Interpretation of the Hadley Centre probabilistic framework

Ben Booth, Mat Collins, Glen Harris, Ambarish Karmalkar, Hugo Lambert, James Murphy, Jonty Rougier, David Sexton

With slides on National climate Scenarios from Suraje Dessai

ICTP, Trieste, 2015

Met Office

Contents:

- Current context for National Climate Projections
- Ingredients for probabilistic UK Climate Projection framework (UKCP09)
    - Climate model simulations
    - Statistical tools
    - Accounting for model discrepancy
    - Sensitivity tests for the projections
- User reception

Climate Scenario construction

- National Climate Change assessments have been carried out by a number of countries. Most are non-probabilistic.

Scenario and climate scenarios

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1950s – usage in military strategy and planning

1970s – usage in the energy business (Royal Dutch/Shell; Van der Heijden, 1997).

1980 – first climate scenario (Wigley et al. 1980)

Slide courtesy: Suraje Dessai

ARTICLES

Scenario for a warm, high-CO_2 world

T. M. L. Wigley, P. D. Jones & P. M. Kelly

Climatic Research Unit, University of East Anglia, Norwich, UK

Plausible patterns for temperature and precipitation changes accompanying a general global warming, such as might occur due to a large increase in atmospheric carbon dioxide levels, are presented. The patterns are determined by comparing the five warmest years in the period 1925–74 with the five coldest in this period. Temperature increases are indicated for most regions, with maximum warming over northern Asia. A few isolated regions show cooling. Precipitation changes are fairly evenly distributed between increases and decreases; the most important features being an increase over India, and decreases in central and south-central USA and over much of Europe and Russia. The latter decreases, should they occur, could have considerable agricultural impact.

MAN has upset the global carbon cycle by burning fossil fuels and, probably, by deforestation and changing land use. The net result of these activities is to increase the CO_2 content of both

Insights into a warm world

Two approaches may be used to derive a scenario for the pattern of climatic changes which might result from a large increase in atmospheric CO_2. These are: numerical modelling using general circulation models (GCMs)[10–12]; and the use of past warm periods as analogues of the future[8,9]. The latter includes the possibility of using recent instrumental data to determine the characteristics of individual warm years which may then be used as analogues of the future.

Both methods have their limitations. GCMs are restricted by their present state of development; current computer power dictates that these models simulate in detail only one part of the atmosphere–hydrosphere–cryosphere system. Most models only consider the atmosphere and use the hydrosphere and cryosphere as externally specified boundary conditions[11]. GCMs do, however, simulate present-day climate reasonably well; and, provided sea-surface temperatures and ice margins are prescribed, they also appear to simulate ice-age climate in a realistic way[11,13]. For a high-CO_2 world we cannot accurately prescribe sea-surface temperatures and should ideally use a coupled ocean–atmosphere model. Although such models do

Scenarios and climate scenarios

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1980s-90s – scientific papers and policy documents use and develop climate scenarios

1990s – first national climate scenarios published (UK)

2001 – IPCC TAR WG1 devotes a chapter to the science of climate scenario construction (Mearns et al., 2001)

2009 – first probabilistic climate change projections published (UK)

Slide courtesy: Suraje Dessai

A chronology of UK climate scenarios

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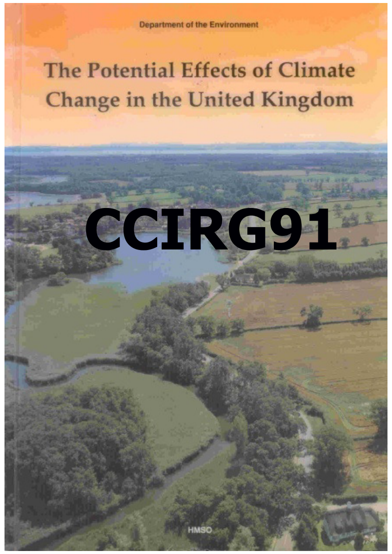
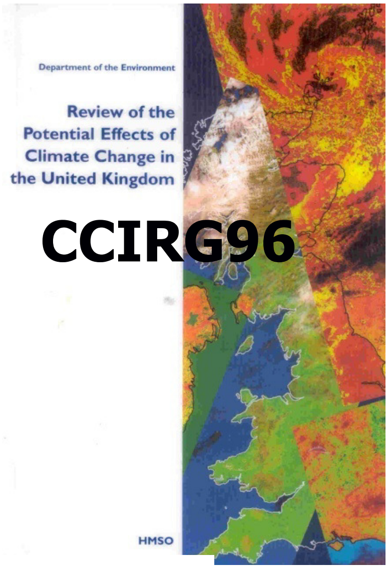
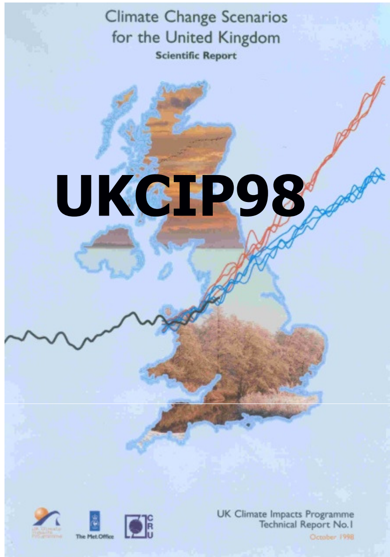
UK Climate Scenarios		UK developments	International developments
	1989	Hadley Centre established	
	1990		IPCC FAR
CCIRG91 scenarios	1991	LINK Project established	
	1992		IPCC IS92 emissions scenarios UN FCCC agreed
	1993		
	1994		UN FCCC comes into force
	1995		
CCIRG96 scenarios	1996		IPCC SAR
	1997	UKCIP established	Kyoto Protocol agreed
UKCIP98 scenarios	1998		
	1999		
	2000	UK climate change programme	IPCC SRES emissions scenarios
	2001		IPCC TAR
UKCIP02 scenarios	2002		
	2003		
	2004		
	2005		Kyoto Protocol comes into force
	2006	UK climate change programme	
	2007		IPCC AR4
~~*UKCIP08 scenarios*~~	2008		

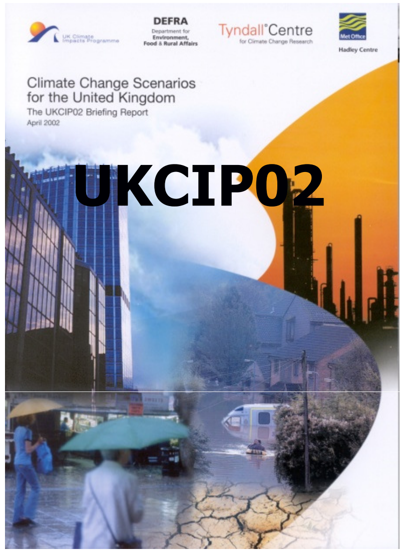
Slide courtesy: Suraje Dessai

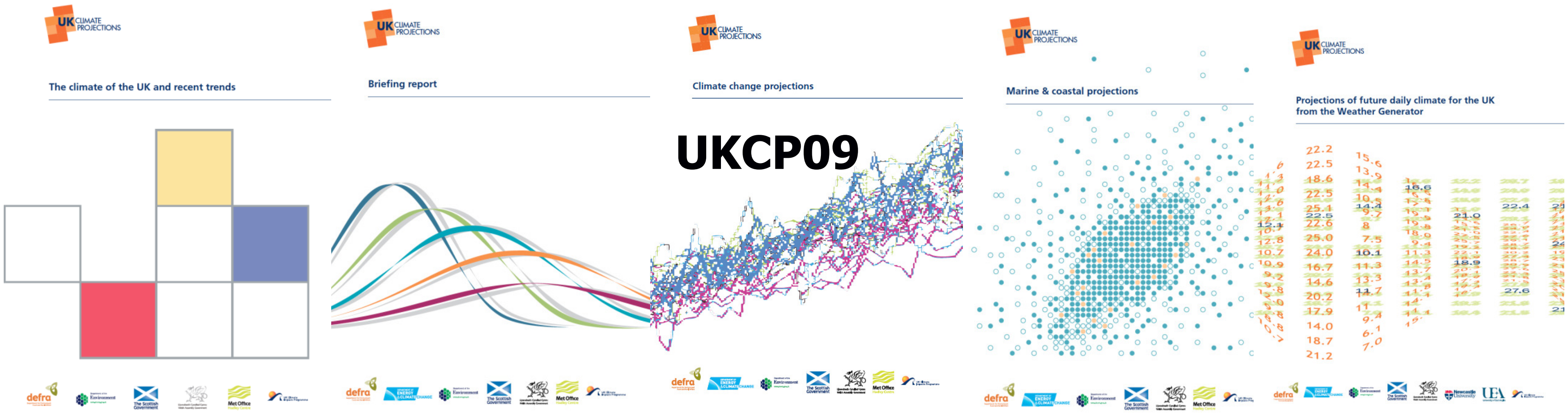
UK Climate Projections











Demand for climate scenarios

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- Early mainstreaming into planning (e.g., water resources in late 1990s) now more diverse
- Success of UKCIP (1997-)
- Research demand (e.g., ARCC programme, 2007-17)
- Climate Change Act (2008)
  - Adaptation Reporting Power (2009): “The UKCP09 Projections are likely to be a useful tool for some organisations in undertaking assessments of their risks from climate change. They will allow decision makers to consider a range of possible future climates, as well as an estimate of the uncertainties surrounding those changes.” (Defra, 2009, p. 8).
  - Climate change risk assessment (2012)

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A chronology of selected national climate scenarios

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	UK	Australia	USA	Netherlands	Switzerland	Europe	International developments
1987		Greenhouse 1987					
1988							IPCC established
1989			EPA report to congress (Smith & Tirpak 1989)				
1990		CSIRO (1990)					IPCC FAR
1991	CCIRG91	CSIRO (1991)					
1992		CSIRO (1992)					IPCC IS92 emissions scenarios & UNFCCC agreed
1993							
1994					Single institutes		UNFCCC comes into force
1995							IPCC SAR
1996	CCIRG96	CSIRO (1996)					
1997							Kyoto Protocol agreed
1998	UKCIP98						
1999							
2000			First US Climate Assessment			ACACIA project	IPCC SRES emissions scenarios
2001		CSIRO (2001)					IPCC TAR
2002	UKCP02						
2003						ATEAM project	
2004							
2005							Kyoto Protocol comes into force
2006				KNMI'06			
2007		CCIA (2007)			CH2050 Scenarios		IPCC AR4
2008							
2009	UKCP09		Second US Climate Assessment			ENSEMBLES project	COP-15 in Copenhagen fails to agree a post 2012 regime
2010							
2011					CH2011	ALARM project	
2012						Climate-ADAPT Map Viewer	
2013							IPCC AR5 WG1
2014		NRM projections	Third US Clim Ass	KNM'I14			IPCC AR5
2015							COP-21 in Paris

Slide courtesy: Suraje Dessai

National climate projections in Europe

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Country	Name of projection	Publ. date	Time horizon	Number of			Data download	Uncertainty representation in	
				Em. sce	GCM	RCMs		maps	graphs
AT	reclip:century	2011	2050	2	2	2	X	Ind.sim.	–
BE	Regional projections (Walloon region)	2011	2100	1	3	3	–		
	CCI-HYDR & INBO (Flamish region)	2009	2100	3	3	3	–	Ind.sim.	Ind.sim.
CH	CH2011	2011	2100	3	4	9	X	MMM	Ind.sim.; % (2.5,50,97.5)
CZ	Projekt VaV 2007-2011	2011	2100	1	1	1	–	Ind.sim.; MMM; sign-rob	Ind.sim.; % (25,50,75)
	Deutscher Klimaatlas	2011	2100	5	4	11	–	% (15, 50, 85)	Ind. simulations
	g							; g ; g	
ES	Escenarios regional. de cambio climático	2009	2100	2	3	9	–	Ind.sim.; MMM	Ind.sim.; MMM; unc.rge (±1 st.dev.)
	PNACC 2012	2013	2100	3	3	3	X	–	% (0, 25, 50, 75, 100)
FI	ACCLIM	2009	2100	3	19	9	–	MMM	MMM; % (5, 95)
FR	Climat de la France …	2012	2100	3	3	2	X	Ind.sim.	% (2.5, 97.5)
HU	OMSZ 2008	2008	2100	1	2	2	–	Ind.sim.	–
IE	C4I	2008	2100	4	5	2	–	Ind.sim.; MMM	–
NL	KNMI'06, Klimaateffectatlas	2006, 2009	2050, 2100	n.a.	5	10	–	Best guess	Unc. Range
NO	Klima i Norge 2100	2009	2100	3	6	10	–	Ind.sim.; MMM; % (5, 50, 95)	Ind.sim.; MMM; % (10, 50, 90); unc.rge (±1 st.dev.)
PL	Projekcje klimatu	?	2100	1	4	7	–	MMM;% (0, 10, 50, 90, 100)	–
UK	UKCP09	2009	2100	3	1	1	X	MMM; % (10, 50, 90)	MMM; PDF/CDF; joint prob. plot

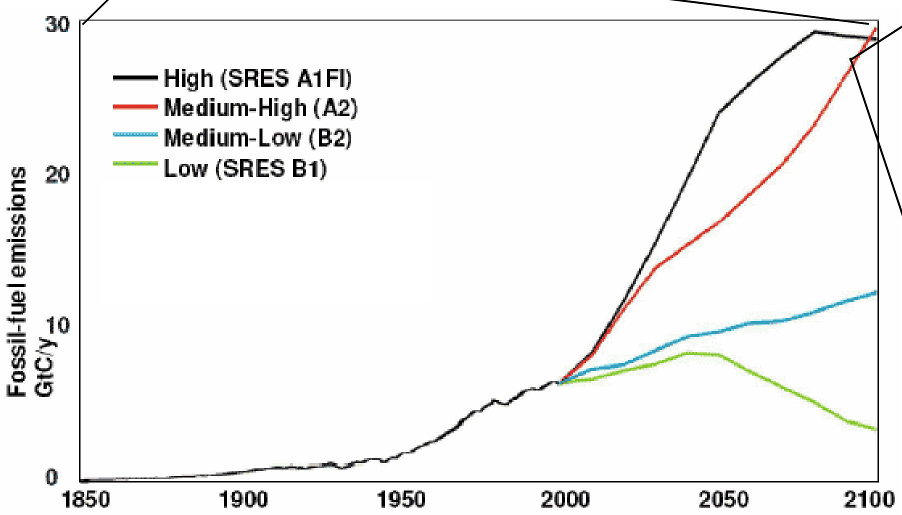
Ind.sim. – individual simulations; MMM – multi-model mean; % - percentiles; sign-rob – robustness of sign; unc.rge – uncertainty range

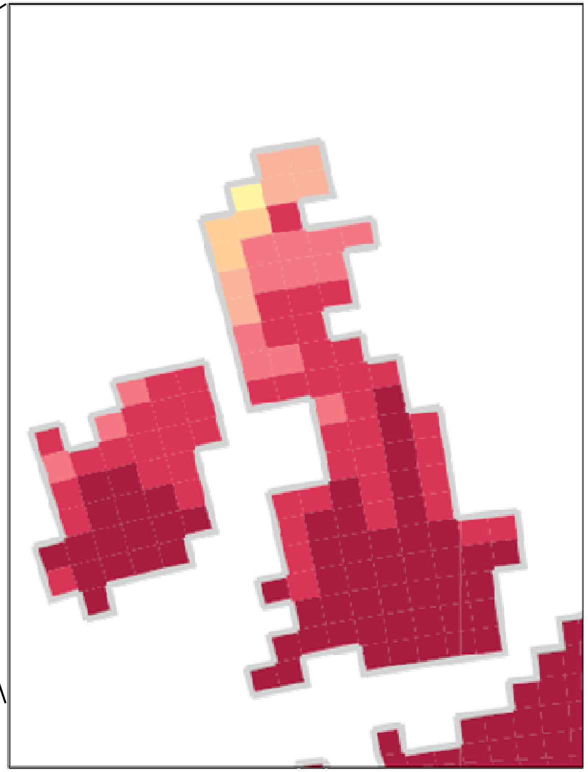
Slide by Stefan Fronzek: adopted from Füssel (2014), in Capela et al. (eds.) Adapting to an Uncertain Climate – Lessons from Practice (via Suraje Dessai)

UK Climate Projections

UKCIP02

2002 2009 2017/8





UKCIP02 presented climate change projections from a single Climate Simulator, for 4 different socio-economic scenarios.
No estimate of climate uncertainty was made

UKCIP02 presented maps of change based on projections from a single model (in this case change in Summer rainfall 2080-2100)

Motivation to moving to probabilities

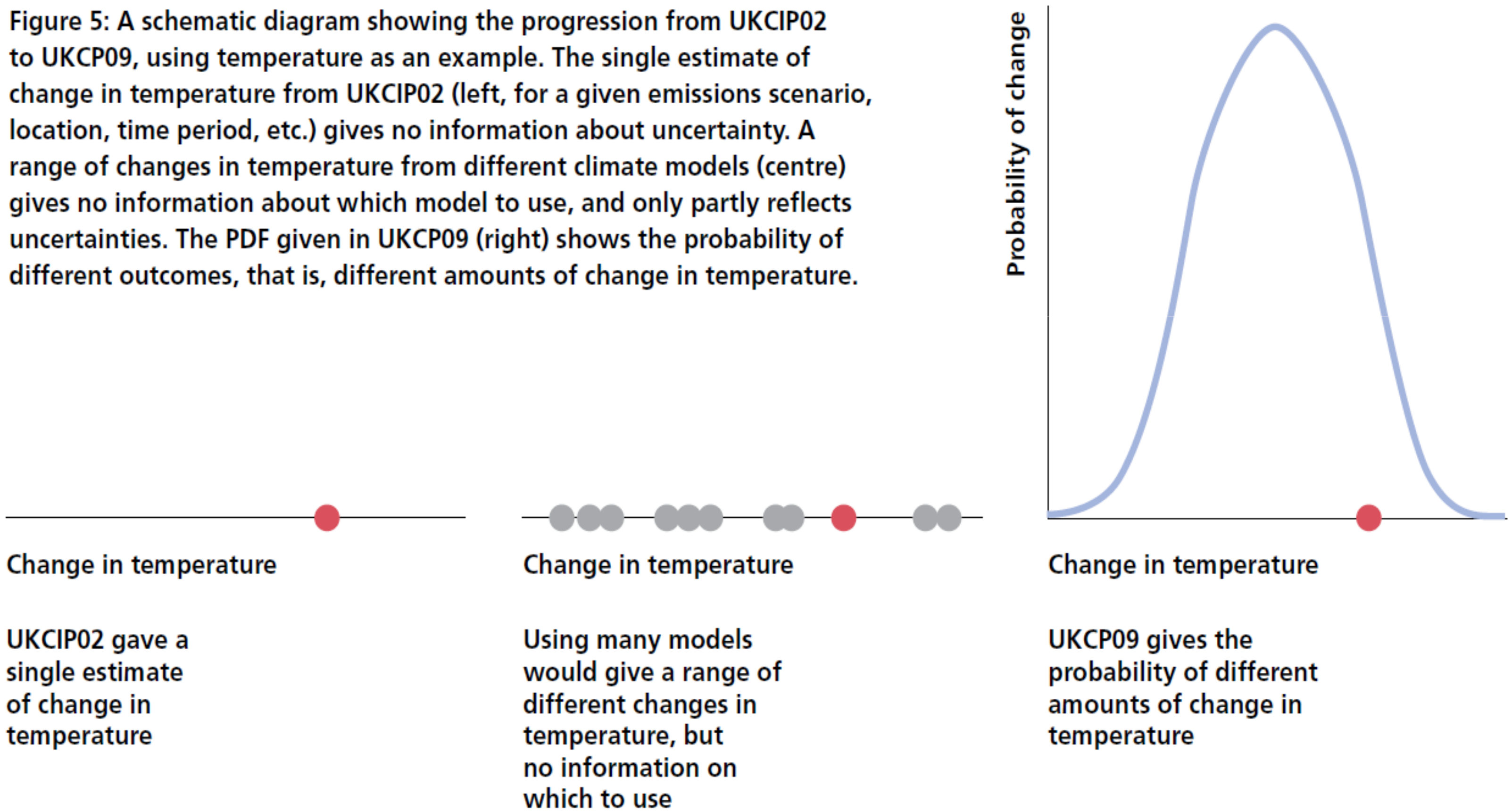
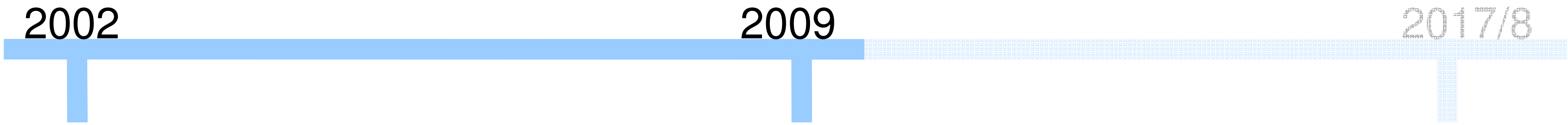
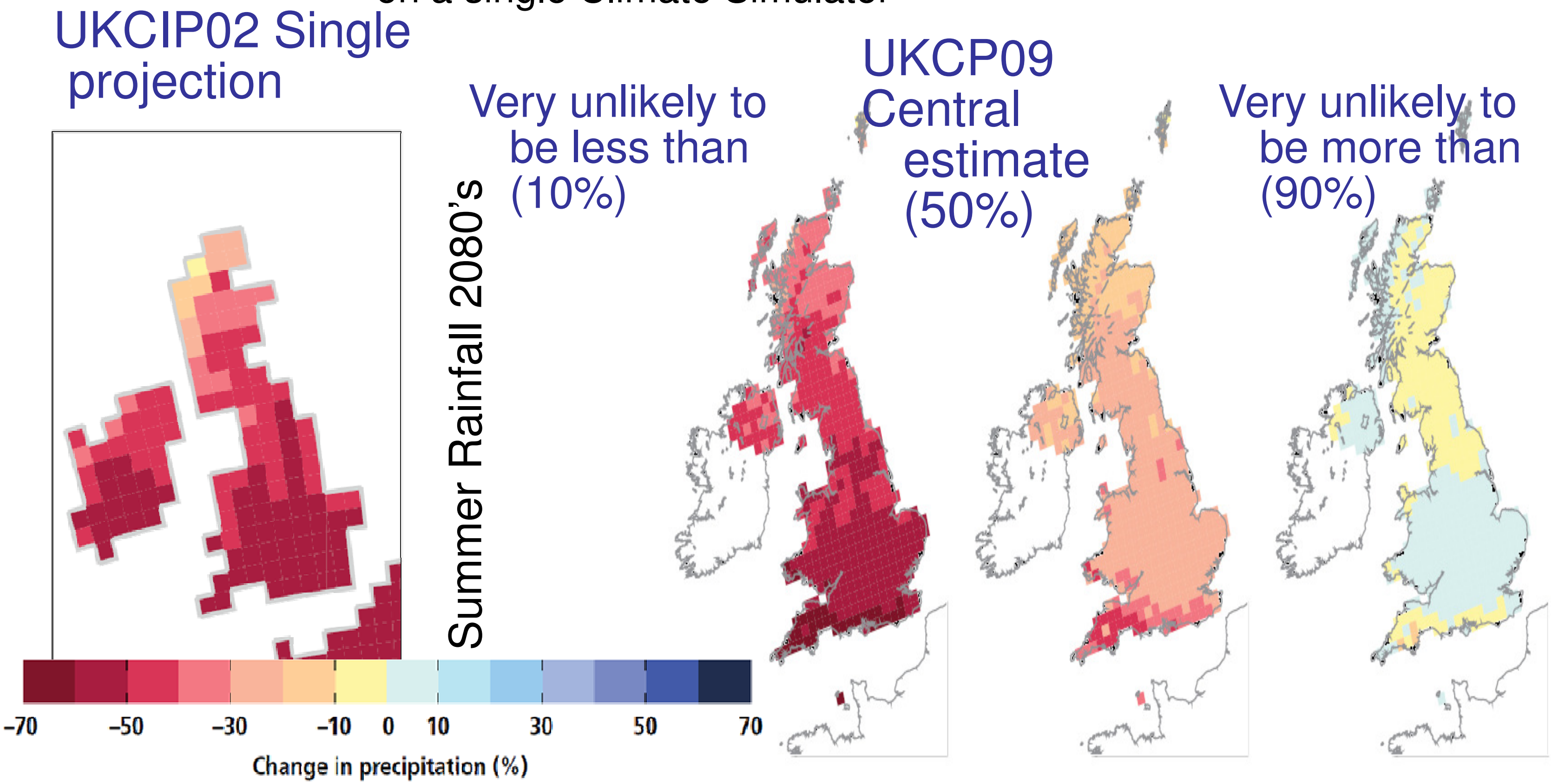


Figure 5: A schematic diagram showing the progression from UKCIP02 to UKCP09, using temperature as an example. The single estimate of change in temperature from UKCIP02 (left, for a given emissions scenario, location, time period, etc.) gives no information about uncertainty. A range of changes in temperature from different climate models (centre) gives no information about which model to use, and only partly reflects uncertainties. The PDF given in UKCP09 (right) shows the probability of different outcomes, that is, different amounts of change in temperature.

UKCP09: Probabilistic Projections



UKCP09 represents our first Probabilistic Climate Change Projections. The probabilities provide a context to see previous projections that relied on a single Climate Simulator

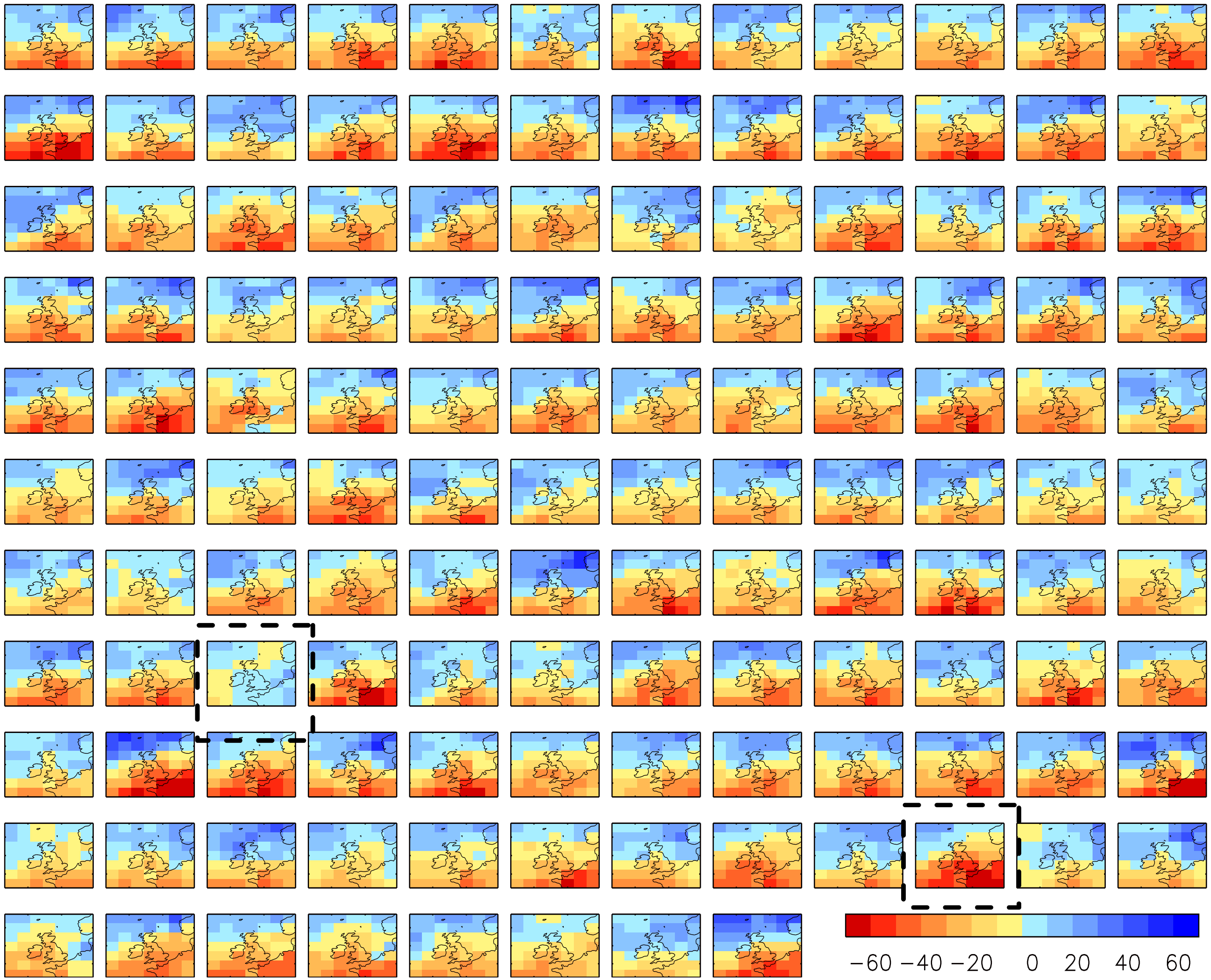


Climate Projections: Ingredients

- Ensemble of Climate Simulators used to explore the modelling uncertainty.
- Statistical tools (emulators) to extend this to explore relationship between parameters and climate simulations.
- Observations to down weight less plausible models (using Baysian approach)
- Other climate models (CMIP3) to estimate Structural uncertainties

Climate Model Simulations

Multiple realisations of equilibrium climate response



Vary 31 parameters of HadCM3, to explore range of climate response due to uncertainty in unresolved processes.

Here: summer percentage rainfall changes in response to doubling of CO2

280 simulations produced

Pragmatic choices: Why perturbed parameter ensembles?

- To assess risk, need to quantify modelling uncertainties

- single-model studies can't do this.

- Could use CMIP3/5 ensembles (National Scenarios released by Australia and Netherlands in 2014 both use processed CMIP5 projections).

Multi-model Ensembles (do sample a variety of model structures):

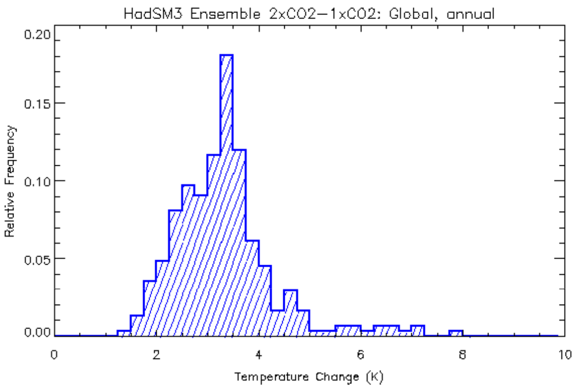
- Models inter-dependant due to common components (sample sizes even smaller than one thinks). Is uncertainty comprehensively sampled?
- Difficult to identify what drives variations across ensemble: is it resolution, low/high top, aerosol chemistry, convection and cloud schemes, microphysics, etc...
- Performance is unequal across ensemble.

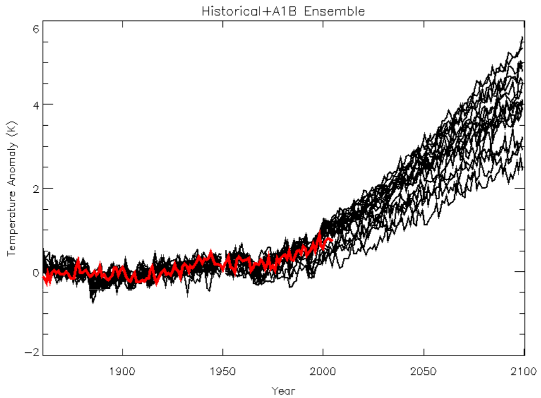
Perturbed Parameter Ensembles (only single model structure sampled)

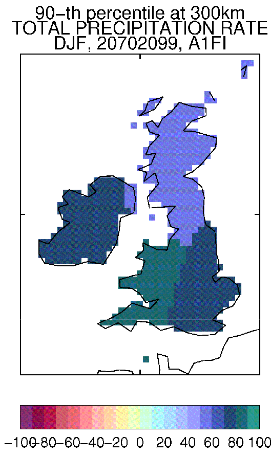
- Designed experiments, with comprehensive sampling, and control over what causes variation in response.
- Can construct statistical models (emulators) to understand, and predict response.
- Allowed us to

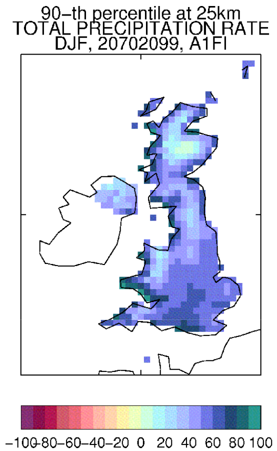
- use very large samples - apply a formal statistical framework
- constrain by observations - make probabilistic projections
- make easy sensitivity analyses - provide more robust projections

Climate Modelling framework





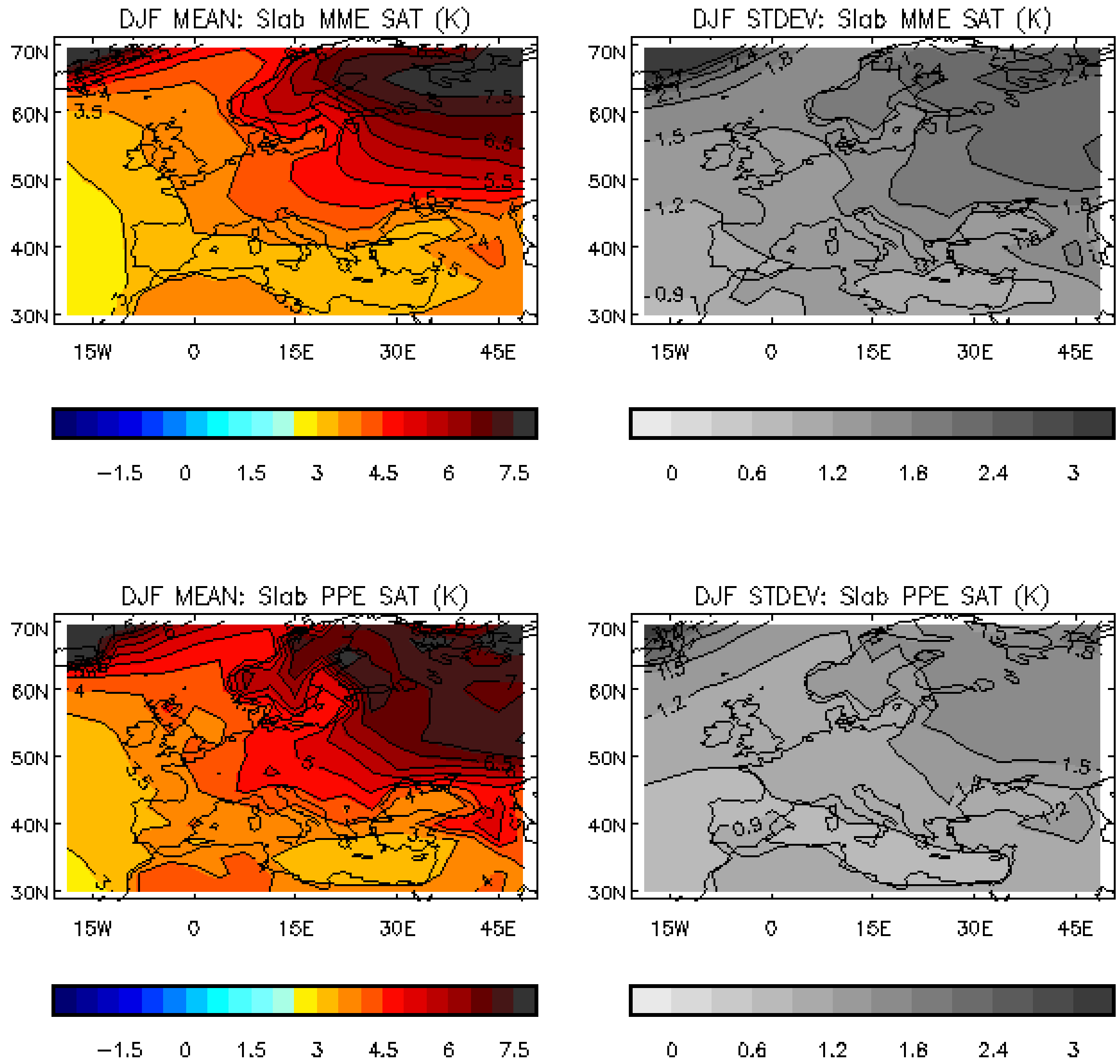




Equilibrium climate change	Transient climate change	Regional climate change

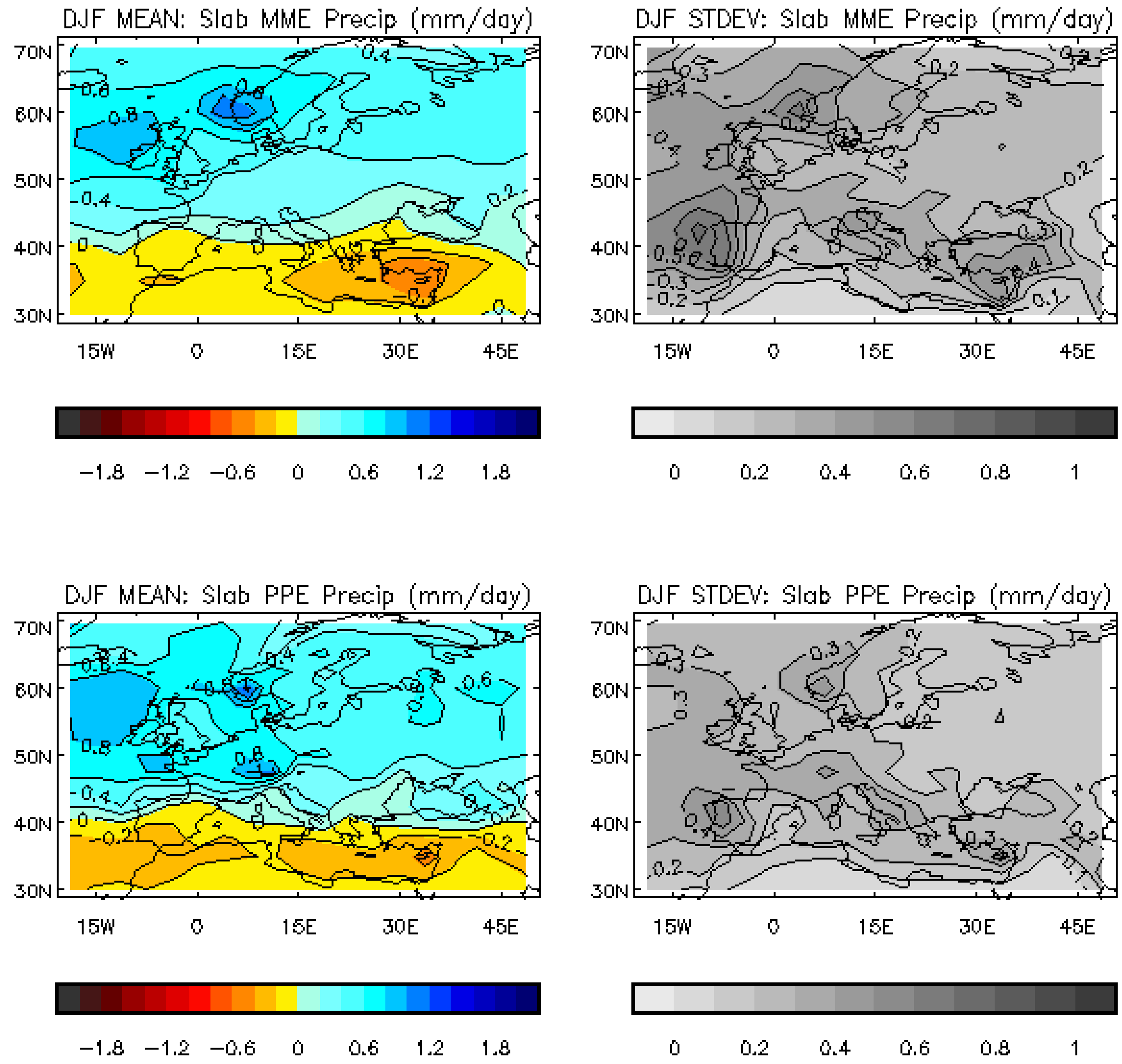
Comparison of MME and PPE responses

Winter Temperature Change at 2xCO2: Mean and Standard Deviation

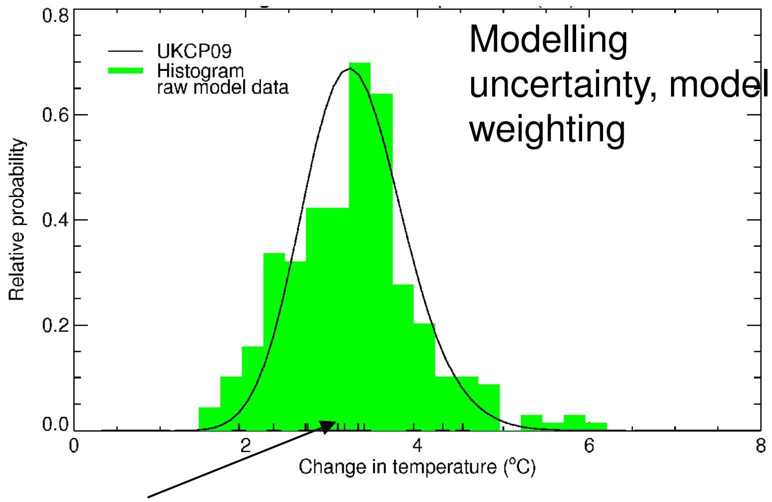


Comparison of MME and PPE responses

Winter Precipitation Change at 2xCO2: Mean and Standard Deviation



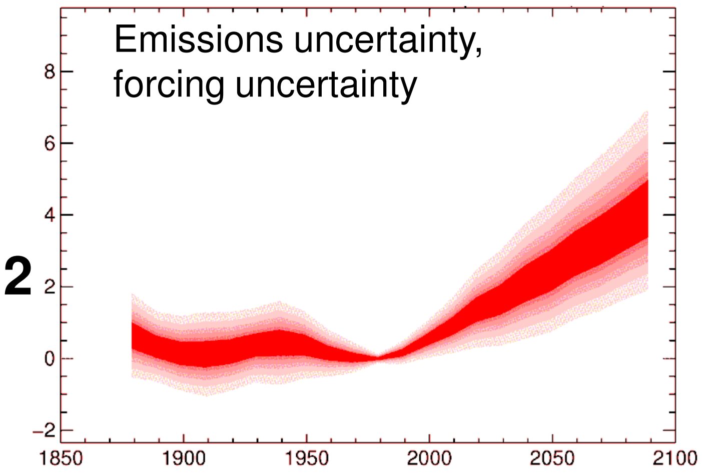
UKCP09 made in three stages



Dashes = Other models

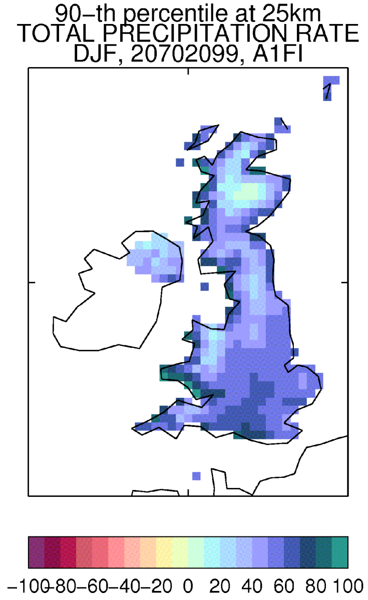
Time Scaling

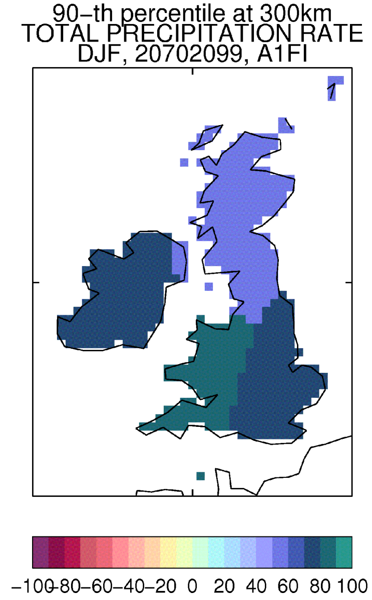
1 → 2



Downscaling

3 ← 2





NOTE: Internal variability added at all three stages

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Statistical Framework

Bayesian prediction (Goldstein and Rougier 2004)

Mathematically rigorous synthesis of multiple lines of evidence from climate models and observations

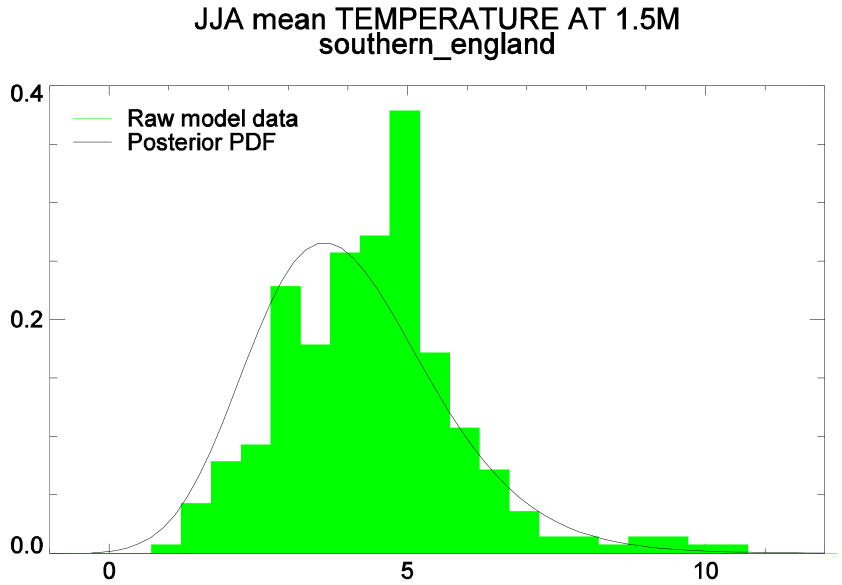
Aim is to construct joint probability distribution p(X, m_h , m_f , y, o, d) of all uncertain objects in problem.

- Model parameters (X)
- Historical and future model output (m_h,m_f)
- True climate (y_h,y_f)
- Observations (o)
- Model imperfections = discrepancy (d)

Need to sample parameter space more thoroughly e.g. 1 million times rather than 280 times.

Main application of PPE: development of the UK national climate scenarios "UKCP09"

Step 1: Equilibrium Response

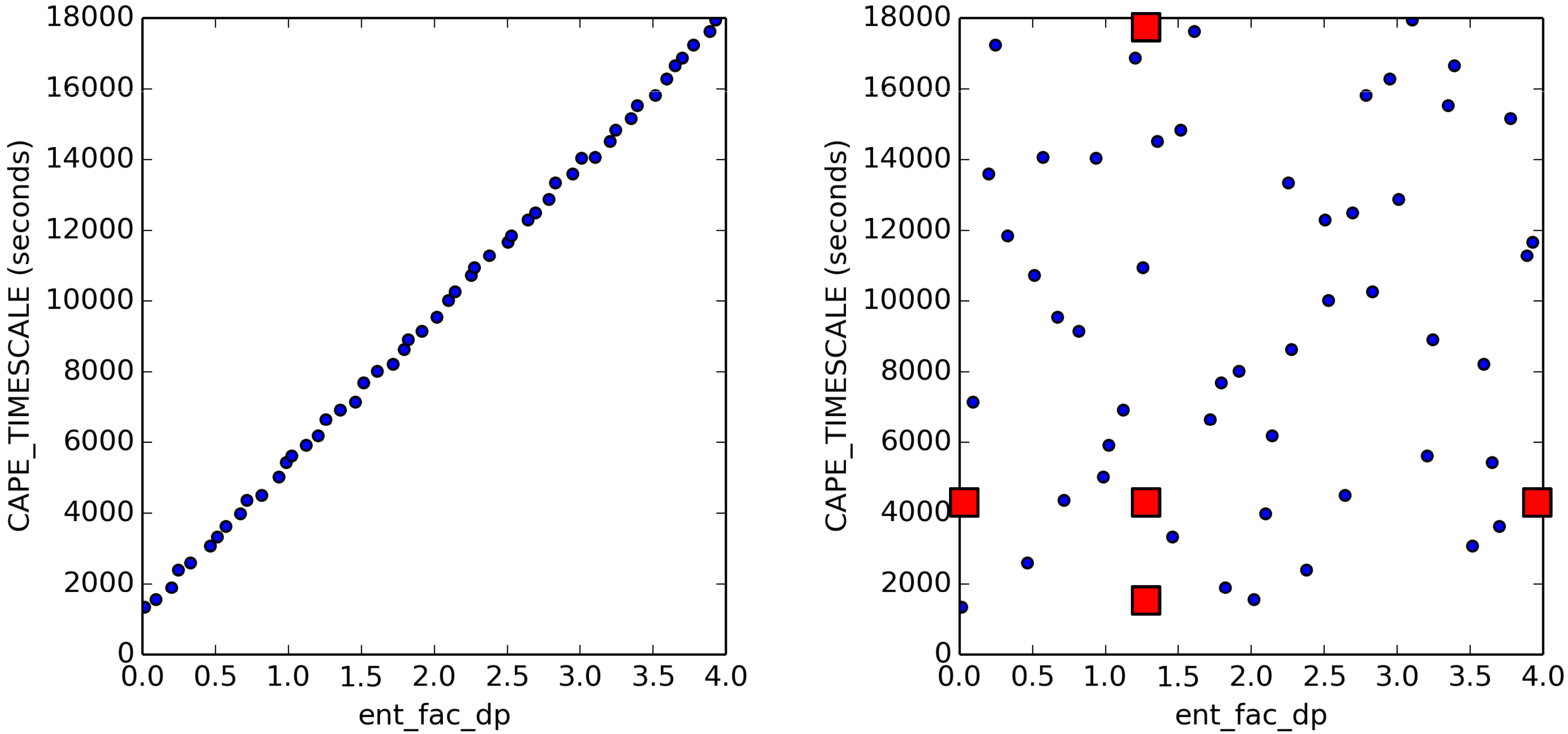


- Construct statistical model (emulator) for response as function of perturbed parameters (regression approach used).
- Compare predictions of historical climate with observations, estimate a likelihood weight for each sampled parameter set.
- Integrate over large sample of untried parameters, producing probabilistic projections, conditional on model and obs.
- Model not perfect, and has structural errors, which are estimated here by comparison with CMIP3. This can adjust PDF.

Design: Perturbing Parameters

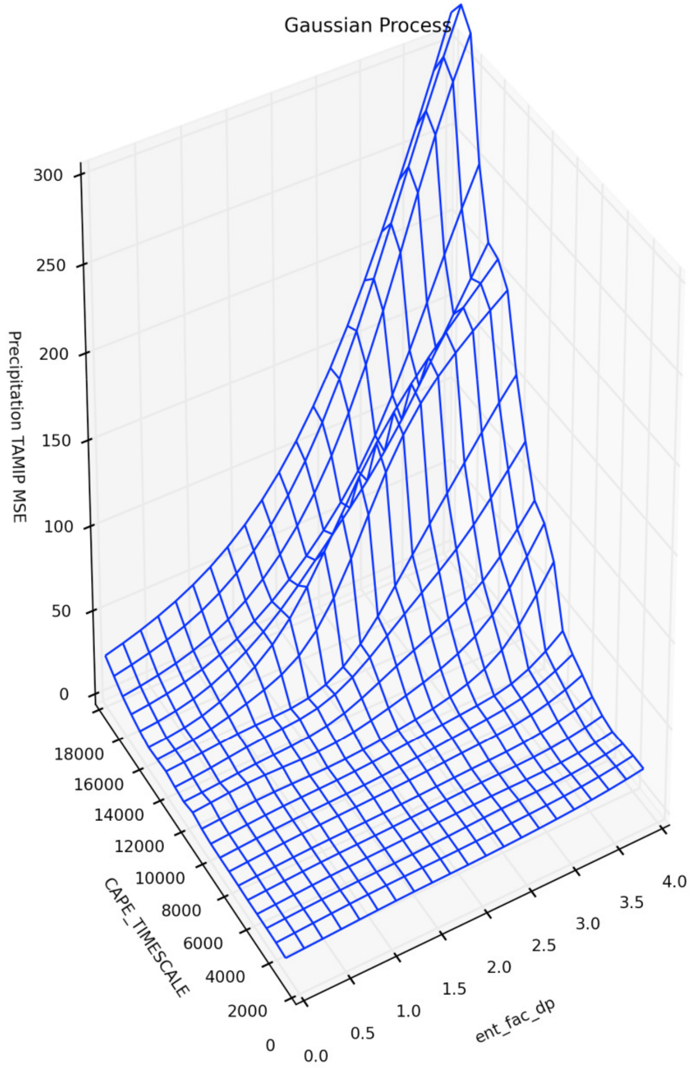
Adopt latin hypercube design for exploring parameter uncertainty (to maximise information gained from Climate Simulators)

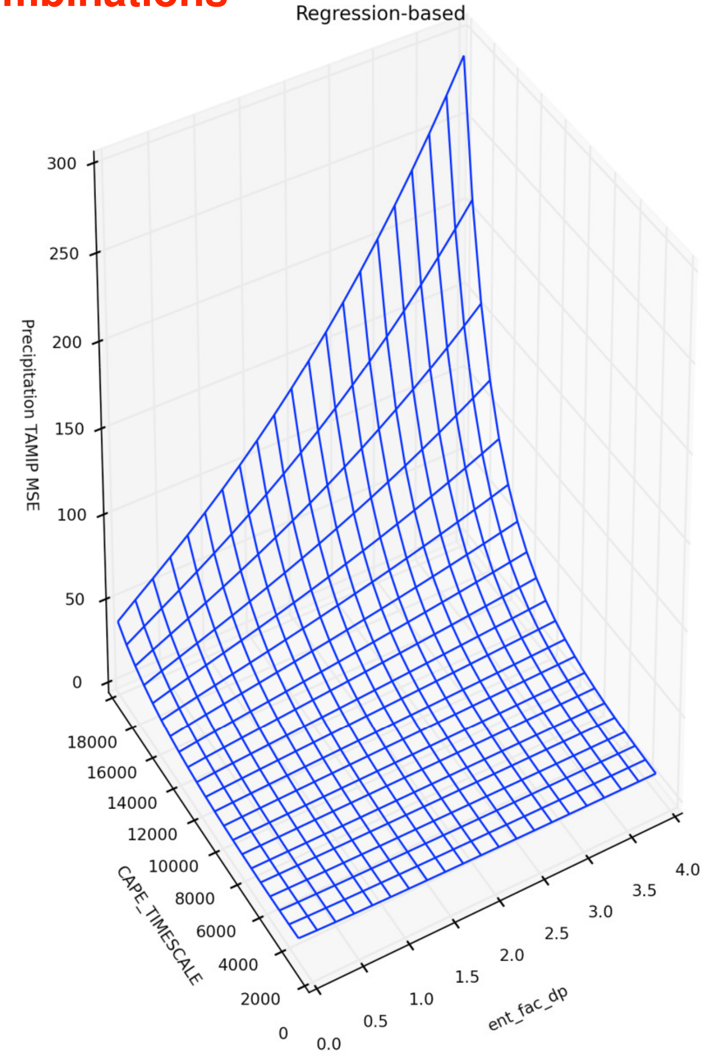
2 examples of a 2D Latin Hypercube (one bad, one good)



Emulators

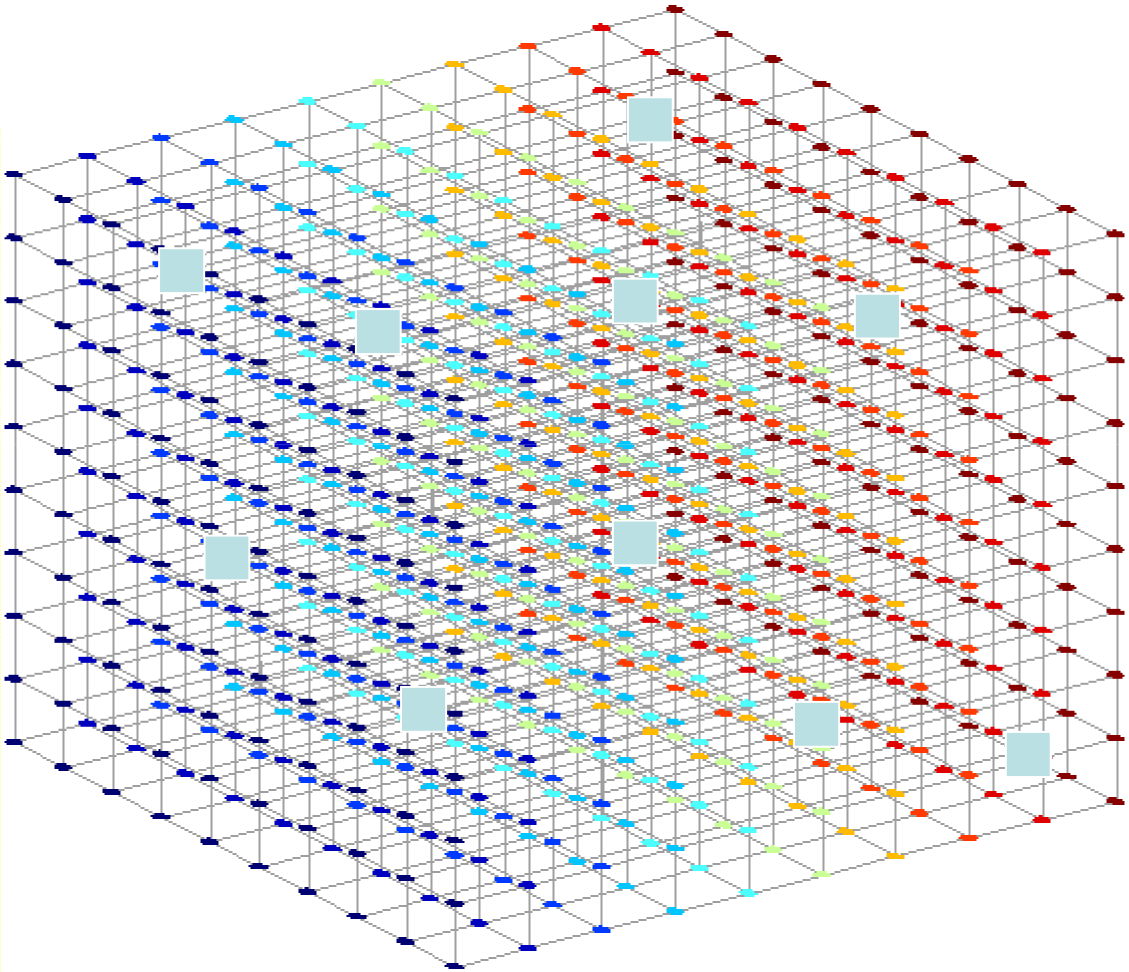
Emulators are statistical models, trained on ensemble runs, designed to predict a distribution of model output at untried parameter combinations



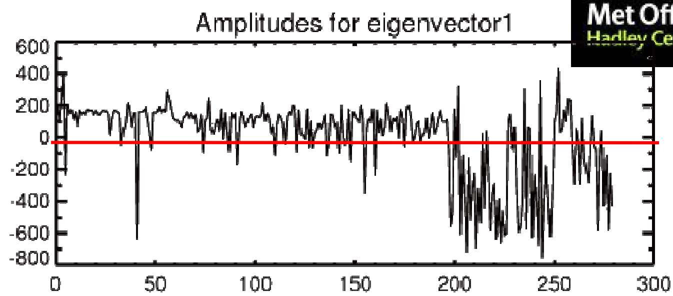


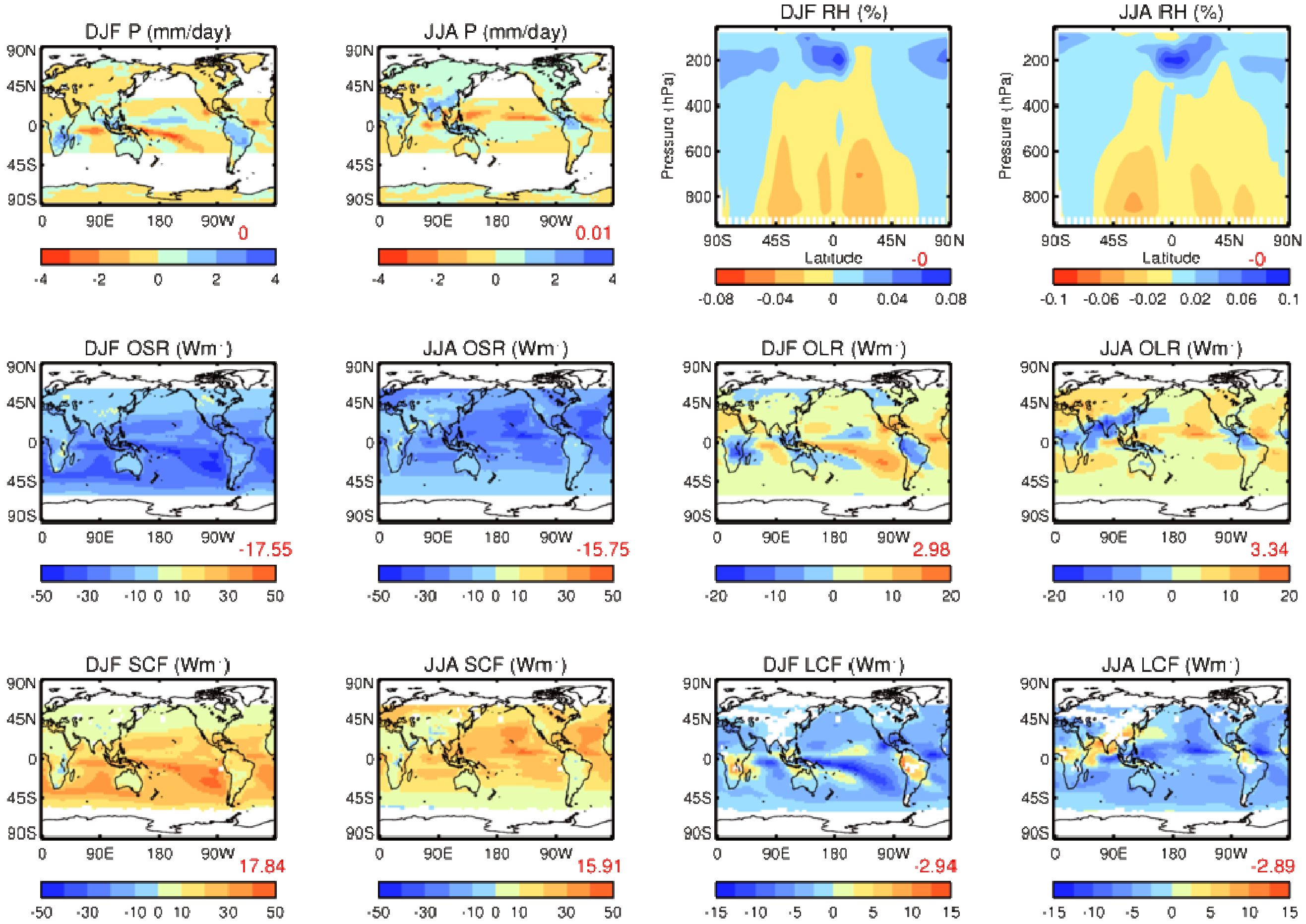
Emulator Schematic

- <u>Pragmatic choices</u>
- Use regression trained on ensemble runs to estimate past and future variables, **m**, at any point of parameter space, **x**, (use transformed variables and take into account some non-linearities)
- Note – need to run models at some quite "remote" regions of parameter space and where response in parameter space is not smooth.



Leading variation of control climate across slab PPE

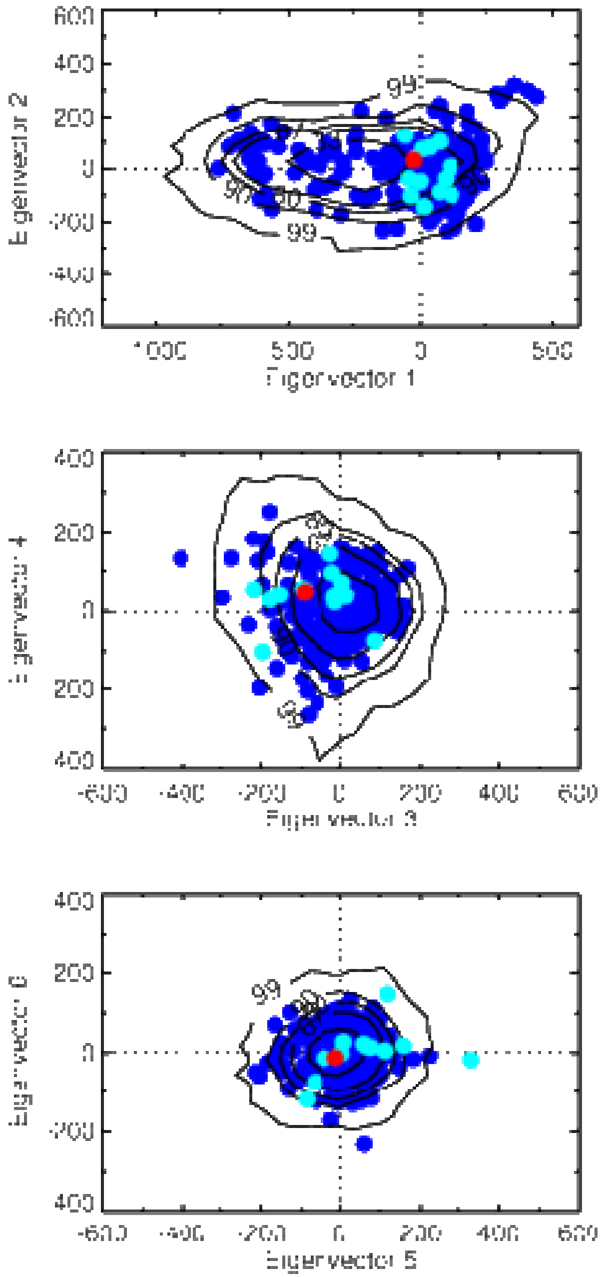




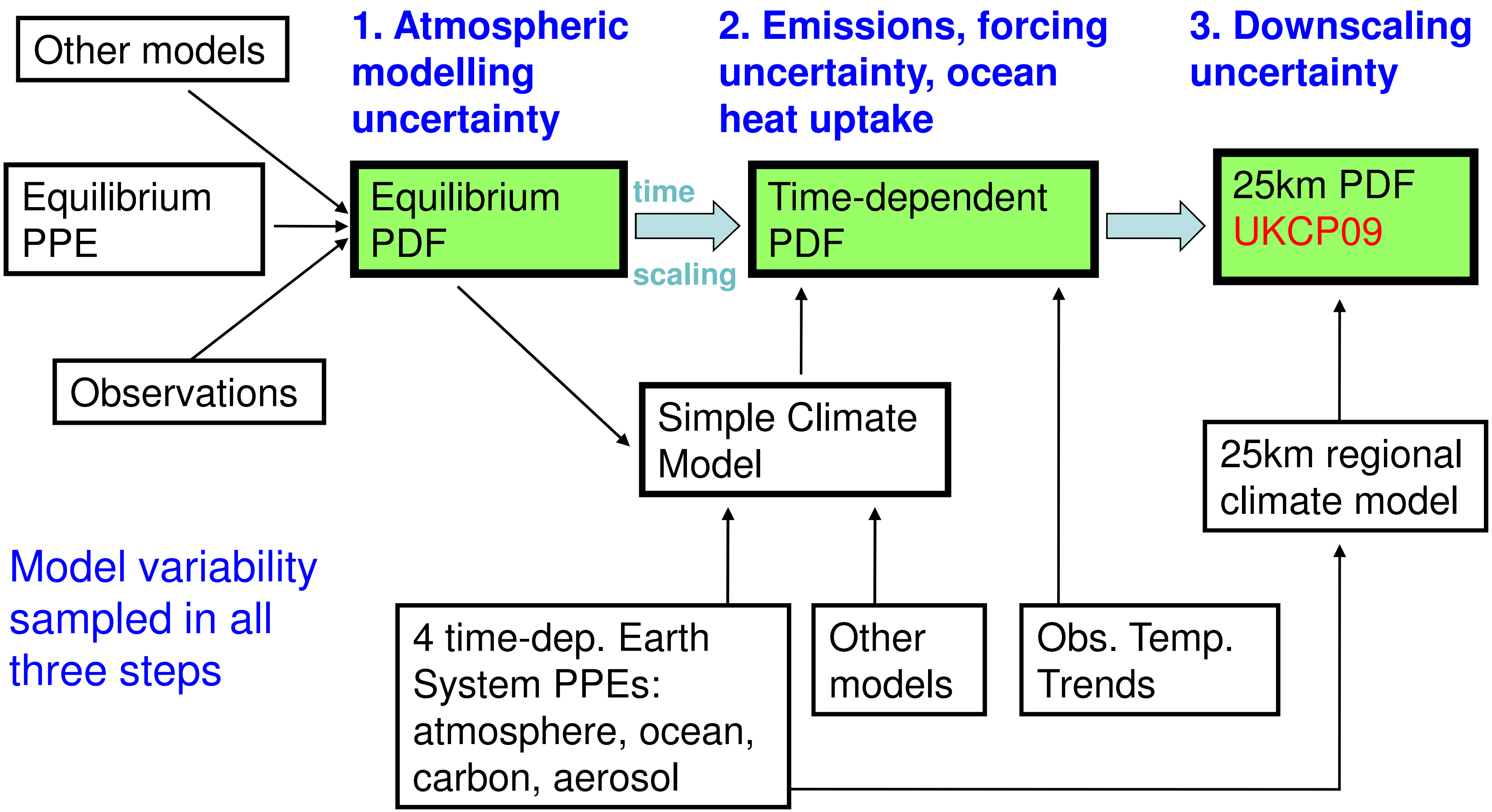
First of six metrics used in Sexton et al (2012) and UKCP09

Importance of spanning the observations

- These are six metrics used to constrain probabilistic projections in UKCP09. They are six leading eigenvectors of a climate state vector
- **Dark blue dots** are 280 QUMP members
- **Black lines** are joint probability density of emulated points
- Light blue dots are multimodel ensemble members
- Red dot is observed value



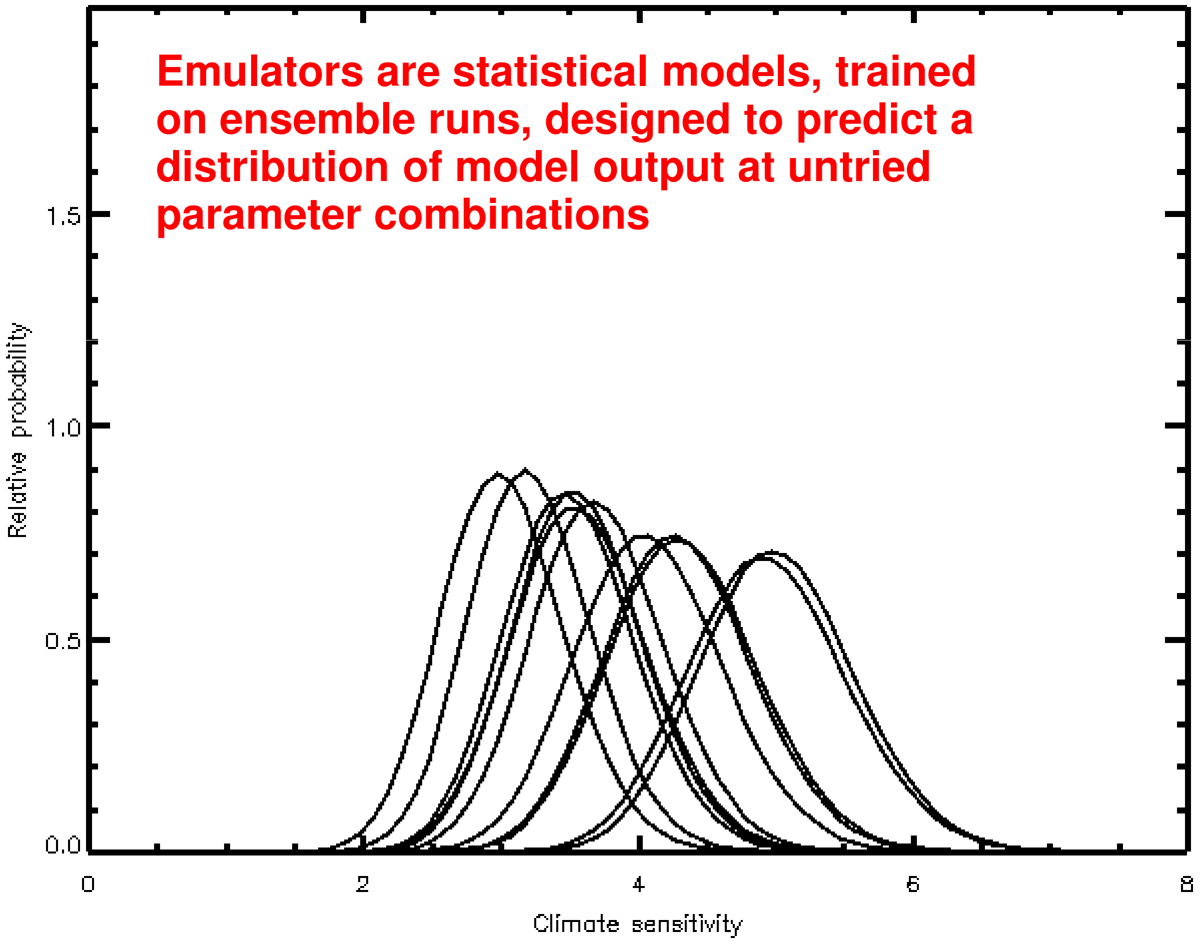
Three steps in production of UKCP09 predictions



Model variability sampled in all three steps

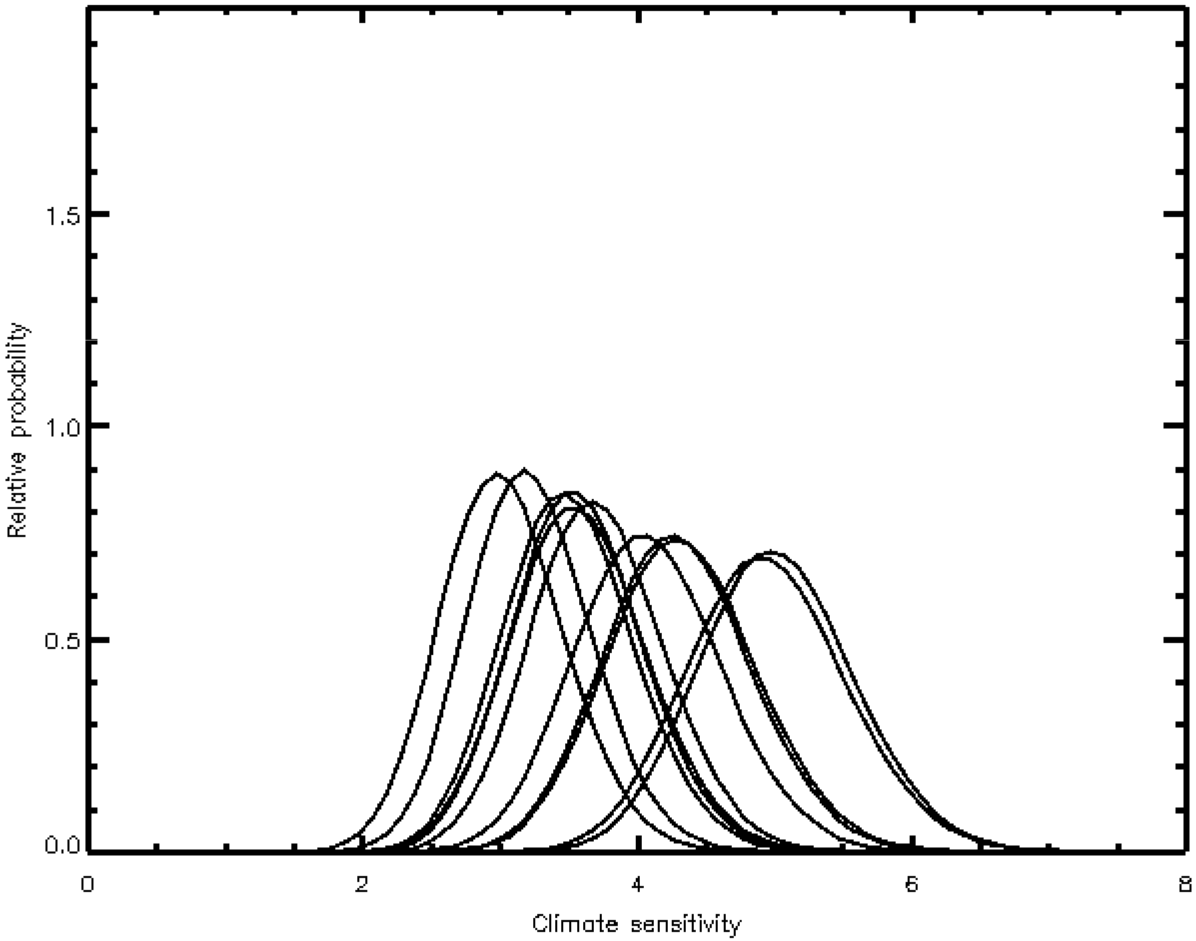
Example of what emulator produces

- An example of 10 randomly chosen combinations of parameter values - emulator gives 10 distributions

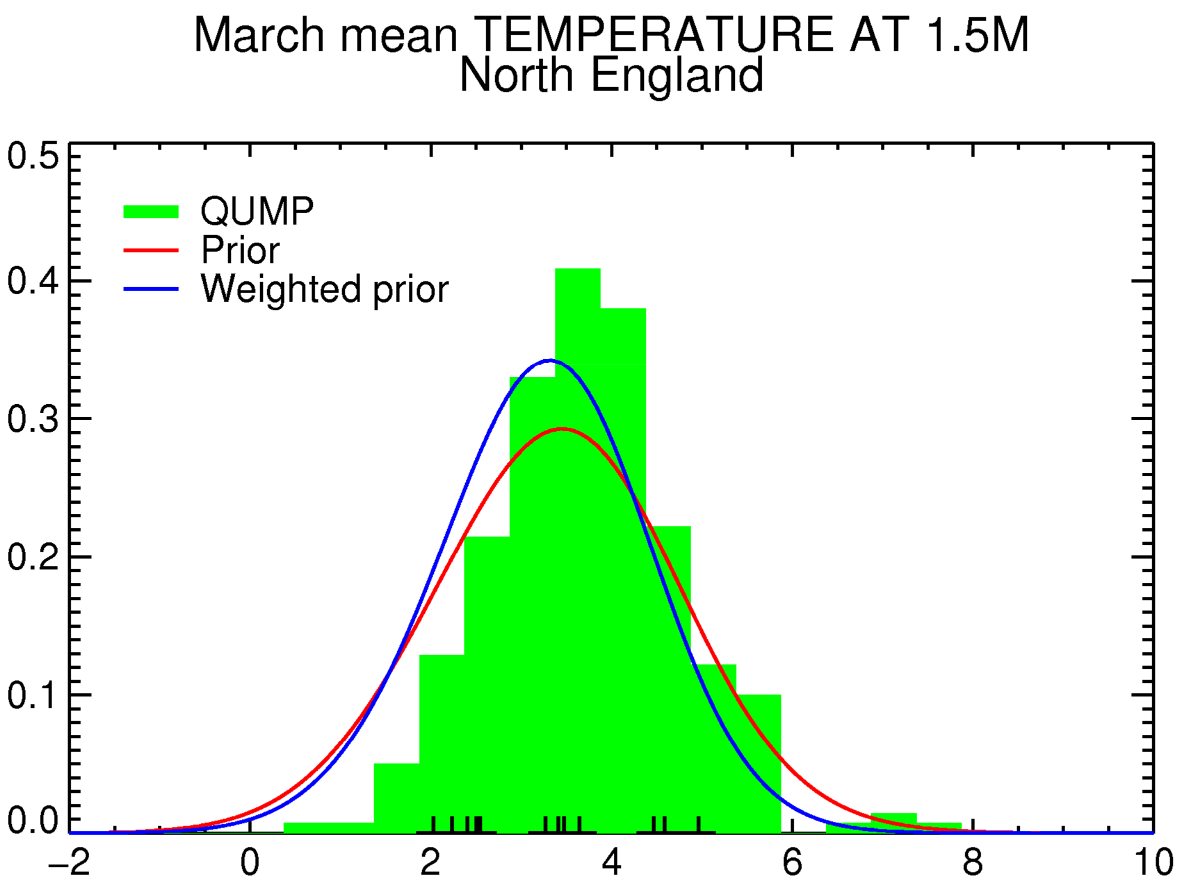


Weighting different model variants

- Weight prediction towards higher quality parts of parameter space



Weighted PDF

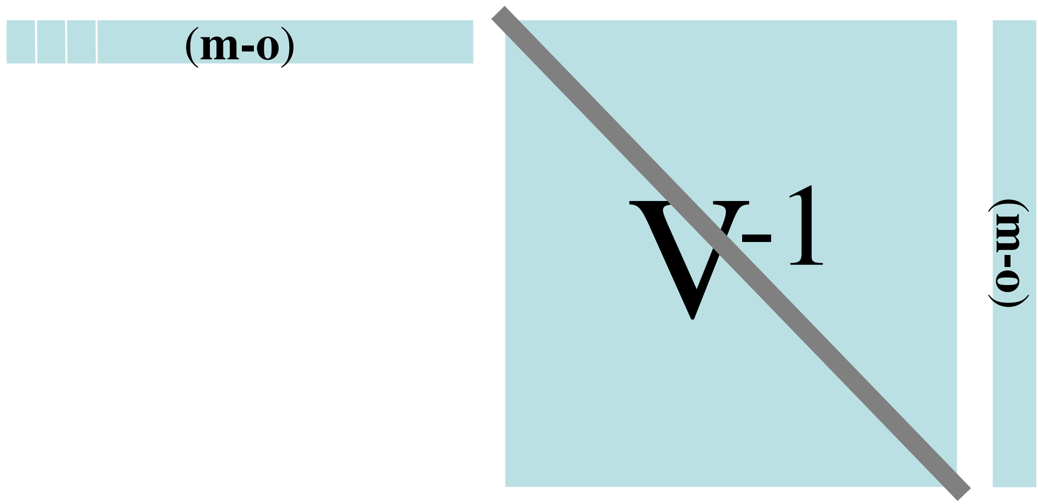


Estimating Likelihood

$$\log L_o(\mathbf{m}) = -c - \frac{n}{2}\log|\mathbf{V}| - \frac{1}{2}(\mathbf{m}-\mathbf{o})^T \mathbf{V}^{-1}(\mathbf{m}-\mathbf{o})$$

V = obs uncertainty + emulator error + discrepancy

$$\log L_0(\mathbf{m}) \sim$$



V is calculated from the perturbed physics and multi-model runs

Structural Model Uncertainty

Estimating discrepancy

Use multimodel ensemble from IPCC AR4 and CFMIP

For each multimodel ensemble member, find point in HadCM3 parameter space that is closest to that member

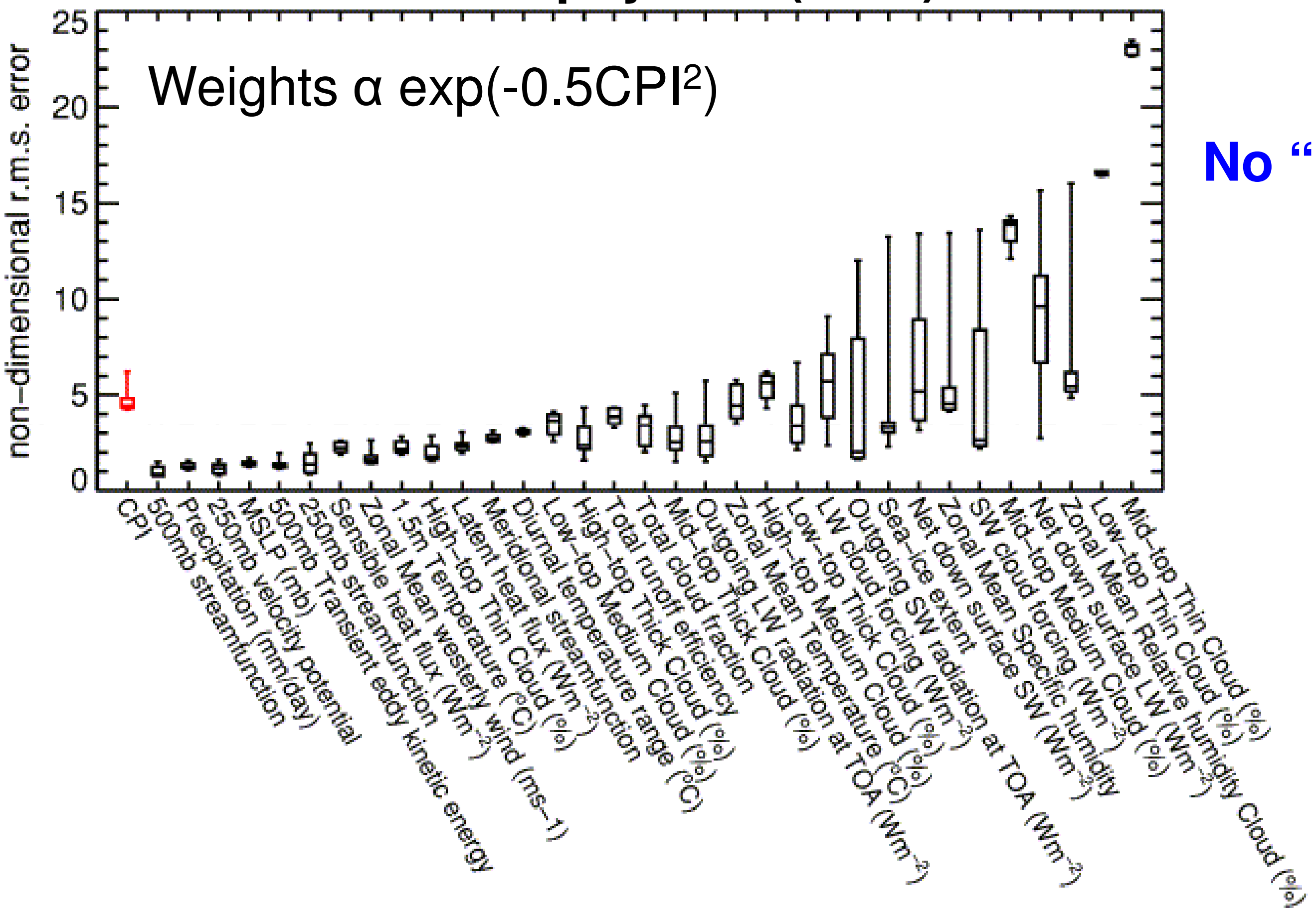
There is a distance between climates of this multimodel ensemble member and this point in parameter space i.e. effect of processes not explored by perturbed physics ensemble

Pool these distances over all multimodel ensemble members

Uses model data from the past and the future

Discrepancy – a schematic of what it does

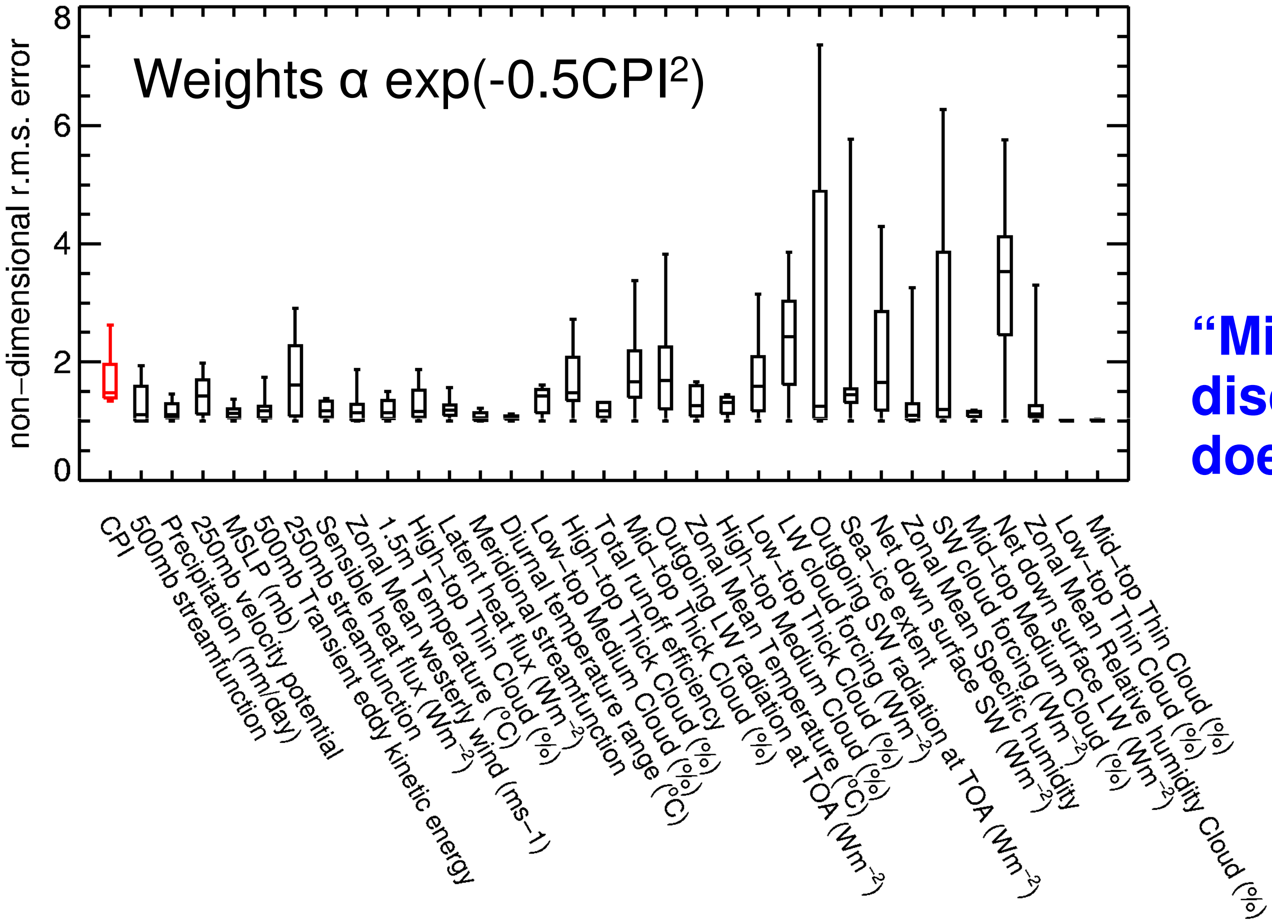
CPI from Murphy et al (2004)



No "discrepancy"

Discrepancy – a schematic of what it does

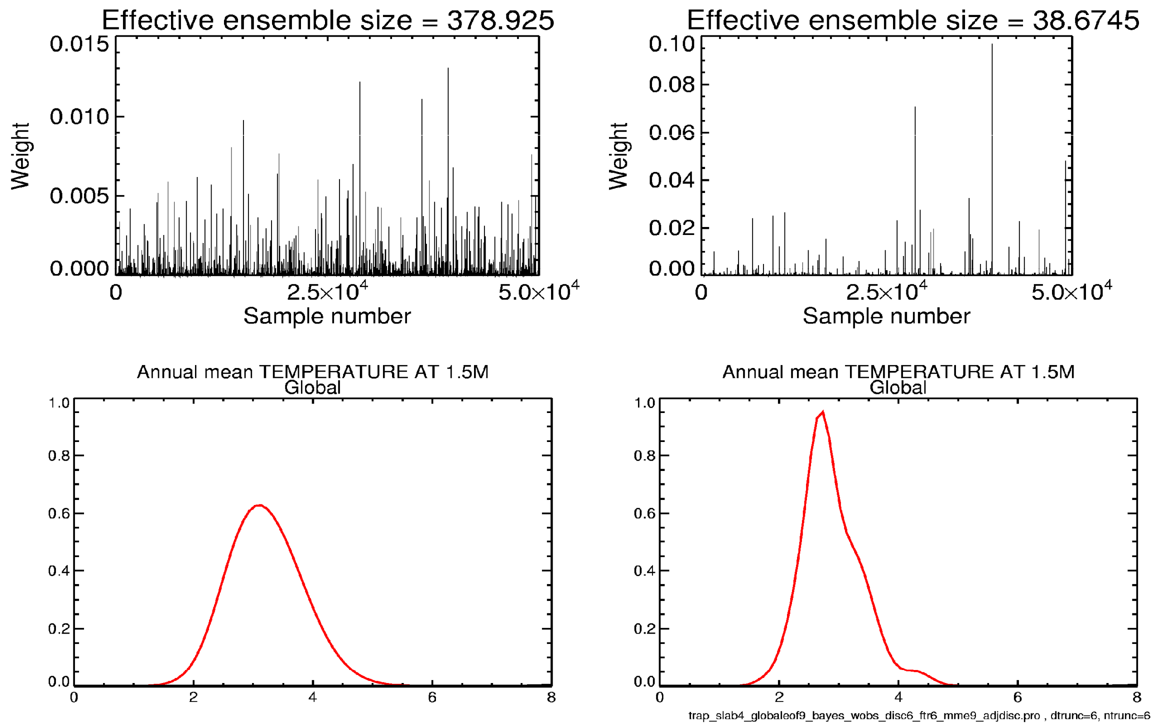
CPI from Murphy et al (2004)



"Mimicking what discrepancy does"

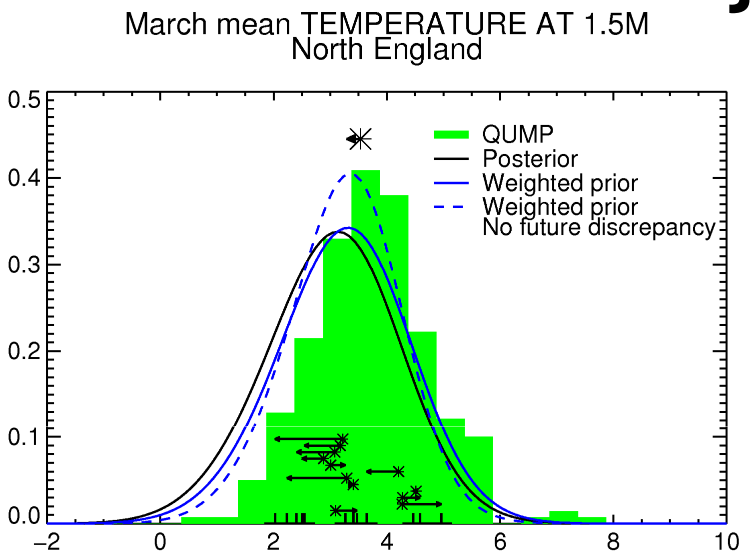
Effect of historical discrepancy on weighting

Discrepancy included **excluded**

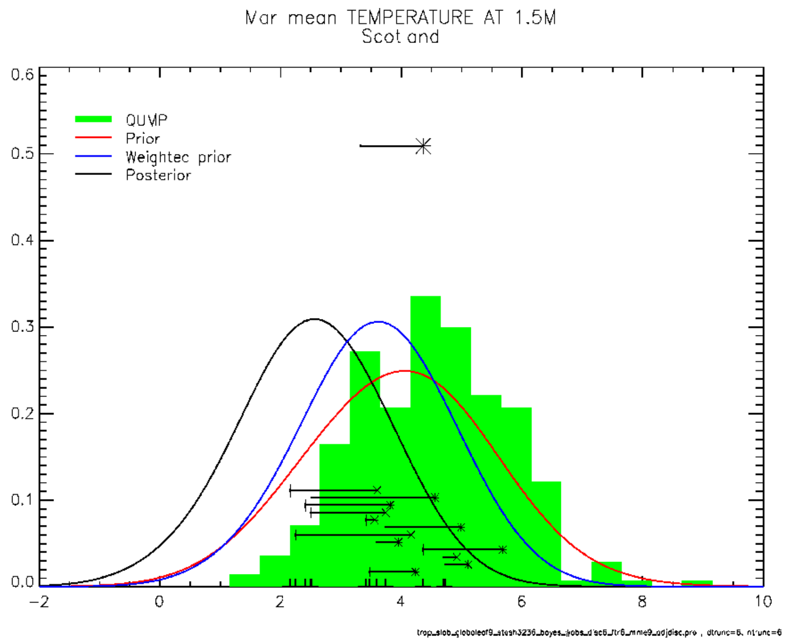


- Estimated from sample size of 50000

Examples of Discrepancy and Projections



For most regions, variables and projection periods, the discrepancy estimated from the multi-model ensemble tends to broaden the PDF, but does not systematically change the mean estimate.

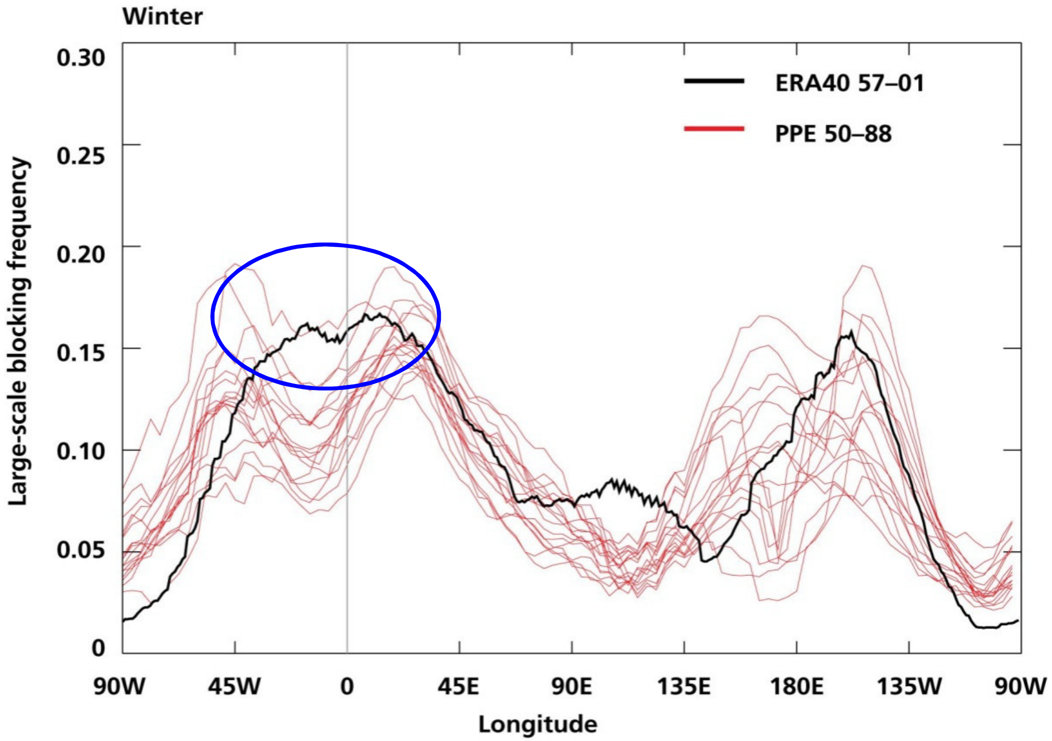


There are some cases where stronger structural errors lead the the discrepancy term doing much more work.

Scotland keeps snow too long in the present day spring (a bias), in future climates, this melts leading to large unrealistic temperature change (not seen in other Climate Models)

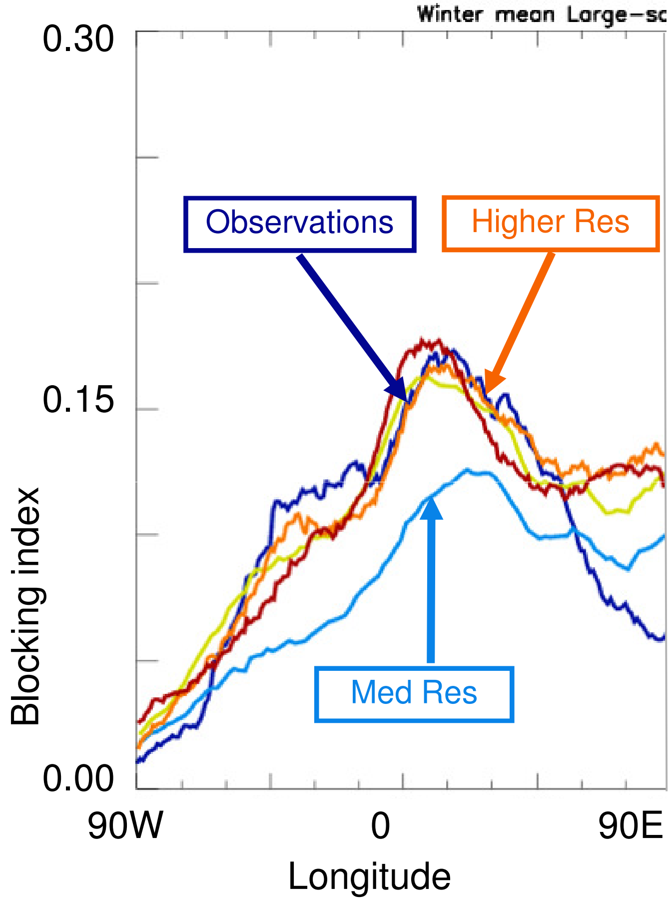
In this case, the Discrepancy acts to shift the PDF as well as broaden.

Example of structural uncertainty, and the potential benefits of higher resolution



- Winter anti-cyclonic blocking frequency for 17 HadCM3 transient coupled-ocean atmosphere PPE members as a function of longitude.
- Winter blocking frequency over UK is underestimated by 16 out of 17 members.

Scaife et al, GRL 2011



- Moving to higher resolution can improve simulation of aspects of variability (such as blocking).

Pragmatic choices: thoughts on discrepancy

➔All methods for model weighting should account for model imperfection.

➔This is not the only possible method for specifying discrepancy. More effort needed in understanding model imperfection and what it means for how model projections are used.

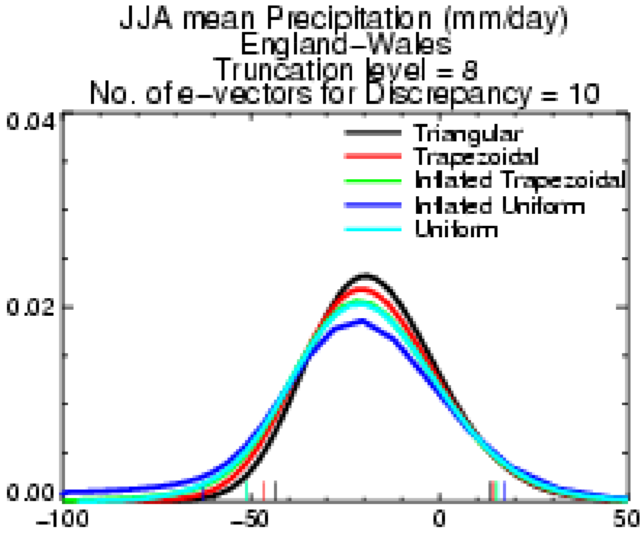
➔Needs to be thought about in terms of many variables rather than one variable at a time. Similar in this respect to way climate models are tuned because tuning is a compromise across many variables, not an optimisation on one variable.

➔But this method for specifying discrepancy means probability distributions will not be able to account for structural uncertainties that are related to systematic errors common to all models used.

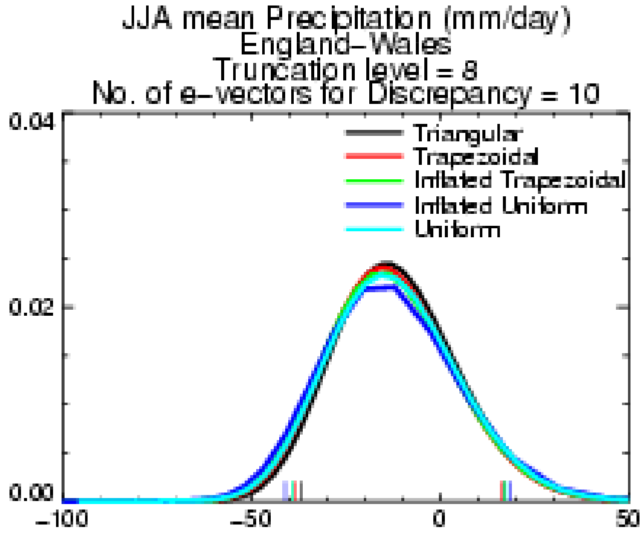
Sensitivity tests

Sensitivity to prior – climate sensitivity

Before observational constraint

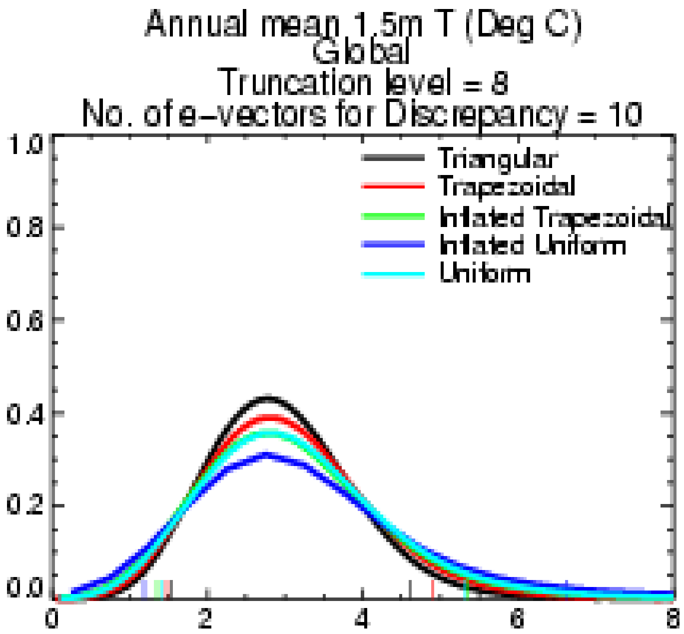


After observational constraint

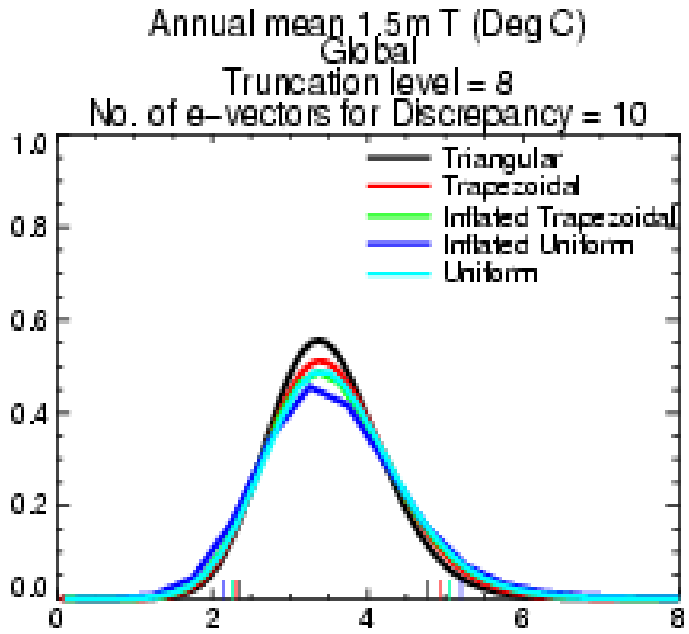


Sensitivity to prior – %ΔUK summer rainfall

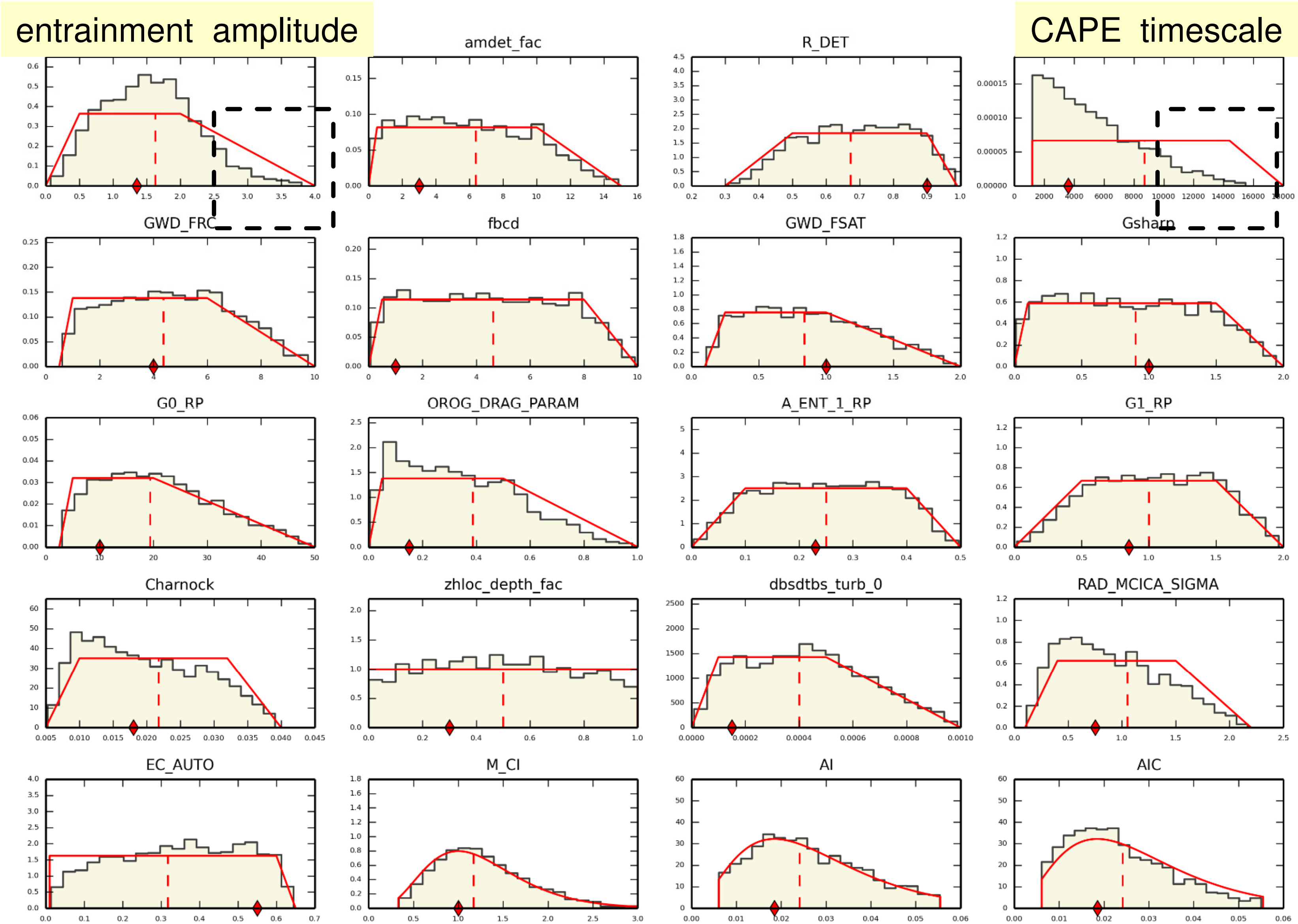
Before observational constraint



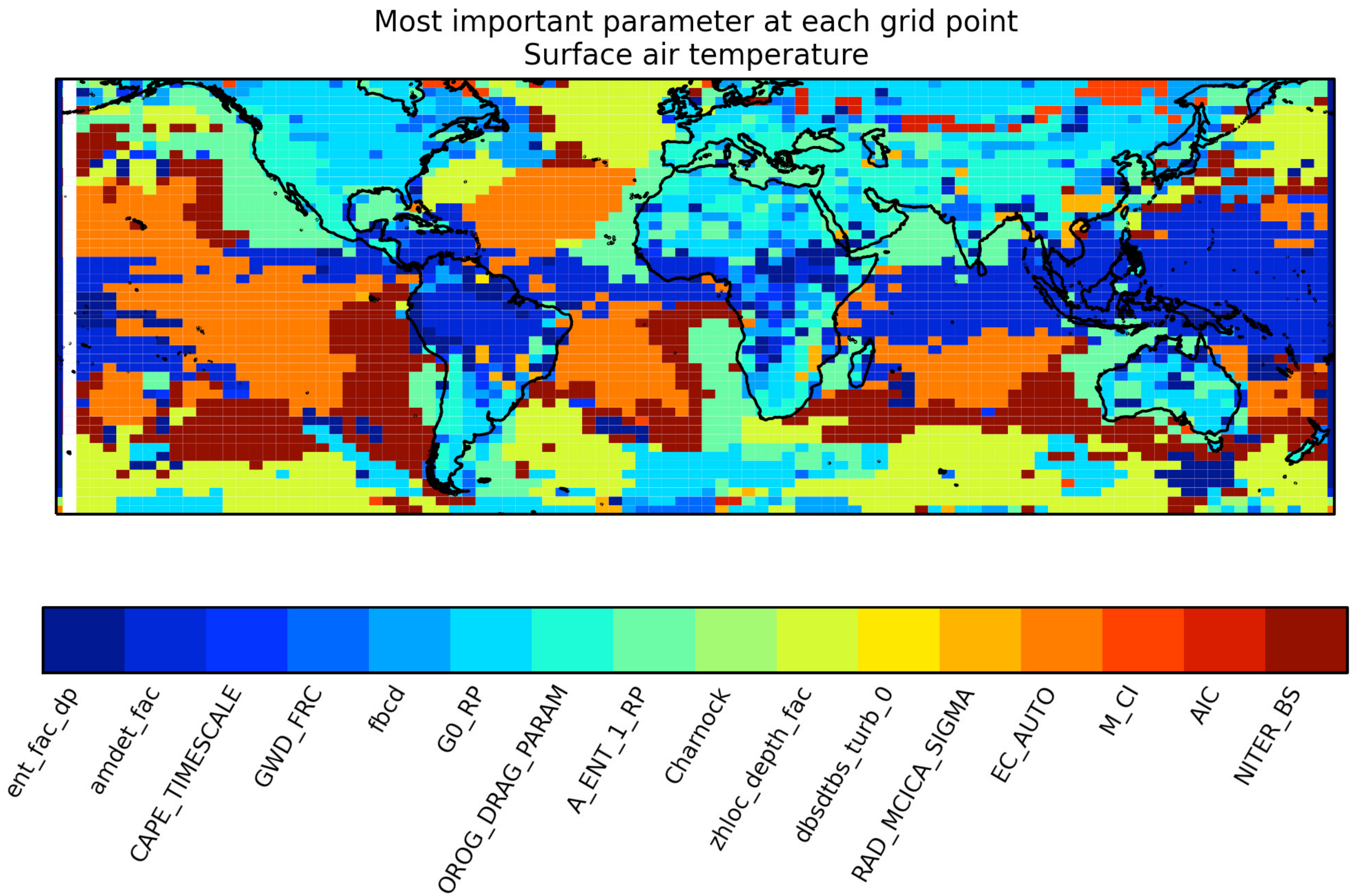
After observational constraint



Effect of model selection on parameter distributions



Most important parameters

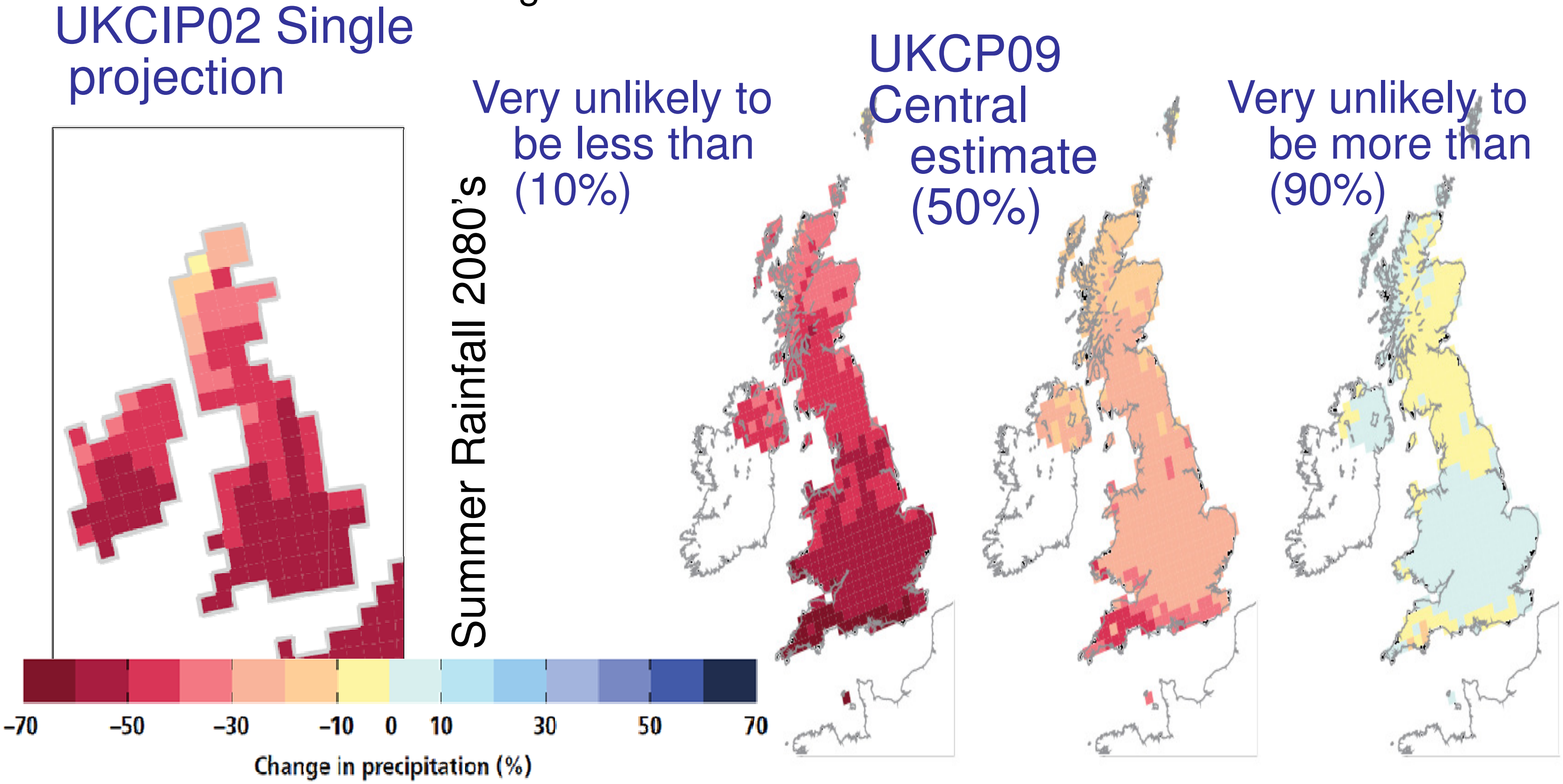


UK Probabilistic Climate Projections

UKCP09: Probabilistic Projections

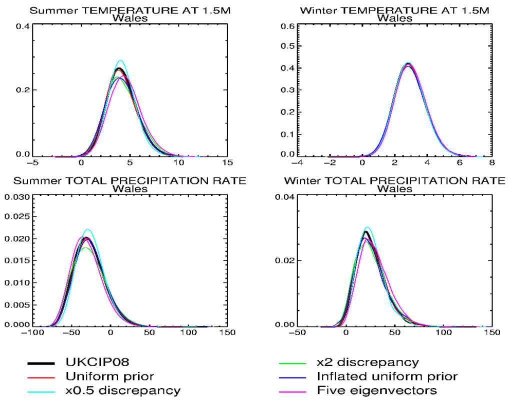
2002 — 2009 — 2017/8

UKCP09 represents our first Probabilistic Climate Change Projections. The probabilities provide a context to see previous projections that relied on a single Climate Simulator



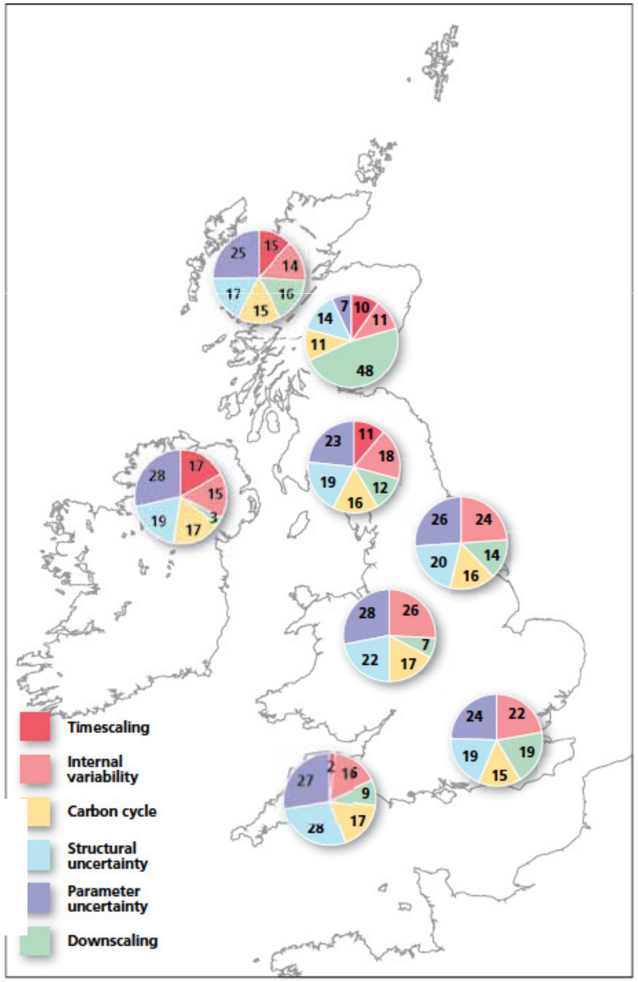
I Improving evidence

- UKCP09 assessment of current evidence so subject to errors common to all current models. Evidence will change in future due to improvements in methods, observations, climate models, and initialisation with observations.
- But sensitivity tests and inclusion of major sources of spread in climate projections demonstrate a robustness of this assessment of current evidence.



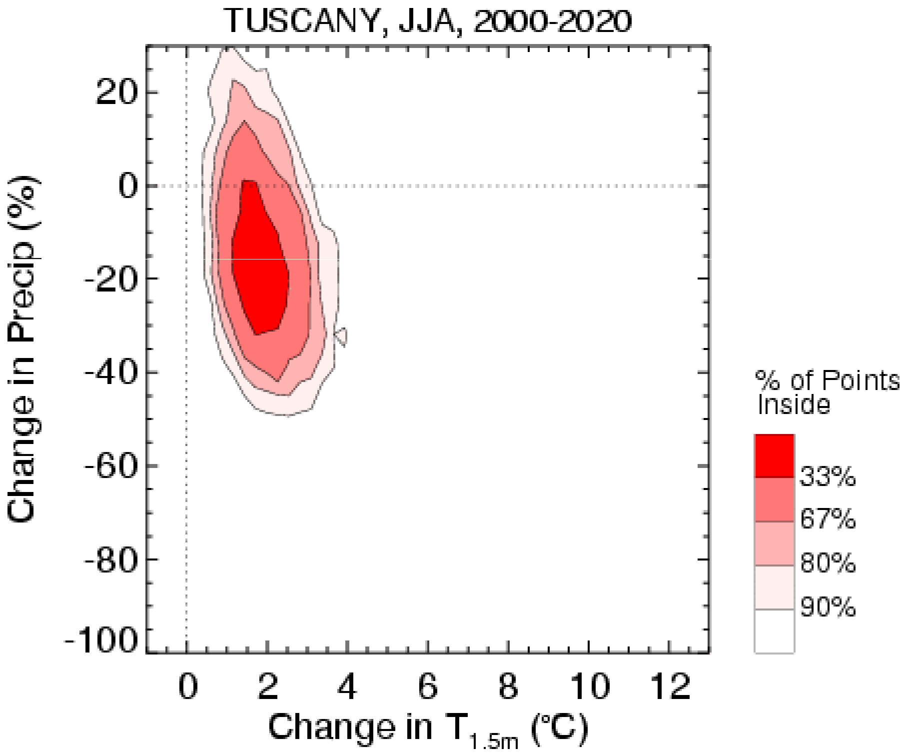
Sensitivity studies

Relative contributions to range of climate response

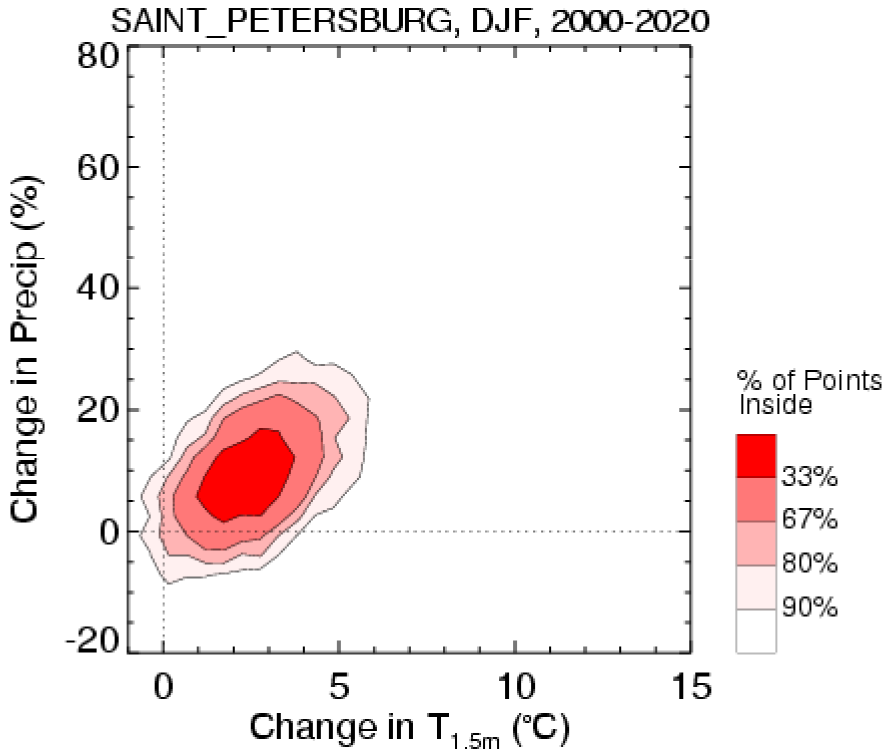


Probabilistic projections in response to A1B emissions

Changes in temperature and precipitation for future 20 year periods, relative to 1961-90, at 300km scale.

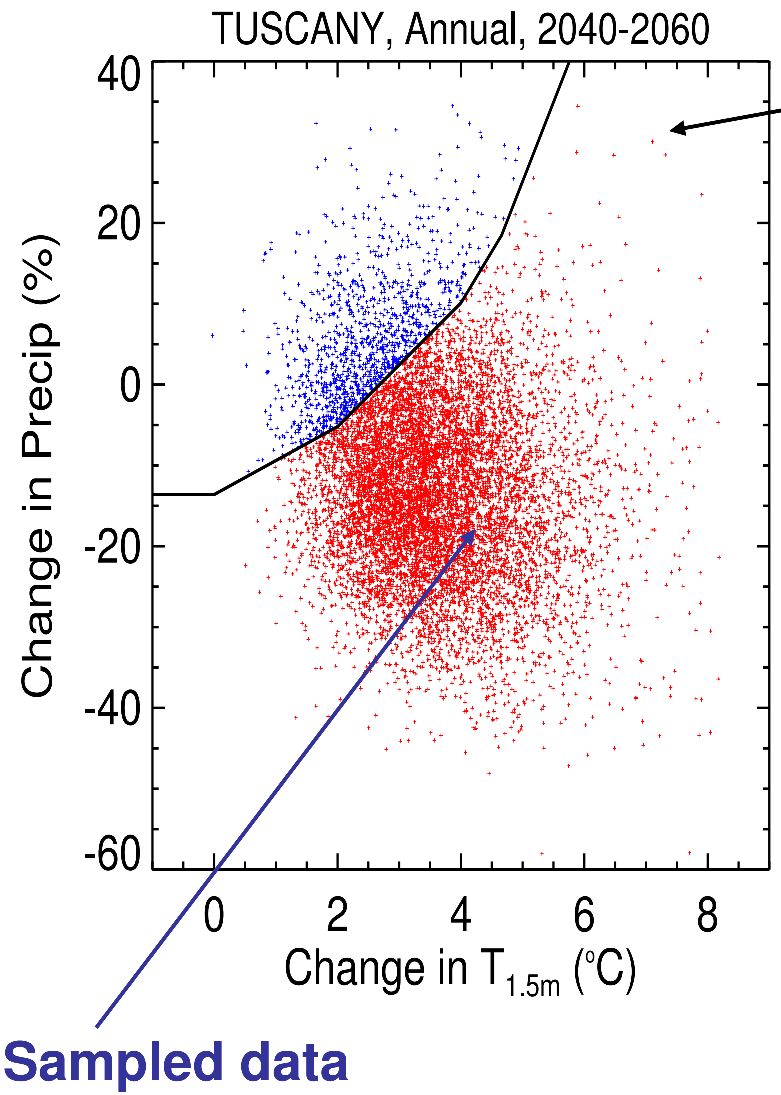


Tuscany, summer



St Petersburg, winter

Societal impact illustration: durum wheat (pasta) yield in Tuscany 2040-2060



Response surface for current yield, including CO_2 fertilization

⇒ 86% risk of a reduction in yield

Thanks to:

Roberto Ferrise, Marco Moriondo, Marco Bindi
Department of Agronomy and Land Management
University of Florence

Examples of user reception

Example Users: Natural England

"Natural England's work on climate change is shaped by its wider remit for the protection and improvement of the natural environment. Climate change is a major threat to the natural environment, its biodiversity and the services it provides, and adaptation is essential to reduce risks, as well as take advantage of any opportunities that arise"

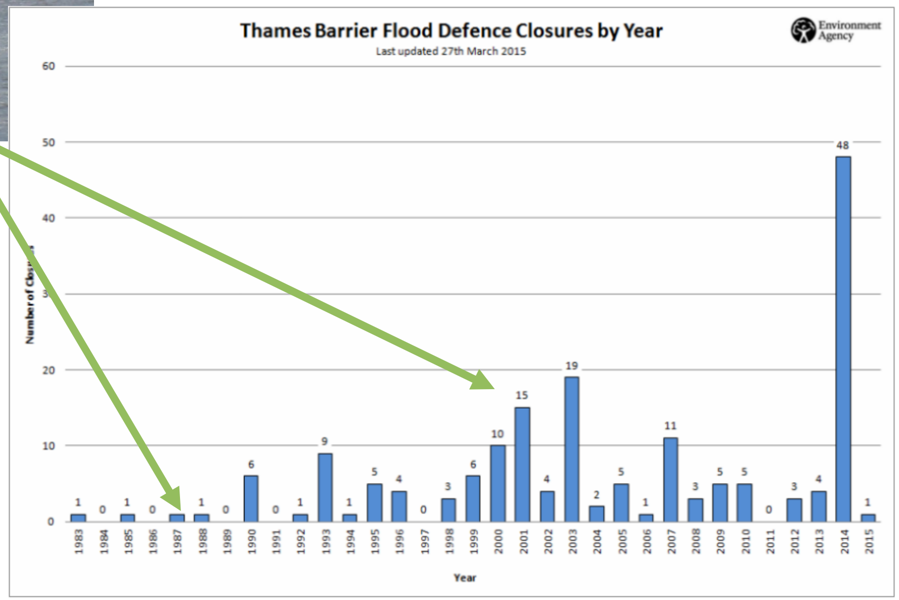
Quote from Summary of Evidence: Climate Change (EIN005)

Information used:
- Qualitative
- Narrative (warmer, wetter, longer seasons, etc)

Example Users: TE2100 Project

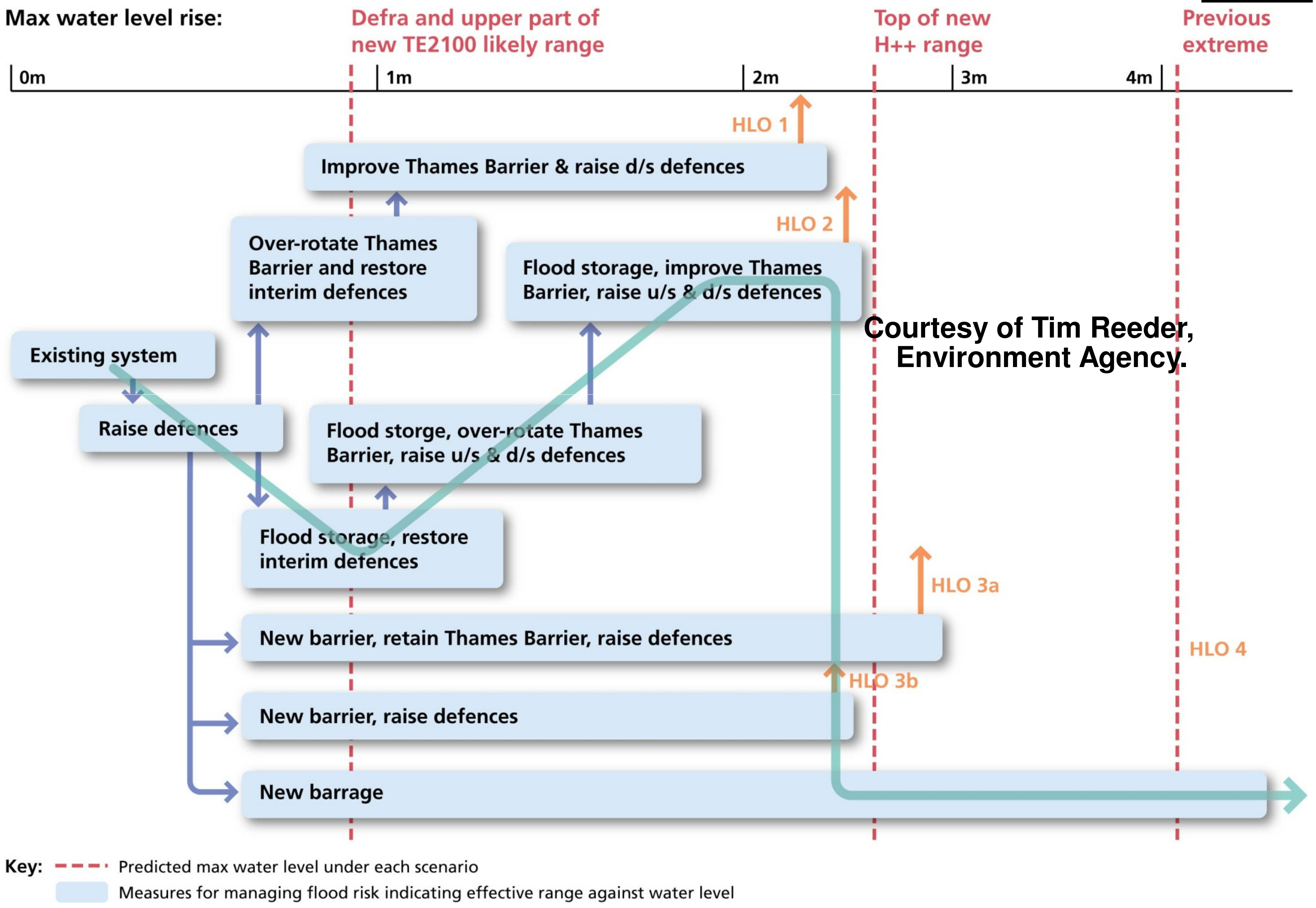
London has a barrier to prevent high tides and river flows causing flooding in the city (negative impacts estimated to be in the £trillion range)

Initially used only once every couple of years, the barrier is now used more frequently – raising questions about whether changing climate will require new infrastructure to keep London dry.

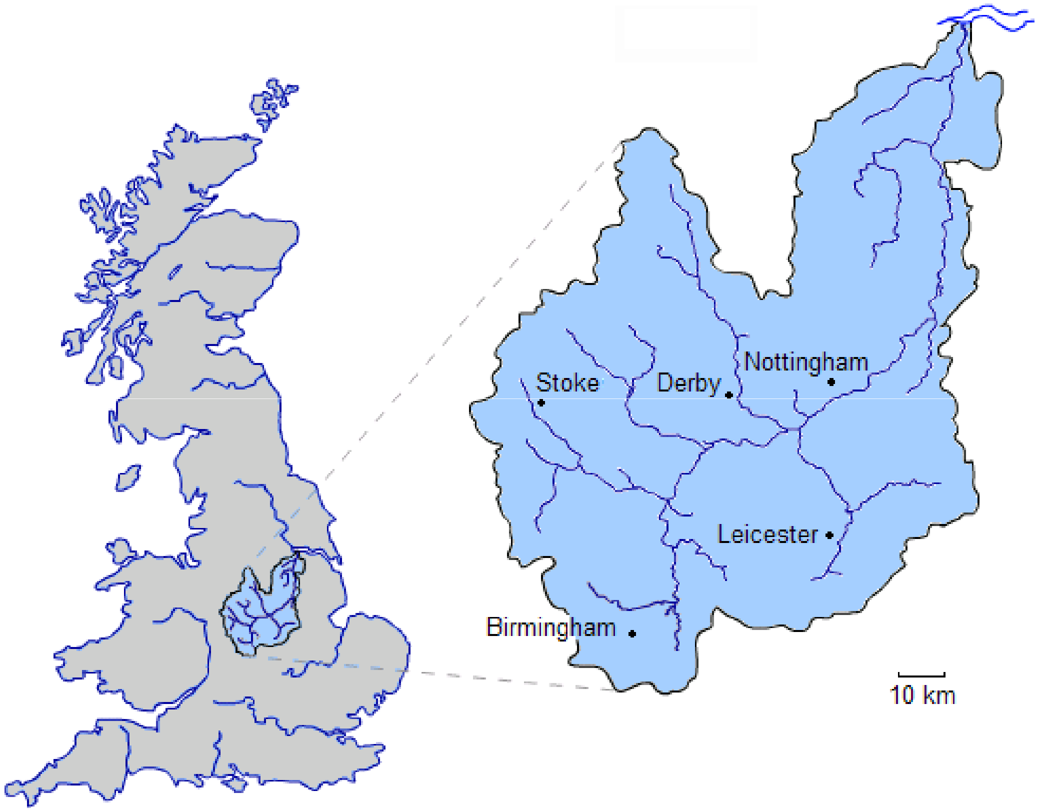


Information used:
Quantitative
Risk adversed (need information on what is possible from high end changes, as well as what is more probable)

Courtesy of Tim Reeder,
Environment Agency.



Example Users: Flood modellers



Flood risks dependent on (often small scale) extreme rainfall events and durations of dry/wet days preceding rainfall.

This information best provided by physically coherent realisations of potential future rainfall changes, such as provided by Regional Climate model simulations

Statistical downscaling approaches can often struggle to capture the spatial and temporal coherent changes that are associated with flood risks.

Information used:

Quantitative

Spatially and temporally coherent realisations of rainfall required to drive river flow models

Examples of how different users are able to make use of projections

	Type of Projections	Conservation	Thames Barrier	Flood modellers
UKCIP02	Single projection	Easy to use/narrative	No estimate of risk of high end changes	Able to use. Limited by ensemble size, spatial scale of information
UKCP09	Full probabilistic	Not able to use quantitative data	Quantitative data. Used high end estimate plus expert judgement	Quantitative data. Needs ensembles of regional models.

Generally findings: With a single projection, users do not need to know their exposure to climate variability/change. With probabilistic information, users need to understand their exposure **before** confronting the data.

Need to work with users to understand their requirements for climate change information

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