Stochastic Physics and Reliable Seasonal Prediction

T.N.Palmer
University of Oxford
ECMWF

How good are medium-range forecasts now? (on a scale of 1-5)?

How good will they be in 30 years time? (on a scale of 1-5)?

How good are seasonal forecasts now? (on a scale of 1-5)?

How good will they be in 30 years time? (on a scale of 1-5)?

- What does “5 = very good” mean? To the public, if a forecast is “very good” it means that it is right roughly 95% of the time.
- Clearly seasonal forecasts do not have that level of skill now.
- Do our current medium-range forecasts have high skill by this measure?

No!

Results are from the operational high-resolution run for Europe (W: -12.5, N: 75, E: 42.5, S: 35), forecast day 5 (= precipitation from +96 to +120 h). The average number of available stations is ~1520.

a. Results for summer (JJA 2011)

iv)Threshold=10 mm

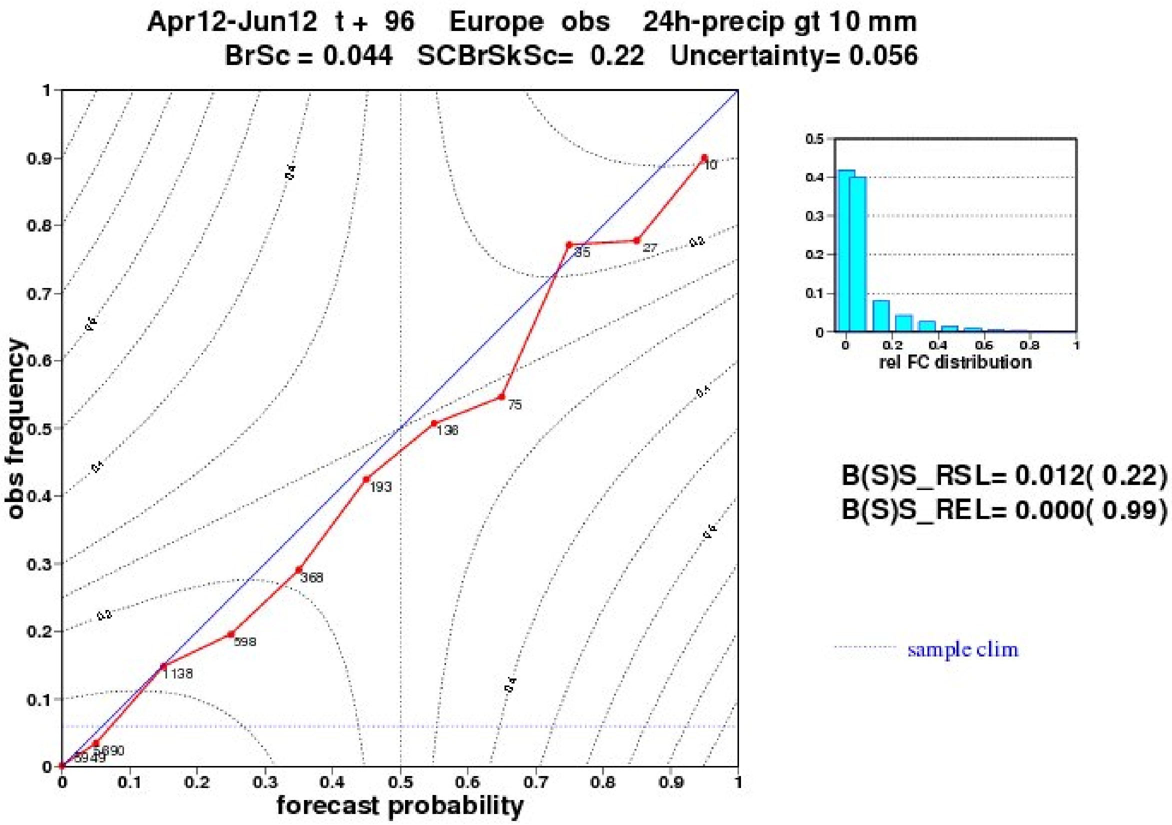
	OBS yes	OBS no
FCST yes	3703	7694
FCST no	7982	120412

Thomas Haiden, personal communication

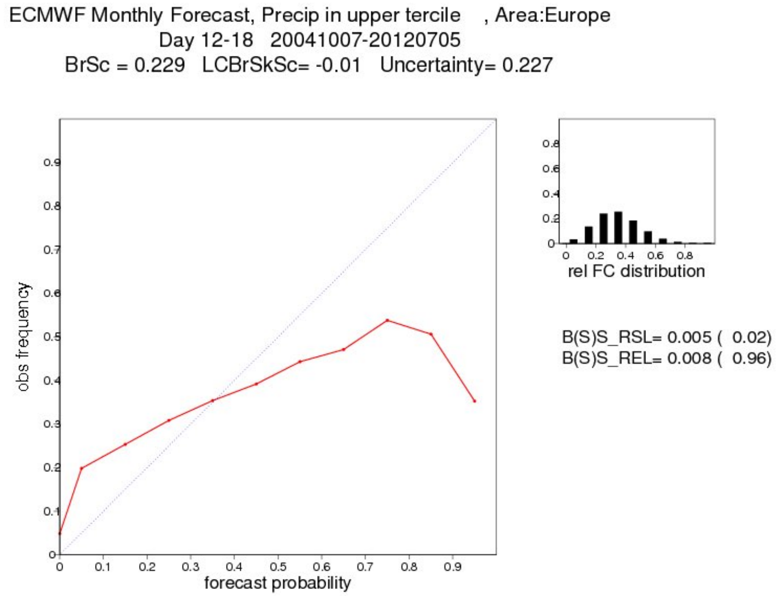
On about 70% of the occasions when the day 4-5 ECMWF high-res forecast said it would rain at least 10mm/day, it didn't!

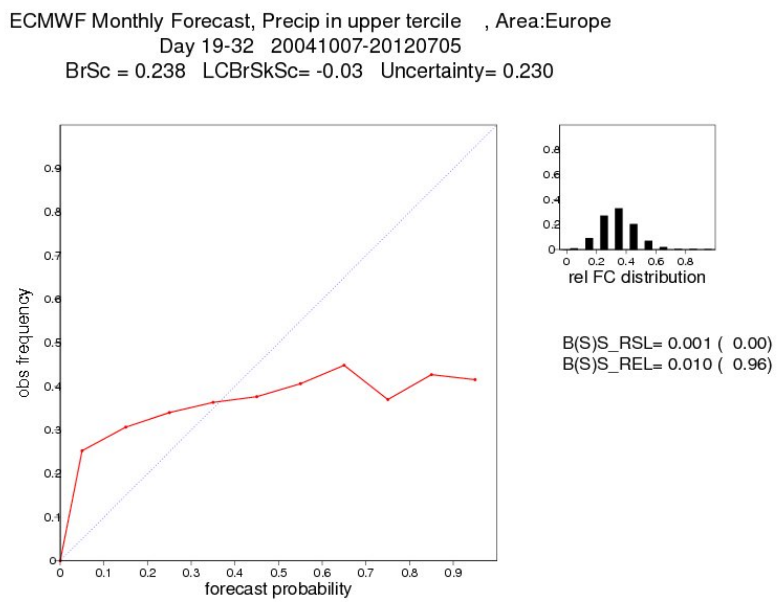
No wonder the public complain about traditional deterministic weather forecasts - from this perspective they are very unreliable.

The ECMWF Ensemble Prediction System



Beyond the medium range, precip forecasts start to loose reliability



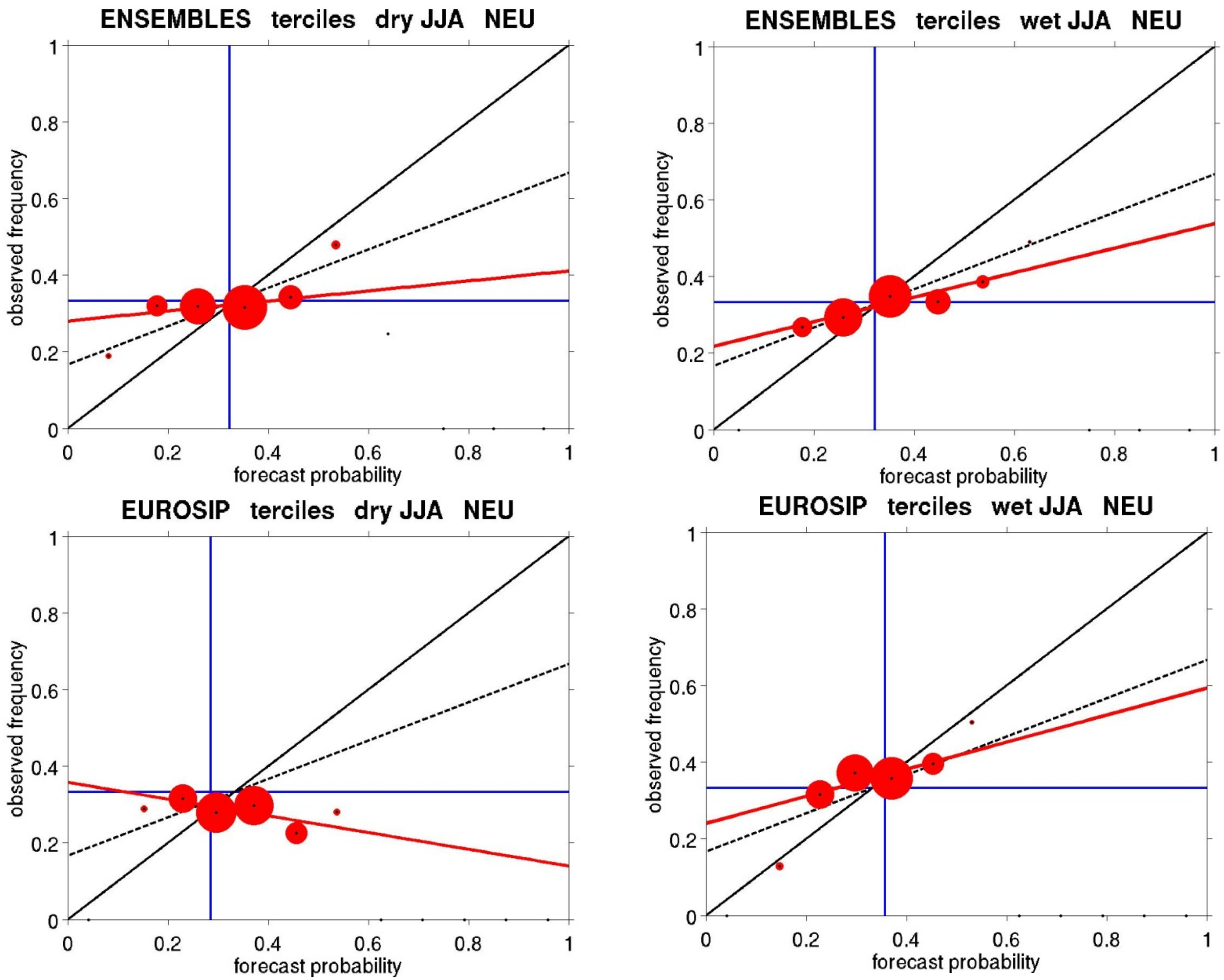


And on the seasonal timescale they can be rather poor

Northern Europe

ENSEMBLES

EUROSIP (E0002)

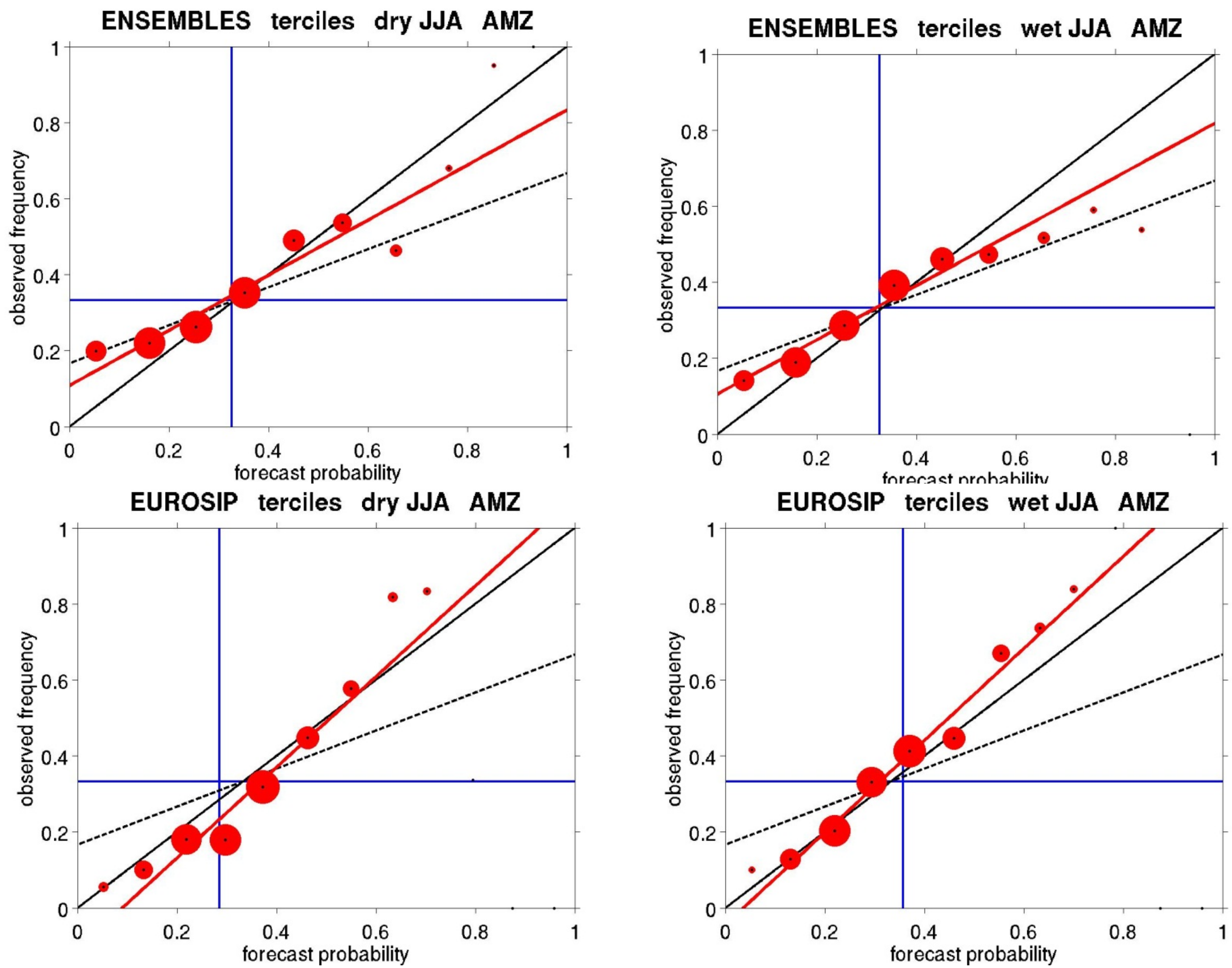


..but not for all regions

Amazon

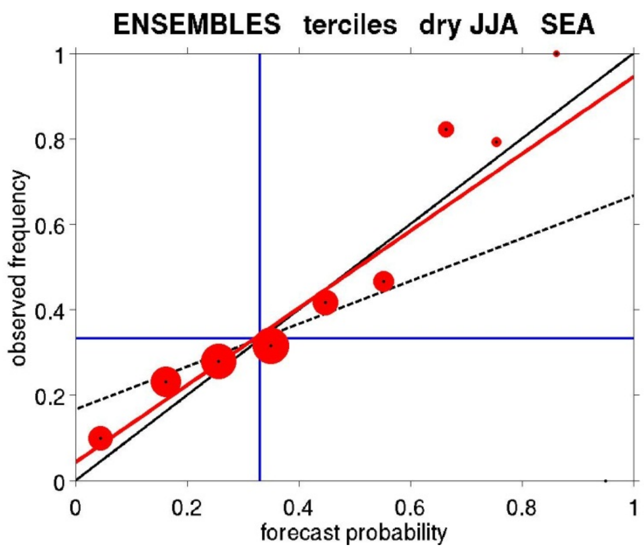
ENSEMBLES

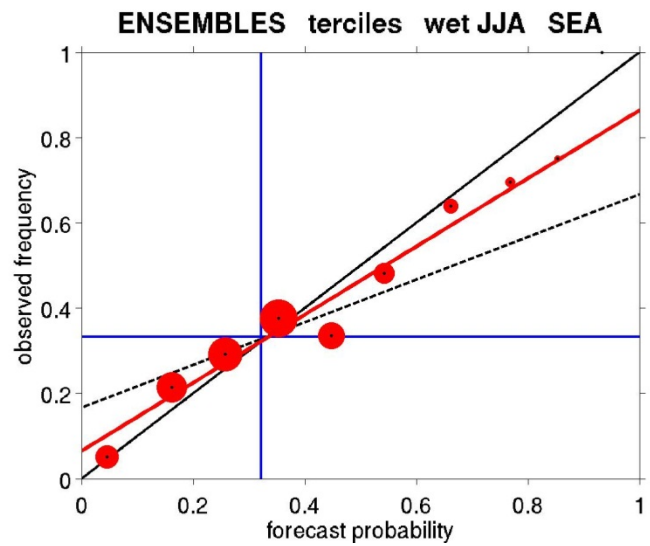
EUROSIP (E0002)



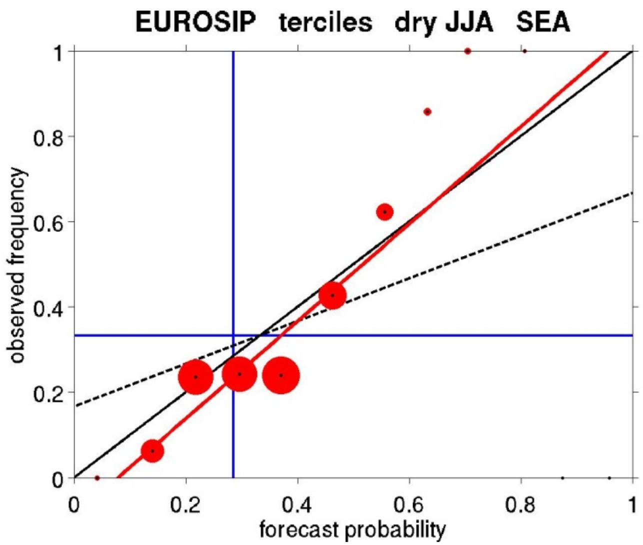
Southeast Asia

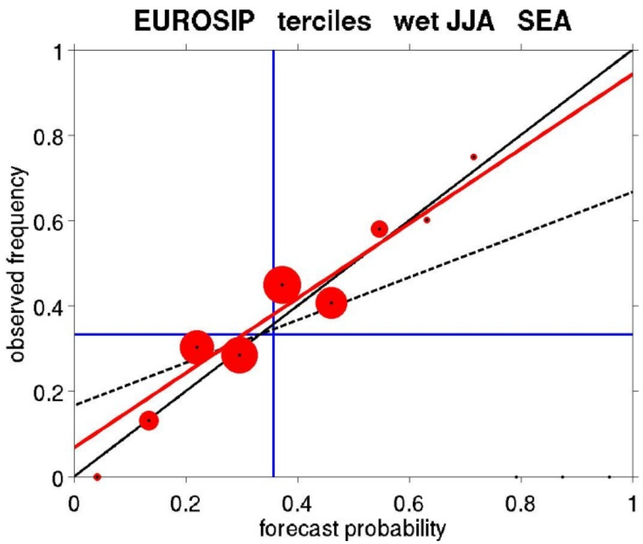
ENSEMBLES



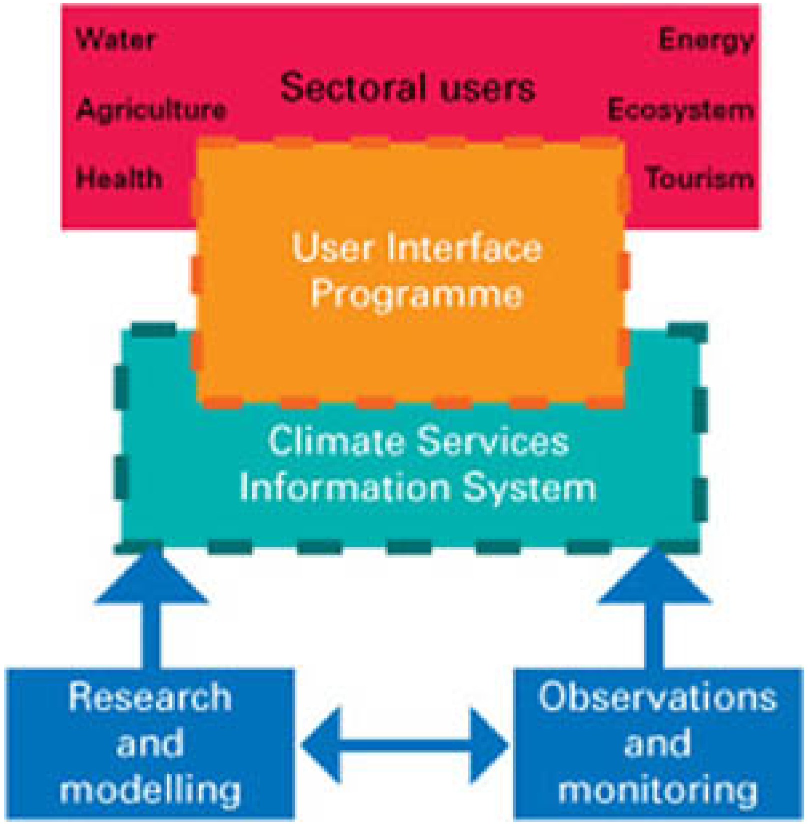


EUROSIP (E0002)





WCC-3

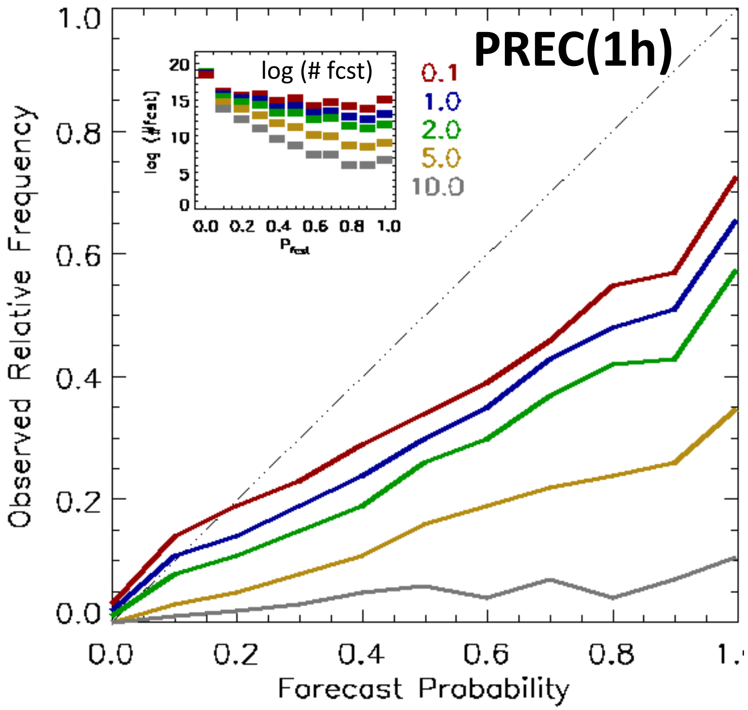


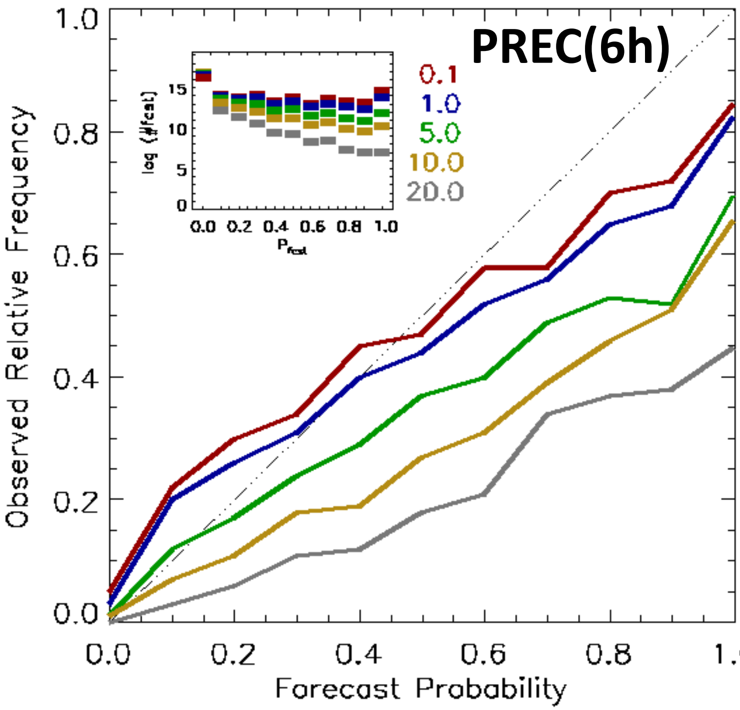
It is **essential** for the development of Climate Services, that our climate forecast systems are reliable.

PREC(1h) Summer 2011 00UTC

Unreliability also a problem for short range forecasts of intense rainfall

Reliability diagram





Christoph Gebhardt, personal communication

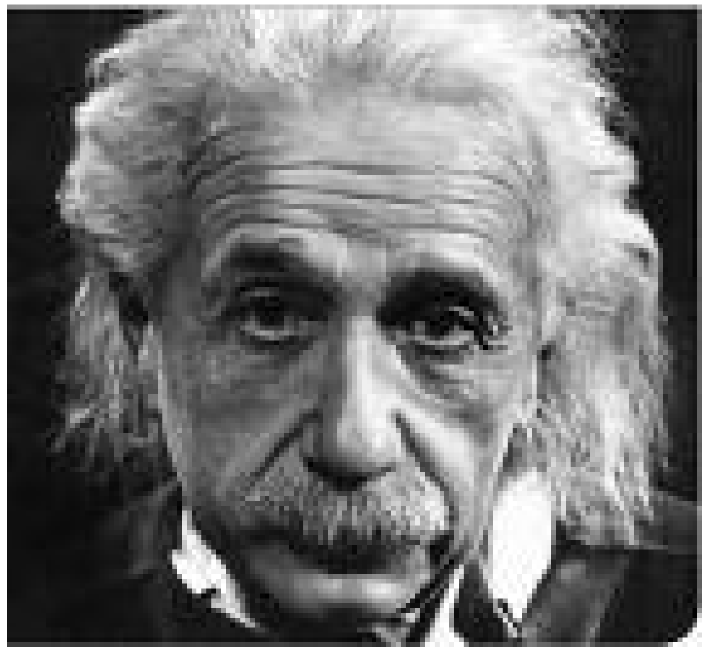
How good will medium range and seasonal forecasts be in 30 years time?

- Not `95% right'. That is both unrealistic and inconsistent with the laws of physics.
- Rather, we should aspire to perfect reliability, ie

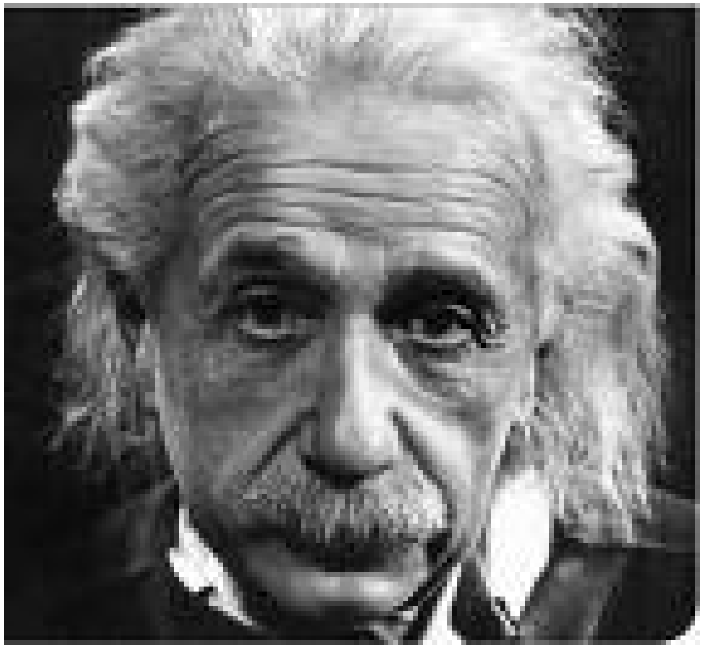
from a subset of cases where the forecast predicts a 95% (more generally p%) chance eg of:

  - An intense convective storm over Reading in the next 12 hours
  - The development of a blocking anticyclone over Northern Europe in 2 weeks time
  - A BBQ summer in the UK or a severe drought in Kenya in the coming season

then the event will have happened 95% (more generally p%) of the time.



Theories of physics should be as simple as possible, but no simpler



Forecasts of weather should be as sharp as possible, but no sharper

Traditional computational ansatz for weather/climate simulators

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

$$X_1 \quad X_2 \quad X_3 \quad \ldots \qquad\qquad \ldots \quad X_n$$

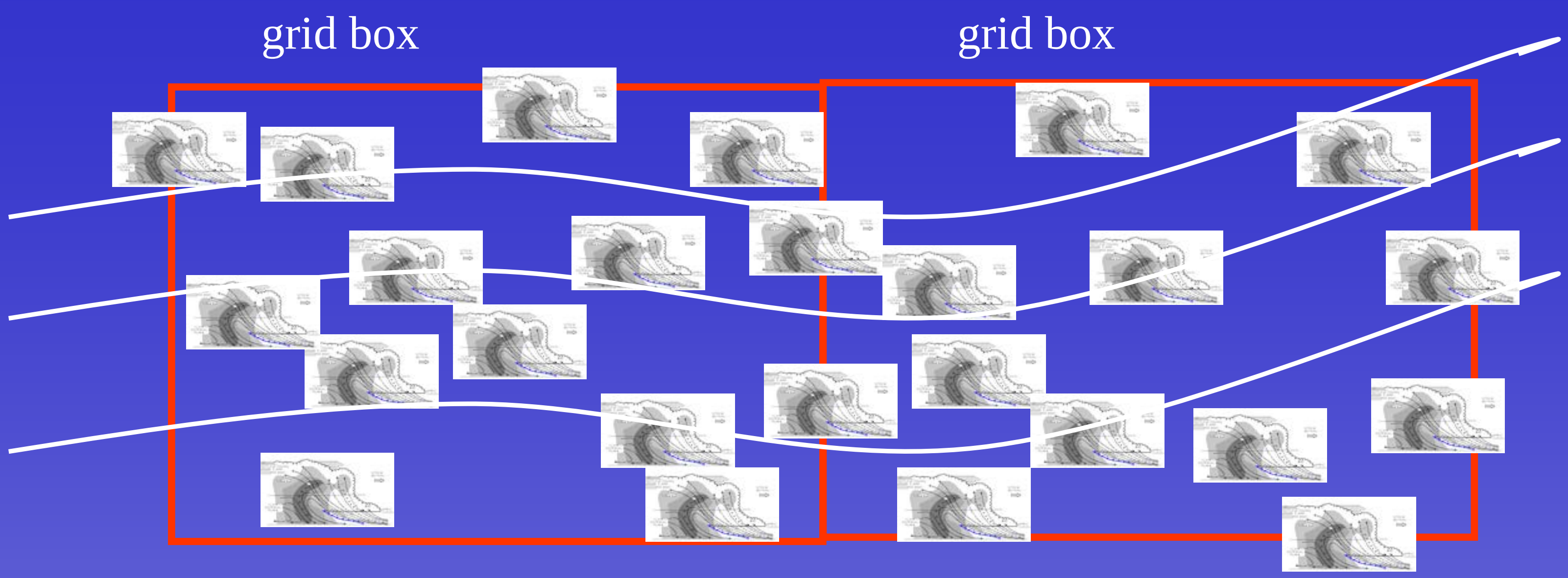
Increasing scale

Eg momentum“transport” by:

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

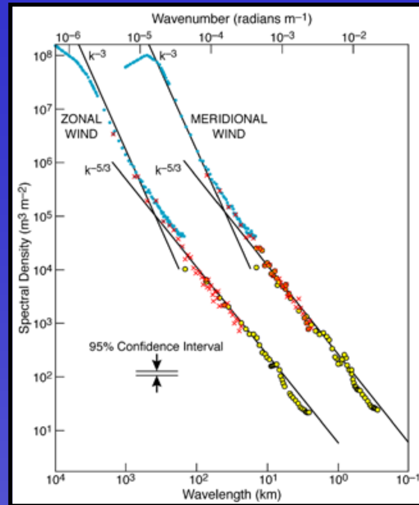
Deterministic local bulk-formula parametrisation

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



Deterministic bulk-formula parametrisation is based on the notion of averaging over some putative ensemble of sub-grid processes in quasi-equilibrium with the resolved flow (eg Arakawa and Schubert, 1974)

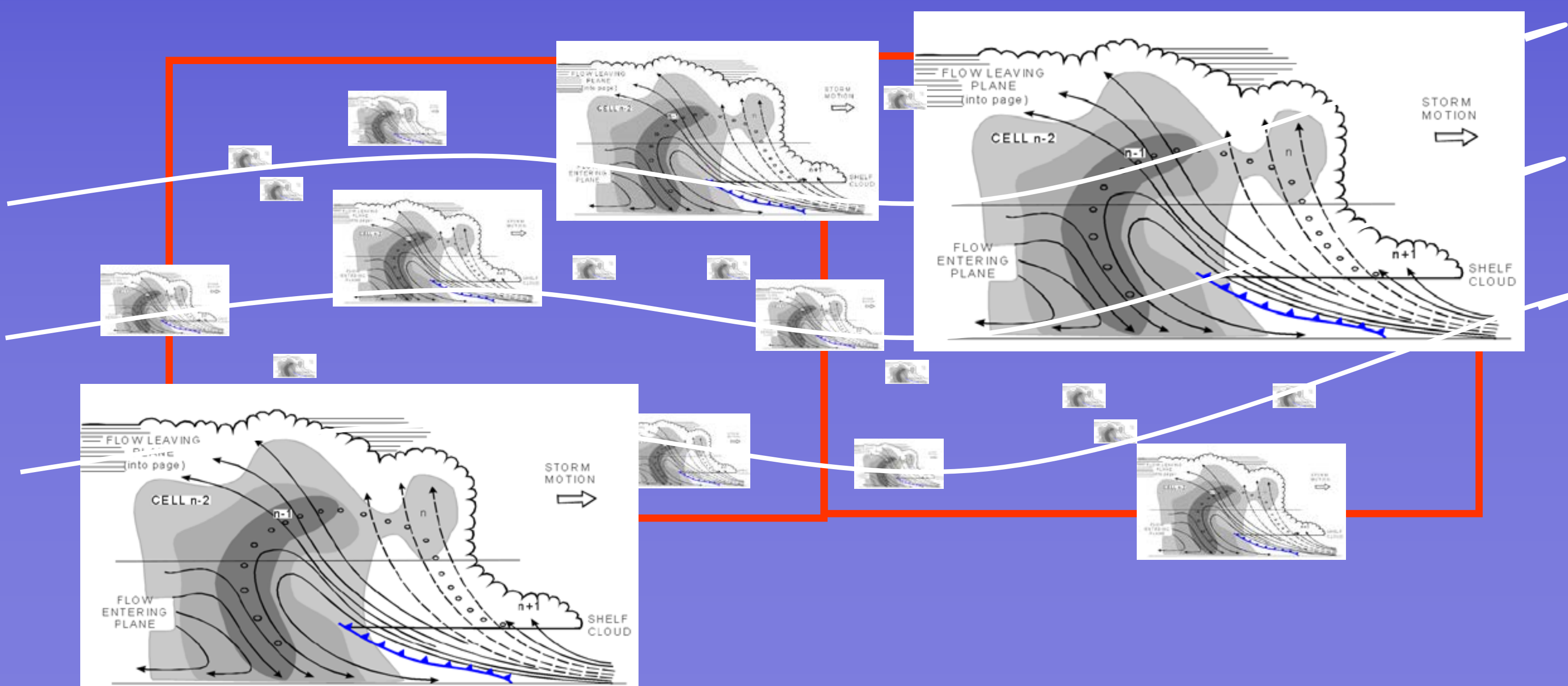
However, ..



is more consistent with …..

grid box

grid box



Stochastic Parametrisation

- Provides the sub-grid tendency associated with a potential realisation of the sub-grid flow, not the tendency associated with an ensemble average of sub-grid processes.

- Can incorporate physical processes (eg energy backscatter) not described in conventional parametrisations.

- Parametrisation development can be informed by coarse-graining budget analyses of very high resolution (eg cloud resolving) models.

Experiments with the Lorenz '96 System (ii)

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

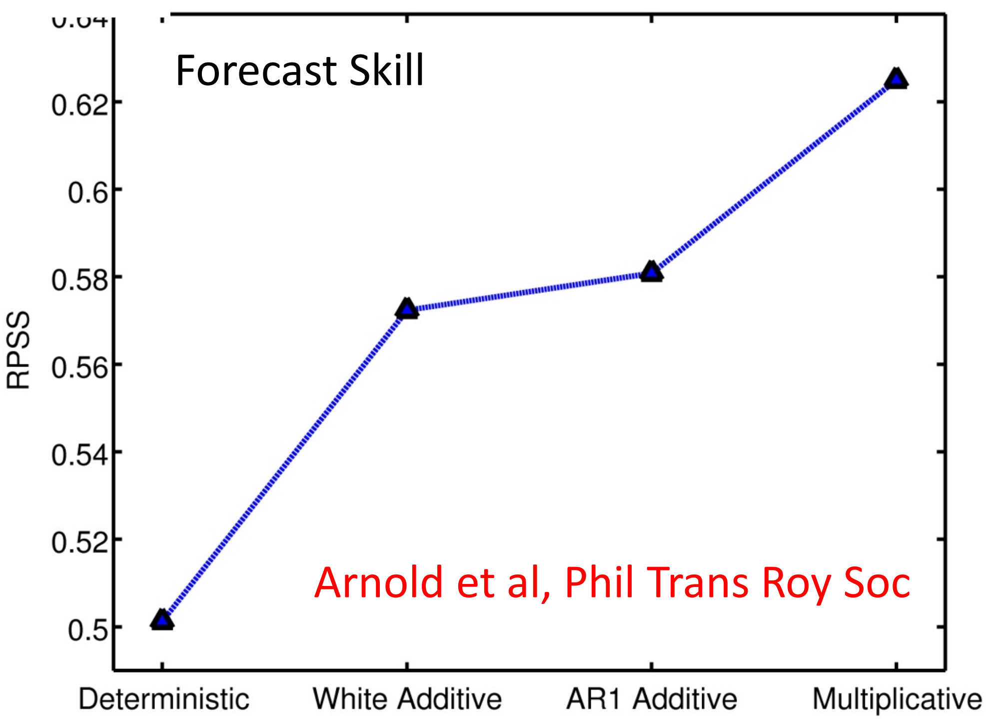
$$\frac{dY_j}{dt} = -cbY_{j+1}\left(Y_{j+2} - Y_{j-1}\right) - cY_j + \frac{hc}{b} X_{\mathrm{int}[(j-1)/J+1]}$$

Assume Y unresolved

Approximate sub-grid tendency by U

RPSS

Better



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

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

TECHNICAL MEMORANDUM

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A stochastic parameterization for deep convection using cellular automata

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To be submitted to J. Atmos. Sci.

February 2012

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Centre européen pour les prévisions météorologiques à moyen terme

Postdoc position available to study this in EPS+seasonal forecasts

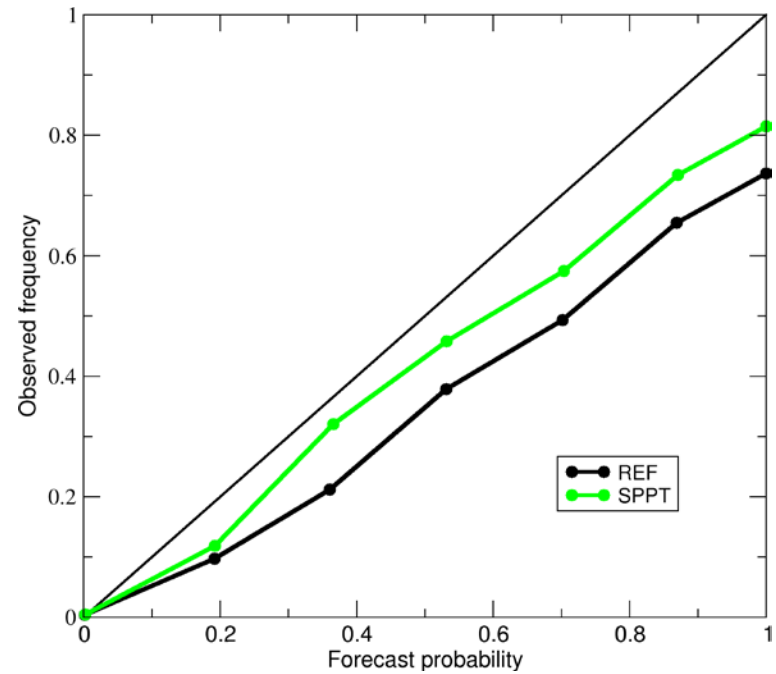
Impact of stochastic physics in a convection-permitting ensemble

François Bouttier * Benoît Vié, Olivier Nuissier and Laure Raynaud

CNRM-GAME, CNRS and Météo-France, Toulouse, France

ABSTRACT

A stochastic physics scheme is tested in the AROME short range convection-permitting ensemble prediction system. It is an adaptation of ECMWF's stochastic perturbation of physics tendencies (SPPT) scheme. The probabilistic performance of the AROME ensemble is found to be significantly improved, when verified against observations over two two-week periods. The main improvement lies in the ensemble reliability and the spread/skill consistency. Probabilistic scores for several weather parameters are improved. The tendency perturbations have zero mean, but the stochastic perturbations have systematic effects on the model output, which explains much of the score improvement. Ensemble spread is an increasing function of the SPPT space and time correlations. A case study reveals that stochastic physics do not simply increase ensemble spread, they also tend to smooth out high spread areas over wider geographical areas. Although the ensemble design lacks surface perturbations, there is a significant end impact of SPPT on low-level fields through physical interactions in the atmospheric model.



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

lead time: 1 month

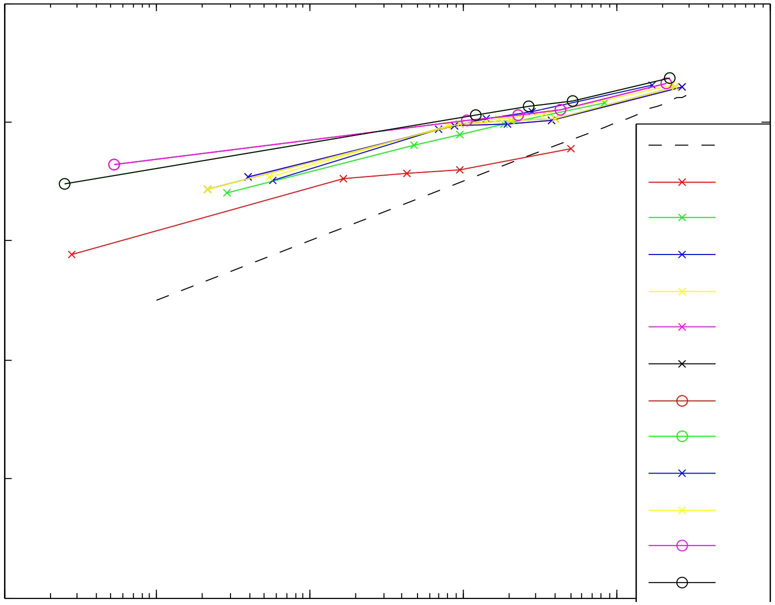
	T2m				precip			
	May		Nov		May		Nov	
	cold	warm	cold	warm	dry	wet	dry	wet
MME	0.178	**0.195**	0.141	0.159	0.085	0.079	0.080	0.099
SPE	**0.194**	0.192	**0.149**	**0.172**	**0.104**	**0.118**	**0.095**	**0.114**
CTRL	0.147	0.148	0.126	0.148	0.044	0.061	0.058	0.075

Hindcast period: 1991-2005
SP version 1055m007

Weisheimer et al GRL (2011)

System 4 is underdispersive in ocean variables

Ensemble Error



Ensemble Spread

Mirek Andrejczuk. Personal communication

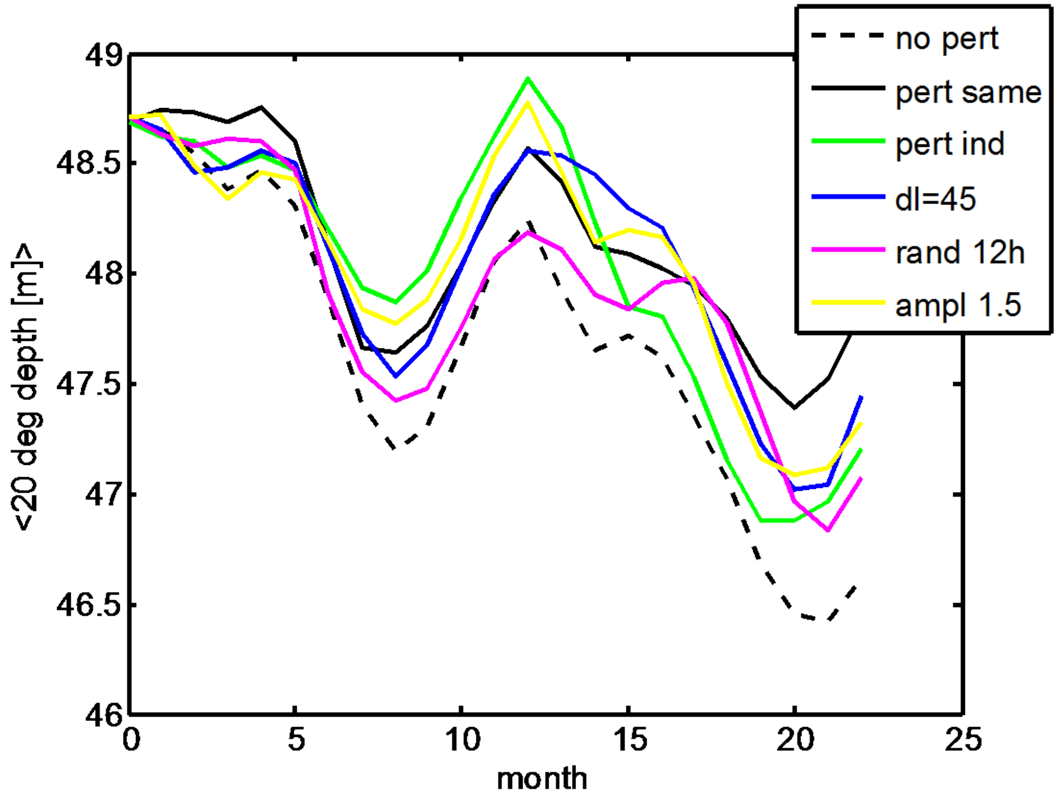
NEMO Equations

$$\frac{\partial U_h}{\partial t} = -\left[(\nabla \times U) \times U + \frac{1}{2}\nabla(U^2)\right]_h - f\,k \times U_h - \frac{1}{\rho_0}\nabla_h p + (1 + r_{Uh}) D^U + F^U$$

$$\frac{\partial T}{\partial t} = -\nabla(TU) + (1 + r_T) D^T + F^T$$

$$\frac{\partial S}{\partial t} = -\nabla(SU) + (1 + r_S) D^S + F^S$$

Spatial correlations as in Buizza et al (1999)



Mirek Andrejczuk. Personal communication

Effects of stochastic ice strength perturbation on

Arctic finite element sea ice modelling

Stephan Juricke,

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Peter Lemke,

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Ralph Timmermann,

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Thomas Rackow

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

18.06.2012

Corresponding author address: Stephan Juricke, Alfred Wegener Institute,

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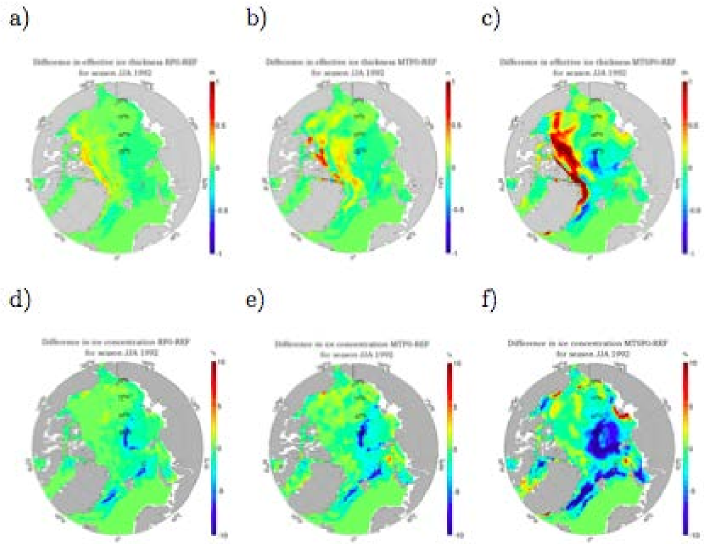
Stephan.Juricke@awi.de

J. Clim Submitted

- The ice strength parameter P* is a key parameter in dynamic-thermodynamic sea ice models.
- Controls the threshold for plastic deformation. Value affected by the liquid content in the sea ice. Cannot be measured directly.
- A stochastic representation of P* is developed in a finite element sea-ice-ocean model, based on AR1 multiplicative noise and spatial autocorrelation between nodes of the finite element grid
- Despite symmetric perturbations, the stochastic scheme leads to a substantial increase in sea ice volume and mean thickness
- An ensemble of eight perturbed simulations generates a spread in the multiyear ice comparable with interannual variability in the model.
- Results cannot be reproduced by a simple constant global modification to P*



Impact of different versions of stochastic P* with respect to a reference run. Top: Sea ice thickness. Bottom: sea ice concentration.

+ Land Surface

A skilful stochastic model cannot be obtained from a tuned deterministic model with bolt-on stochastics.

Quarterly Journal of the Royal Meteorological Society — Q. J. R. Meteorol. Soc. (2012)

RMetS
Royal Meteorological Society

Towards the probabilistic Earth-system simulator: a vision for the future of climate and weather prediction†

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† Based on the 2011 Royal Meteorological Society Presidential Address.

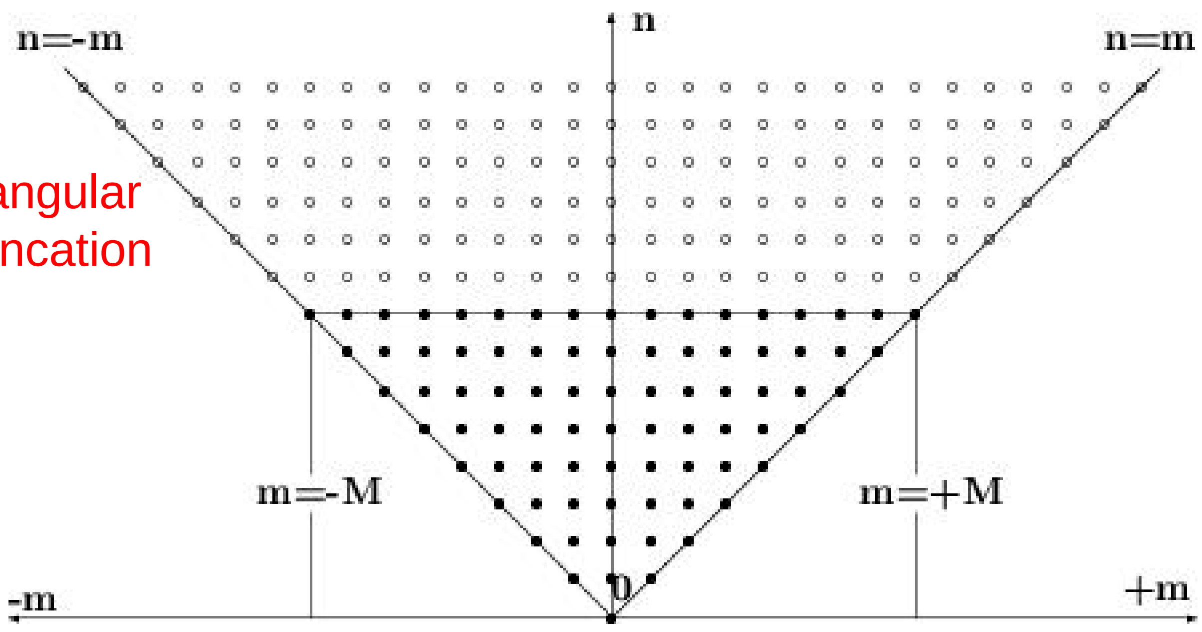
There is no more challenging problem in computational science than that of estimating, as accurately as science and technology allows, the future evolution of Earth's climate; nor indeed is there a problem whose solution has such importance and urgency. Historically, the simulation tools needed to predict climate have been developed, somewhat independently, at a number of weather and climate institutes around the world. While these simulators are individually deterministic, it is often assumed that the resulting diversity provides a useful quantification of uncertainty in global or regional predictions. However, this notion is not well founded theoretically and corresponding 'multi-simulator' estimates of uncertainty can be prone to systemic failure. Separate to this, individual institutes are now facing considerable challenges in finding the human and computational resources needed to develop more accurate weather and climate simulators with higher resolution and full Earth-system complexity. A new approach, originally designed to improve reliability in ensemble-based numerical weather prediction, is introduced to help solve these two rather different problems. Using stochastic mathematics, this approach recognizes uncertainty explicitly in the parametrized representation of unresolved climatic processes. Stochastic parametrization is shown to be more consistent with the underlying equations of motion and, moreover, provides more skilful estimates of uncertainty when compared with estimates from traditional multi-simulator ensembles, on time-scales where verification data exist. Stochastic parametrization can also help reduce long-term biases which have bedevilled numerical simulations of climate from the earliest days to the present. As a result, it is suggested that the need to maintain a large 'gene pool' of quasi-independent deterministic simulators may be obviated by the development of probabilistic Earth-system simulators. Consistent with the conclusions of the World Summit on Climate Modelling, this in turn implies that individual institutes will be able to pool human and computational resources in developing future-generation simulators, thus benefitting from economies of scale; the establishment of the Airbus consortium provides a useful analogy here. As a further stimulus for such evolution, discussion is given to a potential new synergy between the development of dynamical cores, and stochastic processing hardware. However, it is concluded that the traditional challenge in numerical weather prediction, of reducing deterministic measures of forecast error, may increasingly become an obstacle to the seamless development of probabilistic weather and climate simulators, paradoxical as that may appear at first sight. Indeed, going further, it is argued that it may be time to consider focusing operational weather forecast development entirely on high-resolution ensemble

Spectral Dynamical Core

$$\zeta = \sum_{m,n}^{\infty} \zeta_{m,n} e^{im\lambda} P_n^m(\phi)$$

Parametrisation

Triangular Truncation



There are good reasons for wanting to go to convectively resolved models, not just for short-range mesoscale prediction, but for seasonal and longer timescale climate prediction too (Shukla et al, 2010).

This will probably have to wait for exaflop computing.

Europe to double funding for exascale computing

China and Europe outpacing US funding for HPC

By Patrick Thibodeau | Computerworld US | Published 13:16, 21 February 12

The European Commission last week said it is doubling its investment in the push for exascale computing from €630 million to €1.2 billion (£1 billion). The announcement comes even as European governments are imposing austerity measures to prevent defaults.

But exascale systems "pose numerous hard challenges," said the European Commission in a report that accompanied its funding announcements. The challenges include a 100-fold reduction in energy consumption along with development of new programming models. As Europe sees it, solving these challenges creates opportunity for Europe, China and others looking to take on US HPC dominance.

Will bit-reproducible computation continue to be a *sine qua non* in HPC?

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

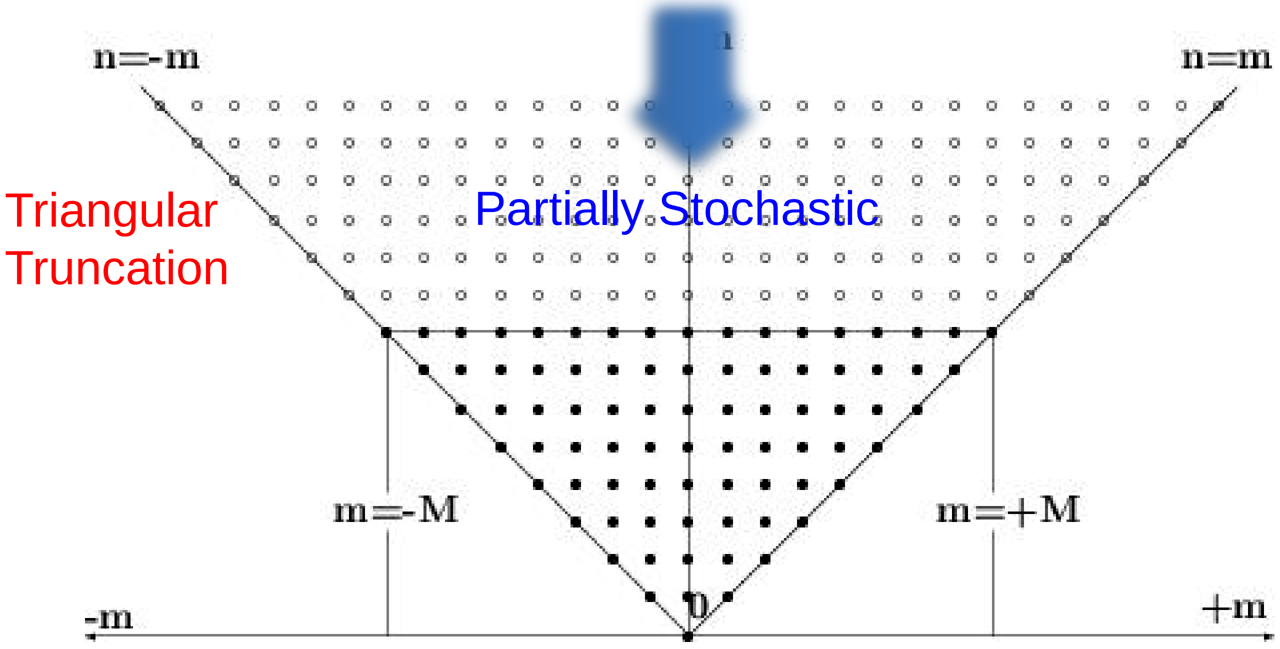
"Increasingly there will be a tension between energy efficiency and error detection",

and asked whether :

"…there needs to be a new software construct which identifies critical sections of code where the right answer must be produced" – implying that outside these critical sections errors can (in some probabilistic sense) be tolerated.

(http://www.ecmwf.int/ newsevents/meetings/workshops/2010/high performance computing 14th/index.html)

Stochastic Parametrisation

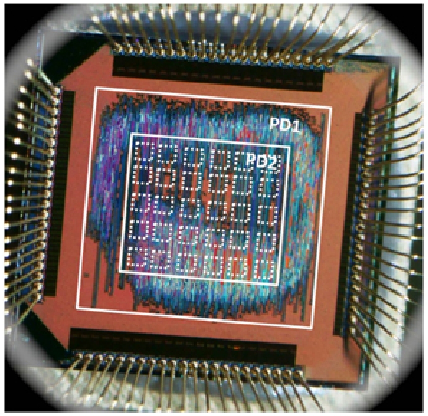


Can this fact be used as a way to overcome the exascale energy barrier and get to reliable convectively resolved global models much quicker than would otherwise be possible?

Superefficient inexact chips

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

Krishna Palem.
Rice, NTU
Singapore



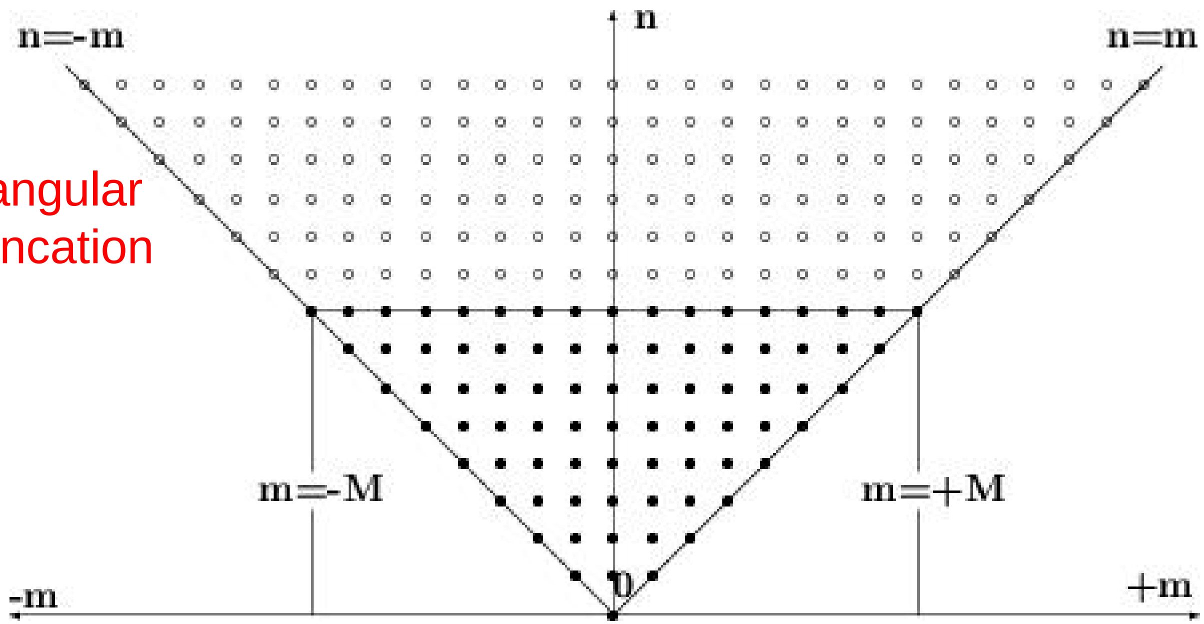
In terms of speed, energy consumption and size, inexact computer chips like this prototype, are about 15 times more efficient than today's microchips.

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).

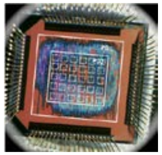
Blue Skies Research: Towards the Stochastic Dynamical Core

Stochastic Parametrisation

Triangular Truncation



Efficiency/speed/inexactness of chip



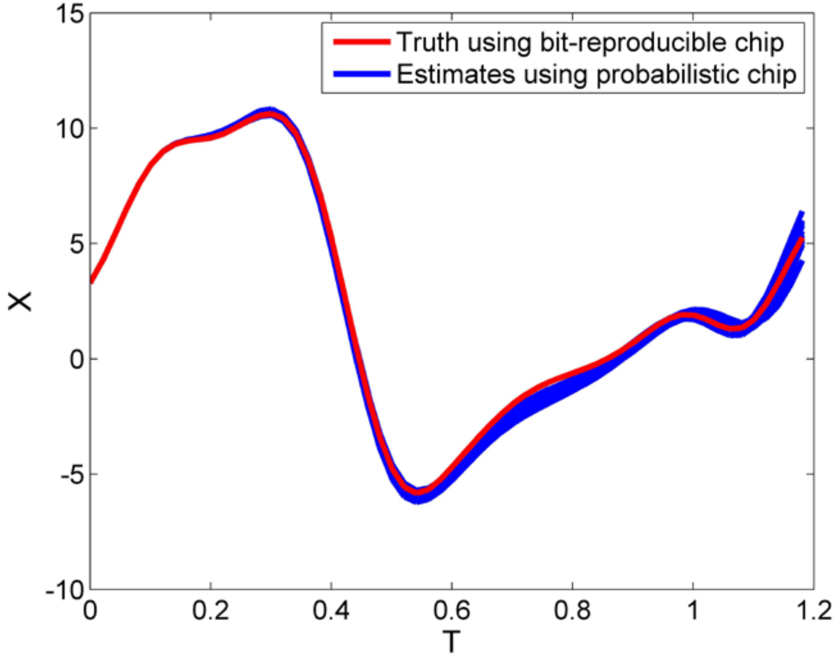
and precision at which the data is stored and passed between processors.

At Oxford we are beginning to work with IBM Zurich to develop these ideas…

Experiments with the Lorenz '96 System

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

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



Hannah Arnold and Hugh McNamara, Personal Communication

A route to reliable cloud resolved climate models?

30 Years Ago

Dynamics

Parametrisation

O(100km
)

Now

Dynamics

Parametrisation

O(10km)

In 30 years

Dynamics

Parametrisation

O(1km)

TWO TIME SCALES FOR THE PRICE OF ONE (ALMOST)

BY LISA GODDARD, JAMES W. HURRELL, BENJAMIN P. KIRTMAN, JAMES MURPHY, TIMOTHY STOCKDALE, AND CAROLINA VERA

Although differences exist between seasonal- and decadal-scale climate variability, predictability, and prediction, investment in observations, prediction systems, and decision systems for either time scale can benefit both.

While some might call Decadal Prediction the new kid on the block, it would be better to consider it the latest addition to the Climate Prediction family. Decadal Prediction is the fascinating baby that all wish to talk about, with such great expectations for what she might someday accomplish. Her older brother, Seasonal Prediction, is now less talked about by funding agencies and the seem mature enough to take care of himself, but in reality he is still just an adolescent and has yet to reach his full potential. Much of what he has learned so far, however, can be passed to his baby sister. Decadal could grow up faster than Seasonal did because she has the benefit of her older brother's experiences. They have similar needs and participate in similar activities, and thus to the extent that they can learn

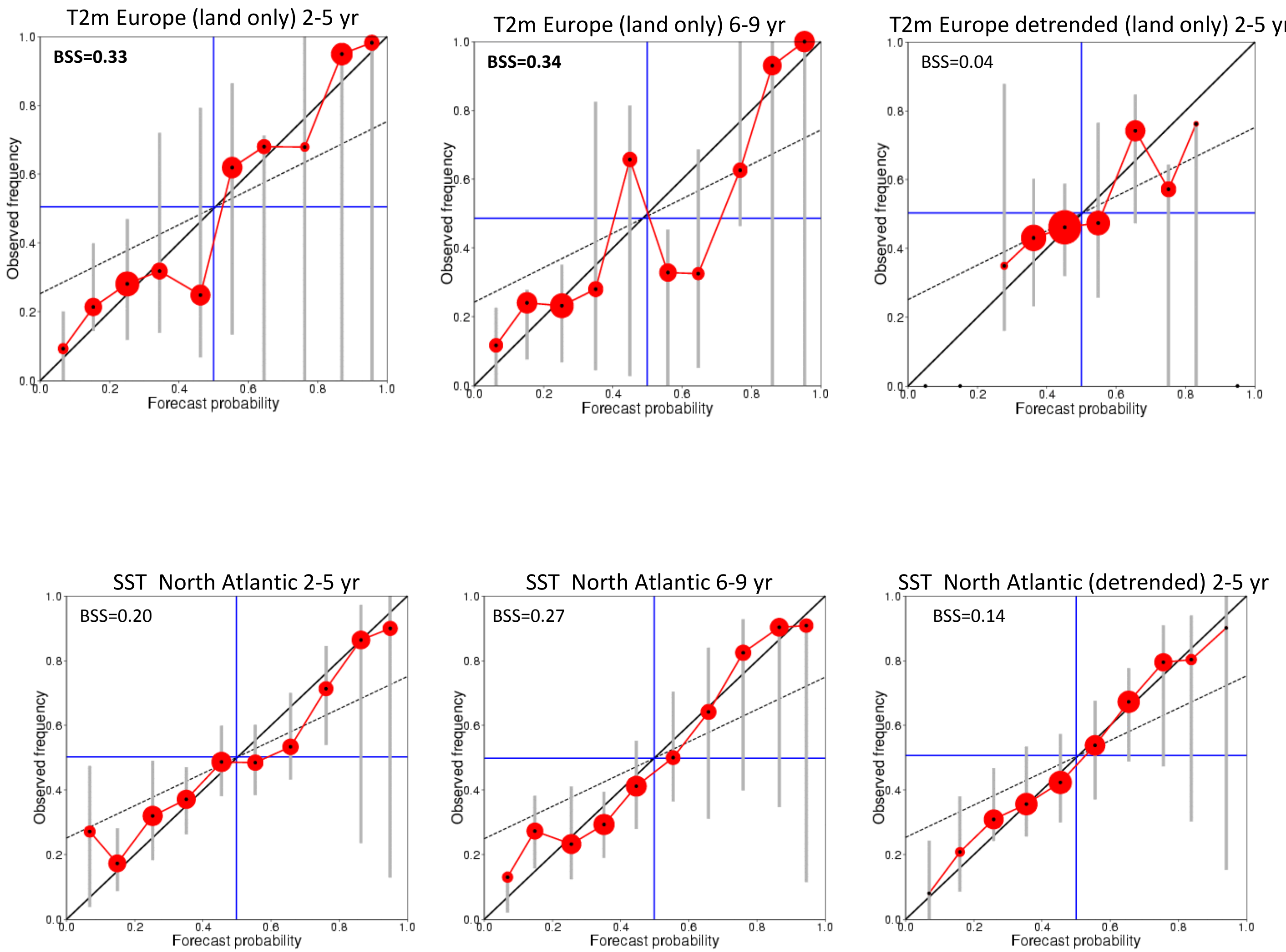
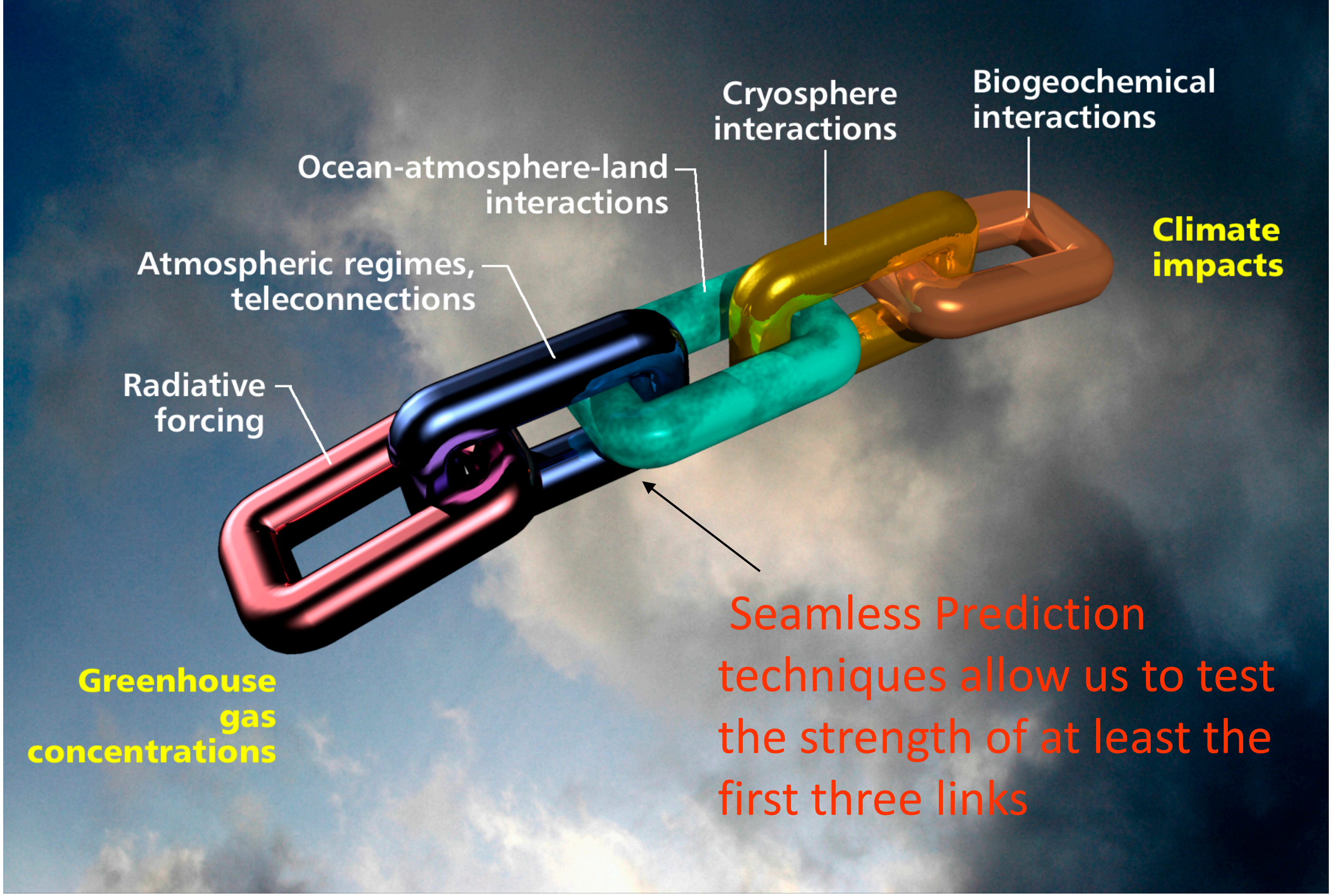

T2m Europe (land only) 2-5 yr
BSS=0.33
T2m Europe (land only) 6-9 yr
BSS=0.34
T2m Europe detrended (land only) 2-5 yr
BSS=0.04
SST North Atlantic 2-5 yr
BSS=0.20
SST North Atlantic 6-9 yr
BSS=0.27
SST North Atlantic (detrended) 2-5 yr
BSS=0.14
Observed frequency
Forecast probability
0.0
0.2
0.4
0.6
0.8
1.0

FIGURE 3

A Nonlinear Perspective on Climate Change

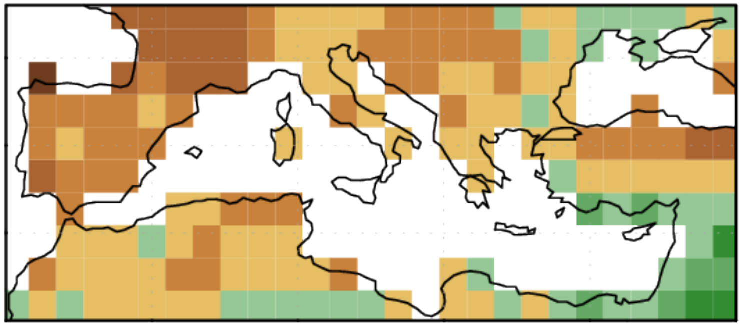


Seamless Prediction techniques allow us to test the strength of at least the first three links

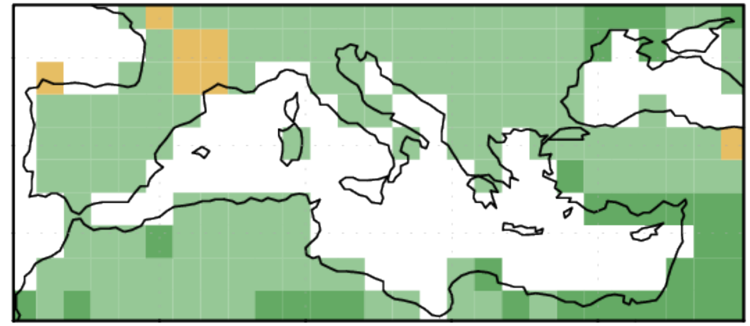
BAMS April 2008 (Palmer, Doblas-Reyes, Rodwell, Weisheimer

MRI–AGCM3.2 probability of dry JJA (2075–2099, Mediterranean Basin)

(a)TL95L64(4–member, raw)

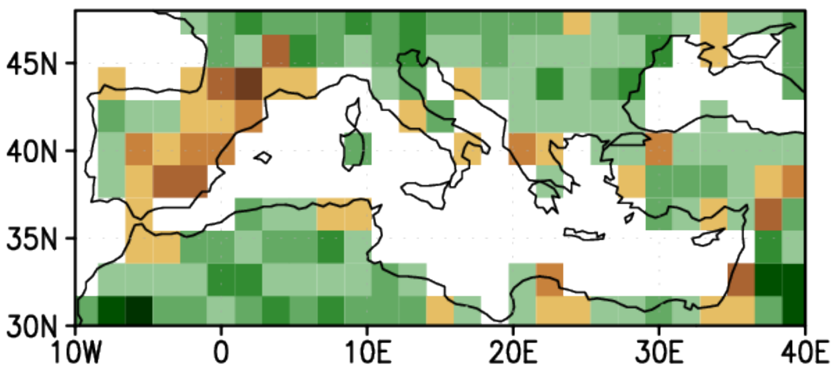


(b)TL95L64(4–member, calibrated)



Calibrated using ENSEMBLES reliability regression lines

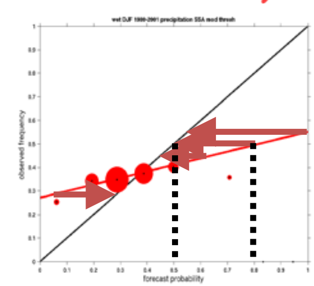
(c)TL959L64



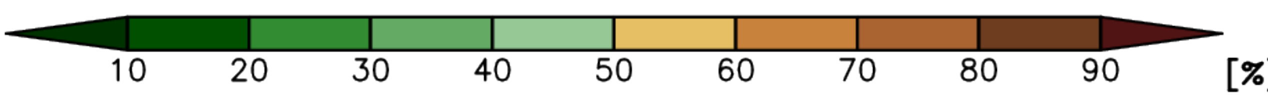
EUROSIP Pcalib=0.4019Praw+0.1993(ε=0.8)

RMSD(TL959 and TL95raw): 0.1916

RMSD(TL959 and TL95calibrated): 0.1242

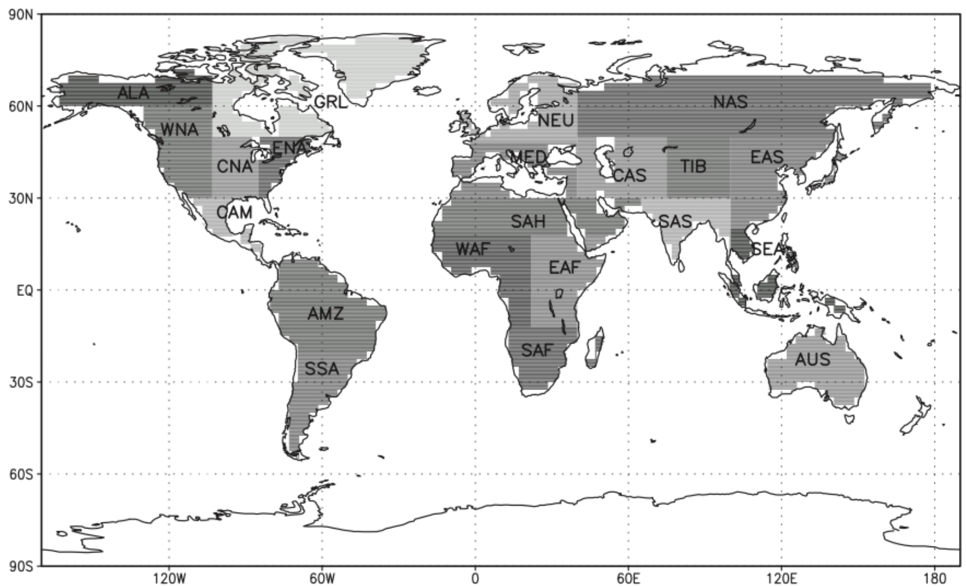


Mio Matsueda, Antje Weisheimer personal communication



Percentage of Giogi regions where some calibration improves climate-change score

DJF dry	76%
DJF wet	85%
JJA dry	95%
JJA wet	100%



Conclusions

- A primary goal for 30 years time is for the direct model output from forecasts on all time ranges – days to seasons and longer - whilst being as sharp as possible, to be reliable.
- The computational representation of the equations of weather and climate is a key source of uncertainty for forecasts.
- Finding reliable representations of model uncertainty must be a core component of research into model development, as we move to higher and higher resolution.