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Using ensemble prediction methods to examine regional climate variation under global warming scenarios

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Abstract

The fate of the North Atlantic thermohaline circulation (THC) is of great significance for regional climate prediction. Research based on both numerical modelling and paleoclimate data has suggested that the THC might be intrinsically bistable, and could have the potential to switch rapidly between its stable modes. Using a low-resolution intermediate complexity model, we investigate the predictability of the response of the THC to anthropogenic forcing in the medium (100 years) and longer term. Using an ensemble Kalman filter we can efficiently tune the climate of ensemble members by varying multiple parameters simultaneously, and flux adjustments are not required to prevent unreasonable model drift. However, some biases remain, and we demonstrate that the common approach of subtracting the bias from a model forecast can result in substantial errors when the model state is close to a nonlinear threshold. Over 100 years of 1% per annum atmospheric CO_2 enrichment, the THC drops significantly but steadily by about 4 or 5 Sv, a result that appears robust over a wide range of scenarios. In the longer term, the THC can collapse entirely, or recover to its original state, and small changes in the present uncertainties can have a large effect on the future outcomes. We conclude that generating reliable forecasts over the next century should be achievable, but the long term behaviour remains highly unpredictable.

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1. Introduction

The climate of north–west Europe is strongly affected by the substantial northward transport of heat by the thermohaline circulation (THC) in the Atlantic Ocean, which is estimated to carry about 1.3 PW of heat northwards across the 25°N latitude line (Ganachaud and Wunsch, 2000). However, numerical modelling experiments (e.g. Manabe and Stouffer, 1988) suggest that this mode of ocean circulation is not unique, and that there is an alternative mode with much weaker THC which carries less heat, leading to a regional cooling of as much as 8 °C (Vellinga and Wood, 2002). Furthermore, paleoclimate records indicate that there have been rapid transitions between warm and cold conditions during both Dansgaard–Oeschger (Dansgaard et al., 1993) and Heinrich (Heinrich, 1988) events, and modelling shows that similar transitions can be triggered by changes in freshwater fluxes (Ganopolski and Rahmstorf, 2001).

It has been suggested that the anthropogenic forcing of the Earth's climate could generate changes in the strength of the THC, both through thermal forcing and from the resulting changes in the hydrological cycle. Experiments with some simpler models suggest that the THC could switch off in the longer term (Rahmstorf and Ganopolski, 1999) although other models indicate an initial drop followed by recovery even if atmospheric CO_2 levels are stabilised at 4× the present day value (Stouffer and Manabe, 2003).

Most projections of anthropogenically-forced climate change using more sophisticated models also show a reduction in the THC over the next 100 years, but there is a large range of uncertainty on these results, with the summary of results presented in the IPCC TAR ranging from a small increase to a decrease of more than 10 Sv over the next 100 years (Cubasch et al., 2001, Section 9.3.4.3). Although all of the model results presented there showed regional warming over that time interval, the rate of warming over NW Europe can be expected to depend heavily on any changes in the THC.

The research presented in the IPCC TAR is effectively an 'ensemble of opportunity', a compilation of integrations using a range of different models and scenarios. Therefore, it cannot be interpreted as a true probabilistic prediction, but merely a selection of scenarios which may cover only part of the range of possible outcomes and which provides no information as to their relative likelihoods. Recent developments in parameter estimation have now opened up the possibility of performing ensemble integrations of models which have been objectively tuned to climate observations, and which therefore have the potential to generate more meaningful probabilistic estimates of future climate.

Tuning the climate of a numerical model is a nonlinear multivariate parameter estimation problem, which has for some time been considered a rather intractable task. Early approaches to this problem have mostly been based around randomised or exhaustive multifactorial sampling of the multivariate parameter distribution (Forest et al., 2000; Knutti et al., 2002), but the cost of these methods is exponential in the number of parameters which are covaried, so they have limited practicality. The Ensemble Kalman filter (EnKF) Evensen (1994) has recently been developed applied to parameter estimation in climate models (Annan et al., 2004; Hargreaves