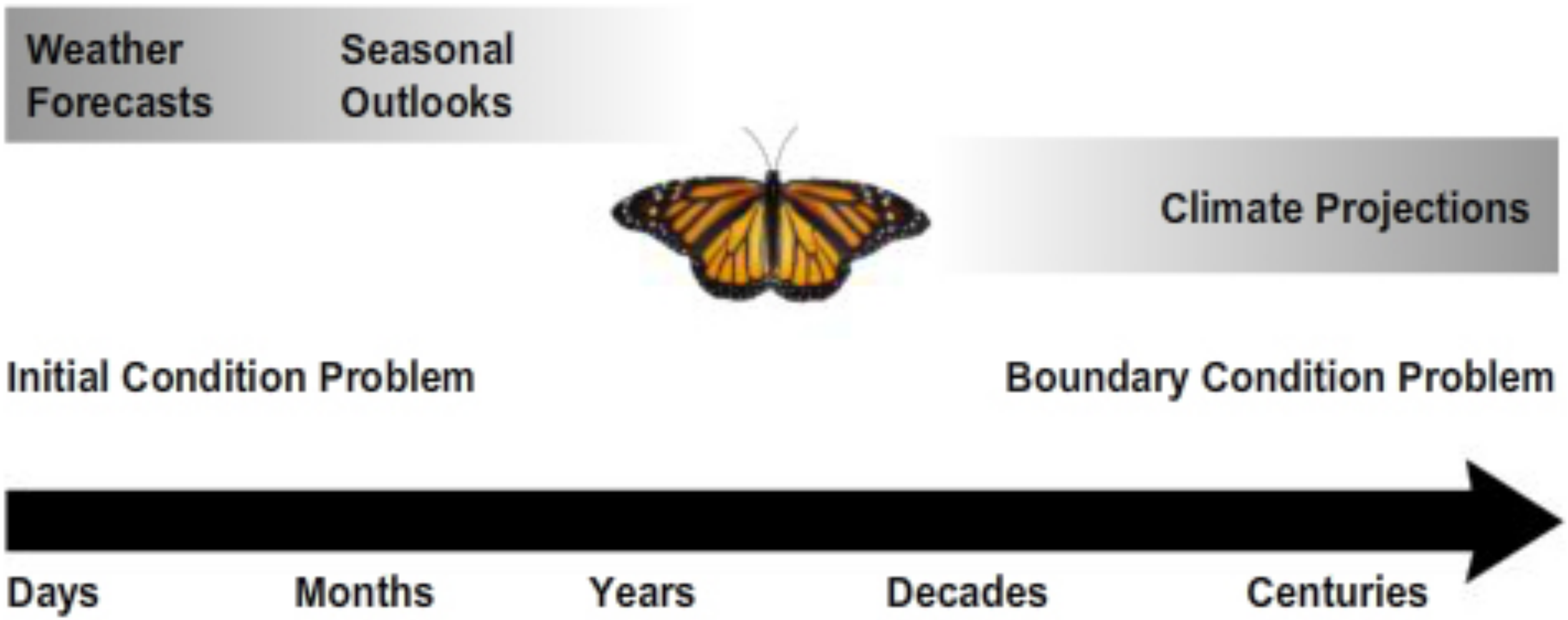
Representing model uncertainty – hierarchy or heterarchy?

Antje Weisheimer

University of Oxford, Department of Physics, AOPP
National Centre for Atmospheric Science (NCAS)
&
European Centre for Medium-Range Weather Forecasts (ECMWF), Reading

Climate forecasts



after Meehl et al. (BAMS 2009)

The purpose of using ensembles of simulations is to represent uncertainties in the underlying dynamic system.

E.g. initial condition ensembles address the chaotic nature of the climate system.

(Objective) Model uncertainties = deficiencies (or inadequacies) in the model itself

Uncertainty is a continuum that ranges from

complete ignorance ⟷ certainty

Three broad categories of uncertainty

Ontological state of complete ignorance

Aleatoric random, irreducible → probability theory

Epistemic resolvable lack of knowledge which we are aware of, reducible

Uncertainty is a continuum that ranges from

complete ignorance ⟷ certainty

Donald Rumsfeld (2002):

There are known knowns: things we know that we know.

There are known unknowns: things we know that we don’t know.

But there are also unknown unknowns: things we don’t know that we don’t know.

unknown knowns: things we don’t know that we know
(things we do not like to know; intentional refusal to acknowledge the things we know)

Sources of model uncertainties (for our type of forecasting models)

Simplifications within the model formulations compared to reality

- Spatial truncation of the resolution of models → unresolved sub-grid scale processes, parametrisations
- Linearised functions to approximate non-linear relations
- Computational constraints (e.g., using climatological rather than prognostic aerosol distributions)
- Omitting processes (e.g. coupling, incompleteness)
- Numerical aspects (algorithmic uncertainty)
- Observational uncertainties

Design errors (un-identified and identified; structural uncertainty)

Lack of correspondence between model and reality (e.g. model parameters with no counterpart in reality)

Gaps in our basic knowledge of the relevant processes

Methods used to account for model uncertainties

- **Multi-model ensembles** (*CMIPs; Iversen et al., 2011*)
- **Parameter perturbations** (*QUMP; Bowler et al., 2008; Ollinhao et al., 2016*)
- **Stochastic physical tendency perturbations** (*Buizza et al., 1999, Palmer et al., 2009*)
- Stochasticity in parametrisations of physical processes (*Shutts, 2005; Plant & Craig, 2008*)
- Multi-physics ensembles (*Charron et al., 2010; Berner et al., 2011*)
- …

Why stochastic parametrisations?

- Are more consistent with the scaling symmetries in the Navier-Stokes equations and the observed atmospheric power-law structure
- Provide specific stochastic realisations of the sub-grid flow, not some assumed bulk average effect
- Describe the sub-grid tendency in terms of a probability distribution constrained by the resolved-scale flow
- Can incorporate physical processes not easily described in conventional parametrisations (e.g. energy backscatter)
- Parametrisation development can be informed by coarse-graining budget analyses of very high resolution (e.g. cloud resolving) models

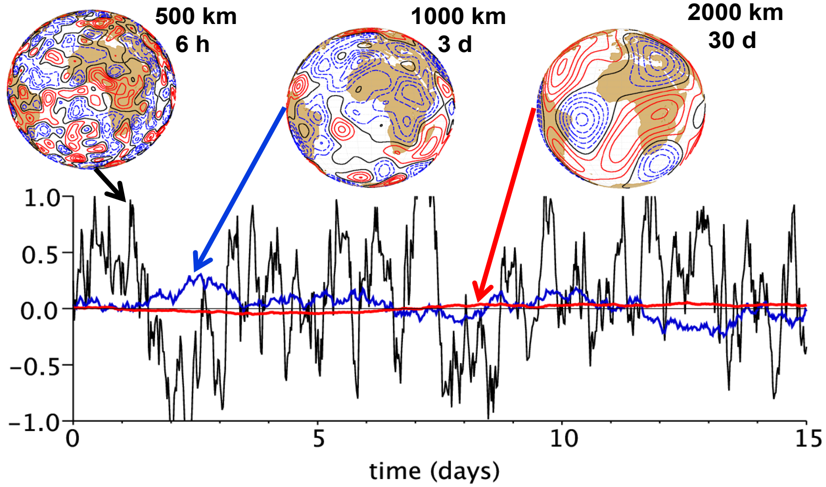
→ *Palmer (QJRMS 2012), Towards the probabilistic Earth-system simulator: A vision for the future of climate and weather prediction.*

Stochastically Perturbed Parameterisation Tendencies (SPPT)

- Operational scheme in ECMWF's ensemble forecasts on all time scales
- Perturbations applied to total parametrised tendency of physical processes as multiplicative noise
- Perturbed physical tendencies:

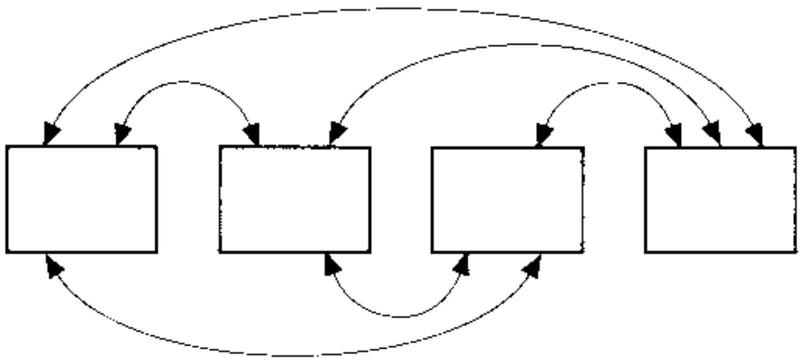
$$X' = (1+r\mu)\,X \qquad \text{for } X=\{u,v,T,q\}$$

- *r* is a uni-variate Gaussian random number described through a spectral pattern generator which is smooth in space and time
- Spectral coefficients of *r* are described with an AR(1) process

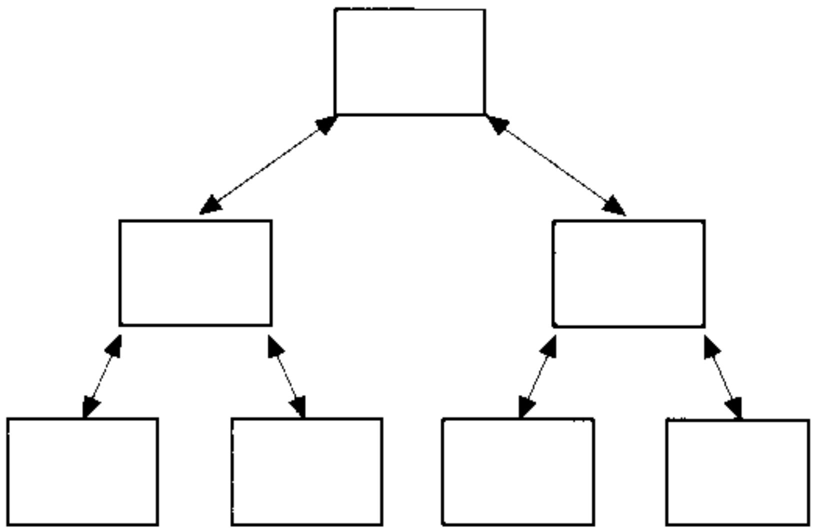


Three components of the SPPT pattern generator with characteristic time and spatial scales

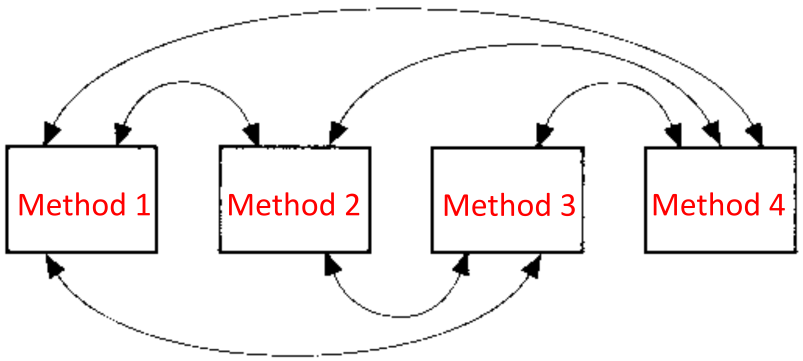
courtesy M. Leutbecher (ECMWF)



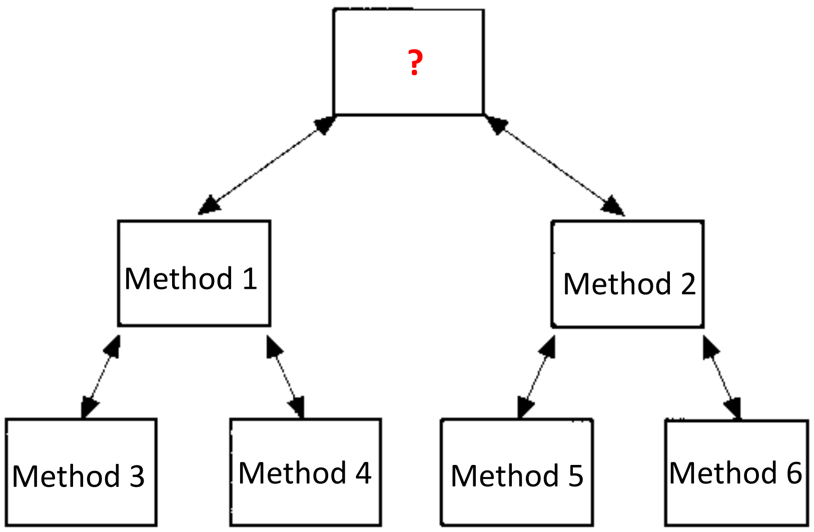
Heterarchy



Hierarchy



Heterarchy



Hierarchy

An example study

Multi-model ensemble (MME)

- five coupled atmosphere-ocean GCMs for seasonal forecasts developed in Europe
- 9 initial condition ensemble members → 45 members

Perturbed parameter ensemble (PPE)

- poorly constrained cloud physics and surface parameters in HadCM3
- simultaneous perturbations to 29 parameters
- no control run available

Stochastic Physics Ensemble (SPE)

- SPPT scheme in coupled ECMWF model
- two-scale perturbed diabatic tendency scheme SPPT
- kinetic energy backscatter scheme
- 9 initial condition ensemble members

- control without stochastic physics (CTRL)

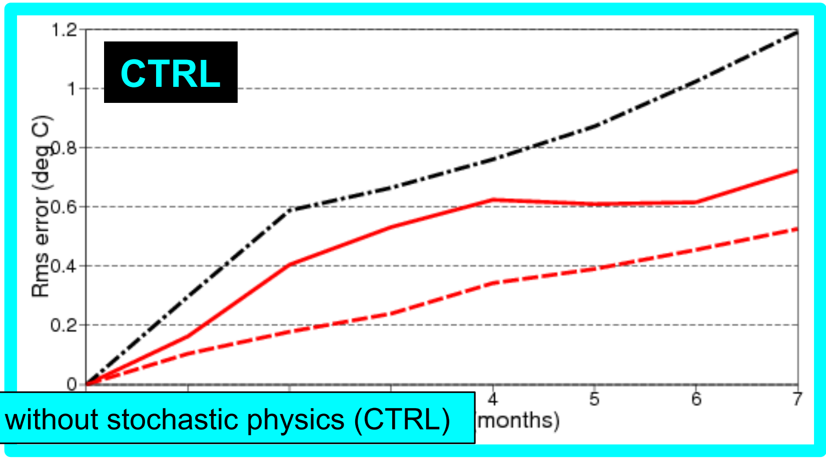
Experimental set-up

- Coupled seasonal retrospective forecasts over the period 1991-2005
  - Initialised on 1st May and 1st November each year
- Assessment of monthly (first month) and seasonal (months 2-4) forecast skill

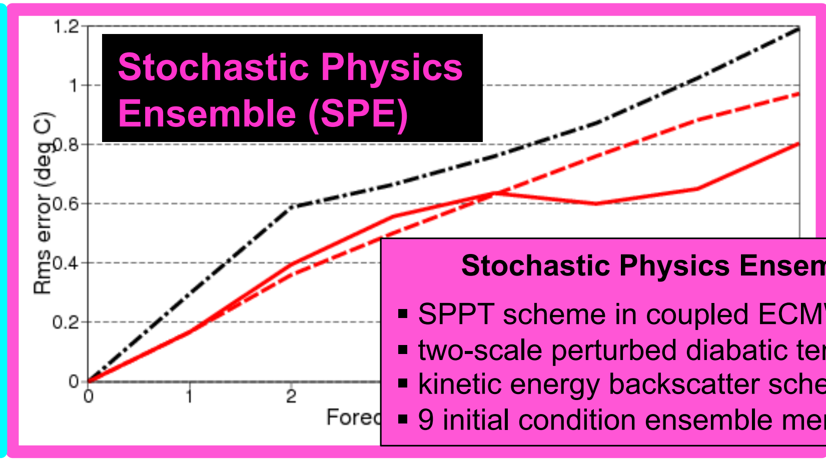
ENSEMBLES

Weisheimer et al. (GRL, 2011)

ENSO SST forecasts quality

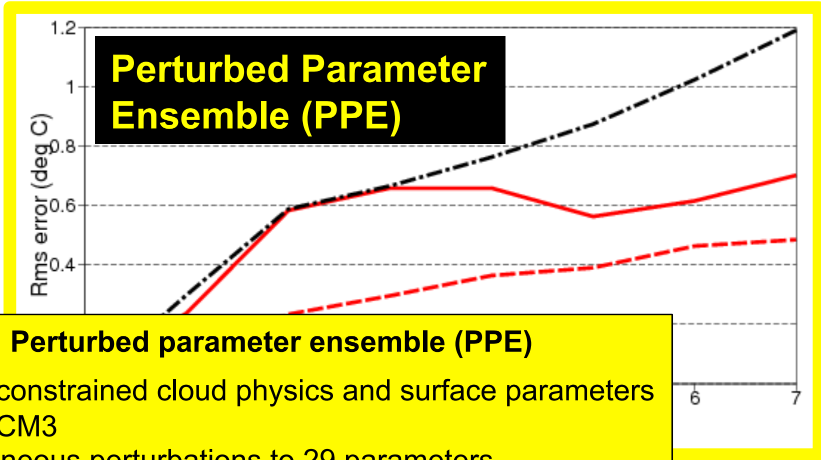


- control without stochastic physics (CTRL)



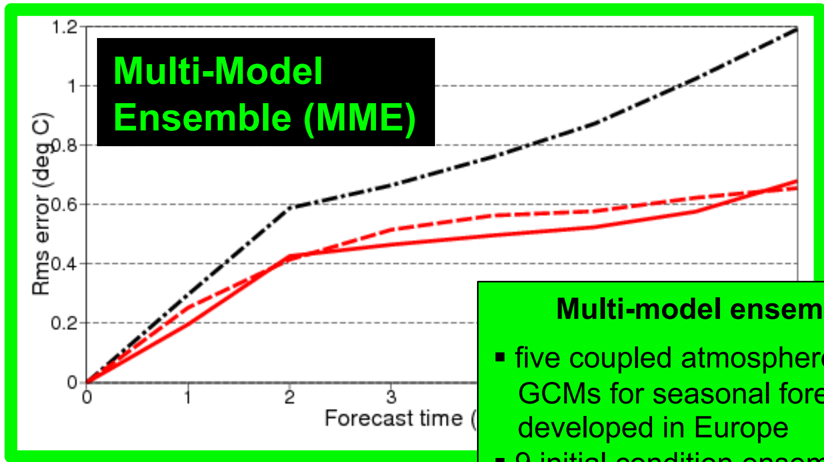
Stochastic Physics Ensemble (SPE)

- SPPT scheme in coupled ECMWF model
- two-scale perturbed diabatic tendency scheme
- kinetic energy backscatter scheme
- 9 initial condition ensemble members



Perturbed parameter ensemble (PPE)

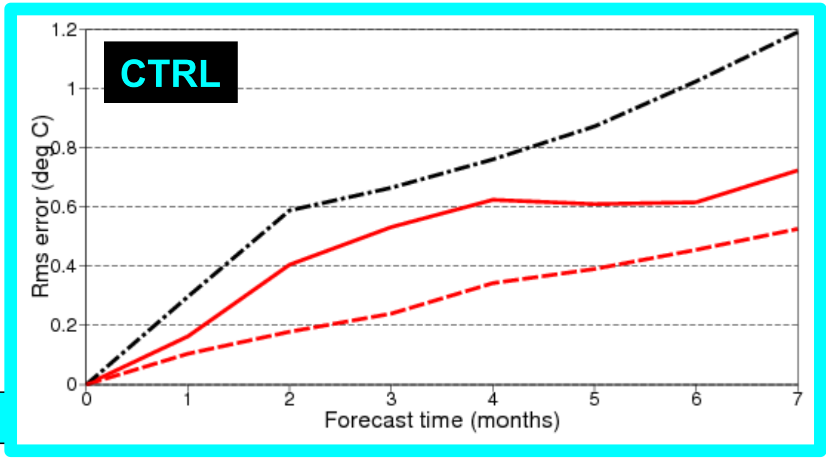
- poorly constrained cloud physics and surface parameters in HadCM3
- simultaneous perturbations to 29 parameters
- no control run available

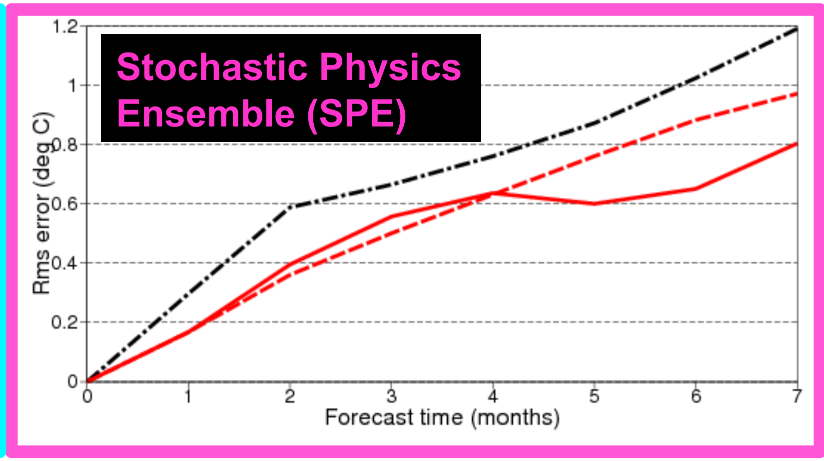


Multi-model ensemble (MME)

- five coupled atmosphere-ocean GCMs for seasonal forecasts developed in Europe
- 9 initial condition ensemble members → 45 members

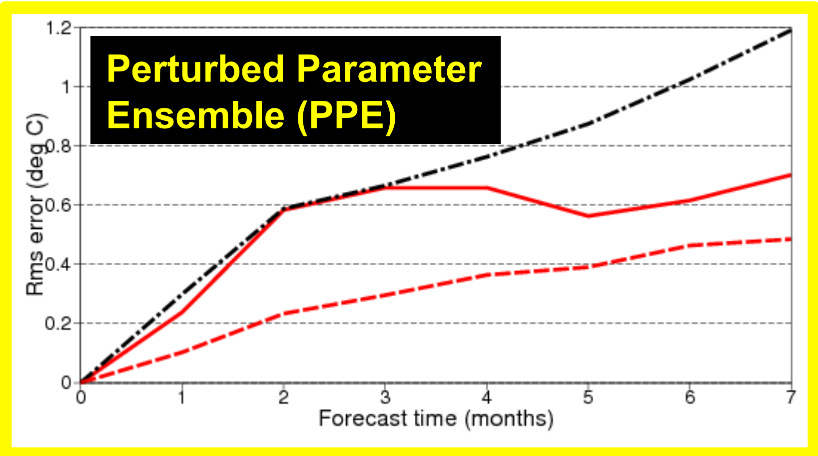
ENSO SST forecasts quality

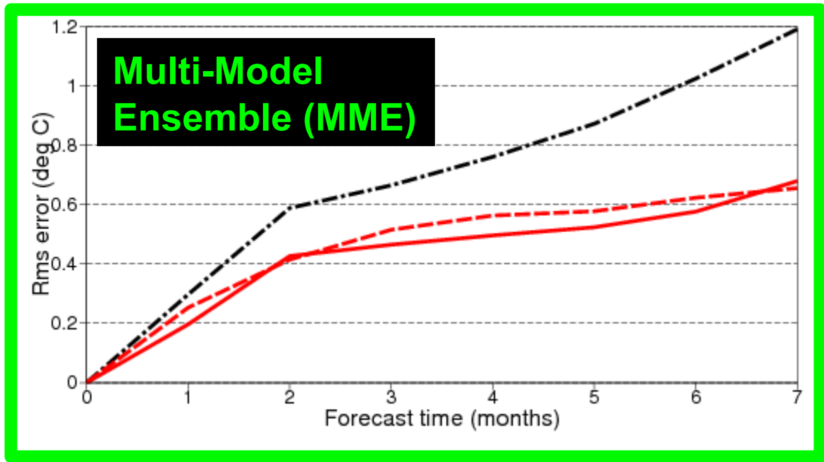




▪ control

ble (SPE)
WF model
ndency scheme
me
mbers

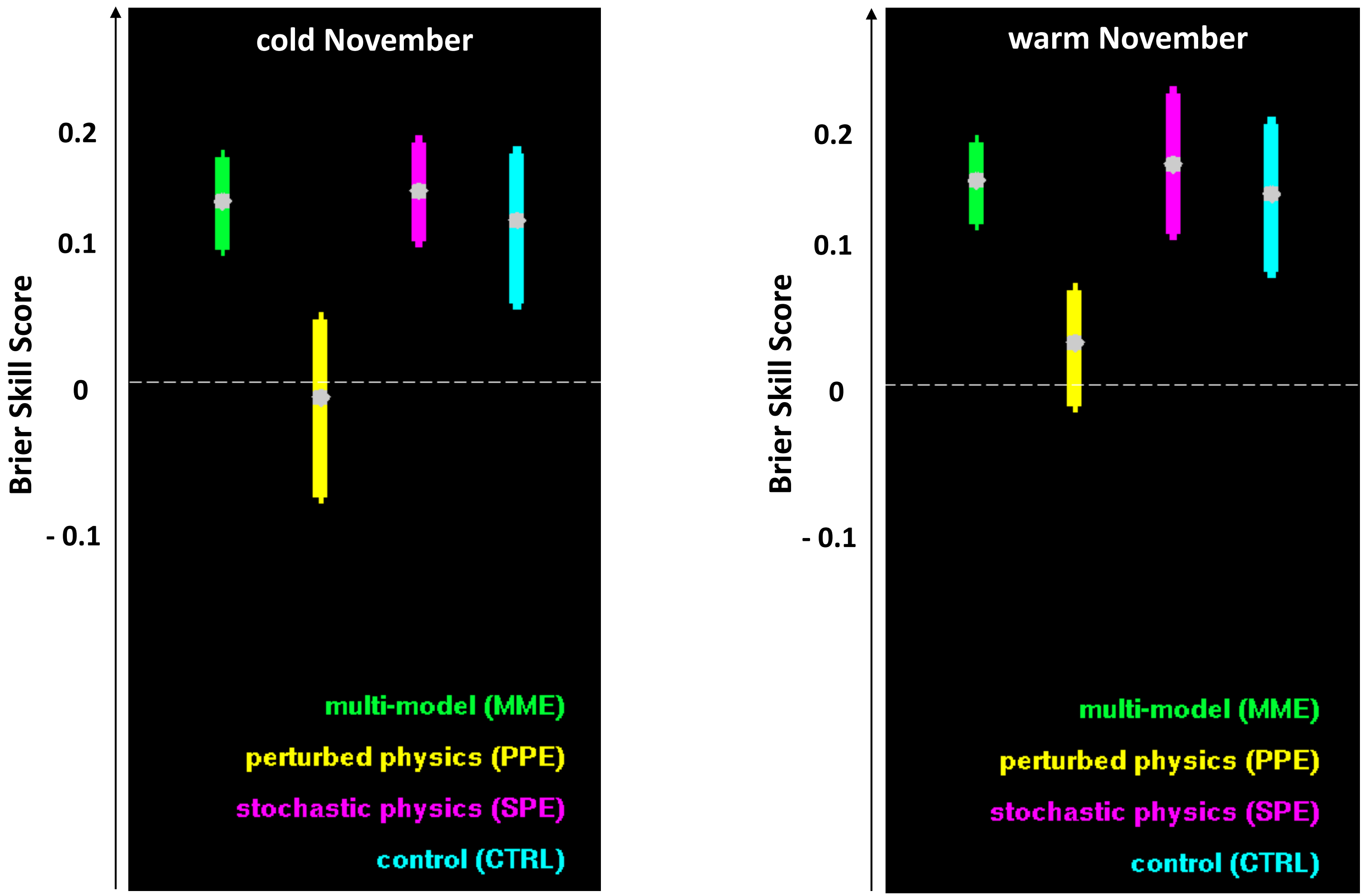




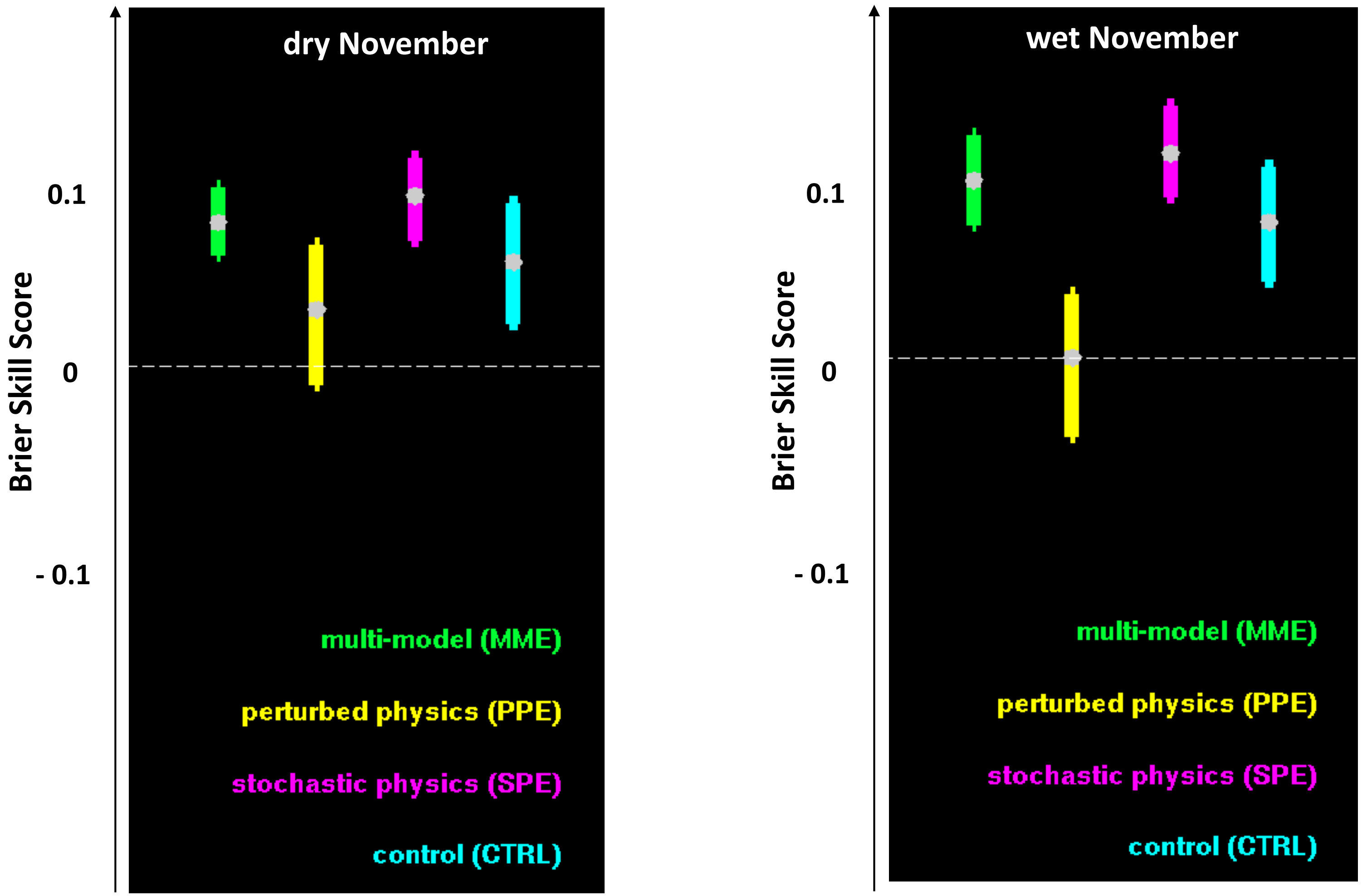
▪ poorly c
in HadC
▪ simultaneous perturbations to 29 parameters
▪ no control run available

ble (MME)
e-ocean
casts
▪ 9 initial condition ensemble members → 45 members

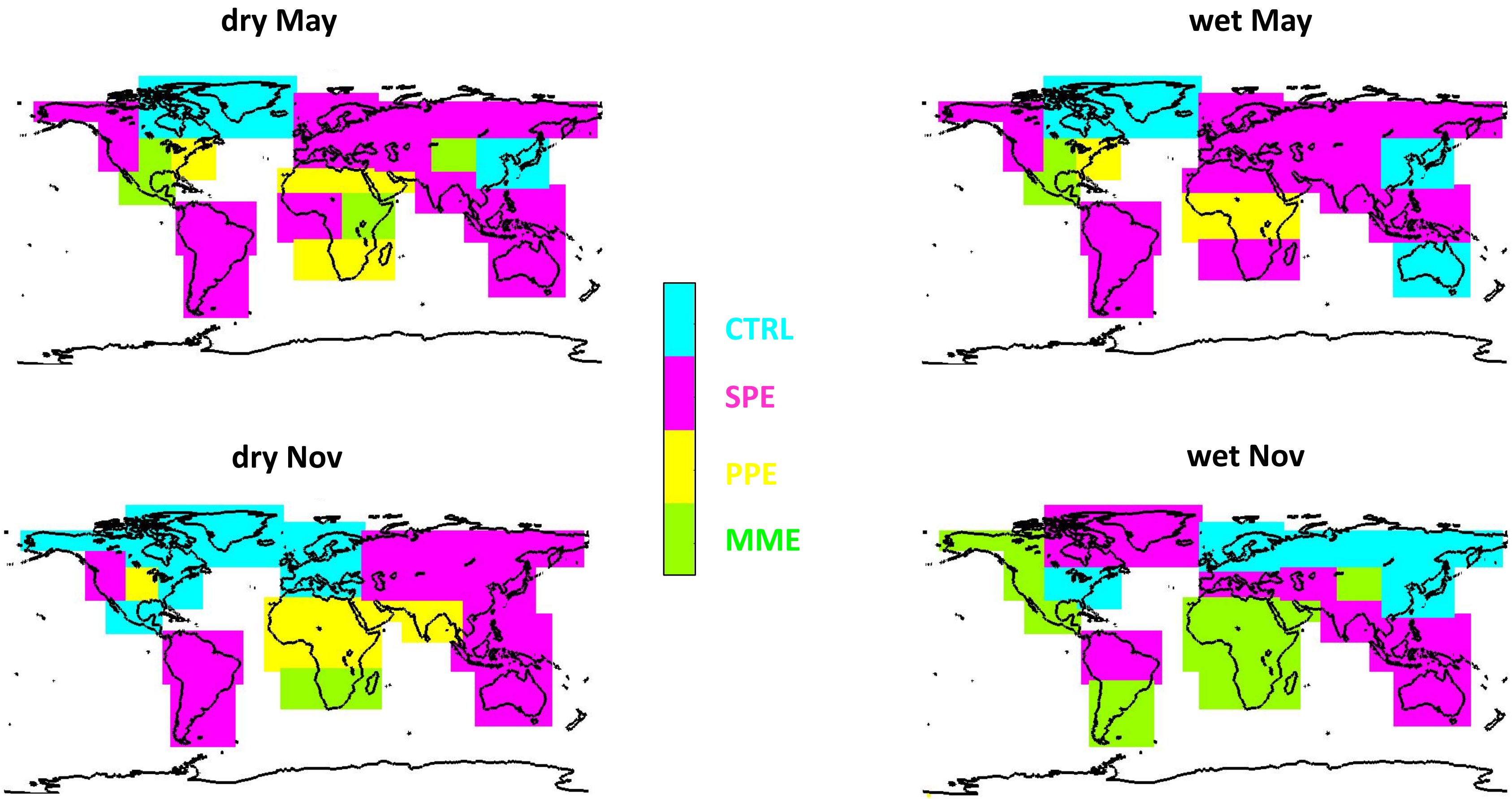
Sub-seasonal forecasts of global land temperature



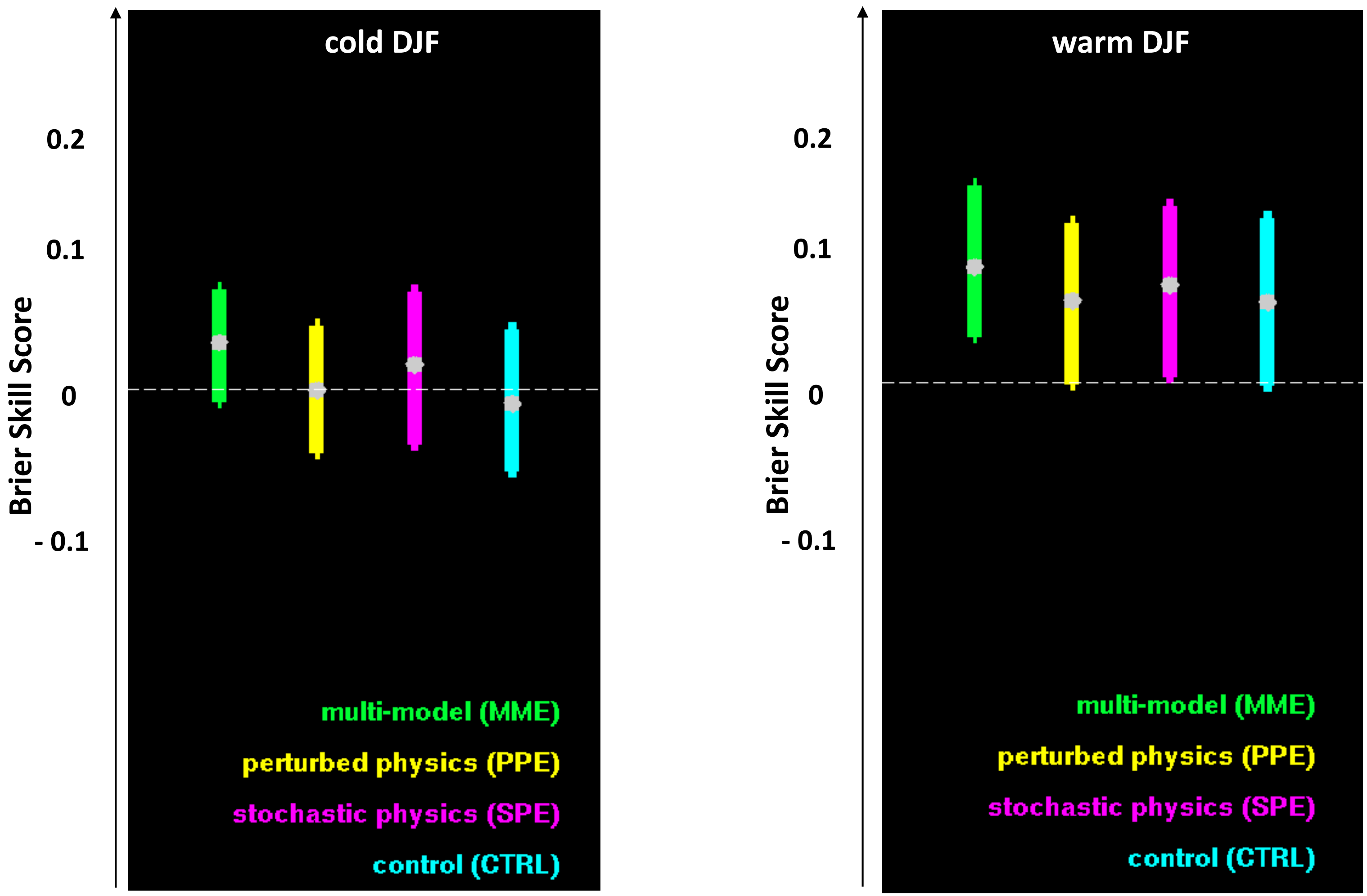
Sub-seasonal forecasts of global land precipitation



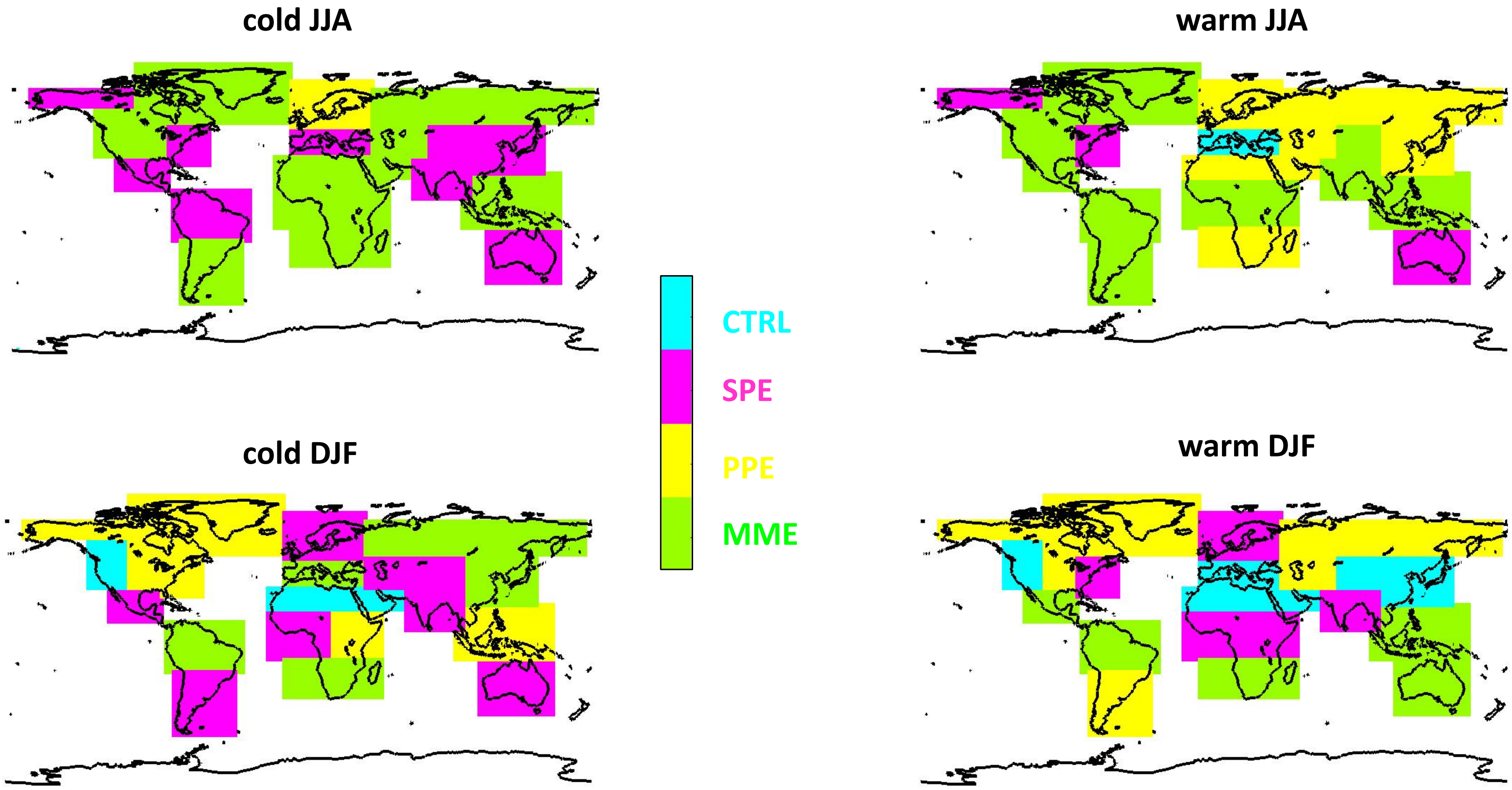
Sub-seasonal forecasts of land precipitation



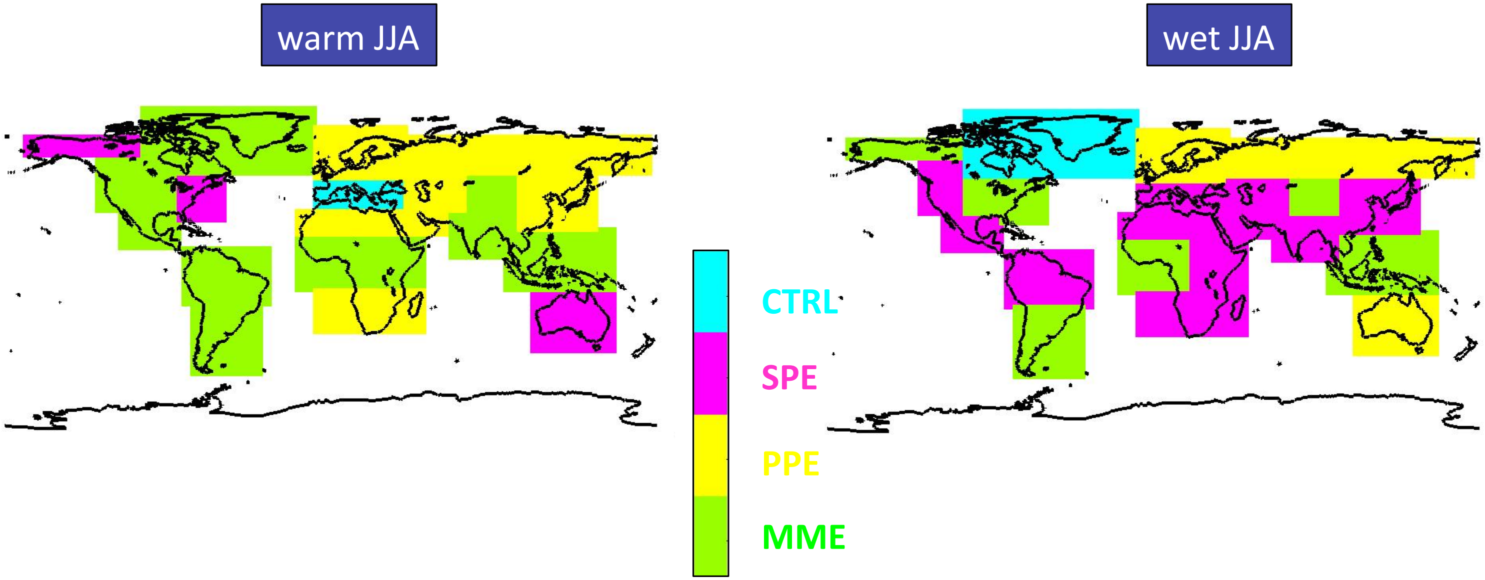
Seasonal forecasts of global land temperature



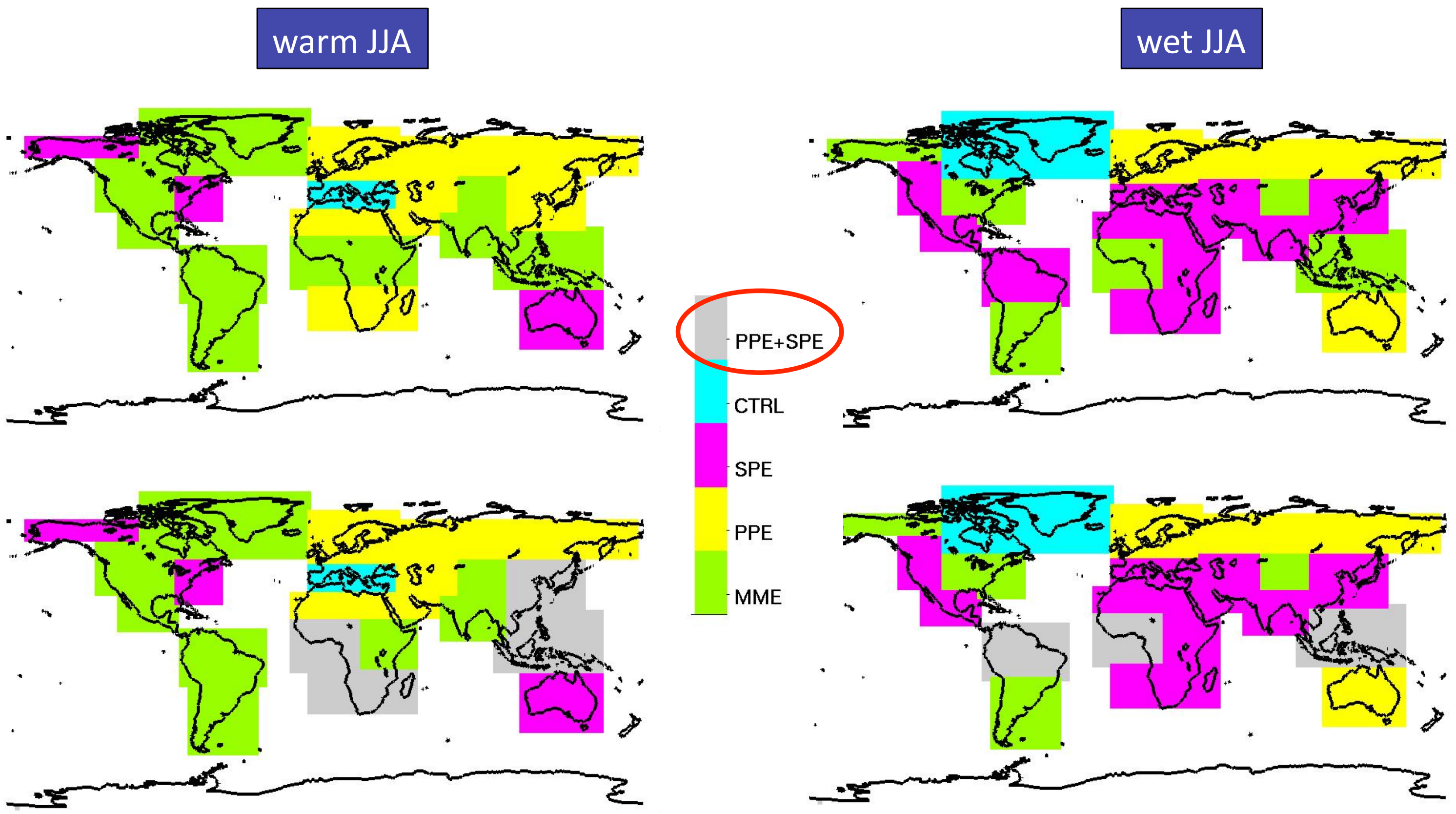
Seasonal forecasts of land temperature



Seasonal forecasts combining PPE and SPE



Seasonal forecasts combining PPE and SPE



Conclusions

Uncertainty is a continuum and its representation in weather and climate forecast models is currently heterarchical (pluralistic, complementary) rather than hierarchical.

Inferences about model uncertainty from idealised models are intrinsically difficult due to

- the changing nature of model uncertainty across models
- the forecasters' need to get as accurate a forecast as possible (→ complex models)

Example study of monthly and seasonal forecasts using multi-model ensembles (MME), perturbed parameter ensembles (PPE) and stochastic perturbations (SPE):

- ENSO: MME very good, SPE improved over CTRL, PPE rather poor
- Monthly forecasts: SPE globally most skilful for most land temperature and precipitation events with regional variations
- Seasonal forecasts: MME (SPE) on average most skilful for temperature (precipitation) over land, regional variations
- Combination of PPE and SPE approaches potentially improves skill further