A Grand Challenge for the Science of Weather and Climate Prediction:
Towards the Prototype Probabilistic Earth-System Model

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and
University of Oxford
There are essentially two types of climate model

1. Idealised models eg

\[ \pi (1 - A) F_{\text{sun}} = 4 \pi \sigma T_{\text{earth}}^4 \]
..or (idealised barotropic vorticity equation)

\[
\frac{\partial}{\partial t} \nabla^2 \psi + J \left( \psi, \nabla^2 \psi + f \right) + \gamma J \left( \psi, h \right) + C \nabla^2 (\psi - \psi^*) = 0
\]

\[\begin{align*}
\gamma x_3 - C(x_1 - x_1^*) \\
-\beta x_3 - Cx_2 \\
-\beta x_2 - \gamma x_1 - Cx_3
\end{align*}\]

Westerly/block flow regimes as multiple equilibria

Charney DeVore, 1979
2. “Ab initio”\textsuperscript{1} climate models eg based on

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

where the weather systems which characterise climate, are modelled explicitly from first principles.

\textsuperscript{1}“Ab initio” models are sometimes, more pejoratively, referred to as “Brute force” models
Towards the Comprehensive Climate Model

1970
Atmosphere

1985
Atmosphere
Land surface

1992
Atmosphere
Land surface
Ocean & sea-ice

1997
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol

2000
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol
Carbon cycle

Off-line model development

Strengthening colours denote improvements in models

1975
1985
1992
1997
2000

The Met.Office Hadley Centre
“Ab initio” models are important if we are to have confidence in predictions of global warming. Eg

\[ \pi(1 - A)F_{\text{sun}} = 4\pi\sigma T_{\text{earth}}^4 \]

Albedo depends on cloud cover, ice cover etc. Cannot be specified a priori, but depends on dynamics.
Ab initio models are also needed, eg to guide adaptation strategies…

Drought Britain
Water shortages and wastage: how it affects you

Will blocking become more prevalent under climate change…more reservoirs, national water grid etc…..??
...and, increasingly, to assess regional impacts of climate geoengineering proposals

Permanent El Nino, shutoff in monsoons.....?????
Frequently-heard paradigm (20th Century vintage):

• Mathematicians (the academic community more generally) develop the idealised, mathematically tractable, models for improved understanding

• "Software engineers in meteorological institutes develop the brute force models for quantitative predictions"

I think this paradigm is outdated. In this lecture I wish to promote a new paradigm for the 21st Century
Standard ansatz for “ab initio” weather/climate models

**Deterministic local bulk-formula parametrisation**

\[ P(X_n; \alpha) \]

**Eg momentum “transport” by:**
- Turbulent eddies in boundary layer
- Orographic gravity wave drag.
- Convective clouds

\[
\rho \left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = \rho \mathbf{g} - \nabla p + \nu \nabla^2 \mathbf{u}
\]
Standard bulk-formula parametrisation assumes the existence of a large ensemble of eg convective cloud systems within a grid box, in quasi-equilibrium with the large-scale flow.

Similar considerations for other parametrised processes, eg orographic gravity wave drag
Parametrisations motivated by statistical mechanics (eg molecular diffusion), but...

Wavenumber spectra of zonal and meridional velocity compositied from three groups of flight segments of different lengths. The three types of symbols show results from each group. The straight lines indicate slopes of $-3$ and $-5/3$. The meridional wind spectra are shifted one decade to the right. (after Nastrom et al, 1984).

...there is no scale separation between resolved and unresolved scales at NWP truncations (eg convection, orography)
Calculate exact PDF of sub-grid temperature tendencies in a coarse-grained (~50km) grid box based on output from a cloud-resolving (~1km) model treated as “truth”.

PDFs are constrained such that parametrised tendencies based on coarse-grain input fields lie within boxes of width 6K/day.

Width of pdf $\propto$ parametrised tendency

Shutts and Palmer, J.Clim, 1987
From Schertzer and Lovejoy, 1993
Definitions of Parametrisation

Traditional definition (Jacob 2010):

“Despite ..computational advances..many of the processes occurring in the atmosphere..remain unresolved. **It is therefore necessary to represent those subgrid-scale processes as a function** of the grid-scale variables. The technique to achieve this...is ..referred to as parametrization. “

*Wikipedia: The mathematical concept of a function expresses the idea that one quantity (the argument of the function) completely determines another quantity (the value of the function).

Consider replacing with

……It is therefore necessary to consider how grid-scale variables might constrain some prior probability distribution of sub-grid processes. The technique to achieve this is referred to as stochastic parametrization.
A stochastic-dynamic paradigm for a Probabilistic Earth-System Model

Potentially Coupled over a range of scales

(Palmer, 1997; 2001)

Increasing scale

Computationally-cheap nonlinear stochastic-dynamic models (potentially on a secondary grid) providing specific realisations of sub-grid motions rather than sub-grid bulk effects.
Examples:

• **Multiplicative Noise** (Stochastically Perturbed Parametrisation Tendencies; SPPT - Buizza et al, 1999)

• **Stochastic Backscatter** (Stochastic Spectral Backscatter Scheme; SPBS, Shutts, 2005, Berner et al 2010)

• **Cellular Automata** (Palmer 1997, Berner et al 2010)

• **Stochastic lattice models** (Majda et al, 2010)

• **Dual grid, stochastic mode reduction** (Majda et al, 2010; Allen et al, 2010)

• **Statistical mechanics of finite sized cloud ensembles** (Plant and Craig 2008)

• **(Perturbed Parameters)** (Stainforth et al, Smith et al)

• **(Superparametrisation)** (Randall et al, 2003)
Five motivational reasons for stochastic parametrisation
1. As a new approach to reducing model biases
Lenny Smith, personal communication
Surface Pressure

Persistent Blocking Anticyclone

Potential Vorticity on 315K
Blocking frequency in DEMETER hindcasts

November start, 1959-2001, 9-member ensembles
January (third month)
ERA40 Single models

CNRM

ECMWF

Met Office
“The mechanisms for atmospheric blocking are only partially understood, but it is clear that there are complex motions, involving meso-scale atmospheric turbulence, and interactions that climate-resolution models may not be able to represent fully.”

“In developing the UKCP09 projections it was decided not to include probabilistic projections for future wind due to the high level of associated uncertainty.”
Will future UK offshore winds be strong enough to provide projected energy needs from renewables?

We don’t know!
Stochastic parametrisation has potential to alter the mean state of the (nonlinear) model.

Eg ball bearing in potential well.
• Experiments with model cycle 31R1
• Experiments with Berner et al (JAS 2009) stochastic backscatter scheme
• Winters (Dec-Mar) of the period 1990-2005
2. As a new approach to representing model uncertainty in ensemble forecasting
Towards Comprehensive Earth System Models

1970
- Atmosphere
- Land surface
- Ocean & sea-ice

1985
- Atmosphere
- Land surface
- Ocean & sea-ice
- Sulphate aerosol

1992
- Atmosphere
- Land surface
- Ocean & sea-ice
- Sulphate aerosol
- Non-sulphate aerosols

1997
- Atmosphere
- Land surface
- Ocean & sea-ice
- Sulphate aerosol
- Non-sulphate aerosols
- Carbon cycle

2000
- Atmosphere
- Land surface
- Ocean & sea-ice
- Sulphate aerosol
- Non-sulphate aerosols
- Carbon cycle
- Atmospheric chemistry

Off-line model development

Strengthening colours denote improvements in models

1975
- 1985
- 1992
- 1997
- 2000
The Met. Office

Hadley Centre

Uncertainty

A Missing Box

Sulphate aerosol
Non-sulphate aerosol
Carbon cycle
Atmospheric chemistry

Off-line model development

Strengthening colours denote improvements in models
Multi-model ensemble
In ENSEMBLES the relative ability of these different representations of uncertainty has been tested:

- Multi-model ensembles
- Perturbed parameters
- Stochastic parametrisation (SPPT+SPBS)

by making probabilistic seasonal climate predictions.
“Giorgi” Regions
<table>
<thead>
<tr>
<th>Region</th>
<th>JJA</th>
<th>DJF</th>
<th>lead time: 2-4 months, hindcast period: 1991-2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>dry</td>
<td>wet</td>
<td>SP best 38 45%</td>
</tr>
<tr>
<td>Amazon Basin</td>
<td></td>
<td></td>
<td>MM best 20 24%</td>
</tr>
<tr>
<td>Southern South America</td>
<td></td>
<td></td>
<td>no SP best 8 10%</td>
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<tr>
<td>Central America</td>
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<td></td>
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<tr>
<td>Western North America</td>
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<td>Central North America</td>
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<tr>
<td>Eastern North America</td>
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<td>Alaska</td>
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<td>Mediterranean</td>
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<td>South East Asia</td>
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<tr>
<td>North Asia</td>
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</tr>
</tbody>
</table>

Comparison of the BSS\(^{\infty}\) for precipitation over land regions: ENSEMBLES multi-model ensemble (MM), perturbed parameter ensemble (PP), ECMWF stochastic physics ensemble (SP) and ECMWF control ensemble (noSP)
Comparison of the BSS($\infty$) for temperature over land regions: ENSEMBLES multi-model ensemble (MM), perturbed parameter ensemble (PP), ECMWF stochastic physics ensemble (SP) and ECMWF control ensemble (noSP).

<table>
<thead>
<tr>
<th>Region</th>
<th>JJA</th>
<th>DJF</th>
<th>BSS Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>cold (3)</td>
<td>cold (3)</td>
<td>MM best (32)</td>
</tr>
<tr>
<td>Amazon Basin</td>
<td>warm (3)</td>
<td>warm (3)</td>
<td>PP best (19)</td>
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<tr>
<td>Southern South America</td>
<td>cold (3)</td>
<td>warm (1)</td>
<td>SP best (25)</td>
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<tr>
<td>Central America</td>
<td>warm (1)</td>
<td>cold (1)</td>
<td>no SP best (8)</td>
</tr>
<tr>
<td>Western North America</td>
<td>warm (3)</td>
<td>warm (1)</td>
<td></td>
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<tr>
<td>Central North America</td>
<td>cold (1)</td>
<td>cold (1)</td>
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<tr>
<td>Eastern North America</td>
<td>cold (3)</td>
<td>warm (2)</td>
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</tbody>
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Lead time: 2-4 months, hindcast period: 1991-2005
SP version 1055m007
3. As a way to make more efficient use of human and computer resources
A community-wide approach to the Climate Model development?
Standard argument against the “Airbus” paradigm:

“We need model diversity in order to be able to estimate prediction uncertainty”

This argument should not be considered dogma, but rather be open to objective scientific evaluation.

The development of a skilful Probabilistic Climate Model allows this argument to be tested, potentially opening the door to greater integration of climate model development, and to much more efficient use of the enormous human and computational resources needed to develop reliable climate prediction models.
4. Emerging Probabilistic Computer Hardware?
A New type of chip: PCMOS (Probabilistic Complementary Metal-Oxide Semiconductor)

Krishna Palem is a hero in the world of microchips, precision and perfection have always been imperative. Every step of the fabrication process involves testing and retesting and it’s almost as if ensuring that every chip calculates the exact answer every time. But Palem, a professor of computing at Rice University, believes that a little error can be advantageous.

Palem has developed a way for chips to use significantly less power in exchange for a small loss of precision. His concept carries the daunting moniker “probabilistic complementary metal-oxide-semiconductor technology” or PCMOS for short. Palem’s premise is that for many applications—in particular those like radio or video processing where the final result isn’t a number—maximum precision is unnecessary. Instead, chips could be designed to produce the correct answer sometimes, but only come close the rest of the time. Because the errors could be small, so would the difference in emissions, Palem believes.

Every calculation done by a microchip depends on transistors’ registering either a 0 or a 1 as electrons flow through them in response to an applied voltage. But electrons move erratically, producing electrical “noise.” In order to overcome noise and ensure that their transistors recognize the correct values, most chips put at relatively high voltage. Palem’s idea is to lower the operating voltage of parts of a chip—specifically, logic circuits that calculate the least significant bits, such as the jitter number 2069. The resulting decrease in signal-to-noise ratio means those circuits would occasionally arrive at the wrong answer, but engineers can calculate the probability of getting the right answer for any specific voltage. “Relaxing the probability of correctness even a little bit can produce significant savings in energy,” Palem says.

Within a few years, chips using such designs could boost battery life in mobile devices such as music players and cell phones. But in a decade or so, Palem’s ideas could have a much larger impact. By then, silicon transistors will be so small that engineers won’t be able to precisely control their behavior or the transistors will be inherently probabilistic. Palem’s techniques could then become important to the continuation of Moore’s Law, the exponential increase in transistor density and thus in computing power, that has prevailed for four decades.

When Palem began working on the idea around 2012, skepticism about the principle behind PCMOS was “pretty universal,” he says. That changed in 2016. He and his students simulated a PCMOS circuit that would be part of a chip for processing videos, such as streaming video in a cell phone, and compared it with the performance of existing chips. They presented the work at a technical conference, and in a show of hands, much of the audience couldn’t observe any difference in picture quality. Applications where the limits of human perception reduce the need for precision are perfectly suited to PCMOS designs, Palem says. In cell phones, laptop computers, and other mobile devices, graphics and sound processing consume a significant amount of power.

Emerging Technologies 2008

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Technolozy
Review

Microsoft's Dazzling App Photosynth

In Iraq, a Technology Surge

MIT News
Cornering Cancer

Probabilistic Chips

A KRISHNA PALEM THOUGHT INTRODUCING A LITTLE UNCERTAINTY INTO COMPUTER CHIPS COULD EXTEND BATTERY LIFE IN MOBILE DEVICES AND MAYBE THE DURATION OF MOORE'S LAW TOO. BY ERNA JOHNETZ

Krishna Palem – Rice University
Technology to Enable 1,000X Performance Over Today’s Digital Processors

SANTA CLARA, Calif., and AUSTIN, Texas – August 17, 2010 – FLASH MEMORY SUMMIT and THE INTERNATIONAL SYMPOSIUM ON LOW POWER ELECTRONICS AND DESIGN – Lyric Semiconductor, Inc. a DARPA- and venture-funded MIT spin-out, today emerged from stealth mode to launch a new technology called probability processing, which is poised to deliver a fundamental change in processing performance and power consumption. With over a decade of development at MIT and at Lyric Semiconductor, Lyric’s probability processing technology calculates in a completely new way, enabling orders-of-magnitude improvement in processor efficiency. Lyric Error Correction (LEC™) for flash memory, the first commercial application of probability processing, offers a 30X reduction in die size and a 12X improvement in power consumption all at higher throughput compared to today’s digital solutions. Lyric Semiconductor has developed an alternative to digital computing. The company is redesigning processing circuits from the ground up to natively process probabilities – from the gate circuits to the processor architecture to the programming language. As a result, many applications that today require a thousand conventional processors will soon run in just one Lyric processor, providing 1,000X efficiencies in cost, power, and size.

For over 60 years, computers have been based on digital computing principles. Data is represented as bits (1s and 0s). Boolean logic gates perform operations on these bits. Lyric has invented a new kind of logic gate circuit that uses transistors as dimmer switches instead of as on/off switches. These circuits can accept inputs and calculate outputs that are between 0 and 1, directly representing probabilities - levels of certainty.
5. Cos the boss said so!
“I believe that the ultimate climate models...will be stochastic, ie random numbers will appear somewhere in the time derivatives” Lorenz 1975.
Where are we now with Stochastic-Dynamic Parametrisation?

- Atmosphere: Partially (SPPT, SPBS)
- Land surface: No
- Ocean: No
- Cryosphere: No
- Biosphere: No
However, stochastic parametrisations are currently “bolt-on” extras, whereas the existence of finite sub-grid pdfs (even when constrained by grid-scale variables) should be considered as primitive in the ab initio development of parametrisations.
Let the time it could take some error at wavenumber $2k$ to infect wavenumber $k$, be proportional to the eddy turn over time $\tau(k) \sim \frac{1}{2}(k)$.

The time it could take for error to propagate $N$ "octaves" to some large-scale wavenumber $k_L$ of interest is

$$\Omega(N) = \sum_{n=0}^{N} \tau(2^n k_L)$$
If $E(k) \sim \ldots$  

$$\Omega(N) = \sum_{n=0}^{N} \tau(2^n k_L)$$

$$= \tau(k_L) \sum_{n=0}^{N} 2^{-2n/3} \sim N \to \infty$$

Hence scaling suggests it could take a finite time for small-scale truncation/parametrisation errors to infect any large scale of interest, no matter how small-scale these uncertainties are confined to.
Clay Mathematics Millenium Problems

- Birch and Swinnerton-Dyer Conjecture
- Hodge Conjecture
- Navier-Stokes Equations
- P vs NP
- Poincaré Conjecture
- Riemann Hypothesis
- Yang-Mills Theory
The Grand Challenge

Mathematicians (the academic community more generally) to help develop a new generation of *ab initio* Earth System Models, modifying or replacing the conventional bulk-formula parametrisation paradigm with innovative stochastic-dynamic mathematics, to aid our ability to predict climate, for the good of society worldwide.
The tools we have to work with:

- Observations
- Cloud resolving models (coarse grain budgets)
- Physics, mathematics and the power of pure reason!
A world-wide network of scientists interested in stochastic parametrisation is being set up, both as an email discussion forum and as the means to set up and promote workshops and conference sessions.

If you are interested in joining this network, please email Judith Berner (NCAR) at berner@ucar.edu