Energy policies avoiding a tipping point in the climate system

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ABSTRACT

Paleoclimate evidence and climate models indicate that certain elements of the climate system may exhibit thresholds, with small changes in greenhouse gas emissions resulting in non-linear and potentially irreversible regime shifts with serious consequences for socio-economic systems. Such thresholds or tipping points in the climate system are likely to depend on both the magnitude and rate of change of surface warming. The collapse of the Atlantic thermohaline circulation (THC) is one example of such a threshold. To evaluate mitigation policies that curb greenhouse gas emissions to levels that prevent such a climate threshold being reached, we use the MERGE model of Manne, Mendelsohn and Richels. Depending on assumptions on climate sensitivity and technological progress, our analysis shows that preserving the THC may require a fast and strong greenhouse gas emission reduction from today's level, with transition to nuclear and/or renewable energy, possibly combined with the use of carbon capture and sequestration systems.

1. Introduction

While it remains extremely difficult to define the level of 'dangerous anthropogenic interference with the climate system' as referred to in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992), it is becoming increasingly clear that certain elements of the climate system may be particularly vulnerable to human activities (in particular greenhouse gas—GHG—emissions), with relatively small changes in emissions above a certain threshold potentially resulting in irreversible regime shifts and significant losses to human welfare. Such elements are referred to by Lenton et al. (2008) as tipping elements, and the associated thresholds as tipping points. Examples include dieback of the Amazon rainforest, loss of Arctic summer sea ice, melting of the West Antarctic ice sheet, and a collapse of the Atlantic thermohaline circulation (THC). Here we choose to focus on the latter possibility, the dynamics of which are relatively well understood, if not well quantified, but our approach could equally well be applied to any other tipping point for which a threshold could be identified in a climate model.

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 and is largely responsible for the relatively mild climate of western Europe. This wind-driven circulation pattern is strongly connected with the formation and sinking of dense water in the North Atlantic, driven by strong heat loss to the atmosphere and by changes in salinity due to precipitation and ice formation, hence the term 'thermohaline circulation'. Changes in surface density in the North Atlantic, driven by anthropogenic surface warming, increased precipitation and glacial meltwater runoff from Greenland, thus have the potential to cause a drastic reduction in the strength of this thermohaline circulation on a decadal timescale, with ensuing changes in climate in the North Atlantic region and beyond, as indicated by paleodata (Stocker, 2000) and model simulations (Stouffer and Manabe, 1999; Vellinga and Wood, 2002; Knutti et al., 2004; Stouffer et al., 2006; Meehl et al., 2007).

The potential impacts of a collapse in the THC could include regional changes in climate of the order of several degrees (Schaeffer et al., 2002; Vellinga and Wood, 2002), and global and local changes in sea level of up to 25–80 cm (Knutti and Stocker, 2000; Levermann et al., 2005; Vellinga and Wood, 2008; Kuhlbrodt et al., 2009; Yin et al., 2009). Initial estimates of THC-induced changes in ocean carbon uptake and in oceanic and terrestrial primary productivity (Joos et al., 1999b; Obata, 2007; Swingedouw et al., 2007; Zickfeld et al., 2008; Kuhlbrodt et al., 2009) suggest that these would be small compared to warming-induced changes, but changes in regional current patterns could lead to the collapse of certain Atlantic fish stocks (Kuhlbrodt et al., 2009).

A comprehensive risk analysis must weigh the potentially drastic impacts of a collapse of the THC against its relatively low probability according to the IPCC (Meehl et al., 2007). However,

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several points should be noted in this respect. Firstly, THC projections are highly uncertain, with model responses ranging from 10% to 50% weakening over 140 years in response to an increase of carbon dioxide (CO_2) levels to four times preindustrial (Gregory et al., 2005). Secondly, IPCC modeling has so far ignored the effects of Greenland meltwater input, considered by some experts to be the main determinant of future THC behavior (Zickfeld et al., 2007). Furthermore, the IPCC projections relate to the possibility of collapse before 2100, whereas the inertia of the climate system is such that emissions in the coming decades may render a collapse inevitable on a longer time horizon. Finally, the elicitation study of Zickfeld et al. (2007) revealed that leading experts believe the range of likely behavior to be significantly wider than the range of model predictions, partly because of known model inadequacies, with a quarter of those interviewed citing a probability greater than 40% of triggering a collapse before 2100 under reasonable forcing scenarios.

To avoid such drastic and potentially irreversible changes, one may design energy policies preserving the THC. Indeed the UNFCCC explicitly states that where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to anticipate, prevent or minimize such effects. To design such policies, 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 (2001); see for instance Wright and Erickson (2003) for a critical discussion of these studies. By contrast, only a few papers have taken explicitly into account a possible collapse of the THC.

Zickfeld and Bruckner (2003, 2008) use a 'tolerable windows approach' (TWA—Bruckner et al., 1999; Petschel-Held 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 considerations appear only as constraints (maximum rate of emission reduction and minimum time span for the transition towards a decarbonizing economy). This TWA is enhanced in particular in Bruckner and Zickfeld (2009) where cost-effective trajectories are derived to reduce the risk of a THC collapse, and in Kuhlbrodt et al. (2009) where the THC and climate modules are coupled to the DICE model of the world economy (Nordhaus, 1994). Several other studies make use of the DICE model in their integrated assessment of a possible THC collapse (Keller et al., 2000; Mastrandrea and Schneider, 2001; Keller et al., 2004; Yohe et al., 2006; McInerney and Keller, 2008). DICE is indeed frequently used in the integrated assessment literature, but it has also been strongly criticized for its over-simplicity, see for instance Kaufmann (1997). In particular, possibilities to curb energy-related GHG emissions are only described in DICE in an aggregated way.

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 energy-related GHG emissions (see Sections 2.1 and 4.1, below). Besides this energy module, MERGE consists of another three interrelated modules: macro-economy, climate and damage. The climate module of MERGE is a rather simple one and does not contain a description of the THC as some of the studies mentioned before. It

is, however, possible to incorporate within MERGE information derived from other climate models in the form of constraints on temperature change. Our approach is thus similar to the one of Keller et al. (2000, 2004) and McInerney and Keller (2008) where 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) using the Bern 2.5-D climate model (Stocker et al., 1992).

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 in avoiding such a threshold. Furthermore, we can assess the extent to which the response is sensitive to the principal uncertain parameters of the climate module, within the approximate range to which such parameters are known. We thus incorporate information from relatively sophisticated climate models pertaining to a complex, non-linear mode of climate system behavior, into an IAM with a relatively sophisticated representation of the energy economy, and also address, in a limited way, the important issue of modeling uncertainty. Although other integrated assessment studies have included much more complex climate models (Bahn et al., 2006; Drouet et al., 2006), or more advanced statistical methods (Keller et al., 2004; McInerney and Keller, 2008), the consideration of uncertain non-linear climate thresholds in a sophisticated energy-economy model represents an important step towards fully integrated assessments with sophisticated treatment of both climate and economic dynamics.

Uncertainty regarding the future behavior 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. Quantitative assessment of the uncertainties associated with climate projection typically involves large ensembles of runs (Knutti et al., 2002) (although other techniques can be applied; Allen et al., 2000; Forest et al., 2002; Annan et al., 2005) and therefore requires highly efficient models. In addition, the THC could respond dramatically to climate change on a decadal timescale, but also respond to past conditions on a millennial timescale. The simulation of future THC behavior, and the quantification of related uncertainties, is thus highly challenging, and a combination of many models and approaches has been used (Rahmstorf et al., 2005; Stouffer et al., 2006).

In this study we make use of results from two types of climate models in addition to MERGE's climate module. To estimate constraints on total warming and on the rate of warming required to avoid a THC collapse, we use results from a large ensemble of runs of the Bern 2.5-D climate model. In updating parameters of the climate module of MERGE, we also make use of results from C-GOLDSTEIN (Edwards and Marsh, 2005) a slightly more computationally demanding model with simplified but three-dimensional ocean dynamics.

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

2. Modeling framework

2.1. MERGE

MERGE is a *M*odel for *E*valuating the *R*egional and *G*lobal *E*ffects 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), namely, those countries who had agreed in 1997 to GHG emission reduction targets: Canada, Australia and New Zealand (CANZ); Eastern Europe and the former Soviet Union (EEFSU); Japan; the USA; and Western Europe (WEUR). The last four correspond to the non-Annex B regions: China; India; Mexico and OPEC (MOPEC); and the rest of the world (ROW).

Fig. 1 displays the four modules of MERGE (energy, macro-economic, climate and damage modules) that enables one to perform integrated assessment of climate and energy 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, hydrogen, synthetic fuels and renewables) and the generation of electricity. It captures substitutions of energy carriers (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 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 value-added aggregate (capital and labor) 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 optimization problems, where economic equilibrium is determined by a single optimization. More precisely, an ETA-MACRO model maximizes a welfare function defined as the net present value of regional consumption. Notice that the wealth of each region includes capital, labor, fossil fuels (viewed as exhaustible resources) as well as its initial endowment in emission permits (if any). MERGE then links the regional ETA-MACRO models by aggregating the regional welfare functions into a global welfare function. Regional ETA-MACRO models are further connected 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 (methane), N_2O (nitrous oxide), HFCs (hydrofluorocarbons)
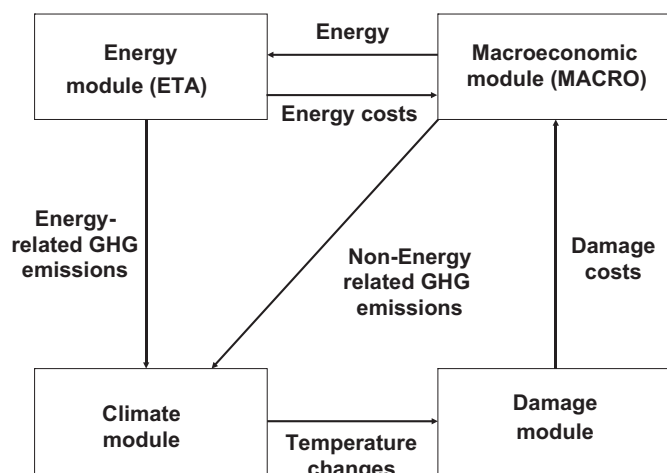
and SF_6 (sulfur hexafluoride). A third module, the climate module, describes how GHG increases in the atmosphere affect temperature. More precisely, it first computes changes in atmospheric GHG concentrations, then the impacts on the earth's radiative forcing balance and finally atmospheric temperature changes. We have revised this climate module updating two key parameters; see Section 2.2 for more details.

Finally, the fourth module is a damage module that quantifies economic losses caused by temperature changes, 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). More details on the evaluation of climate change damage in MERGE can be found in Manne and Richels (2005).

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. To perform such an analysis for a THC collapse would demand that a financial value be placed on the specific damages associated with THC collapse. In this paper, we follow the alternative 'cost-effectiveness' approach which is to require that collapse is avoided, or at least that constraints designed to avoid collapse are satisfied, and derive the GHG emission trajectories that optimize global welfare while remaining within the constraints. Such an analysis relies only on the first three modules of MERGE, strictly confining all evaluation of climate damages to the avoidance of a single, catastrophic event.

2.2. Climate evolution

This section recalls briefly the climate module of MERGE and indicates the parameter update we have performed from version 5. 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 is reduced to the uncertainty in two governing parameters representing climate sensitivity and a lag timescale dependent on ocean dynamics.

As mentioned before, MERGE considers five GHGs: CO_2, CH_4, N_2O, HFCs and SF_6 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). This model represents the natural removal of carbon from the atmosphere by a sum of exponential decay terms, calibrated by reference to three-dimensional model results. Note that MERGE uses a single, fixed impulse-response function and does not include climate-carbon cycle feedbacks. The policy implications of using a similar, albeit somewhat more advanced, empirically fitted model have been discussed by Joos et al. (1999a). Note, however, that we take the carbon-cycle representation as given, and thus do not consider uncertainties in the response of the carbon cycle to global warming. Atmospheric stocks of the other GHGs are computed using simple dynamic equations based on a retention factor (applied on the current stock level) and actual emissions.

The climate module then computes the impact of future atmospheric GHG concentrations on the earth's radiative forcing balance. More precisely, it computes the radiative RF_i (in W m^{-2}) for each of the GHG i considered.

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

$$ET(t) = d_s \times \sum_{i \in G} RF_i - ES(t) \tag{1}$$

Fig. 1. Overview of the MERGE modules.

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

$$d_s = \frac{s}{5.35 \times \ln(2)} \qquad (2)$$

where we choose s as follows[1]: $s=2$ °C for a 'low' climate sensitivity, $s=3$ °C for a 'medium' sensitivity and $s=4.5$ °C for a 'high' sensitivity. This corresponds to the 'likely' range of 2–4.5 °C with a best estimate of 3 °C given by the IPCC (Meehl et al., 2007). This is also consistent with the most recent review of all lines of evidence constraining climate sensitivity (Knutti and Hegerl, 2008). However, it must be emphasized that the range of possible values of climate sensitivity may be much wider than those used here; see for instance Stainforth and et al. (2005).

Finally, the actual temperature AT (in °C) will lag behind the equilibrium temperature as follows:

$$AT(t+1) - AT(t) = c_s \times (ET(t) - AT(t)) \qquad (3)$$

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. Over longer periods, the timescale for equilibration between AT and imposed changes in GHG forcing (ET), as well as the value of the equilibrium temperature itself, will be affected by ocean and terrestrial carbon dynamics as well as cryospheric changes (Knutti and Hegerl, 2008).

This timescale is likely to be more realistically estimated by a model which includes fully three-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, 2005, EM henceforth) which features a three-dimensional ocean and a thermodynamic and dynamic sea-ice component coupled to a one-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 comprehensive climate models. From a randomly generated set of 1000 runs of this model, each with different model parameter values, EM have considered the effect of uncertainty in ocean and atmospheric mixing parameters on idealized equilibrium solutions (representing the preindustrial climate) and on global warming simulations. 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 heuristically defined acceptable range. The mean and range of values for the lag timescale lag_s is derived from this subset for an idealized warming scenario with 1% increase of CO_2 concentration per year. The parameter lag_s is thus chosen as follows[2]: $lag_s = 45$ years when $s=2$ °C, 57 years when $s=3$ °C and 77 years when $s=4.5$ °C. The combination of a low sensitivity and short lag timescale results in a similar warming in the year 2000 as the case with a high sensitivity and a long lag timescale. While both the lag and sensitivity are uncertain, the observed warming over the past century provides a constraint on the combination of these two parameters. In matching sensitivity and lag timescales in this way we are effectively constraining future projections using the past warming (Forest et al., 2002; Knutti et al., 2002,

2003). This is akin to a Bayesian approach although no explicit likelihood function is derived.

The warming rates of the three cases considered are between 0.15 and 0.2 °C per decade, in good agreement with the observed trend of 0.17 ± 0.05 °C per decade (the linear trend over the last 25 years derived in Trenberth et al., 2007) and future trends of about 0.2 °C per decade for the next few decades simulated by comprehensive climate models (Meehl et al., 2007).

Values for the lag timescale obtained from C-GOLDSTEIN should not depend sensitively on the choice of scenario or warming rate, since we assume that the timescale is a fundamental property of the ocean dynamics, but they are found to be relatively sensitive to the period over which the lag time is determined, increasing with the length of the period considered. This indicates that over longer timescales the model behavior is not well fitted by Eq. (3). Indeed, the real system response is controlled by a combination of processes with a range of different timescales, in particular an atmospheric adjustment within a few years is followed by an ocean-dominated response characterized by decadal to centennial timescales (see, for instance Hasselmann et al., 1993; Stouffer, 2004; Knutti et al., 2008). Using only a single-timescale model, such a response can only be fitted approximately. In view of the broad range of parameter values considered, however, we neglect errors induced by the structural simplicity of the climate module. Nevertheless, this indicates the need to incorporate improved ocean and climate dynamics in future integrated assessment studies.

It should also be pointed out that in reducing our consideration of uncertainty to two extreme scenarios relating to the climatic response to atmospheric GHG concentrations, we are not explicitly considering uncertainties in the carbon-cycle component which controls the relation between atmospheric GHG concentrations and emissions. But by allowing for uncertainty in lag and climate sensitivity we do allow for variations in both the transient and equilibrium behavior of the climate component. We also ignore the uncertainty in the large number of coefficients in the economic modules of MERGE and, as noted above, in the structural form of all of the representations.

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 two-dimensional (latitude-depth) representations of the flow in each of the Pacific, Atlantic and Indian Oceans. These three basins are connected via a two-dimensional (longitude-depth) representation of the Southern Ocean (Stocker et al., 1992). The model also includes a one-layer energy and moisture balance representation of the atmosphere (Schmittner and Stocker, 1999) and a thermodynamic representation of sea ice. Some model versions also include a carbon cycle, but we do not make use of it in this study, since the relationship between atmospheric temperature and THC behavior should not depend on the carbon cycle response. In the version used here, GHG forcings are parameterized as changes in radiative forcing at the top of the atmosphere.

Constraints are derived from a Monte-Carlo ensemble of 25,000 global warming simulations with values of climate sensitivity and of all radiative forcing components varied randomly within their uncertainties (Knutti et al., 2002) (see also Table 1 of Knutti et al., 2003). Future emissions were prescribed according to SRES scenario B1 (results were very similar for scenario A2), and five different sets of ocean model parameters were used. Only simulations which matched observed global mean surface warming from 1900 to 2000 and observed

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[1] Notice that in MERGE, s is set by default to around 3.3 °C.
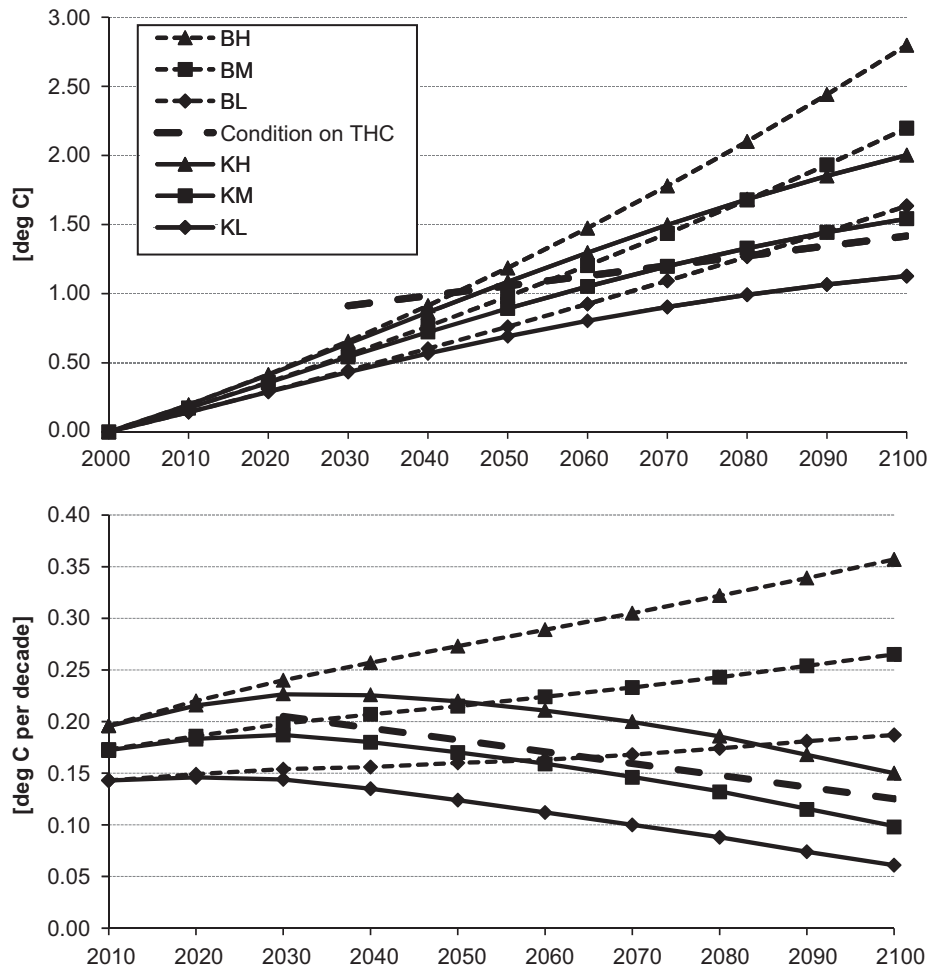[2] Notice that in MERGE, lag is set by default to around 26 years.

Fig. 2. Warming (from 2000) (top) and warming rate per decade (bottom) for the baseline (denoted B.) and Post-Kyoto (denoted K.) scenarios, as well as necessary conditions for preserving the THC, in terms of maximum warming and maximum warming rate, respectively (bold dashed line). Cases .L, .M and .H denote low, medium and high climate sensitivity assumptions, respectively. The model version used assumes endogenous technological progress for selected energy technologies.

global ocean heat uptake from 1955 to 1995 were retained, a subset of around 10% of the simulations.

For the ensemble of simulations used here, the active THC states had maximum Atlantic overturning values between about 15 and 28 Sv, while the collapsed states had less than 5 Sv. In this model, a collapse is generally permanent. To separate the responses, a collapse of the THC was defined as a reduction of over 50% in the maximum Atlantic overturning (i.e., 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 (Tziperman, 1997) or about 10 Sv (Knutti and Stocker, 2002) almost always lead to a collapse of the THC to a level of only a few Sv within a few decades.[3] 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 behavior' refers to the fact that the system naturally avoids intermediate states, thus the value used to separate 'high' and 'low' values should have little effect.

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

$$T \leq \alpha + \beta t, \quad dT/dt \leq \gamma + \delta t \tag{4}$$

where $\alpha = -13.7277\,^{\circ}\text{C}$, $\beta = 0.007212\,^{\circ}\text{C/yr}$, $\gamma = 2.5193\,^{\circ}\text{C/yr}$, $\delta = -0.0011\,^{\circ}\text{C/yr}^2$ and time t is in calender years AD. Thus the allowed temperature change T increases with time, to about 1.4 $^{\circ}$C by 2100 (relative to 2000 level), while the allowed rate of change dT/dt decreases with time (see Fig. 2). This corresponds to the relationship found by Stocker and Schmittner (1997) in the context of the Bern 2.5-D model: relatively large warming can be accommodated only if the warming rate remains low, whereas a relatively high warming rate can be accommodated only early on, while the total warming remains relatively small. The reason is that the ocean is slowly mixing away part of the surface perturbation in the North Atlantic. A given perturbation may be absorbed without a collapse if applied slowly, but the same perturbation may be sufficient to trigger a collapse if applied quickly. This behavior is robust with regard to the structure and parameters of the models but the absolute values of the thresholds depend on the way ocean mixing is parameterized (Knutti et al., 2000). A dependence of the stability on the rate of

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[3] 1 Sv = 1 Sverdrup = 10^6 m^3/s.

change is also seen in some other models (Stouffer and Manabe, 1999). Note that the model version used here incorporates several modifications compared to Stocker and Schmittner (1997), in particular the inclusion of a meridional moisture transport and several changes to ocean mixing parametrization. The threshold for a THC collapse is known to be highly sensitive to both of these factors: Knutti et al. (2000) showed that the threshold could vary by an order of magnitude as a function of the vertical diffusivity (their Fig. 9). The strong dependence of THC stability on moisture transport is explored by Marsh et al. (2004). The THC in the model used here is relatively sensitive compared to other models (Plattner et al., 2008); however, some experts ascribe a probability of up to 30% to THC collapse for a warming of less than 2 °C compared to preindustrial (Kriegler et al., 2009). Given the uncertainty in the value of a possible THC threshold, we regard our results as illustrative of the possible implications if such a low threshold is found to exist.

The constraints are derived by regression, and thus represent the best-estimate linear functions which separate the collapsed and non-collapsed states, in other words, the best estimate of the conditions required to preserve the THC in the Bern 2.5-D model. Note that they cannot guarantee its preservation in the model, and certainly not in the real world. The constraints describe a relationship which should not depend on carbon-cycle behavior, nor on emissions scenario. The ensemble considers a wide range of GHG sensitivity behavior and some range of ocean mixing behavior. Uncertainties in atmospheric dynamics, including hydrological sensitivity, are not directly addressed by the ensemble, although it must be noted that further uncertainties are unlikely to be independent and thus will not be additive. Recall that having derived the constraints, however, we take them to be fixed, and all subsequent consideration of uncertainty in our analysis is reduced to the consideration of high, moderate and low sensitivity cases.

These constraints are then introduced in MERGE in order to determine policies designed to optimize global welfare while preserving the THC. Note, though, that the cost-effectiveness analysis neglects any economic benefits of such preservation. More accurate assessment of the policy implications of preserving the THC will clearly require the development of more advanced, fully integrated assessment models and better quantification of modeling uncertainties, but the approach chosen here is a first step towards such a goal.

A similar concept of limiting the overall magnitude and the rate of change may apply to other thresholds or tipping elements in the climate system (Lenton et al., 2008; Kriegler et al., 2009). Ecosystems, for example, are likely to be able to tolerate more warming when changes are slow and adaptation or migration can compensate for some of the changes, while high rates of changes will decrease the overall magnitude of change that can be tolerated. The threshold for global temperature in 2100 relative to 2000 in this study is about 1.4 °C, i.e., equivalent to about 2 °C warming from preindustrial, the target that many countries have adopted to avoid dangerous impacts from climate change. Thus even if an absolute threshold of the THC is difficult to determine and is model-dependent, the results would also apply to other components in the climate system that exhibit threshold behavior near 2 °C warming. The implications for energy policies derived here are therefore in line with recent estimates of allowed GHG emissions for a 2 °C warming target (Allen et al., 2009; Meinshausen et al., 2009). However, it is essential to note that the widely used 2 °C target relates to the maximum warming, rather than the warming experienced by 2100. Uncertainty in technological developments prevents analysis much beyond 2100, but in the solutions derived here the warming rate at 2100 remains significant. Stricter constraints would therefore be required to satisfy the 2 °C maximum limit.

4. Numerical results

This section will analyze energy policies preserving the Atlantic THC and compare them to alternative policies (business-as-usual and a 'Post-Kyoto' policy).

4.1. Scenario characterization

The database of MERGE corresponds to version 5, with the exception of the climate module, as explained in Section 2.2. Table 1 lists the different sources of electric and non-electric energy supply within the model.[4]

Remaining fossil fuel power plants (COAL-R, OIL-R and GAS-R) are progressively phased out over time. HYDRO has limited capacity reflecting the (limited) potential of the low-cost renewables it represents. MERGE assumes also that existing nuclear technology (NUC) has limited capacity reflecting somehow the current public acceptance of this energy carrier.[5] Conversely, ADV-HC and LBDE represent generic[6] advanced 'high-cost' electricity generation technologies (relying on biomass, nuclear, solar and/or wind) and correspond to 'backstop' technologies (their capacity is not limited). Similarly, in terms of non-electric carbon-free supply, RNEW corresponds to a limited supply of low-cost renewables, such as ethanol from biomass. Whereas NEB-HC and LBDN correspond to an unlimited carbon-free supply of non-electric energy. These technologies are again defined in a generic way, but could refer for instance to hydrogen production using carbon-free processes.[7]

To capture alternative energy futures consistent with preserving the THC, we consider two versions of the model: one with endogenous technological progress in the energy sector, the other one without. In the latter version, neither LBDE nor LBDN are available and costs are assumed to decline every year at a rate of 0.5%. The same cost reduction trend applies in the former version (with learning-by-doing—LBD), except for LBDE and LBDN (that replace, respectively, ADV-HC and NEB-HC). For these two technologies, only a fraction of the cost is exogenously reduced. The remaining part of the cost (learning part) is reduced through accumulation of knowledge in manufacturing and operation, knowledge measured through cumulative installed capacities.[8] For an extensive discussion of the modeling of endogenous technological progress in MERGE, the reader is referred in particular to Kypreos and Bahn (2003) and Manne and Barreto (2004).

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[4] Data are given for Western Europe. Introduction dates and costs may vary by region.

[5] Note, however, that advanced nuclear energy power plants (which should provide increased safety and generate a reduced amount of nuclear waste) are represented in the model by generic technologies (ADV-HC and LBDE, see below) whose capacity is not limited. In addition, the authors acknowledge that the characteristics of the NUC technology, reported in Table 1 for Western Europe but assumed to be the same in all regions, are such that it would, in the absence of its assumed limited capacity, significantly contribute to electricity generation when forced to decarbonize the energy sector.

[6] This corresponds to the modeling philosophy of MERGE that avoids picking specific winners (Manne and Richels, 2004) among advanced carbon-free technologies, but has the drawback of not allowing here the distinction between nuclear and renewable energies.

[7] In the short term, one could envision water electrolysis using low-cost renewable electricity. As the potential for the (current) low-cost renewables is limited, clean production of hydrogen would have to rely after some time on other sources of carbon-free electricity or on other carbon-free processes. For the latter one could for instance envision, in the medium term, coal gasification with CCS or natural gas reforming with CCS, and in the longer term, biomass gasification or high-temperature water splitting using nuclear heat; see for example OECD/IEA (2005).

[8] LBDE: learning part is 50 mills/kWh. LBDN: learning part is 6 US$/GJ. Learning costs decline by 20% for each doubling of cumulative installed capacity.

Table 1
Electric and non-electric energy supply in MERGE5.

Name	Description	Introduction date	Cost in 2000 (mills/kW h)	Carbon emissions (kg C/kW h)
Electric energy supply				
COAL-R	Remaining initial coal fired	Existing	25.3	0.2364
COAL-N	Pulverized coal without CCS	2010	55.0	0.1955
IGCC	IGCC with CCS	2015	62.0	0.0240
COAL-A	Coal-fuel cell with CCS	2040	65.9	0.0068
OIL-R	Remaining initial oil fired	Existing	37.8	0.1795
GAS-R	Remaining initial gas fired	Existing	35.7	0.1044
GAS-N	Advanced combined cycle	2005	30.3	0.0935
GAS-A	Gas-fuel cell with CCS	2020	47.7	0.0000
HYDRO	Hydroelectric and geothermal	Existing	40.0	0.0000
NUC	Remaining initial nuclear	Existing	50.0	0.0000
LBDE	Carbon-free technologies with LBD	2005	100.0	0.0000
ADV-HC	Carbon-free technologies without LBD	2010	100.0	0.0000

Name	Description	Introduction date	Cost in 2000 (US$/GJ)	Carbon emissions (t C/GJ)
Non-electric energy supply				
CLDU	Coal direct use	Existing	3.0	0.0241
OIL1–OIL10	Oil cost categories	Existing	3.0–5.25	0.0199
GAS1–GAS10	Gas cost categories	Existing	2.0–4.25	0.0137
SYNF	Synthetic fuels	2010	9.0	0.0400
RNEW	Renewables	Existing	6.0	0.0000
LBDN	Carbon-free technologies with LBD	2005	14.0	0.0000
NEB-HC	Carbon-free technologies without LBD	2010	14.0	0.0000

CCS stands for carbon capture and sequestration. IGCC stands for integrated gasification combined cycle. LDB stands for learning-by-doing.

For each of these two MERGE versions (with and without learning), several scenarios are analyzed. The first scenarios considered are baseline cases where GHG emissions are not limited. They assume a world population level of 8.7 billion by 2050 and 9.5 by 2100. Between 2000 and 2100, world GDP grows 11 times (up to 382 trillion USD 2000), whereas primary energy supply and carbon emissions increase about four times each (up to around 1600 EJ/year and 27 Gt C, respectively). In terms of CO_2 emissions, our baseline scenario is then close to the SRES A2 scenario (IPCC, 2000).[9] We present here three baseline cases: BL, a case with low climate sensitivity ($s=2\,°C$) and short mean lag for the ocean warming ($lag_s=45$ years); BM with medium climate sensitivity ($3\,°C$) and mean lag (57 years); and BH with high climate sensitivity ($4.5\,°C$) and long mean lag (77 years).[10]

The next scenario is a 'Post-Kyoto' scenario, where constraints are imposed on GHG emissions (instead of temperature changes) as follows.[11] Annex B regions of the Kyoto Protocol (except USA) must comply with their Kyoto target by 2010. Afterwards, Western Europe takes the lead in the reduction effort by abating its GHG emissions by 20% by 2020 (from the 1990 level for CO_2 and from the 2000 levels for the other GHGs) and then reducing its emissions by 10% per decade. The other Annex B regions (including USA) abate their GHG emissions by 10% per decade (from the 2010 levels) from 2020 on. Non-annex B regions join the abatement effort in 2030, reducing their GHG emissions by 5% per decade (from the 2020 levels). As a consequence of these emission constraints, world carbon emissions peak in 2020 at 7.5 Gt C and decrease afterwards to 1.4 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 Post-Kyoto scenarios: KL ($2\,°C$, 45 years), KM ($3\,°C$, 57 years) and KH ($4.5\,°C$, 77 years).[12]

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. Fig. 2 assesses whether our baseline and Post-Kyoto scenarios satisfy these conditions, using the LBD model version for illustration (with similar results for the non-learning model version).

Fig. 2 reveals first that whatever climate sensitivity is chosen our baseline scenario fails to preserve the THC, as both constraints on maximum warming and maximum warming rate are violated. In other words, a 'laissez-faire' policy is here most likely to make a future THC collapse inevitable. Fig. 2 shows next that our Post-Kyoto scenario would only prevent a THC shutdown under a low climate sensitivity. When the climate sensitivity is medium, the implemented emission reductions would merely postpone by a few decades (compared to our baseline) the situation where a future collapse can no longer be avoided. It is also striking to note that under a high climate sensitivity, in the KH scenario (as in the BH scenario), the constraint on maximum warming rate is violated before 2030. In other words, a delay in implementing 'ambitious'[13] emission reductions by only a few decades would, under some conditions, very likely make a future THC collapse inevitable.

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 ($2\,°C$, 45 years), PM ($3\,°C$, 57 years) and PH ($4.5\,°C$, 77 years).

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[9] Note that MERGE makes further assumptions regarding aerosol forcing, sulfur emissions being based on the IIASA B2 marker scenario, and regarding non-CO_2 GHGs following the Energy Modeling Forum 21 (De La Chesnaye and Weyant, 2006); see also Manne and Richels (2005) pp. 180–181.

[10] Notice that for each model version used (with and without learning), respectively, socio-economic development paths and resulting GHG emissions are identical in all three baseline cases. But these cases differ by temperature changes associated with emissions.

[11] This is among several others a possible scenario for 'Post-Kyoto' commitments to result from the current climate negotiations and we have selected it for illustration purposes only.

[12] Note again that for the two model versions used, respectively, socio-economic development paths and resulting GHG emissions are identical for all these Post-Kyoto scenarios. But these scenarios differ by temperature changes associated with emissions. Notice also that emission trajectories are dictated by their constraints and are thus identical for both model versions.
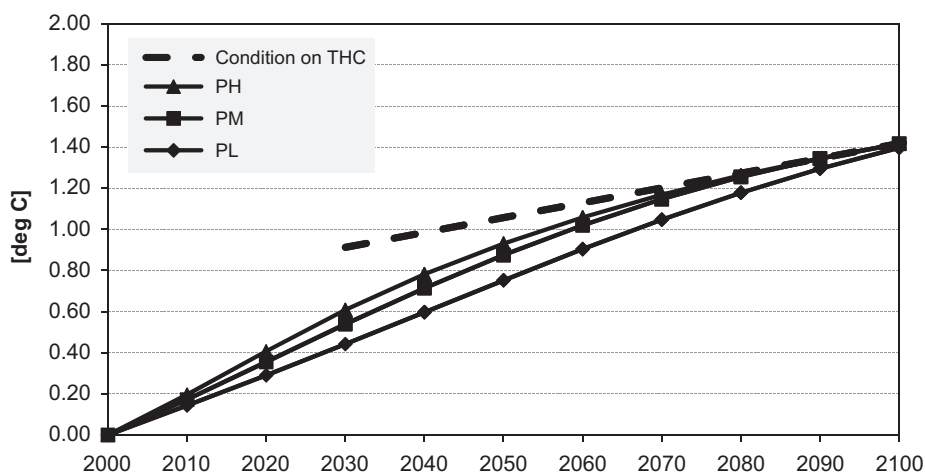
[13] See also Fig. 4 next section.

Fig. 3. Warming (from 2000) for the THC preservation scenarios, under low (PH), medium (PM) and high (PH) climate sensitivity assumptions, respectively, as well as the necessary condition for preserving the THC in terms of maximum warming (bold dashed line). The model version used assumes endogenous technological progress for selected energy technologies.

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 also has perfect knowledge of the actual climate sensitivity. 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. Fig. 3 reports on the evolution of the absolute warming under the three THC preservation scenarios, as the corresponding constraint turns out to be the most demanding[14] condition. Since both model versions yield here again similar results, Fig. 3 reports only on the LBD model version.

Fig. 3 reveals that the THC preservation constraint becomes binding toward the end of the century, by 2090 when climate sensitivity is medium or high, and after 2100 when the sensitivity is low.

Given the simple climate dynamics of MERGE, these constraints on temperature translate simply into conditions for atmospheric GHG concentrations. As an illustration, atmospheric CO_2 concentration in year 2100 reaches 582 ppmv in the PL scenario, 430 in PM and reduces to 364 in PH, when using the LBD model version, with again similar results for the non-learning model version. We would like to stress that a doubling of preindustrial CO_2 atmospheric concentration by 2100 (at around 550 ppmv), sometimes considered in the literature as a 'safe' target, would fail here to preserve the THC except at the lower limit of the assumed possible climate sensitivities. But compared to some previous studies (in particular, Stocker and Schmittner, 1997; Keller et al., 2000) lower CO_2 targets are here required as result of the THC constraints.

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

Fig. 4 shows that CO_2 emissions in the PL scenario follow roughly the baseline trajectory until 2040 in the non-learning model version and until 2050 in the learning one. Afterwards, emissions are reduced to meet the (binding) constraint on absolute warming and follow a trajectory rather parallel to the Post-Kyoto one. In the learning model version, more emissions are allocated in earlier decades, with stronger reductions later when cleaner technologies get more affordable through (endogenous) technological progress. Indeed, cumulative emissions with and without endogenous learning are here very similar, in agreement with recent studies that have highlighted the importance of cumulative emissions, rather than emissions at any given time, in determining the temperature response (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009). In the PM scenario, emissions follow approximately the reduction path of our Post-Kyoto policy, but at lower levels between 2030 and 2080 in order to sufficiently slow down temperature increase. Same remarks apply for the small differences between the non-learning and learning model versions. By contrast, emissions have to be abated more quickly in the PH scenario, and remain at zero from 2070 on, as the assumed high climate sensitivity makes it more demanding to satisfy the constraint on absolute warming. Here both model versions follow identical trajectories, as the lower CO_2 'target' gives no flexibility in allocating emissions over time.

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

Fig. 5 provides for our two model versions the 2010 world primary energy use (for reference) as well as the situation in 2050 and 2100. We will concentrate our comments on the latter situation, where differences amongst scenarios are greatest, looking both at the total energy use and the energy mix. Here the two model versions that assume different dynamics for technological progress (exogenously given or endogenous for selected technologies), yield contrasting results. In the non-learning model version, compared to the baseline, preservation scenarios require from 7% (scenario PL) to 20% (PH) less primary energy. Indeed, curbing energy-related GHG emissions increases here energy prices, as more expensive energy technologies (such as power plants with carbon capture and sequestration—CCS—systems) are selected. This yields GDP losses

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[14] In the sense that this constraint becomes binding earlier than the constraint on the rate of warming. This latter constraint becomes binding only toward the end of the model's horizon (2150) for all preservation scenarios.
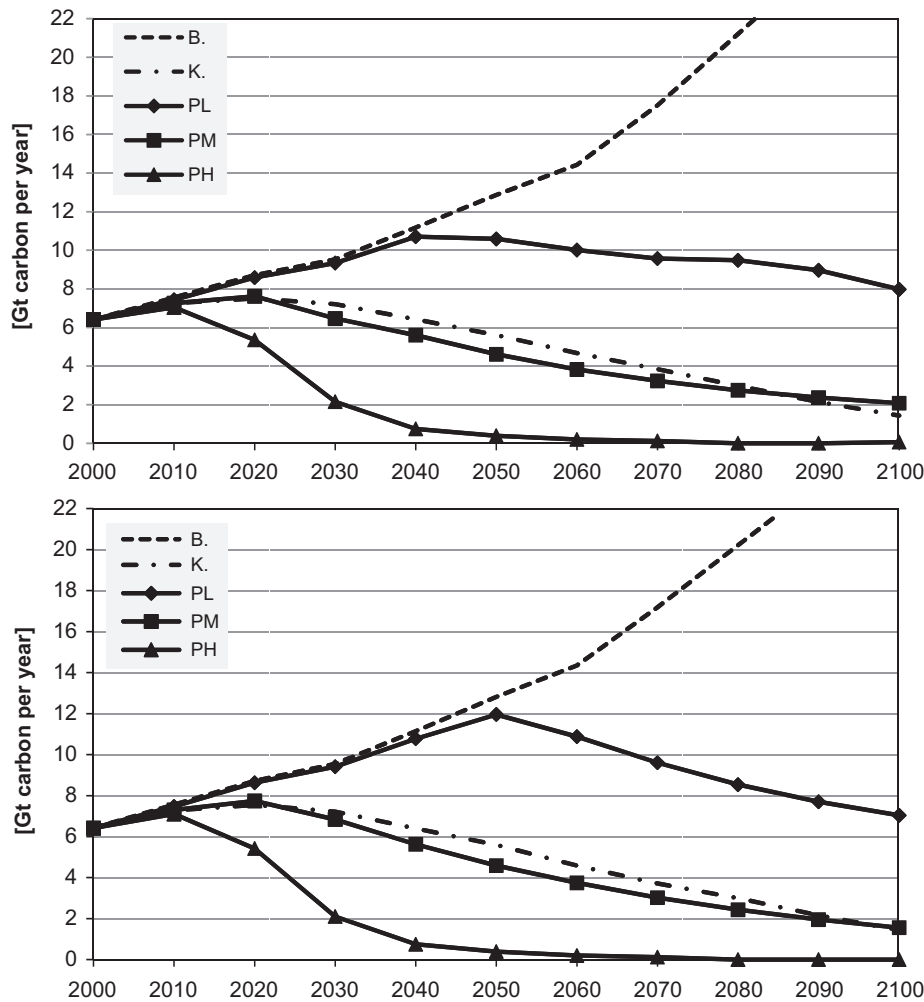
Fig. 4. World energy-related CO_2 emission trajectories under the baseline (denoted B.), the Post-Kyoto (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases .L, .M and .H denote low, medium and high climate sensitivity assumptions, respectively, recalling that emission paths for the baseline and Post-Kyoto scenarios are independent of the assumed climate sensitivity. Top graph corresponds to a model version without endogenous technological progress, bottom graph corresponds to a version that assumes endogenous technological progress for selected energy technologies.

(see Fig. 8 below) and thus less energy to be supplied to the economy. In the learning model version, the dynamics are quite different due to the long-run effects of endogenous technological progress and the associated cost reductions for the advanced (learning) clean technologies (LBDE and LBDN). This translates in particular into lower GDP losses (see again Fig. 8) and lower reduction (compared to the respective baseline) in primary energy supply. Besides changes in primary energy use, preserving the THC in MERGE also requires changes in the energy mix. The main impact here is the increased use of nuclear and renewables[15] at the expense of coal in particular. In the non-learning version, the share of this category is 20% in the baseline, but ranges from 30% in the PL scenario to 49% in PH. This trend is much increased in the learning version; the share rose up to 91% in PH (compared to 27% in the baseline), indicating a much different energy future. In addition, in both model versions, there are also inter-fossil substitutions from coal and oil to gas, especially in the PM and PH scenarios. Note that our Post-Kyoto scenario requires emission reduction levels similar to the ones of the PM scenario by 2100. Primary energy use in the former scenario is then comparable to the latter.

To characterize further changes (compared to the baseline) needed to preserve the THC, Figs. 6 and 7 present, respectively, world electricity generation (by power plant types) and non-electric energy production (by energy carriers) for our two model versions.

We will again focus our comments on the last period (2100). In the non-learning model version, compared to the baseline, coal power plants without CCS (COAL-N) are replaced by power plants with CCS (in particular IGCC in the PL scenario and COAL-A in PM and PH).[16] Whereas in terms of non-electric energy, the use of fossil fuels and especially the use of synthetic fuels (SYNF) is much reduced in favor of carbon-free sources[17] (in particular NEB-HC in the PM and PH scenarios). In addition, some 'high-cost carbon limit relaxation activities' are used in the PH scenario, to help quickly reduce net CO_2 emissions by mid-century and maintain net emissions at zero afterwards. These 'relaxation activities' would correspond to the deployment of generic technologies, such as artificial trees or scrubbing towers, removing CO_2 from ambient air at a cost of $1000 per ton C.[18] We would like to stress

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[15] We recall that MERGE does not allow to distinguish between these two energy carriers.

[16] Note that in all scenarios HYDRO and NUC are used at their full capacity.

[17] Note that in all scenarios traditional renewable such as biomass (RNEW) is used at its full potential by 2100.

[18] Note again that this approach of generic technologies corresponds to the modeling philosophy of MERGE. These technologies act as 'backstop' as their
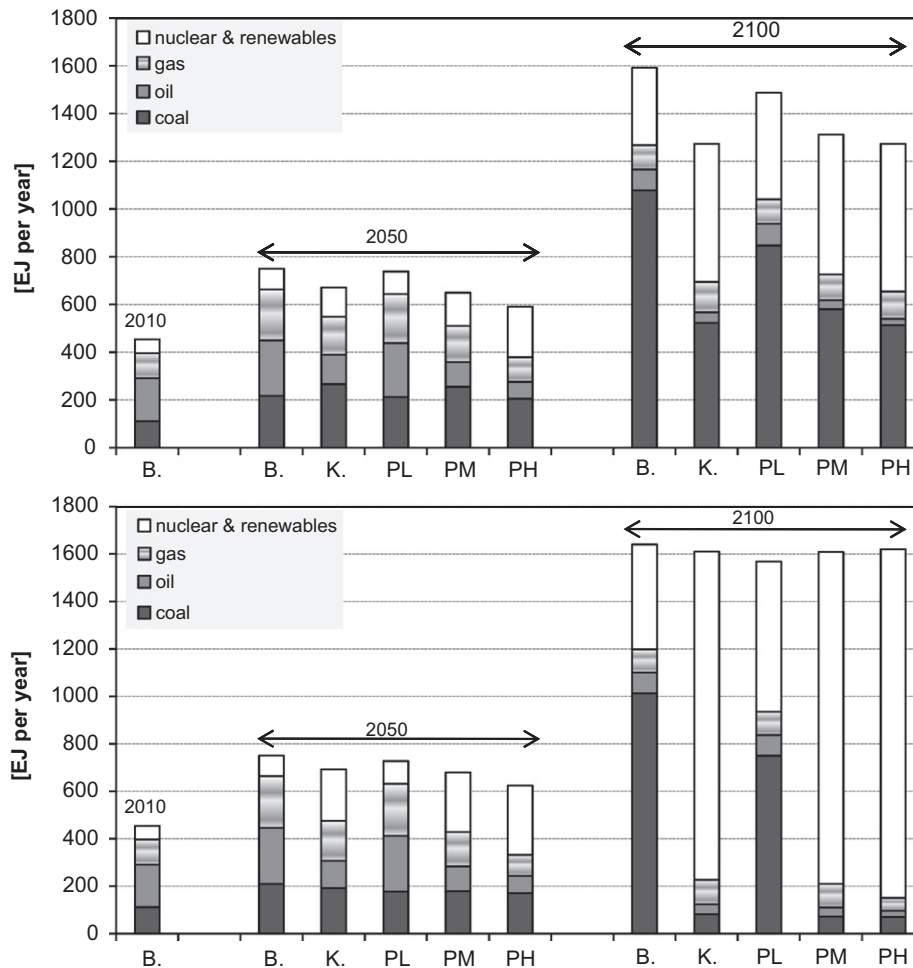
Fig. 5. World primary energy use for the baseline (denoted B.), the Post-Kyoto (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases .L, .M and .H denote low, medium and high climate sensitivity assumptions, respectively. Note that primary energy use for the baseline and Post-Kyoto scenarios are independent of the assumed climate sensitivity. Top graph corresponds to a model version without endogenous technological progress, bottom graph corresponds to a version that assumes endogenous technological progress for selected energy technologies.

that without these carbon dioxide removal (CDR) activities, used at a maximum level of 2.7 Gt C in 2040 (when they contribute around 25% to the emission reduction effort from the baseline), the requested CO_2 'targets' cannot be achieved, which makes preserving the THC when climate sensitivity is high depend on speculative geoengineering options. In the learning model version, compared to the non-learning one, the main difference is the dominant use of the LBDE technology for electricity generation (instead of COAL-A) in the PM and PH scenarios. Similarly, LBDN replaces NEB-HC for non-electric energy production in all THC preservation scenarios.

To summarize the energy sector restructuring required by 2100, preserving the THC requires, in terms of non-electric energy production, the transition towards clean energy carriers such as hydrogen produced from carbon-free technologies (as represented by NEB-HC and LBDN). In terms of electricity generation, two

configurations are possible depending on assumed climate sensitivity and technological progress: an electricity sector dominated by fossil fuel power plants with CCS or by advanced carbon-free technologies relying on biomass, nuclear, solar and/or wind (as represented by LBDE). Beyond energy market forces and private investment efforts, the 'winning' configuration could also result from specific public energy policies such as public R&D and subsidies, to help the realization of the expected technological progress.

Finally, MERGE enables one to assess economic consequences of restructuring the regional energy sectors, compared to the baseline case. Fig. 8 gives world GDP losses (in percentage from the baseline) for the Post-Kyoto trend and THC preservation scenarios. It should be recalled, however, that in this analysis the model assesses only costs of reducing GHG emissions without accounting for the benefits of avoiding a THC shutdown. Indeed, neither market benefits nor more subtle non-market benefits are accounted for here.

Fig. 8 is a good indicator of the economic costs associated with the abatement of GHG emissions. Not surprisingly, the magnitude of the losses is highest in the PH scenario, illustrating the difficulty of setting almost to zero (net) world energy-related carbon emissions in about 40 years (see again Fig. 4). Note that when the transition to a new (less carbon dependent) energy system has been accomplished, the economy regains healthy growth rates and GDP losses are progressively reduced. In
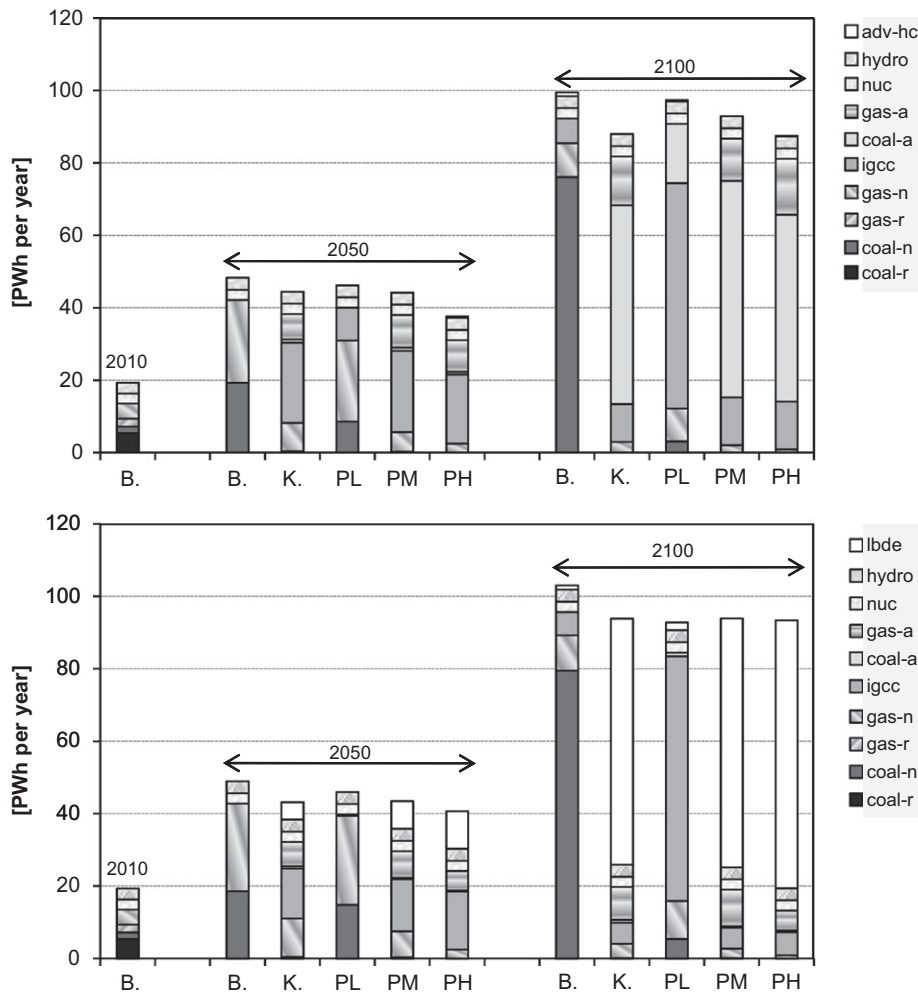
Fig. 6. World electricity generation by power plant types for the baseline (denoted B.), the Post-Kyoto (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases .L, .M and .H denote low, medium and high climate sensitivity assumptions, respectively. Note that electricity generation for the baseline and Post-Kyoto scenarios are independent of the assumed climate sensitivity. Power plant types are: adv-hc and lbde (advanced high-cost carbon-free technologies such as advanced nuclear, biomass, solar and wind), hydro (hydroelectric, geothermal and other existing low-cost renewables), nuc (existing nuclear technology), gas-a & coal-a and igcc (advanced gas and coal plants, respectively, with carbon capture and sequestration), gas-n (advanced gas combined cycle), gas-r and coal-r (remaining gas and coal plants, respectively) and coal-n (pulverized coal plant without CO_2 recovery). Top graph corresponds to a model version without endogenous technological progress, bottom graph corresponds to a version that assumes endogenous technological progress for selected energy technologies.

addition, compared to the model version without learning, GDP losses are reduced in the long run in the version with learning, as regional economies benefit from cost reductions in some advanced clean technologies (resulting from investments over time, following the endogenous representation of technological progress). Now looking at regional economic impacts of THC preservation, some regions suffer more GDP losses than the world average; by decreasing order: MOPEC (Mexico and OPEC) and EEFSU (Eastern Europe and the former Soviet Union) that have the largest endowments of oil and gas, and in the learning model version China that has the largest endowments of coal.

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; Mastrandrea and Schneider, 2001; McInerney and Keller, 2008) 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). Indeed, 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, e.g., Wright and Erickson, 2003) due in particular to large uncertainties associated with the magnitude of damages a THC collapse 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, in the above-mentioned studies the THC is either allowed to collapse under certain conditions, or the proposed optimal policy does not significantly reduce the odds of a collapse. We can, however, compare to some extent our results with: those of Keller et al. (2000) and Bruckner and Zickfeld (2009) when they follow a cost-effective approach, those of McInerney and Keller (2008) when they assess the magnitude of GHG reduction that would preserve the THC, those of Yohe et al. (2006), and those obtained with a tolerable window
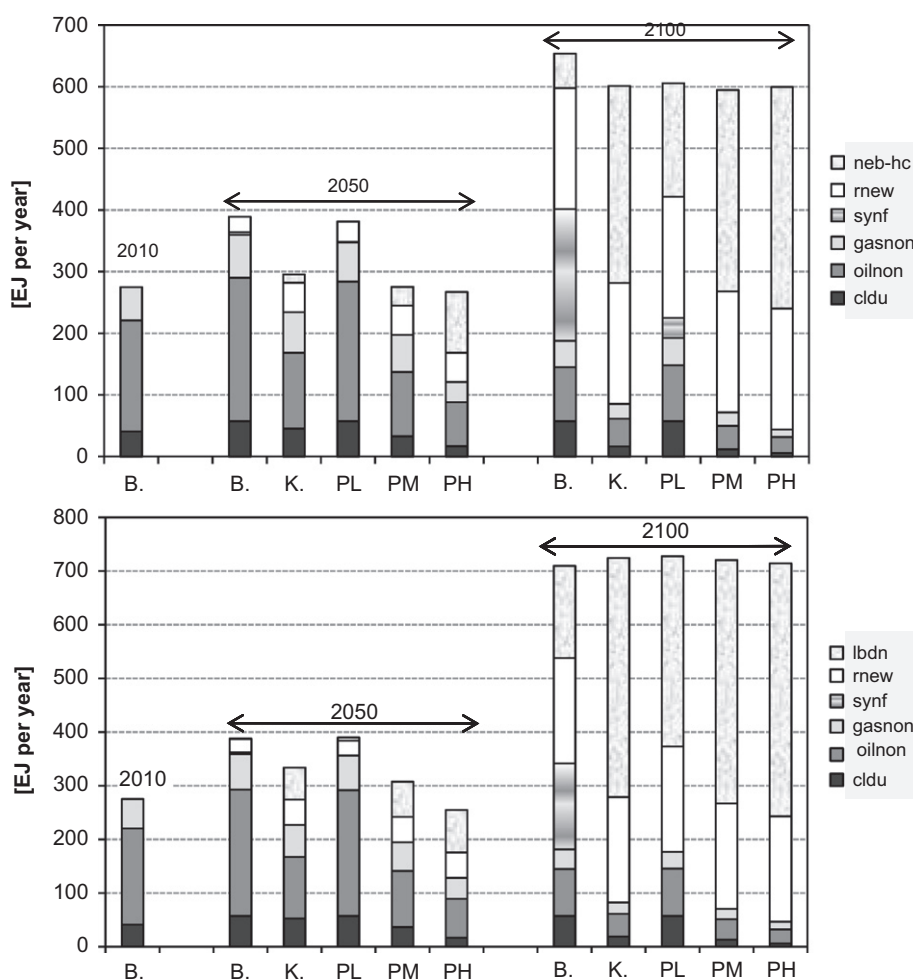
Fig. 7. World non-electric energy production by energy carriers for the baseline (denoted B.), the Post-Kyoto (denoted K.), as well as the THC preservation scenarios (denoted P.). Cases .L, .M and .H denote low, medium and high climate sensitivity assumptions, respectively. Note that non-electric energy production for the baseline and Post-Kyoto scenarios are independent of the assumed climate sensitivity. Energy carriers are: neb-hc and lbdn (advanced high-cost clean carriers such as hydrogen produced using carbon-free processes), rnew (low-cost renewables such as ethanol from biomass), synf (synthetic fuels), gasnon (gas for non-electric use), oilnon (oil for non-electric use) and cldu (coal for non-electric use). Top graph corresponds to a model version without endogenous technological progress, bottom graph corresponds to a version that assumes endogenous technological progress for selected energy technologies.

approach (reported in particular in Zickfeld and Bruckner, 2008; Bruckner and Zickfeld, 2009).

Our results present several similarities with these latter studies. In particular, results show a strong influence of the climate sensitivity on the optimal GHG emission trajectories; the higher the assumed climate sensitivity, the sooner and the stronger the emission reductions necessary to avoid a THC collapse. Similarly, when considering 'high' settings for the uncertain climate parameters (such as the climate sensitivity) most of the studies indicate that even a modest increase in GHG emissions during the next few decades would yield a situation where a future collapse of the THC could no longer be avoided.

However, our results present also some differences compared to the latter mentioned studies. In particular, our approach to preserve the THC generally implies stronger GHG emission reductions (owing to the tighter THC constraints) with the notable exception of McInerney and Keller (2008) that share with us the limitation of not modeling explicitly the THC.[19] Differences may indeed result from the modeling frameworks. But

to some extent, they also reflect our imperfect knowledge of critical THC thresholds.

5. Conclusions

In this paper, we have estimated, using the MERGE model, cost-effective energy policies yielding GHG emission trajectories that would preserve the Atlantic thermohaline circulation (THC) under different settings for uncertain climate parameters (climate sensitivity and rate of ocean warming). Our results are consistent with the existing literature with respect to the finding that under some 'high' settings for the uncertain climate parameters (in particular a climate sensitivity set at 4.5 °C, the upper end of the likely range provided by the IPCC) a small increase in GHG emissions during the next decades would be enough to yield a situation where crossing a particular tipping point in the climate system (here, a collapse of the THC) can no longer be avoided in the (possibly distant) future. Our results also illustrate the possible energy challenges (e.g., almost complete decarbonization of the energy sectors in about 40 years) that would need to be overcome to ensure avoiding a THC collapse if the climate sensitivity (in particular) turns out to be 'high'. The magnitude and speed of the decarbonization requested here would

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[19] They rather impose, as we do, constraints that correspond to necessary conditions for preserving the THC.
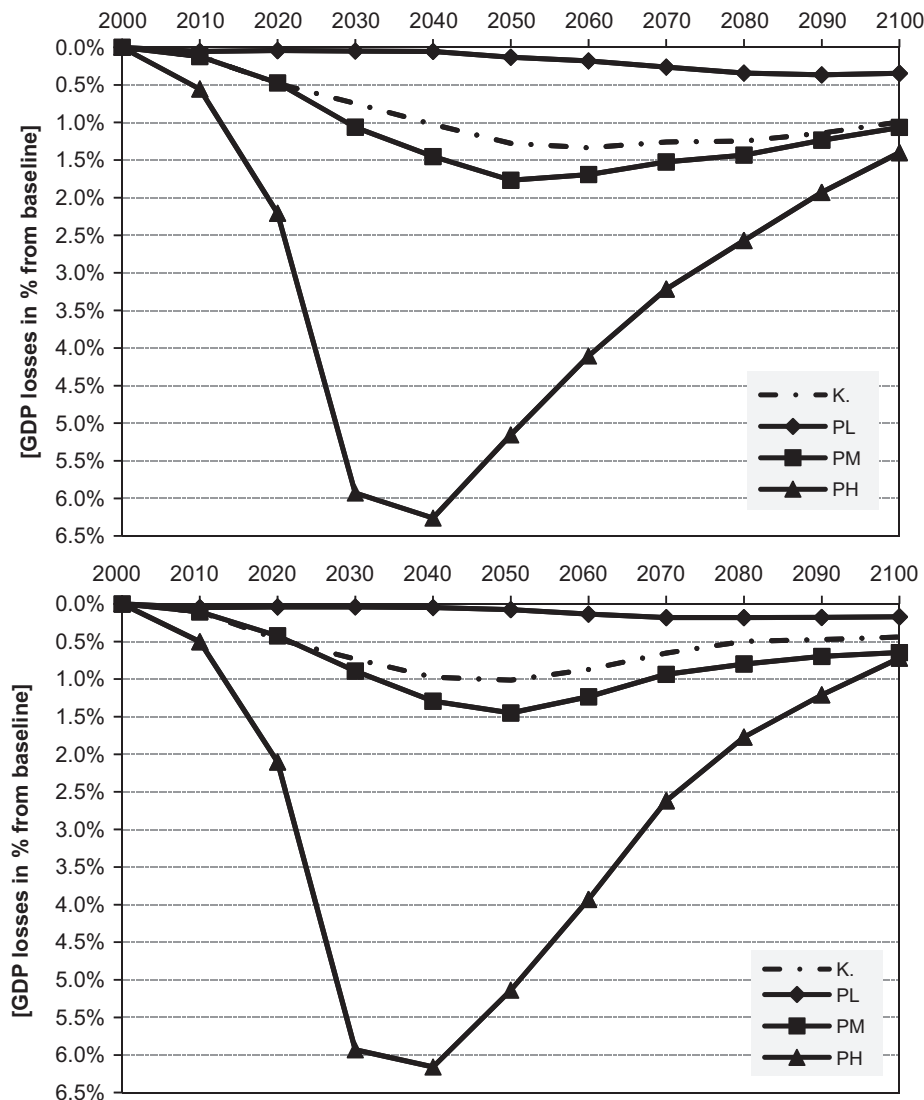
Fig. 8. World GDP losses in percentage from the baseline scenario for the Post-Kyoto (denoted K.) and the THC preservation scenarios (denoted P.). Cases .L, .M and .H denote low, medium and high climate sensitivity assumptions, respectively. Note that GDP losses in the Post-Kyoto scenario are independent of the assumed climate sensitivity. Top graph corresponds to a model version without endogenous technological progress, bottom graph corresponds to a version that assumes endogenous technological progress for selected energy technologies.

also require, according to MERGE, the use of some (geoengineering) CDR measures to remove CO_2 from ambient air. While the more likely case of a 'medium' sensitivity (3 °C) would only involve a reduction in carbon emissions of around 21% by 2050 (compared to the 1990 levels), the large uncertainty in climate sensitivity in particular implies larger reduction targets to limit to acceptable levels the probability of crossing a tipping point in the climate system.

Despite showing some robustness in its results, our approach suffers limitations that call for modeling improvements. In particular, our modeling procedure starts from a relatively simple, reduced dimensionality climate model, then projects its behavior onto the extremely simple, zero-dimensional climate module of MERGE. All feedbacks to the original climate model are neglected. While other studies have incorporated a description of the tipping point within their economic model, these descriptions are usually based on low-dimensional 'box' models (at best). A promising alternative is to couple MERGE to an intermediate complexity climate model such as C-GOLDSTEIN, using the 'oracle' method described in Beltran et al. (2005). Preliminary results of such a coupling have been reported in Bahn et al. (2006), but robustness

of the coupling method remains an issue which calls for further development.

Despite the limitations in the modeling framework and the difficulties in quantifying the risk of tipping points in the climate system, our study nevertheless provides insights for energy policies that go beyond the consideration of a possible THC collapse. Indeed the concept here applies to any other part of the climate system that may experience a threshold that can be avoided by limiting both the warming and the speed of warming. The total allowed warming in 2100 in this study (relative to preindustrial levels) is close to 2 °C, often quoted as a limit for dangerous interference with the climate system, and as such a target for climate stabilization adopted by many countries in the so-called Copenhagen Accord[20] of 2009 (note, however, that here the constraint applies to the warming experienced at 2100; limiting equilibrium warming to 2 °C would thus require tighter emissions targets). Indeed, in a recent expert elicitation, significant probability was attached to the possibility of crossing

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[20] See: http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf.

major tipping points (e.g., dieback of the Amazon rainforest, melting of Greenland, collapse of the West Antarctic ice sheet, shutdown of the THC) for a warming of about 2 °C (Kriegler et al., 2009). Some impacts and tipping points are likely to depend on the rate of warming (Stocker and Schmittner, 1997; O'Neill and Oppenheimer, 2004), in particular those characterizing ecosystem shifts. This has largely been ignored in international negotiations of GHG reduction targets, that focus more on absolute warming. The results of this study are therefore not limited to the discussion of the THC, but are an illustration of the energy policy implications in a case where the total warming is limited to near 2 °C, with the additional condition that the rate of temperature change, and hence the rate of adaptation required, is limited.

Acknowledgments

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