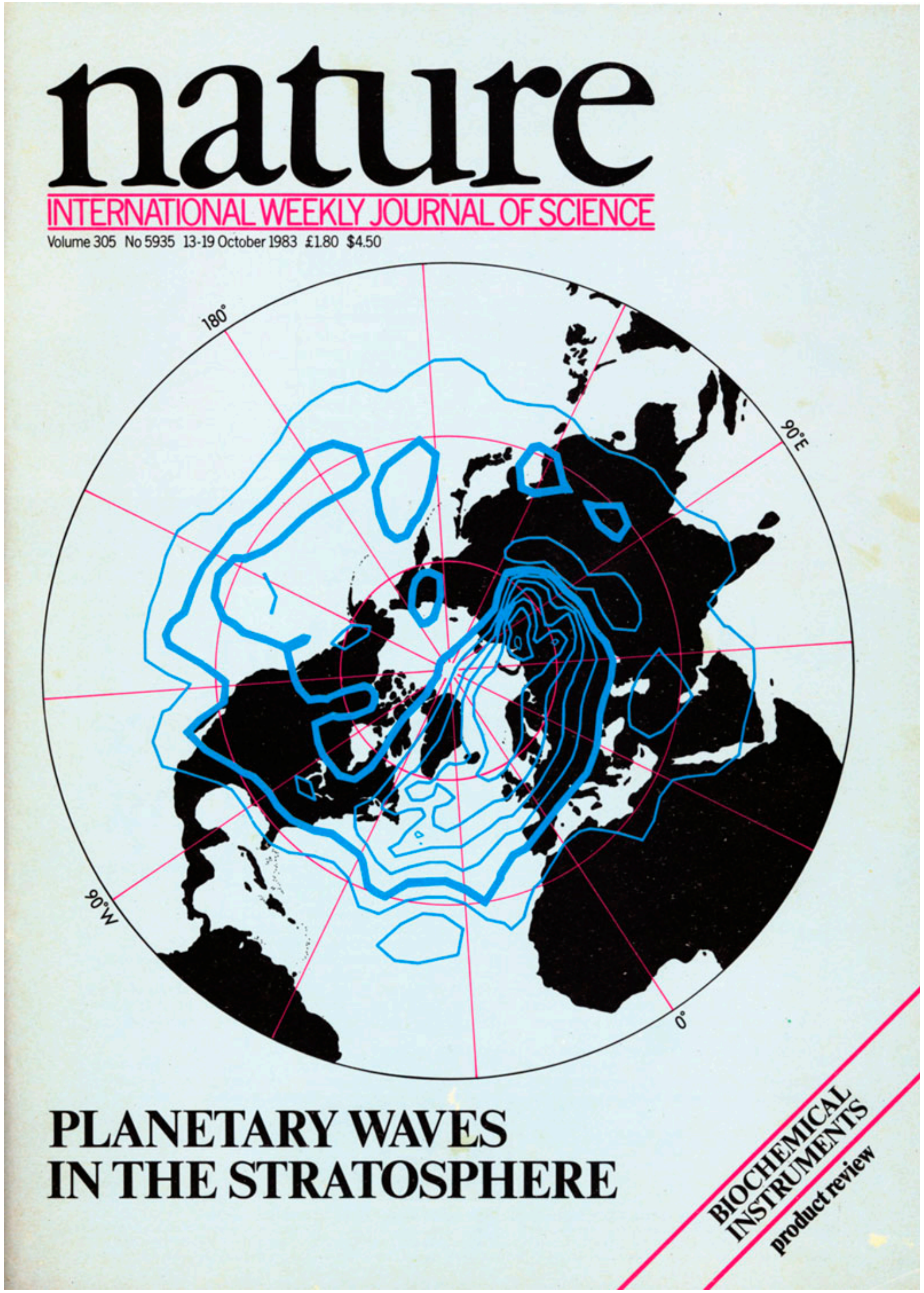
Towards the Seamless Prediction of Weather and Climate

T.N.Palmer, ECMWF.

Bringing the insights and constraints of numerical weather prediction (NWP) into the climate-change arena.

With acknowledgements to :

F.J.Doblas-Reyes, T.Jung, M.Rodwell and A.Weisheimer



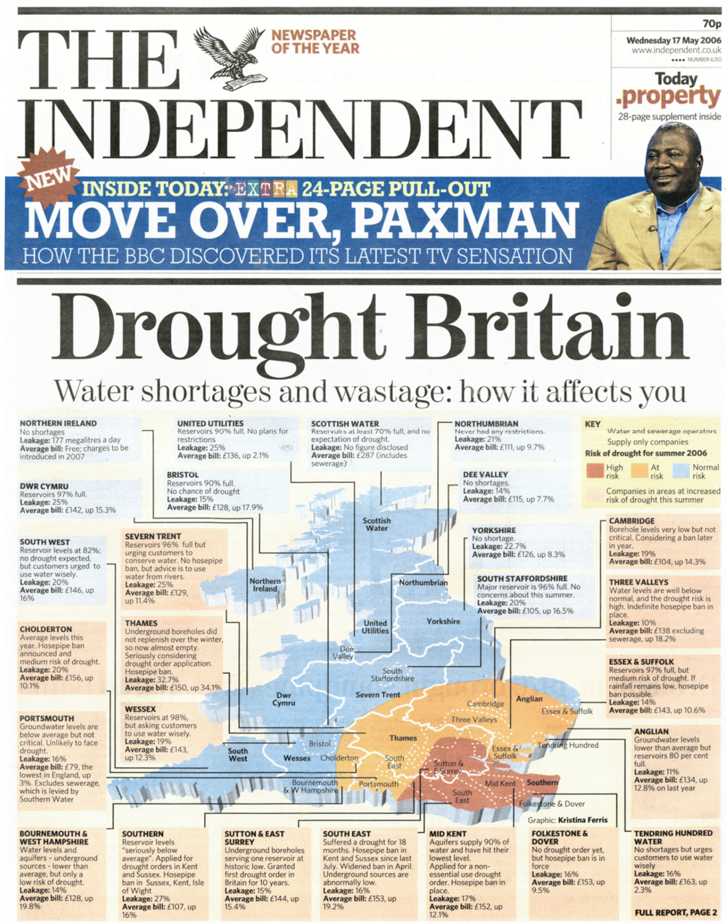
Climate as a Nonlinear Dynamical System

Climate Change is the "defining issue of our era*"

*Ban Ki Moon UN Secretary General

Climate change predictions provide key input to mitigation policies…

…and adaptation strategies



THE INDEPENDENT

NEWSPAPER OF THE YEAR

70p

Wednesday 17 May 2006
www.independent.co.uk
NUMBER 6,110

Today .property
28-page supplement inside

NEW

INSIDE TODAY: EXTRA 24-PAGE PULL-OUT

MOVE OVER, PAXMAN

HOW THE BBC DISCOVERED ITS LATEST TV SENSATION

Drought Britain

Water shortages and wastage: how it affects you

NORTHERN IRELAND
No shortages
Leakage: 177 megalitres a day
Average bill: Free; charges to be introduced in 2007

UNITED UTILITIES
Reservoirs 90% full. No plans for restrictions
Leakage: 25%
Average bill: £136, up 2.1%

SCOTTISH WATER
Reservoirs at least 70% full, and no expectation of drought.
Leakage: No figure disclosed
Average bill: £287 (includes sewerage)

NORTHUMBRIAN
Never had any restrictions.
Leakage: 21%
Average bill: £111, up 9.7%

KEY
Water and sewerage operators
Supply only companies
Risk of drought for summer 2006
High risk / At risk / Normal risk
Companies in areas at increased risk of drought this summer

BRISTOL
Reservoirs 90% full.
No chance of drought
Leakage: 15%
Average bill: £128, up 17.9%

DWR CYMRU
Reservoirs 97% full.
Leakage: 25%
Average bill: £142, up 15.3%

DEE VALLEY
No shortages.
Leakage: 14%
Average bill: £115, up 7.7%

SOUTH WEST
Reservoir levels at 82%; no drought expected, but customers urged to use water wisely.
Leakage: 20%
Average bill: £146, up 16%

SEVERN TRENT
Reservoirs 96% full but urging customers to conserve water. No hosepipe ban, but advice is to use water from rivers.
Leakage: 25%
Average bill: £129, up 11.4%

YORKSHIRE
No shortage.
Leakage: 22.7%
Average bill: £126, up 8.3%

SOUTH STAFFORDSHIRE
Major reservoir is 96% full. No concerns about this summer.
Leakage: 20%
Average bill: £105, up 16.5%

CAMBRIDGE
Borehole levels very low but not critical. Considering a ban later in year.
Leakage: 19%
Average bill: £104, up 14.3%

THREE VALLEYS
Water levels are well below normal, and the drought risk is high. Indefinite hosepipe ban in place.
Leakage: 10%
Average bill: £138 excluding sewerage, up 18.2%

CHOLDERTON
Average levels this year. Hosepipe ban announced and medium risk of drought.
Leakage: 20%
Average bill: £156, up 10.1%

THAMES
Underground boreholes did not replenish over the winter, so now almost empty. Seriously considering drought order application. Hosepipe ban.
Leakage: 32.7%
Average bill: £150, up 34.1%

ESSEX & SUFFOLK
Reservoirs 97% full, but medium risk of drought. If rainfall remains low, hosepipe ban possible.
Leakage: 14%
Average bill: £143, up 10.6%

PORTSMOUTH
Groundwater levels are below average but not critical. Unlikely to face drought.
Leakage: 16%
Average bill: £79, the lowest in England, up 3%. Excludes sewerage, which is levied by Southern Water

WESSEX
Reservoirs at 98%, but asking customers to use water wisely.
Leakage: 19%
Average bill: £143, up 12.3%

ANGLIAN
Groundwater levels lower than average but reservoirs 80 per cent full.
Leakage: 11%
Average bill: £134, up 12.8% on last year

Graphic: **Kristina Ferris**

BOURNEMOUTH & WEST HAMPSHIRE
Water levels and aquifers - underground sources - lower than average, but only a low risk of drought.
Leakage: 14%
Average bill: £128, up 19.8%

SOUTHERN
Reservoir levels "seriously below average". Applied for drought orders in Kent and Sussex. Hosepipe ban in Sussex, Kent, Isle of Wight
Leakage: 27%
Average bill: £107, up 16%

SUTTON & EAST SURREY
Underground boreholes serving one reservoir at historic low. Granted first drought order in Britain for 10 years.
Leakage: 15%
Average bill: £144, up 15.4%

SOUTH EAST
Suffered a drought for 18 months. Hosepipe ban in Kent and Sussex since last July. Widened ban in April. Underground sources are abnormally low.
Leakage: 16%
Average bill: £153, up 19.2%

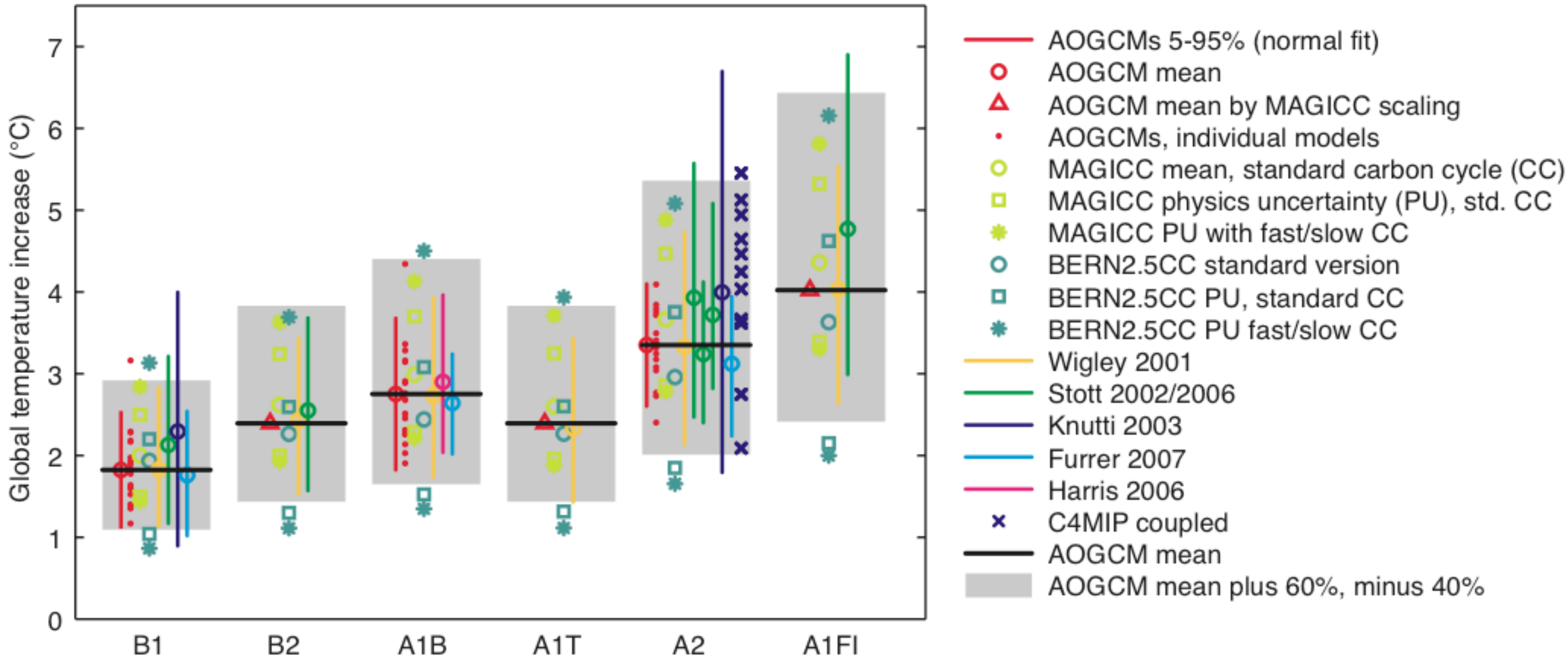
MID KENT
Aquifers supply 90% of water and have hit their lowest level. Applied for a non-essential use drought order. Hosepipe ban in place.
Leakage: 17%
Average bill: £152, up 12.1%

FOLKESTONE & DOVER
No drought order yet, but hosepipe ban is in force
Leakage: 16%
Average bill: £153, up 9.5%

TENDRING HUNDRED WATER
No shortages but urges customers to use water wisely
Leakage: 16%
Average bill: £163, up 2.3%

FULL REPORT, PAGE 2

….. and yet projections of climate change, both globally and regionally, remain uncertain



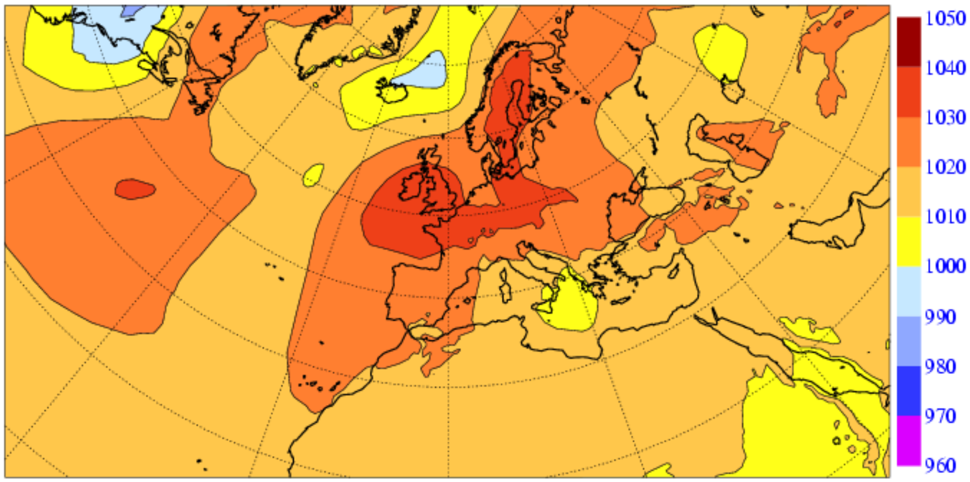
Spread of Global Warming Projections from IPCC AR4 WG1

Figure 10.29

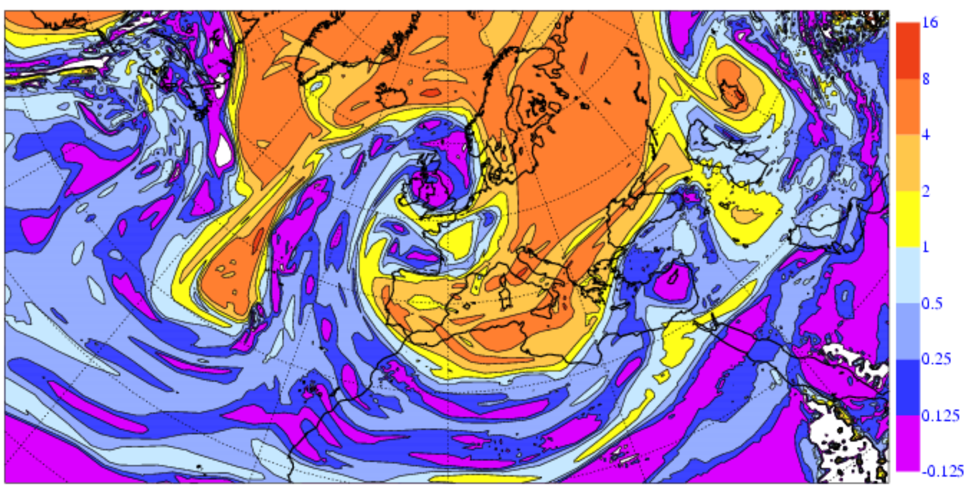
Uncertainty of the First Kind

- Defined as the multi-model ensemble spread of climate-change projections. Has remained large since the first IPCC assessment report.
- There is a fundamental need to reduce uncertainty of the first kind. How?

Surface Pressure



Potential Vorticity on 315K



2005/2006 Drought

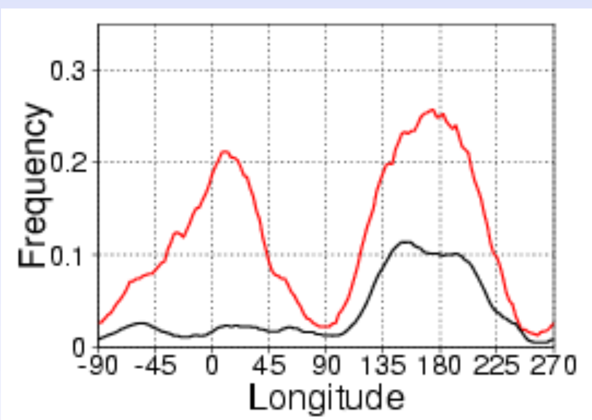
Blocking Anticyclone

How much more frequently will blocking events occur, as a result of increased levels of CO_2?

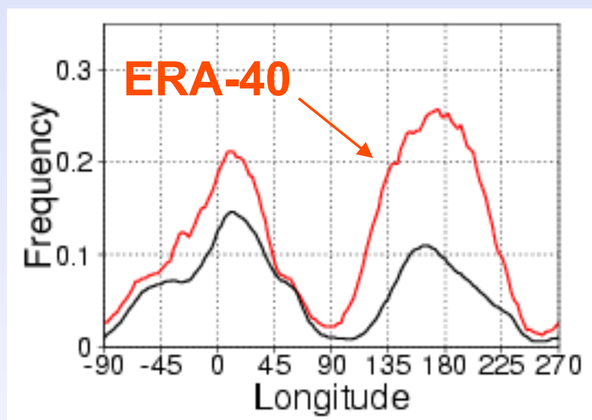
Blocking frequency in climate models

Northern Hemisphere blocking frequency for DEMETER hindcasts
November start, 1959-2001, 9-member ensembles
January (third month

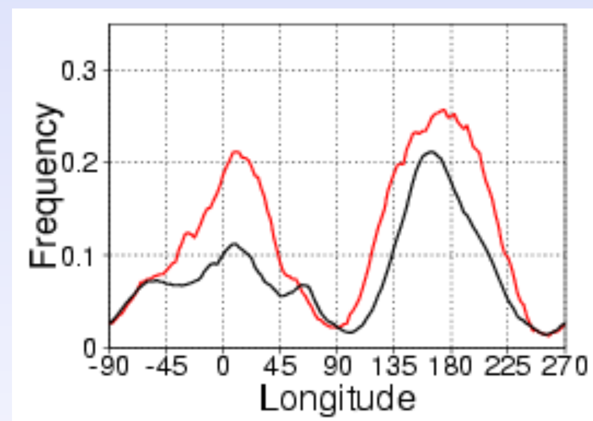
CNRM



ECMWF



Met Office

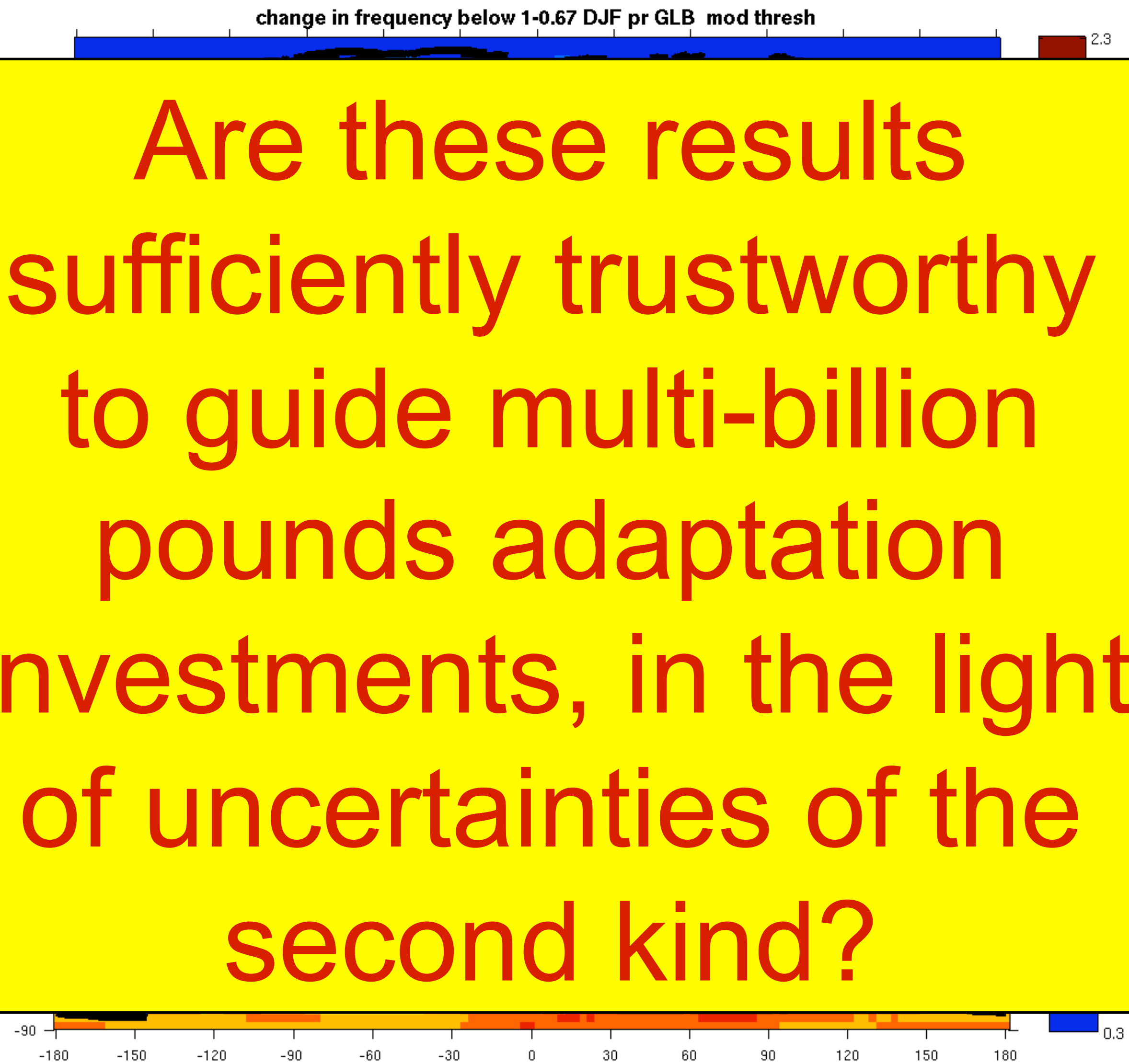


Uncertainty of the Second Kind

- Associated with biases common to all members of a multi-model ensemble of climate models, eg QBO, MJO, blocking, diurnal cycle…
- More "insidious" than uncertainty of the first kind – there is currently no agreed method to quantify, let alone reduce, the impact of uncertainties of the second kind, on climate change projections.

Change in Probability of 20th Century Lower/Upper Tercile Seasonal Precipitation Under Anthropogenic Climate Change

Change in probability of lower tercile precipitation in DJF



Increased risk

Reduced risk

Increased risk

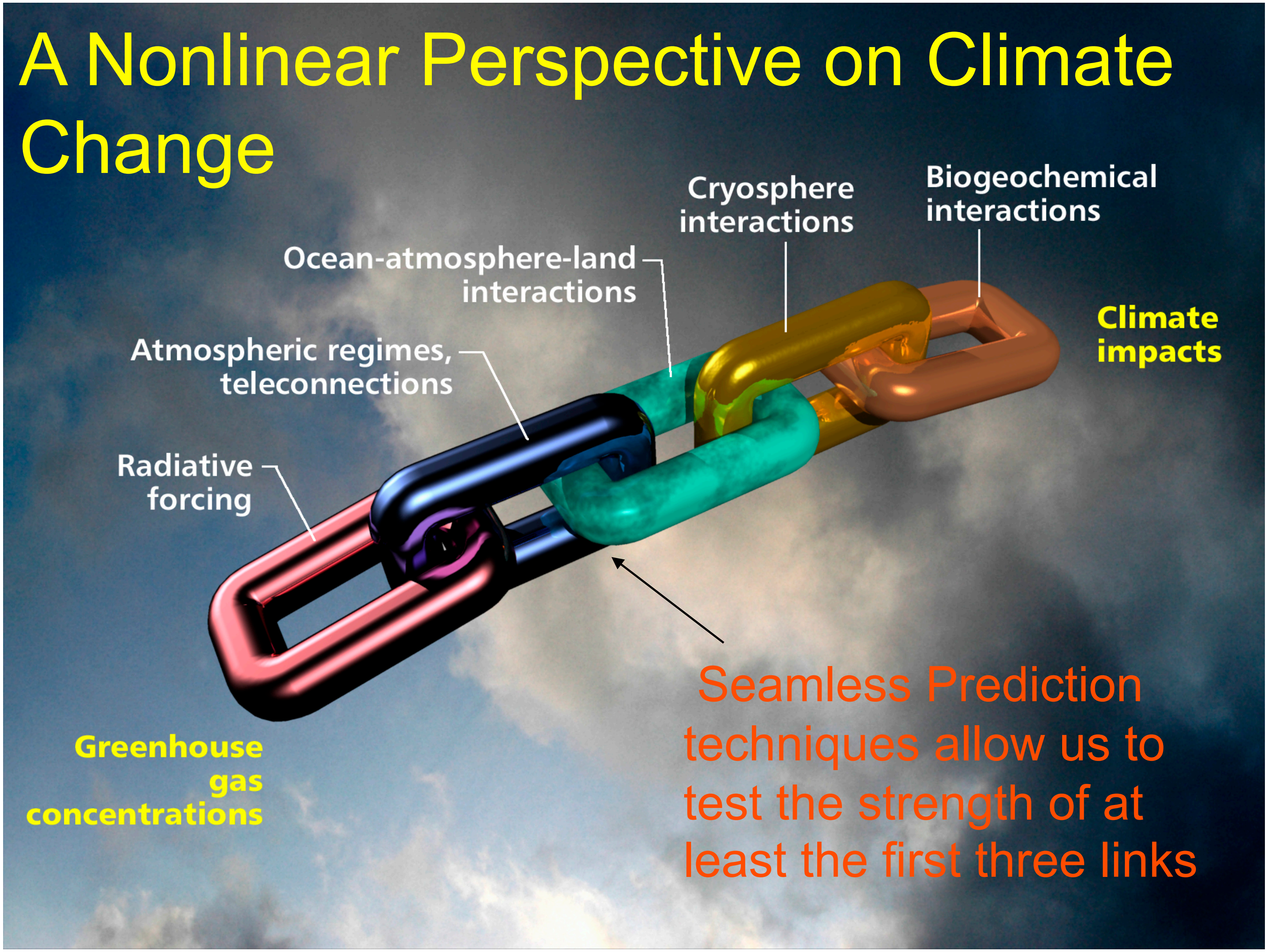
Reduced risk

Change in probability of upper tercile precipitation in JJA

Are these results sufficiently trustworthy to guide multi-billion pounds adaptation investments, in the light of uncertainties of the second kind?

Three Examples of the Potential Impact of Seamless Prediction Techniques

- Short-range NWP tendencies to reduce uncertainty of the first kind
- Seasonal forecast calibration techniques to quantify uncertainty of the second kind
- Stochastic parametrisation to reduce uncertainty of the second kind.


A Nonlinear Perspective on Climate Change
Cryosphere interactions
Biogeochemical interactions
Ocean-atmosphere-land interactions
Atmospheric regimes, teleconnections
Climate impacts
Radiative forcing
Greenhouse gas concentrations
Seamless Prediction techniques allow us to test the strength of at least the first three links

1. Reducing Uncertainties of the First Kind Using 6hr NWP tendencies.

T.N.Palmer and P.J.Webster, 1994: Towards a unified approach to climate and weather prediction. Global Change. European Commission, EUR 15158en, 265-281.

Rodwell, M.J. and T.N.Palmer, 2007: Using numerical weather prediction to assess climate models. Q.J.R. Meteorol.Soc., 133, 129-146.

http://www.newscientist.com - Soaring global warming 'can't be r

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NewScientist.com

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Soaring global warming 'can't be ruled out'

Click to Print

19:03 26 January 2005
NewScientist.com news service
Jenny Hogan

The Earth may be much more sensitive to global warming than previously thought, according to the first results from a massive distributed-computing project.

The project tested thousands of climate models and found that some produced a world that warmed by a huge 11.5°C when atmospheric carbon dioxide concentrations reached the levels expected to be seen later this century.

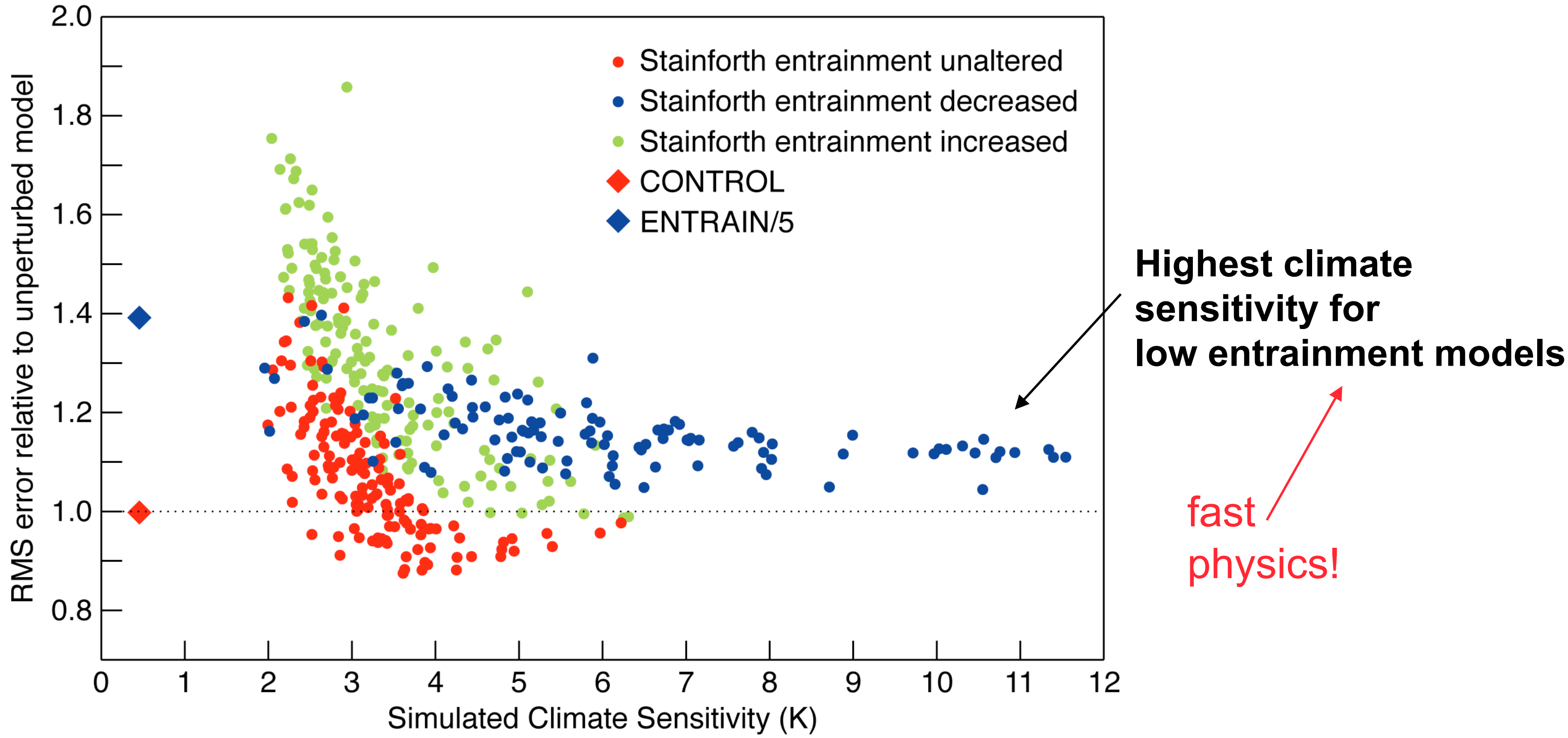
This extreme result is surprising because it lies far outside the 1.4°C to 4.5°C range predicted by the Intergovernmental Panel on Climate Change (IPCC) for the same CO_2-level increase - a doubling of CO_2 concentration from pre-industrial times. But it is possible the IPCC range was wrong because its estimate is based on just a handful of different computer models.

Enlarge image

The climate modelling software divides the Earth's surface into boxes hundreds of kilometres square (image: Climateprediction.net)

"There are no obvious problems with the high temperature models, Stainforth says…. The uncertainty at the upper end has exploded, says team-member Myles Allen."

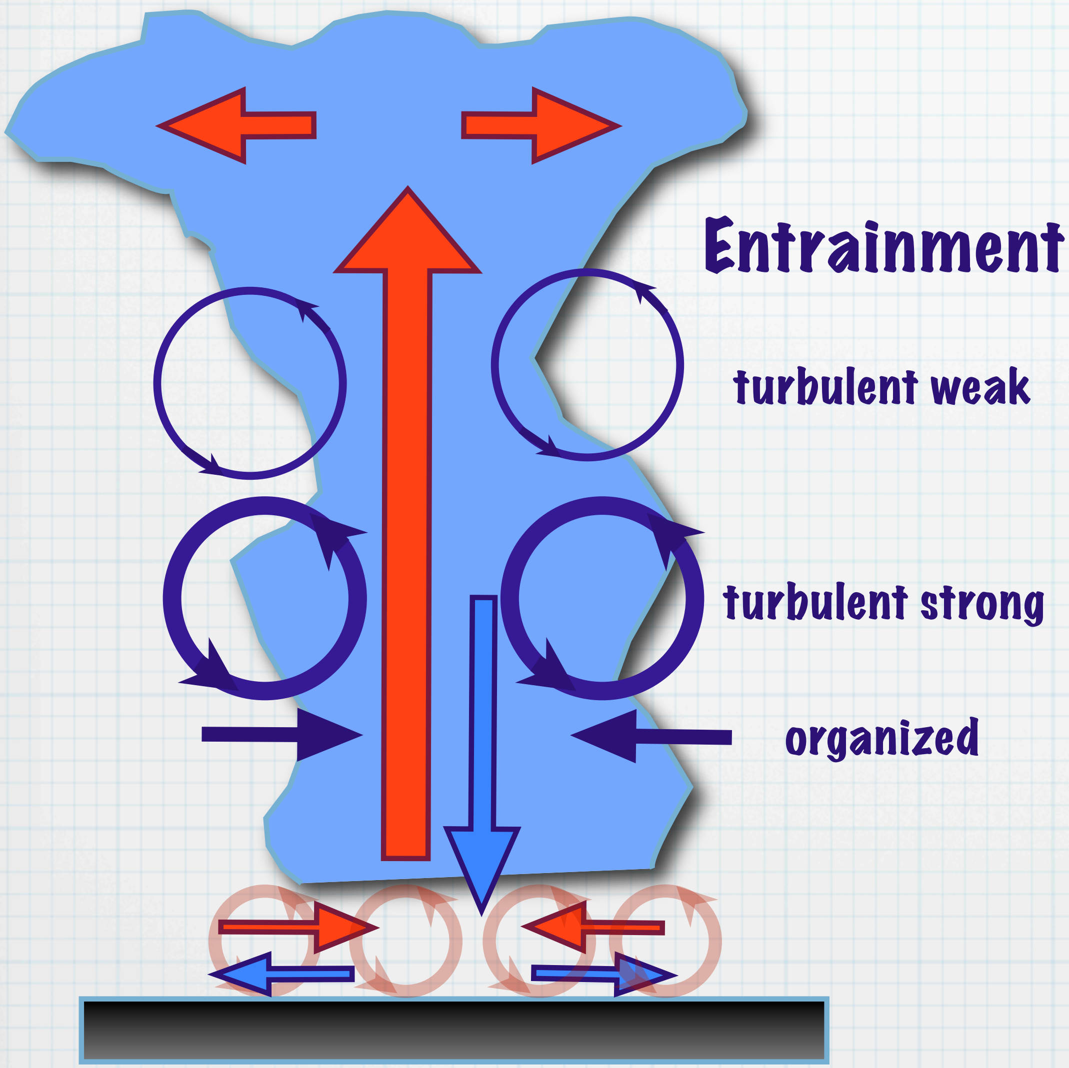
Climate: Error vs Sensitivity



Circles: AGCM + Mixed-Layer model results from Stainforth et al. (2005) show combined RMSE of 8 year mean, annual mean T_{2m}, SLP, precipitation and ocean-atmosphere sensible+latent heat fluxes (equally weighted and normalised by the control).

Diamonds: AGCM results from Rodwell & Palmer (2006) show RMSE from 39 year mean, annual mean T_{850}, SLP and precipitation (equally weighted and normalised by the control).

One key parameter in a convection parametrisation is the entrainment-rate parameter

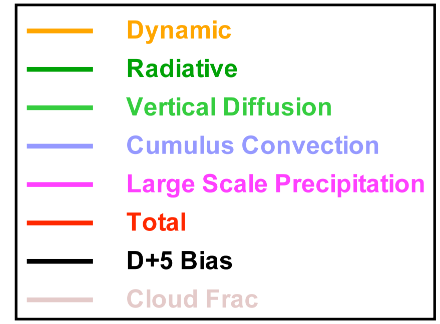


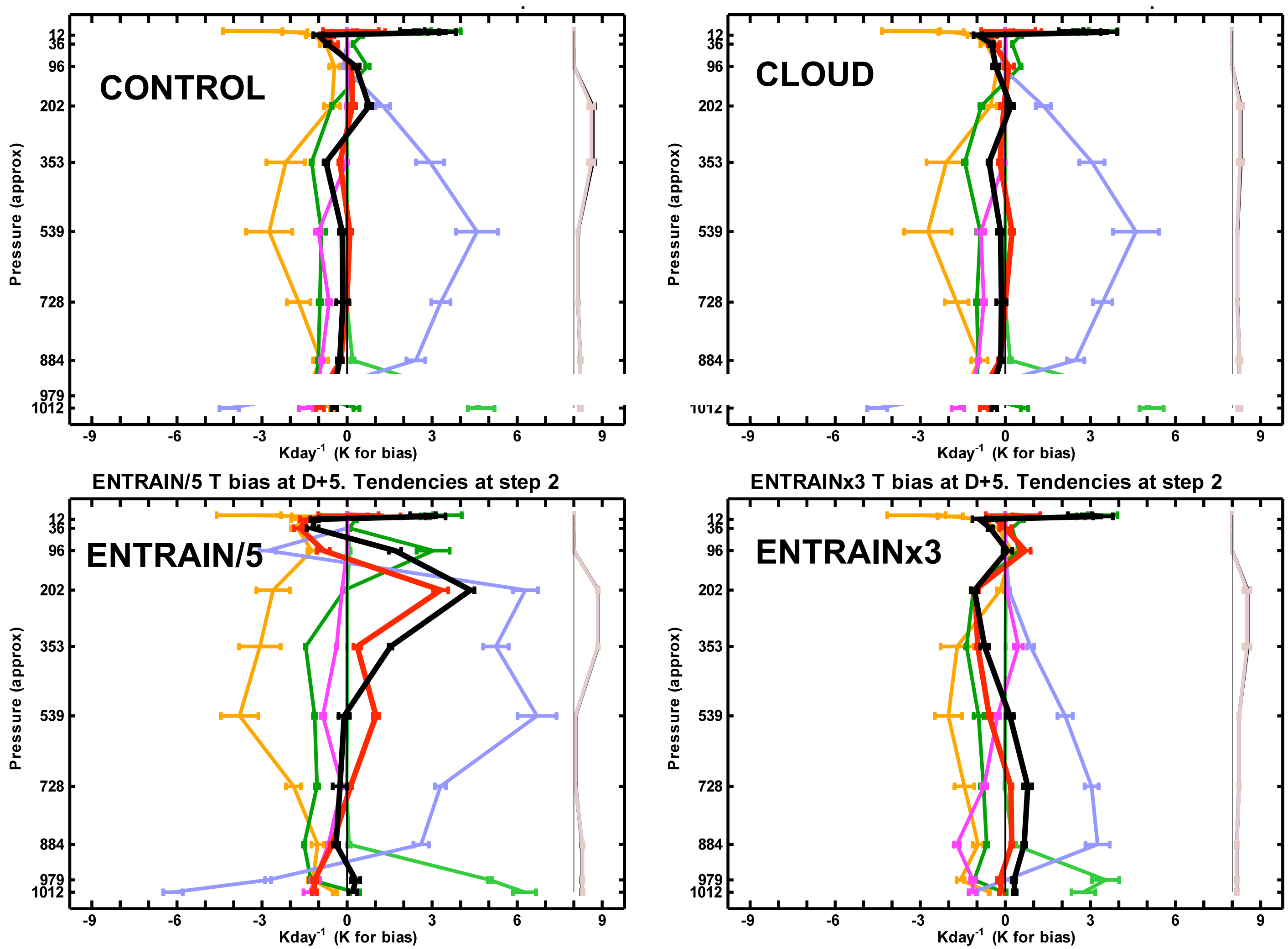
Entrainment

- **mixes** environmental air into convective clouds
- is caused by **turbulence** and/or **organized inflow**
- thereby **reduces the difference of cloud to environment**, which is the fuel the cloud thrives on
- **strength** of its effect depends on **entrainment rate** (model parameter) and **difference in properties** of cloud and environment
- **high** entrainment **rate** and/or very **dry** environment -> **shallow clouds**
- **low** entrainment **rate** and/or very **moist** environment -> **deep clouds**

January 2005 Initial T Tendencies

Caveat: Not same model as Stainforth et al.





ENTRAIN/5 and ENTRAINx3 are out of balance

ECMWF

Advantages of short-range tendency over conventional methods for assessing climate models

- Climate variability is dominated by a few EOFs (eg NAO, PNA, ENSO …etc)
- Hence although individual parametrisations represent specific physical processes, their impact on climate can be degenerate, eg different parametrisations having similar responses
- Leads to classic problem of "compensating errors"
- Hence very difficult to assess what is the "best" set of parametrisations, eg by tuning to 20th Century climate.

ECMWF

Diagnosing Climate Error by Short-Range NWP Tendency

$$\dot{T} = \dot{T}_{dynamics} + \dot{T}_{long-wave\ radiation} + \dot{T}_{short-wave\ radiation} + \dot{T}_{convection} + \ldots$$

Because they represent different physical processes, initial tendencies are approximately orthogonal, ie

$$\|\dot{T}\|^2 \approx \|\dot{T}_{dynamics}\|^2 + \|\dot{T}_{long-wave\ radiation}\|^2 + \|\dot{T}_{short-wave\ radiation}\|^2 + \|\dot{T}_{convection}\|^2 + \ldots$$

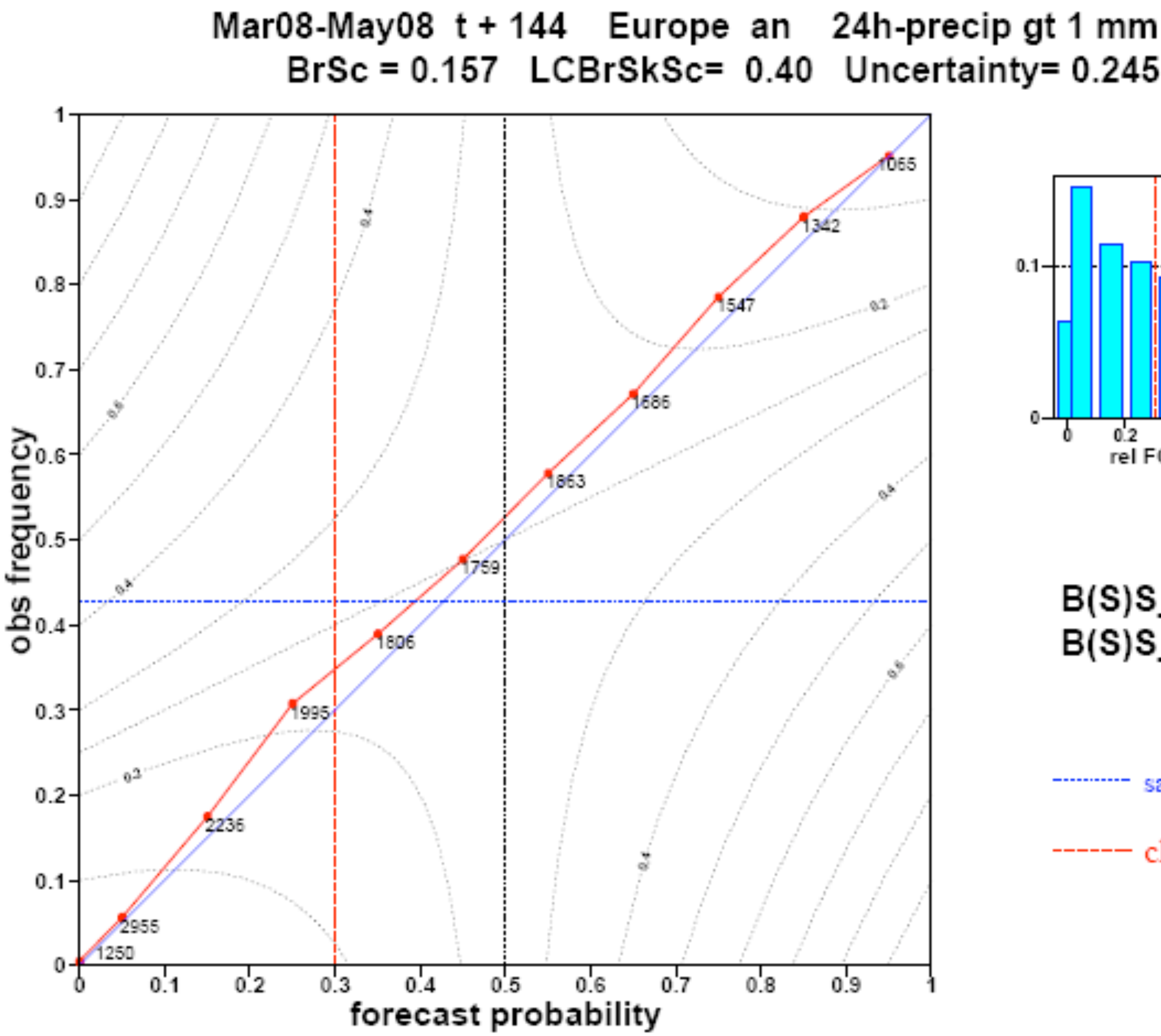
Hence reducing error in the norm of any one tendency will reduce error in the total tendency. Less possibility of compensating error.

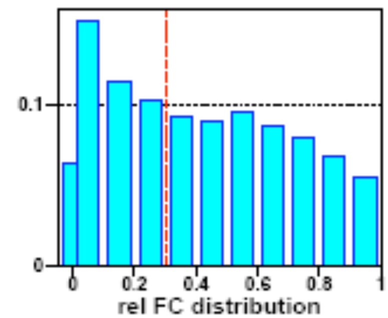
ECMWF

2. Quantifying Uncertainties of the Second Kind Using Seasonal Forecast Reliability Diagrams

Palmer, T.N., F.J. Doblas-Reyes, A. Weisheimer and M.J.Rodwell.
2008: Towards Seamless Prediction: Calibration of Climate-Change Projections Using Seasonal Forecasts. BAMS, 89, 459-470,

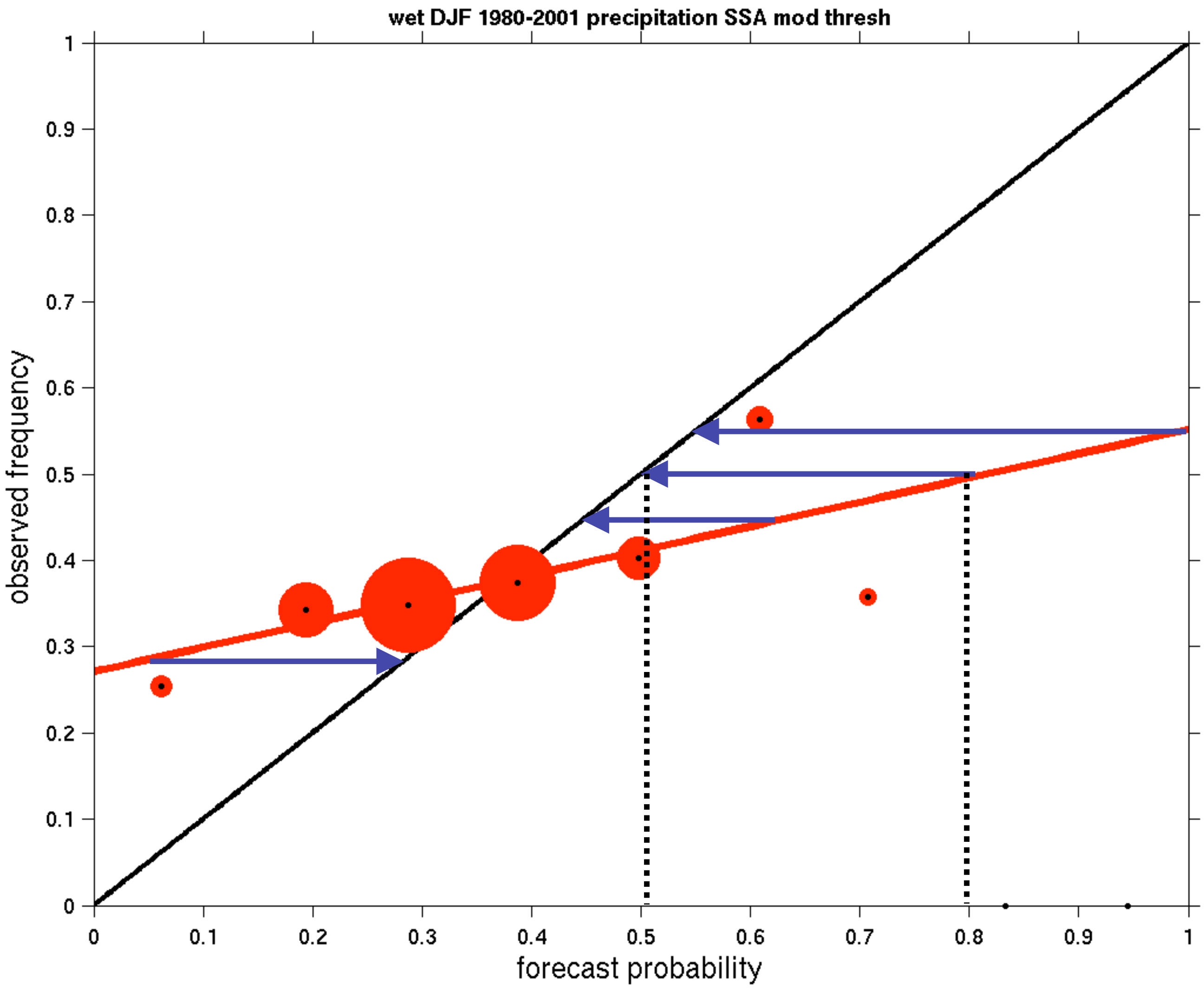
EPS Day 6 Precip Europe March-May 2008





B(S)S_RSL= 0.088(0.36)
B(S)S_REL= 0.001(1.00)

Calibrating Probabilistic Forecasts

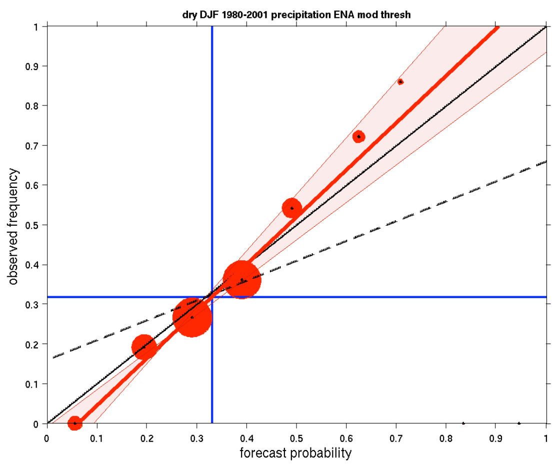


In regions where a multi-model seasonal forecasts are unreliable (due to uncertainties of the second kind) then the climate change signal may similarly be unreliable.

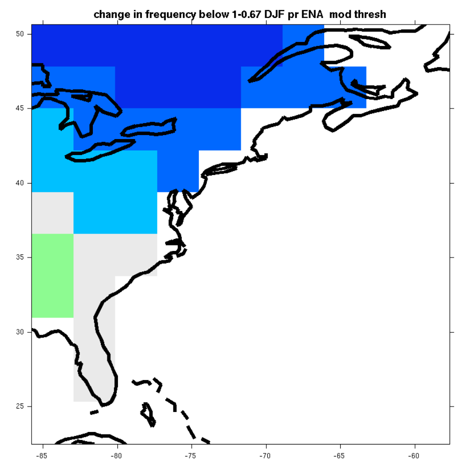
Use seasonal forecasts to calibrate climate change projections of precipitation?

DEMETER Multi-Model Seasonal Predictions

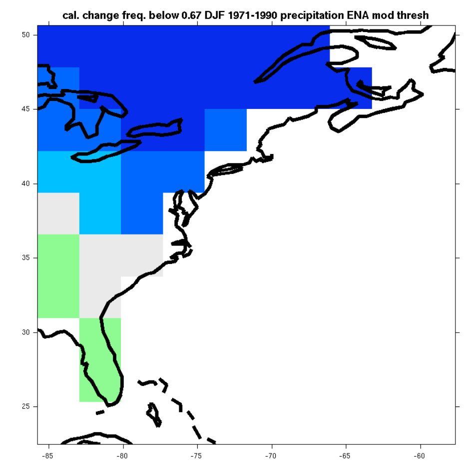
Eastern North America dry DJF



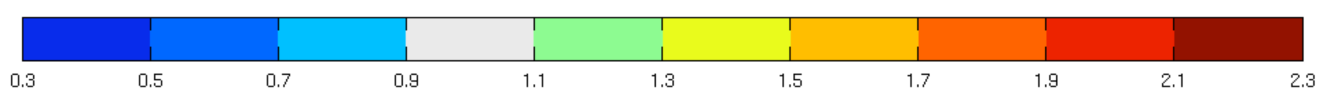
DEMETER Reliability



AR4 Uncalibrated

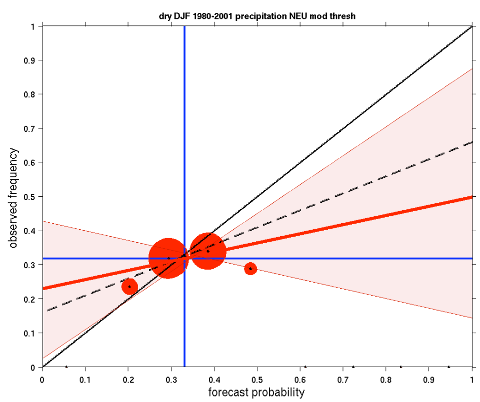


AR4 Calibrated

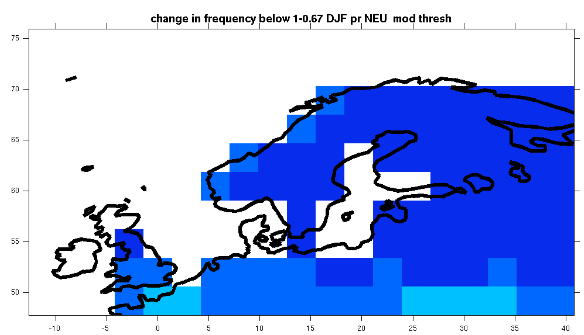


Northern Europe dry DJF

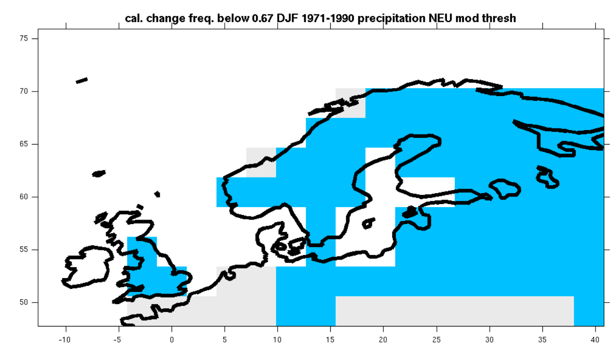
Reliability of seasonal forecasts is poor, hence discount the strong AR4 probabilities



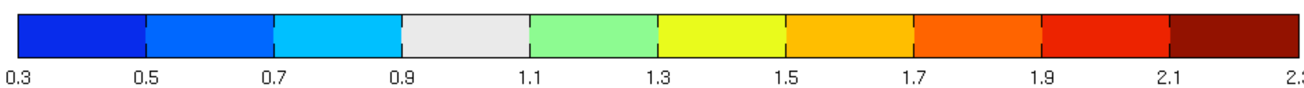
DEMETER Reliability



AR4 Uncalibrated



AR4 Calibrated



Would better decisions be made (eg with regard to regional infrastructure investments for climate adaptation) using the calibrated probabilities compared with the uncalibrated probabilities?

3. Reducing uncertainty of the second kind: stochastic-dynamic parametrisation

Palmer, 2001: A nonlinear dynamical perspective on model error: a proposal for non-local stochastic-dynamic parametrisation in weather and climate prediction models. QJ, 127, 279-304.

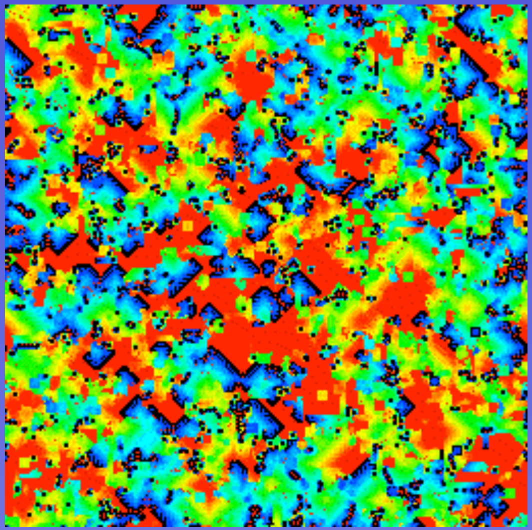
Medium-Range Ensemble Prediction Systems must include representations of model uncertainty in order that ensemble forecasts are not overconfident.

To do this, a stochastic representation of random sub-grid model uncertainties has been developed.

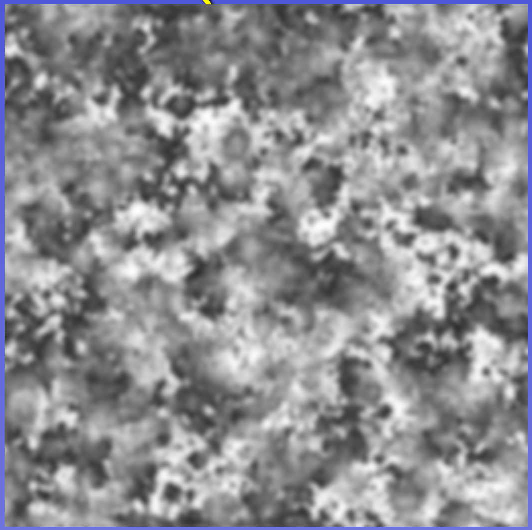
$$\dot{T} = \dot{T}_{dynamics} + \dot{T}_{long-wave\ radiation} + \dot{T}_{short-wave\ radiation} + \dot{T}_{convection} + \ldots$$

Represent each sub-grid tendency as a pdf
(Buizza et al, 1999)

Cellular Automaton Stochastic Backscatter Scheme (CASBS)



smooth → scale



Cellular Automaton state

streamfunction forcing shape Ψ function

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

D = sub-grid energy dissipation due to numerical diffusion, mountain drag and convection

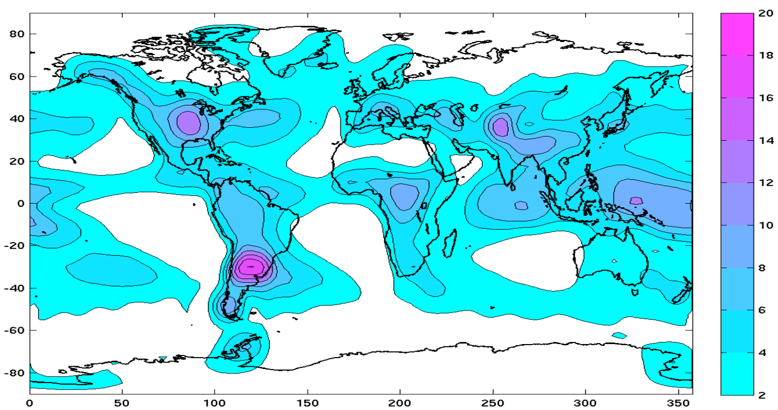
r = backscatter parameter

G.Shutts, 2005

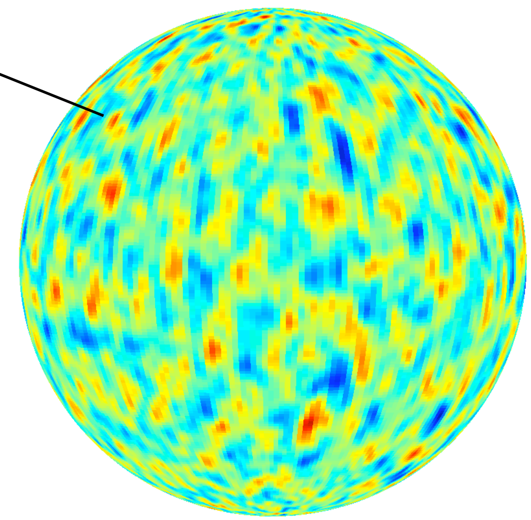
Stochastic Spectral Backscatter Scheme (SPBS)

Rationale: A fraction of the dissipated energy is scattered upscale and acts as streamfunction forcing for the resolved-scale flow (LES) (cf Shutts and Palmer 2004, Shutts 2005)

$$\Delta\psi^* \propto \sqrt{D}\psi'$$



Total Dissipation rate from numerical dissipation, convection, gravity/mountain wave drag.



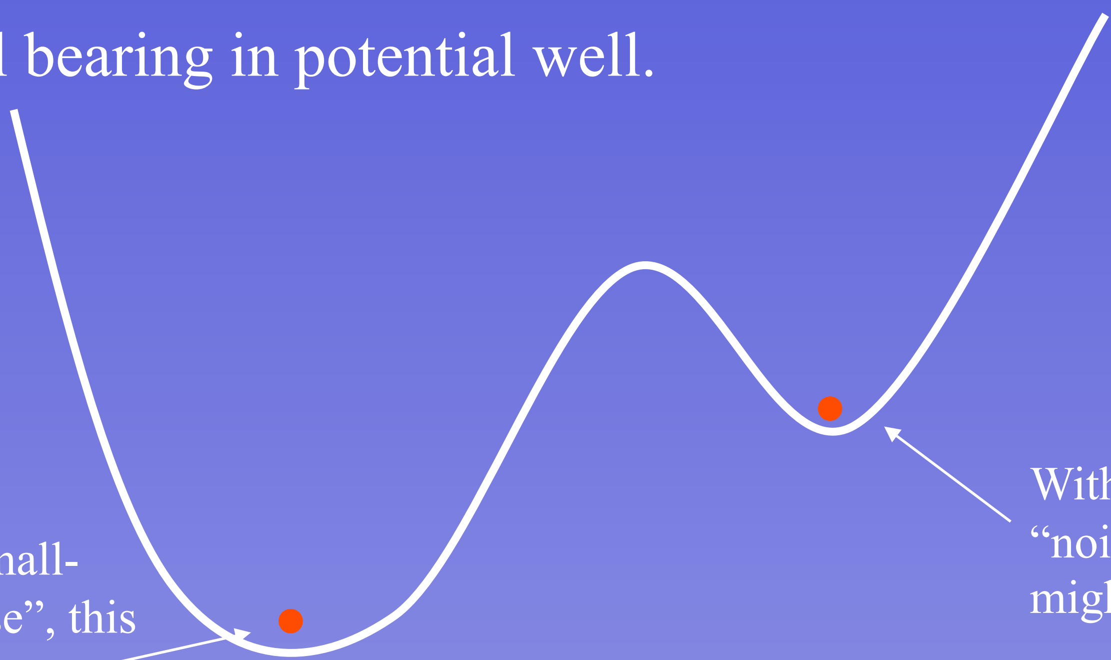
Spectral Markov chain: temporal and spatial correlations prescribed

Berner et al, 2008

Because of the nonlinearities of climate, this stochastic representation of model uncertainty can also reduce systematic biases in climate models.

Can adding noise change the mean state of a system?

Eg ball bearing in potential well.



Without small-scale "noise", this regime is too dominant

Without small-scale "noise", this minimum might be inaccessible

With noise, the mean state shifts to the right

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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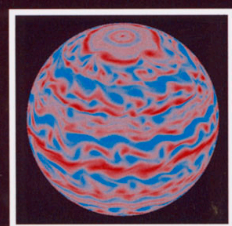
In this issue

Stochastic physics and climate modelling

Papers of a Theme Issue compiled and edited by Tim Palmer and Paul Williams



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If an Earth-System model purports to be a comprehensive tool for predicting climate, it should be capable of predicting the uncertainty in its predictions.

The governing equations of Earth-System models should be inherently probabilistic.

“I believe that the ultimate climatic models….will be stochastic, ie random numbers will appear somewhere in the time derivatives.” Lorenz (1975)

Lorenz E.N. 1975. Climatic Predictability. In “The Physical Basis of Climate and Climate Modelling”. WMO GARP Publication Series No 16. World Meteorological Organisation. Geneva: 265 pp.

Seamless Prediction and Decadal Forecasting

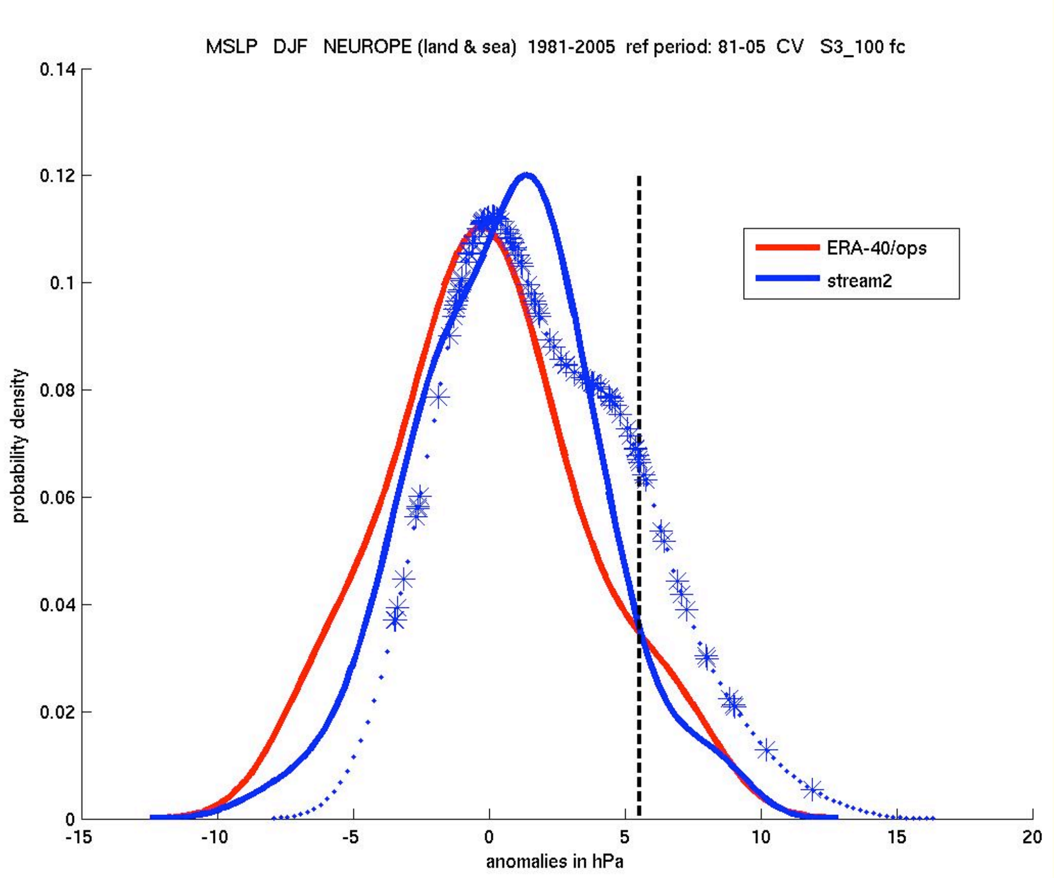
- Decadal prediction provides a meeting ground between the weather and climate communities
    - ❖ Impact of accurate initial conditions (weather)
    - ❖ Impact of greenhouse-gas scenarios (climate)

  and therefore a focus for seamless prediction studies.
- Possible contribution to AR5?

Return to Winter of 2005/6

- How good were the ECMWF seasonal forecasts for Northern Europe?
- Could these predictions have been improved if the a) stratospheric polar vortex, b) the tropics, had been successfully forecast?

Northern Europe (land & sea) DJF 2005/06 sea level pressure



coupled forecast
for DJF 2005/06
with 100 ensemble members

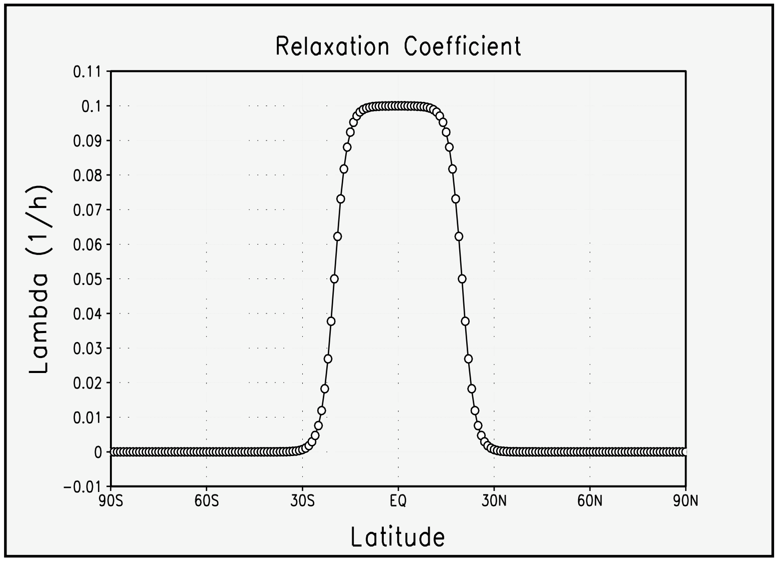
Relaxation Formulation

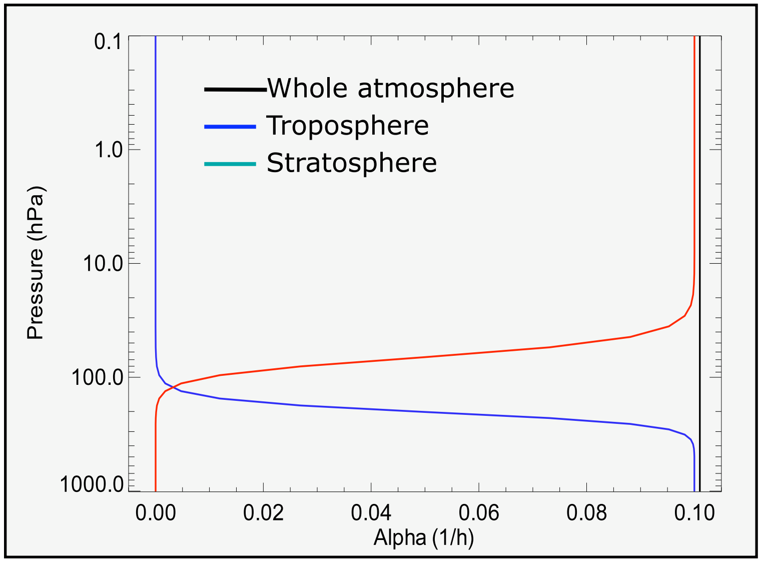
ECMWF model: $$\frac{\partial \mathbf{x}}{\partial t} = M(\mathbf{x})$$

ECMWF model with relaxation: $$\frac{\partial \mathbf{x}}{\partial t} = M(\mathbf{x}) - \lambda(\mathbf{x} - \mathbf{x}^{ref})$$

- Relaxations coefficient, λ, depends on longitude, latitude and height.
- Relaxation for u, v, T and $\ln p_s$ (same λ)
- $\mathbf{x}^{ref}$ is based on (interpolated) ERA-40 data.

Relaxation Regions





Experimental Setup

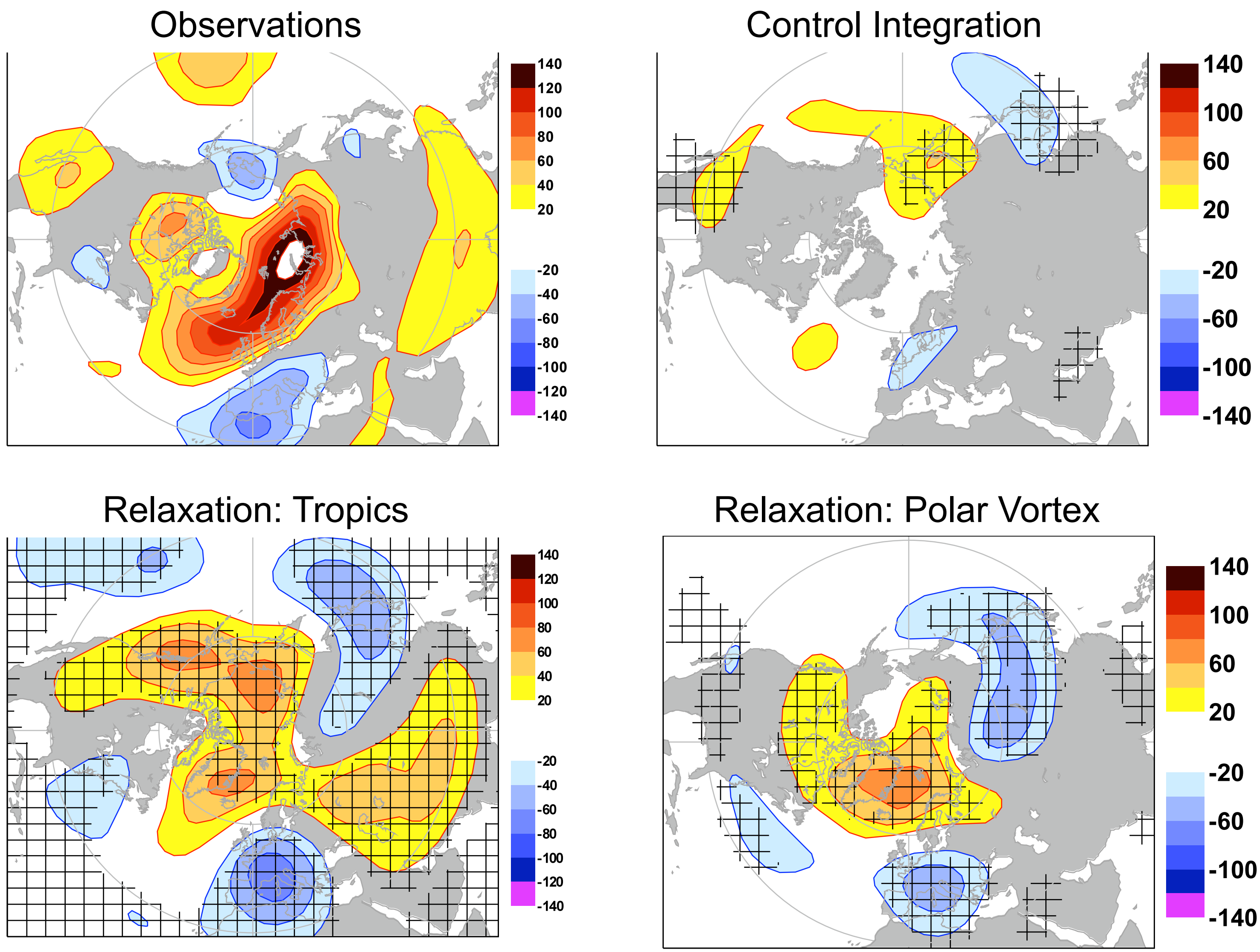
- Model version 32R1 (5/06–5/11 2007)
- T_L95 (210 km) with 60 vertical levels
- Initial and boundary conditions as well as $\mathbf{x}^{ref}$: Operational analyses (interpolated to T_L95L60)
- Ensemble: 17 members (2005111612/to/2005112012/by/6hrs)
- Period of interest: 1/12/05 bis 28/02/06

- Calibration run (16. November, 1990-2006)

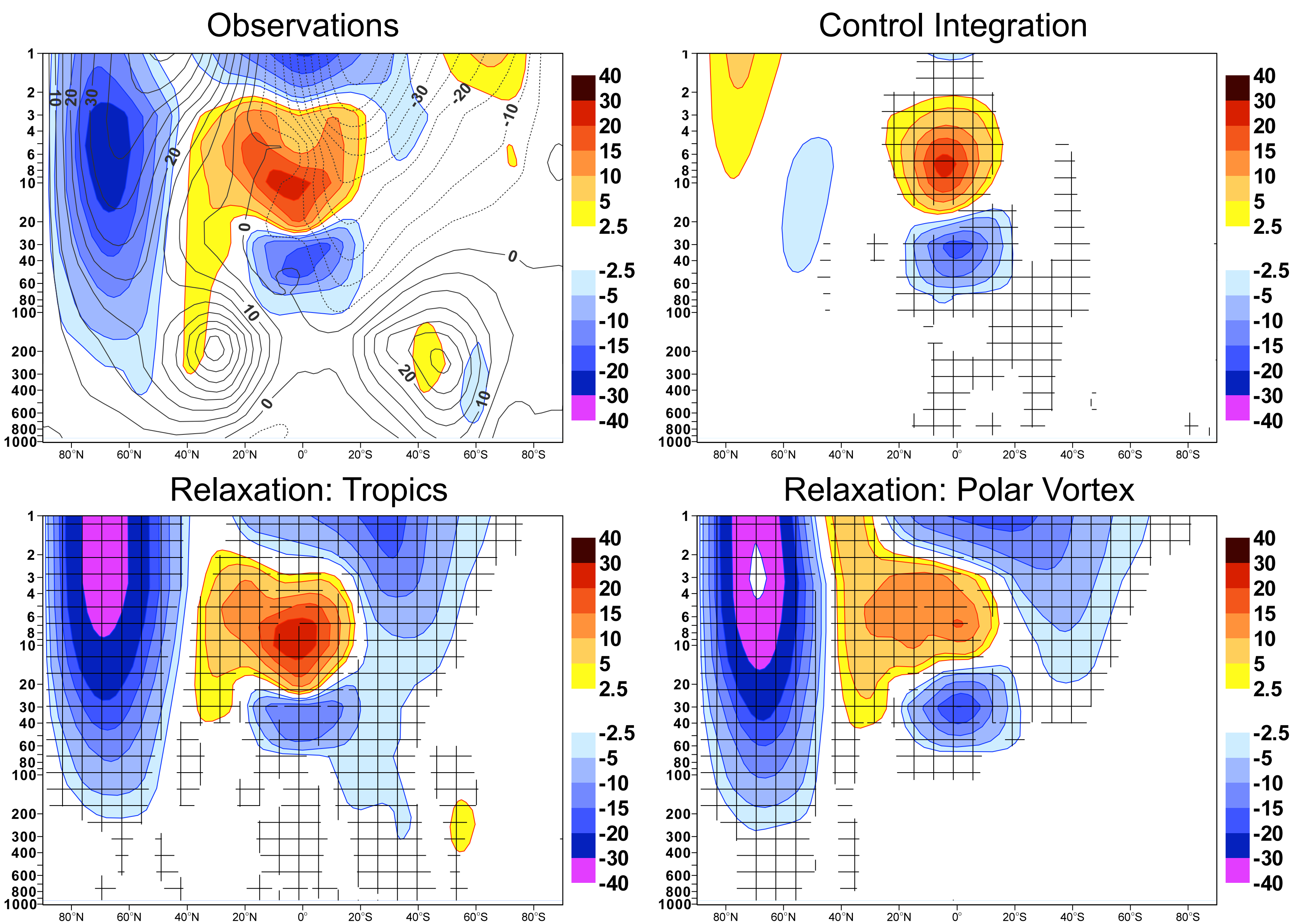
- Control ensemble (observed SST/sea ice)

- Relaxation ensembles (various regions)

Z500 Anomalies (DJF 2005/06)

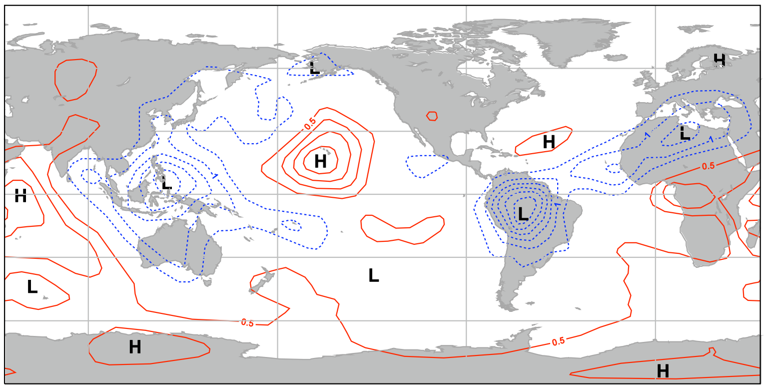


[u]-Anomalies (DJF 2005/06)

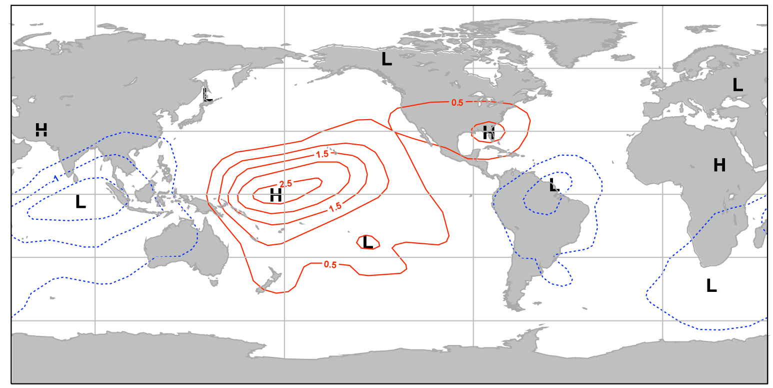


X Anomalies 200-300hPa (DJF 2005/06)

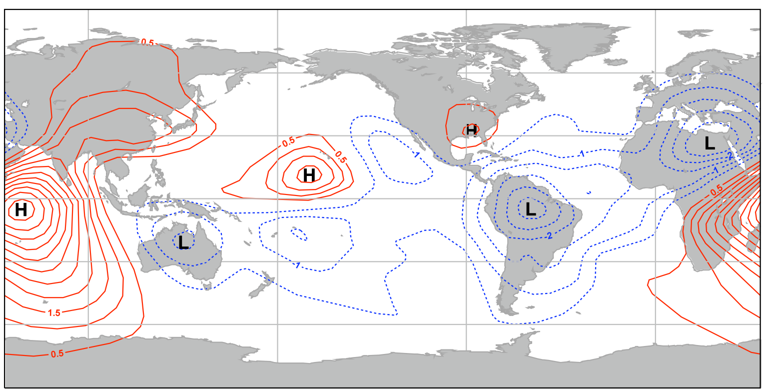
Observations



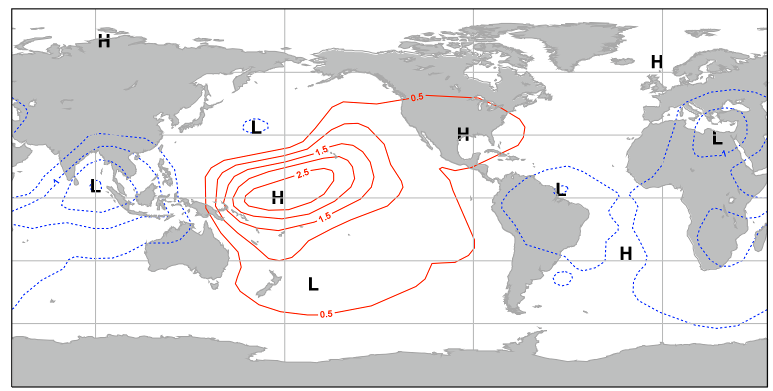
Control Integration



Relaxation: Tropics



Relaxation: Polar Vortex



Notice: “Observed” anomaly = OD(05/06)-E4(Climate), that is, different model formulation + vertical resolution

Conclusions (I)

- Climate change projections are still uncertain
  - ❖ Uncertainty of the first kind (multi-model spread)
  - ❖ Uncertainty of the second kind (common model deficiencies)
- Seamless prediction allows the insights and constraints of numerical weather forecasting to be brought to bear on the climate-change prediction problem
- Decadal prediction is the natural meeting ground between weather and climate communities. Fertile area for 2-way interaction

Conclusions (II)

- Middle atmosphere plays a role in tropospheric climate simulation, but need for major improvements in our ability to simulate the tropics remains a priority.
  - ❖ Need to study how well our ability to simulate climate is improved using convectively-resolved models.
  - ❖ Need for dedicated petaflop computing resources for climate (WCRP Climate Modelling Summit)