On the macro-economic impacts of climate change under informational failures

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Abstract:

Although the sources, extent and physical impacts of the future climate change are highly uncertain, available dynamic economic assessments implicitly assume that economic agents perfectly know them. Perfect foresight, rational expectations or active learning are standard assumptions underlying simulated results. To the contrary, this paper builds on the assumption that economic agents may suffer for a while from limited knowledge about the average and variability of physical impacts of climate change. Using a world dynamic and stochastic general equilibrium model, our simulation results show that identifying the average physical impact is much more crucial than its variability. This finding is robust to the level of risk aversion of economic agents. The rate of pure time preference of economic agents more significantly affects the economic impacts. We also find that the value of information may be negative in the short to medium run.

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Introduction

Available assessments of the future economic impacts of the climate change are still highly divergent. Estimates of the average yearly welfare impact of the climate change range from an optimistic increase of the world GDP by 2.5 per cent (taken from Tol, 2009) to a pessimist decrease by as much as 20 per cent (computed in the Stern review, 2006). Many modeling assumptions contribute to these different figures, such as the highly disputed discount rate used in standard Cost Benefit Analysis (CBA) to balance future impacts relative to current expenditures (see for instance, Gollier, 2010 or Gollier and Weitzman, 2010).

These economic assessments are now mostly performed within stochastic contexts. Indeed most first economic researches adopt determinist economic approaches and thus focus on the average consequences. However it has always been recognized that that there are many unknowns on the different future sources of greenhouse gas (GHG), on the climate sensitivity to GHG changes or on the physical damages of some climate changes (see for instance, Malik et al.,2010). Accordingly many recent economic researches introduce stochastic dimensions in their framework.

We can distinguish three main stochastic approaches developed so far to assess the climate change issue. The first approach consists in performing sensitivity analysis (for instance with Monte-Carlo simulations) of the modeling results to the values of some behavioral parameters, exogenous variables or scenario assumptions. This first approach includes all dynamic deterministic economic models where the behavior of economic agents does not acknowledge the presence of stochastic variables (the certainty equivalence assumption is applied) or where the economic agents are supposed to have perfect foresight (they know the future values of all stochastic variables). The majority of present economic researches can be gathered in this first simple approach. A prominent example is the analysis performed by Nordhaus (2007) with the widely used Dynamic Integrated model of Climate and the Economy (DICE) which is an Integrated Assessment Model (IAM) coupling “basic” climate equations with a stylized dynamic, determinist, general equilibrium model.

While widely perceived as useful, this first approach suffers from the absence of behavioral responses of economic agents to the stochastic variables. To the contrary, the second and third approaches allow economic agents to optimize taking some of them into account. In the second approach, economic agents are supposed to have full information on the structural parameters and the stochastic variables (the density function and the corresponding moments). They furthermore have rational expectations. To our knowledge, few papers so far adopted this approach.[1] By chronological order, these papers include Pizer (1999) who introduces (log normal) labor productivity shocks but imposes a first order

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[1] One reason may be that they were until recently some computational issues to solve large scale dynamic and stochastic models.

approximation on the optimal behavior of economic agents (hence ignoring *in fine* their risk aversion), Bostian and Golub (2008) who solve a stochastic version of the DICE model assuming risk aversion and (log normal) total factor productivity shock, Bukowski and Kowal (2010) who develop a multi-sector Dynamic and Stochastic General Equilibrium (DSGE) model for Poland with risk averse agents and many productivity and external (normal) shocks, Hwang et al. (2011) who again solve a stochastic version of the DICE model assuming that the climate sensitivity parameter is stochastic (with different density functions but otherwise the model is not stochastic, so the true stochastic source is unclear), Crost and Traeger (2011) who introduce the same stochastic dimension in the DICE model in the same manner while distinguishing risk aversion from resistance to inter-temporal substitution, Golosov et al. (2012) who solve a stylized DSGE model close to DICE while imposing exogenous ad hoc saving functions in order to obtain analytic solutions (again without a clear source of the stochastic variable) and finally Dumas et al (2012) where they assume only one stochastic period (with two stochastic event at that period).

In the third approach, economic agents are supposed to have initially only incomplete information on some structural parameters or stochastic variables while full information on the other structural parameters or stochastic variables. But they are assumed to be able to learn at each period and recover full information on all structural parameters and stochastic variables in the (very) long run. When the additional assumption of rational (active) learning with cost-free periodic information is made, then economic agents solve an additional tradeoff between the benefit of controlling emissions and of getting more information when optimizing their abatement efforts. Kelly and Kolstad (1999) pioneered such approach starting from the DICE model. They assume that the average annual global temperature is stochastic (the error term is normal) with the level of GHG as a determinant. The climate sensitivity parameter, which relates the two variables, is unknown to economic agents. They have only priors on this parameter but are able to progressively learn it using a Bayesian updating procedure applied on periodic observations of temperature and GHG levels. These authors conclude that over 90 years are required to learn the true structural parameters. Leach (2007) expands this analysis adding the assumption that the economic agents also do not know the parameter governing the persistence of natural trends in the same global temperature equation. He concludes that the time to learn the true structural parameters may be in the order of thousands of years. The paper of Karp and Zhang (2006) is slightly different as they assume that all structural parameters are perfectly known while some stochastic variables are only partially known. More precisely, these authors develop a simpler economic model with linear-quadratic abatement costs and environmental damages, risk-neutral agents and three (log normal) stochastic sources: one on the marginal benefit of emissions for the regulator (due to the asymmetric information between the regulator and economic agents) and two on the marginal damage function (to both the regulator and economic agents). The moments of two of them are perfectly known and the last one (on the marginal damage) is recovered through passive learning (assumption which fits best with the risk neutrality assumption). They show as expected that the variance of the known shock in the marginal damage function has major impacts on the learning process. If this variance is significant, then periodic observation brings limited information and learning on the unknown marginal damage shock is slow. In this case the anticipation of learning has a negligible effect on the optimal policy.

With respect to this growing literature on climate change and uncertainty, our main contribution is to authorize economic agents to have and stay, at least temporary, with incomplete information about the different stochastic sources they are facing. This leads us to develop a fourth approach allowing (temporary) imperfect foresights by economic agents. This issue has been widely disregarded so far (Tol, 2009) or only discussed qualitatively. For instance, Hallegate et al (2007) conclude from their deterministic computations that the costs of climate change under imperfect foresight are drastically increased when compared to a perfect foresight situation.

Our main contribution is first motivated by the fact that the climate is far from being the only stochastic source faced by many economic sectors. For instance, Nordhaus (2007) finds from DICE simulations that by far the most important uncertain variable for climatic outcomes is the growth in total factor productivity and not the temperature sensitivity coefficient. Lobell and Burke (2008) provide a more concrete justification. They argue that major progresses in understanding crop yield responses to change of mean temperature or precipitation levels are still expected with experimental tests. Moreover these authors find that the single biggest source of uncertainty for most crop yields comes from the uncertainty in the response of crop production to the mean temperature change, followed by the uncertainty on the mean temperature change itself. This major uncertainty of these crop yield responses is simply ignored in aforementioned analyses because factor productivity shocks, when introduced, are exogenous to the climate variables. Our main point here is that it will be very difficult for economic agents (farmers in this instance) to quickly understand the evolution of their total productivity. They may be unable in the first years to discern the climate change impacts from other stochastic sources and hence may not take optimal adaptation/learning decisions. This point echoes the Karp and Zhang result that learning is not worthy when simultaneously other stochastic sources are important.

Our contribution is also motivated by some theoretical results on the decision making modeling under uncertainty (they are obtained in the context of a single stochastic source but remain relevant with many stochastic variables). Geweke (2001) shows that the very existence of the expected utility is not ensured in many cases. More precisely, he demonstrate that the expected utility of a risk averse economic agent endowed with a CRRA utility (log utility aside) often fails to exist when the stochastic consumption is log normal with an unknown second moment. This statistical result leads this author to conclude that the standard rational expectations assumption (that agents know the relevant distributions or that they are able to learn it) is quite fragile. The implication for our paper is that it is inconsistent to assume, as previous papers did in the third approach, that economic agents are able to immediately learn from climate observations while assuming they have CRRA utility functions. Weitzman (2009) builds on the same statistical result to show that the fat tail consumption distribution induced by the unknown climate change variability leads to an infinite expected value of the stochastic discount factor. This infinite value implies that economic agents should postpone any unit of current consumption to mitigate future catastrophe. Weitzman (2009) solves this issue by introducing a lower bound on consumption which is exogenously calibrated using a value of a statistical life. Ikefuji et al. (2011) solve this issue by assuming other utility functions (exponential and Pareto) and solving their two period models by backward inductions (hence with the debatable assumption that terminal conditions must be arbitrarily imposed). McKitrick (2012) shows that this unbounded stochastic discount factor does not emerge when contingent goods are introduced. However he simply assumes the existence of such goods and markets for the long run. In our paper, we do not solve theoretically these different informational issues (using alternative utility functions or alternative decision theory under uncertainty or an augmented micro-structure). Rather we want to offer relative estimates of the extent of these informational issues, relative to the majority obtained with full/perfect information.

In that respect we develop a DSGE model without always imposing the standard rational expectations/perfect foresight assumptions (hence our model can also be viewed as an Agent based model). Our starting modeling point is close to the often-used DICE model with the same major economic mechanisms included. However we simply ignore the climate change equations explaining the sources of the environmental damage and the anthropogenic contribution for two main reasons. First, Bostian and Golub (2010) elegantly recognize that solving a stochastic version of the full DICE model remains today quite challenging (with perturbation methods possibly leading to spurious welfare reversals). By removing the climate equations, we reduce the number of state variables and no longer face computational issues. Second, this assumption is not crucial for our analysis as we consider that many other stochastic sources unrelated to the climate affect the industrial factor productivities and are also unexplained. Our modeling simplification prevents us to perform a policy analysis on the optimal carbon tax in order to reduce current GHG emissions and future damage. In other words, our analysis excludes mitigation options and focus on adaptation strategies under different informational assumptions. We can also view our analysis more relevant in the short to medium run where climate change results from past irreversible decisions due to the (several decades) delay between emissions and impacts.

On the other hand, our economic modeling is less stylized than the DICE one because we introduce two production sectors rather than only one. Otherwise our assumption of incomplete information by economic agents appears less relevant. We suppose the existence of three representative economic agents. The first two are owners of the capital goods used in the two production sectors while the third only have their labor force. We develop three of our model. They are all calibrated on the same Social Accounting Matrix (SAM) built from the GTAP database for 2004. In the first determinist version, we assume that economic agents perfectly know from the first period to the last one all structural parameters and exogenous variables. This version can be simulated assuming different exogenous variables reflecting the imperfect knowledge of the modeler of the impact of climate change on factor productivities or even the imperfect knowledge of factor productivities without climate change. This first determinist version falls within the first stochastic approach that we identify in the literature on climate change. In the second stochastic version, we assume that all economic agents perfectly know the structural parameters, exogenous variables and the distribution of stochastic variables : the productivity shocks in both sectors both with and without the climatic change. In addition, they have rational expectations and thus are able to compute market equilibrium once the values of productivity shocks are revealed. This second version falls within the second approach identified in the literature. The third and last version is again stochastic where we assume that all economic agents suffer from informational failures. They are unable during some periods to identify the stochastic technological impacts of the climate change. By comparing the results of the second and third versions, we will be able to assess the value of information on the true extent of physical impacts of climate change (resulting from past decisions).

This paper is organized as follows. The next section details the specification of the three versions of our model starting from the simple determinist version close to DICE. We also explain the calibration of the different structural parameters. The following section reports the results of illustrative simulations. Market and welfare effects are simultaneously discussed. Sensitivity analyses of results to the level of risk aversion of economic agents and to the variability of the physical impacts of climate change are provided in a third section. The paper concludes with some methodological and normative recommendations.

1. Methodological frameworks

The three versions of our model differ in the information held by economic agents. We start with the simplest version where economic agents have perfect information on all behavioral parameters and future exogenous variables. While presenting this first version, we explicit the several simplifying assumptions we make in order to focus on the informational issues related to the extent of climate change physical impacts.

1.1. The perfect foresight version

Assumptions

We consider a simple (world) economy populated with three different types of economic agents. The first and second types of economic agents represent the households that own capital assets, decide the levels of production, intermediate uses, investments, unskilled labor demands and their own final consumptions subject to technological, capital accumulation and budget constraints. We rule out for simplicity a labor-leisure choice and assume that these economic agents fully allocate their skilled labor in their respective production. The main difference between these two economic agents/sectors is that the second one is producing a composite good that is also used for the formation of the capital. In the empirical part of the paper, we will group farm and food producers in the first type and other producers (manufacture and service) in the second type. As usual, we assume representative agents with infinite horizons, (restrictive) Cobb Douglas periodic preferences and production functions. We also adopt an additive time structure in the overall utility function and thus assume that the risk aversion parameter equals the resistance to inter-temporal substitution (the rate of pure time preference is constant). The third type gathers economic agents who do not own capital assets. These economic agents, that we label unskilled workers for the rest of this paper, sell their labor endowment to productive sectors at the wage rate and consume the two products available on the markets. Their only periodic decision is the optimal allocation of their income to the final consumption of these two goods (so no labor-leisure choice, no savings).

We make the heroic assumption that a (world) social planner exists and optimizes allocation of scarce resources to maximize total economic welfare. This assumption is usually made, such as in the standard DICE model. It avoids us to deal with the possible different information structure held by the different economic agents (and the micro structure with contingent markets) and consequently the distributive issues.

Analytical derivation

Formally, the program of the social planner is given by:

$$Max\ W = \sum_{j=1}^{3}\sum_{t=1}^{\infty} \beta^{t-1} \frac{\left(C_{1jt}^{\alpha_j} C_{2jt}^{1-\alpha_j}\right)^{1-\rho_j}}{1-\rho_j}$$

$$s.t. \sum_{j=1}^{3} C_{1jt} + \sum_{j=1}^{2} IC_{1jt} \leq Y_{1t} = \tilde{\alpha}_{Y1t}(K_{1t})^{\alpha_{K1}}(L_{1t})^{\alpha_{L1}}(IC_{11t})^{\alpha_{IC11}}(IC_{21t})^{\alpha_{IC21}}(\overline{SL}_1)^{\alpha_{SL1}}$$

$$s.t. \sum_{j=1}^{3} C_{2jt} + \sum_{j=1}^{2} \left(IC_{2jt} + I_{jt}\right) \leq Y_{2t} = \tilde{\alpha}_{Y2t}(K_{2t})^{\alpha_{K2}}(L_{2t})^{\alpha_{L2}}(IC_{12t})^{\alpha_{IC12}}(IC_{22t})^{\alpha_{IC22}}(\overline{SL}_2)^{\alpha_{SL2}}$$

$$s.t.\quad K_{jt+1} \leq K_{jt}\left(1-\delta_j\right)+I_{jt},\quad K_{j1}=\overline{K}_{j1}\; j=1{,}2$$

$$s.t.\sum_{j=1}^{2} L_{jt} \leq \overline{L}_t$$

The first constraint of this optimization program captures the market equilibrium condition for "food" products. The second one pertains to the manufactured products and includes the investment demands in the left hand side. The third constraint captures the capital accumulation constraint and finally the last one the equilibrium constraint on the unskilled labor market. Assuming interior solutions we can incorporate the capital accumulation constraints in the market equilibrium conditions for manufactured products. The program then reduces to three constraints and three multipliers (the discounted prices of goods and the wages at each period).

The first order conditions are given by:

$$\alpha_j\left(C_{1jt}^{\alpha_j}C_{2jt}^{1-\alpha_j}\right)^{1-\rho_j} = P_{it}C_{ijt}, i=1{,}2, j=1{,}3, t=1,\propto \quad (1)$$

$$\alpha_{ICij}P_{jt}Y_{jt} = P_{it}IC_{ijt}, i=1{,}2, j=1{,}2, t=1,\propto \quad (2)$$

$$\alpha_{Lj}P_{jt}Y_{jt} = w_tL_{jt}, j=1{,}2, t=1,\propto \quad (3)$$

$$P_{2t} = \beta\left(\left(1-\delta_j\right)P_{2t+1}+P_{jt+1}\alpha_{Kj}\frac{Y_{jt+1}}{K_{jt+1}}\right), j=1{,}2, t=1,\propto \quad (4)$$

Equation (1) expresses the optimal final demands of goods by the three agents. Equation (2) expresses the optimal intermediate demand of goods by producing activities, equation (3) their optimal labor demands. Finally equation (4) expresses the optimal evolution of the capital stocks in the two producing sectors. As usual, the optimal capital stock ensured that the marginal cost of capital stock (the left hand side) equals the marginal benefit (captured by the right hand side). This marginal benefit includes two terms, the next period depreciated capital stocks and the next period additional production.

Calibration and resolution

All these first conditions and market equilibrium constraints must be solved simultaneously in order to determine the optimal evolution of endogenous variables. Exogenous variables are given by the initial values of capital stocks and the labor endowments and by the technological and preference parameters. In order to solve this perfect foresight version, we thus need to calibrate all behavioral parameters, give initial values to the capital stocks and labor endowments and impose some terminal conditions (due to the Euler type equation 4 involving next period variables). Because we adopt Cobb Douglas functions, most behavioral parameters and the values of initial stocks can be retrieved from observed values gathered in a SAM for a given year (such as from the widely used GTAP database) if we simultaneously assume that the world economy in this year was in a steady state (as usual, we normalize all prices in this steady state) . The only two parameters we need to impose are the rate of pure time preference and the risk aversion parameters. In the standard calibration, we assume that these values are equal across agents and are similar to those used in the standard calibration of the DICE model. The rate of pure time preference is fixed at 0.015 and the risk aversion parameter to 2. The SAM used for calibration and the starting point of the model is derived from the GTAP database with slight adjustments: it is provided in appendix 1. Finally we impose the standard terminal condition (as in the DICE model) that in the last simulated period, investment equals the depreciation of capital. The first order condition (4) is thus replaced by

$$I_{jT} = \delta_j K_{jT} \tag{4'}$$

Implementation of scenarios

In order to evaluate the economic impacts of the climate change, we first generate baseline (or without climate change) results and then rerun the model assuming some physical impacts of the climate change. We generate different baselines to reflect the uncertainties about factor productivities. Contrary to Nordhaus (2007) we specify log normal density functions with standard errors equal to 0.05 in both production sectors:

$$\ln\left(\alpha^{0}_{Yjt}\right) \sim N(0; 0.05)$$

This level of standard errors ensures reasonable volatilities of simulated GDP from the baseline results. Again it should be clear that future factor productivities may take different values but the perfect foresight approach, adopted for instance in the DICE model, assume that economic agents perfectly know from the first period the ones that will materialize in the subsequent periods. Like the sensitivity analysis performed by Nordhaus (2007) we perform different runs of the model (200 instead of 100). We thus obtain 200 baselines extending over 100 years. We then simulate the impacts of climate change by assuming that factor productivities take new stochastic values. They reflect the uncertain physical impacts of previous GHG emissions on current and future factor productivities (due to lags between physical emissions and impacts). We again specify log normal probability distributions and assume that the first moment is higher (the double) in the farm sector than in the manufacturing sector. As regards the standard errors of these new stochastic variables, we will consider different values and assume initially that they equal 0.05:

$$\ln\left(\alpha^{f}_{Y1t}\right) \sim N(-0.05; 0.05)$$

$$\ln\left(\alpha^{f}_{Y2t}\right) \sim N(-0.025; 0.05)$$

These shocks are not precisely justified as in the Nordhaus analysis. They just ensure that our average welfare impacts are in the middle of available welfare estimates. We hypothesize that climate changes on agricultural productivies may be greater than on other industries.

We recall that, in this perfect foresight version, it is assumed that economic agents perfectly know from the first period the values of these physical impacts for all future years. We again draw 200 values of these stochastic variables. By solving 200 times the model, we obtain 200 series of economic impacts of the climate change computed over 100 years.

Computing welfare effects

In addition to compute the market effects of the climate change, it is crucial to compute the welfare effects such as to provide normative conclusions. Computing the welfare effect of a climate change scenario is however not straightforward for two reasons. First, in this perfect foresight case, there is an optimal budget allocation across time by our hypothetic social planner (Keen, 1990). For instance, if the social planner perfectly expects a negative productivity shock in farming in the future years, he may decide to reduce the investments in that sector (and allow more final consumptions) before the shock materialize. Direct comparison of periodic utility will lead to the false conclusion that economic agents initially enjoy a decrease of their future productivity. Accordingly we must compute the optimal allocation of periodic utility before computing the equivalent variation as for workers. This optimal periodic utility is obtained from the program:

$$Max\ W = \sum_{j=1}^{3}\sum_{t=1}^{\infty} \beta^{t-1} \frac{\left({C_{1jt}^{opt}}^{\alpha_j} {C_{2jt}^{opt}}^{\alpha_j}\right)^{1-\rho_j}}{1-\rho_j}$$

Subject to:

$$\sum_{j=1}^{3}\sum_{t=1}^{\infty} \beta^{t-1} \frac{\left({C_{1jt}^{opt}}^{\alpha_j} {C_{2jt}^{opt}}^{\alpha_j}\right)^{1-\rho_j}}{1-\rho_j} \leq \sum_{j=1}^{3}\sum_{t=1}^{\infty} \beta^{t-1} \frac{\left({C_{1jt}^{f}}^{\alpha_j} {C_{2jt}^{f}}^{\alpha_j}\right)^{1-\rho_j}}{1-\rho_j}$$

The total welfare effect of a scenario for the world economy is computed as:

$$EV = \sum_{j=1}^{3}\sum_{t=1}^{\propto}\sum_{i=1}^{2} \beta^{t-1} P_{it}^{0}\left(C_{ijt}^{opt} - C_{ijt}^{0}\right)$$

Second, the model is solved over 100 years and not to the infinity. We must therefore acknowledge the wealth (in terms of capital stocks) in the last simulated year that will allow future consumptions. Because we impose a new steady state in the last period (see equation 4'), we simply compute the welfare obtained from last period consumptions in both the baseline and simulation results. This difference is then added to the previous EV expression (appropriately discounted by the rate of pure time preference).

1.2. The full information version

The previous perfect foresight is obviously an extreme assumption on the information held by economic agents. A slightly less extreme assumption is to assume that economic agents and the social planner don't know the future realizations of stochastic variables. So in this full information version, we assume that the social planner solves a truly stochastic and dynamic program. Formally, we solve:

$$Max\ W = E_t \sum_{j=1}^{3} \sum_{t=1}^{\infty} \beta^{t-1} \frac{\left(C_{1jt}^{\alpha_j} C_{2jt}^{1-\alpha_j}\right)^{1-\rho_j}}{1-\rho_j}$$

$$s.t. \sum_{j=1}^{3} C_{1jt} + \sum_{j=1}^{2} IC_{1jt} \leq Y_{1t} = \tilde{\alpha}_{Y1t} (K_{1t})^{\alpha_{K1}} (L_{1t})^{\alpha_{L1}} \left(IC_{11jt}\right)^{\alpha_{IC11}} (IC_{21t})^{\alpha_{IC21}} (\overline{SL}_1)^{\alpha_{SL1}}$$

$$s.t. \sum_{j=1}^{3} C_{2jt} + \sum_{j=1}^{2} IC_{1jt} + I_{jt} \leq Y_{2t} = \tilde{\alpha}_{Y2t} (K_{2t})^{\alpha_{K2}} (L_{2t})^{\alpha_{L2}} (IC_{12t})^{\alpha_{IC12}} (IC_{22t})^{\alpha_{IC22}} (\overline{SL}_2)^{\alpha_{SL2}}$$

$$s.t. \quad K_{jt+1} \leq K_{jt}\left(1-\delta_j\right) + I_{jt}, \quad K_{j1} = \overline{K}_{j1}\ j = 1,2$$

$$s.t. \sum_{j=1}^{2} L_{jt} \leq \overline{L}_t$$

The major difference lies in the stochastic technological parameters in both producing sectors. We assume as usual in DSGE models that current period productivity shocks is observed. So many first order conditions are similar to the previous ones. The main change concerns the first order condition (4) which now involves expectations:

$$P_{2t} = \beta E_t \left(\left(1-\delta_j\right) \tilde{P}_{2t+1} + \tilde{P}_{jt+1} \alpha_{Kj} \frac{\tilde{Y}_{jt+1}}{K_{jt+1}} \right) \tag{7b}$$

This condition is close to the standard capital asset pricing equation (as the equation 4.3 of Bostian and Golub). Our stochastic discount factor involves the prices of goods and thus the "average" marginal utility of consumption. This equation states that it is worthwhile to increase the capital stock by one unit if the marginal cost (the sure left hand side) equals the expected marginal benefit (the uncertain right hand side due to the unknown future productivity shocks). This benefit includes two terms: the value of the depreciated unit of capital in the next period and the additional production valued at next period (uncertain) price.

Solving these first order conditions is much more difficult than in the perfect foresight version. On the other hand, we don't need to impose a terminal condition as equation (4'). We develop a projection approach rather than the now standard perturbation method involving second-order approximations because the latter approach leads to impulse response functions that are independent of the standard errors of shocks (for an explanation, see Schmitt Grohé and Uribé, 2004 or Aruoba et al., 2006). Hence we will not be able to examine the consequences of increased variability of productivity shocks due to climate change. On the other hand, with the projection approach, it is usually more difficult to calibrate the coefficients of impulse responses functions (once we have these impulse response functions, it is straightforward to solve the full model). We solve this issue by initializing these coefficients starting from the results of perturbation approach (we make use here of the Dynare software). Even if we have two dynamic first order conditions (equations 4b), we only need one response. We calibrate the response function of the current price of manufactured goods (in terms of capital stocks and current productivity shocks). All other endogenous variables (including investment levels) are obtained from other first order conditions and market equilibrium conditions. The accuracy of our approach is revealed in the empirical section when we report the Euler equation errors.

In order to simulate the economic impacts of climate change, we first calibrate and simulate a social planner problem assuming that productivity shocks (α_{Yjt}^{0}) follow log normal probability distributions and that the social planner perfectly knows these distributions. We then assume that the social planner is able from the first period to identify the true stochastic impacts of climate change on factor productivities (α_{Yjt}^{Δ}) from the second period onwards. In other words, he immediately learns the physical impacts of climate change on both sectors. We thus simulate a second system of new impulse response functions. We compare the two sets of simulation to compute the economic consequences of climate change. We again perform our assessments using 200 random draws and over a 100 year horizon.

The computation of welfare effects is now made per period. That is, we compute for each period the initial (before climate change) and final (after climate change) total utility. Using prices from the baseline results, we then compute the minimum expenditure to get final utility. The equivalent variation is then obtained by subtracting baseline expenditures. Total welfare is the discounted sum of periodic welfare (discounted by the rate of pure time preference). Formally we have:

$$EV = \sum_{t=1}^{\propto} \beta^{t-1} \left(E\left(P_t^0, U_t^f\right) - E(P_t^0, U_t^0) \right)$$

With:

$$E\left(P_t^0, U_t^f\right) = min \sum_{j=1}^{3} \sum_{i=1}^{2} P_{it}^0 . C_{ijt}^{opt} \text{ s.t. } \sum_{j=1}^{3} \frac{\left(C_{1jt}^{opt^{\alpha_j}} C_{2jt}^{opt^{\alpha_j}} \right)^{1-\rho_j}}{1-\rho_j} \geq \sum_{j=1}^{3} \frac{\left(C_{1jt}^{f\ \alpha_j} C_{2jt}^{f\ \alpha_j} \right)^{1-\rho_j}}{1-\rho_j}$$

Again, for the last period, we must acknowledge that the remaining capital stocks allow future consumptions. We thus compute the value function in the last period (in that respect we retrieve the coefficient of the value function from the calibrated impulse response function) for the baseline and simulation results. The difference is appropriately added to the previous expression (discounted by the rate of pure time preference).

1.3. The version with informational failures

Our third version is very close to the second version with full information. The difference is that the social planner is assumed to be unable to identify the truly stochastic impacts of climate change on factor productivities during the whole horizon of simulations (100 years). We thus consider the other extreme during one hundred years (no learning capacity) and thus are likely to compute the maximum impacts of informational failures. In other words, we assume that the social planner (and economic agents because there are no informational asymmetries) consider that the productivity shocks have not changed and thus behave as if this does not exist.

We concretely compute the economic impacts of the climate change by again comparing counterfactual to baseline results. The baseline results are obviously similar to those obtained with the full information version. The counterfactual results are different because we use the first system of impulse response functions but with different productivity shocks.

By comparing the impacts computed from the second and third versions, we can compute the social value of getting information about the true physical impacts of the climate change. This social value fully takes into account the adaptation (versus no adaptation) strategies implemented by economic agents.

2. Simulation results

The construction of relevant baseline to assess future economic scenarios is often highly critical. In the climate change issue, this issue is also major as the analyses of Mckibbin and Wilcoxen (2009) or even the Nordhaus reveal. We abstract from all these issues and consider that the initial point observed in 2004 is a steady state. The only exogenous changes that occur are productivity shocks. In this section, we present the results with standard values (for the risk aversion parameter, the rate of pure time preference and the standard errors of physical impacts of climate change). Sensitivity analyses of results to these values are provided in the third section.

Our different versions produce numerous results. We focus the analysis of the production and price impacts as well as on the total economic welfare. In the table 1 below, we report the average (and standard errors) of these variables computed over all period. The results of the perfect foresight version represent our benchmark. To be sure that this benchmark is consistent with available results, we perform, similar to Nordhaus, a first simulation where we assume that productivity shocks are null (in other words, we compute the effects at the average).

Table 1. Average market and welfare effects of the climate change according to methodological frameworks (standard errors in parentheses)

Variables	No productivity shocks	Perfect foresight	Full information	Informational failure
Baseline results (without climate change)				
Food price	1 (0.0)	1.026 (0.185)	0.999 (0.054)	0.999 (0.054)
Price of other goods	1 (0.0	1.048 (0.347)	0.997 (0.017)	0.997 (0.017)
Wages	1 (0.0)	1.045 (0.364)	0.999 (0.046)	0.999 (0.046)
Food production	4.004 (0.0)	4.005 (0.214)	4.015 (0.196)	4.015 (0.196)
Prod. of other goods	34.120 (0.0)	34.099 (1.657)	34.169 (1.767)	34.169 (1.767)
log of absolute Euler errors	--	--		
Max			-8.3	-8.3
Mean			-10.4	-10.4
Simulation results (with climate change)				
Food price	1.127 (0.0)	1.142 (0.169)	1.107 (0.061)	1.117 (0.061)
Price of other goods	1.084 (0.0)	1.111 (0.259)	1.064 (0.017)	1.062 (0.017)
Wages	1.040 (0.0)	1.065 (0.265)	1.032 (0.047)	1.017 (0.050)
Food production	3.719 (0.0)	3.721 (0.199)	3.750 (0.186)	3.716 (0.184)
Prod. of other goods	32.732 (0.0)	32.719 (1.575)	33.096 (1.702)	32.641 (1.680)
Log of absolute Euler errors	--	--		
Max			-8.2	-7.9
Mean			-9.9	-8.8
Total welfare				
In trillion dollars	-80.0 (0.0)	-71.3 (61.4)	-70.0 (13.4)	-56.4 (13.4)
In percentage of initial consumption values	-5.09	-4.53	-4.45	-3.47

2.1. Results from the perfect foresight version

Let’s start with the simple case assuming no productivity shocks (first column of table 1). The climate change scenario leads as expected to a decrease of productions: by 7.2 per cent for the food product and by 4.1 per cent for the other goods. These decreases are greater than the shocks that we impose (respectively 5 and 2.5 per cent). Because economic agents and the social planner perfectly know the lower productivities, they invest less in the initial years and prefer to initially enjoy greater consumption. This gradually reduces the optimal capital stocks and hence the production volumes. These effects are obviously moderated by the price effects that are all positive. The welfare effect is obviously negative with a decrease amounting to 80 trillion US dollars. This represents 5.1 per cent of initial consumption (4.2 per cent of initial GDP). This effect would be obviously lower if latent technologies that are less climatic sensitive exist.

When we introduce perfectly known productivity shocks, the results are slightly changed (second column of table 1). Average production effects are very similar (minus 7.1 per cent for food production, 4.0 per cent for the production of other goods compared to the relevant baseline results). Average price levels are slightly greater (in both the baseline and simulation results compared to the first column). The average welfare decreases less in this case (4.6 per cent of initial consumption) due to the concavity of utility functions. Price levels appear much more volatile than production levels over all years. However if we omit the first period, price volatilities (measured by the coefficient of variation) are similar to production volatilities. This makes sense because we impose Cobb Douglas functional forms for technologies. Simulated prices are much more different in the first period when we observe significant investment effects because the social planner already adjusts investment (and consumption) in the first period (this is a standard anticipation effect).

We thus find like Nordhaus that introducing stochastic dimensions by “simple MonteCarlo” simulations does not really change the messages. The difference of our welfare effect is slightly greater than the one found by Nordhaus, because we adopt (fat tailed) lognormal rather than normal distributions.

2.2. Results from the full information version

Let’s now turn to the second stochastic approach identified in the literature, when the social planner doesn’t exactly know the values of stochastic productivities (third column of table 1). We first underline that our Euler errors are small (the approximation of the prices of other goods is such that the error amounts to around 10^{-8} when the price is approximated to one). We are thus confident in our welfare effects. We find that the average production volumes decrease slightly less (compared to the relevant baseline): by 6.6 per cent for food products, by 3.1 per cent for the other goods. Yet we observe a similar average welfare effect amounting to 4.4 per cent of initial consumption. This is explained by a timing effect: with perfect foresight, investment drastically declines in the first period and then quickly stabilizes at a lower level than the initial observation. The final consumptions of the two goods are quite high in the first period (despite lower production of other goods) and then slightly decrease in the remaining periods. With the full information version of our model, investment effects are smoother. Investment levels decrease slightly in the first periods and then recover at higher levels (compared to the perfect foresight approach). Productions, and by way of consequence final consumptions, are thus greater in these remaining periods.

So, even if market effects are not strictly similar due to timing effects, it appears that the perfect foresight and full information approaches lead to the same average welfare effect of the climate change. The dispersion of the welfare effect (across our 200 runs) is however much different (the standard deviation is reduced by a factor 4) due to the smooth effects obtained with the full information approach. These results suggest that we should not expect greater social costs of carbon when one moves from the predominant first approach identified in the literature to the second one.

2.3 Results from the version with informational failures

Consider finally the case where the social planner suffers from informational failures during at least 100 years (last column of table 1). Compared to the full information version, we find greater production and price effects: average food production decreases by 7.4 per cent, the production of other goods by 4.5 per cent. The reason is that investment levels are lesser in this case. That is, the social planner observes decreasing productivities but is still expecting the recovery of these productivities in the future (due to false expectations on factor productivities). Accordingly he has a less prudent behavior and continues to ease final consumptions. In other words, he expects greater productions in the future years that will help to rebuild the capital stocks. This does not really occur and progressively the levels of capital stocks decrease, as well as the production levels. By ignoring the new lower levels of factor productivities, the whole economy continues to consume and becomes less wealthy. The welfare effect of climate change appears less dramatic in this case with a 3.5 per cent decrease (compared to 4.5 per cent in the previous version, hence 22 per cent lower). This welfare effect includes the lower values of capital stocks observed in the last simulated years.

It is tempting at this stage to conclude that the value of information about the true productivity shocks is negative and that we have another situation where the Blackwell theorem does not hold (see for instance Eckwert and Zilcha, 2003). This is not the case. To obtain this welfare effect, we assume so far that the social planner will never learn the true productivity distributions induced by the climate change. Hence we value the last period capital stocks with the value function we get when ignoring the climate change. Let’s now suppose that at year 100, the social planner (and the economic agents) finally learns the true physical stochastic impacts of the climate change (following Geweke (2001) or Weitzman (2009), it is not unreasonable to assume that 100 years of information are required before getting significant statistical results). In this case, the social planner realizes that the capital stocks will not ensure previously expected consumptions for the future. The final levels of capital stocks must be now valued with the value function we get when knowing the stochastic physical impacts of climate change. This value is obviously much lower than the previous one. If we incorporate this new value, the total welfare effect becomes slightly lower than the one obtained with the full information (a decrease by 4.51 per cent compared to 4.45 per cent). This simply means that it is better to learn the damaging effects of climate change sooner than later as we have more latitude to cope with the effects. That is, the sooner we know the existence of the true climate change, the sooner we engage investment efforts (and reduce temporary consumptions) to deal with its negative impacts.

We end up with the traditional debate of whether we should act now (engage some R&D or protecting expenditures) to avoid future “catastrophic” climate events. Or should we wait and see, hoping the next generations will be better able to suffer from some damages (basically the Nordhaus’ view). With the necessary precautions that we must attach to our results (mostly due to exogenously given physical impacts of climate change), it appears that learning now rather than 100 years later is not a great value from an ex ante point of view. This may explain why some countries are more reluctant than others to engage now in significant mitigation and adaptation measures (in addition to the obvious issue of burden sharing between countries).

3. Sensitivity analysis

Previous results are obtained under a variety of assumptions. We now explore their sensitivity to some assumptions that are often analyzed in the literature: the risk aversion coefficient of economic agents, the rate of pure time preference. Both parameters are major factors affecting the social discount rate used (obtained from the Ramsey rule). We also explore the sensitivity of results to the variability of the climate change. The focus is on the welfare cost of climate change.

3.1. Sensitivity of results to the risk aversion parameters

The true attitude of economic agents towards risky prospects (even more towards uncertain prospects) is still a subject of intensive debate among academics. Before we follow Nordhaus assuming CRRA utility functions with risk aversion coefficient of 2. We now examine the impacts of climate change assuming a value of 5. We find nearly no impacts on these welfare impacts (see second line of table 2) and market effects as well (not shown). This finding must be understood in our dynamic context:

economic agents are better able to deal with some stochastic events, for example by delaying or anticipating some economic decisions such as investments. In technical terms, the synthetic value function exhibits less risk aversion than the corresponding instantaneous utility function (see for example Meyers and Meyers, 2005).

Table 2. Sensitivity of welfare effects according to methodological frameworks (standard errors in parentheses)

Variables	Perfect foresight	Full information	Informational failure
Standard results			
Total welfare	-71.3 (61.4)	-70.0 (13.4)	-56.4 (13.4)
Risk aversion parameter (rho = 5)			
Total welfare	-71.3 (75.0)	-70.8 (13.2)	-56.4 (13.4)
Rate of pure time preference (beta = 0.975)			
Total welfare	-39.1 (63.2)	-41.4 (10.2)	-38.2 (10.2)
Variability of physical impacts of climate change (sigma = 0.1)			
Total welfare	-80.5 (88.8)	-62.0 (21.4)	-48.4 (21.5)

3.2. Sensitivity of results to the rate of pure time preference

In this sensitivity analysis, we increase the rate of pure time preference from 1.5 per cent (from Nordhaus) to 2.5 per cent. As usual, we find significant effects on the welfare effects. When this rate is increased, the future expected consequences of the climate change are less valued, hence justifying “inaction”. It also appears that the difference between our three methodological frameworks drastically declines, simply because we put more emphasis in the first periods than the far future.

3.3. Sensitivity of results to the variability of the physical impacts of the climate change

The future physical impacts of the climate change are uncertain. The question is to know whether we should first learn the average or the dispersion of these impacts. To address this issue, we perform a variant where we assume that the standard errors of the (log normal) factor productivities after climate change increase from 0.05 to 0.1:

$\ln(\alpha_{Y1t}^{f}) \sim N(-0.05; 0.1)$

$\ln(\alpha_{Y2t}^{f}) \sim N(-0.025; 0.1)$

As expected, we find that the welfare effects become more volatile. We also find that the average welfare effects decrease when the risk aversion of economic agents is taken into account (second and third versions). This is explained by the log normality assumption on the factor productivities: productivity shocks can become quite severe in some years but these negative consequences can be smoothed with an increase number of “normal” years. In other words, a “static” catastrophic event becomes less catastrophic when viewed in a dynamic context.

Conclusion

Although the sources, extent and physical impacts of the future climate change are highly uncertain, available dynamic economic assessments implicitly assume that economic agents perfectly know them. Perfect foresight, rational expectations or active learning are standard assumptions underlying simulated results. To the contrary, this paper builds on the assumption that economic agents may suffer for a while from limited knowledge about the average and variability of physical impacts of climate change. Using a world dynamic and stochastic general equilibrium model, our simulation results show that identifying the average physical impact is much more crucial than its variability. This finding is robust to the level of risk aversion of economic agents. The rate of pure time preference of economic agents more significantly affects the economic impacts. We also find that the value of information may be negative in the short to medium run.

Several assumptions were made to reach these results, such as the absence of backstop technologies to mitigate and/or adapt to the climate change or the existence of world social planner with full rationality. The impacts of these extreme assumptions clearly deserve further researches.

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Appendix 1: The Social Accounting Matrix for the world economy (2004, trillion US dollars)

	Food Act.	Oth. Act.	Food Mar.	Oth. Mar.	Unskilled	Skilled labor	Capital	Farm HH	Oth HH	Workers	Investment	Total
Food Act.			4004									4004
Oth. Act.				34120								34120
Food Mar.								98	2175	1731		4004
Oth. Mar.	1874							646	14261	11351	5988	34120
Unskilled	955	12127										13082
Skilled labor	129	8502										8631
Capital	1046	13491										14537
Farm HH						129	1046					1175
Oth. HH						8502	13491					21993
Workers					13082							13082
Savings								431	5557			5988
Total	4004	34120	4004	34120	13082	8631	14537	1175	21993	13082	5988	

Source : GTAP dabase 7 (www.gtap.org)