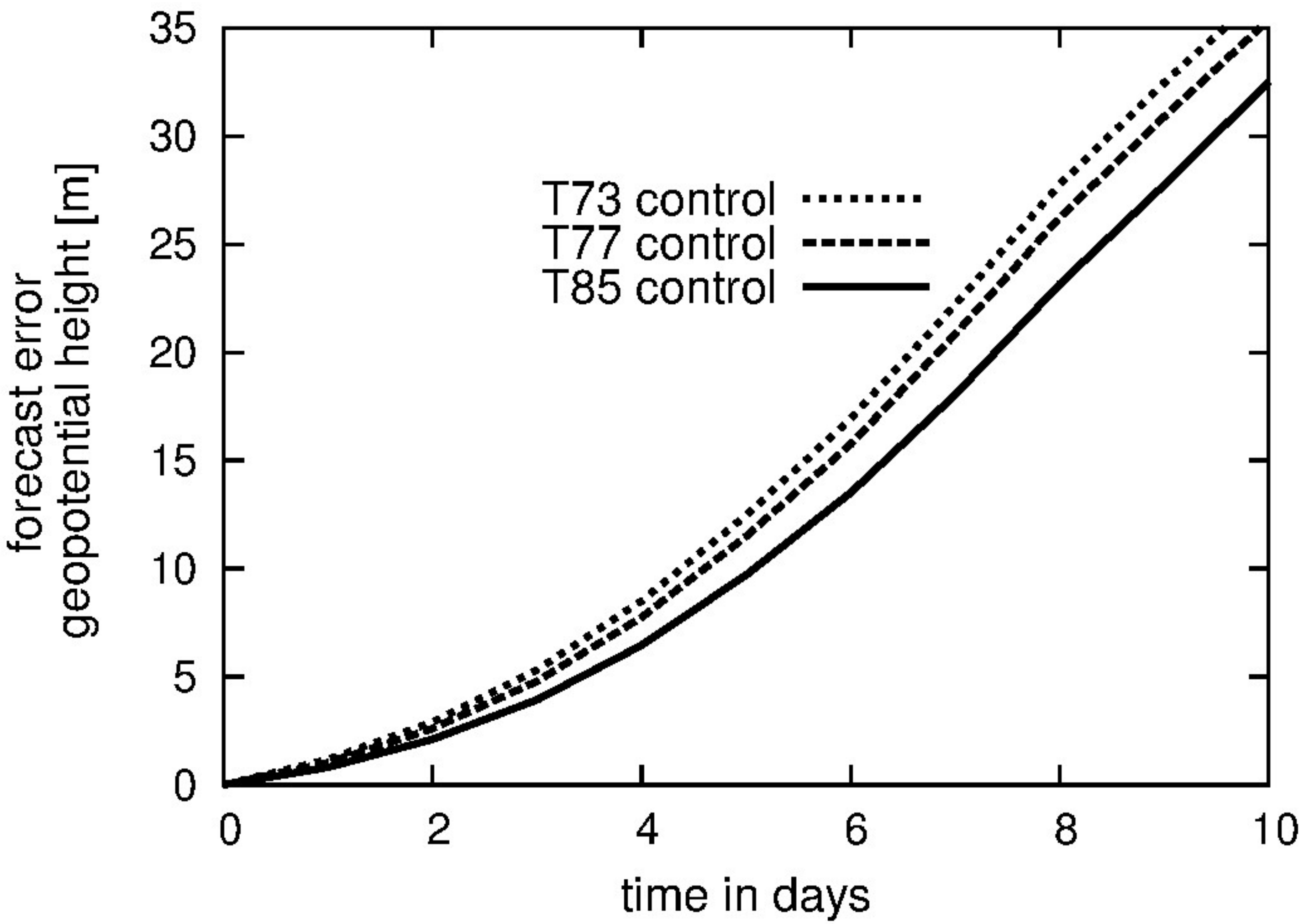
20% fault rate on Y variables


Kernel Density Estimate of PDF of X_i


Cross-correlation of X_i with X_{i+1}

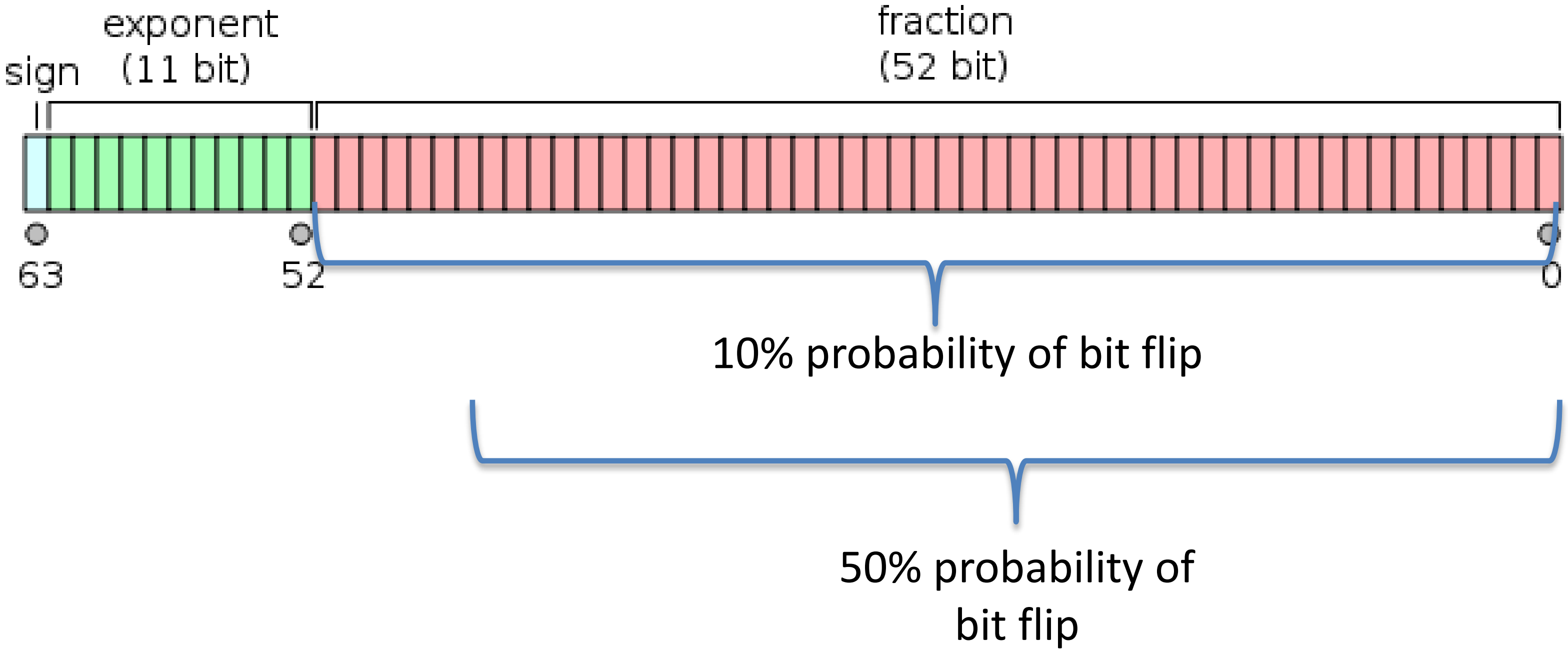
Imprecise L96 is more accurate than parametrised L96

Weather forecasts with imprecise processing



Truth = T159 integration. 500hPa Geopotential height rms error.

Emulator of Stochastic Chip/Reduced Precision on T85 spectral model



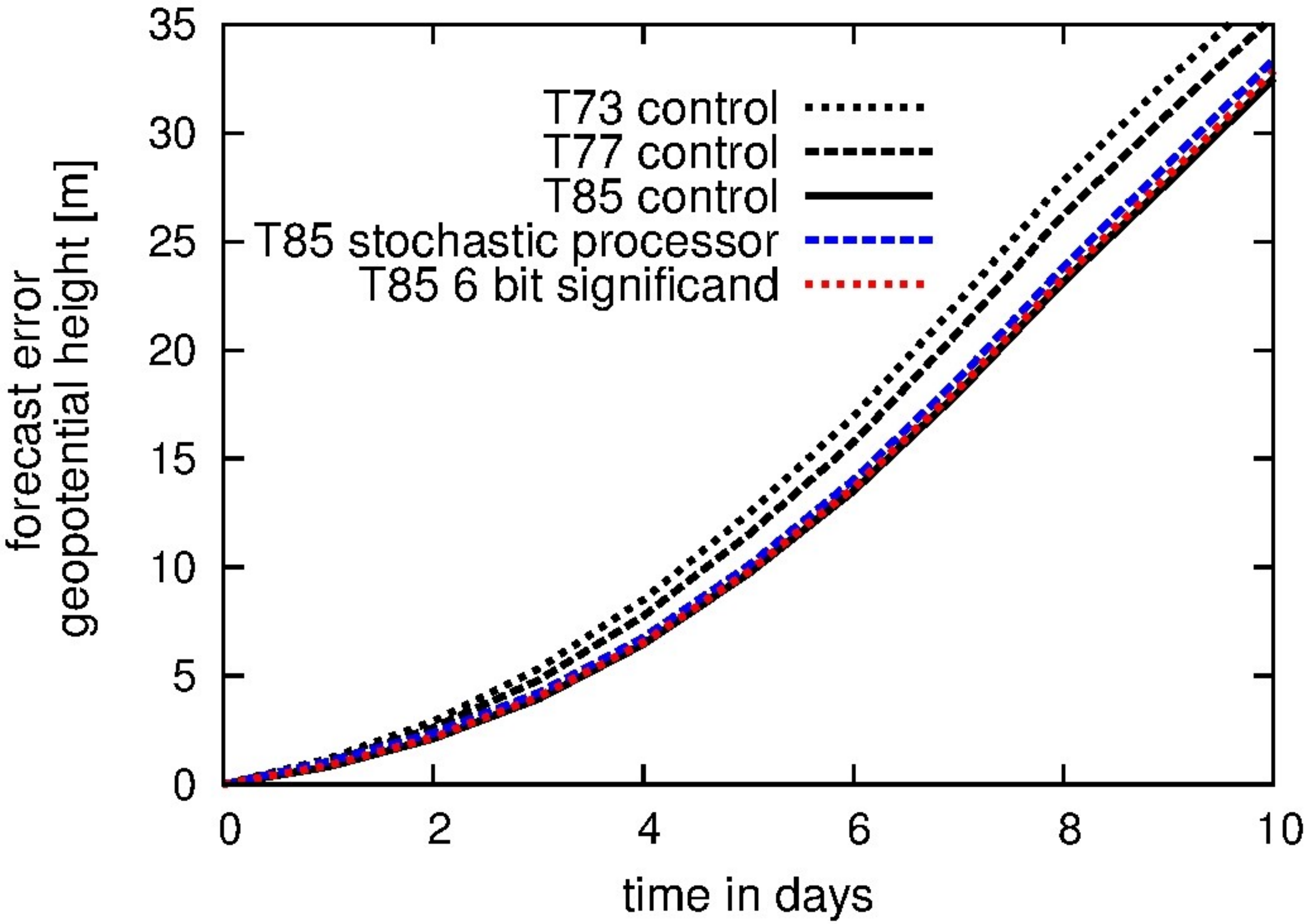
The emulator is used on 50% of numerical workload:

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

Weather forecasts with imprecise processing

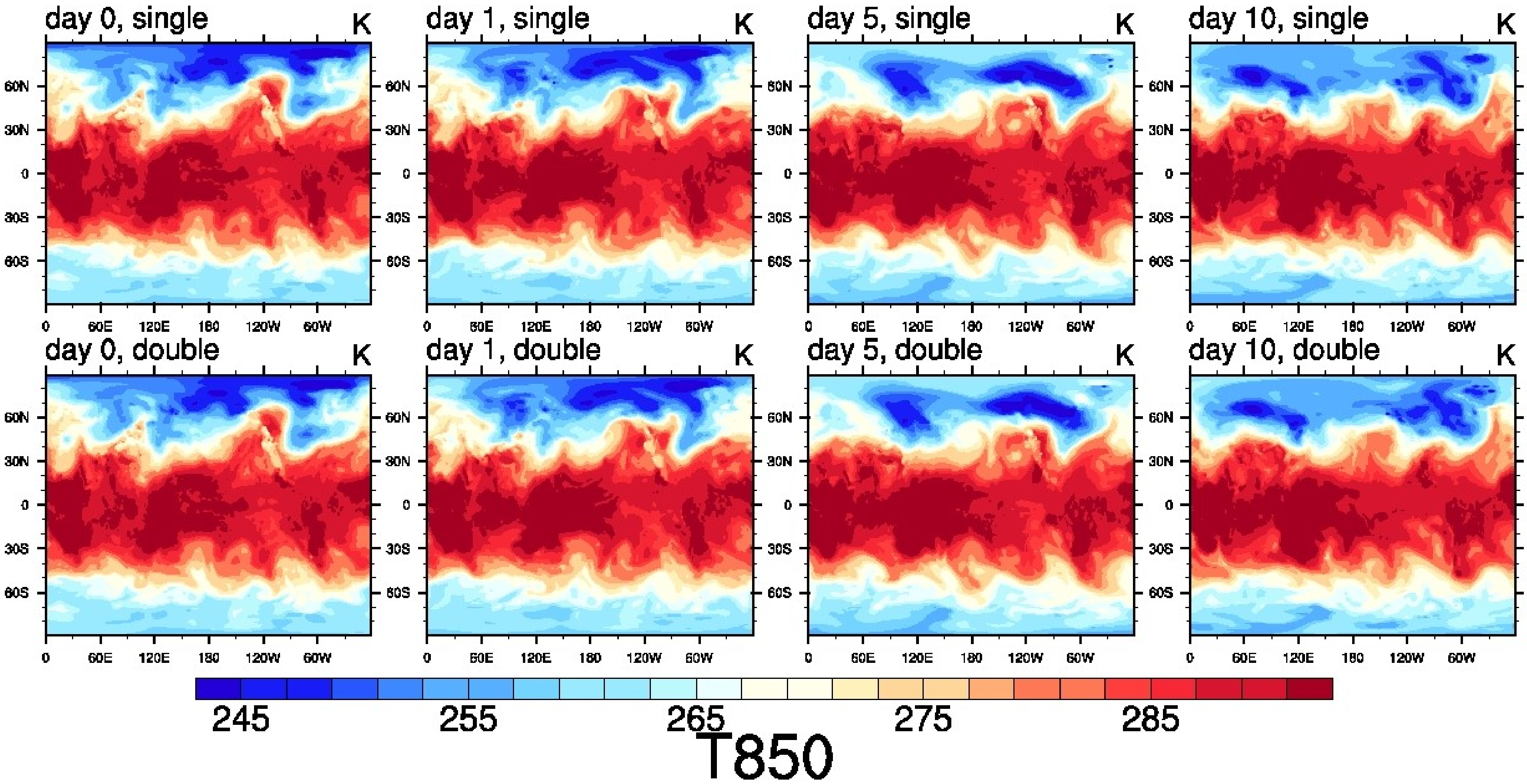


Would the IFS work in single precision?

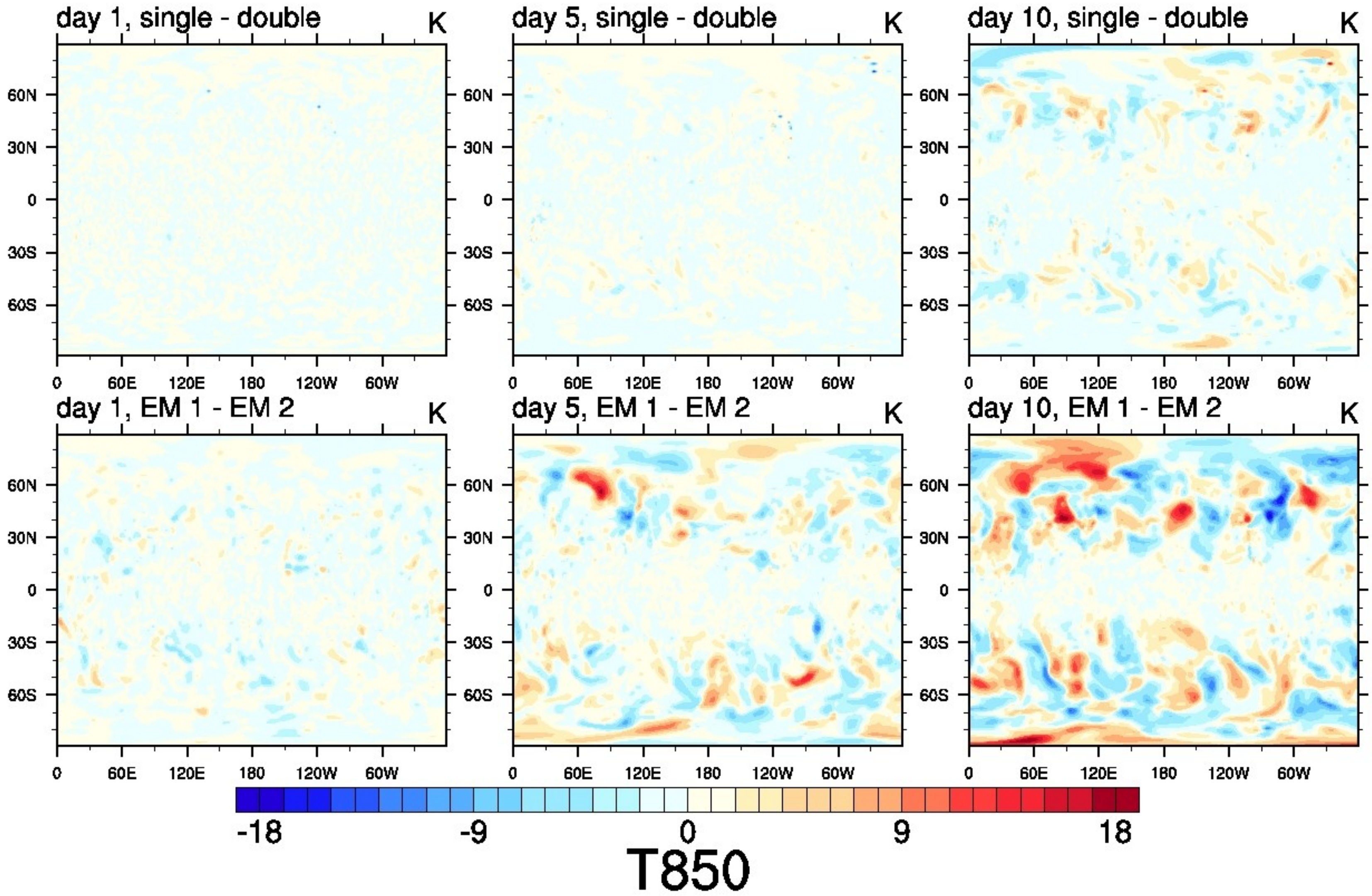
Approach:

- Using OpenIFS, (nearly) all of the double precisionnumbers have been replaced by single precision floating point numbers.
- We perform a weather forecast at T159 resolution with double and with single precision and compare the results.

Would the IFS work in single precision?



Would the IFS work in single precision?



Top row: Differences between the double and the single precision simulation.

Bottom row: Differences between two ensemble members for a T159 IFS forecast with SPPT

Could we run leg2 EPS
at higher resolution
using single precision
arithmetic?

In a presentation at ECMWF on Challenges in Application Scaling in an Exascale Environment, IBM’s Chief Engineer for HPC, Don Grice, noted that:

“Increasingly there will be a tension between energy efficiency and error detection”,

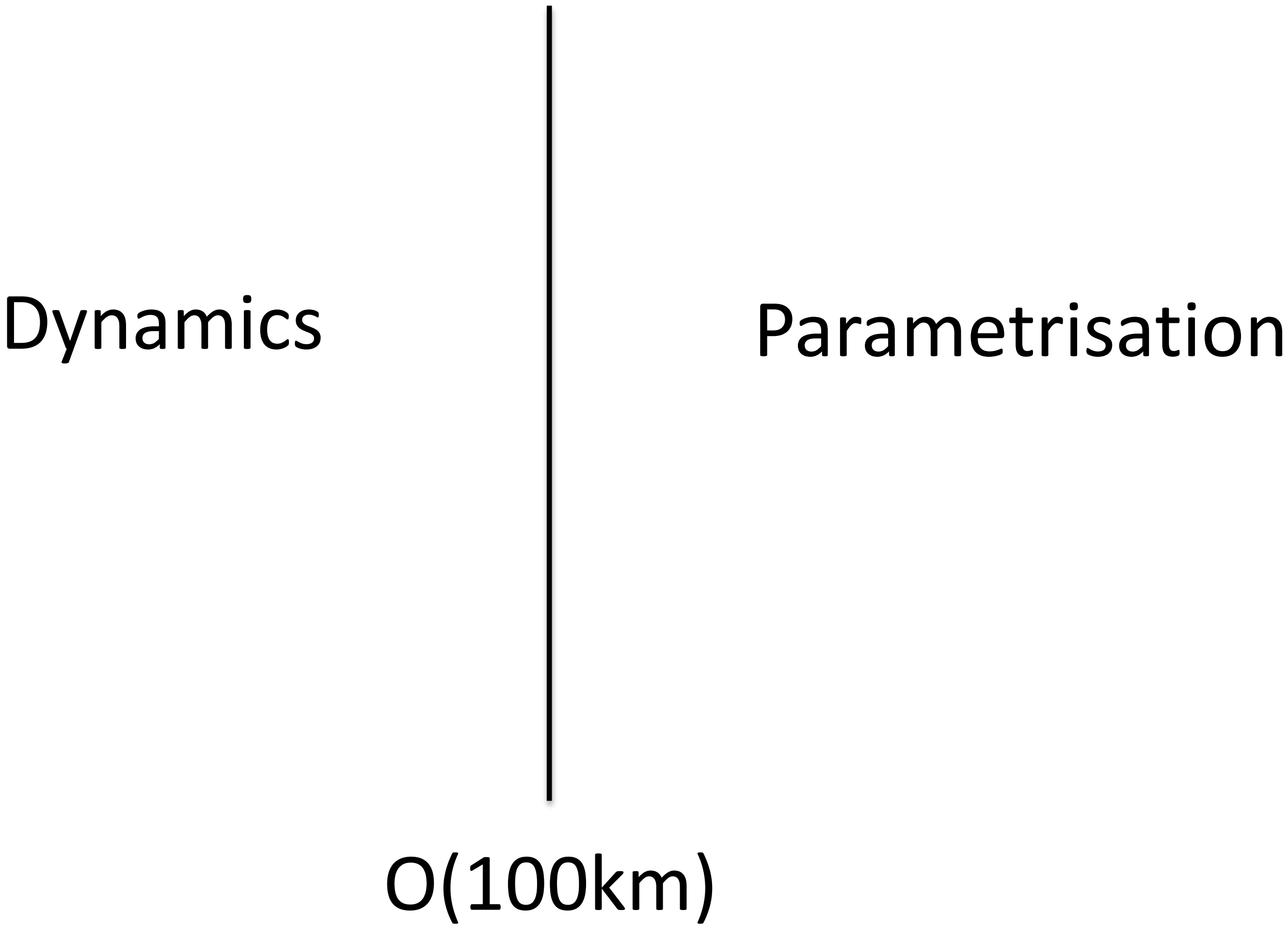
and asked whether :

“…there needs to be a new software construct which identifies critical sections of code where the right answer must be produced”
(http://www.ecmwf.int/ newsevents/meetings/workshops/2010/high performance computing 14th/index.html)

In the context of NWP/Climate models

- Which parts of the code need to be precise and which parts not?
- Where can we drop the need for precise determinism?
- Is a discriminating approach to the use of precision/imprecision, determinism/stochasticity, a credible route for evolution to ultra-high resolution (eg <1km) – and hence more reliable weather and climate forecasts - by 2020?

20 Years Ago

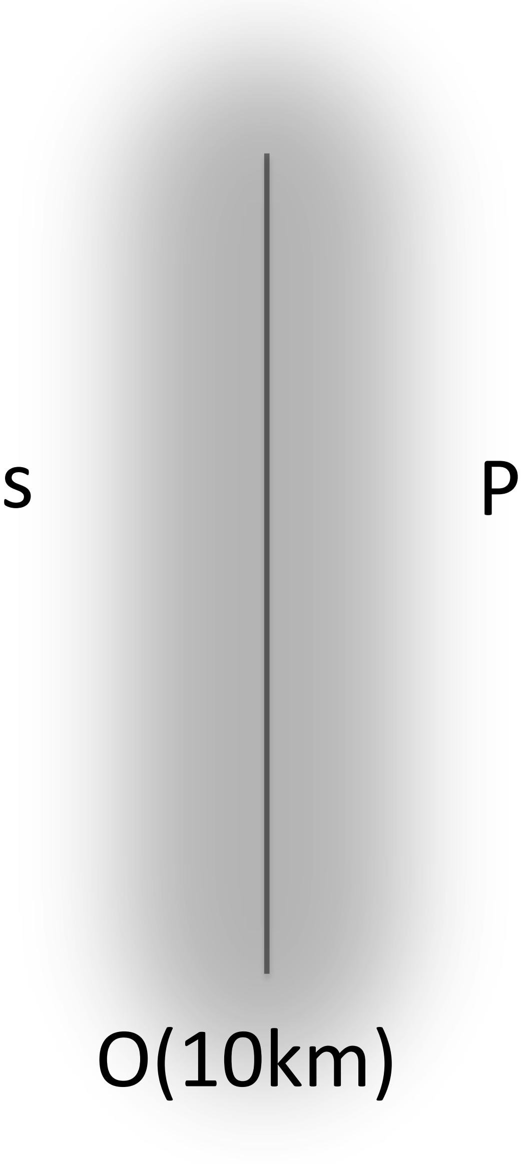


Dynamics

Parametrisation

O(100km)

Now

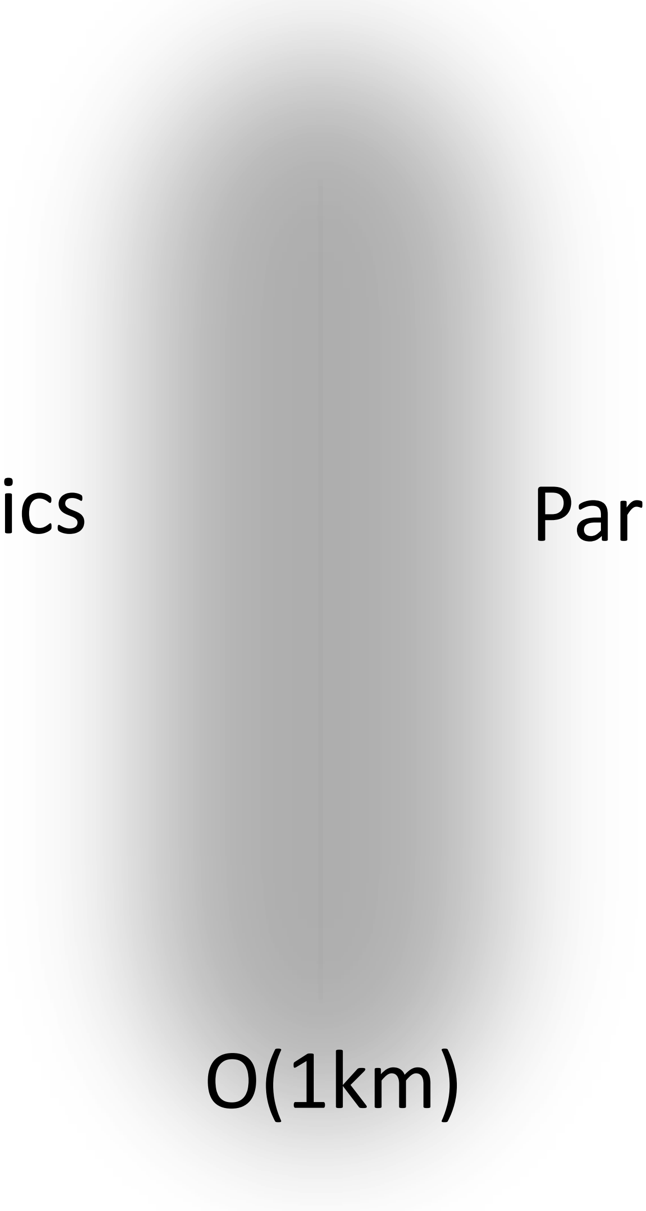


Dynamics

Parametrisation

O(10km)

By 2020?



Dynamics

Parametrisation

O(1km)