

Sensitivity of thermohaline circulation to decadal and multidecadal variability

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In this paper, stochastic freshwater inputs with different variabilities are introduced into an Earth Model of Intermediate Complexity to study their effect on the behaviour of the thermohaline circulation (THC). The variability in the stochastic signal was set to be either decadal or multidecadal (70 years), based on intensity modulation of the *El Niño*-Southern Oscillation (ENSO) phenomenon. The results demonstrate a weakening of the THC in both the decadal and the multidecadal cases. This weakening results in a reduction in air surface temperature, mainly in the North Atlantic. Moreover, the 500-mb stream function also weakens. This causes lower rainfall in Western Europe, except in the areas most influenced by the Gulf Stream. Sea surface temperature is reduced significantly in the area around Greenland, whereas sea surface salinity is reduced around Greenland and in the Gulf Stream, but increased in the Labrador Sea and in Hudson Strait. The latter effects are more marked in the case where the variability of the inputs is multidecadal. The main implication of these results is that the natural decadal or multidecadal variability in freshwater inputs could have noticeable effects on the fate of the THC, which may be superimposed on the effects of climate change.

Keywords: abrupt climate change, decadal and multidecadal variability, stochastic forcing, thermohaline circulation.

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Introduction

The natural variability of the climate system is characterized by a wide range of time-scales that range from years to millennia. In recent years, decadal and multidecadal variability has received a great deal of attention. A better understanding of this variability is required to increase our confidence that observed climate changes are occurring as a result of human activity. Furthermore, to test the performance of climate models, any natural variability must be identified and filtered out. This is particularly important in the decadal case, where the signals of natural variability and anthropogenic influence overlap.

Since the 1980s, scientists have investigated the possibility of abrupt alteration in the environment (i.e. climate transitions that can occur over a few years or decades). Some of these studies relate modifications in the Atlantic Thermohaline Circulation (THC) to the abrupt climate changes prevalent in the high-resolution proxy records from the last glacial cycle (Stocker *et al.*, 2001; Clark *et al.*, 2002; Rahmstorf, 2002), although alternative mechanisms have also been suggested (Renssen *et al.*, 2000; Clement *et al.*, 2001; Broecker, 2003). For the last 8000 years, the THC has existed in a relatively stable state, with no rapid alterations. However, analyses of reconstructions of surface temperatures during the last 330 years show 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 and Mann, 2000). Within the context of global warming, the possibility of abrupt change increases

(Stouffer *et al.*, 2006). In general, Atmospheric-Ocean General Circulation Models (AOGCM) do not forecast a complete shut-down of the THC under the scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC), but the most common results show a slowing of this circulation (Stocker and Schmittner, 1997; Rahmstorf and Ganapolski, 1999; IPCC, 2007).

Modern climate models consist of atmosphere–ocean Coupled General Circulation Models (CGCMs), where all the basic equations of fluid dynamics are integrated. These models simulate the time-dependent, three-dimensional flowfields and the associated transport of mass, heat, and other fluid properties at a resolution of a few hundred kilometres. Any processes occurring below this resolution (such as clouds and ocean eddies) cannot be represented explicitly and must be parameterized to express them in terms of the larger-scale motions. This feature represents the principal source of uncertainty of CGCMs. Advances in supercomputer technology, which has permitted higher model resolutions, have helped to reduce these uncertainties, but significant differences remain between the predicted and the observed patterns of temperature change, and in the distribution of other variables, such as precipitation or sea level rise. In an attempt to mimic the effects of these unresolved processes, stochastic forcing has traditionally been used to represent high-frequency variability in surface fluxes (Hasselmann, 1976).

As discussed by Williams (2005), using stochastic sources in weather forecasting models has met with some success.

Incorporating random noise has provided considerable skill in improving weather forecasting (Buizza *et al.*, 1999), modelling *El Niño* events (Zavala-Garay *et al.*, 2003), atmospheric quasi-biennial oscillation (Piani *et al.*, 2004), atmospheric convection (Lin and Neelin, 2002), ocean sea surface temperature (SST) (Scott, 2003), and the effects of ocean eddies (Berloff, 2005).

The reaction of the global climate system to unexpected perturbations can be surprising, because of its non-linear nature. It is now accepted that random fluctuations in non-linear systems can result in increased stability, or bring about other processes in unexpected ways. When coupled adequately to a non-linear system, sources of noise could result in a rich new phenomenology unknown in the equivalent deterministic noiseless scenario (Wang *et al.*, 1999; Lorenzo *et al.*, 2003; Pérez-Muñuzuri *et al.*, 2003). The different physical mechanisms that cause such ordering effects can be studied with simple models, but there is agreement that the essential ingredient is a combination of effects that include diffusion, non-linearity, forcing, and noise (García-Ojalvo and Sancho, 1999).

The THC is that part of the large-scale ocean circulation that is assumed to be driven by global density gradients created by surface heat and freshwater fluxes. The term “thermohaline” is derived from “thermo”, referring to temperature, and “haline”, referring to salt content; factors that together determine the density of seawater. The global THC is maintained by oceanic density gradients, and consists of cooling-induced deep convection and sinking at high latitudes, and upwelling at lower latitudes, with horizontal currents feeding the vertical flows. It is also important to note that this conceptual picture of the THC includes a highly localized area of convection. Therefore, we could state that the THC is “pushed” by convection and “pulled” by upwelling (Munk and Wunsch, 1998; Marotzke, 2000). In the North Atlantic, where most of the deep sinking occurs, the THC is responsible for the unusually strong northward heat transport. This, together with the equatorward heat transport in the South Atlantic, results in the relative mildness of the western European climate. Detailed GCM investigations of the effects of random noise on the THC have only just begun, but a foretaste of what such studies may reveal has been provided by previous work using simple models (Timmermann and Lohmann, 2000; Monahan, 2002; Taboada and Lorenzo, 2005; Lorenzo *et al.*, 2008). In these studies, when random noise was added to the models, an earlier transition to a shutdown of the THC was observed, compared with the equivalent case without noise. These results, together with the tendency of the AOGCM to exhibit a decrease in the strength of this circulation under global warming conditions, have led to an increased interest in this topic. A weakening or collapse of the THC could trigger the onset of a new Younger Dryas, or at least lessen the consequences of global warming in the North Atlantic and surrounding areas.

The freshwater influx and air–sea heat exchange in the North Atlantic are considered the key parameters that determine the behaviour of the Atlantic THC. If this system is described using a stability diagram that reveals the strength of the THC as a function of the freshwater input into the North Atlantic, a bistable regime can be identified, including a bifurcation point where the THC breaks down (Rahmstorf, 2000). It is therefore possible that minor changes in forcing could cause a sudden change in conditions observed in the THC.

The changes in freshwater transport that occur when regimes change from *El Niño* to *La Niña* conditions, and vice versa, generally influence only the upper part of the ocean, because the

response time is too long for the deeper ocean to be affected on an interannual basis. However, if either of these conditions, *El Niño* or *La Niña*, were to last for an anomalously long period, as observed during the period 1990–1995 with conditions similar to *El Niño*, marked changes in oceanic THC could occur, and these could modify the earth’s climate significantly (Schmittner *et al.*, 2000; Schmittner and Clement, 2002). A study of *El Niño* events established that over the past 475 years, nine very strong events occurred at ~50-year intervals, and a further 40 strong or very strong events every 9 years (Quinn *et al.*, 1987). At the same time, a Sea Surface Temperature Anomaly (SSTA) in the equatorial Pacific can cause a decadal modulation of ENSO events (White and Cayan, 2000), and Atlantic Multidecadal Oscillation (AMO) can provoke a multidecadal variability of THC (Dong *et al.*, 2006).

A lengthening of the *El Niño* and *La Niña* cycles could result from changes in levels of greenhouse gas or the decadal variability of the climate system (Trenberth and Hoar, 1996). This could result in a greater influence of the large surface freshwater flux variability on the THC and on the climate system in general. Simulations, such as the one presented herein, will be crucial to understand and possibly predict the long-term changes associated with this large surface freshwater flux variability (Gautier *et al.*, 1996; Schmittner *et al.*, 2000; IPCC, 2001; Dong *et al.*, 2006).

In this study, we analyse the effect of stochastic freshwater input with a decadal and multidecadal variability around Greenland, using an Earth System Model of Intermediate Complexity (EMIC). In the following section, we describe the EMIC used in this study and the characteristics of the stochastic forcing. After that, we present the results of the model using stochastic freshwater inputs with a variability of 10 and 70 years, respectively.

The model

The atmosphere–ocean model used in this study is the ECBilt–Clio model. This is a three-dimensional coupled atmosphere–ocean–sea ice model developed by the Koninklijk Nederlands Meteorologisch Instituut (KNMI). This model has been applied in many studies of the past, present, and future climate (Goosse and Fichefet, 1999; Renssen *et al.*, 2002; Petoukhov *et al.*, 2005; Timm and Timmermann, 2007).

The atmospheric component is the ECBilt model (Opsteegh *et al.*, 1998), a spectral T21 global three-level quasi-geostrophic model that uses simple parameterizations to simulate the diabatic processes. The model is realistic, in the sense that it contains the minimum amount of physics necessary to simulate the mid-latitude planetary and synoptic-scale circulation in the atmosphere, as well as its variability at various time-scales.

The Clio model (Goosse and Fichefet, 1999) comprises a primitive equation, free-surface ocean general circulation model coupled to a thermodynamic–dynamic sea–ice model. The oceanic component includes a relatively sophisticated parameterization of vertical mixing. A three-layer sea–ice model, which takes into account sensible and latent heat storage in the snow–ice system, 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 latitude and longitude, and the ocean is divided into 20 unevenly spaced vertical layers. The Clio model has a rotated grid over the North Atlantic Ocean to circumvent the singularity at the pole.

To introduce natural decadal and multidecadal atmospheric variability not simulated with the model, random fluctuations were added in an additive way into the freshwater flux around Greenland (Fichefet *et al.*, 2003; IPCC, 2007). The intensity of the freshwater input varied in accordance with white Gaussian noise [Standard deviation of a signal x is given by the equation: $[(1/(n-1)) \sum_{i=1}^n (x_i - \bar{x})^2]^{1/2}$, where the sample average is $\bar{x} = (1/n) \sum x_i$, and n is the signal length. The correlation function of a white Gaussian process of zero mean is given by (García-Ojalvo and Sancho, 1999):

$$\langle \xi_w(t) \xi_w(t') \rangle = 2A\delta(t - t'), \quad (1)$$

where δ is the delta function, A the intensity of the noise, $2A$ its variance, and $\langle \rangle$ denotes an average value over the probability distribution of the random field. We used the “gasdev” function to generate the noise. This stochastic forcing was introduced into the ocean basin of the Greenland–Iceland–Norwegian Sea (GIN Sea). Figure 1 indicates the points where the forcing was applied, with all points receiving the same forcing for a certain period.

The GIN Sea was chosen because it is characterized by a more intense sinking in the North Atlantic and fluctuations in flux of freshwater could activate a change in this convection. Previous studies and measurements have revealed that the freshwater flux is a noisy signal at an interannual-decadal time-scale (Cunningham *et al.*, 2007). These fluctuations could be caused or amplified by a melting of the ice cover or an increase in precipitation as a result of anthropogenic-induced climate change (Fichefet *et al.*, 2003; IPCC, 2007). It is also possible that variability of the ENSO could modify the freshwater balance in the tropical Atlantic and provide a coupling mechanism between low and high latitudes (Quinn *et al.*, 1987; Schmittner *et al.*, 2000; White and Cayan, 2000; IPCC, 2001; Dong *et al.*, 2006).

Results

Before applying the stochastic freshwater fluxes, we ran the model to a steady state. Then we looked for a collapse or significant weakening of the THC, by imposing a freshwater discharge into the surface waters near Greenland, to investigate the ability of the model to simulate these conditions. We found that a near total collapse of the THC occurred when a continuous discharge of 0.8 Sv in Greenland was incorporated. This flux is close to the range envisaged for events that were driven by meltwater release during the last glacial era and the subsequent deglaciation (Clarke *et al.*, 2003). The result of this first simulation was a decrease in the maximum meridional overturning stream function in the North Atlantic, from 30 to ~ 2 Sv. This caused a significant cooling effect in the North Atlantic, which spread throughout the northern hemisphere, and a slight warming in the southern hemisphere. In Figure 2a, the anomalies of temperature with respect to the steady state are shown for the simulation when a freshwater flux of 0.8 Sv was introduced to the GIN basin. Figure 2b illustrates the behaviour of the maximum meridional overturning stream function in the North Atlantic. This parameter will hereafter be taken as representing THC. These results are consistent with palaeoproxy reconstructions (Tziperman, 2000).

As mentioned in the Introduction, a complete collapse of the THC is unlikely during the next 20 years (IPCC, 2007), but previous studies have revealed substantial uncertainties in the model's THC response (Stouffer *et al.*, 2006). The THC is potentially sensitive to the addition of freshwater and to changes in surface fluxes induced by natural variability or by anthropogenic changes. This sensitivity, and the disagreements among the model simulations, may be attributed to the complexity of the climate system. Moreover, as discussed earlier, there are many unresolved processes in all the climate models, which could have an influence on the climate dynamics in our simulations.

As stated earlier, the aim of our study was to consider the effect of natural variability in freshwater flux, by investigating the likelihood of approaching the threshold of collapse of the THC

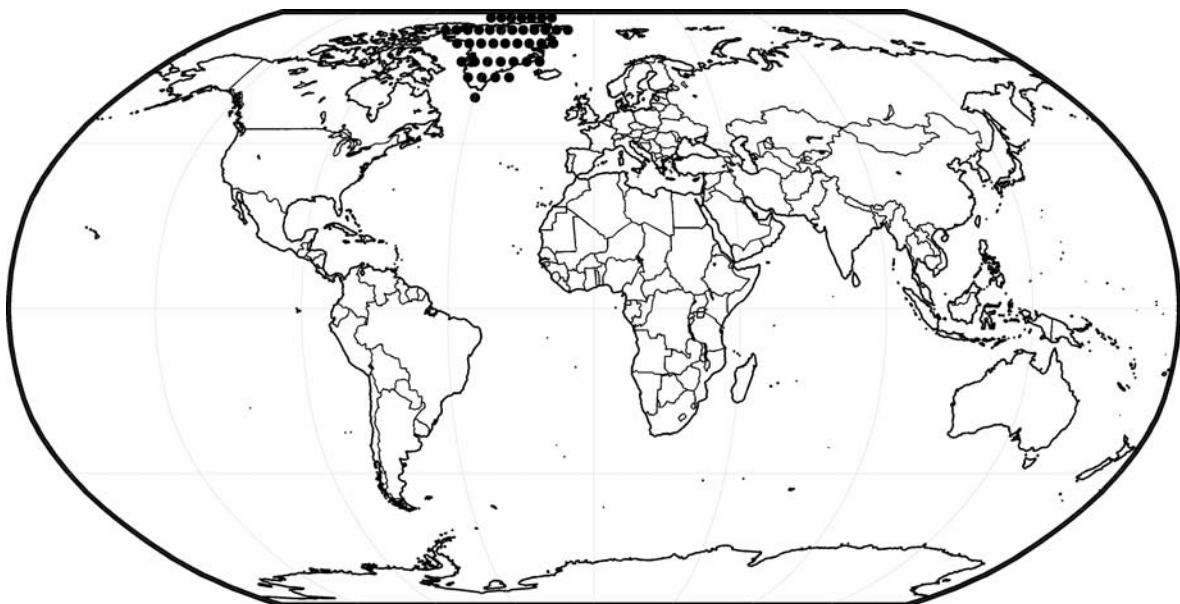


Figure 1. World map displaying the GIN Sea basin where the stochastic forcing of freshwater was added.

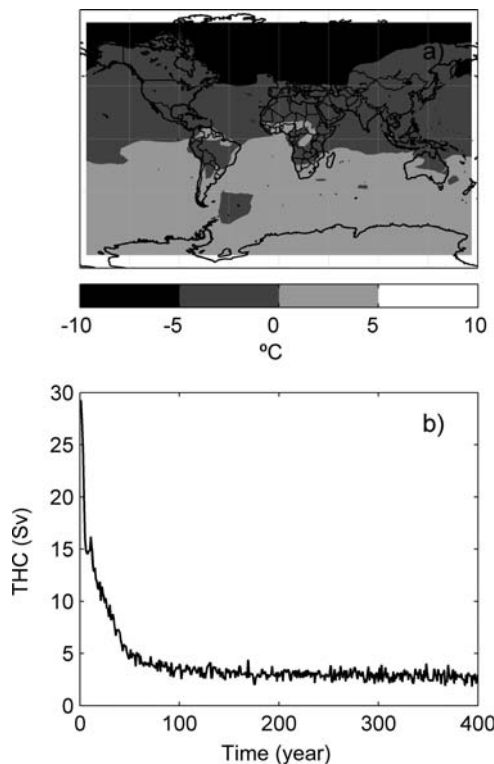


Figure 2. (a) Annual mean surface temperature anomaly ($^{\circ}\text{C}$) with the THC collapsed. (b) Response of the THC after a continuum discharge of 0.8 Sv in the GIN Sea basin.

resulting from this natural variability. It should be remembered that this effect would be superimposed on the effect of global warming.

To incorporate natural variability into the model, stochastic freshwater inputs with a variability of 10 and 70 years were simulated around Greenland. The length of the model run was 800 years, using initial conditions that were generated with a 1200-year spin-up run, during which no stochastic forcing was applied. The intensity of the freshwater input varied according to a white Gaussian noise distribution with zero mean and a standard deviation of ~ 0.16 Sv. These values were chosen because previous studies indicated that the strength of the forcing freshwater flux could vary between 0.1 Sv, which is the magnitude predicted for a large CO_2 -induced climate change ($4 \times \text{CO}_2$), and 1 Sv. The latter is within the range envisaged for events driven by meltwater release during the last glacial era and the deglaciation (Clarke *et al.*, 2003; Stouffer *et al.*, 2006). Moreover, previous work established that the difference in freshwater export during *La Niña* and *El Niño* years is ca. 0.1 Sv for the Atlantic Ocean (Schmittner *et al.*, 2000; Schmittner and Clement, 2002).

Figure 3 shows the results of different stochastic freshwater inputs applied to the Greenland Basin and the responses observed in the behaviour of the THC. Figures 3a and b show the steady-state condition before any forcing was applied. Figures 3c and d show the results after forcing with a decadal variability (i.e. the intensity of the discharge was altered randomly every 10 years). The forcing could be either positive, so increasing the freshwater flux over the studied area, or negative, thereby decreasing the freshwater flux. The decadal variability can be considered to

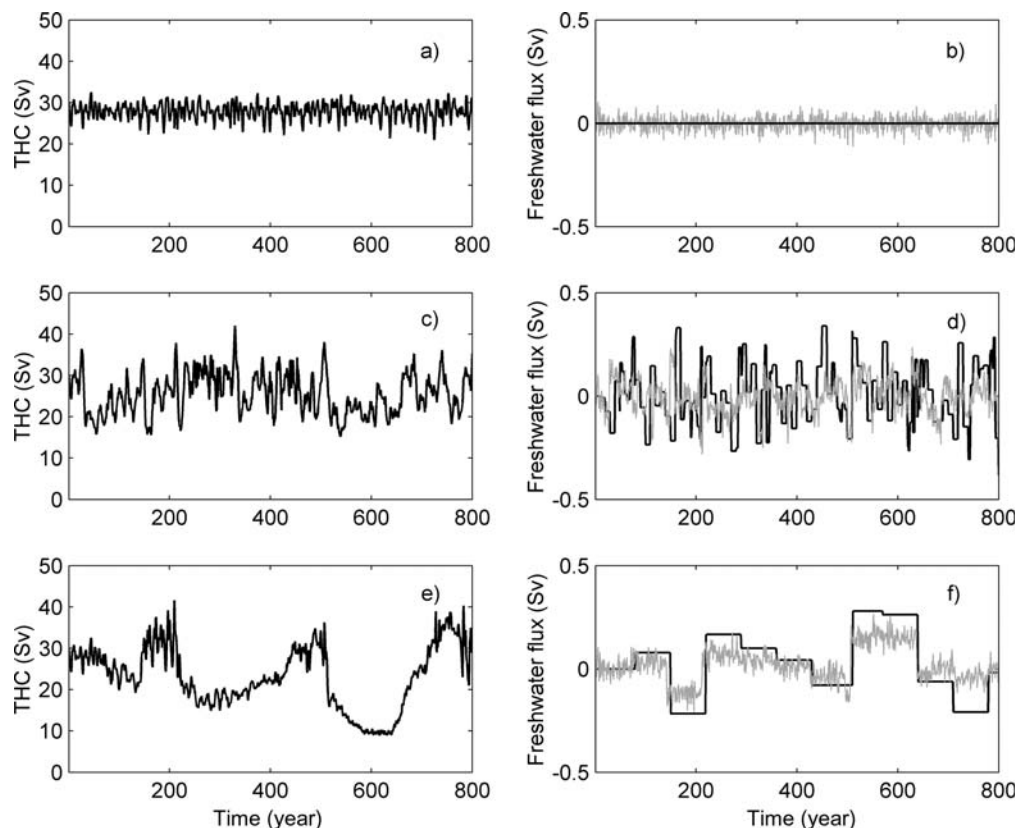


Figure 3. Behaviour of the THC and freshwater flux added in the GIN basin for the three simulations. (a) and (b) without forcing; (c) and (d) with freshwater input with decadal variability; and (e) and (f) with freshwater input with multidecadal variability.

represent the decadal modulation of the ENSO. Figures 3e and f illustrate the behaviour of the THC when the forcing was characterized by a multidecadal variability of ~ 70 years. This variability could be related to very strong *El Niño* events or to changes in the AMO (Dong *et al.*, 2006). Although neither Figure 3c nor e reveals a shutdown of the THC, the weakening evident here could have significant effects on a range of different variables, as will be discussed later.

Figures 4a and b show the surface temperature anomalies with respect to the control experiment. These reveal that the northern hemisphere, and specifically the North Atlantic, is most affected by decadal and multidecadal scales of variability. With the weakening of the THC, the northward heat transport is reduced, producing a local cooling in the Labrador Sea of up to 4°C for decadal variability (Figure 4a) and 9°C for multidecadal variability (Figure 4b). In the latter case, the cooling extends around Greenland. An interesting effect revealed in Figure 4a is the warming of the Greenland Sea, which compares in terms of magnitude with the cooling of the Labrador Sea. This warming effect is manifested in an increasing total heat flux at the surface of the Greenland Sea, which is not presented here, but was observed in the simulations. This result would indicate a northward shift in oceanic deep convection (Stouffer *et al.*, 2006). The input of freshwater weakens the deep convection in the 50° – 70°N belt, but in the Barents and Nordic Seas, where the freshwater input was not forced directly, it could provide the conditions necessary to trigger a sinking of the water mass. For multidecadal variability, the intensity of the warming is lower. The response to the weakening of the THC in the southern hemisphere is almost negligible,

and characterized by a small degree of warming. The reduction of heat transport in a northward direction could constitute the cause of this warming in the southern hemisphere (Stouffer *et al.*, 2006).

Figure 4c shows the time-series of the average anomalies in the global surface temperature, for both the decadal and the multidecadal cases. Positive freshwater inputs induce a decrease in the surface temperature attributable to a weakening of the THC, although it weakens for only a short period. Although the collapse of the THC is not complete, the decrease in temperature is not negligible. Figure 4d reveals that the North Atlantic area is most affected by the weakening of the THC, whereas no significant change is observed in the southern hemisphere. We will hereafter only present the figures that represent variability in the stochastic forcing with a period of 70 years, because although the quantitative results of the decadal variations in forcing are different, the qualitative results are similar.

Investigation of the average 500 hPa stream function indicates that a weakening of the THC influences the intensity of the polar jet stream. Figure 5a shows the anomaly of the average stream function when a forcing with a multidecadal variability is applied in the GIN basin. A weakening of the stream function between 30°N and 65°N is evident. Figure 5b illustrates the temporal evolution of the stream function anomalies during the 800 years of the model run. Figure 5c confirms the weakening of the polar jet at high latitudes. Finally, Figure 5d illustrates a regional average of zonal wind anomalies at 200 mb, plotted against latitude. The values are low, but they corroborate the behaviour observed in the analysis of the stream-function variable. This

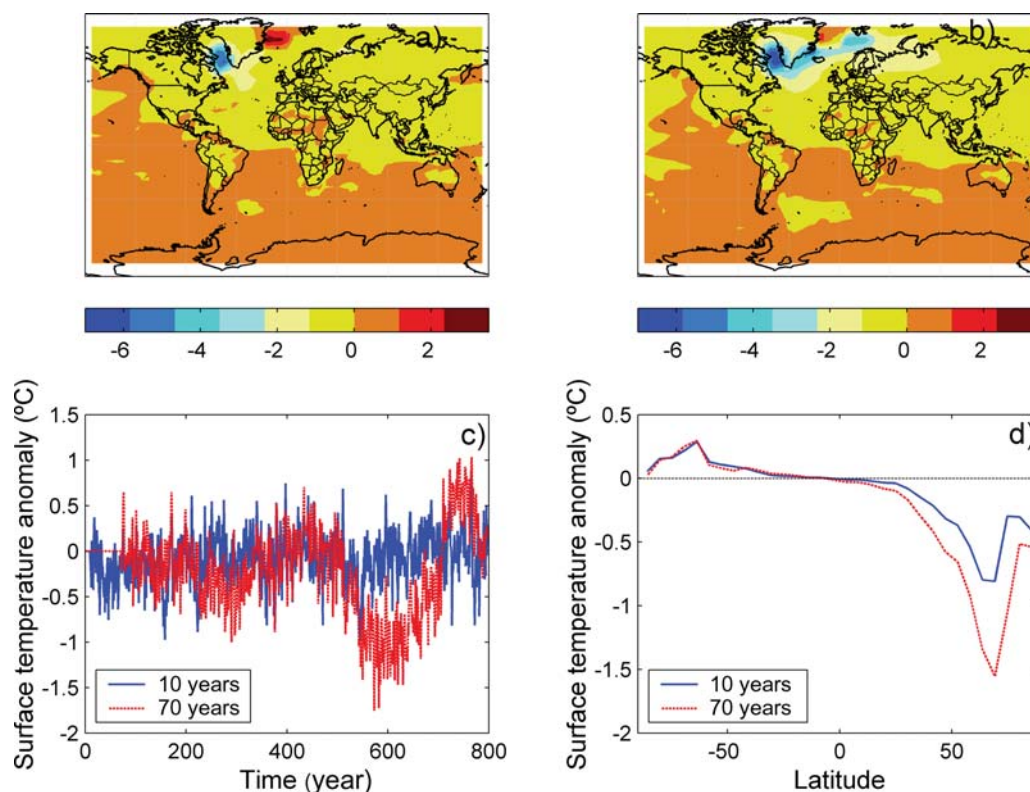


Figure 4. Mean surface temperature ($^{\circ}\text{C}$) during the 800 years simulated for different variability in the freshwater input: (a) decadal variability, (b) multidecadal variability, (c) time-series of anomaly in global mean surface temperature ($^{\circ}\text{C}$) during the 800-year simulation with different time-scales in the variability of freshwater flux, and (d) anomaly in mean surface temperature in relation to latitude.

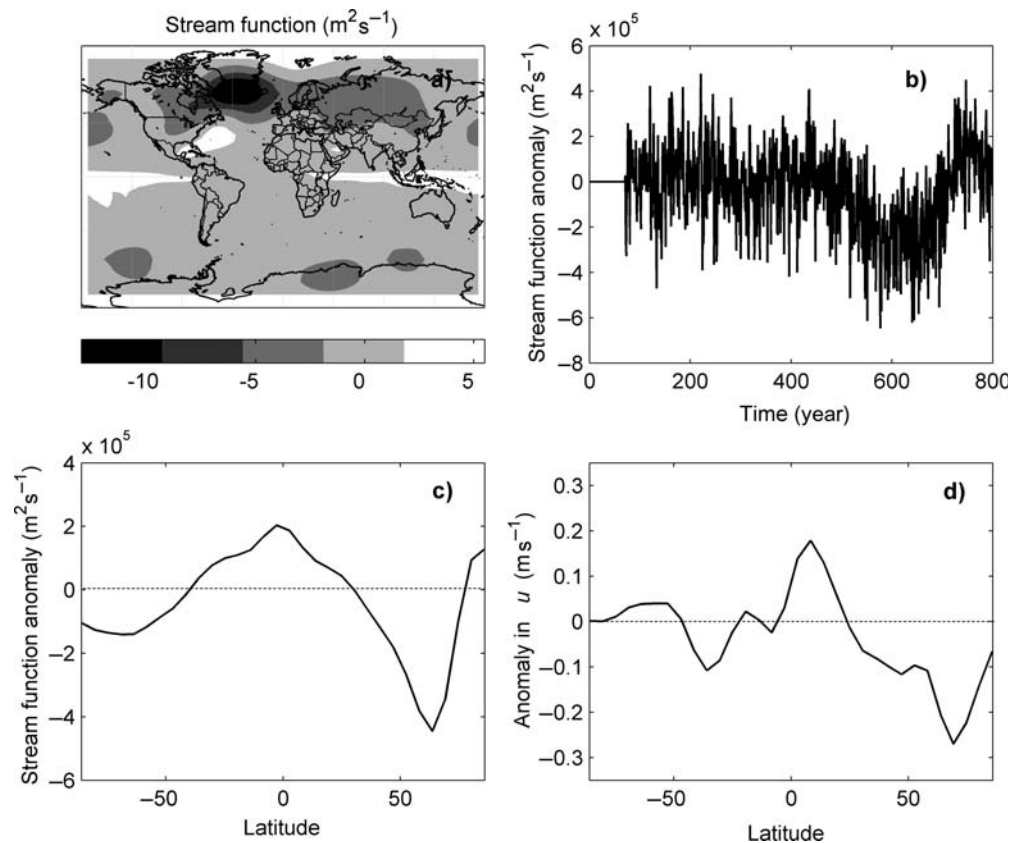


Figure 5. (a) Mean stream function ($\text{m}^2 \text{s}^{-1}$) during the 800-year simulation for a variability of 70 years in the flux of freshwater. (b) Anomaly time-series of the mean stream function ($\text{m}^2 \text{s}^{-1}$) during the 800-year simulation. (c) Anomaly of the mean stream function ($\text{m}^2 \text{s}^{-1}$) in relation to latitude. (d) Anomaly in average zonal winds (m s^{-1}) vs. latitude for the 200 mb level.

phenomenon may be a consequence of a weakening of the THC, which results in a less energetic atmosphere, and in turn the polar jet is also reduced (Stouffer *et al.*, 2006). The results using decadal variability are similar, though less intense. Furthermore, surface flux anomalies are significantly negatively correlated ($r = -0.86$) with the THC anomalies. Because SST and THC anomalies are themselves highly correlated ($r = 0.89$), we conclude that surface flux anomalies in the ocean are a result of SST anomalies caused by variations in THC (Latif *et al.*, 2006). This flux influences the atmosphere, causing a reduction in the intensity of the polar jet.

Analysis of the trends in precipitation reveals a decrease in western continental Europe, although the precipitation following the track of the Gulf Stream is increased. The results are similar in the two simulations, although here we only present the results for multidecadal variability, because these are more pronounced. In Figure 6a, the anomaly in the average precipitation using multidecadal variability in the forcing characteristics is illustrated. We can see that for Greenland, the precipitation increases over the east coast and decreases over the west coast. Important positive anomalies over the equatorial area, and negative anomalies over the tropical area and subtropical North Atlantic, are evident, these being more pronounced in the multidecadal case. This behaviour reflects changes in the position of the Intertropical Convergence Zone (ITCZ) and corresponding changes in the rainfall patterns in equatorial countries (Chiang *et al.*, 2000; Biasutti *et al.*, 2005). Figure 6b shows the time evolution of the anomalies

in precipitation for the period simulated. Figure 6c, which illustrates the temporal average of the anomalies in precipitation plotted against latitude, demonstrates a generalized decrease in precipitation and changes in the ITCZ in the North Atlantic. Figure 6d shows that these changes in precipitation are associated with changes in evaporation, which indicates an appreciable decrease in the northern hemisphere.

The changes in SST following the perturbation of the freshwater input, and the consequent weakening of the THC (Figure 7a and b), mimic the observed behaviour of the surface air temperature (Figure 4). We do not present the results obtained using a variability of 10 years, but we previously noted that if we used a variability of 10 years, the cooling was centred in the Labrador Sea. When we increased the period of the variability to 70 years, this cooling was extended to the entire area around Greenland (Dai *et al.*, 2005). The slight warming noted for the northern North Atlantic can be explained by the increase in surface temperature seen in Figure 4. Figure 7b indicates that the temporal evolution of the SST anomalies is modulated slightly by the forcing. Figure 7a shows that the cooling of the SST is located in the middle and high latitudes (up to $\sim 70^\circ \text{N}$) of the north hemisphere, whereas only small variations are observed in the southern hemisphere. A further direct effect of the freshwater input is the decrease in sea surface salinity (SSS) over the Greenland Basin. The maximum freshening is concentrated between latitudes 50°N and 70°N , in particular in the Labrador Sea and the Hudson Strait. In the southern hemisphere, the

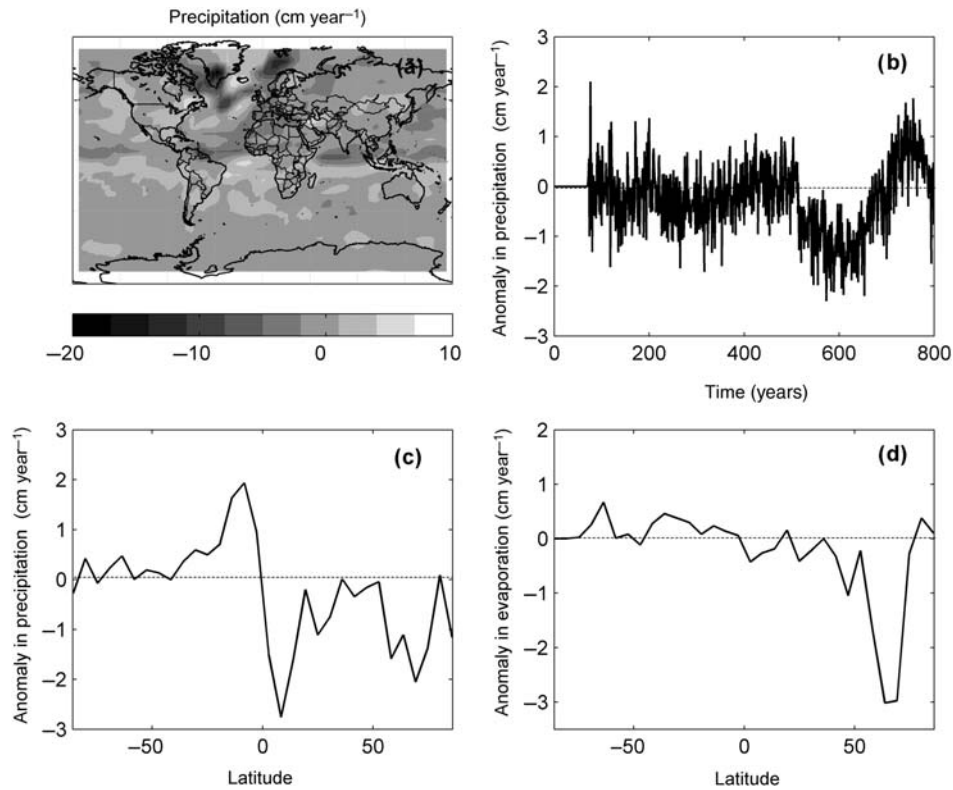


Figure 6. (a) Mean precipitation (cm year^{-1}) during the 800 years of period simulated for a variability of 70 years in the input of freshwater. (b) Time-series of anomaly of mean precipitation (cm year^{-1}) during the 800 years of period simulated. (c) Anomaly of mean precipitation (cm year^{-1}) vs. latitude. (d) Anomaly of average of evaporation (cm year^{-1}) vs. latitude.

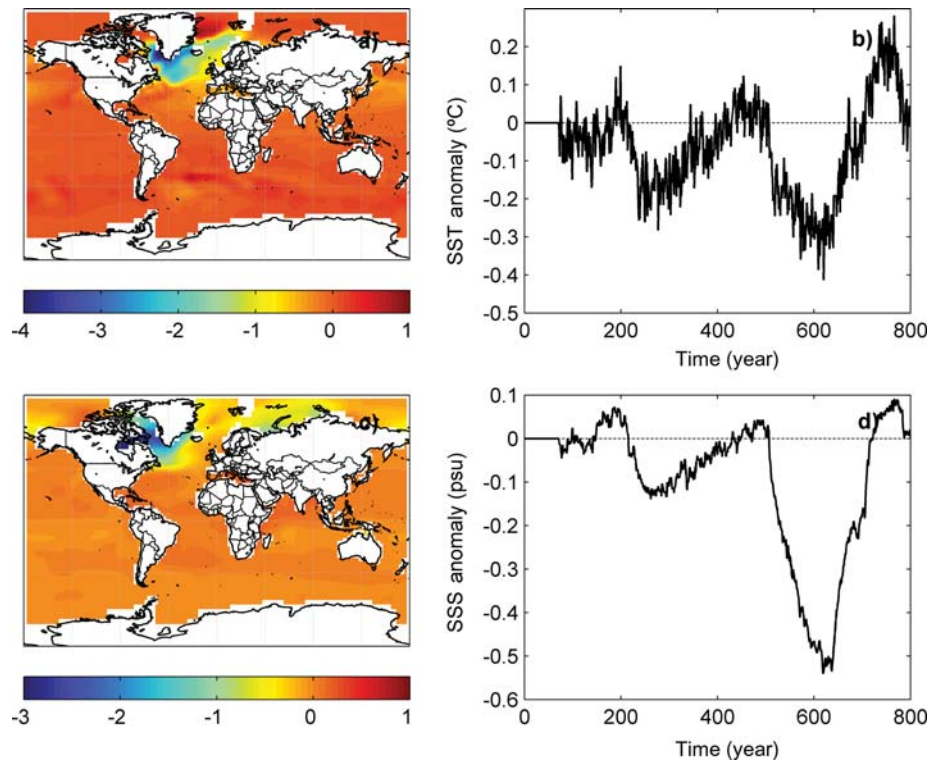


Figure 7. (a) Mean sea surface temperature (SST; $^{\circ}\text{C}$) during the 800-year simulation of variability in the input of freshwater of 70 years. (b) Time-series of anomaly of mean SST ($^{\circ}\text{C}$) during the 800-year simulation. (c) Mean sea surface salinity (SSS; psu) during the 800-year simulation. (d) Time-series of SSS (psu) anomaly during the 800-year simulation.

salinity exhibits very small variations with increments of ~ 0.5 psu (Figure 7c). Figure 7d shows the global average of the temporal evolution of the SSS anomalies.

Conclusions

In this study, we investigated the influence of signals with noisy intensity and different time-scales on THC, using the ECBilt–Clio model. We focused on the effect of a decadal (10 years) and multidecadal scale (70 years). The choice of these periods was motivated by previous studies that demonstrated that changes in the freshwater flux were related to the ENSO. This phenomenon is characterized by decadal and multidecadal modulations, caused by the variability of SSTA in the Equatorial Pacific. Results indicate that if an input of freshwater is introduced in the model, and the intensity of this input varies in a random way using variability periods of either 10 or 70 years, THC does not collapse, but it does weaken. This weakening is more pronounced if the variation in freshwater input is simulated stochastically every 70 years. Weakening of this circulation causes air surface temperature to diminish, mainly in the North Atlantic. A weakening of the stream function at 500 mb is also observed, indicating that the atmosphere in the northern hemisphere is less energetic, and consequently, rainfall decreases over Europe. The effects on SST are similar to those for surface air temperature, but in this case, the area affected is mainly the North Atlantic around Greenland, with a greater effect also occurring because of multidecadal scale variation, so that SSS diminishes around Greenland, mainly in the Labrador Sea and Hudson Strait.

In summary, the results of the study demonstrate that the addition of a signal that varies stochastically with a decadal or multidecadal period could induce a weakening of the THC.

Current knowledge suggests that the probability of a complete collapse of the THC is low, but this view should be treated with caution, because the models do not reproduce decadal and multidecadal variability satisfactorily, nor do they consider processes that occur below certain temporal and spatial scales. Such deficiencies could mask the real dynamics of the climate system. The picture that emerges in IPCC AR4 is that the most likely scenario for THC is a weakening during the 21st century, provoked by climate change. The simultaneous weakening that could occur because other mechanisms are in play, such as the one proposed herein, increases the probability of a complete collapse of the THC.

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