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Abstract

The Atlantic thermohaline circulation (THC) is an important component in the climate system because it strongly influences conditions in the North Atlantic region. Most climate models simulate a reduction of the THC in response to global warming, some even a complete and potentially irreversible shutdown. To avoid such irreversible climate changes, one may design climate policies that curb greenhouse gas emissions to levels preventing a THC collapse. To evaluate such mitigation policies, we use a slightly enhanced version (E-MERGE) of the MERGE model of Manne, Mendelsohn and Richels, where the climate module's parameters have been revised with the latest findings of the Intergovernmental Panel on Climate Change. Depending on the assumed climate sensitivity, our analysis shows that preserving the THC may require in particular a strong carbon dioxide emission reduction from todays level.

Résumé

La circulation thermohaline atlantique est une composante importante du système climatique parce qu'elle influence fortement les conditions dans la région de l'Atlantique Nord. La plupart des modèles climatiques simulent une réduction de la circulation thermohaline en réponse au réchauffement global; certains modèles simulent même un arrêt, potentiellement irréversible, de la circulation thermohaline. Pour éviter de tels changements climatiques irréversibles, on peut concevoir des politiques climatiques qui réduisent les émissions de gaz à effet de serre à des niveaux prévenant un arrêt de la circulation thermohaline. Pour évaluer de telles politiques de prévention, nous utilisons une version légèrement améliorée (E-MERGE) du modèle MERGE de Manne, Mendelsohn et Richels, où les paramètres du module climatique ont été révisés avec les dernières estimations du Groupe Intergouvernemental d'experts sur l'Évolution du Climat. Dépendamment de la sensibilité présumée pour le climat, notre analyse montre que préserver la circulation thermohaline peut en particulier nécessiter une réduction importante des émissions de dioxyde de carbone par rapport à leur niveau actuel.

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1 Introduction

Extreme climatic events can have severe economic and social consequences IPCC (2001a). Such events range from individual droughts, floods and storms to changes in mean temperatures and weather patterns possibly connected with larger-scale changes in ocean circulation, sea and land-ice cover. Here we focus on the possibility of a collapse of the Atlantic meridional overturning circulation. The dynamics of such an event are understood in outline at least, although the associated probabilities remain extremely uncertain Knutti *et al.* (2003).

The present-day circulation of the Atlantic features a strong surface current, the Gulf Stream and its extension, which transports warm water into high northern latitudes where it sinks to great depth, returning southwards as a cold, dense boundary current. The formation and sinking of dense water in the north is driven by strong heat loss to the atmosphere and changes in salinity due to precipitation and ice formation. The resulting circulation pattern is thus frequently referred to as the thermohaline circulation (THC) although the circulation is also strongly and nonlinearly influenced by wind forcing.

This overall pattern of circulation is responsible for the relatively mild climate of Europe. However, analytical and numerical studies, as well as paleoclimate data, indicate that it may not be the only stable state of Atlantic circulation Stocker *et al.* (2001), Alley *et al.* (2003). Changes in surface temperature, precipitation, winds and sea ice formation, driven by greenhouse gas (GHG) emissions, in combination with natural intrinsic climate oscillations, may cause the circulation to change drastically over a period of decades in a so-called ‘thermohaline collapse’ to a state with a much weaker northward extension of the Gulf Stream and hence a radically different climate in the North Atlantic region.

To avoid such drastic changes, one may be tempted to design a climate policy preserving the THC. Such an approach would be in line with the United Nations Framework Convention on Climate Change UNFCCC (1992) that has called for the “*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*”.

To design such a climate policy, one may rely on integrated assessment, an interdisciplinary approach that uses information from different fields of knowledge, in particular socio-economy and climatology. Integrated Assessment Models (IAMs) are tools for conducting an integrated assessment, as they typically combine key elements of the economic and biophysical systems, elements that underlie the anthropogenic global climate change phenomenon.

Several studies conducted with IAMs have already considered the generic possibility of ‘catastrophic’ climate changes, but without focusing on any of the specific geophysical ‘catastrophes’ listed by the IPCC (2001c); see for instance Wright and Erickson (2003) for a critical discussion of these studies. By contrast, only a few papers have taken explicitely into account a possible collapse of the THC.

Zickfeld and Bruckner (2002) use a 'tolerable windows approach' Bruckner *et al.* (1999) to compute emission corridors preserving the THC. Their IAM consists of a simple, impulse-response climate model from the ICLIPS toolbox Bruckner *et al.* (2003) coupled to a dynamic, four-box model of the Atlantic THC. Socio-economic consideration appears only as constraints (maximum rate of emission reduction and minimum time span for the transition towards a de-carbonizing economy). Keller *et al.* (2000, 2004) and Mastrandrea and Schneider (2001) use the DICE model Nordhaus (1994) as one of the main components of their integrated assessment. DICE is a simple and transparent dynamic growth model that has been used in various studies but that has also been strongly criticized for its over-simplicity, see for instance Kaufmann (1997). In particular, possibilities to curb CO_2 emissions are only described in DICE in an aggregated way.

The climate component in the study of Mastrandrea and Schneider (2001) is similar to that of Zickfeld and Bruckner (2002), with a consistent coupling achieved by iteration between the climate and economic growth components. In Keller *et al.* (2000), the possibility of THC collapse is accounted for by incorporating constraints on CO_2 concentrations (and thus implicitly also on emission rates) derived from the work of Stocker and Schmittner (1997) who used the Bern 2.5-D model. Their climate representation is thus very similar to that employed here (see Section 3). Keller *et al.* (2004) take this approach a stage further by using the results as input to a probabilistic optimisation procedure which addresses the uncertainty in climate sensitivity and threshold-specific damage by using a minimal number of samples (100) to construct probability density functions.

In a first attempt to detail energy choices preserving the THC, we use in this paper the MERGE model of Manne *et al.* (1995), another well-established IAM. It uses in particular an energy module that details several technological options to curb CO_2 emissions (see Section 2.1, below). Besides this energy module, MERGE consists of another three interrelated modules: macro-economic growth, climate and damage. As far as the climate module is concerned, the structure of MERGE requires that it can be solved analytically, thus we are restricted to extremely simple representations of climate dynamics within the model itself. However, MERGE may also contain information derived from other climate models in the form of constraints.

In this study we design such constraints to avoid the collapse of the THC. Although the reduction of complex natural climate dynamics to a simple set of constraints constitutes a drastic simplification, our approach allows us to investigate the basic response of MERGE to a possible collapse. Furthermore, we can assess the extent to which the response is sensitive to the principal uncertain parameters of the climate submodule, within the approximate range to which such parameters are known. As such, this represents an important step towards integrated assessment studies with more complicated models. Uncertainty regarding the future behaviour of the natural climate system, even for a given, fixed emissions scenario is, to a large extent, inevitable due to the uncertainty of many forcings and feedback processes in the climate system Stocker *et al.* (2001), IPCC (2001a), Knutti *et al.* (2003). Quantitative assessment of the uncertainties associated with climate prediction typically involves large ensembles of runs Knutti *et al.* (2003) (although other techniques can be applied, Annan *et al.* (2004), Forest *et al.* (2001), Allen *et al.* (2000)) and therefore requires highly efficient models, especially when the behaviour of the deep ocean is involved. The behaviour of the THC poses special modelling problems since, although the THC may be capable of responding dramatically to change within decades, its response also depends on historical forcing conditions over a period of hundreds of years or more.

In this study we make use of results from two types of climate models in addition to MERGE's climate submodule. To estimate constraints on total warming and on the rate of warming required to avoid thermohaline collapse, we use results from a large ensemble of runs of the Bern 2.5-D climate model Stocker *et al.* (1992). In updating parameters of the climate submodel of MERGE, we also make use of results from C-GOLDSTEIN Edwards and Marsh (subm.) a slightly less efficient model with more complete ocean dynamics.

The remainder of this paper is organised as follows. In Sections 2 and 3, we recall the main characteristics of MERGE (2.1), describe our update of the climate module (2.2) and define necessary conditions for the preservation of the THC. Section 4 presents some numerical results and finally Section 5 some concluding remarks.

2 Modelling framework

2.1 MERGE

MERGE is a M̲odel for E̲valuating the R̲egional and G̲lobal E̲ffects of GHG reduction policies. As far as the regional disaggregation is concerned, MERGE distinguishes among nine geopolitical regions. The first five regions constitute Annex B of the Kyoto Protocol to the UNFCCC United Nations (1997): Canada, Australia and New Zealand (CANZ); Eastern Europe and the former Soviet Union (EEFSU); Japan; OECD Europe (OECDE) and the USA. The last four correspond to the non-Annex B regions: China; India; Mexico and OPEC (MOPEC); and the rest of the world (ROW).

Figure 1 displays the four modules of MERGE (energy, macro-economic, climate and damage modules) that enables one to perform integrated assessment of climate policies.

The first module (ETA) corresponds to a bottom-up engineering model. It describes the energy supply sector of a given region, in particular the production of non-electric energy (fossil fuels, synthetic fuels and renewables) and the generation of electricity. It captures substitutions of energy forms (e.g., switching to low-carbon fossil fuels) and energy technologies (e.g., use of renewable power plants instead of fossil ones) to comply with GHG (CO_2 and CH_4) emission reduction requirements.

The second module (MACRO) corresponds to a top-down macro-economic growth model. It balances the rest of the economy of a given region using a nested constant elasticity of substitution production function. The latter allows substitutions between a

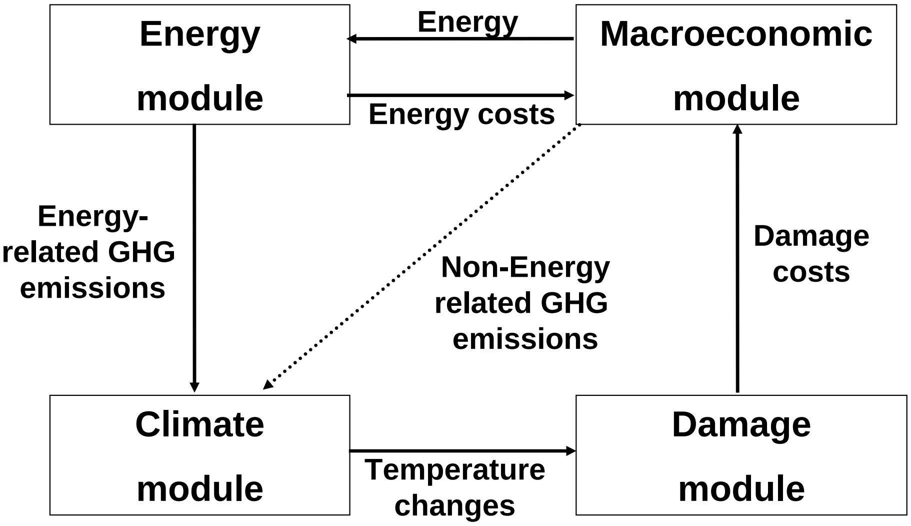

Figure 1: Overview of the MERGE modules.

value-added aggregate (capital and labour) and an energy aggregate (electric and non-electric energy). MACRO captures macro-economic feedbacks between the energy system and the rest of the economy, for instance impacts of higher energy prices (due to GHG emission control) on economic activities.

The resulting regional ETA-MACRO models are cast as optimisation problems, where economic equilibrium is determined by a single optimisation. More precisely, an ETA-MACRO model maximises a welfare function defined as the net present value of regional consumption. Notice that the wealth of each region includes capital, labour, fossil fuels (viewed as exhaustible resources) as well as its initial endowment in emission permits (if any). MERGE links then the regional ETA-MACRO models by aggregating the regional welfare functions into a global welfare function. Regional ETA-MACRO models are further linked by international trade of oil, gas, emission permits, energy-intensive goods as well as an aggregate good in monetary unit (numéraire good) that represents all the other traded goods. A global constraint ensures that international trade of these commodities is balanced.

ETA-MACRO models yield anthropogenic emissions of CO_2, CH_4 and N_2O. A third module, the climate module, describes how GHG increases in the atmosphere affect temperature. More precisely, it first computes changes in atmospheric GHG concentrations, then impacts on the earth's radiative forcing balance and finally mean temperature changes. We have revised this climate module updating several parameters with the latest IPCC findings; see Section 2.2 for more details.

Finally, the fourth module is a damage module that assesses how temperature changes cause quantifiable economic losses, distinguishing among market damages (damages that can be valued using market prices) and non-market damages (to elements like biodiversity that do not have direct market value).

Using its four modules, MERGE may be used to perform cost-benefit analysis to determine GHG emission trajectories that balance costs of GHG reduction with benefits of avoiding climate changes. In this paper, we perform instead cost-effectiveness analyses to find optimal GHG emission trajectories that enable one to stay below maximum temperature change limits. Such analyses rely only on the first three modules.

2.2 E-MERGE

This section recalls briefly the climate module of MERGE and indicates the parameter update we have performed from version 4.6. For a detailed presentation of this module, the reader is referred to Manne *et al.* (1995). In updating parameters, we take the simplest possible approach to uncertainty in their values. The problem reduces to the uncertainty in two governing parameters representing climate sensitivity and a lag timescale dependent on ocean dynamics. We span the range of likely responses simply by matching extreme values of these parameters to obtain 'best' and 'worst' case scenarios of atmospheric temperature response.

As mentioned before, MERGE considers three GHGs: CO_2, CH_4 and N_2O, whose emissions come from energy as well as (exogenously assumed) non-energy sources. Based on these emissions, the climate module computes future atmospheric stocks of these GHGs.

Atmospheric stocks of CO_2 are computed using the carbon cycle model of Maier-Reimer and Hasselmann (1987). The effect of using a more complicated, but still essentially empirically fitted, rather than physically based, model have already been considered by Joos *et al.* (1999). We do not expect that the inclusion of such a model here would qualitatively affect our conclusions, which are focused on the basic sensitivity of MERGE to a possible THC collapse.

Atmospheric stocks of CH_4 and N_2O (in Giga tonne) are computed as follows:

$$S_{g,t+1} = k_g * S_{g,t} + E_{g,t} \tag{1}$$

where for a gas g (CH_4 or N_2O), $S_{g,t}$ is its atmospheric stock in year t, k_g its retention factor and $E_{g,t}$ the emissions in year t. Notice that the time step used in (1) is 1 year. The parameter k_g is estimated as follows:

$$k_g = 1 - \frac{1}{\tau_g} \tag{2}$$

where τ_g is the atmospheric lifetime of gas g. Following Joos *et al.* (2001), these parameters have been updated as follows: $\tau_{\mathrm{CH_4}} = 8.4$ years and $\tau_{\mathrm{N_2O}} = 120$ years.

The climate module then computes the impact of future atmospheric GHG concentrations on the earth's radiative forcing balance. Following again Joos *et al.* (2001), the radiative forcing RF (in $\mathrm{W\,m^2}$) for CO_2 is:

$$RF_{\mathrm{CO_2}}(t) = 5.35 * \ln\left(\frac{\mathrm{CO_2}(t)}{\mathrm{CO_2}(t_0)}\right) \tag{3}$$

where the value of the coefficient in (3) has been updated from a previous value of 6.3 W m^{-2}, $\mathrm{CO_2}(t)$ is the atmospheric CO_2 concentration (in ppm) at year t and t_0 corresponds to the starting model year (2000). The radiative forcing of N_2O (in W m^{-2}) is computed as follows:

$$\begin{aligned} RF_{\mathrm{N_2O}}(t) \quad = \quad & 0.12 * \left(\sqrt{\mathrm{N_2O}(t)} - \sqrt{\mathrm{N_2O}(t_0)}\right) \\ & - f\left(\mathrm{CH_4}(t_0), \mathrm{N_2O}(t)\right) + f\left(\mathrm{CH_4}(t_0), \mathrm{N_2O}(t_0)\right) \end{aligned} \tag{4}$$

where the value of the coefficient in (4) has been updated from a previous value of 0.14 W m^{-2}, $\mathrm{N_2O}(t)$ (resp. $\mathrm{CH_4}$(t)) is the atmospheric N_2O (resp. CH_4) concentration (in ppb) at year t and f is a function that accounts for the overlap in CH_4 and N_2O. Notice that the computation of the radiative forcing of CH_4 has not been updated.

The radiative forcing effect on the long-term equilibrium temperature ET (in °C) is next computed as follows:

$$ET(t) = d_s * (RF_{\mathrm{CO_2}}(t) + RF_{\mathrm{CH_4}}(t) + RF_{\mathrm{N_2O}}(t)) - ES(t) \tag{5}$$

where $ES(t)$ corresponds to a cooling effect (in °C) of exogenously assumed sulfur emissions and d_s is a parameter (in °C W^{-1} m^2) depending on the assumed climate sensitivity s (in °C). This parameter d_s[1] is estimated as follows:

$$d_s = \frac{s}{5.35 * \ln(2)} \tag{6}$$

where we choose s as follows: $s = 2$ °C for a 'low' climate sensitivity, $s = 3$ °C for a 'medium' sensitivity and $s = 4$ °C for a 'high' sensitivity. Parameter s is thus chosen within the uncertainty range (1.5 to 4.5 °C) given by the IPCC (2001b). Finally, the actual temperature AT (in °C) will lag behind the equilibrium temperature as follows

$$AT(t+1) - AT(t) = c_s * (ET(t) - AT(t)) \tag{7}$$

where $c_s = 1/lag_s$. Over the next century or so the atmospheric lag timescale lag_s is essentially controlled by the uptake and transport of heat by the global ocean circulation, whereas over longer periods changes to the cryosphere will extend this timescale. This

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[1] Notice that in MERGE 4.6, $d = 0.572$.

timescale is likely to be more realistically estimated by a model which includes fully 3-dimensional ocean dynamics. This estimate is expected to be highly sensitive to ocean mixing parameters, and long integrations are required to evaluate it for any given parameter set. Thus an efficient model is still required to estimate the range of possible values of lag_s.

A suitable model is C-GOLDSTEIN Edwards and Marsh (subm.) (EM) which features a 3-dimensional ocean and a thermodynamic and dynamic sea-ice component, but, like the Bern 2.5-D model Stocker *et al.* (1992), only a 1-layer energy and moisture balance representation of the atmosphere. C-GOLDSTEIN is an order of magnitude less efficient than the Bern 2.5-D model, but still several orders of magnitude faster than high-resolution coupled models. From a randomly generated set of 1000 runs of this model, EM have considered the effect of ocean and atmospheric mixing parameters on idealised equilibrium solutions and global warming predictions. EM define a subset of 21 of these simulations for which the agreement between long-term averages of spatially-resolved atmospheric and oceanic data and equilibrium solutions unforced by anthropogenic emissions lies within an acceptable range. The mean and range of values for the lag timescale lag_s is derived from this subset for a particular idealised warming scenario. The parameter lag_s is thus chosen as follows.[2]: $lag_s = 77$ years when $s = 2$, 57 years when $s = 3$ and 45 years when $s = 4$ Note that the association of low atmospheric GHG sensitivity s and long atmospheric lag timescale lag_s values is purely intended to span the widest reasonable range of atmospheric temperature responses, effectively giving 'best' and 'worst' case scenarios.

Notice that lags obtained from C-GOLDSTEIN should not depend sensitively on the choice of scenario or warming rate, but are found to be relatively sensitive to the period over which the lag time is determined. This indicates that over longer timescales the model behaviour is not well fitted by the exponential approach to equilibrium assumed by (7). However, at this stage we are interested in the gross sensitivity of MERGE's predictions to the behaviour of its simple climate submodel. The much more subtle issue of the errors induced by the inability of such a simple model to faithfully represent the behaviour of more complex climate models must remain an issue for further research.

3 Preserving the THC

To estimate the level and rate of GHG emissions likely to induce a collapse of the THC we use the Bern 2.5-D climate model. This model is based on 2-dimensional (latitude-depth) representations of the flow in each of the Pacific, Atlantic and Indian Oceans. These three basins are connected via a 2-dimensional (longitude-depth) representation of the Southern Ocean Stocker *et al.* (1992). The model also includes a 1-layer energy and moisture balance representation of the atmosphere Schmittner and Stocker (1999) and a thermodynamic representation of sea ice. In the version used here, GHG forcings are parameterised as changes in radiative forcing at the top of the atmosphere.

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[2] Notice that in MERGE 4.6, $lag = 40$ years.

Constraints are derived from a Monte-Carlo ensemble of 25000 global warming simulations with values of climate sensitivity and of radiative forcing components for each of the 32 GHGs varied randomly within their uncertainties Knutti *et al.* (2003). Future emissions were scaled to SRES scenario B1 (results were very similar for scenario A2) and 5 different sets of ocean model parameters were used. Only simulations which matched observed global mean surface warming from 1900 to 2000 and observed ocean heat uptake from 1955 to 1995 were retained, a subset of around 10% of the simulations. A collapse of the THC was defined as a reduction of over 50% in the maximum Atlantic overturning (ie the maximum northward flux of water mass in the Atlantic) compared to the equilibrium overturning in the absence of anthropogenic climate forcing. Previous studies have found that a relatively sharp transition in the THC occurs Marsh *et al.* (2004) such that values of overturning less than 12 Sv (1 Sv = 10^6 m^3/s) (Tziperman, Nature 1997) or about 10 Sv Knutti and Stocker (2002) lead to a collapse of the THC to a level of only a few Sv within a few decades. The exact value of such a threshold, if it exists in nature, remains extremely difficult to determine, but taking a threshold value of 50% is in broad agreement with the numbers quoted above. Indeed, the term ‘threshold behaviour’ refers to the fact that the system naturally avoids intermediate states, thus the value used to separate ‘high’ and ‘low’ values should have very little effect.

To a first order, the simulations satisfying the threshold of less than 50% THC reduction can be characterized by two necessary constraints on the maximum absolute warming and on the maximum warming rate, both linear functions of time.

4 Numerical Results

This section will analyse climate policies preserving the Atlantic THC and compare them to alternative policies (business-as-usual and Kyoto like policy).

4.1 Scenario characterisation

Notice first that the database of E-MERGE corresponds to that of MERGE 4.6, with the exception of the climate module, as explained in Section 2.2. Notice further that E-MERGE, contrary to the original MERGE model, for the sake of simplicity, does not consider endogenous technological progress in the energy sector. For an extensive discussion of considering endogenous technological progress in MERGE, the reader is referred in particular to Kypreos and Bahn (2003) and Bahn and Kypreos (2003).

The first scenarios considered are baseline cases where GHG emissions are not limited. They assume a world population level of 8.9 billion by 2050 and 10.1 by 2100. Between 2000 and 2100, world GDP grows almost 9 times (up to 294 trillion USD 1990), whereas primary energy supply and carbon emissions increase about 4 times each (up to 1598 EJ/year[3] and 25.1 Gt C, respectively). Notice that in terms of CO_2 emissions, our baseline scenario is

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[3] 1 EJ = 10^{18} J.

relatively close to the SRES A2 scenario IPCC (2000). We present here three baseline cases: BL, a case with low climate sensitivity ($s = 2$ °C) and long mean lag for the ocean warming ($lag_s = 77$ years); BM with medium climate sensitivity (3 °C) and mean lag (57 years); and BH with high climate sensitivity (4 °C) and short mean lag (45 years).[4]

The next scenario is a 'Kyoto trend' scenario, where constraints are imposed on CO_2 emissions as follows. Annex B of the Kyoto Protocol (except USA) must comply with their Kyoto target by 2010. Afterwards, they have to reduce their emission by 5% per decade. They are joined in this reduction trend by the USA in 2020 and by non-Annex B regions in 2050. As a consequence of these reduction constraints, world carbon emissions peak in 2050 at 9.7 Gt C and decrease afterwards to 7.1 Gt C by 2100. Depending again on the assumed (low, medium or high) climate sensitivity and mean lag for the ocean warming, we present three Kyoto trend scenarios: KL (2 °C, 77 years), KM (3 °C, 57 years) and KH (4 °C, 45 years).[5]

Recall now that Section 3 has defined constraints on maximum absolute warming and maximum warming rate that correspond to necessary conditions for preserving the THC. Figure 2 assesses whether our baseline and Kyoto trend scenarios satisfy these conditions.

Figure 2 reveals first that the necessary condition on maximum warming is less demanding than the one on maximum warming rate. We will thus concentrate our comments on the second necessary condition. Notice first that whatever the assumed climate sensitivity, our baseline scenario fails to preserve the THC. We recall, however, that in terms of CO_2 emissions, this scenario is at the high end of the SRES. Nevertheless, it is interesting to note that (for the BH scenario) the combination of high emission level and climate sensitivity violates the constraint for preservation of the THC between 2030 and 2040. In other words, a delay of emission reductions by only several decades would be very likely, under some conditions, to make a future collapse inevitable. It is also striking to note that the CO_2 reductions imposed by the Kyoto trend scenario do not prevent a THC shutdown when climate sensitivity is either medium or high. They merely postpone by a few decades at most the situation where a collapse can no longer be avoided.

Finally, the last scenario corresponds to a 'THC preservation' policy, where a collapse is prevented by imposing our constraints on maximum absolute warming and maximum warming rate. Depending once more on the assumed climate sensitivity and mean lag for the ocean warming, we present three THC preservation scenarios: PL (2 °C, 77 years), PM (3 °C, 57 years) and PH (4 °C, 45 years).

4.2 Preservation policies

We assume here that there is a world regulator (e.g., United Nations) that monitors the Earth's warming. This regulator has also a prefect knowledge of the actual climate sensi-

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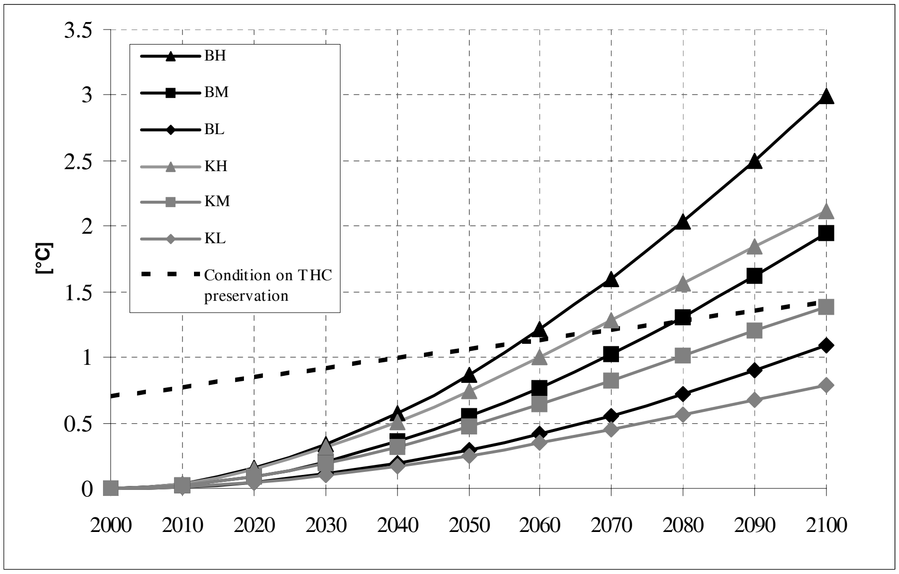
[4] Notice that socio-economic development paths and resulting GHG emissions are identical for all these scenarios. The later differ only by the climatic impacts of these emissions.

[5] Same remark as in the previous footnote.



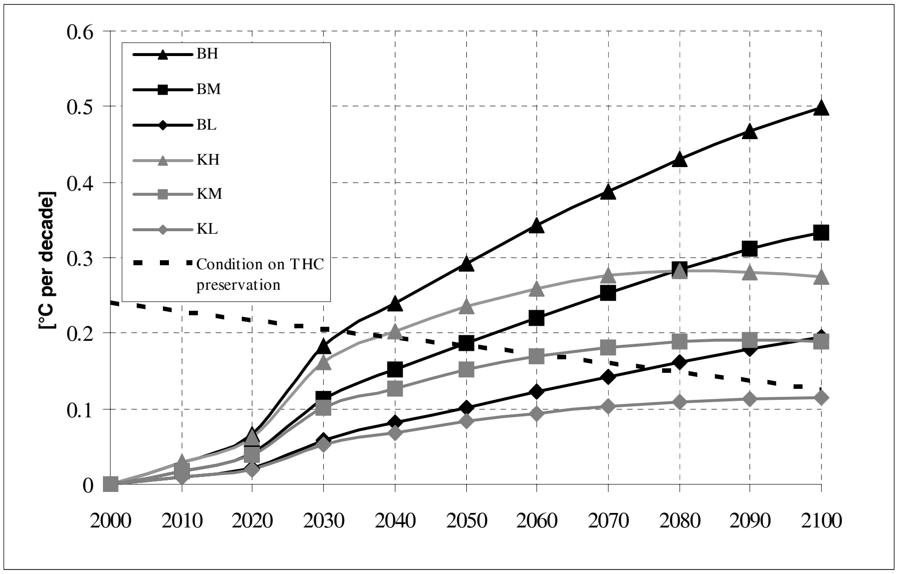


Figure 2: Warming (from 2000) (top) and warming rate per decade (bottom) for the baseline (denoted B.) and Kyoto trend (denoted K.) scenarios, as well as necessary conditions for preserving the THC, in terms of maximum warming and maximum warming rate respectively. Cases L, M and H denote low, medium and high climate sensitivity assumptions respectively.

tivity. It is then able to impose, depending on the assumed climate sensitivity, worldwide GHG emission reductions such that our necessary conditions on THC preservation are respected. We have seen in the previous Section 4.1 that the condition on maximum warming rate is the more demanding. Figure 3 reports on the evolution of the warming rate under the three THC preservation scenarios.

It is apparent from Figure 3 that the higher the assumed climate sensitivity, the sooner the THC preservation constraint becomes binding: in year 2100 when the sensitivity is low, 2070 when medium and 2050 when high. In the latter case, the constraint is again not binding in 2070, as the GHG reduction effort in the previous decades yields here a slight margin, and towards the end of the horizon, where the constraint on absolute warming becomes binding.

Given the simple climate dynamics of E-MERGE, these constraints on temperature translate simply into conditions for atmospheric GHG concentrations. As an illustration, atmospheric CO_2 concentration at year 2100 reaches 599 ppm in the PL scenario, 507 in PM and 446 in PH. We would like to stress that a doubling of pre-industrial CO_2 atmospheric concentration by 2100 (at 550 ppm), sometimes considered in the literature as a 'safe' target, would fail here to preserve the THC except at the upper limit of the assumed possible climate sensitivities.

Conditions for GHG concentrations yield in turn conditions for GHG emissions. In the E-MERGE model, the energy sector is the endogenous source of anthropogenic GHG emissions. Figure 4 displays the world energy-related CO_2 emissions under the three THC preservation scenarios, as well as under the baseline and Kyoto trend scenarios, recalling that in the two latter cases, emission paths do not depend on the assumed climate sensitivity.[6]

Figure 4 shows that CO_2 emissions in the PL and PM scenarios follow roughly the baseline trajectory until 2040 and 2020 respectively, whereas the PH scenario follows the Kyoto trend trajectory until 2020. Afterwards, all trajectories show a sharp reduction, to meet the (binding) constraint on warming rate. Notice however the increase around 2070 in the PH scenario, as the constraints on THC preservation (warming and warming rate) are not binding. There is also an increase around 2080 in the PM scenario, but here the strong reduction forced in 2070 to respect the constraint on warming rate, that becomes binding for the first time, can be compensated in 2080 while having again the constraint on warming rate binding. It has to be noted here that the timestep used in E-MERGE is 10 years, thus these oscillations constitute a form of unresolved oscillatory behaviour which would certainly be modified if the timestep were reduced. Such behaviour is however a characteristic of imposing a state constraint within a control problem, which corresponds to the modelling paradigm of E-MERGE.

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[6] Notice also that our Kyoto trend scenario imposes a constraint on CO_2 emissions only, whereas in the THC preservation scenario, one has the flexibility to reduce also (energy related) CH_4 emissions.

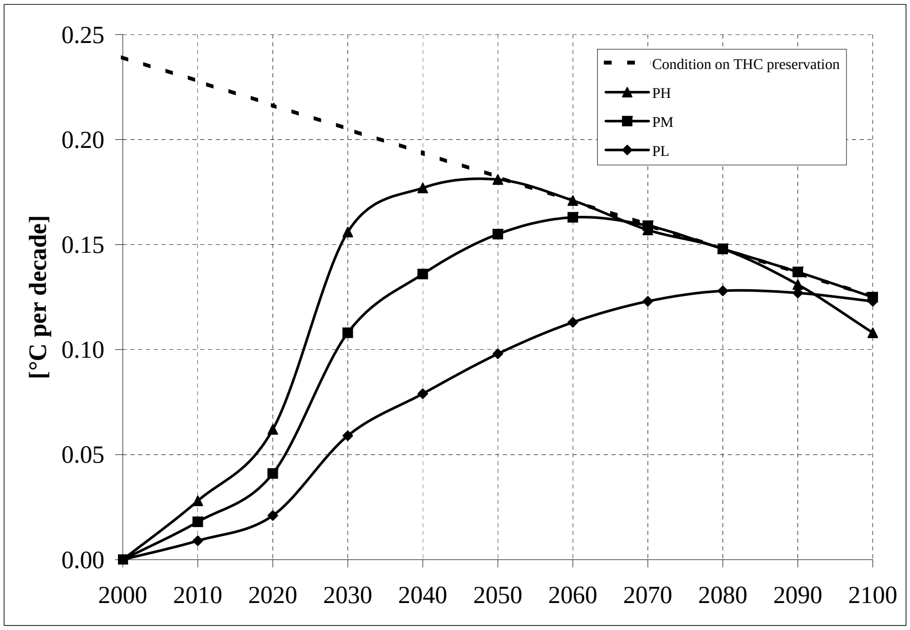

Figure 3: Warming rate for the THC preservation scenarios, as well as the necessary condition for preserving the THC in terms of maximum warming rate. Cases L, M and H denote low, medium and high climate sensitivity assumptions respectively.

In order to follow the emission trajectories (in particular CO_2) the model calculates the required restructuring of the regional energy sectors, recalling again that in E-MERGE energy sectors are the endogenous source of anthropogenic GHG emissions. Figure 5 reports on the world primary energy use for the three THC preservation scenarios in comparison to the baseline and Kyoto trend scenarios.

Figure 5 provides for reference the 2000 world primary energy use as well as the situation in 2050 and 2100. We will concentrate our comments on the last period where differences among scenarios are the greatest. Notice first that the baseline and Kyoto trend scenarios follow rather similar patterns, with only slightly less primary energy and fossil fuels used in the latter scenario. Now compared to the baseline, the THC preservation scenarios require from 14 % (scenario PL) to 18% (PH) less primary energy. Indeed, curbing energy related GHG emissions increases energy prices. On the one hand, this yields GDP losses. On the other hand, the other two production factors (capital and labour) becomes less expensive compared to energy. They can thus substitute partly for energy in the production structures. Both effects yield less energy demanded by the economy. Besides using less primary energy, preserving the THC also requires changes in the energy mix. The main impact here is the increased use of renewables and nuclear energy. The share of this

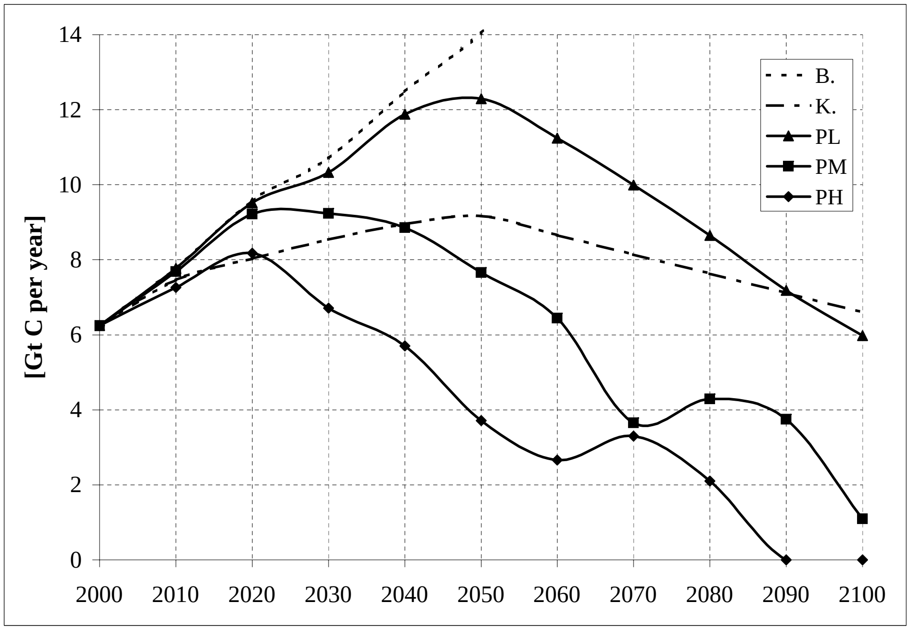

Figure 4: World energy related CO_2 emission trajectories under the baseline (denoted B.), the Kyoto trend (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases L, M and H denote low, medium and high climate sensitivity assumptions respectively, recalling that emission paths for the baseline and Kyoto trend scenarios are independent of the assumed climate sensitivity.

category is 27% in the baseline, but ranges from 37% in the PL scenario to 53% in PH. There are also inter-fossil substitutions from coal to gas, especially in the PM and PH scenarios. The fact that a significant amount of fossil energy (coal, in particular) is still used while preserving the THC might surprise the reader. In fact, fossil energy is here mostly used in power plants equipped with carbon capture systems, which explains the fact that emissions are able to sink to zero at 2090 in the PH scenario. Figure 6, which displays world electricity generation by power plant types, illustrates that point. Recall also that in E-MERGE technological progress is exogenously assumed. With an endogenous representation of technological progress or with different assumptions for the cost evolution of renewable energy technologies, different configurations of the regional energy systems (relying more on renewable energies) could be selected to achieve the GHG emission reductions.

Finally, E-MERGE enables one to assess economic consequences of restructuring the regional energy sectors, compared to the baseline case. Figure 7 gives world GDP losses (in percentage from the baseline) for the Kyoto trend and THC preservation scenarios. It should be recalled, however, that in this analysis the model assesses only costs of reducing

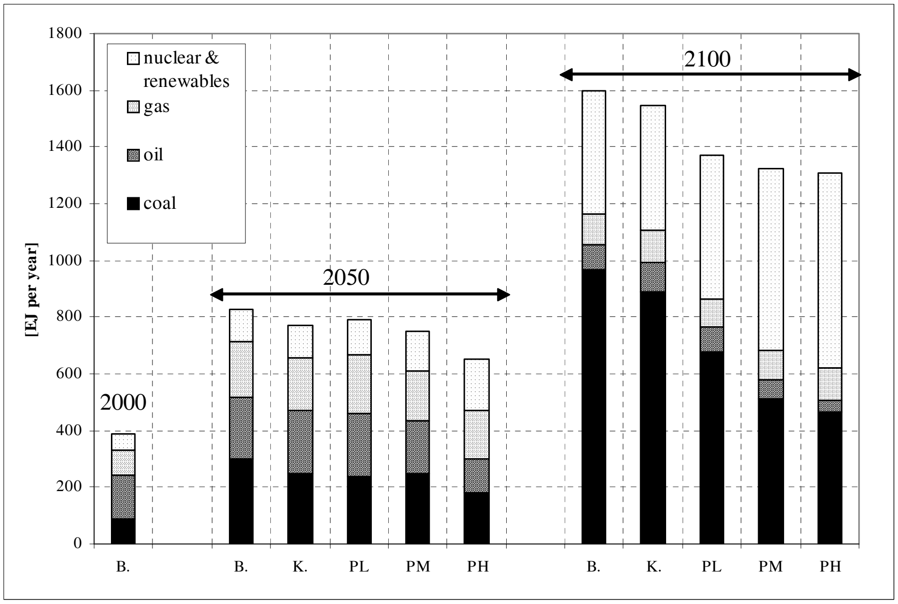

Figure 5: World primary energy use for the baseline (denoted B.), the Kyoto trend (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases L, M and H denote low, medium and high climate sensitivity assumptions respectively. Note that primary energy use for the baseline and Kyoto trend scenarios are independent of the assumed climate sensitivity.

GHG emissions without accounting for the benefits of avoiding a THC shut-down. Indeed, neither market benefits nor more subtle non-market benefits are here accounted for.

4.3 Comparison to previous studies

Our paper follows a cost-effective approach to determine an optimal configuration of the regional economies and energy systems that respects necessary conditions for preserving the THC. By contrast, several previous studies (Keller *et al.* (2000, 2004) and Mastrandrea and Schneider (2001)) have followed (at least partly) a cost-benefit approach that balances costs of reducing GHG emissions with benefits associated with avoiding a THC collapse.

A cost-effective approach to the THC issue has several limitations (Keller *et al.* (2004)): it does not in particular consider the possibility of only postponing a collapse (and the associated damages) and considers implicitly (from a cost-benefit perspective) infinite damages associated with a collapse. But a cost-benefit approach to abrupt climate changes itself suffers several limitations (see for instance Wright and Erickson (2003)) due in particular to: the large uncertainties associated with the magnitude of damages a THC collapse

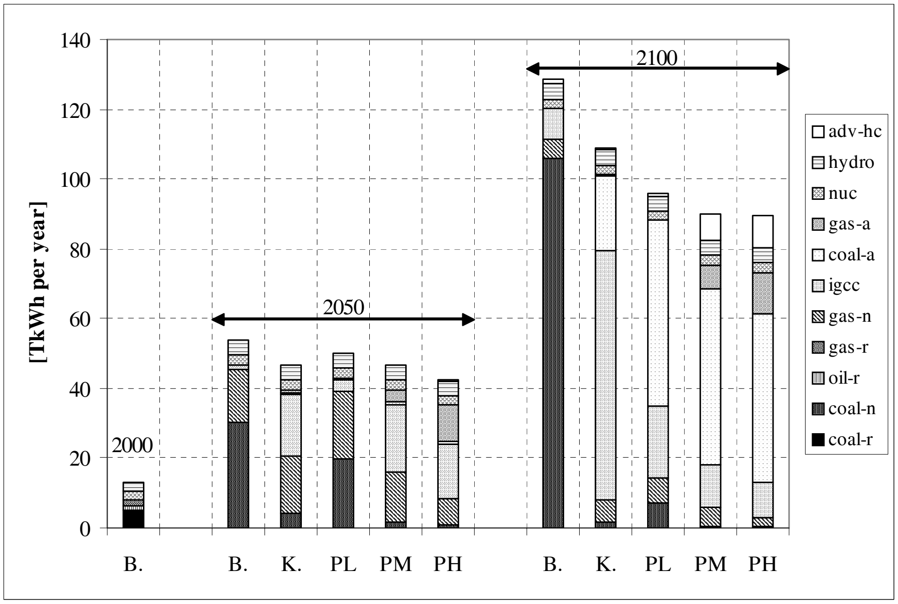

Figure 6: World electricity generation by power plant types for the baseline (denoted B.), the Kyoto trend (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases L, M and H denote low, medium and high climate sensitivity assumptions respectively. Note that electricity generation for the baseline and Kyoto trend scenarios are independent of the assumed climate sensitivity. Power plant types are: adv-hc (advanced high-cost renewables), hydro (hydroelectric, geothermal and other existing low-cost renewables), nuc (existing nuclear technology), gas-a & coal-a & igcc (advanced gas and coal plants respectively with carbon capture and sequestration), gas-n (advanced gas combined cycle), gas-r & oil-r & coal-r (remaining gas, oil and coal plants respectively) and coal-n (pulverized coal plant without CO_2 recovery).

would cause and to the controversial issue of choosing a discount rate (in particular for accounting the future benefits of avoiding a collapse).

Because of these different approaches, our results do not compare easily to those of studies following a cost-benefit approach. Indeed, the latter studies often recommend to let the THC collapse when assuming in particular certain damage levels. We can however compare our results with those of Zickfeld and Bruckner (2002) and also with those of Keller *et al.* (2000) when they follow a cost-effective approach.

As in these latter two studies, our results show a strong influence of the climate sensitivity on the optimal CO_2 emission trajectories: the higher the assumed climate sensitivity, the sooner and stronger the emission reductions necessary to avoid a THC collapse.

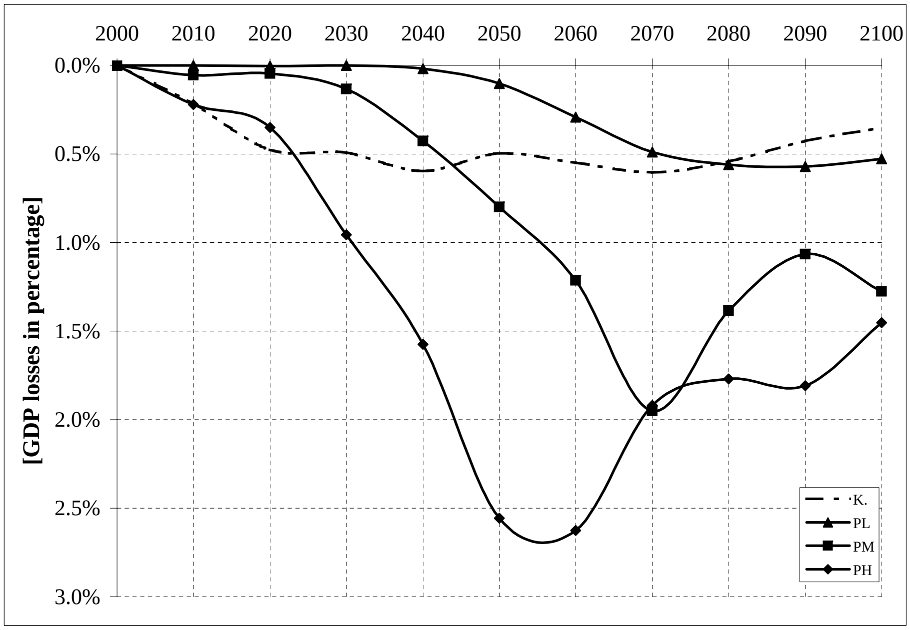

Figure 7: World GDP losses in percentage from the baseline scenario for the Kyoto trend (denoted K.) and the THC preservation scenarios (denoted P.). Cases L, M and H denote low, medium and high climate sensitivity assumptions respectively. Note that GDP losses in the Kyoto trend scenario are independent of the assumed climate sensitivity.

Likewise, we report costs to preserve the THC (in terms of GDP losses due to emission abatement) rather similar to those reported by Keller *et al.* (2000) who found a maximum of 2.3% GDP losses (from the baseline) compared to 2.6% in our case (scenario PH) where emission reductions are more stringent, see below. Notice here that Zickfeld and Bruckner (2002) do not report on GDP losses.

However, our results present also some discrepancies compared to the two studies mentioned. In particular, Zickfeld and Bruckner (2002) report that the SRES A2 scenario IPCC (2000) does not reach any critical threshold yielding a THC collapse with a 1.5 or 2.5 °C climate sensitivity within the 21st century . By contrast, our BL scenario, a case with a 2 °C climate sensitivity and where CO_2 emissions are close to the ones of the SRES A2 scenario, violates the necessary condition on maximum warming rate for the THC preservation before 2080. Likewise, to preserve the THC when the assumed climate sensitivity is 4 °C, Keller *et al.* (2000) report a necessary CO_2 emission reduction of around 70% by 2100 compared to their baseline scenario. By contrast, when assuming the same climate sensitivity, our THC preservation conditions require CO_2 emissions under scenario

PH to be set to zero by 2100. We believe that such discrepancies are symptomatic of our imperfect knowledge of critical THC thresholds.

5 Conclusions

In this paper, we have estimated optimal GHG emission reduction policies, depending on assumed climate sensitivities, in order to preserve the Atlantic thermohaline circulation. We would like to highlight here some important findings, which appear robust in the sense that they are similar to those of some previous studies.

Firstly, as in Zickfeld and Bruckner (2002) the combination of high emission levels and high climate sensitivity yields a situation where the THC collapses in our model. Moreover, our results suggest that a Kyoto trend scenario to reduce GHG emissions would not be enough to preserve the THC when climate sensitivity is either medium (3 °C) or high (4 °C).

Secondly, the maximal effort to preserve the THC, in terms of GDP losses relative to the baseline, is less than 3%, a value comparable to the one reported by Keller *et al.* (2000). Although these losses correspond to trillions of USD, such losses are still tiny compared to the almost ninefold increase in world GDP taking place between 2000 and 2100, see for instance Azar and Schneider (2002) for similar arguments. Furthermore, we recall here once more that our study does not consider any benefits of preserving the THC.

Despite showing some robustness in its results, our approach suffers several limitations that call for some modelling improvements.

Firstly, our modelling procedure starts from a relatively simple, reduced dimensionality climate model, then projects its behaviour onto the extremely simple, zero-dimensional climate model within MERGE. All feedbacks to the original climate model are neglected. A more consistent procedure, in which the dynamical behaviour of the more complex climate model, and feedbacks with the economic model, are retained has been demonstrated to be possible by Drouet *et al.* (2005) using the DICE model of Nordhaus and Boyer (2000) and C-GOLDSTEIN (Edwards and Marsh (subm.)), a higher dimensional climate model. These techniques could equally well be employed to link regional ETA-MACRO models (part of the MERGE model) with C-GOLDSTEIN.

Secondly, despite the fact that uncertainty on the key climate parameters has been taken into account to determine our THC preservation constraints (cf. Section 3), each of our THC preservation cases (scenarios P.) assumes a perfectly known climate sensitivity. A more appropriate approach could be to explicitly take into account uncertainty on climate sensitivity when determining the optimal climate policy. By defining probabilities for different levels of sensitivity, one could for instance propose a ‘hedging’ climate policy IPCC (2001d) using classical stochastic programming techniques.

Thirdly, our analysis of the development of regional energy systems suffers from the simplification we have made in failing to explicitly consider endogenous technological progress (for energy technologies). The consideration of endogenous progress, however, yields computational difficulties, as it is associated with increasing returns to adoption. Indeed, the more experience is accumulated in a given technology, the more its (investment) cost is reduced and the more likely its adoption becomes. Such mechanisms yield a non-convex optimisation problem; see again Kypreos and Bahn (2003) and Bahn and Kypreos (2003) for an illustration of this in the context of MERGE. This requires the use either of ad-hoc heuristics or of so-called global optimisation techniques.

We leave these different modelling improvements for future research.

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