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The Role of Stochastic Forcing in Climate Models: The Case of Thermohaline Circulation

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1. Introduction

At present both daily and seasonal weather forecasts as well as long-term climate predictions are the result of the implementation of multiple and complex numerical models. The history of numerical models to predict the weather goes back to the 1950s and 1960s and since then computational breakthroughs have enabled us to go from simple box models to complex models that take into account a multitude of phenomena and processes occurring in the whole climate system. However despite the great strides made in recent years and great experience in the development of such models we must interpret the results taking into account the limitations and uncertainties inherent in any numerical model.

Among the most challenging major constraints in developing a climate model, we can identify three potentially difficult to solve: The first is that the climate system by its nature presents a nonlinear chaotic behaviour, which makes a weather forecast of more than seven or nine days unpredictable. This behaviour is alluded to in the famous butterfly effect discovered by Edward Lorenz in 1963. The second problem facing the modelers is the number of simplifications and assumptions introduced in the models through what is known as parameterizations. The parameterizations simulate the behaviour of processes that due to either the temporal or spatial scales of the model cannot be solved. Finally the third problem that arises is that despite progress in recent years models are always limited to represent part of the climate system but not all. Many fluctuations due to complex processes or biological or chemical components are omitted. In this way, we can find processes that are not considered but have a relevant role in the outcome. An example of this has been the recent inclusion of sulfur aerosols in climate models. This improvement has allowed us to propose an explanation for the asymmetry of the climatic evolution in the two hemispheres in the context of climate change experienced in recent decades. The improvement of models are continuous, but there are many important processes of the global system not present in the actual models: sources and sinks of oceanic and continental carbon, cycle of methane, increment of tropospheric ozone, the role of organic and mineral aerosols, synoptic variability, etc. These improvements involve a greater cost both computationally and in mathematical development. In recent years, modelers have begun working with the ideas proposed by Hasselmann and Epstein which propose to mimic some processes not considered in the models with different stochastic forcings (Hasselmann, 1976). At the moment, the list of success of results is large: introducing random noise has demonstrated considerable skill in improving weather forecasts through the ensemble technique (Buizza et al. 1999), in modelling El Niño events (Zavala-Garay et al. 2003), in the study of the atmospheric quasi-biennial oscillation (Piani et al. 2004), in modelling atmospheric convection (Lin & Neelin 2002), in enhancing ocean sea-surface temperature predictability (Scott 2003) and in modelling the impacts of ocean eddies (Berloff 2005).

The purpose of this chapter is to present the problem of unresolved scales in climate models using stochastic climate models. In particular we will present the study that considers the behaviour of the ocean thermohaline circulation (THC). The choice of this dynamical system is because in the last decades it has been established (Rahmstorf, 2000) that THC plays a main role regulating North Atlantic climate and also because this system can experience sudden changes. At present we do not completely understand THC dynamics but we know that it is a global phenomenon with interhemispheric and inter-ocean exchanges influenced by the topography of the ocean floor, the global distribution of wind stress, surface heat and freshwater fluxes. Despite not knowing completely the dynamics of THC, the conceptual picture is very well known, consisting of convection areas that 'push' the THC, in addition to a broad upwelling branch that occurs over the worlds' oceans, 'pulling' the THC (Manabe & Stouffer, 1993). Therefore, among other factors, the behaviour of THC depends on north Atlantic surface water being sufficiently cold and salty to destabilize the water column and produce deep water formation. In this way, THC formation is very sensitive to air-sea heat exchange and freshwater input in the North Atlantic. On the other hand, these two parameters are expected to vary due to climate change produced by greenhouse gases accumulation in the atmosphere and eventually these changes can produce a complete shutdown of the ocean overturning in the North Atlantic. The fate of THC under those new conditions has been the subject of a scientific debate (Broecker, 1987). THC was nominated the Achilles heel of actual climate, highlighting the possibility that minor changes in parameters can cause a sudden change in climate conditions (Broecker, 1991; Broecker, 1997). Those abrupt changes are not new in the climate system and can be produced by natural variability. Specifically, paleoclimatic data suggests that past abrupt changes of THC dynamics have taken place (Stocker et al., 2001; Rahmstorf, 2002) with THC oscillating between a warm mode similar to the present-day Atlantic, a cold mode with North Atlantic deep water (NADW) forming south of Iceland, and a switched-off mode. Those changes have provoked abrupt changes in surface climate (Clark et al., 2002). Therefore the possibility of a sudden change is not a theoretical one but a real possibility.

The influence of THC on climate, the possibility of an abrupt change in its mode of operation and the evidence in paleoclimate data of abrupt changes in the past have resulted in detailed investigations of the dynamical behaviour of the THC. Many modelling studies have been done in the last decades on this topic, but lack of predictability near thresholds implies that abrupt climate changes will always have more uncertainty than gradual climate change (Knutti & Stocker, 2002). Moreover, there are other underlying uncertainties added to nonlinearity. First of all, to know what the exact situation is now is not an easy question. In this regard, the initial condition is somewhat undefined. We must recall that in nonlinear systems this is a critical question, because depending on how close to the threshold we are, the behaviour of the whole system facing the same perturbation will be very different.

WOCE (World Ocean Circulation Experiment) project has obtained a value of 15 +/-2 Sv that can be used as a reference value (Ganachaud & Wunsch, 2000). From direct observations made using the deployed array of moored instruments in the context of the Rapid Climate Change program (RAPID) (Cunningham et al., 2007) we can see variability around this value. The second source of uncertainty is that the increasing rate of freshwater input (Stocker & Schmittner, 1997) and the location of this input are also important and unknown variables. Moreover in 3D models it has been demonstrated that THC behaviour depends greatly on the vertical mixing parameterization (Knutti et al, 2000). Moreover, it is necessary to know the "hydrological sensibility" (Rahmstorf and Ganopolsky, 1999), namely, the rate of change of hydrological cycle in a warming atmosphere. How much is the warming going to increase runoff from glaciers, rivers and marine ice? Also, the problem of climate change itself is not yet well established and some quite surprising feedbacks can appear. In this way, Delworth & Dixon, 2000 have proposed that, in a scenario of global heating, the NAO (North Atlantic Oscillation) would be preferentially in the positive phase, enhancing North Atlantic winds. These enhanced winds will cause a cooling of surface water that can cancel the effects of freshening. On the other hand, Latif et al. 2000 has proposed a similar mechanism but related to the ENSO (El Niño-Southern Oscillation) pattern. But, superimposed on those uncertainties is the fact that internal or natural variability on different scales may also play a main role in determining the THC stability (Knutti & Stocker, 2002; Alley et al., 2001; Monahan, 2002; Taboada & Lorenzo, 2005; Lorenzo et al., 2009). The influence of noise on the fate of THC in the context of climate change has not been as extensively studied as atmosphere-ocean global climate models (AOGCMs) and intermediate models without noise. As we have mentioned above, the main aim of this chapter is to show the effects of adding noise to the equations that drive the dynamics of the THC, in order to better estimate unresolved scales.

2. The role of stochastic forcings

As mentioned in the introduction section, modern climate models integrate basic fluid dynamical equations. They simulate the time-dependent three-dimensional flow fields and associated transports of mass, heat, and other fluid properties at a resolution of typically a few hundred kilometres. However, processes below this resolution (such as clouds and ocean eddies) cannot be represented explicitly and must be parameterized, that is, expressed in terms of the resolved larger scale motions. This is the one of biggest sources of uncertainty of GCMs. On the other hand, in most climate models, short time scale weather forcing is not represented or is smoothed.

These simplifications do not always ensure a correct result in the long-term behaviour of a system as complex as the climate system. Remember that the chaotic nature of this system allows small changes or disturbances in certain conditions or parameters to create large variations in the medium-term prediction, with even larger errors possibly accumulated in the long term. In meteorological studies, medium-and long-term solutions to these problems were found by developing ensemble prediction techniques. In this case, different models are run with different initial or boundary conditions or diverse parameterizations in order to create a wider range of dispersion in the model results, thus covering all possible values that could develop naturally in the atmosphere.

With the ensemble prediction technique, some of the shortcomings of the medium-term predictions have been improved, but in climate predictions we need more. As mentioned previously, many processes that relate to small spatial and temporal scales are omitted or approximated in climate prediction studies and this may taint some results. In recent decades the idea of Hasselmann and Epstein to simulate these processes with random noise has gained strength. The role of these noisy sources in the models would play a similar role to the noise on a particle moving in a potential well. Without noise, the system has a tendency to remain in a state. When noise is added, the random perturbations increase the likelihood of the particle to overcome the potential barrier and move to the other state. This phenomenon is known as the paradigm of stochastic resonance (figure 1) and plays an important role in the transition probabilities which are known to depend on sensitivity to noise levels (Gammaitoni et al., 1998; García-Ojalvo & Sancho, 1999; Pérez-Muñuzuri et al., 2003; Lorenzo et al., 2003).

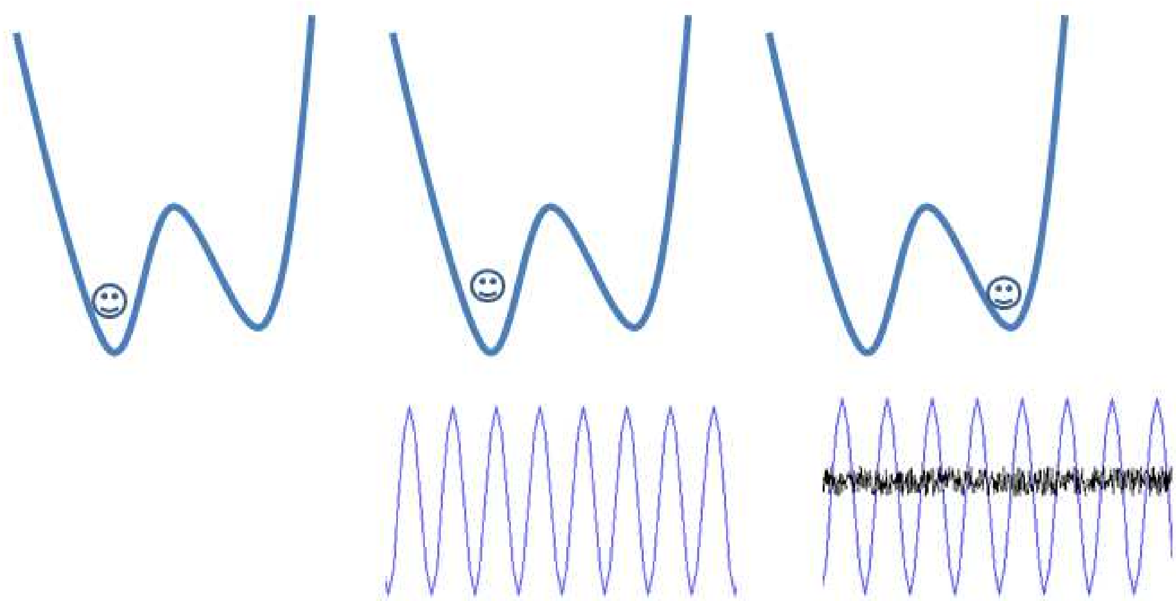

Fig. 1. Paradigm of stochastic resonance: In a symmetric double-well potential the presence of an optimal dose of noise will induce hopping events between the two wells.

As an example, most GCMs cannot be used to understand the long- term evolution of ENSO. An analysis of several GCMs suggests that it is very rare that an atmospheric GCM reproduces the correct spatial distribution, phase and seasonal behaviour of the observed subannual variability (Zhang 2005). However this kind of variability exists and when the models don't consider it, one could expect these inaccuracies to propagate to other time-scales. Zavala et al., 2008 have studied the possibility to improve our understanding of ENSO irregularity, adding the unresolved variability from observations to the GCMs. In this particular case, the irregular behaviour of ENSO has been suggested to result from nonlinear resonances of the ENSO mode with the annual cycle, from small changes in the background state or from the sporadic forcing of subannual variability on the ENSO mode (Zavala-Garay et al., 2008 and references in there). In other studies simple linear models were used to estimate the decadal response of the extratropical ocean to wind stress forcing, assuming a flat bottom, a mean state at rest, and no dissipation (Frankignoul et al., 1997; Cessi & Louazel, 2001).

In particular, we will present in this chapter the results found in previous works of the authors where stochastic forcing has been added to numerical models to analyze the behaviour of the Thermohaline Circulation (THC). As we mentioned above the choice of this example is because THC is a bistable process which implies the existence of critical points, where predictability becomes dramatically low. A shut down of the THC might be an irreversible process because of its multiple equilibriums, which have been reported by ocean and climate models of different complexity (Stommel, 1961; Bryan, 1986; Marotzke & Willebrand, 1991; Stocker & Wright, 1991). Previous works on simple models have studied the effect of these transitions induced by noise on the behaviour of the THC. Timmerman and Lohman in (Timmermann & Lohmann 2000) used a simple box model to study the stability of the THC as a function of the meridional temperature noise level. This stochastic temperature can either be interpreted as the representation of unresolved physical processes or as the expression of a thermohaline time scale separation. Monahan et al. (2008) study how the Meridional Overturning Circulation (MOC), the branch of the North Atlantic THC, varies over a wide range of spatial and temporal scales in response to fluctuating 'weather' perturbations that may be modelled as stochastic forcing. In that study, the authors analyzed the effects of noise on the variability of the MOC. In particular, they saw the role of noise on the transitions between the states of MOC and its role in the appearance of the Dansgaard-Oeschger events that are characteristic of glacial periods (Monahan et al., 2008). Other authors (Monhanan, 2001, Kuhlbrodt & Monahan, 2003) have studied a somewhat counterintuitive effect of adding noise to the equations that drive the dynamics of THC. This effect is the stochastic stabilization. In the first case with a simple box model, the effect of adding noise is that THC remains in a more stable state than would occur in the deterministic case. The second work focuses on deep convection and also arrives at the conclusion that adding noise changes the dynamical characteristic of the system. Such research proves that adding noise to simulate climate variability in different temporal or spatial scales influences the stability of the climate system in general and of the THC in particular.

The aforementioned studies illustrate the possibility of noise-induced transitions between different regimes of THC when random noise is considered in climate models, in this case related to a hypothesis of a massive sudden freshwater input.

3. Experiments and results

Two experiments are presented in this paper, both showing the possibility of a shutdown or weakening of the THC when a stochastic discharge of freshwater input is added around Greenland. In the first experiment a low complexity ocean-atmosphere coupled model was used to investigate the possibility of a collapse of the THC, taking into account the synoptic atmospheric variability. This kind of model can only give qualitative results but, they it is very useful for understanding parameter space and for building hypotheses. In a second experiment, the qualitative results found in the simplified model were reproduced in a model of intermediate complexity that is more realistic and represents a prelude to general circulation models.

3.1 Low complexity ocean-atmosphere coupled model

The “toy” model considered in the first part of our study is an atmosphere-ocean model which has been taken from a previously published work by Roebber (1995). The atmospheric part of the model is represented by a low-order model introduced by Edward Lorenz (1984) and defined by three equations:

$$\begin{aligned} \frac{dX}{dt} &= -Y^2 - Z^2 - aX + aF \\ \frac{dY}{dt} &= XY - bXZ - Y + G \\ \frac{dZ}{dt} &= bXY + XZ - Z \end{aligned} \tag{1}$$

Where X, Y and Z represent the meridional temperature gradient and the amplitudes of the cosine and sine phases of a chain of superposed large scale eddies, respectively. F characterizes the meridional gradient of diabatic heating and G is the asymmetric thermal forcing, representing the longitudinal heating contrast between land and sea. a=0.25 and b=0.4 are two constants.

The oceanic part of the model is a box model (Figure 2) representing THC in the North Atlantic Ocean. In this model, Qs denotes the equivalent salt flux, T_{a1} and T_{a2} correspond to restoring air temperatures, and q is the Thermohaline circulation. The explicit equations of the model and the ocean model constants can be found in Roebber 1995 and Taboada & Lorenzo (2005).

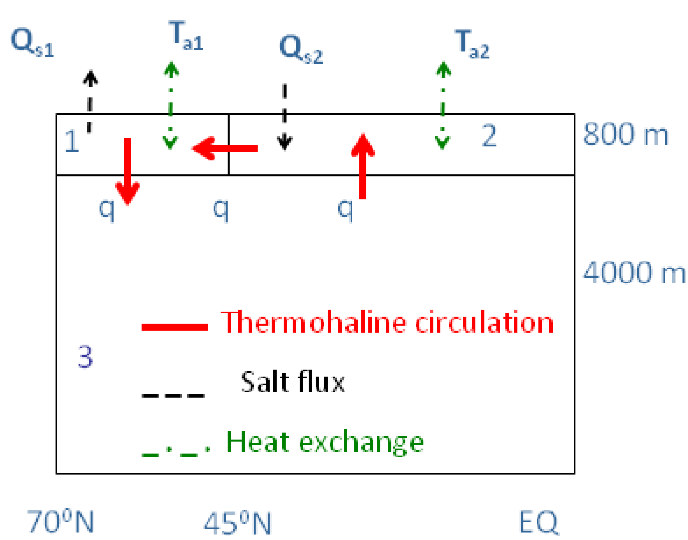

Fig. 2. Geometry of the North Atlantic through a box model. q represents the thermohaline circulation and the sense of the arrows indicates a positive circulation.

The influence of the atmosphere on the ocean model is through the variables F and G, which present a seasonal variation and whose equations are:

$$\begin{aligned} F(t) &= F_0 + F_1 \cos \omega t + F_2 (T_2 - T_1) \\ G(t) &= G_0 + G_1 \cos \omega t + G_2 T_1 \end{aligned} \tag{2}$$

Where ω is the annual frequency and t=0 at winter solstice. The values chosen are, F_0=4.65, F_1=1, F_2=47.9, G_0=-3.60, G_1=1.0 and G_2=4.0254. These suppositions insure that F and G remain bounded by qualitatively plausible constraints for collapse flows (Latif et al., 2006). On the other hand, the ocean is coupled to the atmospheric model through the restoring temperatures T_{a1} and T_{a2} and the equivalent salt flux Q_s with the next expressions:

$$\begin{aligned} T_{a1}(t) &= T_{a2} - \gamma X(t) \\ Q_s(t) &= 0.00166 + 0.00022(Y^2 + Z^2) \end{aligned} \tag{3}$$

where γ=0.06364 and T_{a2}=25ºC are constants and the parameterization of $Q_s(t)$ is due to the assumption that the eddy water vapour transport is directly proportional to the eddy sensible heat flux given by Y^2+Z^2.

In this toy model the synoptic scale variability is not considered and following the ideas of Hasselmann and Epstein, random fluctuations were added in an additive way in parameters F and G to introduce the synoptic variability inside this model. These fluctuations were specified by white Gaussian noise with zero mean and whose correlation function is given by Equation 4. This kind of noise parameterization suitably simulates the processes that lay below the resolution of the model. In other previous work (Clark et al., 2002), the effect of atmospheric processes on the ocean has been taken into account as white noise.

$$\langle \xi_w(t)\xi_w(t') \rangle = 2A\delta(t-t') \tag{4}$$

where δ is the delta function, A is the intensity of the noise, 2A its variance, and $\langle\rangle$ denotes an average over the probability distribution of the random field.

In our experiment it was analyzed whether high-frequency variations in the meridional gradient of diabatic heating or in the longitudinal heating contrast between land and sea could induce significant changes in the ocean circulation with a transition to an off state of the THC. To carry out this study the model was run under present-day conditions, with an approximated value of 15Sv (1 Sv ≅ 10^6 m^3s^{-1}). Q_{s1}=Q_{s2}=Q_s(t) and stochastic perturbations of white Gaussian noise were introduced in the parameter F or G of the model.

The addition of noise in F, produces a greater variability in the THC but a transition from ″on″ to "off" state is not observed. This result is understandable because the effect of variations in F is translated as noise in the difference between temperature T_{a1} and T_{a2} and increments or decrements between northern and southern latitudes in North Hemisphere could strengthen or weaken the THC, but a collapse would be very difficult because the basic differences between north and south are maintained (Broecker, 1987).

Different is the case of a forcing in the parameter G (Figure 3) because this parameter is introduced in salt flux Q_s and in this case noise affects the difference between the temperature in the land and the temperature in the ocean. An increment in the temperature of the land can provoke a net freshwater flux into the northern part of the North Atlantic with the consequent loss of salinity and the collapse of THC (Broecker, 1987). In the real climate, that means that it is easier to collapse THC changing the budget evaporation-precipitation, than changing differences in temperatures.

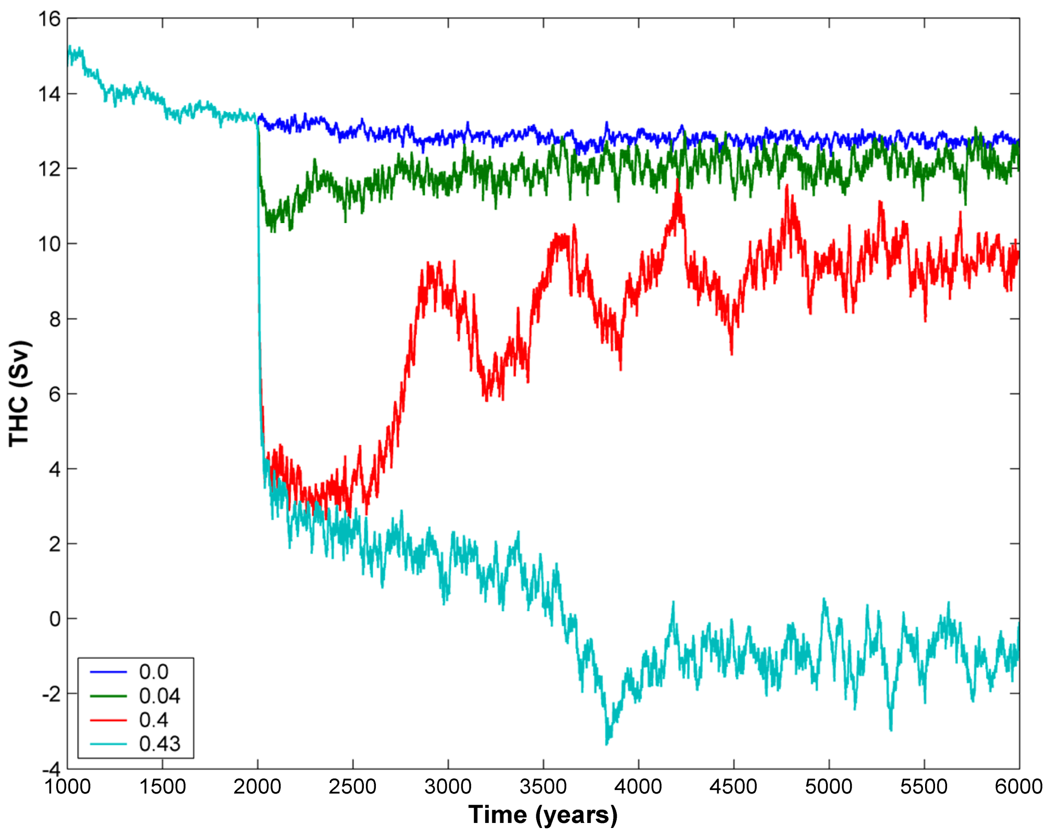

Fig. 3. Behaviour of the THC when a stochastic forcing on the zonal gradient in diabatic heating, G, is applied. The different values correspond to different values of the intensity of the applied noise.

With this toy model, it was also observed that the threshold necessary to collapse the THC is very sensitive to atmospheric greenhouse gases concentration. In Figure 4 it is shown that when decreasing the value of γ, related with the effects of global warming, the difference in temperature between the equator and the poles will diminish (Rahmstorf, 1996) and the high-frequency synoptic variations could provoke a collapse in THC easier than in actual conditions with lower values of concentration of CO_2.

Therefore, with this toy model it is possible to observe that the noise added to a model in order to mimic the variability not present in the model is able to modify the expected behaviour. Bistable systems such as the THC change from one state to another depending on their proximity to critical transition points when some fluctuations are considered. Although in actual conditions a collapse of the THC is not probable, changes such as global warming may bring the system nearer to critical points where the transition to a state of collapse will be made possible.

3.2 Earth model of intermediate complexity

The results discussed in the previous sections from a toy model have been reproduced in an analogous way in an earth model of intermediate complexity (EMIC). This section shows some results obtained from the model ECBilt-Clio after adding noise from freshwater input around Greenland (Lorenzo et al., 2008). This work corroborates the importance of considering the most likely processes in the development of a climate model to achieve more realistic results.

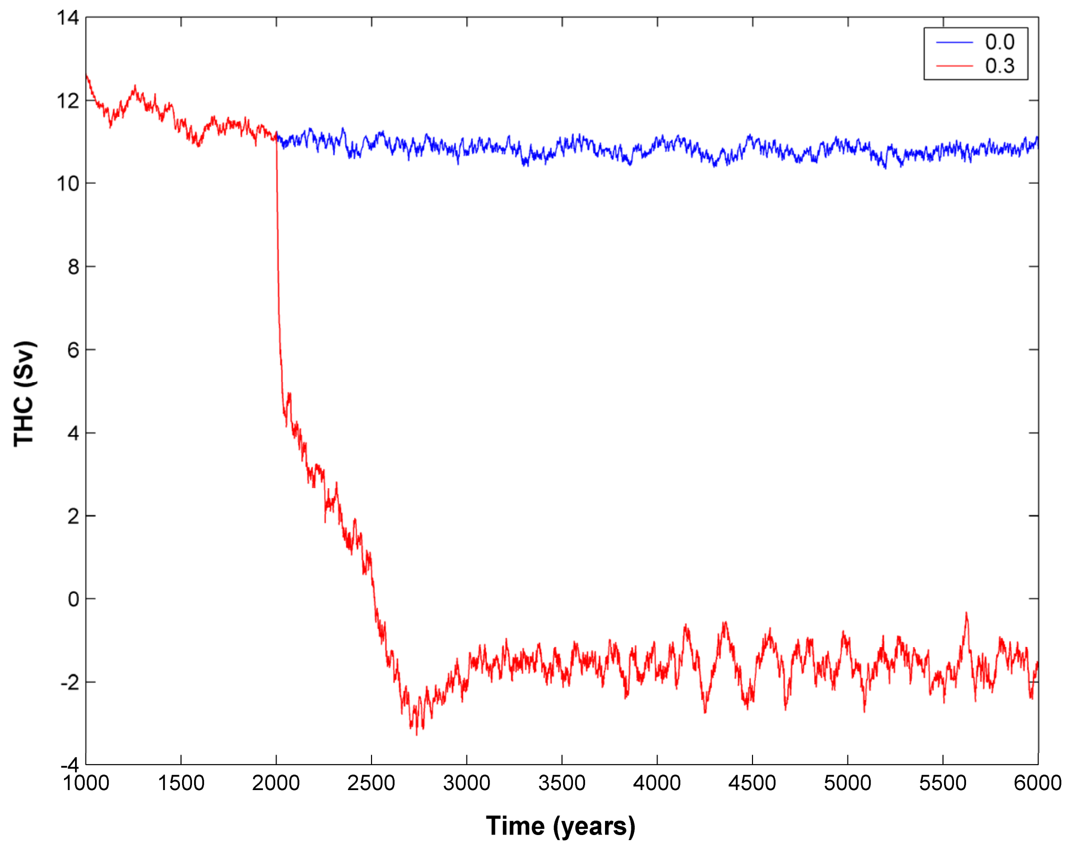

Fig. 4. Effects of a stochastic perturbation on the zonal gradient in diabatic heating G after a weakening of the THC due to a increasing of the CO_2 concentration, γ=0.045, for two values of the intensity of the applied noise A.

The model chosen is an earth system model of the intermediate complexity. Such models are realistic in the sense that they contain the minimum amount of physics that is necessary to simulate the midlatitude planetary and synoptic-scale circulations in the atmosphere as well as its variability on various timescales. We chose this model, developed at the Koninklijk Nederlands Meteorologisch Instituut, because it is simple to execute and it is one of the models of intermediate complexity used in the elaboration of the Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2001; IPCC, 2007). The atmospheric component uses the ECBilt model, a spectral T21 global three-level quasi-geostrophic model that uses simple parameterizations to simulate the diabatic processes (Opsteegh et al., 1998). The oceanic component is simulated by the Clio model which comprises a primitive equation, free-surface ocean general circulation model coupled to a thermodynamic-dynamic sea-ice model (Goosse & Fichefet, 1999). The oceanic component includes a relatively sophisticated parameterisation of vertical mixing and a three-layer sea-ice model, which takes into account sensible and latent heat storage in the snow-ice system. It simulates the changes of snow and ice thickness in response to changes in surface and bottom heat fluxes. In the computation of ice dynamics, sea ice is considered to behave as a viscous-plastic continuum. The horizontal resolution of the Clio model is 3° in both latitude and longitude and there are 20 unevenly spaced vertical layers in the ocean. The Clio model has a rotated grid over the North Atlantic Ocean in order to circumvent the singularity at the pole.

In our study, we stabilize the model ECBilt-Clio in the actual state and then we add stochastic forcing to introduce natural decadal and multidecadal atmospheric variability not simulated by the model. This forcing was introduced in the model through the addition of random Gaussian noise in the freshwater discharge around Greenland with a variability of 10 and 70 years (Lorenzo et al., 2008). The length of the experiments was 800 years, using initial conditions that were generated using a 1200 year spin-up run during which no stochastic forcing was applied. The intensity of the freshwater input varied, following a white Gaussian noise distribution that had zero mean and a standard deviation around 0.16 Sv. This value was chosen because previous studies showed that the strength of the forcing freshwater flux should lie between 0.1 Sv, which is the magnitude predicted for a large CO_2 induced climate change (4 x CO_2), and 1 Sv, which is within the range envisaged for events driven by meltwater release during the last glacial era and the deglaciation (Stouffer et al., 2006; Clarke et al., 2003). Moreover, previous work showed that the difference in freshwater export between La Niña and El Niño years is on the order of 0.1 Sv for the Atlantic (Schmittner et al., 2000; Schmittner & Clement, 2002).

The results obtained with the intermediate complexity model confirm the hypothesis suggested with the toy model. In the actual context a complete collapse of the THC is not probable, but a weakening of the circulation is observed when the synoptic and decadal natural variability of some climate processes is introduced, and results show that it is enough to observe significant changes in the climate system.

Figure 5 shows the temporal evolution of the THC in 3 different cases: without introducing a random discharge of freshwater around Greenland, introducing a random input decadal variability and introducing a random multidecadal discharge through that region.

In any of the considered cases the THC does not collapse, but a weakening is experienced. In that case the signal does have a significant impact on the behaviour of variables such as air surface temperature, sea surface temperature, precipitation or streamfunction. In Figure 6 the anomalies observed in these variables are shown.

We can see that although the THC is not collapsed several effects are considered when natural variability is introduced in the model using a stochastic forcing. In this case, the results correspond to a multidecadal variability related with the existence of an oscillatory mode of variability with a period of ~70 years involving fluctuations in the intensity of the THC in the North Atlantic (Delworth & Mann, 2000). The images show a cooling in the North Hemisphere with changes in the global precipitation patterns, mainly in the Intertropical Convergence Zone, ITCZ, and changes in the jet stream (Lorenzo et al., 2009).

Other variables, such as the sea surface salinity, geopotential or the NAO index (Lorenzo et al., 2008) have been analyzed and notable changes have been measured when a decadal or multi-decadal variability were considered in the freshwater flux of the GIN Sea. This should alert us to the need to add to the climate models many of the scales of natural variability that are not considered in most models in the name of simplicity.

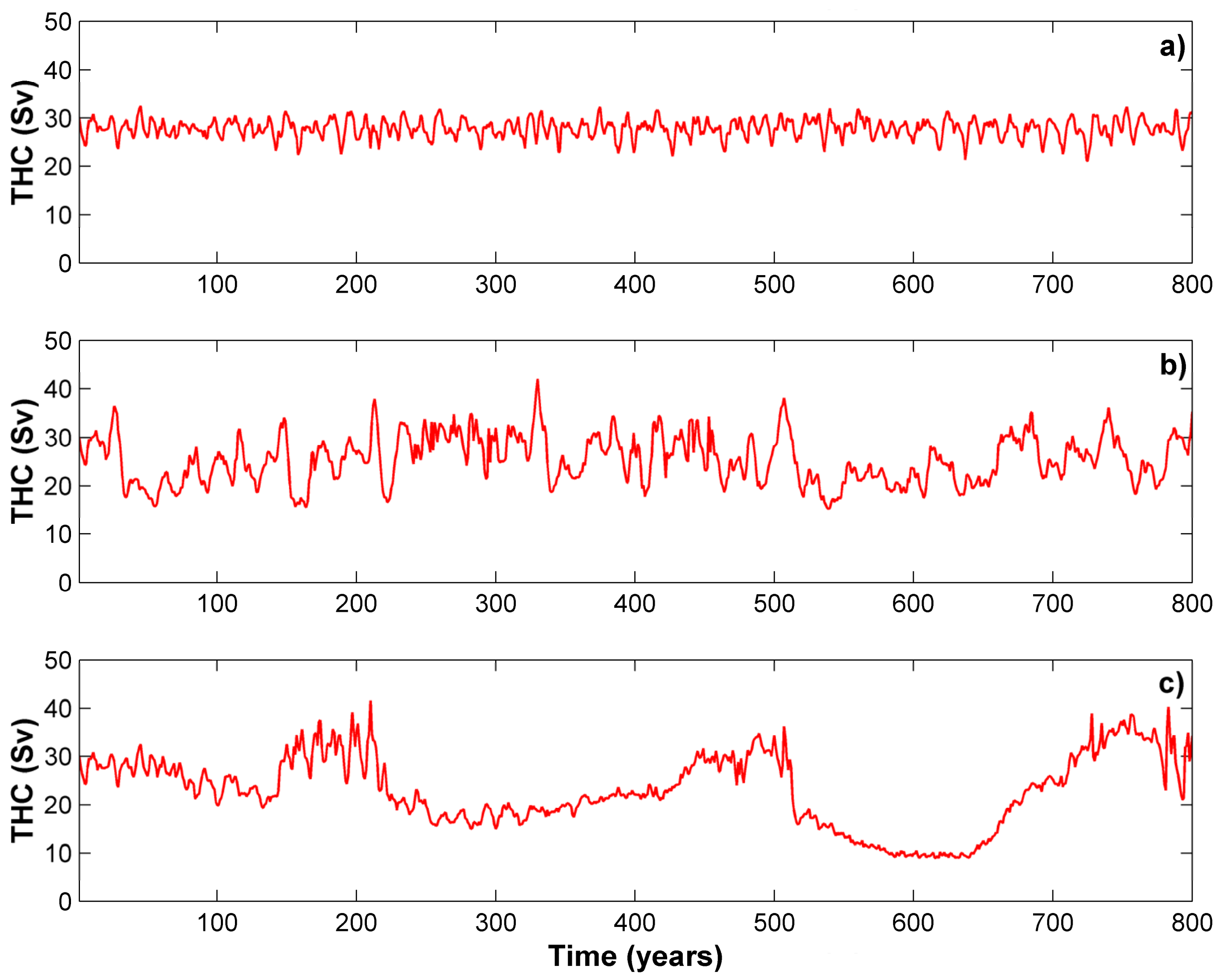

Fig. 5. Behaviour of the THC three simulations. (a) without forcing; (b) with random freshwater input with decadal variability added in the ocean basin of the Greenland/Iceland/Norwegian Sea (GIN Sea); and c) the same b) but with multidecadal (70 years) variability.

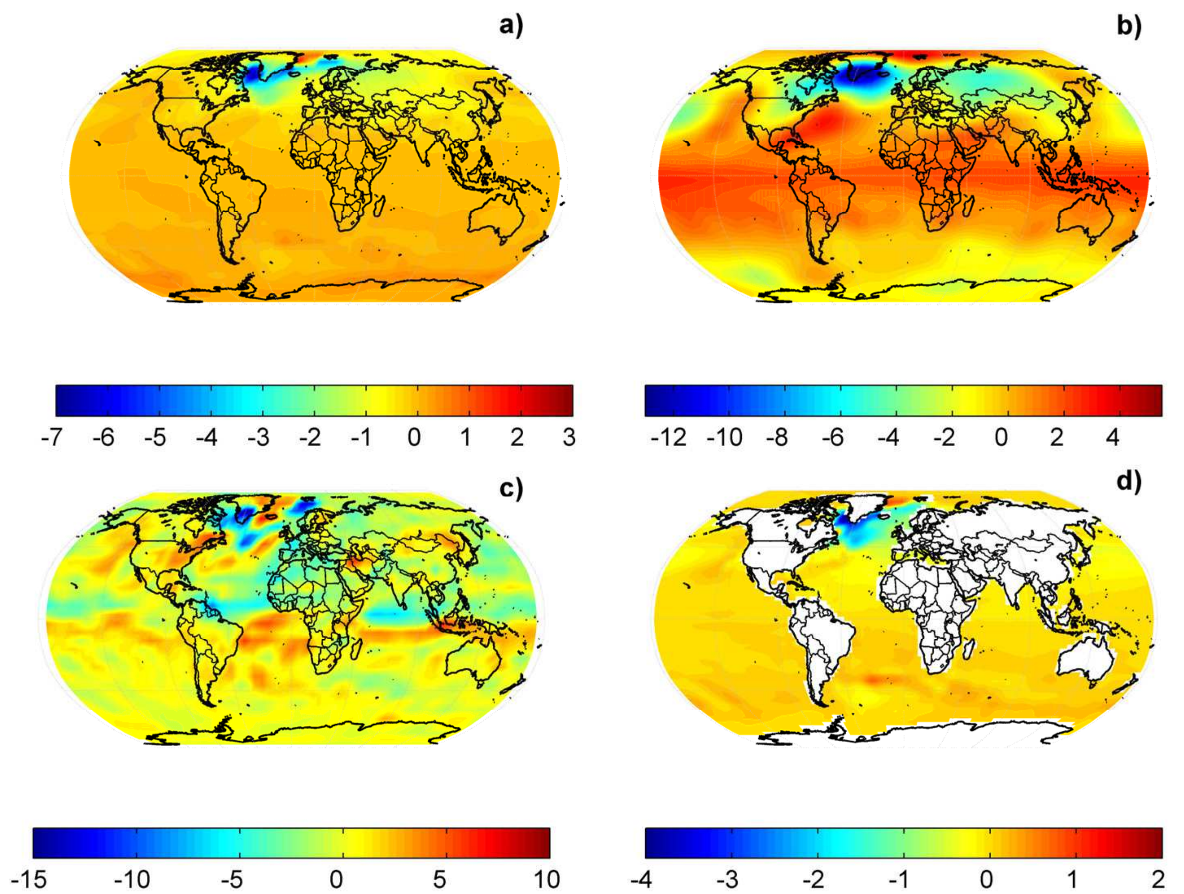

Fig. 6. a) Anomaly of mean surface temperature (ºC). b) Anomaly of mean streamfunction ($m^2 s^{-1}$). c) Anomaly of mean precipitation (cm $year^{-1}$) and d) Anomaly of mean sea surface temperature SST (ºC) all them during the 800-year simulation for a variability of 70 years in the flux of freshwater. The averaging period for the anomalies is computed relative to an unperturbed control run.

4. Conclusions

In this chapter we have shown the effect of the climate's natural variability, simulated through white Gaussian noise at different temporal scales, on the behaviour of THC. This noise has been added to two different models: a low complexity ocean-atmosphere coupled model and an earth model of intermediate complexity previously used in the reports of the IPCC. In these experiments the relevance of the variability of high frequency in the climate was observed. Here, the attention was focused on the case of thermohaline circulation and the addition of white Gaussian noise but in the bibliography there are numerous examples in which the addition of random noise, white or colored, can improve the understanding of certain climate processes like El Niño events, the quasi-biennial oscillation, the atmospheric convection or ocean eddies, amongst others. In our particular case, it was observed that a critical noise level exists which induces an abrupt transition of the salinity statistics. This abrupt transition induces a sudden change in the THC behaviour, which provokes a significant change in the climate. Even if adding noise does not induce a complete shutdown, climate in the North Atlantic would be affected. The concept of noise-induced transitions explains this qualitative behaviour. Furthermore, changing noise amplitudes could lead to rapid changes in the mean state and, in the context of climate variability, to abrupt climate transitions.

In this chapter we intend to call attention to those unresolved scales and processes in the models. We have shown the example of the variability in the discharge of freshwater in the GIN Sea, but there are many other unresolved processes models: gravity waves, clouds, ocean eddies, small-scale turbulence… The complexity and computational cost of a conventional resolution of them still seems far away, so the alternative stochastic approach, based on noise, seems to be the more suitable solution (Williams, 2005). In agreement with Williams (2005) we think that the inclusion of stochastic forcing in the next generation of climate models is necessary to give a more realistic view of climatic processes that occur around us.

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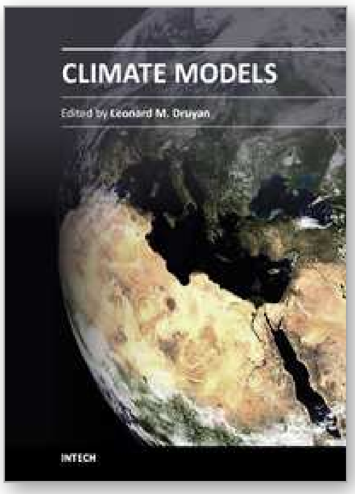

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