Climate Change, Chaos and Inexact Computing

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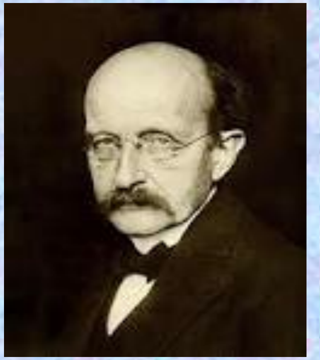
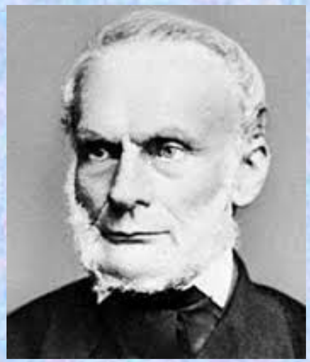
Comprehensive weather/climate models play an important role in modern society

- Forecasting extreme weather events (e.g. for Disaster Risk Reduction)
- To provide scientific input on climate mitigation (decarbonising the world economy)
- To provide guidance on infrastructure investment for regional climate adaptation
- To try to foresee regional consequences of geoengineering proposals ("Plan B")

Comprehensive Earth-System models are based on the laws of physics eg





$$E = \hbar\omega$$

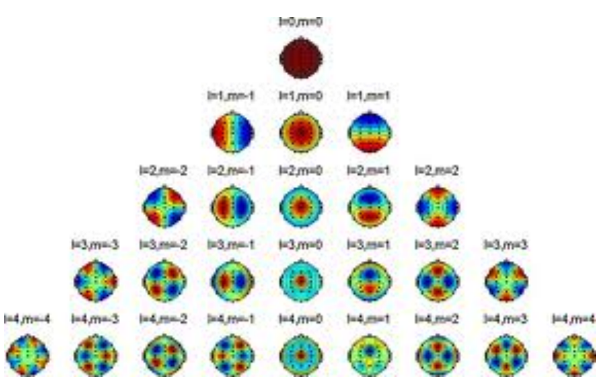
$$\mathbf{F} = m\mathbf{a}$$

$$\delta Q = TdS$$

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

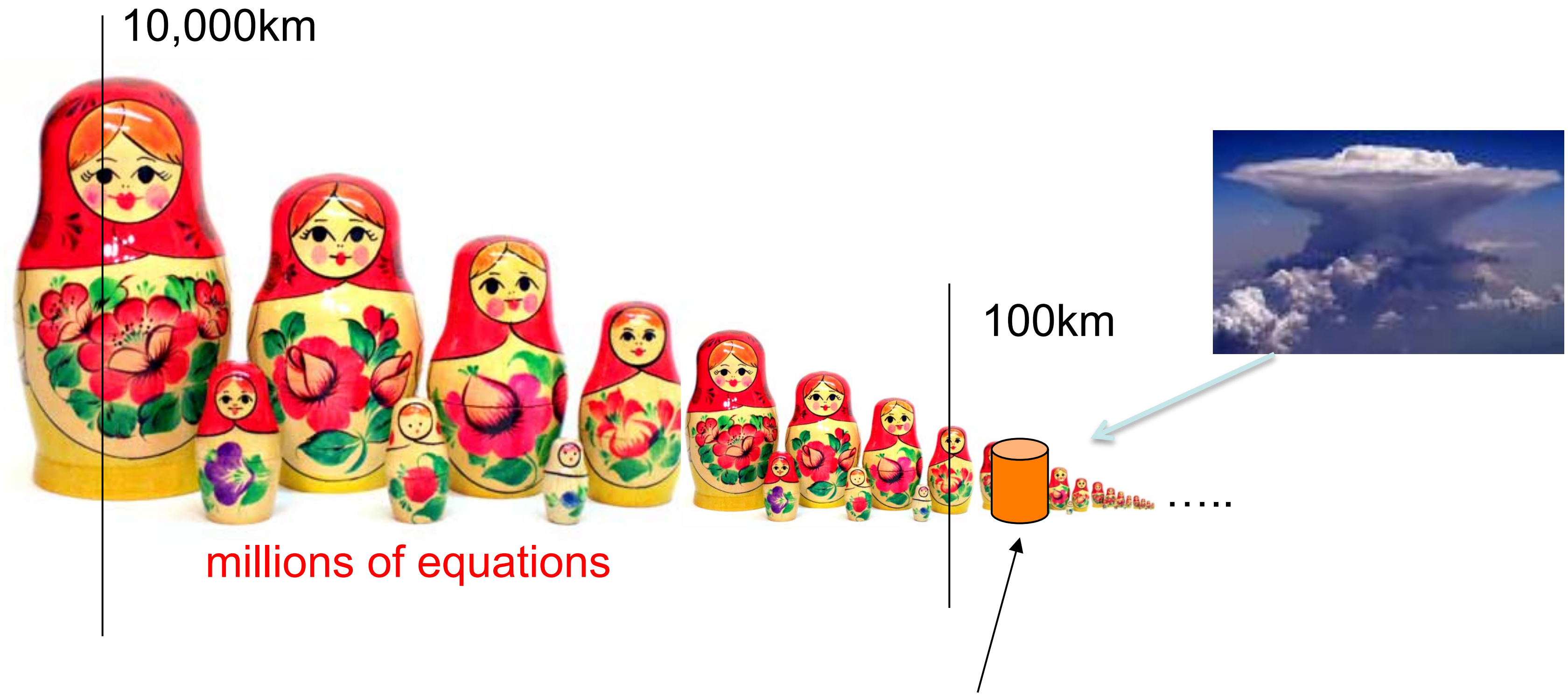
$$\zeta = \sum_{m\ l}^{\infty} \zeta_{ml} e^{im\lambda} P_l^m(\phi)$$

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



Unpacks into billions of individual equations, describing scales of motion from planetary scales to microscopic scales.

Even the world's biggest computers aren't big enough to represent all scales of motion in the atmosphere down to viscous scales



Simplified approximate closure formulae to describe the effect of atmospheric processes (eg clouds) that the simulator can't resolve. The principal source of model biases.

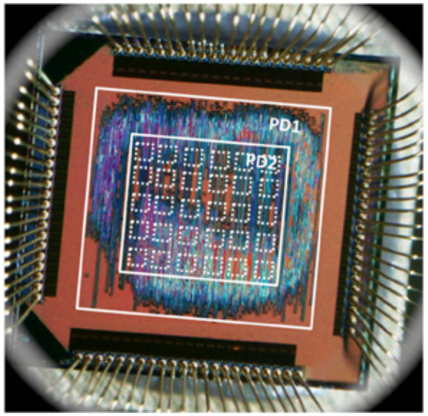
Exaflop computer (10^{18} floating point computations/s) will allow climate models to start resolving individual (deep convective) cloud systems, but…

- Individual climate centres will have to wait many years before they can afford one (2030s?). Can society afford to wait that long?
- Climate institutes must pool resources to afford dedicated exascale computing within the coming decade (cf Climate-CERN-ICTP)
- Energy costs will be very substantial, and will limit what can be achieved.
- Is there an alternative to conventional energy-intensive bit-reproducible computing?

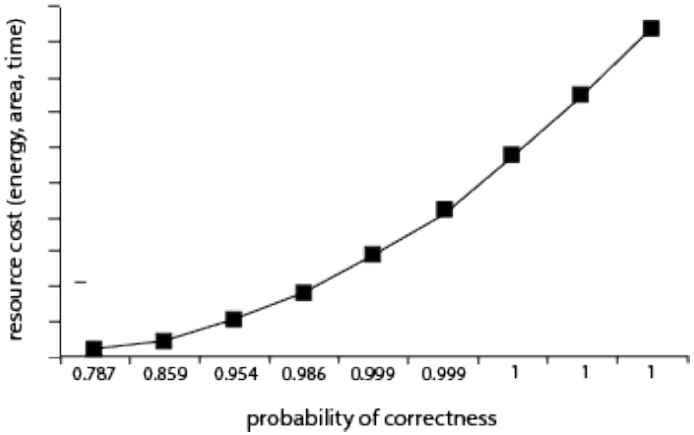
Superefficient inexact chips

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

Prototype
Probabilistic
CMOS
Chip



Krishna Palem.
Rice University



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).

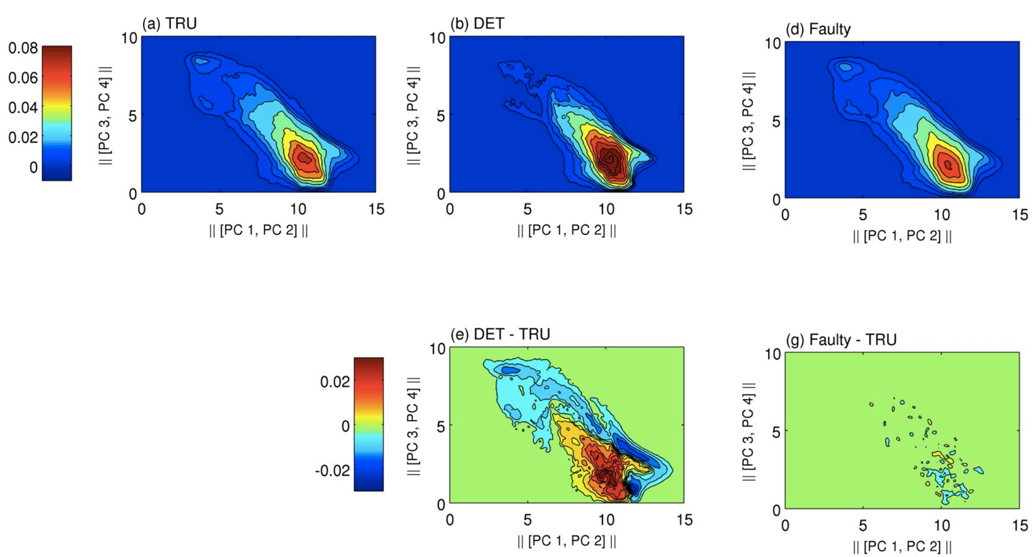
Experiments with the "2-Scale" Lorenz '96 System

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

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

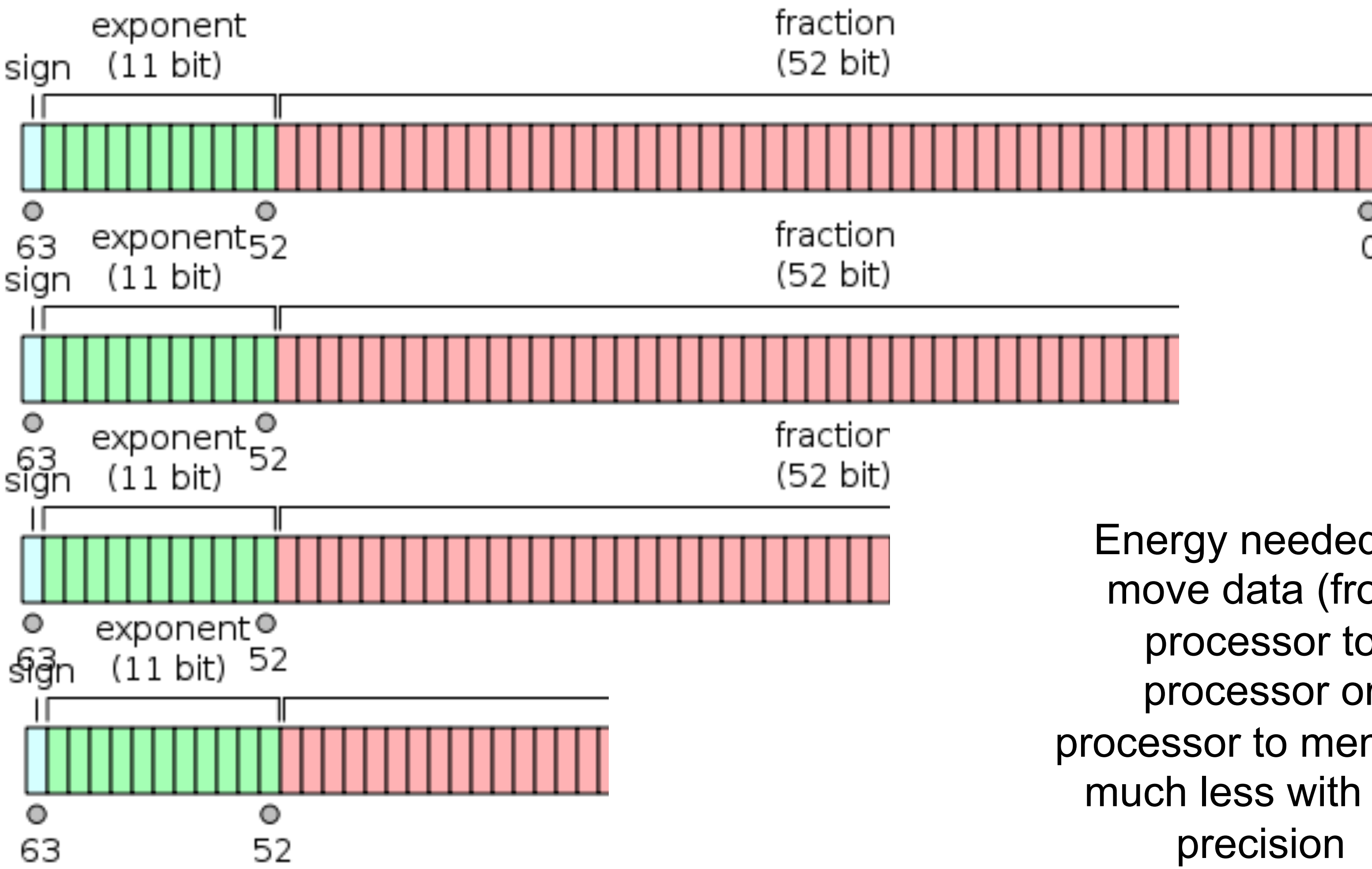
Deterministic parametrisation of Y

Stochastic Chip Emulator



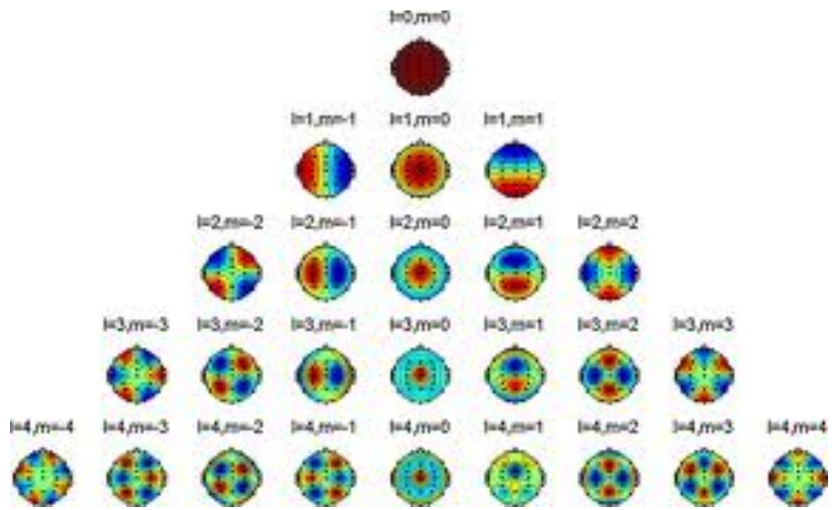
Christensen et al, Climate Dynamics, 2014 + Düben+ McNamara

Do we need to represent variables eg near the truncation scale by double precision floating point numbers?



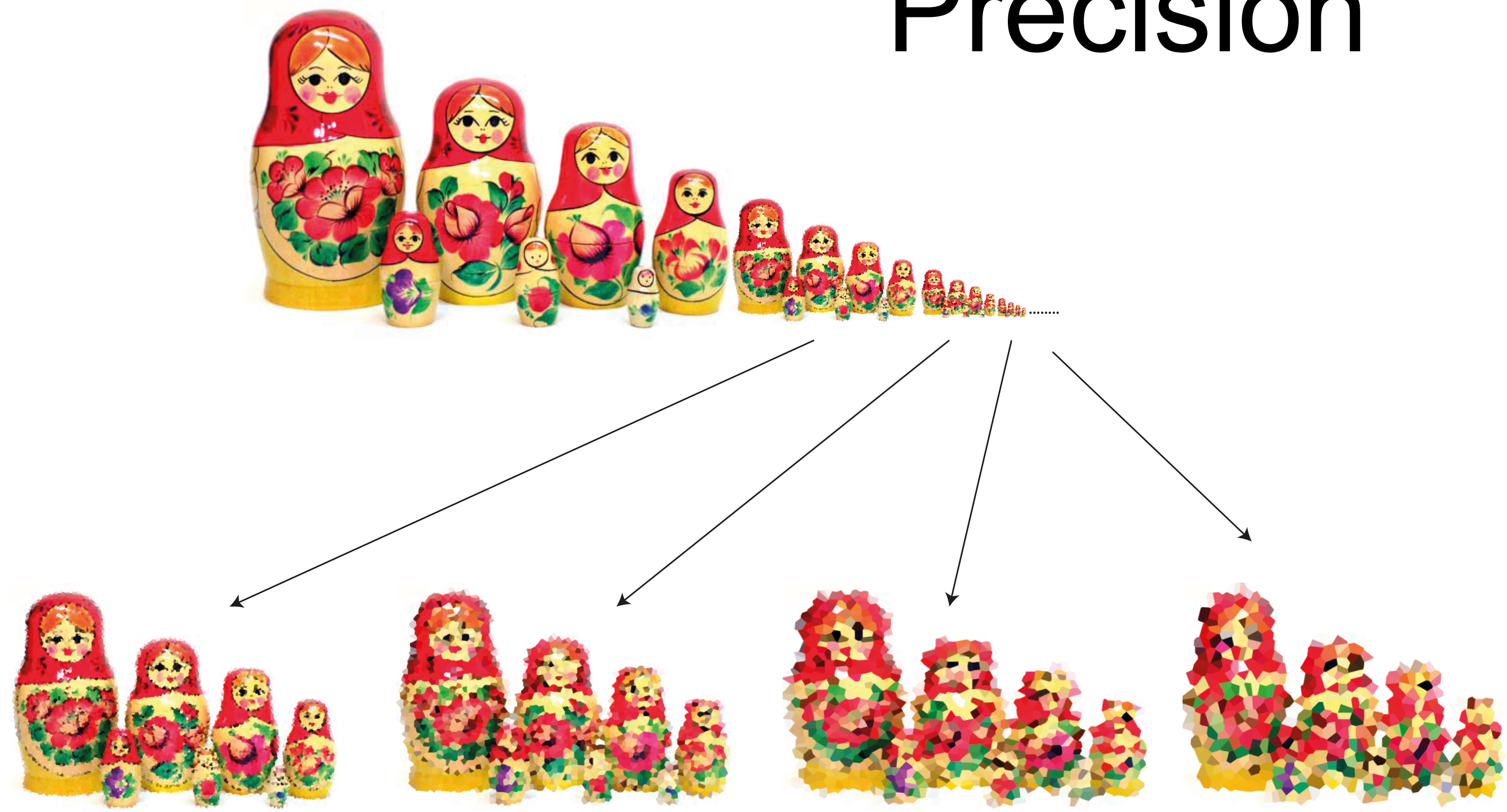
Energy needed to move data (from processor to processor or processor to memory) much less with low precision representations

A fast-track route to cloud-resolved global climate models?



Decreasing precision, and determinism

Greater Accuracy with Less Precision



By degrading precision as a function of scale, we can, for a given energy resource, represent more of the spectrum of scales with the full N-S equations.

The underpinning theoretical question

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

How to quantify the information content in the N-S variables as a function of scale (in the light of scale-dependent chaotic variability)?

The important practical question

Supercomputers with variable and programmable levels of inexactness will require significant hardware redesign.

Chip manufacturers will not develop these unless they perceive there is a substantial market for them.

Could the notion of inexact computing be relevant in other areas of physics (astro, cosmology, plasma, solid state, high energy, etc….)?

If so, please email me at t.n.palmer@atm.ox.ac.uk