Tellus (2006), 58B, 586–590
Printed in Singapore. All rights reserved

TELLUS

The economic implications of carbon cycle uncertainty

By STEVEN J. SMITH* and JAMES A. EDMONDS, *Joint Global Change Research Institute, 8400 Baltimore Avenue Suite 201, College Park, MD 20740-2496, USA*

(Manuscript received 30 December 2005; in final form 3 July 2006)

ABSTRACT

This paper examines the implications of uncertainty in the carbon cycle for the cost of stabilizing carbon dioxide concentrations. Using a state of the art integrated assessment model, we find that uncertainty in our understanding of the carbon cycle has significant implications for the costs of a climate stabilization policy, with cost differences denominated in trillions of dollars. Uncertainty in the carbon cycle is equivalent to a change in concentration target of up to 100 ppmv. The impact of carbon cycle uncertainties are smaller than those for climate sensitivity, and broadly comparable to the effect of uncertainty in technology availability.

1. Introduction

The increase in atmospheric carbon dioxide (CO_2) concentrations over the past century has been driven, by the most part, by human use of fossil fuels and land use changes. Substantial increases in emissions from fossil fuel are likely to occur over the next several decades (Nakicenovic and Swart, 2000). At present about half of the carbon released into the atmosphere is taken up by the oceans and terrestrial biosphere. The relative magnitude of the mechanisms behind this uptake are unclear (Houghton, 2003), which leads to uncertainty in future behaviour, and the future rate of carbon uptake in particular.

A number of studies have explored the economic implications of stabilizing the concentration of CO_2 (see e.g. Metz et al., 2001). However, these studies treat the carbon cycle as if it were known with certainty. We use a state-of-the-art integrated assessment model, MiniCAM, to show that the economic cost associated with stabilizing the concentration of CO_2 is highly dependent on the representation of carbon cycle processes. We consider here only the effect of uncertainties in our understanding of the carbon cycle by using a single emissions scenario. Other uncertainties, such as those associated with demographic, economic and technological developments are not considered. We report a range of costs that vary by a factor of 5 in response to carbon cycle uncertainty alone. Reducing this uncertainty has obvious economic value to managing the risks of climate change.

*Corresponding author.
e-mail: ssmith@pnl.gov
DOI: 10.1111/j.1600-0889.2006.00217.x

2. Method

2.1. Introduction

We will approach this issue by posing the following question: given a CO_2 concentration target, how do carbon cycle uncertainties affect the economic cost of achieving the target? The models and scenarios used will be described below. The overall philosophy behind this approach is similar to that in Edmonds and Smith (2006), except that in this work a CO_2 concentration target is used instead of a global-mean temperature change target.

2.2. The O^{bj}ECTS MiniCAM

The Object-Oriented Energy, Climate, and Technology Systems (O^{bj}ECTS) MiniCAM is a long-term, global integrated assessment model of energy, economy, agriculture and land use, that considers the sources of emissions of a suite of greenhouse gases (GHGs), emitted in 14 globally disaggregated regions,[1] the fate of emissions to the atmosphere, and the consequences of changing concentrations of greenhouse related gases for climate change over a time period ranging from 1990 to 2095. The MiniCAM begins with a representation of demographic and economic developments in each region and combines these with assumptions about technology development to describe an internally consistent representation of energy, agriculture, land-use and economic developments that in turn shape global emissions and concentrations of GHGs. GHG concentrations in turn determine radiative forcing and climate change.

[1]The United States, Canada, Latin America, Western Europe, Eastern Europe, the Former Soviet Union, the Mideast, Africa, India, China, other South and East Asia, Australia and New Zealand, Japan and Korea.

The equation structure of the MiniCAM is described in Edmonds et al. (2004a). Its energy-economy roots can be traced back to Edmonds and Reilly (1985). The MiniCAM begins with a demographic profile for each region, derives the regional labour force, and combines this with assumptions about the long-term equilibrium rate of labour productivity to derive potential gross domestic product (GDP). Realized GDP is the potential GDP modified by the feedback effect of energy costs. Realized GDP sets the system scale. Energy, agriculture, land and emissions-rights markets are solved endogenously within this aggregate economic frame. The model provides an internally consistent, equilibrium analysis of technologies within the global system. General equilibrium effects and connections, however, are not modelled. That is, the allocation of capital and labour across production processes are assumed to occur within the context of larger long-term economic equilibrium. While this simplification could exert a downward bias on the estimate of economic costs of emissions mitigation, in practice the effect seems small (see e.g. Weyant, 2004).

The MiniCAM has a strong focus on energy production, transformation and use. The model tracks the production of fossil fuels, namely oil, natural gas and coal as well as non-fossil primary energy forms including nuclear, wind, solar, and hydro. The model transforms primary energy forms to those that are consumed in final use. Transformation processes include, refining, power generation, and hydrogen production. A variety of technology options are available to produce all of the end-use energy forms: liquids, gases, solids, electricity and hydrogen. In this exercise, we assume that hydrogen technology is never competitive in transport and that CO_2 capture and storage in geologic reservoirs is not employed as a mitigation option. Energy is consumed in three final-use sectors: buildings, industry and transportation.

The model has been continuously revised and updated to include an expanded set of processes, such as agricultural production and land-use allocation, and additional technology options. The MiniCAM was one of the models employed to develop the IPCC emissions scenarios described in the Special Report on Emissions Scenarios (SRES, Nakicenovic and Swart 2000). We employ the version of MiniCAM implemented in the O^{bj}ECTS framework (Kim et al., 2006). The O^{bj}ECTS framework is a flexible modelling system written in the C++ language using eXtensible Markup Language (XML) input and output formats. The same general equation structure as used in previous model versions was implemented within the O^{bj}ECTS framework. The general equilibrium Second Generation Model (SGM; Edmonds et al., 2004b) has also been implemented in the O^{bj}ECTS framework.

The agriculture and land-use portion of the model is not used for the results presented here as our focus is on the effect of the carbon cycle on climate stabilization. We wish to examine this effect absent the complex interactions between future land-use changes, carbon policy, and commercial biomass production. Accordingly, anthropogenic net land-use change emissions are assumed to follow a fixed time path for all scenarios considered here and commercial biomass production is not utilized. Feedbacks between CO_2 fertilization and the carbon cycle are, therefore, included (see below), but the potential effects of anthropogenic land-use changes that differ between scenarios are not considered. The interactions between land-use changes and climate policy will be examined in future work. In addition, emissions of non-CO_2 GHGs are held fixed at the levels determined in the multigas stabilization scenario reported in Smith and Wigley (2006).

2.3. *Carbon dioxide stabilization scenarios*

The O^{bj}ECTS MiniCAM incorporates the MAGICC simple climate model (Wigley and Raper 1992, 2002; Raper et al., 1996) as used in the IPCC Third Assessment Report (Cubasch et al., 2001). The carbon cycle component of the MAGICC model operates with a balanced global carbon cycle for both historical and future time periods. Input assumptions are specified for net anthropogenic deforestation and ocean fluxes for the decade of the 1980s as well as the strength of temperature-feedbacks. The MAGICC model then adjusts the strength of the CO_2 feedback in order to balance the carbon cycle over this decade (Wigley, 1993). Terrestrial carbon cycle feedbacks are included as temperature dependent reductions in carbon-pool timescales. A temperature feedback on respiration and gross primary productivity are also included. While the detailed behaviour of climate feedbacks on the carbon cycle is undoubtedly complex, these representations, as shown below, are capable of reproducing the range of results from more complex carbon cycle models.

For this study we will use the carbon cycle component of the MAGICC model to construct scenarios that span a plausible range of carbon cycle behaviour. Following Wigley and Raper (2001) terrestrial climate feedback and net deforestation parameters were adjusted in the MAGICC model to produce high, mid and low carbon feedback scenarios. In the high feedback scenario, current net deforestation emissions are assumed to be low, which implies that the CO_2 fertilization effect is also relatively small (Houghton, 2003). Coupled with a high level of temperature feedback, this scenario results in higher atmospheric CO_2 concentrations for a given emissions scenario. The opposite assumptions were used to construct a low carbon cycle feedback scenario.

The sensitivity studies conducted with the ISAM and Bern models, as reported in appendix II of Houghton et al. (2001), were used as guides to set the values of these parameters. Figure 1 shows a comparison of the SRES B2 illustrative scenario with our high, medium, and low carbon cycle parameters with the sensitivity cases from Houghton et al. (2001). Our high, mid, and low feedback cases are close to those from these two intermediate complexity carbon cycle models. Our high case was chosen to match the Bern model high case, which is significantly higher

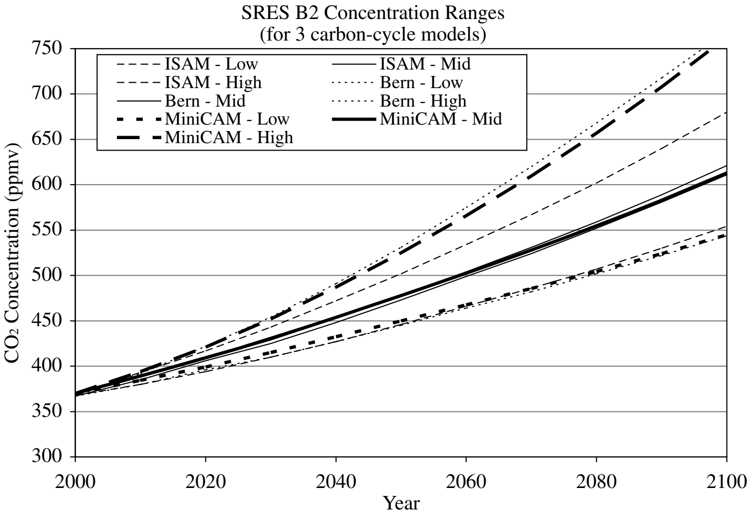

Fig. 1. Comparison of carbon cycle model results for the high, medium, and low cases used for the O[bj]ECTS MiniCAM results presented here (thick lines) with sensitivity studies presented in Houghton et al. (2001) for the Bern and ISAM models.

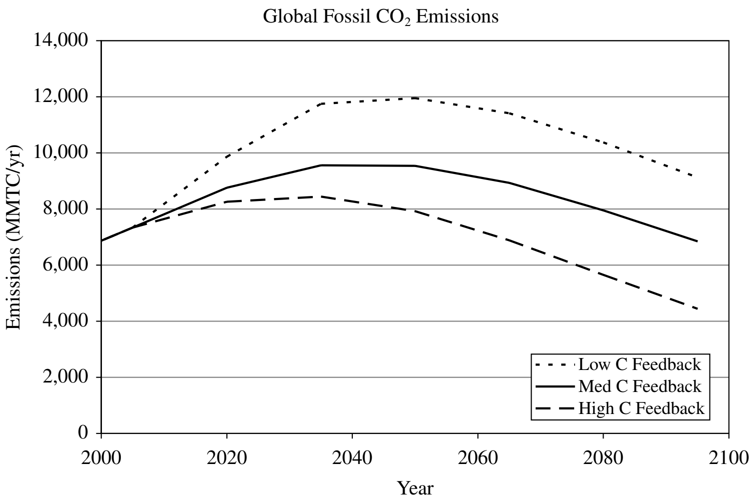

Fig. 2. Emissions pathways for stabilization at 550 ppmv for three carbon cycle scenarios.

than the ISAM high case. The three sensitivity cases presented here, therefore, represent a plausible range of potential carbon cycle responses. While we have not explicitly considered potential future changes in the behaviour of ocean carbon uptake, to the extent which such changes are included in the model uncertainty exercises used for calibration (Houghton et al., 2001) we have covered the overall magnitude of the potential uncertainty range.

The results here use the SRES B2 scenario as implemented in the O[bj]ECTS MiniCAM, see Smith et al. (2005) for implementation details. The SRES B2 scenario is a ‘dynamics as usual’ scenario where, in the MiniCAM implementation, emissions of CO_2 increase to 22 GtC yr^{-1} by 2100.

Three stabilization cases were constructed corresponding to these three carbon cycle scenarios. To construct these cases we began with the 550 ppm concentration stabilization paths from Wigley et al. (1996), updated to correspond to recent historical concentration data as used in the MAGICC model and new MiniCAM baseline emissions pathways. These concentration paths were inverted to determine CO_2 emissions pathways for each of the carbon cycle scenarios discussed above. The resulting emissions paths are shown in Fig. 2. Emissions in the mid carbon cycle case peak at slightly below 10 GtC yr^{-1} in midcentury. For the high carbon cycle feedback case emissions must peak earlier and at a lower level, just over 8 GtC by 2030, in order to follow the specified concentration pathway. If the carbon cycle exhibits a lower level of feedbacks then emissions can increase further while still achieving the same concentration goal.

The high and low emissions paths shown in Fig. 2, if used with the medium carbon cycle assumptions, result in stabilization at 650 and 500 ppmv, respectively. In other words, our carbon cycle uncertainty cases are equivalent to +100 and −50 ppmv change in the CO_2 concentration target.

Another way to view the impact of these assumptions is to examine the carbon uptake in these scenarios. We define total carbon uptake as the net carbon uptake by the terrestrial ecosystem and the oceans, which includes the assumed fixed pathway for net deforestation. In the mid case, the net carbon uptake increases from a current value of 1 GtC yr^{-1} to nearly 2 GtC/year by midcentury. In the high carbon-feedback case total net uptake decreases over the century and changes sign, with a net release of around 1 GtC yr^{-1}r by the end of the century. In the low carbon feedback case total carbon uptake increases to over 4 GtC yr^{-1} by the end of the century.

We now turn to our main result, the economic implications of carbon cycle uncertainty.

Table 1. Total discounted cost of a CO_2 concentration stabilization policy in millions of year $2005 USD (see text)

Carbon cycle scenario	Total mitigation cost
Low C cycle feedback	1,190,000
Mid C cycle feedback	3,250,000
High C cycle feedback	6,290,000

3. Results

In order to examine the economic implications of carbon cycle uncertainty we have constrained the O^{bj}ECTS MiniCAM model to follow each of the emissions paths shown in Fig. 2. We assume that all nations participate in the emissions mitigation activities and that all mitigation is undertaken such that at any point in time the cheapest mitigation options are always undertaken first, regardless of where and in what sector they may be found. This is sometimes referred to as 'where' flexibility (Richels et al., 1996). While these assumptions are admittedly unrealistic, it is beyond our ability to predict a 'realistic' international emissions mitigation regime. Because we assume perfect 'where' flexibility, our costs, in any period are an idealized representation.

In each model period where emissions are above the constraint, a common global price is applied to fossil-fuel carbon emissions everywhere and in all applications. The carbon price is adjusted until emissions equal the specified value in each period. As the carbon price increases, the energy system adjusts by a combination of shifts to lower carbon technologies, more efficient use of energy, and lower consumption of energy services. These shifts are illustrated in Edmonds et al. (2004a).

The resulting carbon price pathways are shown in Fig. 3. The carbon price for the mid case increases to over $750/TC by the end of the century. Note that, while this scenario does contain significant technological advances in terms of energy end-use efficiency and electric generation technologies, we have not included advanced technologies such as CO_2 capture with geologic storage or hydrogen use for passenger transportation.

Achieving the same result for the high carbon feedback scenario requires a carbon price that is 50% higher than the central case by the end of the century. This higher cost represents the lower level of emissions that would be allowed (Fig. 2) under a case where there is significantly lower uptake of anthropogenic carbon by the terrestrial carbon cycle. The opposite occurs for a more favourable behaviour of the carbon cycle where greater uptake of anthropogenic carbon takes place. In the low carbon feedback scenario, the carbon price is lower and the carbon price is not applied until a later date.

A summary of the results is provided in Table 1, which presents the total discounted cost of the carbon policy. The total carbon payments over time are discounted from to 2095 to 2005 at an interest rate of 5% and are presented in 2005 USD. At this discount rate, payments in 2095 are reduced by a factor of 81 as compared to payments made in 2005. The total cost of achieving CO_2 concentration stabilization ranges from 1.2 to 6.3 trillion USD. In the more favourable case, the lower carbon tax plus the later need for policy implementation contributes to a significantly lower cost.

We can compare the results here to those of Edmonds and Smith (2006), although only approximately because of the

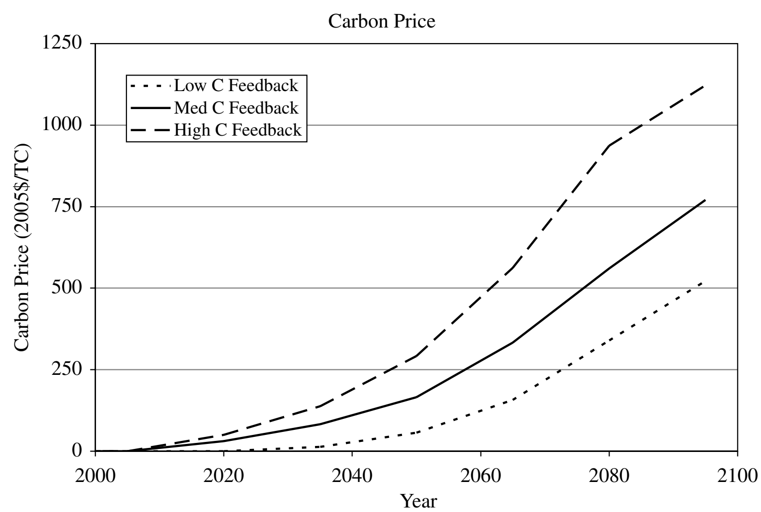

Fig. 3. Carbon price for stabilization at 550 ppmv for three carbon cycle scenarios. Prices are in $2005.

different policy target considered. Uncertainty in the climate sensitivity has a larger effect on costs than uncertainty in the carbon cycle (Edmonds and Smith, 2006). The economic impact of carbon cycle uncertainties are larger than the effect of any individual technology choice, although the effect of technology combinations (i.e. the presence or absence of multiple technologies) can have a larger impact than carbon cycle uncertainties. We note, however, that it is somewhat difficult methodologically to rigorously compare uncertainties in physical parameters with assumptions about future technology availability.

We have shown that uncertainty in the carbon cycle results in a large range in the cost of achieving CO_2concentration stabilization. While the carbon cycle model used is relatively simple, the range in carbon cycle response used here is illustrative of the range determined by more complex models. It should be pointed out, however, that the range of carbon cycle behaviour represented here does not necessarily encompass the entire range of possible responses. For example, it is possible that feedback effects could have quite different dynamics than presently included in carbon cycle models. Experimental evidence, for example, suggests that CO_2 feedbacks might be transient, effectively saturating much sooner than modelled. Other feedbacks, such as stimulation by nitrogen deposition, could also be operating. Further, there are important interactions between land-use changes and the carbon cycle that have not been considered here. Nevertheless, these calculations provide a sense of economic importance surrounding uncertainty in carbon cycle processes and underlines the value of research to improve on the present state of scientific understanding of the carbon cycle.

4. Acknowledgments

The authors would like to thank Cesar Izaurralde and Leon Clarke for helpful comments. We would also like to thank Larry Williams for encouraging us to undertake this line of investigation. The comments of three anonymous reviewers greatly improved the presentation of the material. Support for this research was provided by the Electric Power Research Institute and the United States Department of Energy Office of Science integrated assessment programme.

References

Cubasch, U., Meehl, G. A., Boer, G. J., Stouffer, R. J., Dix, M. and co-authors 2001. Chapter 9. Projections of Future Climate Change. In: *Climate Change 2001: The Scientific Basis*. (eds J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu). Cambridge University Press, Cambridge, UK, pp. 239–287.

Edmonds, J. and Reilly, J. 1985. *Global Energy: Assessing the Future*, Oxford University Press, Oxford, United Kingdom.

Edmonds, J. A. and Smith, S. J. 2006. The Technology of Two Degrees. In: *Avoiding Dangerous Climate Change*. (eds H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe). Cambridge University Press, Cambridge, UK.

Edmonds, J., Clarke, J., Dooley, J., Kim, S. H., Smith, S. J. 2004a. Stabilization of CO_2 in a B2 world: insights on the roles of carbon capture and storage, hydrogen, and transportation technologies, *Energy Econ.* **26**, 517–537.

Edmonds, J. A., Pitcher, H. M. and Sands, R. D. 2004b. *Second Generation Model 2004: An Overview*. Pacific Northwest National Laboratory, PNNL-14916.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J. and co-authors. 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge, UK, pp. 239–287.

Houghton, R. A. 2003. Why are estimates of the terrestrial carbon balance so different? *Global Change Biol.* **9**(4), 500–509.

Kim, S. H., Edmonds, J. A., Smith, S. J., Wise, M. and Lurz, J. 2006. The Object-oriented Energy Climate Technology Systems (O^{bj}ECTS) Framework and Hybrid Modeling of Transportation. *Energy J.*, in press.

Metz, B., Davidson, O., Swart, R. and Pan, J. (eds) 2001. *Climate Change 2001: Mitigation. The Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Nakicenovic, N. and Swart, R. (eds). 2000. *Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, U.K.

Raper, S. C. B., Wigley, T. M. L. and Warrick, R. A. 1996. In: *Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies* (eds J. D. Milliman and B. U. Haq). Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 11–45.

Richels, R., Edmonds, J., Gruenspecht, H. and Wigley, T. 1996. The Berlin Mandate: The Design of Cost-Effective Mitigation Strategies. In: *Climate Change: Integrating Science, Economics and Policy*, CP-96-1:29-48. (eds N. Nakicenovic, W. D. Nordhaus, R. Richels and F. L. Toth). International Institute for Applied Systems Analysis, Laxenburg, Austria, 20 pp.

Smith, S. J. and Wigley, T. M. L. 2006. Multi-Gas Forcing Stabilization with the MiniCAM. *Energy J.*, in press.

Smith, S. J., Pitcher, H. and Wigley, T. M. L. 2005. Future Sulfur Dioxide Emissions. *Climatic Change* **73**(3), pp. 267–318.

Weyant, J. P. (ed) 2004. EMF 19 Alternative Technology Strategies for Climate Change Policy. *Energy Econ.* **26**(4), 501–755.

Wigley, T. M. L. 1993. Balancing the carbon budget - implications for projections of future carbon-dioxide concentration changes. *Tellus* **45B**, 409–425.

Wigley, T. M. L. and Raper, S. C. B. 1992. implications for climate and sea-level of revised IPCC emissions scenarios. *Nature* **357**, 293–300.

Wigley, T. M. L. and Raper, S. C. B. 2001. Interpretation of high projections for global-mean warming. *Science* **293**(5529), 451–454.

Wigley, T. M. L. and Raper, S. C. B. 2002. Reasons for larger warming projections in the IPCC Third Assessment Report. *J. Climate* **15**, 2945–2952.

Wigley, T. M. L., Richels, R., Edmonds, J. A. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* **379**, 240–243.