Representing Model Error in Weather and Climate Prediction

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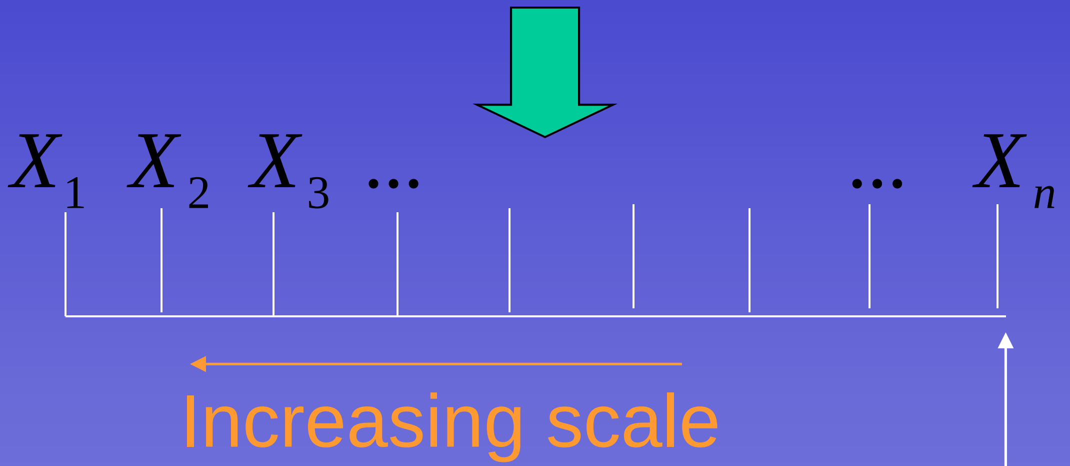
Traditional computational ansatz for weather and climate models

Eg

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



X_1 X_2 X_3 … … X_n

Increasing scale

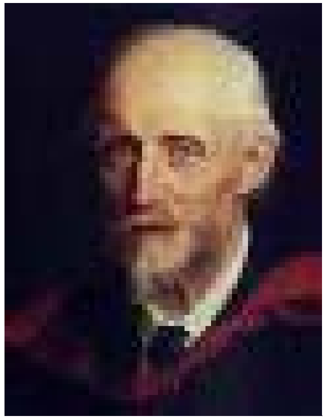
Eg momentum“transport” by:

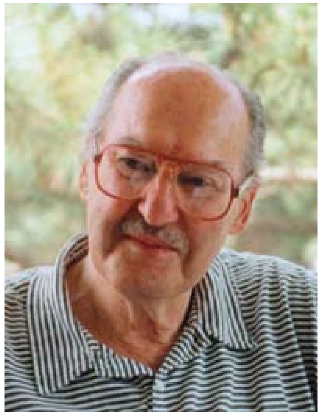
- Turbulent eddies in boundary layer
- Orographic gravity wave drag.
- Convective clouds

Deterministic local bulk-formula parametrisation

$$P\left(X_n;\alpha\right)$$

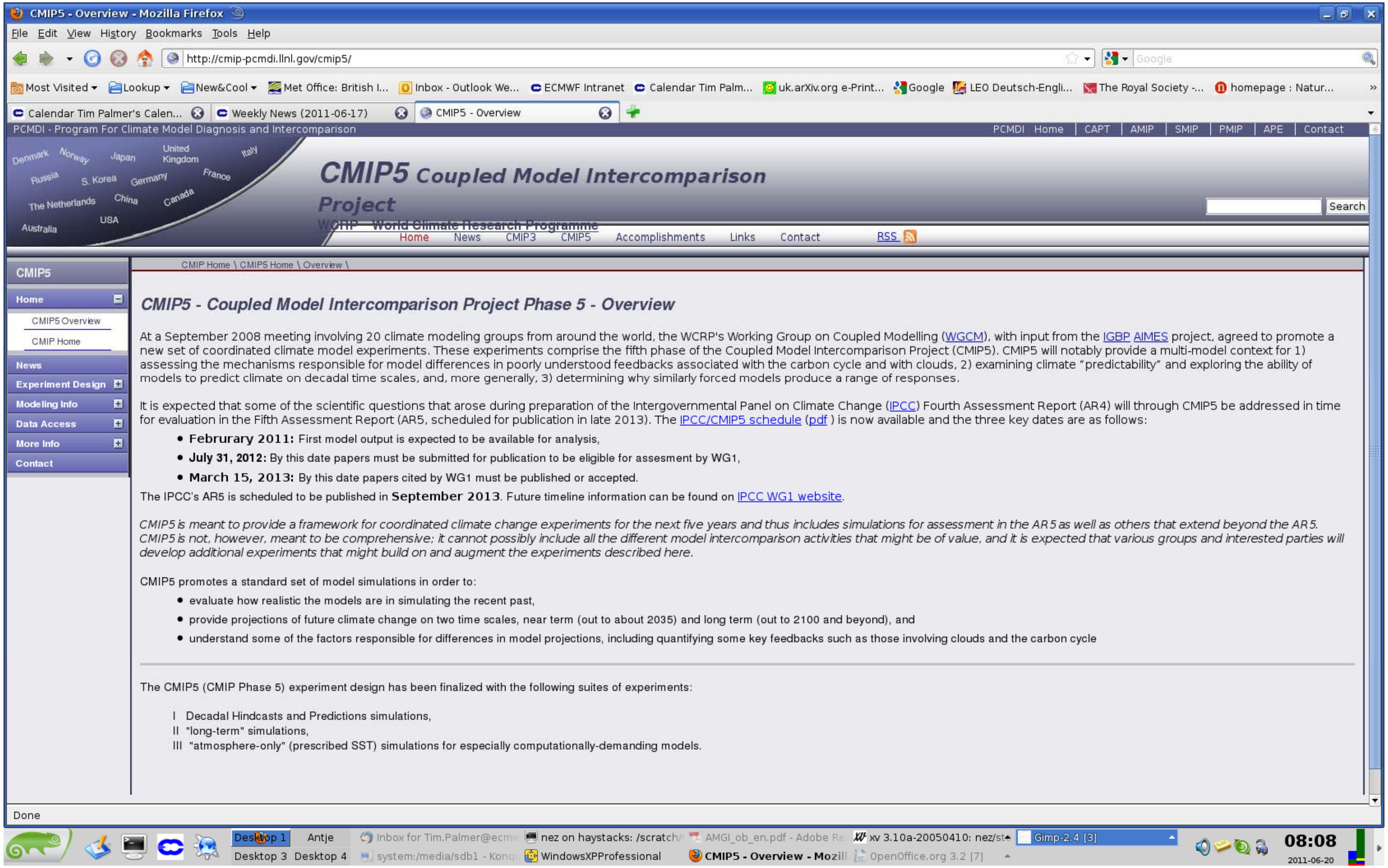
Deterministic closures have a venerable history in fluid mechanics,





but what is the (flow-dependent) impact of errors and uncertainties in these compuational representations of the equations of motion?

The Multi-Model Ensemble



CMIP5 - Coupled Model Intercomparison Project Phase 5 - Overview

At a September 2008 meeting involving 20 climate modeling groups from around the world, the WCRP's Working Group on Coupled Modelling (WGCM), with input from the IGBP AIMES project, agreed to promote a new set of coordinated climate model experiments. These experiments comprise the fifth phase of the Coupled Model Intercomparison Project (CMIP5). CMIP5 will notably provide a multi-model context for 1) assessing the mechanisms responsible for model differences in poorly understood feedbacks associated with the carbon cycle and with clouds, 2) examining climate "predictability" and exploring the ability of models to predict climate on decadal time scales, and, more generally, 3) determining why similarly forced models produce a range of responses.

It is expected that some of the scientific questions that arose during preparation of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) will through CMIP5 be addressed in time for evaluation in the Fifth Assessment Report (AR5, scheduled for publication in late 2013). The IPCC/CMIP5 schedule (pdf) is now available and the three key dates are as follows:

- **Februrary 2011:** First model output is expected to be available for analysis,
- **July 31, 2012:** By this date papers must be submitted for publication to be eligible for assesment by WG1,
- **March 15, 2013:** By this date papers cited by WG1 must be published or accepted.

The IPCC's AR5 is scheduled to be published in **September 2013**. Future timeline information can be found on IPCC WG1 website.

CMIP5 is meant to provide a framework for coordinated climate change experiments for the next five years and thus includes simulations for assessment in the AR5 as well as others that extend beyond the AR5. CMIP5 is not, however, meant to be comprehensive; it cannot possibly include all the different model intercomparison activities that might be of value, and it is expected that various groups and interested parties will develop additional experiments that might build on and augment the experiments described here.

CMIP5 promotes a standard set of model simulations in order to:

- evaluate how realistic the models are in simulating the recent past,
- provide projections of future climate change on two time scales, near term (out to about 2035) and long term (out to 2100 and beyond), and
- understand some of the factors responsible for differences in model projections, including quantifying some key feedbacks such as those involving clouds and the carbon cycle

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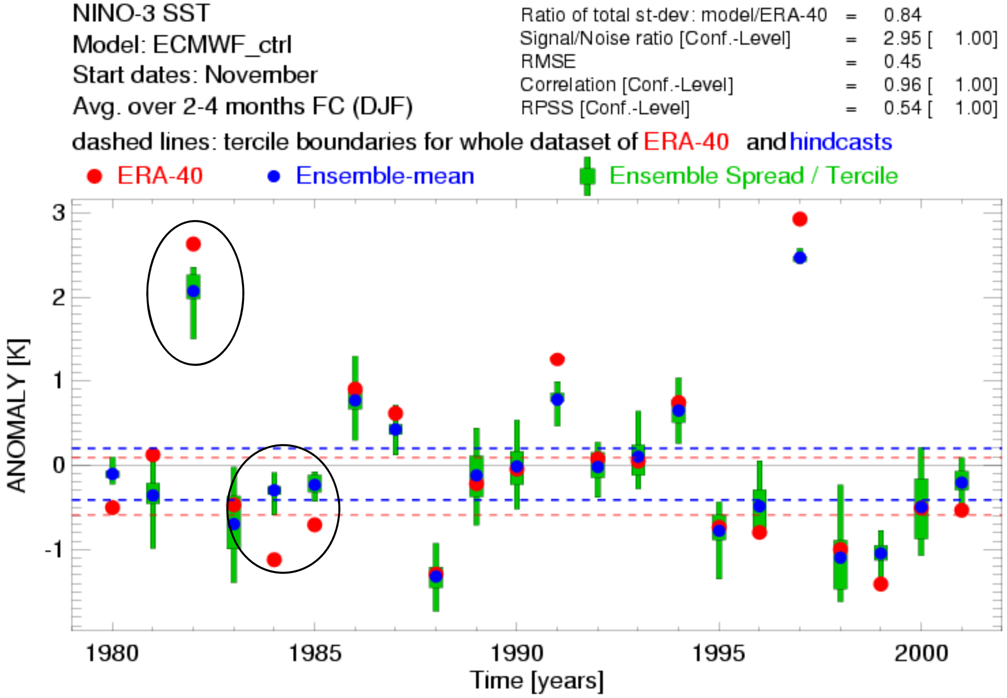
The CMIP5 (CMIP Phase 5) experiment design has been finalized with the following suites of experiments:

I Decadal Hindcasts and Predictions simulations,
II "long-term" simulations,
III "atmosphere-only" (prescribed SST) simulations for especially computationally-demanding models.

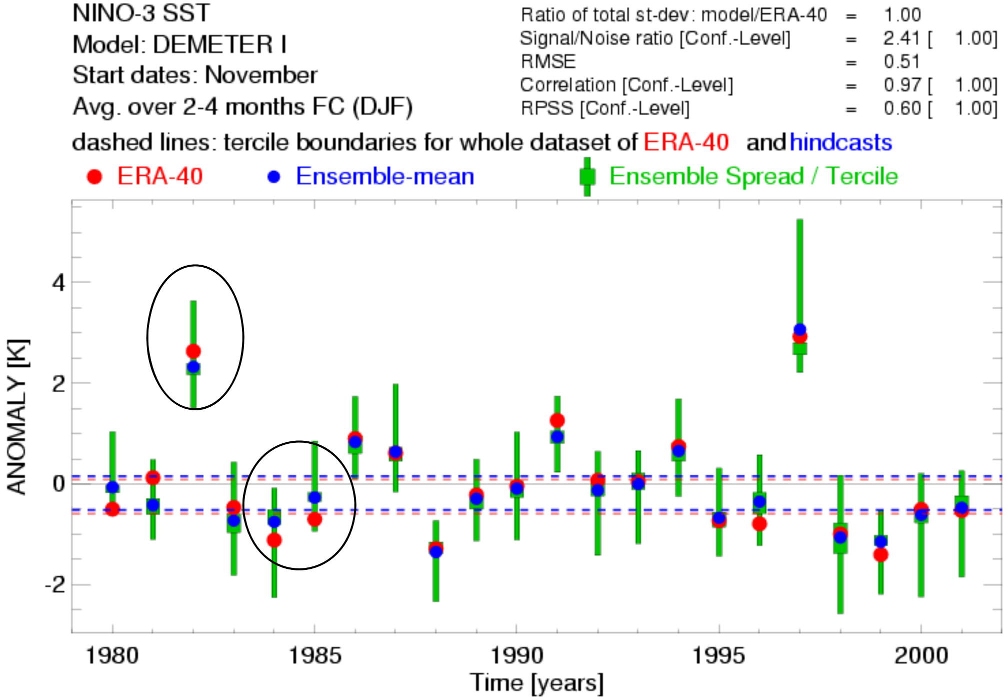
Δημητηρ

Development of a
European Multi-Model Ensemble System
for
Seasonal to Interannual Prediction

ECMWF
Model



DEMETER
MME



Palmer et al,
2004;
Hagedorn et
al 2005

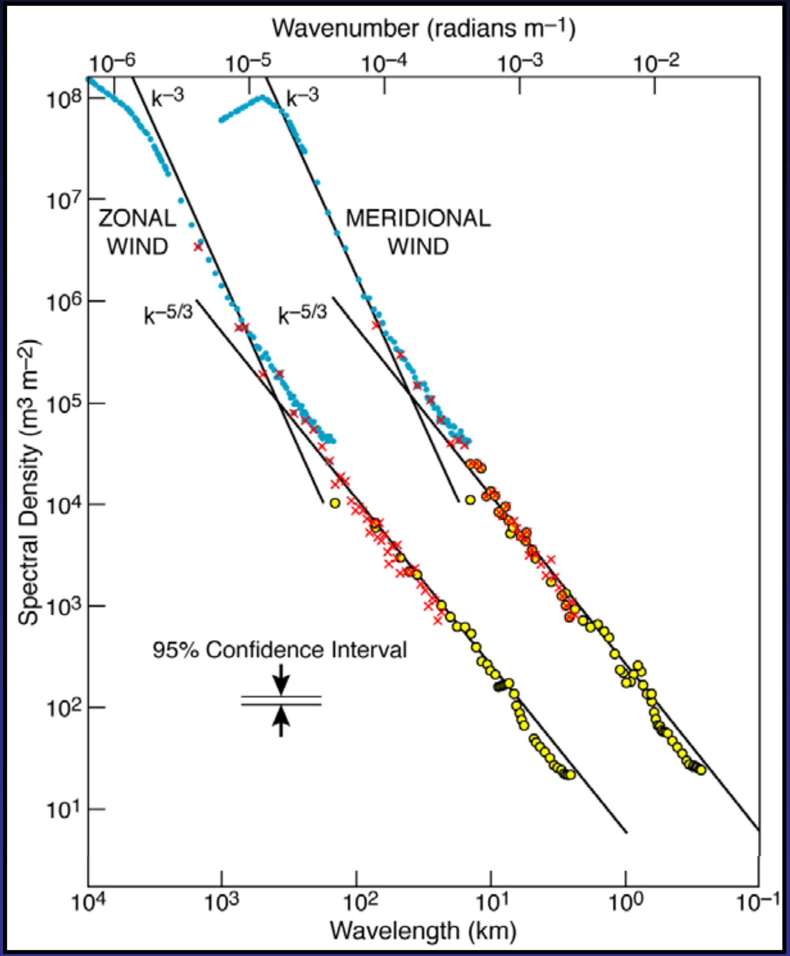
On the Effective Number of Climate Models

Pennell and Reichler. J.Clim. 2011

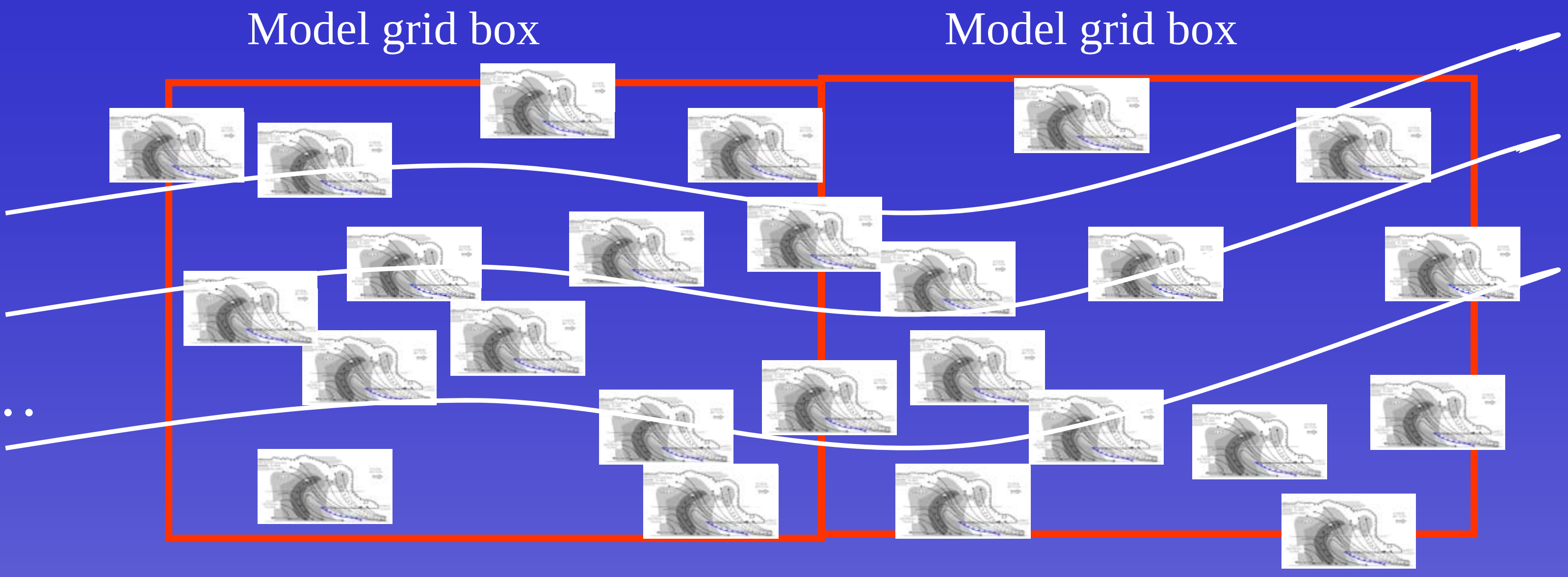
“For the full [CMIP3] 24-member ensemble, this leads to an M_{eff} that…lies only between 7.5 and 9.”

“The strong similarities in model error structures found in our study indicate a considerable lack of model diversity. It is reasonable to suspect that such model similarities translate into a limited range of climate change projections.”

Observations indicate a (shallow) power law for atmospheric energy wavenumber spectra

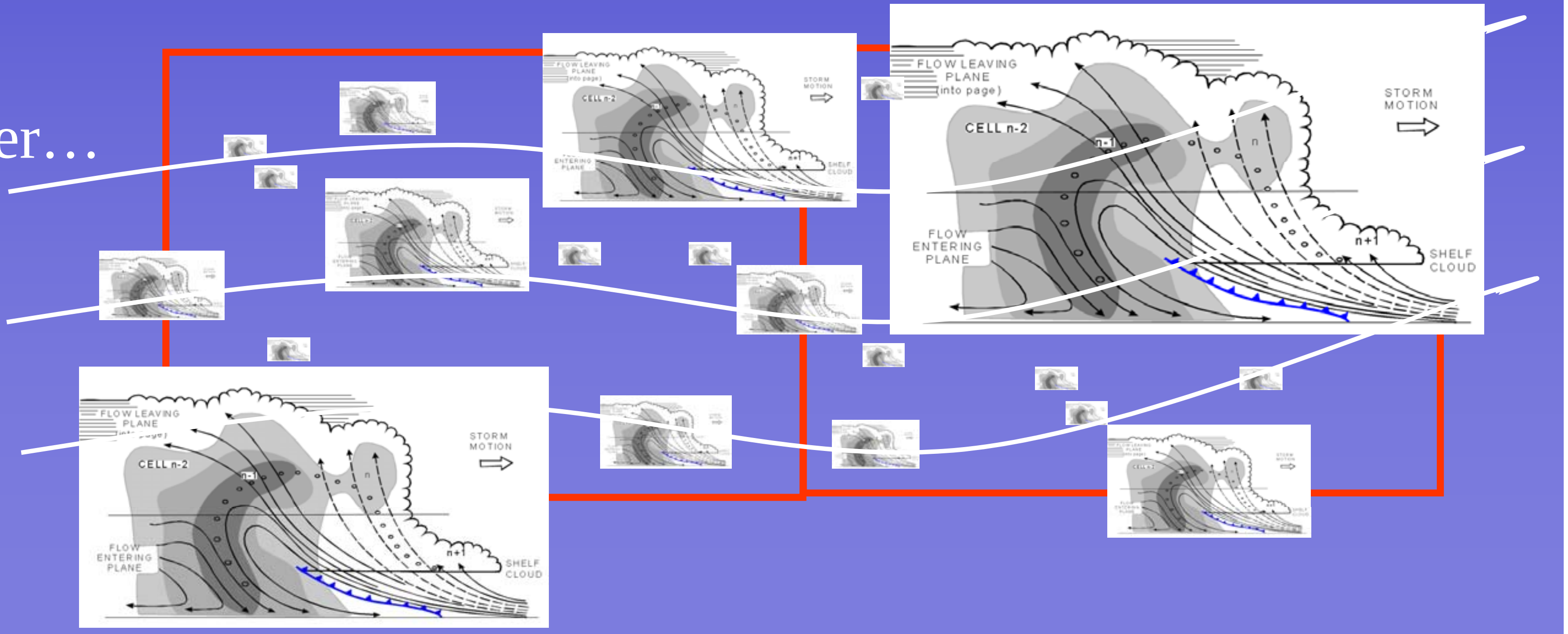


No scale separation between resolved and unresolved processes in weather and climate models



Ie not …

But rather…



Power law consistent with scaling symmetries for Navier Stokes

Let $\mathbf{v},\ p$ be a solution to the Navier Stokes equations.

Then, for any $\tau \in \mathbb{R}^+$,

$$\mathbf{v}_\tau(x,t) = \tau^{-1/2}\mathbf{v}\left(\frac{x}{\tau^{1/2}}, \frac{t}{\tau}\right)$$

$$p_\tau(x,t) = \tau^{-1}p\left(\frac{x}{\tau^{1/2}}, \frac{t}{\tau}\right)$$

is also a solution pair

The Multi-Model Ensemble

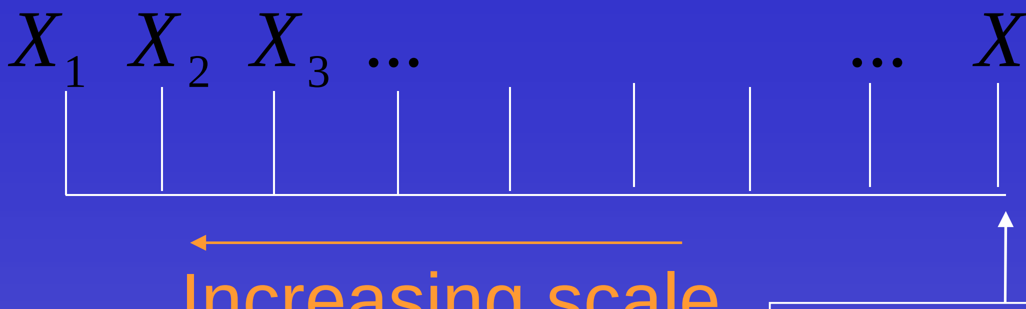
✓

- A pragmatic approach to the representation of model uncertainty
- Engenders a community spirit (all weather/climate institutes contributing to a common probabilistic product)!
- Positive results over single-model ensembles eg in seasonal forecast studies (less true for medium range)

✗

- Limited (effective) ensemble sizes
- Insensitive to structural uncertainty (associated with the violation of scaling symmetries by the deterministic truncation/parametrisation ansatz.)

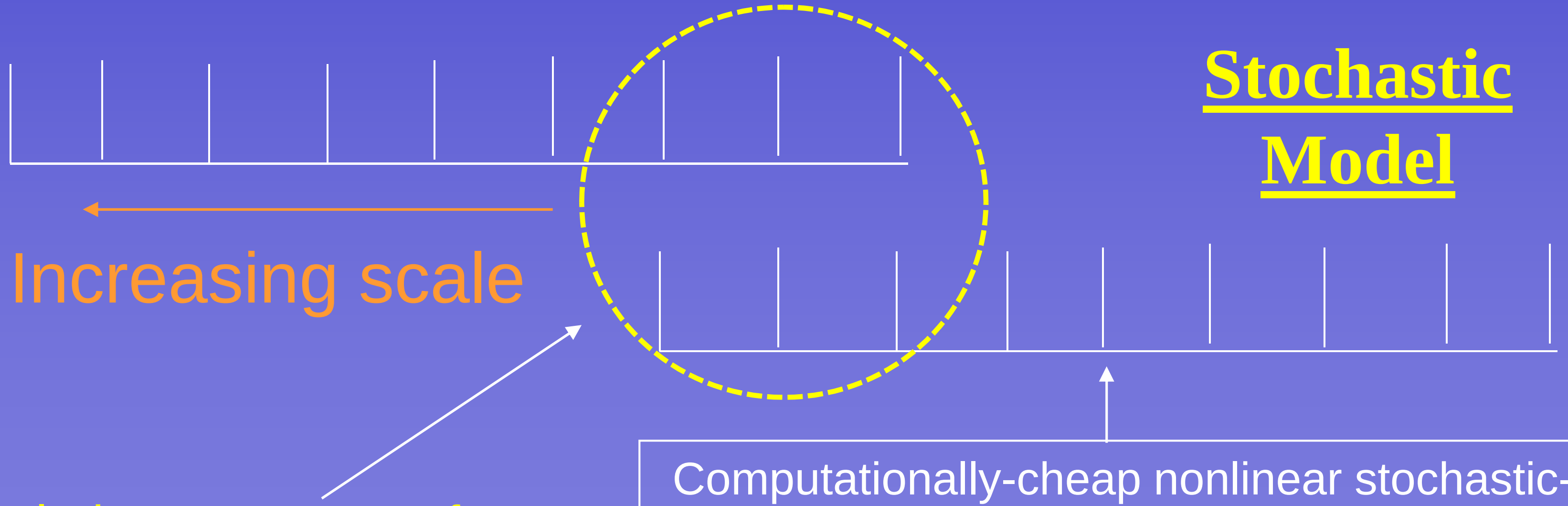
Deterministic Model



Increasing scale

Deterministic formula to represent bulk effect of "ensemble" of sub-grid processes

Stochastic Model

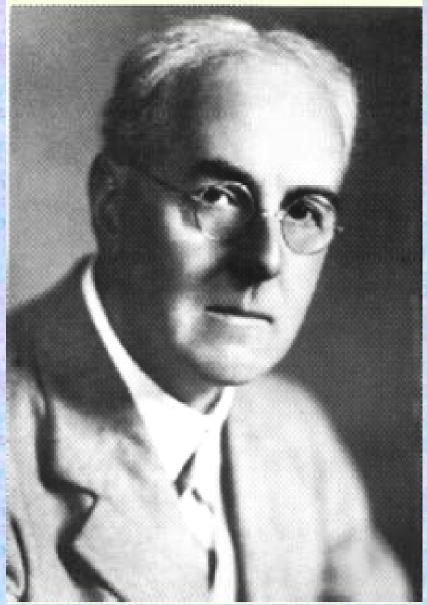


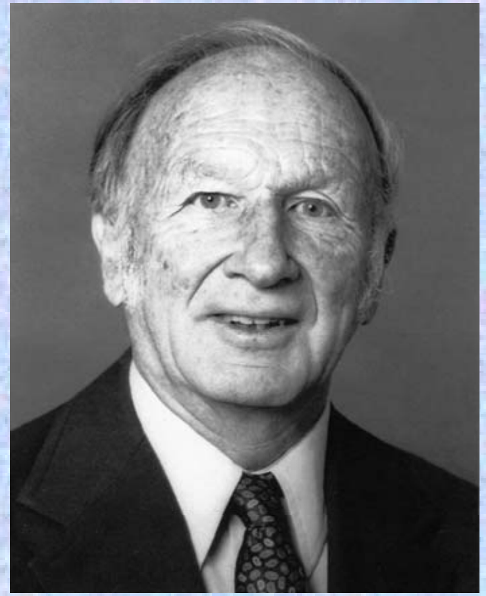
Increasing scale

Coupled over a range of scales

Computationally-cheap nonlinear stochastic-dynamic model, providing specific realisations of sub-grid processes

Although deterministic modelling of fluids has a long and venerable history, stochastic closures are more consistent with the work of:





"I believe that the ultimate climate models..will be stochastic, ie random numbers will appear somewhere in the time derivatives" Lorenz 1975.

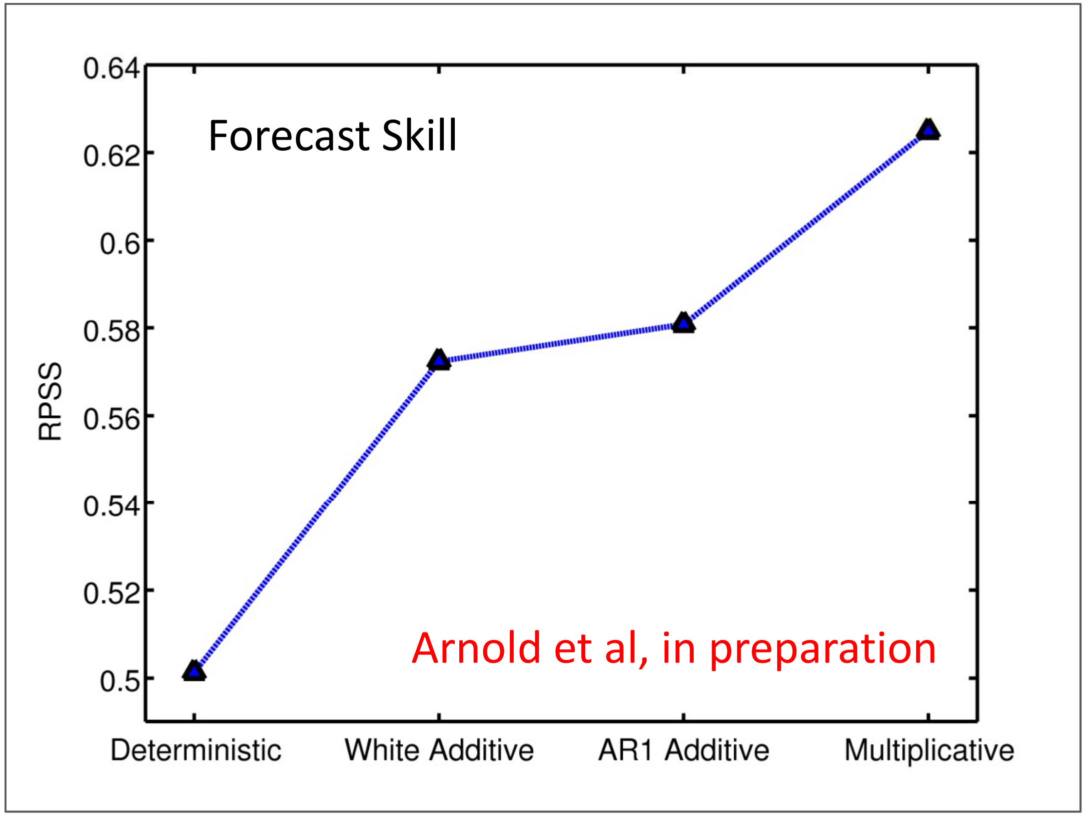
Experiments with the Lorenz ‘96 System (i)

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

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

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

Stochastically Perturbed Parametrisation Tendencies (Multiplicative Noise)

$$X_p = (1 + r\mu) X_c$$

Buizza et al, 1999

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

Spectral pattern generator Spectral coefficients based on independent AR1 processes.

Clipped in boundary layer and stratosphere.

Total deterministic parramtrised tendency

$$\sigma_1 = 0.5, \quad \tau_1 = 6\text{hrs}, \ \ \mathrm{L}_1 = 500\text{km}$$

$$\sigma_2 = 0.2, \quad \tau_2 = 30\text{days}, \ \ \mathrm{L}_2 = 2500\text{km}$$

Realisations of spectral pattern generator

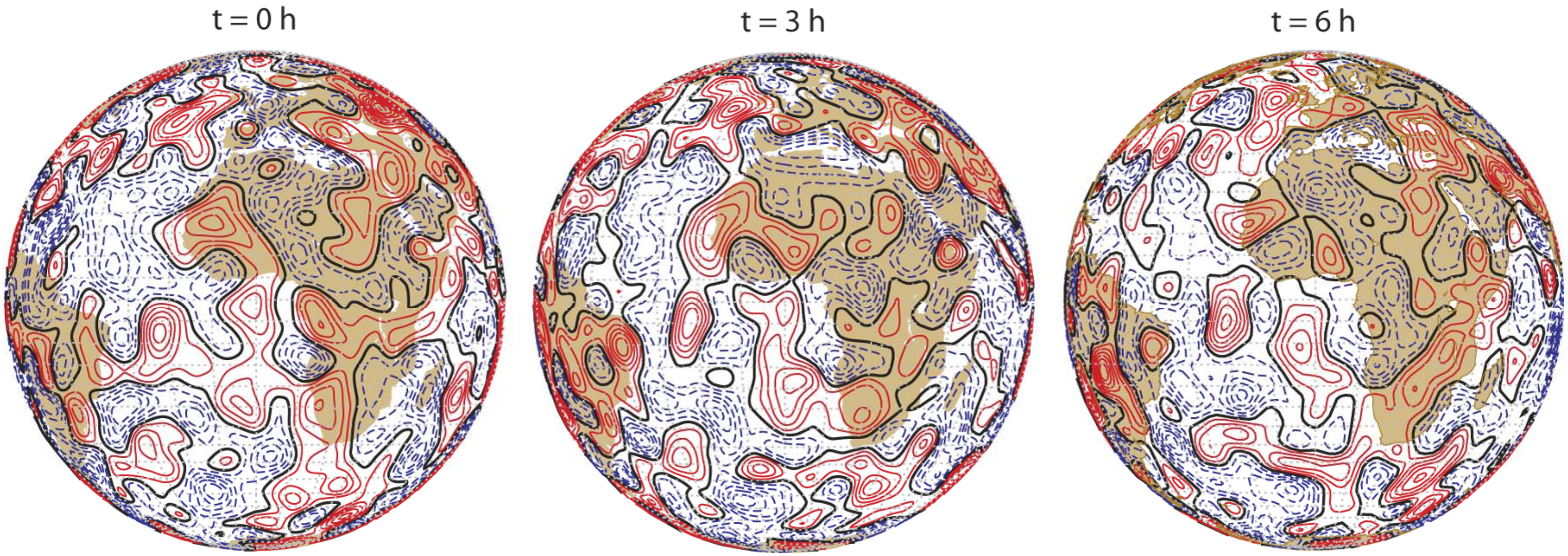
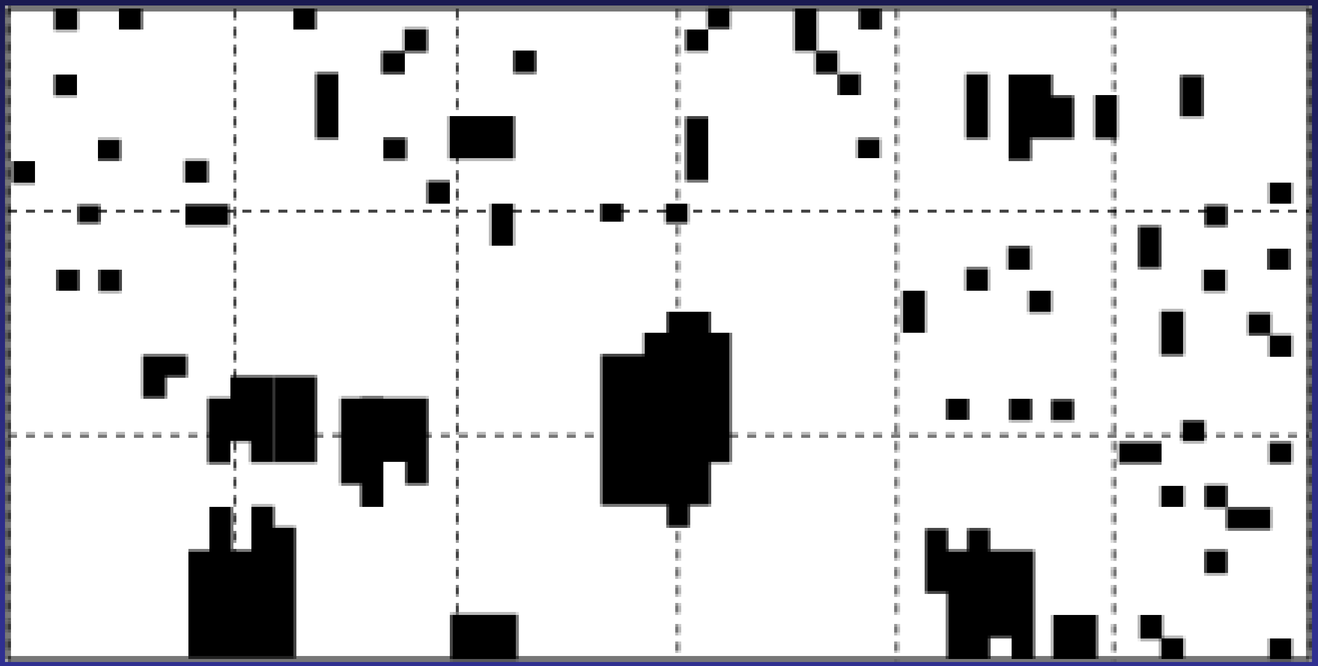


Fig 1

Stochastic-Dynamic Cellular Automata

Eg for convection



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

(Palmer; 1997, 2001; Shutts 2005; Berner et al, 2008

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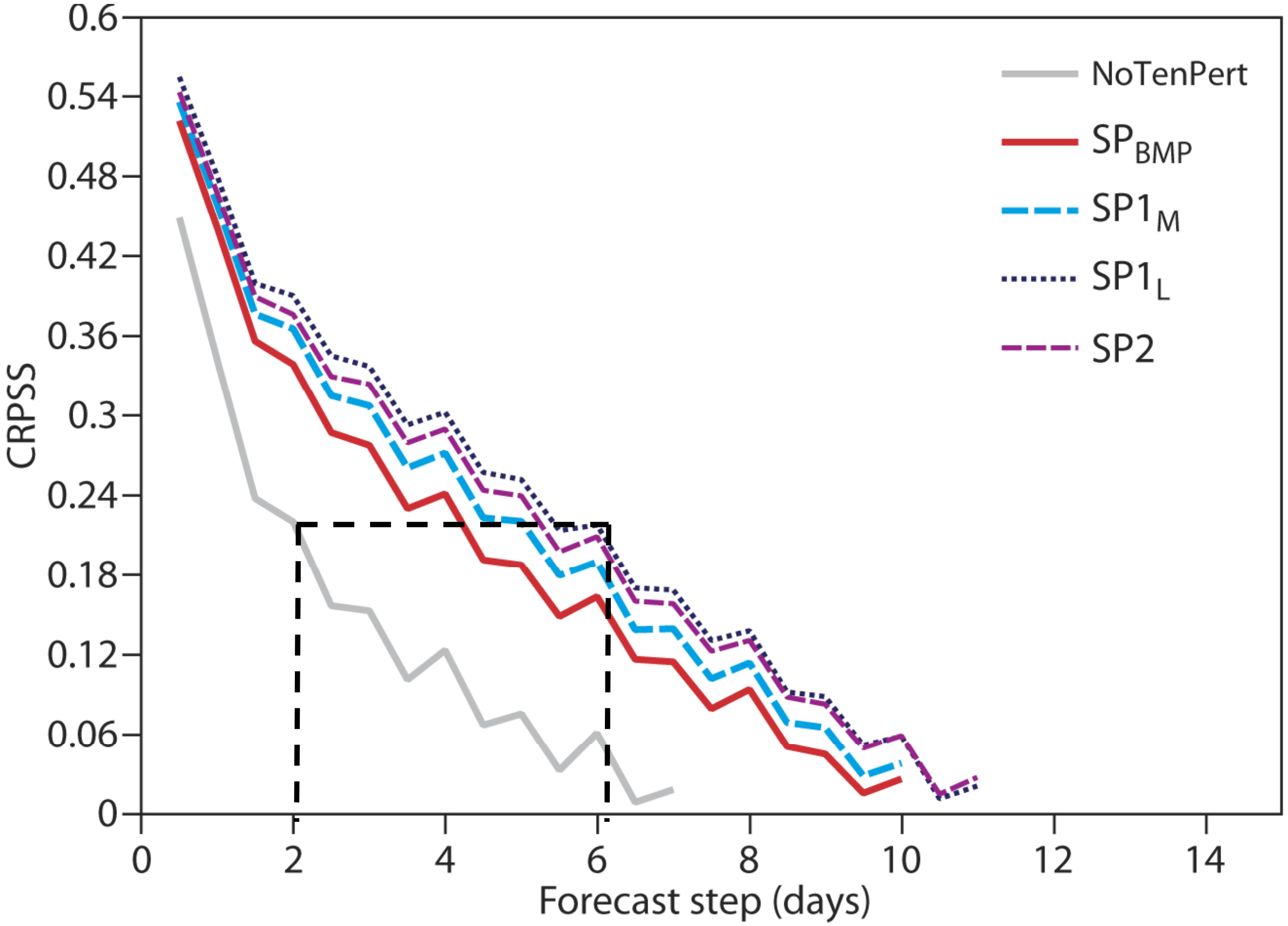
Medium-Range Predictions of 850hPa Temperature (Tropics)



Brier Skill Score: ENSEMBLES MME vs ECMWF stochastic physics ensemble (SPE)

lead time: 1 month

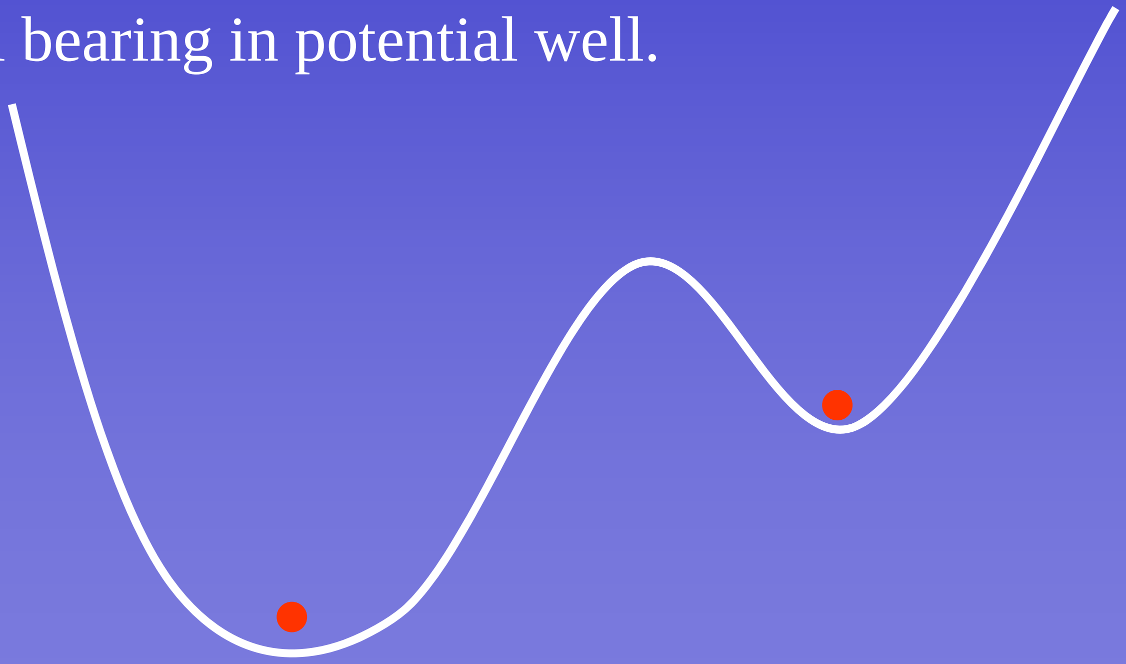
	T2m				**precip**			
	May		**Nov**		**May**		**Nov**	
	cold	**warm**	**cold**	**warm**	**dry**	**wet**	**dry**	**wet**
MME	0.178	**0.195**	0.141	0.159	0.085	0.079	0.080	0.099
SPE	**0.194**	0.192	**0.149**	**0.172**	**0.104**	**0.118**	**0.095**	**0.114**
CTRL	0.147	0.148	0.126	0.148	0.044	0.061	0.058	0.075

Hindcast period: 1991-2005
SP version 1055m007

Weisheimer et al (2011)

Stochastic parametrisation has potential to reduce climate model bias

Eg ball bearing in potential well.



$\mathrm{CNT_{T95}}$-ERA40

Z500 Difference eto4-er40 (12-3 1990-2005)

$\mathrm{CNT_{T511}}$-$\mathrm{CNT_{T95}}$

Z500 Difference eut3-eto4 (12-3 1990-2005)

$\mathrm{SPBS_{T95}}$-$\mathrm{CNT_{T95}}$

Z500 Difference ezeu-eto4 (12-3 1990-2005)

T95

T511

T95+Stochastic backscatter parametrisation

$$\boxed{\frac{\partial \psi}{\partial t} = \Psi(x, y) \cdot \sqrt{rD}}$$

Berner et al (2011)

Stochastic Parametrisation

✓

- Potentially a more rigorous approach to the representation of model uncertainty - more consistent with underlying scaling symmetries, power laws etc.
- Competitive with multi-model ensembles on monthly/seasonal timescales
- Could engender a very collaborative community spirit (all weather/climate institutes contributing to a common probabilistic model)!

✗

- Limited results to date
- Needs to be developed at the process level (cf μ)
- Needs to be extended to other components of the earth-system (oceans, land surface etc)

Network on Stochastic Parameterization and Modelling

- Initiated at a recent Isaac Newton Institute programme on mathematics and climate
- Moderated by Judith Berner (NCAR) and Tim Palmer, (Univ. of Oxford, ECMWF)
- URL has info on how to subscribe and post messages and get help from the site administrator
- Every member can post to list
- **Sign up at http://mailman.ucar.edu/mailman/listinfo/stoch**

Experiments with the Lorenz ‘96 System (ii)

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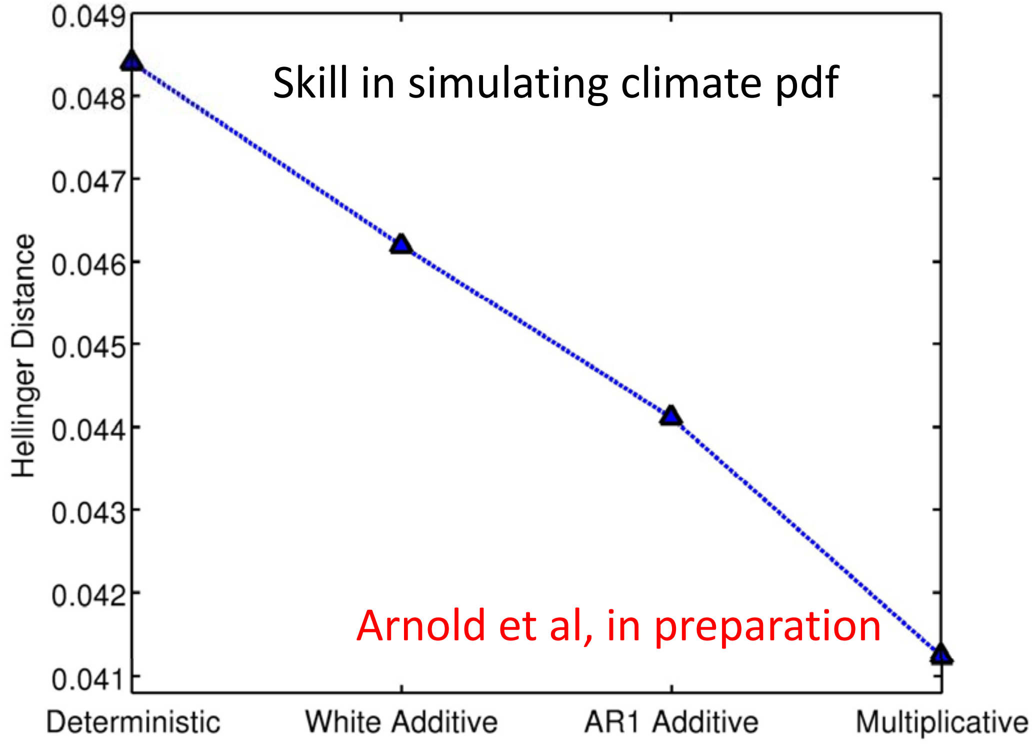

Skill in simulating climate pdf

Arnold et al, in preparation

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

Where:
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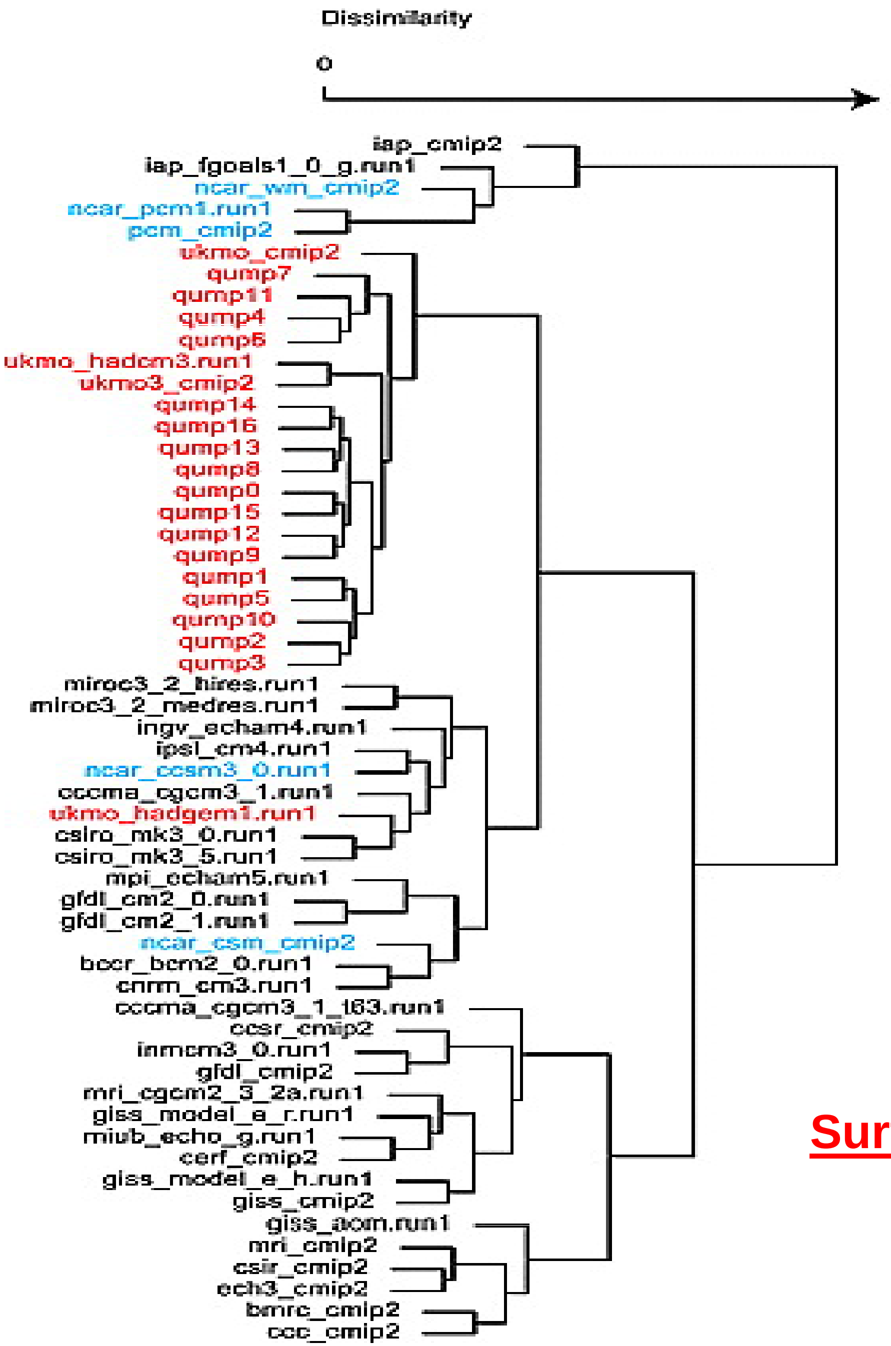
Fit parameters from full model

Masson and Knutti, 2011

Perturbed parameter ensemble cluster together



Surface Temperature