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Using GENIE to study a tipping point in the climate system

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We have used the Grid ENabled Integrated Earth system modelling framework to study the archetypal example of a tipping point in the climate system; a threshold for the collapse of the Atlantic thermohaline circulation (THC). eScience has been invaluable in this work and we explain how we have made it work for us. Two stable states of the THC have been found to coexist, under the same boundary conditions, in a hierarchy of models. The climate forcing required to collapse the THC and the reversibility or irreversibility of such a collapse depends on uncertain model parameters. Automated methods have been used to assimilate observational data to constrain the pertinent parameters. Anthropogenic climate forcing leads to a robust weakening of the THC and increases the probability of crossing a THC tipping point, but some ensemble members collapse readily, whereas others are extremely resistant. Hence, we test general methods that have been developed to directly diagnose, from time-series data, the proximity of a 'tipping element', such as the THC to a bifurcation point. In a three-dimensional ocean–atmosphere model exhibiting THC hysteresis, despite high variability in the THC driven by the dynamical atmosphere, some early warning of an approaching tipping point appears possible.

Keywords: eScience; Earth system modelling; climate change; Atlantic thermohaline circulation; tipping point; early warning

1. Introduction

The phrase 'tipping point' captures the intuitive notion that, for some systems under particular conditions, a small nudge or perturbation can make a big difference to their future state. A more rigorous definition, applicable to climate (Lenton *et al.* 2008), introduces the concept of 'tipping elements': those

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components of the climate system, at least subcontinental in scale, that—under particular conditions—can be switched into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point, in forcing and a feature of the system, at which the future state of the system is qualitatively altered. This deliberately broad definition encompasses a range of nonlinear responses, including both equilibrium properties (e.g. bifurcations) and critical rates of forcing. It also encompasses rapid (decadal or less), gradual (centennial) and slow (millennial time scale) transitions.

The archetypal example of a tipping element in the climate system is the Atlantic Ocean circulation, which may pass a tipping point involving the collapse of North Atlantic Deep Water (NADW) formation and the associated thermohaline circulation (THC). Ice-core records of climate change in Greenland during the last ice age reveal rapid climate change events that are frequently attributed to the crossing of thresholds and consequent transitions in the Atlantic THC. The truth is almost certainly more complex, with changes in the sea-ice cover and atmospheric circulation probably also involved and both potentially exhibiting thresholds. Nonetheless, the THC provides a useful case study of a tipping element because theory suggests that it should exhibit multiple bifurcation points (Dijkstra & Ghil 2005).

Recognition that there are two stable regimes of flow for the THC (figure 1) dates back to the classic conceptual model of Stommel (1961). This has a region of bistability where both THC 'on' and 'off' states are stable for a range of boundary conditions. Under sufficient freshwater forcing of the North Atlantic, a bifurcation point is reached where the 'on' state disappears and the THC inevitably switches off, through an advective spindown that takes the order of a century. As freshwater forcing is reduced, the circulation remains 'off' until a second bifurcation point is reached, where the off state disappears and the THC inevitably switches on. This produces the following three regimes for the THC as a function of climate boundary conditions: (i) only the on state is stable, (ii) both the on and off states are bistable, and (iii) only the off state is stable. In either regime (i) or (ii), the THC can be switched off rapidly (within a decade), by adding sufficient freshwater to the regions of NADW formation to halt convection. However, once the perturbation is removed, in (i) the THC will recover, whereas in (ii) it will remain off. This schematic (figure 1) of bifurcation points and hysteresis in the THC is supported by the results of a range of intermediate complexity models (Rahmstorf *et al.* 2005). However, the most complex coupled ocean–atmosphere general circulation models (OAGCMs) have, up to now, not been systematically tested due to excessive computational cost.

Numerous future projections of the THC have been undertaken with disparate results. Most models agree on a general weakening of the THC under anthropogenic climate change (Gregory *et al.* 2005), but whether the THC collapses, and under what magnitude of freshwater forcing, varies widely between models and (as we will discuss) within ensembles of a given model. The proximity of the initial climate state to a THC tipping point, ranges in models over 0.1–0.5 Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m}^3\,\mathrm{s}^{-1}$) additional North Atlantic freshwater input (Rahmstorf *et al.* 2005). The extent of future global warming and its relationship with the net freshwater balance of the North Atlantic are also critically uncertain. Freshwater input to the North Atlantic has already increased by at least 0.026 Sv (Lenton *et al.* 2008), equivalent to shifting the system state

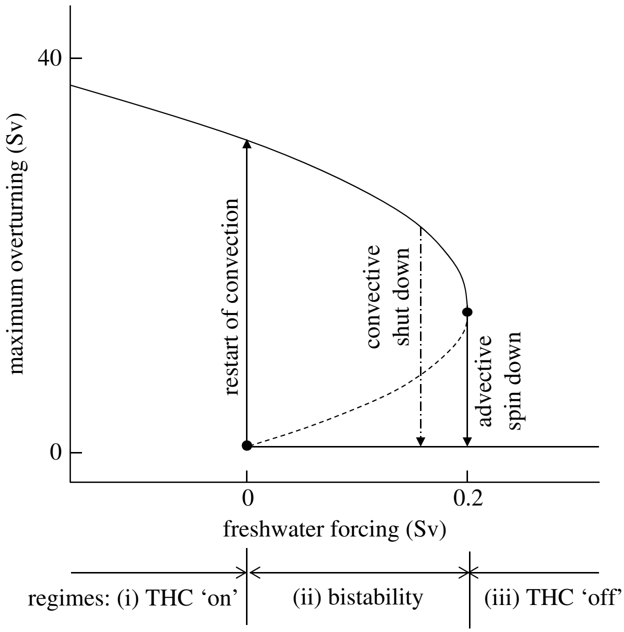

Figure 1. Schematic of states and transitions of the Atlantic THC, based on Stommel (1961) and Rahmstorf *et al.* (2005). When freshwater is added to or removed from the northern North Atlantic (x-axis), this affects the strength of the Atlantic meridional overturning circulation (y-axis), which can also depend on its initial state (bistability). Numbers are purely illustrative. Solid lines indicate 'on' and 'off' stable states of the THC, dashed curve indicates an unstable state. Black dots indicate bifurcation points and solid arrows (from them) indicate inevitable THC transitions. The dot-dashed downward arrow illustrates a THC transition forced before bifurcation, potentially by stochastic noise pushing the system past the unstable state and into the stable 'off' state.

slightly to the right in figure 1. In the future, predicted increases in regional precipitation are likely to make the dominant contribution to freshwater forcing, but if the Greenland ice sheet melts over the next millennium this will contribute 0.1 Sv. Working Group 1 of the Intergovernmental Panel of Climate Change (IPCC 2007) recently gave a low (less than 10%) probability of collapse in the THC this century. This reflects the behaviour of the latest generation of fully coupled OAGCMs, and the apparent stability of the THC during the pre-industrial Holocene. However, most 'state-of-the-art' models have only been subjectively tuned (to achieve, for example, a reasonable present strength of the THC) and have not been systematically constrained by the available data, or their ability to simulate, for example, past climate states.

2. The GENIE framework and eScience tools

The THC is a system with uncertain thresholds, of uncertain proximity, being approached at an uncertain rate. As such, it makes a good case study for the use of eScience tools and methods. The Grid ENabled Integrated Earth (GENIE) system modelling framework (Lenton *et al.* 2008) provides new component modules (Edwards & Marsh 2005; Lenton *et al.* 2006, 2007), facilitates the flexible construction of alternative Earth system models (Lenton *et al.* 2007; Armstrong *et al.* in press), provides advanced and automated methods of constraining model parameter values with the available data (Price *et al.* 2006*a*,*b*), enables large ensemble studies on the Grid (Marsh *et al.* 2004; Price *et al.* 2006*a*; Lenton *et al.* 2007; Fairman *et al.* 2008), supports complex workflows (Fairman *et al.* 2008) and provides Grid-based data handling and post-processing facilities (Price *et al.* 2006*a*).

GENIE has adapted the software developed by the Geodise project (Eres *et al.* 2005) to build a Grid-enabled problem-solving environment. The Geodise toolboxes integrate compute and data Grid functionality into the MATLAB and JYTHON environments familiar to scientists and engineers. In particular, the Geodise Compute toolbox provides an interface to the computational Grid through functions that invoke classes in the Java CoG v. 1.2 (von Laszewski *et al.* 2001). These functions allow a user to submit compute jobs to the Grid, transfer files using GRIDFTP and monitor jobs and resources. Model configuration metadata can be loaded into the environment and modified with ease. The user is able to submit simulations to a wide range of heterogeneous compute resource through a single function call.

GENIE has been built upon the Geodise data management platform to provide a Grid-enabled distributed file and data archive. The system enables users to annotate their data with rich descriptive metadata in the form of XML. The system exploits the ORACLE 10G XML database to support storage, query and retrieval of XML instance documents. The strength of the system is that the user-defined metadata can be associated with the data files to enable much richer description of the data. Thus, more powerful data processing applications can be built. Through careful design of an XML Schema, the database provides efficient and extensible storage. As GENIE models evolve, the database keeps pace without the need for administrative intervention (the creation or modification of database tables and columns).

Within GENIE, we have developed a large number of scripted workflows that orchestrate, compute and database activities to enable different types of study. One key example is parameter estimation. Whenever a new model is coupled together, a retuning is usually required. As with many design problems, the nonlinear response of a model to its parameters and the often conflicting tuning targets make this a difficult problem to solve. We use a multi-objective optimization algorithm, which involves the iterative evaluation of response surface models (RSMs) followed by the execution of multiple Earth system simulations. These computations require an infrastructure that provides high-performance computing (HPC) for building and searching the RSMs (typically HPC clusters) and high-throughput computing (typically CONDOR) for the concurrent evaluation of a large number of models. Grid computing technology is essential to make this algorithm practical for the users.

A second key type of workflow is the collaborative study of large ensemble simulations. Users upload experiment definitions into the database and specify the parameters and boundary conditions of the simulations that need to be carried out to generate the results. Members of the project can progress the simulations to completion via a series of checkpoints and restarts of the long-running models. While the experiment is incomplete, users retrieve intermediate restart files from the database and submit simulations to compute resource, uploading the results upon completion. Since users are free to contribute resource at any time, the system proves to be a scalable means of pooling resource across multiple institutions.

While the scripting approach proves an accessible means of providing scientists with powerful core functionality for model management on the Grid, there are significant limitations to the nature of the workflows that can be expressed and the robustness with which they can be executed in the MATLAB environment over long periods of time. To provide a robust hosting environment and improve the efficiency with which large ensemble studies can be performed, we have recently applied MICROSOFT WINDOWS WORKFLOW FOUNDATION (WF; Fairman *et al.* 2008).

To establish the existence (or not) of THC thresholds, we have made use of the ability to construct and tune a traceable hierarchy of Earth system models and undertake systematic searches of their parameter space. To make robust future projections, we have used the tools to rigorously handle uncertainties and try to constrain them by using available data. The THC studies described herein only use a subset of the available GENIE modules and couple them using our standard architecture. Other science components (see Lenton *et al.* 2006, 2007) and a more flexible approach to coupling them (Armstrong *et al.* in press) are described elsewhere.

3. Establishing the existence of a THC tipping point

First, we sought to establish whether the THC tipping points exist in coupled ocean–atmosphere models and, if so, map out where they lie in model parameter space. Our rationale has been to search for bistability of the THC, as this is a sufficient condition for the existence of bifurcation points. Two families of the GENIE model have been used: (i) GENIE-1 (Lenton *et al.* 2006) built on C-GOLDSTEIN (Edwards & Marsh 2005), which includes the three-dimensional frictional geostrophic ocean model GOLDSTEIN coupled to a two-dimensional, single layer, energy-moisture balance atmosphere model, and two-dimensional dynamic and thermodynamic sea ice and (ii) GENIE-2 (Lenton *et al.* 2007), which couples GOLDSTEIN to a three-dimensional full primitive equation atmospheric general circulation model (the Reading intermediate general circulation model (IGCM) 3.1), and two-dimensional thermodynamic (slab) sea ice. In both the cases, a variety of ocean and atmosphere resolutions are available. We adopted a three-dimensional ocean model as standard in GENIE, to try and advance over some previous intermediate complexity models that use two-dimensional representations of the Atlantic, Indian and Pacific Ocean basins. As with most dynamical ocean models, GOLDSTEIN alone exhibits THC bifurcations (Edwards & Shepherd 2002).

Marsh *et al.* (2004) searched for bistability in the coupled C-GOLDSTEIN model by systematically varying parameters controlling atmospheric moisture transport from the Atlantic to the Pacific and from equatorial regions to high latitudes. The original simulations were launched through a web portal and the output was handled using an early version of our Grid-based data management system (Gulamali *et al.* 2003). Over 40 million model years were simulated using distributed computing resources, specifically the ‘flocking’ together of three

Condor pools across the Grid. The results showed a relatively narrow region of bistability for the Atlantic THC. Subsequently, performance-guided scheduling was introduced to improve the throughput of simulations in such large ensembles. Recently, a search of the same parameter space has been undertaken using GENIE-1 with an ocean–atmosphere carbon cycle, improved ocean convection scheme and higher vertical resolution in the ocean. A non-dominated sorting genetic algorithm (NSGA2) multi-objective optimization method (Price *et al.* 2006*b*) was used to tune 12 model physical parameters towards ocean temperature, salinity, surface atmospheric temperature and humidity data, and eight biogeochemical parameters towards ocean phosphate and alkalinity data. Windows WF provided a robust environment for managing the ensemble simulations (Fairman *et al.* 2008). Increased ocean vertical resolution was found to narrow the region of THC bistability, whereas the feedback from interactive carbon dioxide acts to broaden it slightly.

Recently, Yin *et al.* (2006) suggested that the THC threshold behaviour may disappear due to coupling a fully dynamical three-dimensional atmosphere to a three-dimensional ocean. However, their methods, with relatively short integrations and flux correction towards the present state, may have qualitatively influenced the results. Theory would suggest that 'noise' from the atmosphere may blur the bifurcation structure of the ocean, but not remove it (M. Ghil 2007, personal communication). To convincingly assess the effects of a dynamical atmosphere on the THC demands multiple long integrations. However, coupled models with a dynamical atmosphere are much more computationally demanding than those without. In our case, a 1000-year integration of GENIE-2 takes approximately 100 CPU hours in contrast to 1 CPU hour with GENIE-1.

Hence, we turned again to eScience to undertake a systematic search for THC bistability in GENIE-2 with different ocean resolutions (Lenton *et al.* 2007). Our Grid-enabled problem-solving environment was used to tune 30 physical parameters of the dynamical atmosphere model towards the climate data for surface fluxes using a genetic algorithm (Price *et al.* 2006*a*), and then to set up and execute the ensemble simulations and process the results. In total, 428 000 model years were simulated, using distributed computing resources, including five nodes of the National Grid Service, three institutional clusters and one Condor pool. The study took a total of three months, including the inevitable quiet phases of preparation, assimilating early results and designing further experiments. These were interspersed by bursts of concentrated computation, where the use of distributed computing peaked at approximately 100 CPU days per day. All versions of GENIE-2 were found to exhibit bistability of the THC and, contrary to existing results (Yin *et al.* 2006), feedbacks from the atmosphere were found to extend the region of bistability. The width and position of the region of bistability also varied considerably with changes in ocean resolution.

Here, we present some new results, from a conventional hysteresis experiment with GENIE-2, where a flux of freshwater to the Atlantic in the region 50–70° N is progressively increased and then decreased at a slow rate of 0.05 Sv kyr^{-1} (as in Rahmstorf *et al.* 2005). We use a $64\times32\times8$ resolution ocean that matches the surface grid of the IGCM (and hence does not require flux corrections associated with interpolation). Parameter settings are as in Lenton *et al.* (2007) and the model is the ensemble member with the Atlantic-to-Pacific freshwater flux at

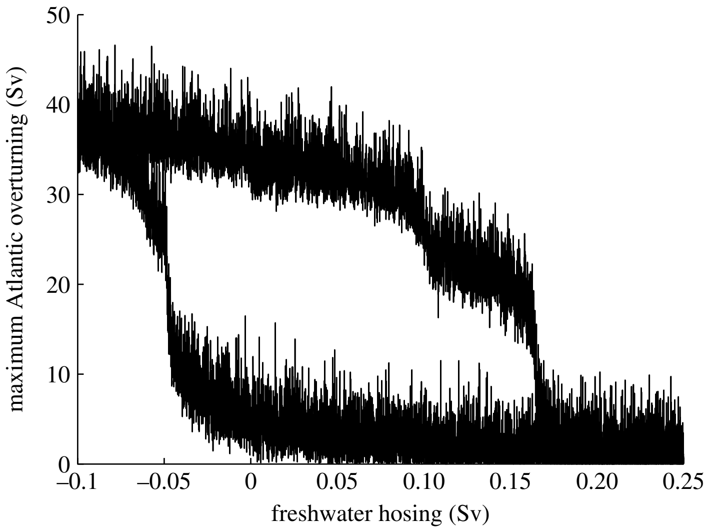

Figure 2. GENIE-2 hysteresis loop obtained by applying a flux of freshwater to the Atlantic in the region 50–70° N, which is progressively increased and then decreased at a slow rate of 0.05 Sv kyr^{-1}. The version of GENIE-2 used couples the GOLDSTEIN ocean at 64×32×8 resolution (with a longitude–latitude surface grid) to the IGCM atmosphere (T21 resolution, seven vertical levels) and thermodynamic (slab) sea ice. Parameter settings are as in Lenton *et al.* (2007) and the model is the ensemble member with the Atlantic-to-Pacific freshwater flux at 50% of its default value.

50 per cent of its default value. This places it just inside the bistable regime near the monostable 'on' regime. GENIE-2 exhibits THC hysteresis (figure 2), further confirming that there are THC bifurcation points in this OAGCM. Interestingly, there is also a step slowdown in the THC when the forcing reaches approximately 0.10 Sv, preceding a full THC collapse at approximately 0.17 Sv. As the forcing is reduced, the THC does not switch back on until it reaches approximately −0.05 Sv. A high level of inter-annual variability in THC strength is apparent, due to weather noise from the dynamical atmosphere, but this does not remove the threshold behaviour.

Having established the existence of THC bistability and corresponding thresholds in both reduced dimensionality and fully three-dimensional coupled models, a pertinent question becomes whether (and at what point) future anthropogenic forcing could cause a THC threshold to be crossed?

4. Assessing the vulnerability of the THC to future forcing

In model worlds, there is a clear connection between the location of the initial climate state, within or relative to the region of bistability, and its vulnerability to perturbation, e.g. of the freshwater balance of the North Atlantic. In either GENIE-1 (Marsh *et al.* 2004; Fairman *et al.* 2008) or GENIE-2 (Lenton *et al.* 2007), the ensemble members in the bistable regime that are closer to the bifurcation to the monostable 'off' regime need less freshwater perturbation (e.g. 0.1 Sv over 100 years) to induce a collapse of the THC. The THC collapses in the bistable regime are irreversible because the THC switches to the stable off state.

However, as in other model studies (Stouffer *et al.* 2006), even ensemble members in the monostable on regime can be forced into a THC collapse with large freshwater hosing fluxes (e.g. sustained 1 Sv). Such collapses are reversible once the forcing is removed—the THC reverts to the stable on state—but they highlight that a tipping point for NADW formation is a ubiquitous feature of models and is independent of whether a particular model exhibits hysteresis (Lenton *et al.* 2008).

Statements by the IPCC (2007) that a THC collapse this century is 'very unlikely' (meaning less than 10% probability) are based, at least in part, on runs with full OAGCMs that each typically have just one, subjectively chosen, parameter set. They also lack a potentially significant source of freshwater from Greenland ice sheet melt. Although none of those runs (IPCC 2007, p. 773) show a THC collapse this century, a subsequent more complete Earth system model does (Mikolajewicz *et al.* 2007). To try and better constrain the vulnerability of the THC to anthropogenic forcing, GENIE team members have pioneered the use of advanced methods of model calibration using the available data.

In a series of studies (Hargreaves *et al.* 2004; Annan *et al.* 2005; Hargreaves & Annan 2006), an ensemble Kalman filter (EnKF) and the data for ocean temperature and salinity and atmospheric surface temperature and humidity have been used to constrain 12 physical parameters of C-GOLDSTEIN. In each study, the posterior ensemble of 54 model versions represents the remaining joint uncertainty in the model and the data. On forcing a given ensemble forward with an idealized CO_2 trajectory, the THC behaviour typically diverges with some ensemble members collapsing irreversibly, some collapsing reversibly and some not collapsing at all (Hargreaves *et al.* 2004). When also assimilating limited data on the strength of the THC, this tends to increase the THC strength in the model and shift the ensemble away from a THC threshold (Hargreaves & Annan 2006). In a contribution to IPCC (2007), ensembles with different values of climate sensitivity were forced to different CO_2 stabilization levels (Plattner *et al.* 2008). For a mid-range climate sensitivity (3°C for a doubling of pre-industrial CO_2), all ensemble members show a transient THC weakening, but the majority (approx. 80%) are resistant to THC collapse even under stabilization at 1000 ppm CO_2 (D. Cameron 2008, personal communication). Introducing additional potential sources of freshwater (e.g. Greenland ice sheet melt) and thus producing more rapid movement in the direction of THC bifurcation leads to a greater fraction of the ensemble exhibiting THC collapse (Hargreaves & Annan 2006). The EnKF results suggest that the data and the model used are insufficient to fully constrain the long-term vulnerability of the THC to collapse; under a given forcing scenario, typically some ensemble members collapse and some do not. However, a century time-scale weakening of the THC is robustly predicted, and the error on this prediction is narrowed considerably by the model calibration with the data.

Ideally, THC vulnerability should be expressed in probabilistic terms, e.g. the likelihood of a THC weakening of a given amount at a given point in future forcing. An alternative Bayesian approach to this has been pursued by creating a statistical emulator of C-GOLDSTEIN, i.e. a simpler, faster representation of the response of the full model (Challenor *et al.* 2006). Constructing the emulator required many runs of the full model, making use of distributed computing. The emulator itself is computationally very cheap, allowing its probability density function to be precisely evaluated, even with relatively simple, e.g. Monte Carlo, sampling. Running ensembles forward under various CO_2 concentration scenarios and considering other uncertainties, a striking 30–40 per cent probability of a drop in Atlantic overturning below 5 Sv by 2100 was found. The discrepancy with the EnKF results may be partly a consequence of including higher values of climate sensitivity.

Both the rate and eventual magnitude of climate change are thought to be important for the fate of the THC, based on early model results showing that the rate of reaching a given CO_2 stabilization level could determine whether the THC collapsed or not (Stocker & Schmittner 1997). GENIE results tend to disagree, but they do show that the rate at which CO_2 levels recover after fossil fuel emissions cease affects the proportion of ensemble members in which the THC collapses (Hargreaves & Annan 2006). Ideally, THC vulnerability should be related to CO_2 emission trajectories rather than CO_2 concentration trajectories, as the former are the direct focus of mitigation efforts. To do this requires an Earth system model with a closed carbon cycle, e.g. GENIE-1. In initial results, the final change in THC strength on a millennial time scale was found to be independent of the rate at which a given amount of fossil fuel CO_2 was emitted (Lenton *et al.* 2006).

5. Testing methods for anticipating a tipping point

Existing results suggest that constraining the physical parameters of one of our models to best capture the recent climate state does not adequately constrain the proximity of the THC to a threshold. Ensemble members with a stronger initial THC are generally less vulnerable to THC collapse. However, there can still be ensemble members with a relatively strong initial THC that are vulnerable to eventual collapse (Hargreaves & Annan 2006). Hence, we have pursued other approaches in trying to establish the proximity of the THC to a threshold.

In general, a physical system that is approaching a bifurcation point will show characteristic behaviour in the spectral properties of its time-series data (e.g. Lenton *et al.* 2008). Picture the present state of the system as a ball in a curved potential well (attractor) that is being nudged around by some stochastic noise process, e.g. weather. The ball continually tends to roll back towards the bottom of the well—its lowest potential state—and the rate at which it rolls back is determined by the curvature of the potential well. The radius of the potential well is related to the longest immanent time scale in the system. As the system is forced towards a bifurcation point, the potential well becomes flatter (i.e. the longest immanent time scale increases). Consequently, the ball will roll back more sluggishly. It may also undertake larger excursions for a given nudge. At the bifurcation point, the potential well disappears and the potential becomes flat (i.e. the longest immanent time scale becomes infinite). At this point, the ball is destined to roll off into some other state (i.e. alternative potential well). Potentially useful diagnostics of an approaching bifurcation, in response to, for example, stochastic noise forcing are thus a slowing of the response time to perturbations, which can manifest as a shift to lower frequency variations and/or an increase in the amplitude of variability.

Such diagnostic changes have been observed in models approaching a tipping point. In a version of the Stommel (1961) model with stochastic forcing, as bifurcation is approached, there is a shift to both lower frequency fluctuations and increased amplitude at low frequencies (Kleinen *et al.* 2003). In GENIE-1, oscillations of the THC can arise as freshwater forcing is applied to an ensemble member close to the THC bifurcation point (Marsh *et al.* 2004), and they increase in amplitude and period as bifurcation is approached. In other THC models, stronger freshwater forcing results in lower frequency oscillations (Sakai & Peltier 1995) and bifurcation is preceded by increased amplitude of oscillations (Aeberhardt *et al.* 2000).

Held & Kleinen (2004) developed a method of extracting a trend in the longest immanent time scale by seeking to isolate its dynamics (averaging over shorter term variability) and examine its decay rate to perturbations (κ) using a simple lag-1 autocorrelation function (ACF). They show that the method works, in principle, in simulations with the CLIMBER-2 model subjected to stochastic freshwater forcing and slowly forced to cross a THC threshold. However, they note that it may require a long (Holocene) time series to establish the value of κ, especially as model-based estimates range over at least 10^{-1}–10^{-3} yr^{-1}. Livina & Lenton (2007) offer a variation on this method using detrended fluctuation analysis (DFA) to assess the proximity of a threshold from the power-law exponent describing correlations in the time-series data. At a critical threshold, the data become highly correlated across short- and middle-range time scales and the time series behaves as a random walk with uncorrelated steps. In simulations with GENIE-1 subject to different magnitudes of stochastic freshwater forcing and slowly forced to cross a THC threshold, the method shows a clear trend of increased correlation in the data as the threshold approaches. The method has the advantage of not demanding aggregation of the data, so a more sparse time series may be used, but it still needs to span a sufficient time interval to capture the (as yet poorly constrained) value of κ.

Attempts to anticipate a threshold should work best at low noise levels because a high level of noise can cause a system to transit between states well before a bifurcation point is reached (Kleinen *et al.* 2003). For a method of anticipating a threshold to be useful, the time it takes to find out proximity to a threshold and act to move the system away from it must be shorter than the time in which noise would be expected to cause the system to change state. That 'mean first exit time' is typically a sensitive function of the amplitude of noise and the proximity of the system to the bifurcation point (Kleinen *et al.* 2003).

The high level of THC variability driven by atmospheric noise in GENIE-2 should make it a tough test case for methods of anticipating a tipping point. Hence, we applied the methods to the forward branch of the hysteresis experiment (figure 2), which passes through a step slowdown of the THC and then a switch off (figure 3*a*). The 'ACF propagator' (figure 3*b*) shows a striking upward trend when the THC slowdown occurs (after year 4000), indicating a distinct slowing in the decay rate of perturbations and hence a flattening of the potential well. It then recovers (to year 5000) as the THC stabilizes, before going up sharply as THC collapse sets in, approaching a critical value of '1', which corresponds to infinitely slow decay and bifurcation—a flat potential. The 'DFA propagator' (figure 3*c*) appears less sensitive to the THC slowdown, but shows more of an early warning of THC collapse, with an upward trend in the propagator, indicating increasing correlations in the data. It also approaches a critical value of '1' after the THC

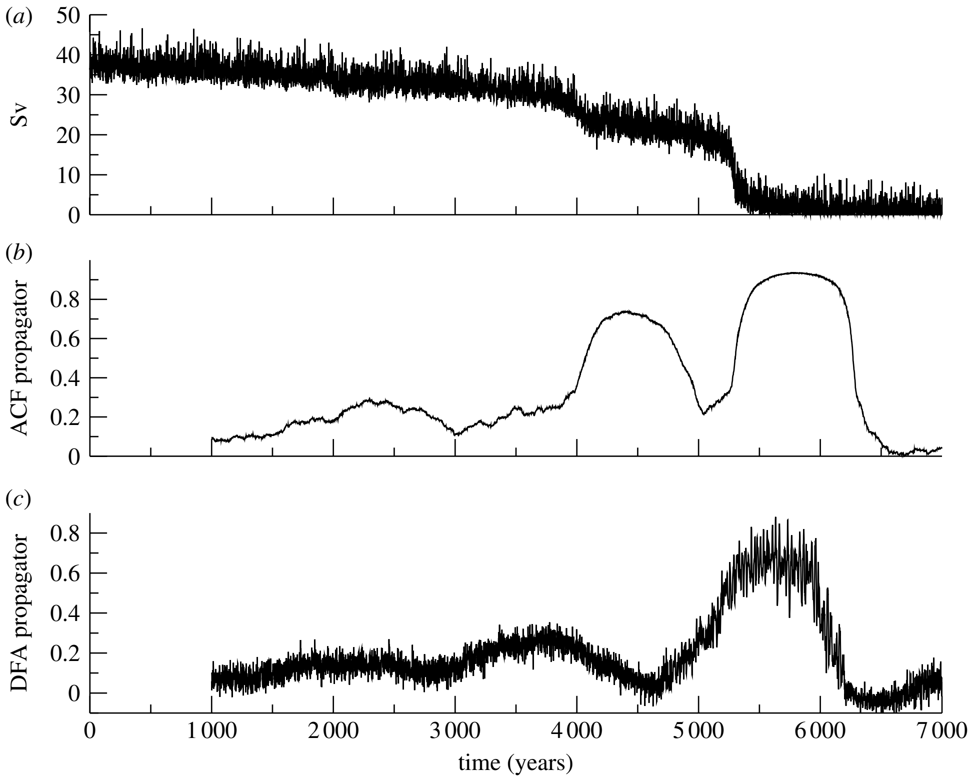

Figure 3. A test of methods to anticipate bifurcation using the forward branch of the GENIE-2 THC hysteresis loop (figure 2). Freshwater forcing starts at -0.1 Sv and increases at $0.05\ \mathrm{Sv\ kyr^{-1}}$ to 0.25 Sv, producing a step slowdown and then a collapse of the THC ((*a*) maximum Atlantic meridional overturning circulation). The annual data are not aggregated as this would leave too few points to work with. (*b*) The 'ACF propagator' is a measure of slowing decay rate of perturbations in the data and hence the flatness of the potential well. A critical value of '1' corresponds to infinitely slow decay and bifurcation—a flat potential. (*c*) The 'DFA propagator' is a measure of increasing correlations in the data, and the power-law exponent is re-scaled so that a value of '1' corresponds to criticality. A sliding window of length 1000 points is used in both the cases and the propagators are mapped to the fronts of the windows, so they are based on the past 1000 years of the THC data at any given time.

collapses. Both propagators are well below the critical value when THC collapse begins, consistent with the notion that noise triggers the transition before the bifurcation point is reached. Once the THC has collapsed, both methods recognize the discontinuity in the data as a near-critical value of the propagator.

6. Conclusion: use of eScience in early warning systems

Early results from direct monitoring of the Atlantic (e.g. at approx. 25° N) indicate that the real THC exhibits a high level of short-term variability in strength. Such noise could trigger the THC to collapse long before a bifurcation point is reached. However, our results with GENIE-2 (figure 3) offer some hope that, despite such a high level of noise, it may still be possible to get some useful indication of increasing vulnerability of the THC, if it approaches a tipping point. Unfortunately, there is another problem in that the longest immanent time scale in the ocean may be significantly longer than the likely interval of strong anthropogenic forcing of climate. Given this, if human activities can push the THC past a bifurcation point, the potential for seeing a reliable signature of the bifurcation before we reach it may be limited (Keller & McInerney 2007). There is also a fundamental need for longer, high-resolution records of Atlantic THC strength through the Holocene, in order to establish the distance of the background state of the THC from a bifurcation point. From careful analysis of such records, the resulting value of κ could then be assimilated in climate models to better constrain their THC state and thus give more reliable projections of future behaviour (Held & Kleinen 2004). Monitoring of the THC is still extremely valuable, in that it can help establish its present strength (a critical data constraint for models), its short-term modes of variability and, after a few decades, any net trend in THC strength.

Although the THC may be a particularly challenging case study for the design of a tipping point early warning system, it highlights the value of a combined approach of real-time monitoring, extracting key information from long historical time series and careful data assimilation into models that can simulate all relevant time scales and modes of variability. Some other potential tipping elements in the climate system (Lenton *et al.* 2008) involving atmospheric dynamics and coupling to the land surface have much shorter immanent time scales than the ocean, thus reducing the need for long palaeodata time series for the anticipation of thresholds. These systems, particularly the Indian summer monsoon and West African monsoon, are linked to food production and the livelihoods of many people, and should arguably be given priority attention. eScience has great potential to help in the design and deployment of tipping point early warning systems, in so far as it can aid (i) the construction and execution of a suitable hierarchy of models, (ii) the provision of near real-time data from distributed monitoring networks, and (iii) the realistic treatment of uncertainties and probabilities in the models (through large ensembles) and the assimilation of the data to constrain probabilistic forecasts.

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