ON CLIMATE CHANGE AND ECONOMIC GROWTH

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Abstract

The economic impact of climate change is usually measured as the amount by which the climate of a given period will affect output or GDP in that period. This paper draws attention to some of the dynamic effects through which climate change may affect economic growth and hence future output. In particular, the paper looks at saving and capital accumulation. With a constant savings rate, a lower output due to climate change will lead to a proportionate reduction in investment which in turn will depress future production (capital accumulation effect). If the savings rate is flexible, forward looking agents may change their savings behavior to accommodate the impact of future climate change. Again this alters growth prospects (savings effect). In an endogenous growth context, the two effects may be exacerbated through changes in labour productivity and the rate of technical progress. Simulations using a simple climate-economy model suggest that the capital accumulation effect is important, especially if growth is endogenous, and may be larger than the direct impact of climate change. The savings effect is less pronounced and its sign is ambiguous. In most cases, the savings effect is negative, that is, faced with climate change households increase current consumption rather than saving more to compensate for future damages. The indirect effects are relatively larger for smaller direct effects; the indirect effects are also relatively larger for growth mechanisms more prevalent in richer countries. Ignoring the growth effects of climate change thus leads to a substantial underestimate of the impacts of climate change, particularly in richer economies.

Key words

Climate change; impacts; saving; economic growth

JEL Classification

D6, D91, E21, O13, Q01, Q2

1. Introduction

In most studies of the economic impact of global warming the effects of climate change are assessed and valued separately sector by sector, and then added up to form an estimate of the overall change in social welfare (e.g., Nordhaus, 1991; Cline 1992; Fankhauser, 1995: Tol, 1995; Mendelsohn and Neumann, 1999). This is known as the enumerative approach.[1] It is well-known and widely documented in the literature that this method ignores potentially significant "horizontal interlinkages", that is interactions between sectoral impacts such as agriculture (where irrigation needs may go up) and water (where supply may decrease). See Smith *et al.* (2001) and Tol *et al.* (2000) for a discussion.

Equally important, but less well documented, is the fact that the enumerative approach also neglects dynamic interlinkages. Enumerative studies are concerned with only one time period and ask how the climate observed in that period affects social welfare at that particular point in time. In doing so, they ignore intertemporal effects and fail to provide information on how climate change may affect output in the longer term. This paper seeks to close this gap by exploring the links between climate change and growth.

The main such link or dynamic effect is via *capital accumulation*. If we assume a constant savings rate, the amount of investment in an economy will be reduced if climate change has a negative impact on output (and vice versa if impacts are positive). Over the longer term this will lead to a reduction in the capital stock and a lower GDP. In an endogenous growth context, this capital accumulation effect may be exacerbated if lower investment also slows down technical progress and improvements in labour productivity or human capital accumulation.

A second dynamic effect has to do with *saving.* In a world with perfect foresight we can expect forward-looking agents to change their savings behavior in anticipation of future climate change. This, too, will affect the accumulation of capital and hence growth and future GDP. It is unclear, a priori, whether this savings effect will be positive or negative. On the one hand, savings rates may go up because agents wish to compensate for the shortfall in future income. On the other hand,

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[1] The term is due to Cline (1994).

climate change could reduce the productivity of capital and, faced with a lower rate of return on capital, agents may prefer to consume more today.

Integrated assessment models with an economic foundation (e.g., Nordhaus, 1994; Peck and Teisberg, 1993; Tol, 1999) usually incorporate the capital accumulation effect and sometimes the savings effect because their design is based on neo-classical growth theory. But they do not usually separate the dynamic effects explicitly. In this paper we try to do so. Section 2 discusses the theoretical links between climate change and growth based on an analysis of the steady state of a stylized growth model. In Section 3 we simulate the magnitude and direction of the dynamic effects using DICE, a relatively simple and widely used climate-economy model (see Nordhaus 1994). We also investigate the sensitivity to alternative specifications of the mechanisms of growth. Section 4 estimates the effect of climate change on the rate of growth, and Section 5 concludes.

2. A Theoretical Model of Climate Change and Growth

Model description

To study the basic interlinkages between climate change and economic growth we use a standard Ramsey-Cass-Koopmans growth model, in which a social planner is faced with the following intertemporal optimisation problem:

(1) $$\max \int_0^\infty u(c,T) \cdot e^{(n-x-r)t}\, dt \quad ,$$

subject to:

(2) $$\dot{K} = F(K,L,T) - cL - d(T)K \ ,$$

(3) $$\dot{L} = n(T) \cdot L;\ L_0 = 1\, ,$$

where u denotes the utility function, c is per capita consumption; F is output; K is capital, depreciating at rate *ä*; and *ñ* is the discount rate.

L is labour supply, which grows at rate n, starting from an initial, normalised level of 1; The variable should be interpreted as being about *effective* labour, that is the growth rate n reflects both changes in population (p) and labour productivity (x), i.e. $n = p+x$. Note that labour productivity is exogenous in this formulation. We will look at models with endogenous productivity improvements in the next section.

For simplicity, climate change is represented by an exogenous, time-independent indicator, T (for temperature). The larger T, the more pronounced are the impacts of climate change. Climate change affects the optimisation at up to four levels:

- Non-market impacts such as the amenity value of climate and the effect on recreational and environmental assets. Non-market impacts directly affect the utility function, and we assume them to be negative, $u/\ \ T = u_T < 0$, although the impact literature has also identified potential benefits (Smith *et al.* 2001).

- Market impacts such as changes in agricultural yields, which enter the production function. Again we assume the net impact to be negative, $F/\ \ T = F_T < 0$, notwithstanding arguments in the more recent literature that market impacts may initially be positive at least for some regions (e.g., Mendelsohn and Neumann 1999; Tol 1999).

- Health and mortality impacts associated with more widespread diseases such as malaria. These affect both population growth and the productivity of the labour force, and are believed to be predominantly negative, $n/\ \ T = n_T < 0$ (McMichael *et al.* 2001).

- The impact on the longevity of capital. This effect is less established in the literature, although some adaptation studies (e.g., Fankhauser *et al.* 1999) have pointed out that a continuously changing climate will require more frequent adjustments in the capital stock, especially with respect to defensive expenditures (e.g. the strengthening of sea walls and dykes). This can be captured in an increased speed of capital depreciation, $ä/\ \ T = ä_T > 0$.

If output is homogeneous of degree one in labour and capital, we have:

(4) $$k = \frac{K}{L}; \dot{k} = \frac{\dot{K}}{L} - \frac{K}{L} \cdot \frac{\dot{L}}{L}; f(k) = F(k,1,T); Lf(k) = F(K,L,T),$$

and (2) and (3) can be combined to:

(5) $$\dot{k} = f - c - dk - nk.$$

Solving the model yields, after some manipulation:

(6) $$\dot{c} = -\frac{u_c}{u_{cc}}(f_k - d - r),$$

where subcripts denote derivatives. Equations (6) and (5) are the two equations of motion driving the system. The steady state is defined by $\dot{c} = \dot{k} = 0$, which implies:

(7) $$f_k = d + r\ ,$$

(8) $$c = f - dk - nk\ .$$

Capital accumulation

The impact of climate change on capital accumulation can be derived by totally differentiating (7), which yields the following expression for $k/\ T$:

(9) $$\frac{\partial k}{\partial T} = \frac{d_T - f_{kT}}{f_{kk}}\ .$$

Equation (9) tells us that climate change affects capital in the steady state through two channels, both negative. First, climate change makes capital more short-lived, $\ddot{a}_T > 0$. This reduces the return on capital because the benefit stream associated with a given investment becomes shorter (recall that $f_{kk} < 0$). Second, if we assume market impacts to be multiplicative (as in DIC E) the return on capital is also lower because climate change reduces the marginal product of capital, $f_{kT} < 0$. A lower return on capital leads to reduced investment and a lower capital stock.

Saving

We now turn to saving. If saving, S, is defined as output minus consumption, we can use (4) and (8) to derive:

(10) $$S = F - cL = L(f - c) = L(d + n)k\ .$$

Differentiating S with respect to T yields

(11) $$\frac{\partial S}{\partial T} = L\left[(d_T + n_T)k + (d + n)\frac{\partial k}{\partial T}\right].$$

By substituting (9) into (11) we derive:

(12) $$\frac{\partial S}{\partial T} = L\left[d_T \left(k + \frac{(d+n)}{f_{kk}} \right) + n_T k - (d+n)\frac{f_{kT}}{f_{kk}} \right]$$

Equation (12) tells us that climate change affects saving in the following ways:

- Non-market impacts, $u_T < 0$, do not affect saving because climate change is exogenous and thus acts only to rescale utility.

- The effect of market impacts on saving is negative (since $f_{kT} < 0$, $f_{kk} < 0$). This is the mirror image of the capital accumulation effect discussed above. Faced with a lower capital productivity, consumers decide to reduce investment and the capital stock.

- The health impacts of climate change also affect saving negatively, $n_T < 0$ because less people need less capital.

- The impact of accelerated capital depreciation, $ä_T > 0$, is ambiguous. On the one hand, savers wish to compensate for the shorter live time of capital by providing additional funds. On the other hand, they are discouraged from doing so because of the lower return on capital (the capital accumulation effect again).

3. The Magnitude and Direction of Dynamic Effects

To gain further insights we now turn to a numerical model of climate change, the well-known DICE model developed by Nordhaus (1994). We use the functional forms and parameters as in DICE, but exclude the option of emission reduction and fix the temperature scenario. Although DICE is a model of the world economy, we can also interpret the results as those of a small country without control over atmospheric CO_2 concentrations. We only have to rescale the variables and reinterpret the impact of climate change as the impact including adjustments in international trade – note that below we only present relative results.

The direction of the savings effect

The first question we try to answer concerns the direction of the dynamic effects. From the theoretical considerations we know that the capital accumulation effect is negative, that is it will exacerbate the negative impact of climate change. The sign of the savings effect, in contrast, had been ambiguous in the steady state of the theoretical model. We need a numerical model to estimate the relative importance of the different components of the savings effect identified in Section 2.

Some adjustments to the model were needed for this exercise, as DICE does not distinguish all the channels through which climate change affects savings, and instead assumes that all impacts are channeled through the production function. We altered DICE to model the effect of climate change on population growth, depreciation and utility, keeping the direct impact the same as in the benchmark case where the impact was on output alone. For population, we assumed that the value of a statistical life is 200 times per capita income (Tol, 1999).

To emphasize the savings effect we assume an impact scenario where a 3 C warming reduces GDP by 5%. As the review of Smith *et al.* (2001) showed, impacts will probably lie well below the 5% mark in most countries. However, inflating the direct impacts in this way makes it easier to identify the indirect dynamic effects on growth.

Figure 1 shows the effects of the four alternative pathways, analysed in steady state in the previous section. The dynamic effects on saving are the same as in the steady state. Climate change impacts on utility do not affect savings; impacts on depreciation increase savings and impacts on population decrease savings. Note that the latter effect is very small; the former may increase the savings rate by a factor of 1.01, for a benchmark impact of 5% of GDP for a 3 C warming. Climate change impacts on output slightly decrease savings.

The net effect is that – unless the depreciation effect is substantial – the savings effect will be negative. That is, consumers choose not to increase investment to maintain economic growth, but to decrease investment in favour of current consumption. Consumers will *lower* savings, thus reducing economic growth so as to maintain current consumption.

The magnitude of dynamic effects

Next, we use DICE to derive a rough understanding of the magnitude of some of the linkages between climate change and growth. To do this, we run the model – with climate change impacting on economic output – in two different modes, associated with different growth models (see Barro and Sala-I-Martin, 1995; Romer, 1996; and the appendix):

- The *Solow-Swann* specification: In the traditional Solow-Swan growth model saving is an exogenously given fraction of income. Technological progress is also exogenous. We can use this model to isolate the capital accumulation effect by comparing its GDP predictions with the direct impacts of climate change. The exogenous savings rate was derived from the DICE base run in which there is no climate change. This savings rate is optimal, given the DICE parameters, in a world without climate change.

- The *Ramsey-Cass-Koopmans* specification: This is the original model structure of DICE and similar to that of the theoretical model of Section 2. Savings rates are determined endogenously, and are hence affected by climate change. Technical progress on the other hand is exogenous. The comparison of this specification with the Solow-Swann model will provide insights into the magnitude of the savings effect.

In addition, we use two endogenous growth specifications to see how the dynamic effects differ if investment decisions also affect human capital accumulation and technical progress. Again, they can be associated with two standard growth models (see appendix for detailed specifications):

- The *Mankiw-Romer-Weil* specification: In this model (due to Mankiw *et al*. 1992) technological progress is exogenous and savings are given. The crucial distinction of this model is that, besides *physical* capital, the model also includes *human* capital. Comparing this specification with Solow-Swann gives an indication of how climate change affects human capital accumulation. To arrive at the Mankiw-Romer-Weil specification we assume that the output elasticities of physical and human capital are identical, and that their sum is equal to the output elasticity of physical capital in the Ramsey-Cass-Koopmans model. We assume that in the base year (1965), physical capital and human capital are equal in size, and half as big as the physical capital in the Ramsey-Cass-Koopmans model. The savings rate is equal to the savings rate in the Solow-Swan model, and divided equally over investments in physical and human capital. We use the total factor productivity to calibrate the output of the Mankiw-Romer-Weil model to the output of the Solow-Swan model in the absence of climate change.

- The *Romer* specification: This model is similar to the Mankiw-Romer-Weil model in that savings are exogenous and technological progress endogenous. In the Romer (1990) model there is no human capital stock. Instead, part of the physical capital stock and part of the labour force are used in research and development to increase labour productivity (see also Grossman and Helpman, 1991, and Aghion and Howitt, 1992). The output of R&D is a generalized Cobb-Douglas function. This specification indicates how climate change would affect productivity. We assume that all parameters and savings are the same as in the Solow-Swan model. The shares of labour and capital devoted to R&D are constant. We use labour productivity to calibrate the output of the Romer model to the Solow-Swan model in 1965. We use R&D productivity to calibrate the output for the other periods, assuming there is no climate change.

Figure 2 compares the direct impacts of climate change with the indirect dynamic effects for the different model specifications, using losses in per capita consumption as the damage indicator. As before, we assume an impact scenario where a 3 C warming reduces GDP by 5%. Figure 2 highlights the compounding nature of the dynamic effects, which grow both in absolute and relative terms over time.

The magnitude of the indirect effects differs across the models. The capital accumulation effect (the difference between Solow-Swan and direct costs) is much larger than the savings effect (the difference between Solow-Swann and the Ramsey-Cass-Koopmans specification), which is barely distinguishable. Both are slightly bigger, in absolute terms, than the direct losses of climate change. The dynamic effects are strongest in an endogenous growth context, particularly in the Mankiw-Romer-Weil model where consumption losses can grow to almost twice the size of direct impacts. The Romer model shows the same effect, but smaller. This is because in these specifications a larger part of the growth is internal to the model, rather than exogenously specified technological progress. This makes the model more sensitive to reductions in output, and hence investments in human capital (Mankiw-Romer-Weil) or research and development (Romer).

Figure 2 also includes the indirect effects in the Ramsey-Cass-Koopmans model if climate change impacts affect capital depreciation rather than output. In this case, savings go up, as discussed above (see Figure 1). Also in this case, the indirect effects are negative, albeit very small; increased savings largely compensates accelerated depreciation, but do not offset it. Compared to the case without climate change, impacts add a constraint to utility optimization; utility cannot increase and, as consumption is the only argument in the utility function, consumption must fall as well.

Figure 3 shows the size of the dynamic effects, relative to the direct effect, for different levels of climate change impact, ranging from 1% to 15% of GDP for 3 C warming. The comparison is limited to the Solow-Swan and the Mankiw-Romer-Weil models and shows that the indirect effect is relatively less important for larger benchmark climate change impacts. This is because direct impacts grow linearly with benchmark impacts whereas investment falls inversely proportional with direct impacts, capital falls less than proportional with investment, and output and consumption are less than linear in capital.

For large impacts, indirect damages are *smaller* relative to direct impacts in later time periods. In later time periods, the less-than-linear effect of benchmark damages on indirect impacts is compounded over time. For small impacts, indirect damages are *larger* relative to direct impacts in later time periods. For smaller impacts, indirect impacts are more linear in benchmark damages; in later time periods, the capital accumulation effect is larger.

4. The Rate of Growth

We next turn to the question of how significant climate change may be for long-term growth prospects, using the same model and model specifications as in the previous section. Figure 4 compares the impact of climate change on growth rates for the four model specifications. The effect is smallest in the Solow-Swan model, although its results are again very close to those of Ramsey-Cass-Koopmans and Romer. The Mankiw-Romer-Weil model shows the greatest impact of climate change on growth. As before, the impact on growth rates is increasing over time, as the dynamic effects begin to bite, but the effect is not substantial enough to change a future path of (moderate) long-term growth into one of continually negative growth and recession. Hence, climate change does not conflict with weak sustainability as defined for example by Hartwick (1977) and Pearce and Atkinson (1993).

The question of negative growth is analysed further in Figure 5, which compares the growth rates in the Solow-Swan and Mankiw-Romer-Weil models for a wider range of impact estimates. Economic growth falls more for higher impacts, but less than linearly so, as the effect is through the capital stock, and consumption is less than linear in capital.

Figure 5 shows that, in the long run, for high direct impacts, climate change may indeed reverse economic growth, even in the optimistic Solow-Swan model, and per capita income may fall. The direct damages required for such an outcome are, however, substantial – at least 15% of GDP for 3 C warming. For most regions, such a scenario is unlikely to be associated with continuous climate change, but very large impacts of this magnitude cannot be excluded in the most vulnerable countries, particularly low-lying deltaic and island nations (see Smith *et al*. 2001). Impacts of this magnitude may also be consistent with a climate catastrophe or large-scale discontinuity, such as a change in thermohaline circulation. In other words, for most climate change scenarios and most countries, negative climate change impacts are likely to reduce the rate of economic growth, but unlikely to reverse a long-term path of increasing per capita income. However, the possibility of negative growth cannot be fully excluded.

5. Conclusions

This paper draws attention to the fact that the direct impact of climate change on the economy is not the only way in which global warming affects future output. The prospect of future damages (or benefits) also affects capital accumulation and people's propensity to save, and hence the rate of economic growth. In an endogenous growth model this also means a different rate of technical progress, which enhances the savings and capital accumulation effect. The capital accumulation effect, and probably also the savings effect, are both negative, which suggests that the traditional enumerative studies underestimate the true impact of climate change. The dynamic effects are unlikely to reverse the prospect for future long-term growth, except in the most vulnerable countries or if the direct impacts of climate change are much more substantial than currently assumed.

The indirect effects are relatively smaller if the direct effects are bigger. As poorer countries are generally thought to have larger direct impacts (cf. Smith *et al.*, 2001), the enumerative method underestimates the total effects more in richer than in poorer countries. This attenuates the distributional implications of climate change. Countries with different levels of income also have different mechanisms of growth. From rich to poor, physical capital accumulation, human capital accumulation, and research and development are the most important growth engine (e.g., Funke and Strulik, 2000). Comparing the results of our different growth models, the indirect effects on the rich are again relatively larger than those on the poor, but the indirect effects on the middle incomes are largest.

The dynamic effects discussed in this paper are not the only channels through which climate change may affect growth. Scheraga *et al.* (1993) have pointed out the effect climate change may have on the structure of economies. Different economic sectors are affected differently by climate change, and as a result investment decisions will change and some sectors will grow faster than others, thereby changing the size and composition of GDP. For instance, to maintain food production, more investment may have to be channeled into agriculture, and the need for investment in defensive expenditures will grow. Arguably, such a change in the structure of an economy could have an impact on its long-term growth potential. Similarly, international trade may well exacerbate negative impacts in one place and alleviate impacts somewhere else (Darwin and Tol, 2001), while international capital would change the prospects of growth.

Perhaps more importantly, the 'new economic geography' literature has reminded us of the importance of climate and disease as a determinant of long-term economic development. Gallup *et al.* (1999) argue that vector-borne diseases, particularly malaria, can have such a large effect on labour productivity that some countries, particularly in Sub-Saharan Africa are trapped in a vicious cycle of disease-low productivity-poverty-deficient health care. Climate change may well lead to an increase in vector-borne diseases, which could make more countries vulnerable to this poverty-disease trap. For instance, Gallup *et al.* (1999) find that malaria slows economic growth in Africa by about 1% per year, while McMichael *et al.* (1996) find that a degree of global warming may increase malaria by some 10%. Masters and McMillan (2001) find a clear positive relationship between mild frost and economic development. They speculate that frost kills pests and pathogens, so that human and agricultural productivity is higher in temperate climates. Again, climate change may reduce this advantage.[2]

A final comment has to concern the choice of model. An economic response to climate change that reduces saving and shifts consumption from the future to the present obviously falls foul of a key goal of climate change policy, intergenerational equity. It is important to make explicit therefore the underlying objectives of the model we used, which is to maximize aggregate social welfare, expressed as the present value of utility achieved over time. This representation is typical for growth models, but it may not be an appropriate objective for climate change policy, or should at least not be its only goal. Models concerned explicitly with maintaining intergenerational equity would probably recommend different savings and investment rates than those derived here. Quite possibly, they would recommend the accelerated accumulation of man-made capital to compensate future generations for the loss of a conducive climate – in line with the sustainability literature – but the confirmation of this assertion has to be left to future research.

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[2] Gallup *et al.* (1999) and Masters and McMillan (2001) also show that, on average, hotter countries are poorer and grow slower. However, theirs are simple statistical models. Lacking a careful modeling of cause-effect chains, these results cannot be extrapolated to climate change. Note the alternative mechanisms offered.

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APPENDIX – GROWTH MODELS

The numerical models used in Sections 3 and 4 are based on DICE (Nordhaus 1994), but use the following specifications for output and capital accumulation.

The Solow-Swan model

(A1) $$Y(t) = \frac{A(t)\, K^{a}\, L^{1-a}}{(1 + bT(t)^{2})}$$

where Y is output, A is productivity, K is physical capital, L is labour, T is temperature, t is time and *á*=0.25.

(A2) $$\dot{K} = s(t)Y(t) - d\,K(t)$$

where s is the savings' rate and *ä*=0.1 is the depreciation rate.

The Ramsey-Cass-Koopmans model

The Ramsey-Cass-Koopmans model is identical to the Solow-Swan model, except that the savings rate is determined by intertemporal optimization. Without climate change, productivity and savings are set to be equal in both models.

The Mankiw-Romer-Weil model

(A3) $$Y(t) = \frac{A(t)\, K^{a}\, H^{a}\, L^{1-2a}}{(1 + b\,T(t)^{2})}$$

where H is physical capital and *á*=0.25.

(A4) $$\dot{K} = 0.5s(t)Y(t) - d\,K(t)$$

(A5) $$\dot{H} = 0.5s(t)Y(t) - d\,H(t)$$

The savings rate is as in the Solow-Swan model. Productivity is set so that output is the same as in the Solow-Swan model in the absence of climate change impacts (*â*=0).

The Romer model

(A6) $$Y(t) = \frac{A(t)((1-g_K)K)^a ((1-g_L)L)^{1-a}}{(1+bT(t)^2)}$$

where $ã_K$=0.05 is the share of capital used in research and development, $ã_L$=0.10 is the share of labour used in research and development and *á*=0.25.

(A7) $$\dot{K} = s(t)Y(t) - d\,K(t)$$

(A8) $$\dot{A} = B(t)\,(g_K K)^l\,(g_L L)^l\,A(t)^l$$

where *ë*=0.25 and *B* is the productivity of research and development. Savings are as in the Solow-Swan model. R&D productivity is set so that output is the same as in the Solow-Swan model in the absence of climate change impacts (*â*=0).

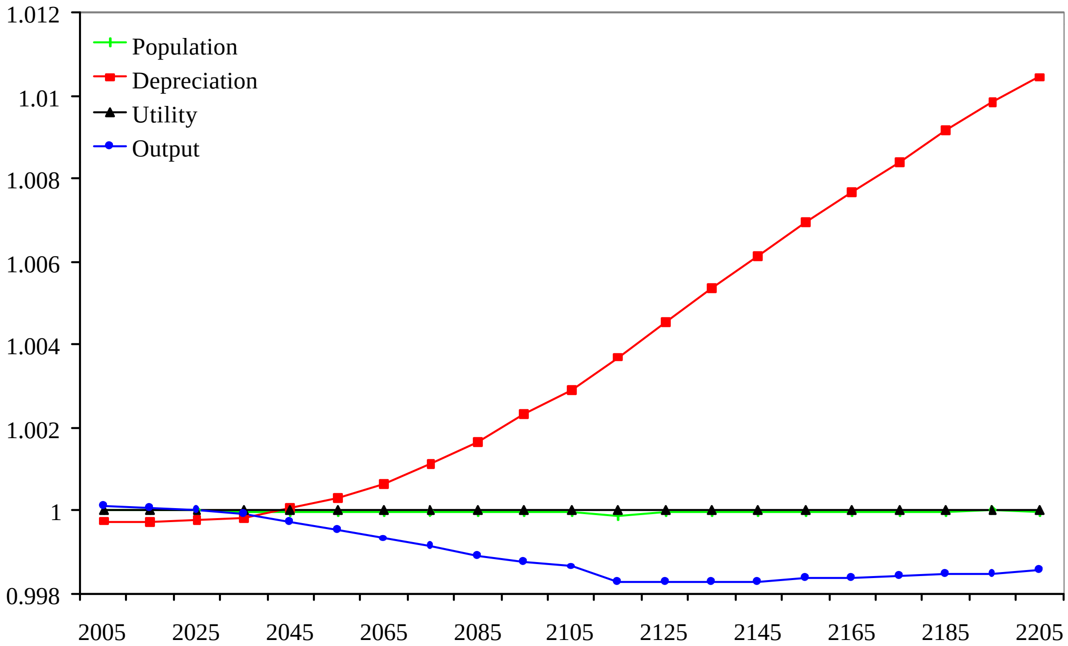


Figure 1. The effect of climate change impacts on the savings' rate according to four alternative pathways through which impacts affect the economy; all results are normalized with the savings rate in absence of climate change; climate change impacts may be felt on population growth, on capital depreciation, on utility, and on economic output.

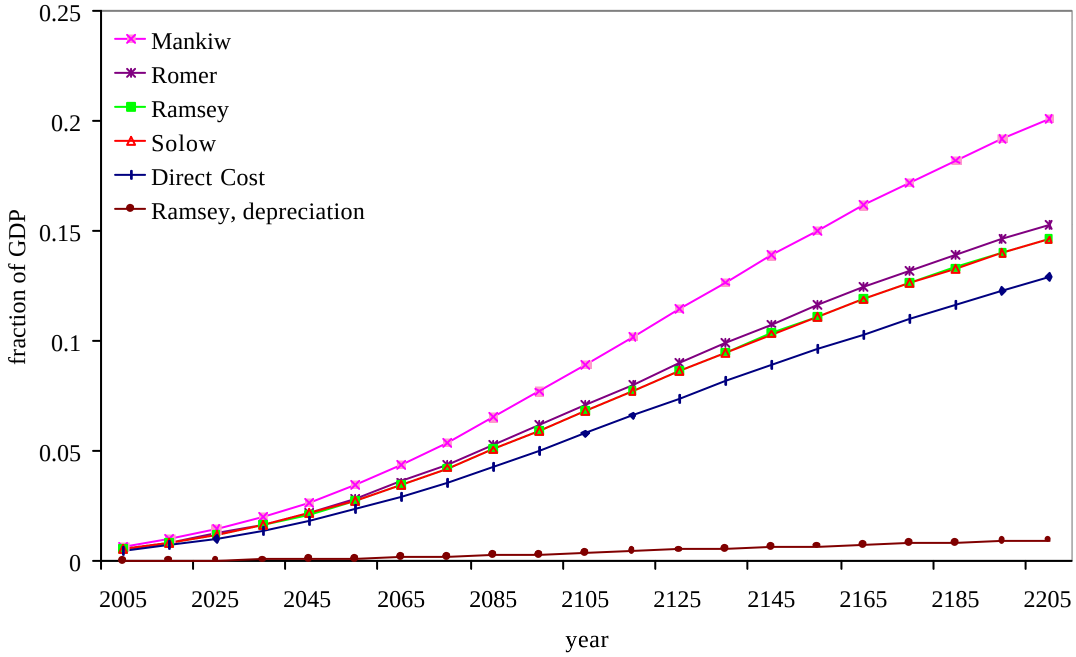


Figure 2. The economic impact of climate change (as a fraction of per capita GDP), compared to the no-climate change case, and assuming a global mean temperature increase of 3 C causes 5% GDP damage; for the Ramsey-Cass-Koopmans model, results are shown for case in which climate change impacts affect output as well as deprecation; for other models, impacts affect output.

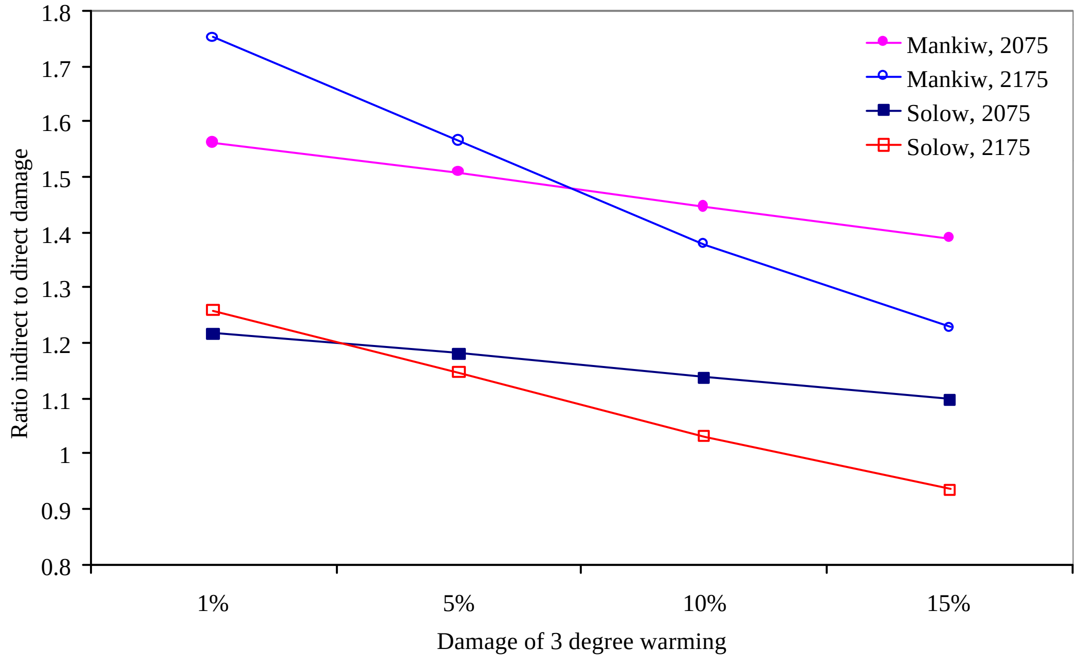


Figure 3. The ratio of indirect dynamic impacts to the direct impacts of climate change, in different climate change damage scenarios.

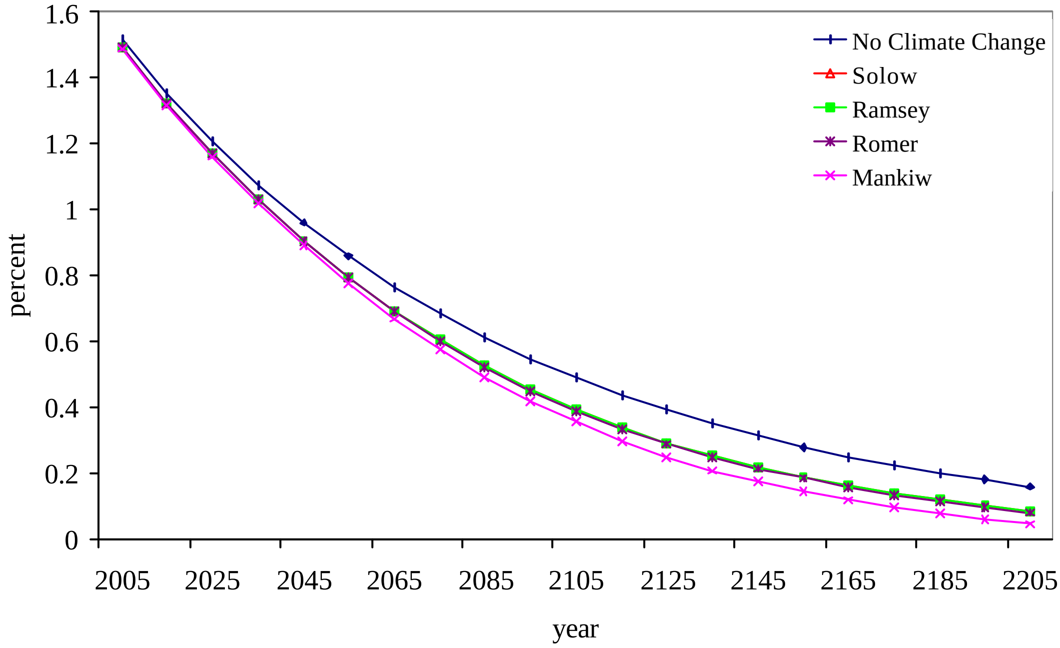
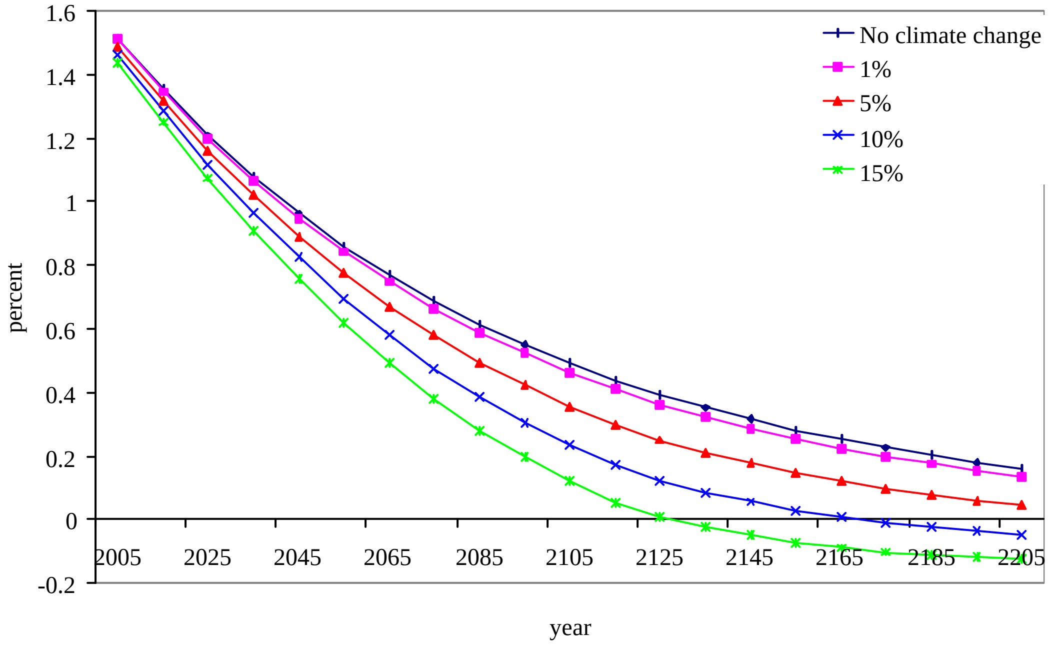


Figure 4. Growth in per capita income for different growth models, assuming a global mean temperature increase of 3 C causes 5% GDP damage.



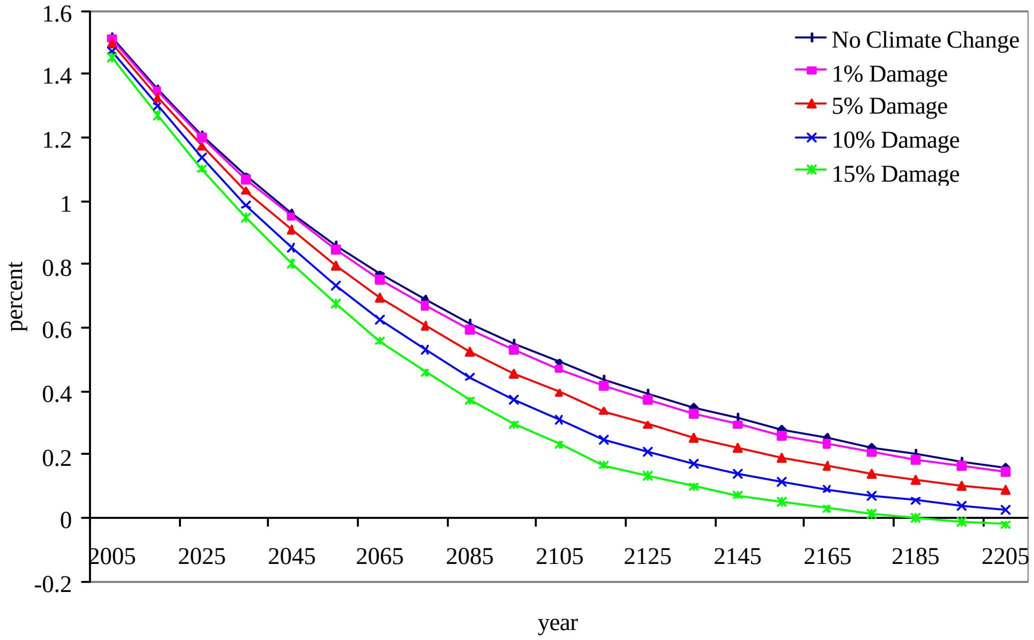


Figure 5. Growth rate in per capita income for different climate change damage scenarios: Solow-Swan model (bottom panel) and Mankiw-Romer-Weil model (top panel).