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<b>PU</b>	Public	PU
<b>PP</b>	Restricted to other programme participants (including the Commission Services)	
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<b>CO</b>	Confidential, only for members of the Consortium (including the Commission Services)	

## **WP1.2: Systematic documentation and intercomparison of ensemble perturbation and weighting methods**

Various papers have been written which form the basis of this deliverable. In a suite of papers the Oxford and Hadley Centre teams detail new developments in the methodology of ensemble climate predictions of 21<sup>st</sup> century climate, while the ECMWF have made progress on the seasonal to decadal forecasting problem.

As well as a paper presenting early results from the *climateprediction.net* "grand ensemble" (which shows that parameter perturbations often add non-linearly, widening the range of physically plausible model sensitivities (Stainforth et al, 2005)) UOXFDC have also completed work into issues surrounding the methodology behind probabilistic climate forecasting, in particular regarding methods for ensemble weighting (Frame et al., 2005) and model error (Allen et al., 2005). This work is currently being consolidated, and extended, in a series of articles by members of the Oxford team.

The Hadley Centre have been working with an expert in statistics from the University of Durham, UK, to improve upon the methodology of Murphy et al (2004) for generating probabilistic climate change predictions from medium-sized ensembles of climate change simulations. The method of Murphy et al (2004) has been shown by Rougier (2004) to fit reasonably well into the more general Bayesian methodology of Goldstein and Rougier (2005). In the Bayesian framework a joint probability distribution is generated that measures the probability of all combinations of values for all uncertain objects in a problem. Key components are; ensembles of complex model simulations in which key parameters are varied, an *emulator* which uses statistical and reduced-complexity physical models to generate pseudo-ensemble members in unsampled regions of model parameter space, and a *discrepancy* term which is intended to account for systematic imperfections in the climate model from approximations, missing processes and "structural" uncertainty, i.e. fundamental deficiencies in the way models represent physical processes. It is intended to develop methods of estimating this term by using results from perturbed parameter ensembles to predict the results of other climate models containing alternative structural assumptions. The discrepancy term has not, to date, been considered in climate predictions for any time horizon, and although this work is focussed on centennial-scale predictions it may also be of use in seasonal-decadal prediction.

In a largely methodological paper, the Oxford ENSEMBLES team addressed the issue of the role of prior assumptions in probabilistic climate forecasts (Frame et al, 2005). A key determinant of future climate change is the climate sensitivity, or equilibrium warming in response to a doubling of CO<sub>2</sub>. As an alternative to using the spread of results from climate models or surveys of expert opinion, several studies have attempted to constrain climate sensitivity with a combination of models of varying complexity and recent observations. All have failed to eliminate a high upper bound which, when used in forecasts of 21<sup>st</sup> century climate change, assigns a high probability to relatively rapid warming. We showed that assumptions made in most papers about the prior distribution of climate sensitivity have a strong influence on the range found for its posterior distribution; equally defensible assumptions give very different results. The impact of these arbitrary assumptions can, however, be substantially reduced by considering their implications for observable climate variables, such as the warming attributable to greenhouse gases over the 20th century. In the absence of non-linear climate change, this yields an objective, observationally constrained 5-95% range for climate sensitivity of 1.2-5.7K.

In Piani et al (2005), the *climateprediction.net* ensemble is used to search for constraints on the response to increasing greenhouse gas levels among present day observable climate variables. The search is conducted with a systematic statistical methodology to identify

correlations between observables and the quantities we wish to predict, namely the climate sensitivity and the climate feedback parameter. A predictor of climate sensitivity and the feedback parameter (defined here simply as the inverse of climate sensitivity) is sought among the variables of the 8yr mean control climate for which we have available observational and reanalysis data sets. The focus is on linear predictors to simplify the methodology and minimize the risk of over fitting, but a natural generalization in future work would be to relax the linearity condition. Allowing for correlations between these observable quantities improves the accuracy of the uncertainty analysis. Following the practice of climate change detection studies, we assume the correlation structure of model-data discrepancies can be modelled by internal climate variability, so we begin by projecting both observations and members of the *climateprediction.net* ensemble onto EOFs of 8-year mean climate of the HadCM3 coupled model, with individual variables within these EOFs weighted by the inverse of the globally averaged standard deviation of HadCM3 climate variability. We then find linear combinations of these EOFs (“rotated” or REOFs) such that, when members of the *climateprediction.net* ensemble are projected onto them, the resulting projections are uncorrelated with each other. We assume the quantities we wish to estimate (climate sensitivity and the feedback parameter) can be predicted by a simple linear model. Using this method our best estimate of climate sensitivity is 3.3 K. When an internally consistent representation of the origins of model-data discrepancy is used to calculate the probability density function of climate sensitivity, the 5th and 95th percentiles are 2.2 K and 6.8 K respectively. These results are sensitive, particularly the upper bound, to the representation of the origins of model-data discrepancy.

The book chapter by Allen et al. (2005) focusses on how to quantify and minimise the cumulative effect of structural model imperfections (sometimes called model error) that result either from incomplete observations or understanding or cannot be eliminated because they are intrinsic to the structure of the model. The discussion focusses on minimising the effects of such “model error”. A fundamental issue is the lack of a universal objective metric or norm for model error: expert judgement is required in deciding how to measure the distance between two models or model-versions in terms of their input parameters or structure. Hence, any method of allowing for model error by sampling the space of “all possible models” would require a subjective judgement in deciding how to measure distance within this space. In weather forecasting, model forecasts can be independently verified and falsified by the real world. In climate forecasts – of 2100 temperature for instance – this is not the case. The lack of a falsification/verification procedure presents a problem in determining the relative credibility of different methods, several of which have recently appeared in the literature. However, it does not necessarily follow that we need to treat all forecasts as having equal status. Allen et al argue that an appropriate test is whether or not a forecast is likely to have converged, in the sense that further developments in modelling (increasing model resolution, or including different parameterisations) are unlikely to result in a substantial revision of the estimated distribution of the forecast variable in question. Under this philosophy, the aim is to render model error as irrelevant as possible, by ensuring that our forecasts depend on data and on the constraints that all physically conceivable models share, rather than on any specific set of models. Such “STable Inferences from Data (STAID) will not change except through the painstaking acquisition and incorporation of new data. Allen et al lay out a methodology for STAID probabilistic forecasting by looking for convergent results across nested ensembles.

The Bayesian approach being developed at the Hadley Centre differs somewhat in philosophy from the STAID approach. While it will give results which (like STAID) are influenced by observational constraints and uncertainties similar to those captured in Piani et al (2005), it is being designed to place greater weight on the spread of outcomes obtained by varying physical parameterisations in GCM ensemble runs according to expert-specified distributions, and will be more dependent on estimates of model error, hence allowing scope for the uncertainty range to narrow in future as model physics improves. The availability of these complementary approaches will place the ENSEMBLES project in the strong position of

being able to assess the dependence of the predicted changes on two plausible, but distinct, methodologies.

So far, the Hadley Centre has placed most effort into the emulation component of their Bayesian methodology. The ensemble in Murphy et al (2004), which perturbed parameters one at a time, has been augmented in two stages. First, a new 128-member ensemble was produced, based on multiple parameter perturbations designed to a) sample the range of climate sensitivity among model versions that were predicted to simulate the present-day climate reasonably well, and b) fill the parameter space efficiently (Webb et al, 2005). Second, emulators have been developed for several regional and global mean variables based on these two ensembles. Subsequently, the ensemble size is gradually being extended so that the emulators better represent the interactions between pairs of parameters.

In Rougier et al (in preparation), the complementary strengths of the Hadley Centre and *climateprediction.net* HadSM3 experiments have been exploited to provide a better probabilistic prediction of climate sensitivity. The prediction is prior to any weighting by observational constraints and, therefore, can be seen as an indication of the uncertainty in family of HadAM3 models. The prediction is done in two stages. First, the *climateprediction.net* ensemble from Stainforth et al (2005), which is a comprehensive and systematic exploration of how 6 parameters affect sensitivity, is used to build a Bayesian regression model with no prior information. This stage identifies the main effects plus important 2-way and 3-way interactions of the six parameters and estimate their magnitudes. This provides prior information for a Bayesian regression model based on data from the Hadley Centre experiment which explores 29 parameters using an experimental design that fills parameter space more efficiently but less systematically. The other advantage of this method is that it provides a means of combining two different estimates of climate sensitivity (*climateprediction.net* estimate sensitivity from 15-year runs whilst the Hadley Centre estimate it once the run has equilibrated).

Emulation has also been extended so that time-dependent probability distributions can be generated in the future once the emulators of equilibrium response have been finalised. Large ensembles of General Circulation Model (GCM) simulations with coupling to a dynamic ocean are required to explore modelling uncertainty and make probabilistic predictions of future transient climate change at regional scales. It is not yet computationally feasible to produce these so Harris et al (2005) have developed a technique to emulate the response of an ensemble of fully-coupled GCM simulations by scaling equilibrium patterns of climate change derived from much cheaper ensembles of GCMs coupled to a mixed-layer (slab) ocean. Climate feedback parameters are diagnosed for each slab member and used to drive an Energy Balance Model (EBM) to predict the time series of the global surface temperature anomaly expected for different parameter combinations in the atmospheric, land and sea-ice components of the model. The EBM projections are then used to scale normalised patterns of change derived for each slab member to emulate the GCM response when coupled to a dynamic ocean. Predictions made using the pattern scaling technique are validated by comparison with predictions from a small ensemble of fully-coupled GCM simulations using the same parameter combinations, and applying the same forcing scenario to the EBM as the GCM. Cross-validation permits an estimation of the spatial and temporal dependence of prediction error, and also allows estimation of a correction field to correct discrepancies between the scaled equilibrium patterns and the transient response, reducing the emulation error. The emulated responses and prediction error are then combined to produce transient regional frequency distributions. For example, Fig.1 shows the emulated transient uncertainty for Northern Europe winter precipitation with a 1% per annum increase in CO<sub>2</sub> concentration, for 129 multiple physics parameter perturbations of the model. The emulation technique has been validated for temperature and precipitation, although it can be applied to any surface climate variable that demonstrates a scaleable, approximately linear response to forcing.

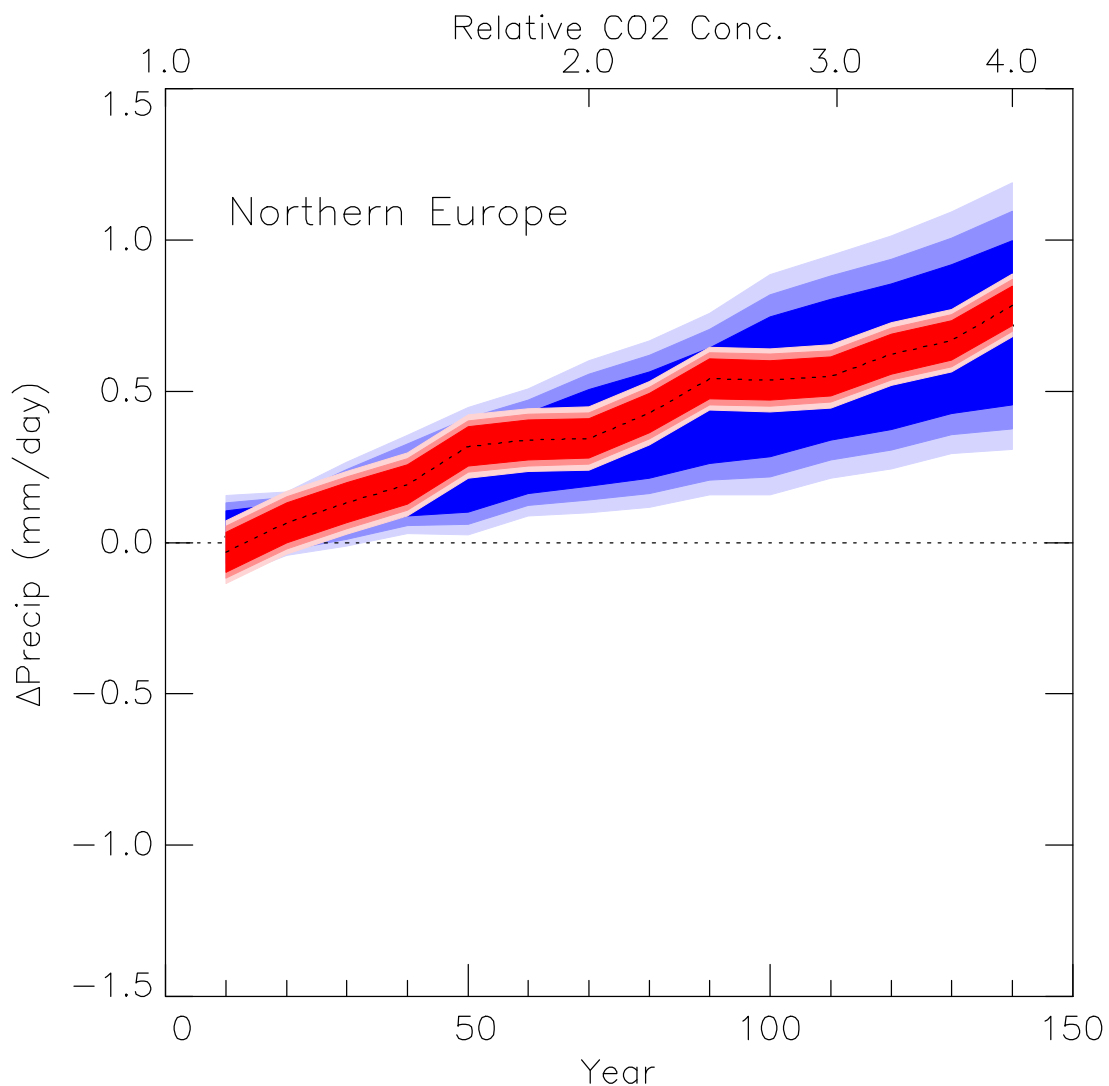


Figure 1. Uncertainty in winter precipitation changes (blue plume) over North Europe for a scenario where CO<sub>2</sub> concentrations increase by 1% per year. Each time slice is a frequency distribution estimate using the method of Harris et al (2005). The red plume indicates the uncertainty for the standard HadSM3 run to indicate the relative magnitude of modelling uncertainty and internal variability. Dark, medium and light shading indicate 80%, 90% and 95% confidence intervals.

To date, large perturbed parameter ensembles have been carried out only with the HadSM3 model. However, progress has been made towards investigation of modelling uncertainties in the EGMAM-model, by testing different values in the cloud parameterisation. This was preliminary work for a detailed sensitivity test of time-dependent climate change to parameter perturbations, which has now started.

1. Investigation of the possibilities to implement existing perturbed-physics schemes for the EGMAM model was made in cooperation with ENSEMBLES project partners in order to generate ensembles of perturbed physics model runs.
2. A full ensemble of 20<sup>th</sup> century simulations (natural experiment, GHG experiment, solar experiment, volcanic experiment, all forcings experiment, 3 simulations each) was created with the ECHO-G model (FUB in RT2A.2). Initial conditions were taken from a long historical simulation (ERIK). (For more information see FUB contributions in RT2A.2) These simulations were used to develop initial schemes to represent model uncertainties.

Analysis was performed on global and regional scales. On the global scale, simulations within one experiment are characterised by a comparably small spread. There is a notable signal-to-noise ratio with respect to the GHG and volcanic forcings. At regional scales the focus was on the North Atlantic/European sector, investigating to what extent typical patterns of atmospheric circulation variability are affected by the different (oceanic) initial conditions. We find a very robust 1<sup>st</sup> and 2<sup>nd</sup> EOF pattern representing the NAO and a blocking situation.

### Seasonal to Decadal prediction

Progress towards designing a new multi-model ensemble for seasonal-to-decadal ensemble prediction has been achieved. The models contributing to this multi-model exercise are IFS/HOPE and IFS/OPA (ECMWF), GloSea and DePreSys (Met Office), ARPEGE/OPA (Meteo-France and CERFACS), ECHAM5/MPI-OM1 (IfM). Most of these models are updates of those used in the DEMETER experiment (Palmer et al. 2004), especially concerning the atmospheric components. Furthermore, GHG, volcanic, solar and aerosol forcings have been included in most of them. It is expected that the improvement of some individual models will benefit the forecast quality of the multi-model predictions. In addition, a new stochastic physics backscatter scheme has been developed at ECMWF to account for uncertainty arising from the stochastic effects of sub grid scale processes (Palmer et al. 2005). The system, initially tested for medium-range ensemble forecasts, is currently undergoing a set of preliminary tests in seasonal forecast mode. In principle, this system will also be relevant to climate prediction on interannual to decadal and longer time scales.

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### c) Deviations from the project work programme and corrective actions

There have been changes in the personnel of the FUB. One person assigned to contribute to ENSEMBLES has left the institute and will be replaced in September. One PhD student was employed in March 05. To support the progress of the modelling experiments one part time scientist was hired also in March 05.