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On climate change and economic growth

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Abstract

The economic impact of climate change is usually measured as the extent to which the climate of a given period affects social welfare in that period. This static approach ignores the dynamic effects through which climate change may affect economic growth and hence future welfare. In this paper we take a closer look at these dynamic effects, in particular 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) and, in almost all cases, future consumption per capita. If the savings rate is endogenous, forward looking agents would change their savings behavior to accommodate the impact of future climate change. This suppresses growth prospects in absolute and per capita terms (savings effect). In an endogenous growth context, these 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 technological change is endogenous, and may be larger than the direct impact of climate change. The savings effect is less pronounced. The dynamic effects are more important, relative to the direct effects, if climate change impacts are moderate overall. This suggests that they are more of a concern in developed countries, which are

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believed to be less vulnerable to climate change. The magnitude of dynamic effects is not sensitive to the choice of discount rate.

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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, the interaction of sectoral impacts such as the connection between 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.

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 welfare in the longer term. This paper seeks to close this gap by exploring, both theoretically and numerically, the dynamic effects that link climate change and economic growth.

The main 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, a lower GDP and, in most cases, lower consumption per capita. 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 *savings.* 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, climate change reduces the productivity of capital and, faced with a lower rate of return, agents may prefer to invest less and consume more today.

Integrated assessment models with an economic foundation (e.g., Nordhaus, 1994; Peck and Teisberg, 1992; Tol, 1999) usually incorporate the capital accumulation effect and sometimes the savings effect because their design is based on neo-classical growth theory.

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

But they do not normally separate the dynamic effects explicitly. In this paper we try to do so. Section 2 discusses the theoretical links between climate change and growth by looking at 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

2.1. 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 maximizes the utility of identical consumers in the following intertemporal optimization problem:

$$\max \int_0^\infty u(c, T)\, \mathrm{e}^{(n-\rho)t}\, \mathrm{d}t, \tag{1}$$

subject to:

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

$$\dot{L} = n(T)L, \qquad L_0 = 1, \tag{3}$$

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

L is labour supply, which grows at rate n, starting from an initial, normalised level of 1; growth in labour supply is exogenous in this formulation and basically reflects changes in population. More sophisticated models would interpret the variable as *effective* labour. The growth rate n then reflects both changes in population (p) and labour productivity (x), $n = p + x$, with x an endogenous variable. 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 optimization 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, $\partial u/\partial T = u_T < 0$, although the impact literature has identified potential non-market benefits as well (Smith et al., 2001).
- Market impacts, such as a change in agricultural yields, which enter the production function. Again we assume the net impact to be negative, $\partial F/\partial T = F_T < 0$, 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). Output could fall either because productivity falls or because output is destroyed by climate change.

- Health and mortality impacts associated with more widespread diseases such as malaria. These affect population growth[2] and are believed to be predominantly negative, $\partial n/\partial T = n_T < 0$ (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). More frequent extreme events (e.g., storms) will also affect the longevity of capital. This can be captured in an increased speed of capital depreciation, $\partial\delta/\partial T = \delta T > 0$.

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

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

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

$$\dot{k} = f - c - \delta k - nk. \tag{5}$$

Solving the model yields, after some manipulation:

$$\dot{c} = -\frac{u_c}{u_{cc}}(f_k - \delta - \rho), \tag{6}$$

where subscripts denote derivatives. Eqs. (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

$$f_k = \delta + \rho, \tag{7}$$

$$c = f - \delta k - nk. \tag{8}$$

2.2. Capital accumulation

We first look at the impact of climate change on capital. To isolate the capital accumulation effect we keep the savings rate exogenously fixed. Agents are not allowed to adjust their savings behavior in response to climate change. With the savings rate set at a constant fraction of output, $\bar{s} = 1 - c/f$ Eq. (8) becomes

$$\bar{s}f = (\delta + n)k. \tag{9}$$

This is the familiar steady-state condition of the Solow–Swan model (see for example Barro and Sala-I-Martin, 1995). By totally differentiating Eq. (9) we get

$$\frac{\partial k}{\partial T} = \frac{k(\delta_T + n_T) - \bar{s}f_T}{\bar{s}f_k - \delta - n}. \tag{10}$$

Note that the denominator in this expression is negative. Because the savings function, $\bar{s}f(k)$, is concave it intersects the linear depreciation schedule, $(\delta + n)k$, from above at the steady state. That is, it has a flatter slope, $\bar{s}f_k < (\delta + n)$.

[2] In more sophisticated models health impacts also affect the productivity of the labour force. This would count as a market impact, again with $\partial F/\partial T = F_T < 0$.

Eq. (10) tells us that the four channels of climate change impact identified earlier affect the capital-labour ratio as follows:

- Non-market impacts, $u_T < 0$, do not affect capital accumulation because climate change is exogenous and thus acts only to rescale utility.[3]
- Market impacts in the form of a reduction in output, $f_T < 0$, have a negative effect. If less output is produced, a lower absolute amount can be devoted to capital accumulation, and the capital-labour ratio, k, is reduced.
- However, the amount of labour available in the steady state is also reduced because of the health impacts of climate change, $n_T < 0$. This will push up the capital-labour ratio and may at least partially offset the market impacts.
- The capital stock is further reduced because it is depreciating faster, $\delta_T > 0$, which, everything else being equal, will again reduce the capital-labour ratio.

The overall effect of climate change on the *accumulation* of capital is in principle ambiguous. However, it seems safe to speculate that the capital accumulation effect will probably be negative. A cursory look at the impact literature suggests that the market and depreciation effects are likely to outweigh the health effect in most countries. The exception may be some of the most vulnerable poor countries, where the health impacts of climate change tend to be disproportionately high and the amount of capital per worker disproportionately low. We also know that the effect on the *absolute* capital stock, K, is clearly negative (since we can ignore the health impact in this case as it works through the denominator of the capital-labour ratio).

2.3. Saving

We now turn to saving. If gross saving per capita, s^G, is defined as output minus consumption, we can use Eq. (8) to derive

$$s^G = f - c = (\delta + n)k. \tag{11}$$

Differentiating s^G with respect to T yields

$$\frac{\partial s^G}{\partial T} = (\delta_T + n_T)k + (\delta + n)\frac{\partial k}{\partial T}. \tag{12}$$

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

$$\frac{\partial k}{\partial T} = \frac{\delta_T - f_{kT}}{f_{kk}}. \tag{13}$$

By substituting (13) back into (12) we derive

$$\frac{\partial s^G}{\partial T} = \delta_T\left(k + \frac{\delta + n}{f_{kk}}\right) + n_T k - \frac{(\delta + n) f_{kT}}{f_{kk}}. \tag{14}$$

[3] This is true for strictly non-market impacts only. However, non-market impacts typically also include landscapes and health-impacts that have an effect on the markets for recreation and health care. Such effects are here included under market impacts.

Eq. (14) tells us that the four climate change impacts of the model affect saving in the following ways:

- Non-market impacts, $u_T < 0$, do not affect saving for the same reason as they did not affect capital accumulation. Climate change is exogenous and acts only to rescale utility.
- Assuming market impacts are multiplicative (as in DICE), their effect on saving is negative. Climate change reduces the marginal product of capital, $f_{kT} < 0$, which means that the return on capital is lower. Faced with a lower capital productivity, consumers decide to reduce investment and the capital stock declines (recall that $f_{kk} < 0$).
- The health impacts of climate change also affect saving negatively, $n_T < 0$. If there are fewer people in the future they will need less capital.
- The impact of accelerated capital depreciation, $\delta T > 0$, is ambiguous. On the one hand, savers wish to compensate for the faster deterioration of their capital stock by providing additional funds. On the other hand, they are discouraged from doing so because more short-lived capital also means lower returns: The benefit stream associated with a given investment is cut short.

Two features of Eqs. (12)–(14) are worth pointing out before we move to their numerical estimation. The first observation has to do with the difference between gross and net savings. The direction of the (gross) savings effect in Eq. (14) is undetermined because the capital depreciation effect, $\delta_T > 0$, is partially positive. Agents will save more to compensate for accelerated capital depreciation and at least in theory this could offset the other, negative effects of climate change on saving. However, if instead of gross savings we look at net savings, $s^{\mathrm{N}} = nk$, Eq. (14) simplifies to

$$\frac{\partial s^{\mathrm{N}}}{\partial T} = n_T k + n\frac{\delta_T - f_{kT}}{f_{kk}} < 0, \tag{15}$$

an expression that is unambiguously negative. Savers will not set aside enough extra money to compensate for all negative effects. They will consciously cut net investment with a view to reduce the capital stock. Unlike in the case with a fixed savings rate, the impact of climate change on capital accumulation Eq. (13) is clearly negative.

The second point worth noting is on the discount rate. Intuitively, we would expect that a lower discount rate would lead to higher savings in the face of climate change. People with a higher regard for future welfare would save more to compensate for the expected losses. However, the opposite is the case. A lower discount rate (parameter ρ) will, obviously, lead to higher steady state saving. However, introducing climate change at this higher saving level will trigger a more strongly negative reaction. With a lower discount rate, people will respond more strongly to the lower future productivity of capital and cut savings by more. This is because the marginal productivity of capital is lower when capital is abundant, so that investments can be cut with smaller repercussions for production. We can see this by substituting Eq. (7) into (12):

$$\frac{\partial s^{\mathrm{G}}}{\partial T} = (\delta_T + n_T)k + (f_k - \rho + n)\frac{\partial k}{\partial T}. \tag{16}$$

The lower ρ in Eq. (16), the more negative the expression becomes.

3. The magnitude of dynamic effects

To gain further insights on the relative importance of the dynamic effects we now turn to a numerical model of climate change. We choose the well-known DICE model developed by Nordhaus (1994) as the basis of our simulations. It should be noted that DICE does not distinguish the four channels through which climate change affects growth we identified in Section 2. Instead, it assumes that all impacts are channeled through the production function. This is acceptable as the concern in this section is less with the mechanics of the dynamic effects and the channels through which they arise, than with their magnitude and importance.[4] DICE is also a model of the world economy, we can easily interpret the results as those of a small country without control over atmospheric CO_2 concentrations.[5]

Some adjustments to the model are, however, needed to make it suitable for our purposes. We use the functional forms and parameters as in DICE, but exclude the option of emission reduction and fix the temperature scenario. To distinguish between the savings and capital accumulation effect, we run the model in two different modes, associated with different growth models (see Barro and Sala-I-Martin, 1995; Romer, 1996; and Appendix A):

- The *Solow–Swan* specification: In the 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 (Nordhaus, 1994) and similar to 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–Swan 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 A 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–Swan 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

[4] Experiments with an altered version of DICE that distinguishes the four channels confirm that the market impact channel dominates the overall results.

[5] To do so, 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.

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 for all periods 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 simplified version[6] of 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; 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 for the case without climate change.

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) shows, 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.

Fig. 1 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. It also 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–Swan 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).

Fig. 2 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.

[6] This simplification is due to Romer (1996).

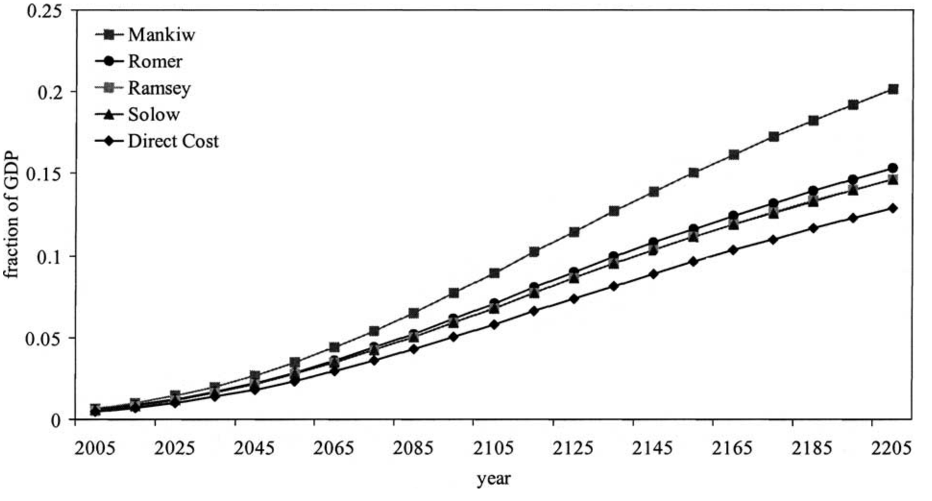


Fig. 1. The economic impact of climate change (as a fraction of per capita GDP), compared to the no-climate change case, and assuming a global mean temperature increase of 3 °C causes 5% GDP damage; for the Ramsey–Cass–Koopmans model, results are shown for case in which climate change impacts affect output as well as deprecation; for other models, impacts affect output; the Ramsey–Cass–Koopmans and Soow–Swan results are very similar.

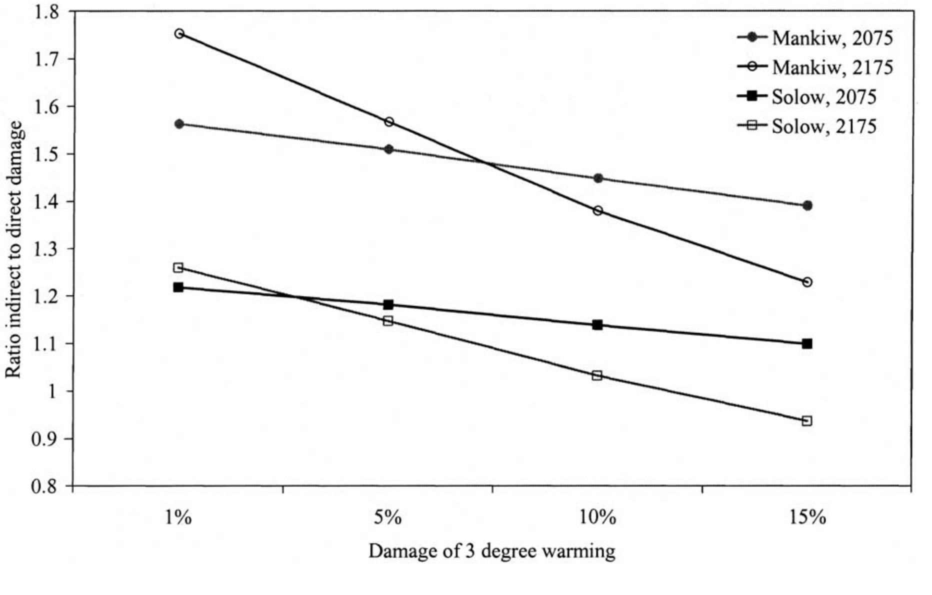


Fig. 2. The ratio of indirect dynamic impacts of the direct impacts of climate change, in different climate change damage scenarios.

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. The implication of this is that the static enumerative method underestimates the economic impacts of climate change more for low static impacts than for high static impacts. High static impacts are estimated for developing countries, and low impacts for developed countries (Smith et al., 2001). The dynamic effect thus attenuates the distributional consequences of climate change impacts.

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. Fig. 3 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).

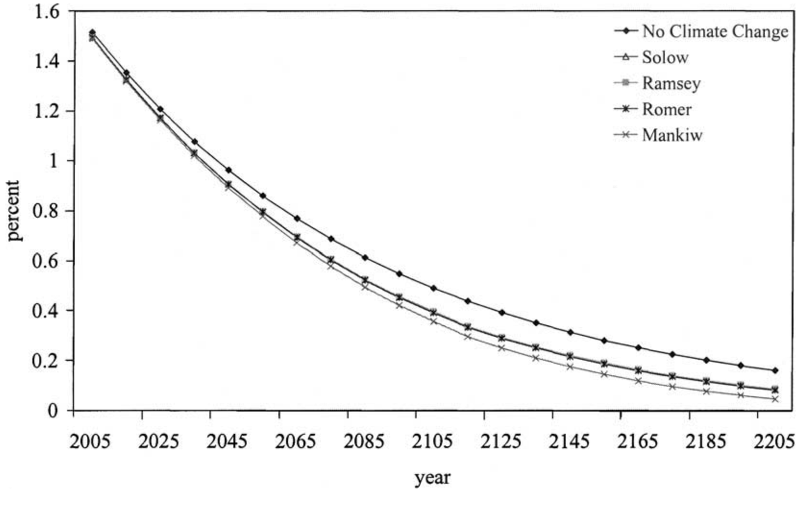
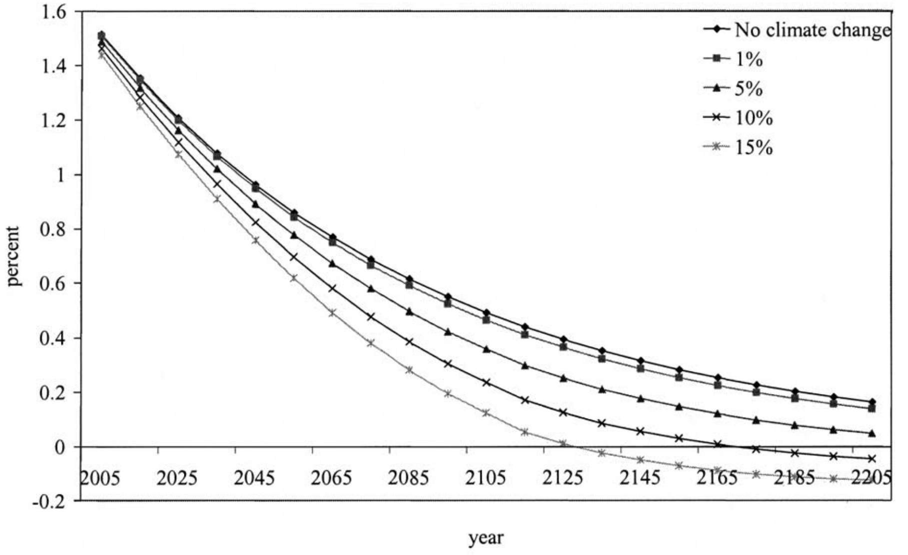


Fig. 3. Growth in per capita income for different growth models, assuming a global mean temperature increase of 3 °C causes 5% GDP damage; the Solow–Swan, Ramsey–Cass–Koopmans and Romer results are very similar.



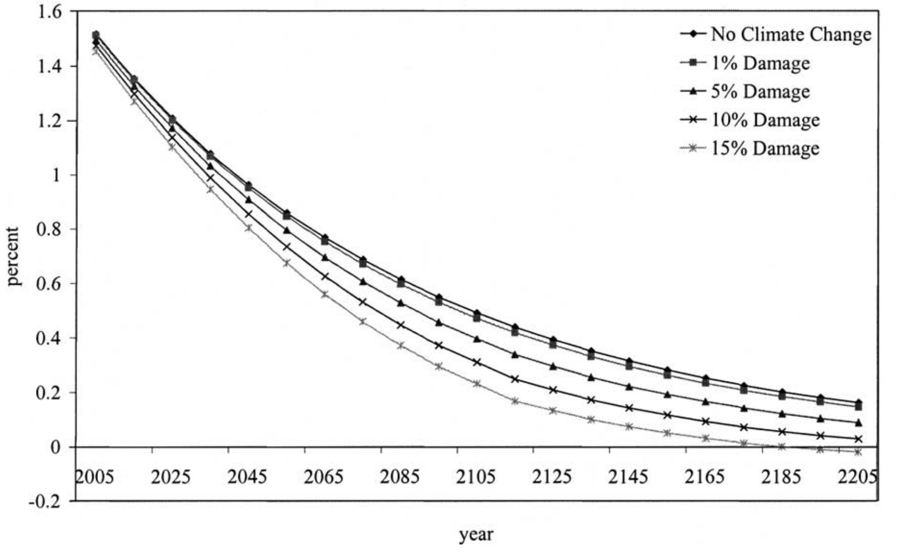


Fig. 4. Growth rate in per capita income for different climate damage scenarios: Solow–Swan model (bottom panel) and Mankiw–Romer–Weil model (top panel).

The question of negative growth is analysed further in Fig. 4, 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.

Fig. 4 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. Discussion and 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 welfare. 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 theoretical analysis suggests that both the capital accumulation effect and the savings effect are negative in sign, although there may be special cases. Climate change will always have a negative effect on the absolute capital stock, and the capital-labour ratio is also certain to decrease if agents are allowed to change their savings behavior. If the savings rate is fixed, it may be possible for the capital-labour ratio to decrease if health effects are the dominant impact of climate change. This case might arise in certain particularly vulnerable least developing countries but judging from the impacts literature does not apply more broadly. The impact of climate change on gross saving is ambiguous, but net savings will always be reduced (hence the unambiguously negative effect on capital).

These results hold independently of the choice of discount rate. In fact reducing the discount rate will aggravate rather than reduce the negative impact of climate change on saving, capital and growth. A lower discount rate does entice economic agents to save more for the benefit of future generations. However, faced with climate change, they will reduce this savings rate sharply because the climate change-induced reduction in capital productivity is more keenly felt with a low discount rate.

The theoretical analysis shows that the traditional enumerative studies of climate change impacts underestimate the true costs of climate change. However, the numerical simulations suggest that 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 numerical results show differences in the magnitude of the dynamic effects depending on model specifications and parameter values. Generally, the dynamic effects are most pronounced in the Mankiw–Romer–Weil specification, which includes human capital. This model also shows the highest sensitivity to changes in impact assumptions. The Solow–Swan specification with fixed savings rates is least affected by the dynamic effects. Not surprisingly, the importance of dynamic effects grows over time, as changes in savings and investment decisions are compounded as time goes on. The dynamic effects are also relatively larger, the smaller direct (static) impacts of climate change.

As poorer countries are generally thought to have larger direct impacts (Smith et al., 2001), the traditional enumerative method may underestimate the total effects most strongly in developed countries. This is further pronounced if we consider that countries with different levels of income have different growth mechanisms. In very poor countries, physical capital accumulation is most important. If countries grow richer, human capital accumulation becomes more important, and in fully developed economies, knowledge accumulation becomes more important (Funke and Strulik, 2000). The Solow–Swan and Ramsey–Cass–Koopmans models emphasize physical capital accumulation, and are less sensitive to climate change. The Mankiw–Romer–Weil and Romer models emphasize human capital and knowledge accumulation, respectively, and are more sensitive to climate change.

This paper is only a first step toward a better understanding of the links between climate change and economic growth. Many questions remain and we need to bear in mind the limitations of the modeling approach we have chosen. First, the savings and capital accumulation 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. As a result of climate change some sectors will grow faster than others, thereby changing the size and composition of GDP. In addition, the demand for defensive investments, such as sea walls, may well grow at the expense of other investments. Arguably, such changes in the structure of an economy could have an impact on its long-term growth potential. Similarly, the model we use is one of a closed economy, and international trade may well exacerbate negative impacts in one place and alleviate impacts somewhere else (Darwin and Tol, 2001). Similarly, countries are linked through international capital flows. Climate change would affect the supply of capital (through its effect on income) as well as the relative rates of return on investment.

By choosing standard growth models, we have overlooked the powerful lessons that the ‘new economic geography’ literature has taught us about 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.[7] However, Acemoglu et al. (2001) argue for a much weaker and much more indirect influence of climate on development.

A final comment has to concern the ethical underpinnings of the model we have chosen. The objective of our model was 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. Indeed, an economic response to climate change that reduces saving and shifts consumption from the future to the present falls foul of a key goal of climate change policy: intergenerational equity. However, broadening the approach to include a wider set of social objectives will have to be left to future research.

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Appendix A. Growth models

The numerical models used in Sections 3 and 4 are based on DICE (Nordhaus, 1994), but use the specifications for output and capital accumulation discussed below. Initial conditions, parameters and scenarios (labour, productivity) are taken from Nordhaus (1994). Nordhaus uses a Ramsey–Cass–Koopmans model. The other three models are calibrated such that, in the absence of climate change, production and consumption are equal in all time periods to the Ramsey–Cass–Koopmans model. The main calibration parameter is productivity. Parameters are chosen such that, in the absence of climate change, models converge to a balanced growth path.

A.1. The Solow–Swan model

$$Y(t) = \frac{A(t)K^{\alpha}L^{1-\alpha}}{1+\beta T(t)^2}, \tag{A.1}$$

[7] 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.

where Y is the output, A the productivity, K the physical capital, L the labour, T the temperature, t the time and $\alpha = 0.25$; $\beta = 0.05/9$ for the base case.

$$\dot{K} = s(t)Y(t) - \delta K(t), \tag{A.2}$$

where s is the savings' rate and $\delta = 0.1$ the depreciation rate. The savings rate s is at each point in time set equal to the savings rate of the Ramsey–Cass–Koopmans model without climate change impacts; it gradually falls from 19% at present to 16% in 2300.

A.2. 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. For this, we used the DICE model of Nordhaus (1994) as implemented in GAMS. We also took productivity, labour and the initial capital stock from DICE.

A.3. The Mankiw–Romer–Weil model

$$Y(t) = \frac{A(t)K^{\alpha}H^{\alpha}L^{1-2\alpha}}{1 + \beta T(t)^2}, \tag{A.3}$$

where H is human capital and $\alpha = 0.25$.

$$\dot{K} = 0.5s(t)Y(t) - \delta K(t), \tag{A.4}$$

$$\dot{H} = 0.5s(t)Y(t) - \delta H(t). \tag{A.5}$$

The savings rate is as in the Solow–Swan model (or Ramsey–Cass–Koopmans without climate change). Productivity at each point in time is set so that output is the same as in the Solow–Swan model in the absence of climate change impacts ($\beta = 0$). Initially, human and physical capital are set equal to each other and, because of symmetry, the remain equal throughout the entire simulation period.

A.4. The Romer model

$$Y(t) = \frac{A(t)(1-\gamma_k)K)^{\alpha}((1-\gamma_L)L)^{1-\alpha}}{1 + \beta T(t)^2}, \tag{A.6}$$

where $\gamma K = 0.05$ is the share of capital used in research and development, $\gamma L = 0.10$ is the share of labour used in research and development and $\alpha = 0.25$.

$$\dot{K} = s(t)Y(t) - \delta K(t), \tag{A.7}$$

$$\dot{A} = B(t)(\gamma_K K)^{\lambda}(\gamma_L L)^{\lambda}A(t)^{\lambda}, \tag{A.8}$$

where $\lambda = 0.25$ (so that the model converges to a balanced growth path in the absence of climate change; Romer, 1996) and B is the productivity of research and development. Savings and initial capital $K(0)$ are as in the Solow–Swan model. Initial productivity $A(0)$

and R&D productivity $B(t)$ are set so that in each period output is the same as in the Solow–Swan model in the absence of climate change impacts ($\beta = 0$).

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