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Working Paper No. 288

April 2009

Climate Feedbacks on the Terrestrial Biosphere and the Economics of Climate Policy: An Application of *FUND*

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Abstract: Previous versions of the FUND model assumed, like many integrated assessment models, that the carbon cycle is independent of climate change. I here introduce a feedback through which warming leads to higher net emissions. This increases the atmospheric concentration of carbon dioxide in the year 2100 by 100 (20-200) ppm. This leads to a higher estimate of the Pigou tax. The benefit of emission reduction now includes the direct benefits of lower emissions as well as the indirect benefits of a smaller feedback, but the latter effect is small. For any given stabilization target, abatement costs are substantially higher with the climate feedback than without. Abatement costs become sensitive to assumptions about climate change. Non-CO_2 emission reduction becomes essential for meeting CO_2 concentration targets. For pessimistic assumptions about the strength of the feedback, model results (for the 21st century) become sensitive to small variations in parameters.

Key words: Climate policy; integrated assessment; carbon cycle

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1. Introduction

Models should be as simple as possible, but not simpler. This also holds for Integrated assessment models (IAMs). IAMs combine reduced form models of the various components of the climate change problem to shed light on climate policy – and the perfect IAM has just enough complexity to generate an important insight. The perfect IAM does not exist, of course, but (Smith & Edmonds 2006) have recently argued that most IAMs have a serious deficiency. The simplifying assumption that the uptake of carbon dioxide by the terrestrial biosphere is independent of climate, may have led to a substantial underestimate of the effort and cost required to meet any target for stabilization of the atmospheric concentration of greenhouse gases. In this paper, I test this with a different IAM, and extend the analysis to costs and benefits.

The representation of the carbon cycle in IAMs has been under scrutiny before (Joos et al. 1999;Schultz & Kasting 1997), but earlier work was focused on alternative representations of a *static* carbon cycle. One of the crucial assumptions about the carbon cycle is the atmospheric life-time of carbon dioxide, as this determines whether emissions should be reduced or eliminated if concentrations are to be stabilized (Kolstad 2005). This paper is focused on the hitherto largely neglected dynamics of the carbon cycle – neglected by climate economists, that is. As argued below, this not only changes the level of ambition and costs of climate policy (as would be the case with alternative static representations), but it also introduces new interactions. There is an additional premium on emission reduction, as the terrestrial feedback falls with abatement. Additional parameters, such as the climate sensitivity, affect the atmospheric concentration of greenhouse gases.

Section 2 describes the model. Section 3 discusses the impacts of the climate feedback of the terrestrial biosphere on cost-benefit analysis, while Section 4 considers cost-effectiveness analysis. Section 5 concludes.

2. The model

I use Version 2.9 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.9 of FUND has the same basic structure as that of Version 1.6 (Tol 1999;Tol 2001;Tol 2002c), except for the impact module (Tol 2002a;Tol 2002b). The source code and a complete description of the model can be found at http://www.fund-model.org/.

Essentially, FUND is a model that calculates damages of climate change and impacts of greenhouse gas emission reduction for 16 regions of the world by making use of exogenous scenarios of socioeconomic variables. The scenarios comprise of projected temporal profiles of population growth, economic growth, autonomous energy efficiency improvements and carbon efficiency improvements (decarbonization), emissions of carbon dioxide from land use change, and emissions of methane and of nitrous oxide. Carbon dioxide emissions from fossil fuel combustion are computed endogenously on the basis of the Kaya identity. The calculated impacts of climate change perturb the default paths of population and economic outputs corresponding to the exogenous scenarios. The model runs from 1950 to 2300 in time steps of a year, though the outputs for the 1950-2000 period is only used for calibration, and the years beyond 2100 are used for the approximating the social cost of carbon under low discount rates. The scenarios up to the year 2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). For the years from 2100 onward, the values are extrapolated from the pre-2100 scenarios. The radiative forcing of carbon dioxide and other greenhouse gases used by FUND is determined based on Shine *et al.* (1990). The global mean temperature is governed by a geometric buildup to its equilibrium (determined by the radiative forcing) with a half-life of 50 years. In the base case, the global mean temperature increases by 2.5˚C in equilibrium for a doubling of carbon dioxide equivalents. Regional temperature increases, which are the primary determinant of regional climate change damages (except for tropical cyclones, as discussed below), are calculated from the global mean temperature change multiplied by a regional fixed factor, whose set is estimated by averaging the spatial patterns of 14 GCMs (Mendelsohn et al. 2000).

The model considers the damage of climate change for the following categories: agriculture, forestry, water resources, sea level rise, energy consumption, unmanaged ecosystems, and human health (diarrhea, vector-borne diseases, and cardiovascular and respiratory disorders). Impacts of climate change can be attributed to either the rate of temperature change (benchmarked at 0.04˚C per year) or the level of temperature change (benchmarked at 1.0˚C). Damages associated with the rate of temperature change gradually fade because of adaptation (Tol 2002a).

FUND considers emission reduction of the three main greenhouse gases: carbon dioxide, methane, and nitrous oxide. For methane and nitrous oxide, simple abatement cost curves are used (Tol 2006). For carbon dioxide, the model is more elaborate. Initially, abatement costs rise more than proportionally with abatement effort, but costs become linear after a backstop price is reached. There are mild intertemporal spillovers between and within regions that reduce costs (Tol 2005a).

FUND is fully described on http://www.fund-model.org/. The model specification used here is as in the publications listed above. In this paper, I modify the carbon cycle. The atmospheric concentration of carbon dioxide follows from a five-box model:

(1a) $$Box_{i,t} = \rho_i Box_{i,t} + 0.000471 \alpha_i E_t$$

with

(1b) $$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to *Box i* and ρ the decay-rate of the boxes (ρ = exp(-1/lifetime). See Table 1 for the parameters. The model is due to (Maier-Reimer & Hasselmann 1987), its parameters are due to (Hammitt et al. 1992). Carbon dioxide concentrations are measured in parts per million by volume. Below, I refer to Equation (1) as the static carbon cycle; it is static in the sense that it is not affected by climate change.

There is a feedback from climate change on the amount of carbon dioxide that is stored and emitted by the terrestrial biosphere. Instead of modelling the full dynamics, I keep the uptake by the terrestrial biosphere as it is – that is, Equation (1) is not affected – and add emissions from the terrestrial biosphere. Emissions from the terrestrial biosphere follow

(2a) $$E_t^B = \beta\left(T_t - T_{2000}\right)\frac{B_t}{B_{\max}}$$

with

(2b) $$B_t = B_{t-1} - E_{t-1}^B$$

where E^B are emissions (in million metric tonnes of carbon); t denotes time; T is the global mean temperature (in degree Celsius); B_t is the remaining stock of potential emissions (in million metric tonnes of carbon, GtC; $B_{\max}$ is the total stock of potential emissions; $B_{\max}$ = 1,900 GtC; β is a parameter; β = 2.6 GtC/ºC, with a lower and upper bound of 0.6 and 7.5 GtC/ºC. The model is calibrated to the review of (Denman et al. 2007).

Figure 1 shows the atmospheric concentration of carbon dioxide for the business as usual scenario and for β = 0, β = 0.6 GtC/ºC, β = 2.6 GtC/ºC, and β = 7.5 GtC/ºC. Without the climate feedback of the terrestrial biosphere, ambient CO_2 goes up to 817 ppm in 2100. With the feedback, this is 903 ppm, with a range of 838 to 1040 ppm. The terrestrial biosphere clearly makes a difference.

3. Efficient climate policy

An efficient climate policy selects emission reduction so as to maximize net present welfare. Essentially, abatement costs are balanced against the avoided damages of climate change. I here only approximate the optimum. In the first period, marginal abatement costs equal the marginal damage costs. However, I let marginal abatement costs rise with the rate of discount rather than with the growth rate of the marginal damage costs (Hotelling 1931). This approximation facilitates comparison with the cost-effectiveness analysis below.

I first compute the marginal damage cost of carbon dioxide emissions along the business as usual or no climate policy scenario (Tol 2005b). This is done by slightly perturbing that scenario, computing net present value of the difference in impacts, and normalizing that with the difference in emissions. The results are shown in Table 2 as the social cost of carbon. I then impose a carbon tax equal to the social cost of carbon, and recomputed the marginal damage cost along the new emissions trajectory. This is iterated until the carbon tax equals the marginal damage costs. The results are shown in Table 2 as the Pigou tax (Pigou, Arthur C. 1920).

As a carbon tax reduces emissions, one would expect that the Pigou tax is lower than the social cost of carbon. Table 2 confirms that this is the case. By the same token, if the feedback of climate change on the terrestrial biosphere leads to higher concentrations of carbon dioxide in the atmosphere, then one would expect that the social cost of carbon is higher. Again, Table 2 confirms that this is the case. In the central case, the social cost of carbon is 19% higher with the feedback factor than without; this is 5% and 49% in the low and high cases, respectively.

For the Pigou tax, there are two effects at work. Firstly, higher concentrations imply higher marginal damage costs. Secondly, abatement not only reduces anthropogenic emissions, but also the feedback on the terrestrial biosphere. This bonus increases the difference between the social cost of carbon and the Pigou tax. Table 2 shows that the first effect dominates. The feedback increases the Pigou tax by 18% in the central case, and by 4% and 46% in the low and high cases. The Pigou tax is 88% of the social cost of carbon without feedback, and 86% with the highest feedback. The difference is so small because the climate system has so much momentum.

Table 3 shows a sensitivity analysis for the social cost of carbon. I first vary the pure rate of time preference. Obviously, the social cost goes up as the discount rate goes down, but the relative change varies in an unpredictable way. This is because the terrestrial feedback differs in speed rather than in size – cf. Equation (2). Furthermore, the level of climate change has a mix of positive and negative effects, while the rate of climate change is unambiguously negative and CO_2 fertilization unambiguously positive (in the model). A different feedback effect affects all of these at once, and a different discount rate emphasizes different aspect of the time profile. Hence, the relative effects are hard to predict. However, a higher terrestrial feedback is always bad, regardless of the discount rate. Table 3 also shows the results for different values of the climate sensitivity. The social cost of carbon is substantially larger if the planet warms faster. If the planet warms more slowly, the social cost of carbon is negative, and more so if the terrestrial feedback is stronger. The negative cost is explained by CO_2 fertilization, which is stronger as the terrestrial feedback is stronger. CO_2 fertilization also dampens the negative impacts if the climate sensitivity is larger, while faster warming means that the terrestrial feedback is exhausted sooner so that its impacts are more concentrated in the 21^{st} century. Table 3 also shows the social cost of carbon without CO_2 fertilization, underlining the importance of this factor.

4. Cost-effective climate policy

A cost-effective climate policy meets a given target at the lowest possible cost. To a first approximation, this implies that the marginal costs of emission reduction is equal between countries and greenhouse gases, and rises with the rate of discount. The initial carbon is the only difference, therefore, with the efficient policies discussed above. Furthermore, the optimization problem is uni-dimensional. I select two stabilization targets, viz. 3.4 Wm^{-2}, 4.6 Wm^{-2} and 5.8 Wm^{-2} or 520 ppm CO_{2eq}, 650 ppm CO_{2eq} and 810 ppm CO_{2eq}. The highest and lowest targets were also used in the US CCSP (Clarke et al. 2007) but are otherwise arbitrary; the middle target is between the other targets.

Table 4 shows the results. A stricter target requires a higher initial carbon tax, and implies a sharper reduction in economic growth. If the terrestrial biosphere releases more carbon into the atmosphere due to climate change, it is tougher to meet the target. Carbon taxes go up, and economic growth falls further. Opinions differ as to the strain the economy can and should take. However, climate policy would almost wipe out economic growth if the target is 4.6 Wm^{-2} and if the climate feedback of terrestrial biosphere is at its maximum – the same target is two orders of magnitude smaller if there is no feedback.

Table 5 shows the results for the initial carbon of a sensitivity analysis around the 4.6 Wm^{-2} target. There is an extensive literature on the costs of emission reduction, and on cost-effective strategies. The same sensitivities apply here. The results in Table 5 focus on those parameters that affect the impact of the terrestrial feedback. Cost-effective trajectories to meet a radiative forcing target are insensitive to the warming that would be caused by that forcing if there is no feedback. However, if the terrestrial biosphere releases carbon in response to climate change, the cost-effective trajectory is sensitive.

Table 5 reveals that the initial carbon tax goes up (down) if the climate sensitivity[1] goes up (down), as one would expect, and that the effect is of the same order of magnitude as the effect of the terrestrial feedback itself. As both parameters are fairly uncertain, the interaction may create a fat tail (Weitzman 2009).

Table 5 also displays the impact of alternative parameterization of the static component of the carbon cycle (Equation (1); Table 1). In the base case, the zero-carbon-tax scenario has an atmospheric concentration of carbon dioxide of 817 ppm in 2100 without a climate feedback on the carbon cycle, which goes up to 903 ppm with the climate feedback (for β = 2.6 GtC/ºC). Although (Hooss et al. 2001) uses very different parameters, the 2100 concentration is 823 ppm without feedback and 910 ppm with. Using the parameters of (Maier-Reimer & Hasselmann 1987), the 2100 concentration is 860 ppm without feedback and 957 ppm with. Table 5 shows the initial carbon tax needed to stabilize at a radiative forcing of 4.6 Wm^{-2}. With a zero or small climate feedback, the tax rates are similar between the alternative specifications of the static carbon cycle. However, results diverge for a high climate feedback. This underlines that the climate feedback is a dynamic feedback in the mathematical sense of the word, and introduces a bifurcation in the system.

Table 5 also varies the efficacy of non-CO2 greenhouse gas emission reduction – essentially, the cost function is varied so that the same carbon tax would yield twice or half the amount of methane and nitrous oxide emission reduction as in the base case. Again, the effect on the initial carbon tax is in the same order of magnitude as the terrestrial feedback. That is, methane and nitrous oxide play a crucial role in keeping the warming sufficiently in check to prevent massive releases of carbon from the terrestrial biosphere.

5. Discussion and conclusions

The positive feedback of climate change on the terrestrial biosphere component of the carbon cycle implies that efficient climate policy is more stringent than in the case

[1] The climate sensitivity is defined as the equilibrium increase of the global mean surface air temperature due to a doubling of the atmospheric concentration of carbon dioxide.

without such feedback because (a) climate change is more severe and its impacts are worse, and (b) there is "reduced feedback" premium on emission reduction. The latter effect is small compared to the former. There are no clear interactive effects of the terrestrial feedback with the discount rate or the climate sensitivity, but the impact of the terrestrial feedback on the social cost of carbon is dampened by the positive effects of CO_2 fertilization on agriculture. This implies that one can reasonably approximate the impact of the climate feedback with the effect of higher baseline emissions.

The positive feedback of climate change on the terrestrial biosphere component of the carbon cycle implies that cost-effective climate policy is more expensive for the same target than in the case without such feedback. If the feedback is large, more ambitious stabilization targets may be unattainable. The feedback would be reinforced if the warming is faster than expected, if non-CO_2 greenhouse gas emission reduction is less effective, or if other parts of the carbon cycle are less advantageous. This implies that one can reasonably approximate the impact of the climate feedback with the effect of higher baseline emissions or more stringent targets. However, this is true for modest values of the climate feedback parameter only. For high values, there appears to be a "bifurcation" – that is, certain targets can be achieved at reasonable cost for one set of parameters choices, but alternative (and superficially similar) parameter choices imply much higher abatement costs. This bifurcation does not apply to the impacts of climate change because there is no target date (e.g., emissions in 2100), because the total feedback is limited by the stock of carbon dioxide in the terrestrial biosphere, and because of the discount rate.

As ever, the above results are predicated on the model and its parameters and scenarios. The modification of the carbon cycle is particularly simple and the results should be tested against other, more realistic specifications. At the same time, the simple formulation used here can readily be included in other integrated assessment models so that one can test the robustness of my findings against alternative representations of the impact of climate change or the costs of emission reduction. Future research should particularly focus on the two main findings (1) that the climate feedback on the terrestrial carbon cycle has approximately the same effect as higher baseline emissions and (2) that there is a possible bifurcation in costs and feasibility. The latter conclusion may negate the former conclusion, but the bifurcation seems to hold for small part of the parameter space only and may disappear under uncertainty or a less rigid application of the target date. Future research should also explore other feedbacks, such as on the ocean carbon cycle and the permafrost. The results presented here show a definite impact on the level of the costs of climate policy and a possible impact on the dynamics of climate policy. The size of the impact is such that further research is worthwhile.

On the policy side, the results show that climate policy will be more expensive (or less feasible) than previously thought but at the same time show that emission abatement is more urgent.

Acknowledgements

Geoff Blanford had constructive comments on an earlier version of the paper. Financial support by the Electric Power Research Institute is gratefully acknowledged.

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Table 1. Parameters of the "five-box carbon cycle model" of (Maier-Reimer & Hasselmann 1987) according to the standard calibration in FUND (Hammitt, Lempert, & Schlesinger 1992), according to (Hooss, Voss, Hasselmann, Maier-Reimer, & Joos 2001), and according to the original calibration (MR&H).

FUND	Life time	∞	363.0	74.00	17.00	2.000
	Fraction	0.130	0.200	0.320	0.250	0.100
Hooss	Life time	∞	236.5	59.52	12.17	1.271
	Fraction	0.132	0.311	0.253	0.209	0.095
MR&H	Life time	∞	313.8	79.80	18.80	1.700
	Fraction	0.142	0.241	0.323	0.206	0.088

Table 2. The social cost of carbon and the Pigou tax for various strengths of the climate feedback on the terrestrial carbon cycle.

Feedback	None	Low	Mid	High
Social cost of carbon ($/tC)	1.93	2.03	2.30	2.87
Pigou tax ($/tC)	1.70	1.77	2.01	2.48
PT/SCC[a] (%)	88.08	87.44	87.39	86.44

[a] Pigou tax / social cost of carbon.

Table 3. A sensitivity analysis of the social cost of carbon ($/tC) for various strengths of the climate feedback on the terrestrial carbon cycle.

Pure time preference	Climate sensitivity	CO_2 Fertilization	Climate feedback terrestrial biosphere			
%/year	˚C/2xCO_2		None	Low	Mid	High
3	2.5	Yes	1.93	2.03	2.30	2.87
1	2.5	Yes	16.44	17.32	19.49	22.52
0	2.5	Yes	56.86	60.73	68.28	74.55
3	1.5	Yes	-3.69	-3.71	-3.79	-4.02
3	4.5	Yes	20.34	21.14	23.15	25.47
3	2.5	No	9.02	9.19	9.67	10.61

Table 4. The marginal and total costs of meeting various stabilization targets for various strengths of the climate feedback on the terrestrial carbon cycle.

Feedback	None	Low	Mid	High
Initial carbon tax ($/tC in 2005)				
No target	0	0	0	0
5.8 Wm^{-2}	6	7	15	71
4.6 Wm^{-2}	19	23	56	1461
3.4 Wm^{-2}	111	131	229	>2000
Reduced growth (difference with baseline growth, in percent per year)				
No target	2.006[a]	0.000	0.001	0.002
5.8 Wm^{-2}	0.015	0.017	0.025	0.264
4.6 Wm^{-2}	0.022	0.027	0.206	1.880
3.4 Wm^{-2}	0.506	0.519	1.138	-

[a] Average annual growth of the global economy between 2000 and 2100 for the case without carbon feedback and without climate policy.

Table 5. Initial carbon tax necessary for meeting a radiative forcing target of 4.6 Wm^{-2} for the base case, low and high climate sensitivities (1.5ºC/2xCO_2 and 4.5ºC/2xCO_2 versus 2.5ºC/2xCO_2), low and high efficacy of non-CO2 abatement (half and double), and two alternative calibrations of the static carbon cycle model (cf. Table 1) for various strengths of the climate feedback on the terrestrial carbon cycle.

Feedback	None	Low	Mid	High
Base	19	23	56	1461
Low climate sensitivity	19	21	34	88
High climate sensitivity	19	24	82	>2000
Low non-CO_2 gas abatement	17	19	34	98
High non-CO_2 abatement	21	27	1205	>2000
Hooss	20	24	59	>2000
MR&H	24	28	71	>2000

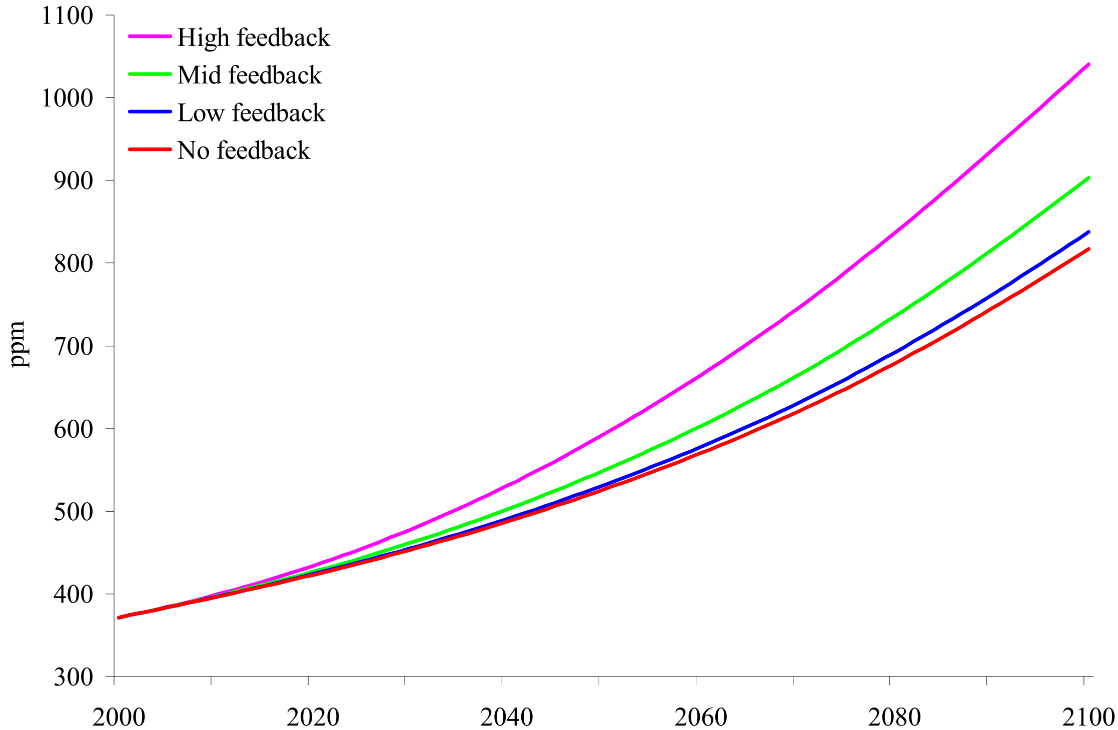

Figure 1. The atmospheric concentration of carbon dioxide under the business as usual scenario for four alternative specifications of the climate feedback of the terrestrial biosphere.

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