An Overview of Approaches to Probabilistic Projections of Future Climate Change (Based on Multi-Model Ensembles for the most part)

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What this talk is about:

My attempt at organizing those methods that have been proposed to synthesize the information in CMIP* - kind ensembles, for probabilistic future climate change projections

What this talk is not about:

- Model evaluation methods
- Successful, or not, applications of methods to impact analysis/decision making

Two dimensions along which to classify probabilistic methods, each of them offering a binary choice.

First dimension: what do the ensemble members represent in relation to the "truth" that we are after

- Each of the member is sampled from a distribution (eventually) centered around the truth: the "Truth + Error" view.

- Each of the member is (eventually) considered as "indistinguishable" from the truth and any other member.

Hannan and Hargreaves, 2010, GRL,37
Reliability of the CMIP3 Ensemble

Hannan and Hargreaves, 2011, JCLIM,24
Understanding the CMIP3 Multimodel Ensemble

IPCC Good Practice Guidance Paper
on the Use of MMEs

- As a consequence of the first choice the use of the ensemble seeks some form of **consensus** and would characterize the **uncertainty** of this consensus estimate as **decreasing with the ensemble size**

- As a consequence of the second choice the **range of the ensemble corresponds to the range of uncertainty**, and the **truth is not a synthesis but falls somewhere among the members** (weather forecasting view of ensemble forecasting)

Second dimension: weights or no weights?

- Do we trust each model equally?
- Do we apply some kind of reweighting?
  - Could be 0/1
  - Could be derived on the basis of formal likelihood models
  - Could be derived heuristically on the basis of expert judgment (statisticians don't like that)

Truth+Error, Weighted

- All these methods are after some kind of unobserved truth which the models are aiming for.
- Observations help constrain the estimate of this truth, or train the calibration of the model output and their combination, and the result is interpretable as a weighted combination of model output.
- The result is an estimate of this truth, and an estimate of its uncertainty, and those method that approach the truth as a random quantity come up with a Bayesian posterior probability distribution for it.
- As it is natural in these cases the uncertainty diminishes as we add observations/models.

Basic Structure of Truth + Error Models

- $Z_H = Y_H + W_H$
- $X_{Hm} = Y_H + R_{Hm}$
- $X_{Fm} = Y_F + R_{Fm}$

- W_H is the effect of internal variability
- R_{Hm}, R_{Fm} is the effect of both model internal variability and model error

- $R_{Hm} \sim N(0, S^2)$
- $R_{Fm} | R_{Hm} \sim N(l * R_{Hm}, c * S^2)$

Indistinguishable, Weighted or Not

- For all these methods the final result is some type of empirical histogram of the model projections (sometimes filled-in through some bootstrap exercise), or some parametric representation of it, describing a population distribution which is assumed to be the population to which reality belongs.

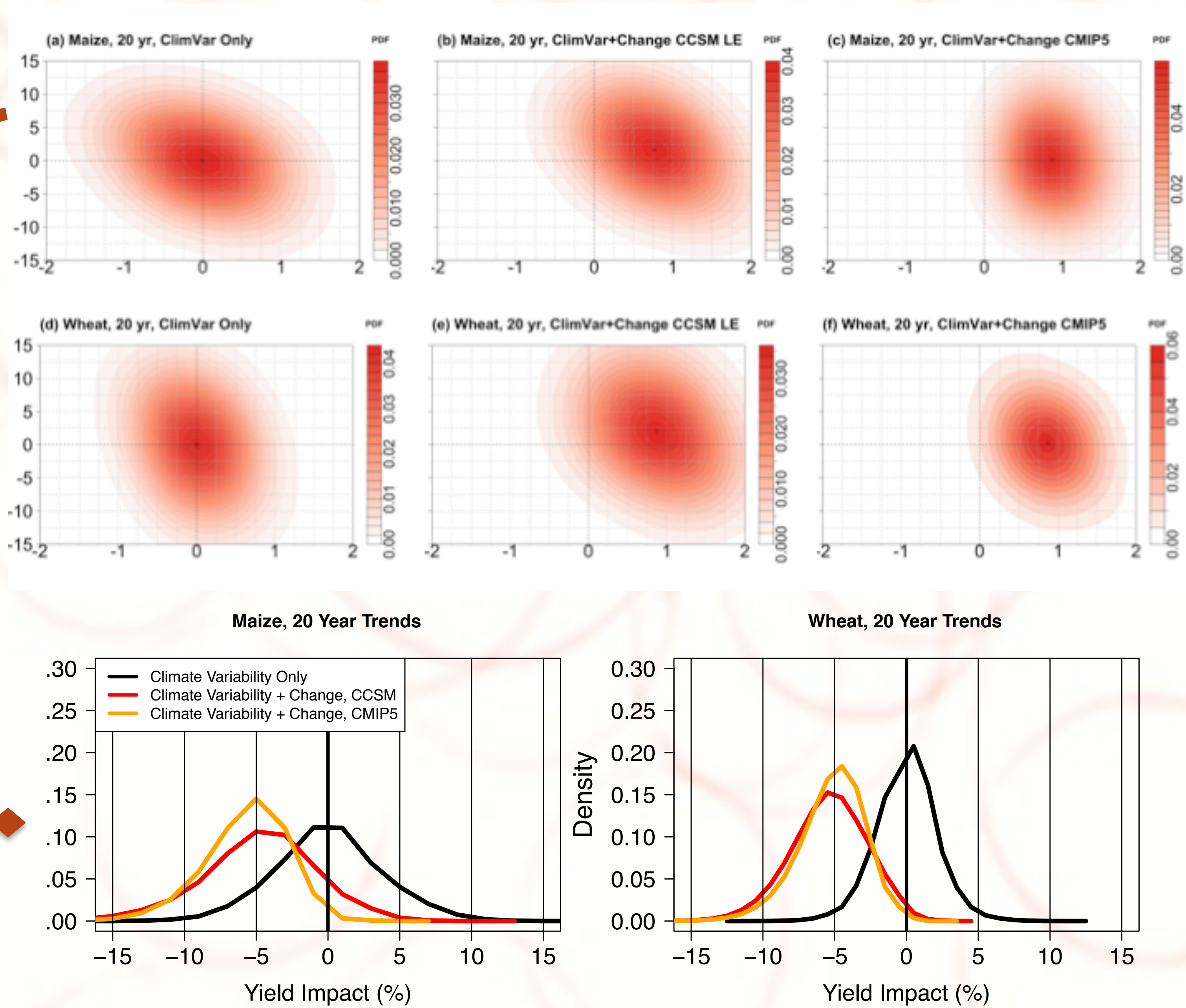
- For these methods the choice is either a democratic one, giving to any one model one vote, or not, where observations and/or some measure of model consensus help discriminate and reweight the individual members.
  - some measure of bias,
  - some measure that involves distributional quantities (e.g., distribution of daily quantities as modeled compared to as observed).
  - D&A analysis,
  - 0/1 weighting scheme (eliminating some of the models, giving equal weight to the remaining).

Basic Idea of Indistinguishable

$$\Pr(Y_R \geq y_R) = \frac{\sum_{m=1}^{M} w_m I(X_{Rm} \geq y_R)}{\sum_{m=1}^{M} w_m}$$

Y_R is reality
X_{Rm} is model output
W_m are weights

An example, from a recent paper



- For most of the studies in the literature (regions) the results of weighting or not weighting are not significantly different (it's not easy to find emergent constraints).
- For some, usually at very specific regional scales as opposed to large, global scales, the result of weighting model differently changes the overall location of the distribution.

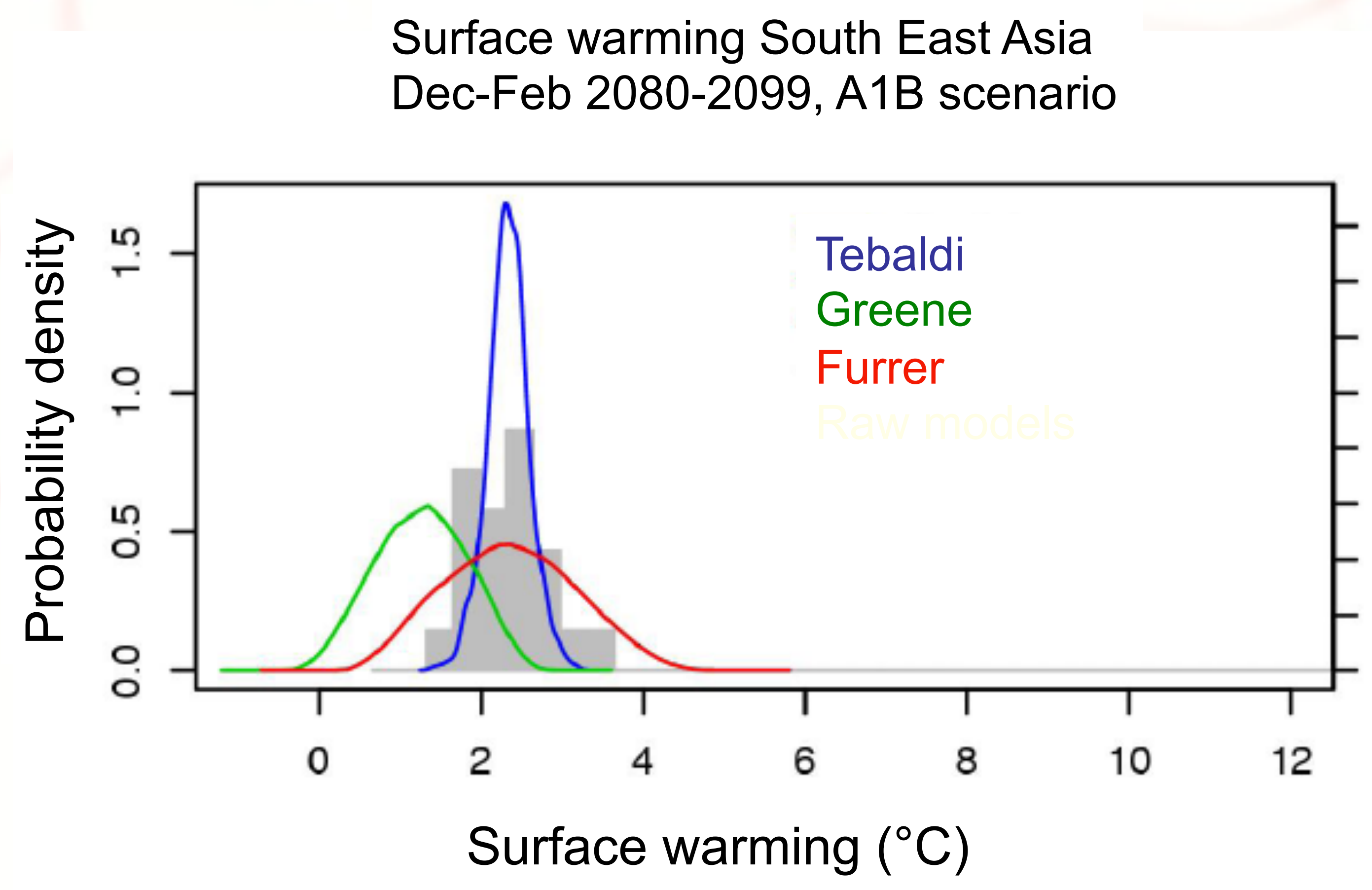
Comparisons of methods deliver two main messages

Even within each of the two categories (truth + error vs. indistinguishable) the assumptions matter, and deliver PDFs of different width and different location

The width of the PDF does decrease with the number of data points (models and/or observations) for the methods in the Truth + Error category

The idiosyncrasies of the MME as a statistical sample make formalisms, rigorous quantification, robust estimates very hard

Assumptions, esp. in the weighting matter for the result

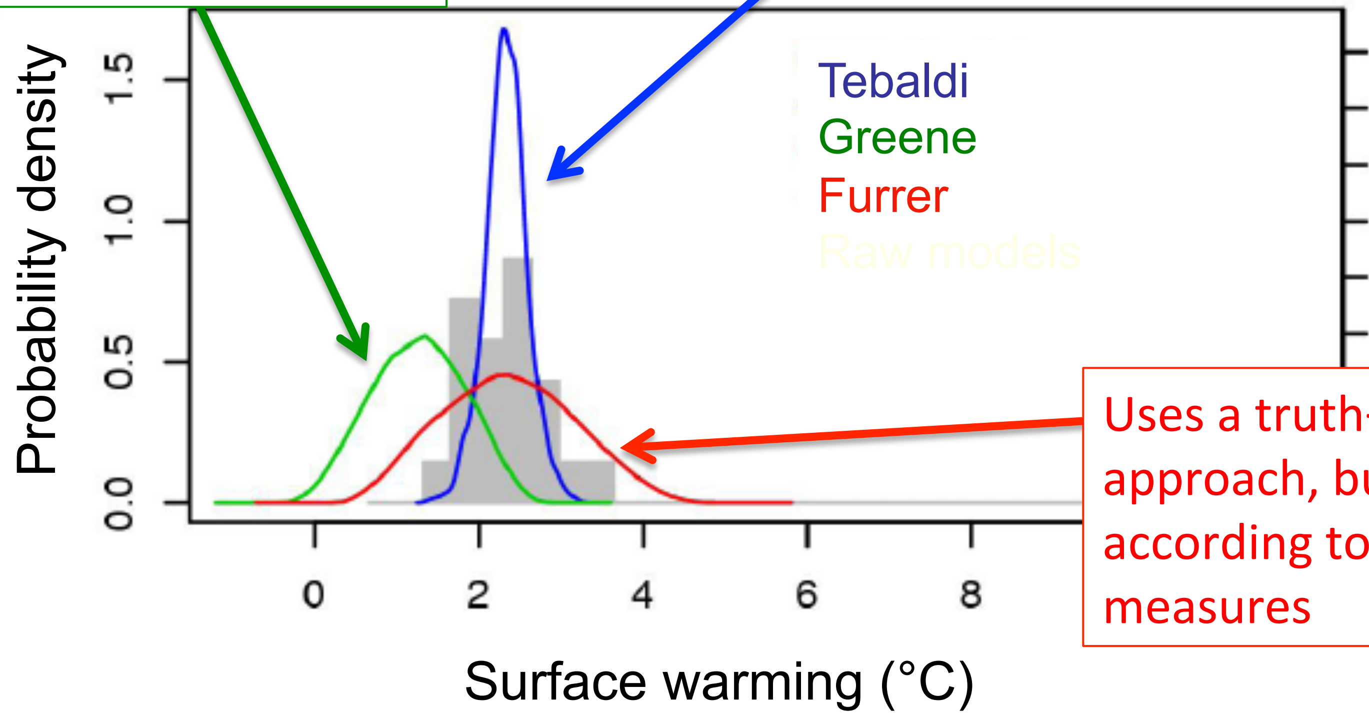


Tebaldi and Knutti, Phil Trans Roy Soc, 2007

Assumptions, esp. in the weighting matter for the result

Uses a truth+error approach but weighs according to past performance on regional trends

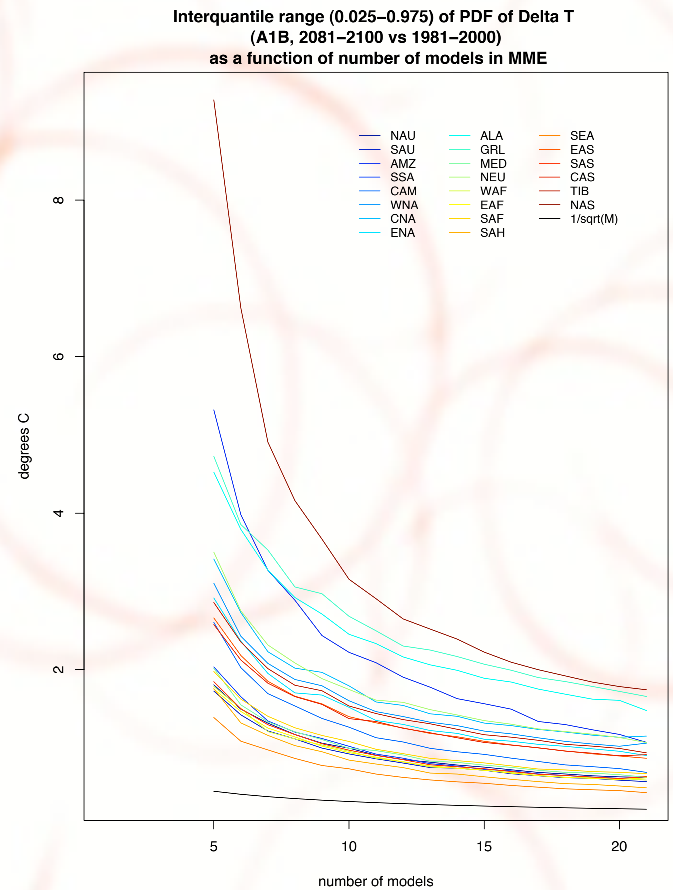
Uses a truth+error paradigm and weighs according to regional bias and consensus



Uses a truth+error approach, but weighs according to global bias measures

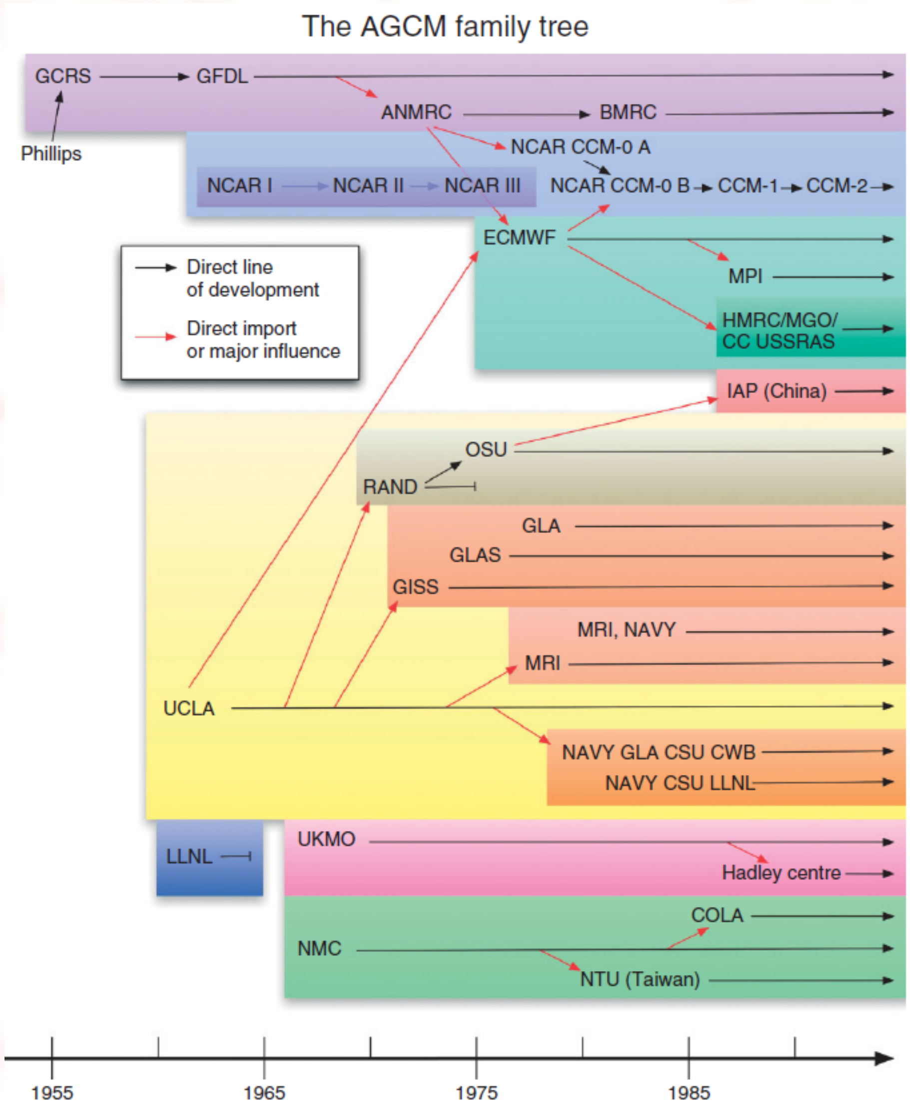
Tebaldi and Knutti, Phil Trans Roy Soc, 2007

Width as a function of ensemble size



Climate model genealogy

Models are not independent



Edwards, WIRE 2011

Final thought
The third dimension:
general purpose vs. regionally specific projections

- There is a spectrum of purposes for which multi-model analysis will be relevant, from IPCC-WG1-Ch. 12-like purposes, through IAM implementation that need global scale projections, all the way to very specific regional and sectoral adaptation studies.
- For the first type of activity the indistinguishable, non-weighted option is IMO defensible: invoke pattern-scaling, characterize its uncertainty across models (and scenarios), couple it with extensive exploration, through simplified models, of the uncertainties in global average temperature change.
- For the type of activity that has a very specific focus, discriminating on the basis of performance over a comprehensive set of metrics relevant to the regional climate (or the aspect of climate relevant to the impact analysis) may be justified, practical and hopefully relevant (!).

Truth+Error, Weighted

- Buser et al. 2009 Bayesian multi-model projection of climate: bias assumptions and interannual variability
- Smith et al. 2009 (wrapping up Tebaldi et al. 2004, 2005 and similar to Tebaldi and Sanso' 2009) Bayesian modeling of uncertainty in ensembles of climate models
- Furrer et al. 2007 (in EES similar to Furrer et al. 2007 GRL) Multivariate Bayesian analysis of Atmosphere – Ocean General Circulation Models
- Boulanger et al. 2007 Projection of future climate change conditions using IPCC simulations, neural networks and Bayesian statistics. Part 2: Precipitation mean state and seasonal cycle in South America
- Greene et al. 2006 Probabilistic multimodel regional temperature change projections
- Berliner and Kim 2008: Bayesian design and analysis for superensemble-based climate forecasting
- Bracegirdle and Stephenson 2012 Higher precision estimates of regional polar warming by ensemble regression of climate model projections
- Chandler 2013 Exploiting strength, discounting weaknesses: combining information from multiple climate simulators
- Karpechko et al., 2013 Improving Antarctic total ozone projections by a process oriented multiple diagnnostic ensemble regression
- Sansom et al., 2013 Simple uncertainty frameworks for selecting weighting schemes and interpreting MME climate change experiments
- Sexton et al. 2012 Multivariate probabilistic projections using imperfect climate models
- Smith et al., 2009 Bayesian modeling of uncertainty in ensembles of climate models
- Stephenson et al., 2012 Statistical problems in the probabilistic prediction of climate change

Indistinguishable, Weighted

- Moise and Hudson 2008 Probabilistic predictions of climate change for Australia and southern Africa using the reliability ensemble average of IPCCCMIP3 model simulations
- Palmer et al. 2008 Toward seamless prediction: Calibration of climate change projections using seasonal forecasts
- Min et al. 2007 Probabilistic climate change predictions applying Bayesian model averaging
- Laurent and Cai 2007 A maximum entropy method for combining AOGCMs for regional intra-year climate change assessment
- Shukla et al. 2006 Climate model fidelity and projections of climate change
- Dessai et al. 2005 Limited sensitivity analysis of regional climate change probabilities for the 21st century
- Giorgi and Mearns 2002 Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the "reliability ensemble averaging'' (REA) method
- Pierce et al. 2009 Selecting global climate models for regional climate change studies
- Perkins and Pitman 2009 (similar to Pitman and Perkins 2008) Do weak AR4 models bias projections of future climate changes over Australia?
- Watterson 2008 Calculation of probability density functions for temperature and precipitation change under global warming
- Brekke et al. 2008 Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments
- Suppiah et al. 2007 Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report
- Benestad 2004 : Tentative probabilistic temperature scenarios for northern Europe.
- Bhend and Whetton 2013 Effective constraints for regional climate change projections. 12th IMSC
- Bishop and Abramowitz 2013 Climate model dependence and the replicate Earth paradigm
- Raisanen et al. 2010 Weighting of model results for improving best estimates of climate change
- Christensen et al. 2010 Weight assignment in regional climate models
- Cox et al., 2013 Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability
- Harris et al. 2013 Probabilistic Projections of transient climate change
- Watterson and Whetton 2011, Distributions of decadal means of temperature and precipitation change under global warming

Indistinguishable, Non-weighted

- Giorgi 2008 A simple equation for regional climate change and associated uncertainty
- Murphy et al. 2007 * A methodology for probabilistic predictions of regional climate change from perturbed physics ensembles
- Ruosteenoja et al. 2007 GCM-based regional temperature and precipitation change estimates for Europe under four SRES scenarios applying a super-ensemble pattern-scaling method
- Raisanen and Ruokolainen 2006 Probabilistic forecasts of near-term climate change based on a resampling ensemble technique
- Dettinger 2006 A component-resampling approach for estimating probability distributions from small forecast ensembles
- Raisanen and Palmer 2001 A probability and decision-model analysis of a multimodel ensemble of climate change simulations