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The persistence of shocks in GDP and the estimation of the potential economic costs of climate change

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ABSTRACT

Integrated assessment models (IAMs) typically ignore the impact climate change could have on economic growth. The damage functions of these models assume that climate change impacts have no persistence at all, affecting only the period when they occur. Persistence of shocks is a stylized fact of macroeconomic time series and it provides a mechanism that could justify larger losses from climate change than previously estimated. Given that the degree of persistence of climate impacts is unknown, we analyze the persistence of generic shocks in observed GDP series for different world regions and compare it to that of the leading IAMs. Under the working hypothesis of interpreting the direct impact of climate change as such shocks, the implications for growth are investigated for two RCP scenarios. The way of introducing climate shocks to GDP in most IAMs can be interpreted as assuming an autonomous, costless, large and effective reactive adaptation capacity.

1. Introduction

The causes and consequences of environmental problems tend to be highly complex and trespass disciplinary boundaries (e.g., Akhtar et al., 2013; de Vos et al., 2013; Döll et al., 2013). Integrated assessment (IA) and IAMs provide a framework to address these problems by synthesizing diverse knowledge, data, methods and perspectives with the accent differing in terms of the disciplines involved (Hamilton et al., 2015; Kelly et al., 2013). IA/IAMs have been used for the study of a wide variety of environmental issues including air pollution (Vedrenne et al., 2014), land degradation (Ibáñez et al., 2014), water management (Letcher et al., 2007), agriculture (Ewert et al., 2014), among others.

IAMs are extensively used for investigating the potential consequences of climate change on the world economy and its regions. These models typically consider a range of aspects such as agriculture, energy, human health, water and coastal resources, human settlements and ecosystems, sea level rise and in some cases catastrophic impacts (i.e., large discontinuities in the climate system). Damage functions are commonly calibrated using meta-analysis of the sectoral estimates available in the literature in order to represent the impacts of climate change for a benchmark warming (e.g., 2.5 °C; see Nordhaus and Boyer, 2003; Hope, 2006; Tol, 2009; among others). Most IAMs summarize all this information in one or two aggregated damage equations to represent the regional and/or global impacts expected for a particular increase in global annual mean surface temperature. For the purposes of this paper it is important to notice that: 1) in general, the damage functions are calibrated to *static* impact estimates corresponding to a prescribed warming scenario such as doubling of atmospheric CO_2 or a specific equilibrium global temperature change (Hitz and Smith, 2004; Parry et al., 1999). Neither transient changes in climate, nor their consequences in natural and human systems are considered. Time itself and temporal dynamics are absent from these estimates. However, the impacts and changes a system has experienced in the past can strongly influence how it can deal with present and future impacts: resilience, vulnerability and adaptation capacity are time and path dependent and can strongly modify the

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magnitude of impacts (e.g., Denton et al., 2014). 2) The impact functions interpolate these static benchmark estimates of the costs of climate change for different values of equilibrium global/regional temperatures. When applied to transient climate scenarios, a time subscript is added to match that of a particular climate projection. As such, unless explicitly modeled in the impact functions, all impact dynamics other than those imparted by the dynamics of the climate projection and in some cases by the economic growth model (Fankhauser and Tol, 2005), are excluded. 3) Most IAMs express all the diverse effects of climate change over the different sectors and systems as an aggregated percent reduction/increment of a GDP baseline scenario and impose this as a direct shock to global/regional welfare.[1] Climate changes gradually and over long period of time and therefore climate shocks to GDP occur in a sequence.

The present paper contributes to the efforts made by the integrated assessment modeling community to identify relevant shortcomings in IAMs and to propose ways to overcome them (e.g., Jakeman et al., 2006; Giupponi et al., 2013 and the *Thematic Issue on Innovative Approaches to Global Change Modelling* in Volume 44 of *Environmental Modelling and Software*). Exploring the sensitivity of IAMs to parameter values has been an important way forward for better understanding both the assumptions contained in IAMs' specification as well as for identifying key parameters determining the models' outcomes (e.g., Butler et al., 2014; Nordhaus, 1992). However, some assumptions in IAMs are not explicitly expressed in their equations and their effects can be harder to assess. In this paper we investigate the sensitivity of these models to the persistence of impacts and we propose a modification to make the impact dynamics explicit in the damage functions, contributing to improved IAM transparency (Schwanitz, 2013; Schneider, 1997).

The impacts of climate change in an IAM framework are, of course, persistent because of the persistence of the climate system, which is largely determined by the changes in the abundance of long- and short-lived radiative active substances in the atmosphere (e.g., CO2, aerosols), and by the dynamics of the long- and short-term responses of the climate system, governed to a large degree by the heat capacity of the ocean. However, the response of natural and human systems to physical impacts also imparts persistence, which is related to their intrinsic resilience and adaptive capacities. These characteristics determine the system's capacity and time to recover as well as the possibility of undergoing permanent changes (e.g., Holling, 1973; Denton et al., 2014; Gunderson, 2000; Tol, 1996; Hallegatte, 2014; Fankhauser and Tol, 2005; Dell et al., 2012). These dynamics are inherent to the system being affected and different to those of the changes in climate mentioned above. For example, a variety of economic and socioeconomic processes can amplify or damp the persistence of climate change shocks (e.g., lower expected returns of investment and/or higher risks could make impacts more persistent through reduced investment; adaptation processes such as improving production technology could make climate shocks less persistent). The dynamics of the economy can make climate change impacts even more persistent not only due to changes in productivity and capital accumulation (Fankhauser and Tol, 2005) but also to other factors such as the speed and capacity to adapt and adjust of the different economic sectors (e.g., Hallegatte, 2014).

The persistence imparted by the climate is outside of the scope of this paper, as instead we focus on analyzing the dynamics of the damage functions. Models with more complex representations of the climate system tend to be more persistent (see Alex and Marten, 2011 for a comparison of IAMs climate models). A large part of the IAMs used for estimating the costs of climate change do not explicitly model the physical impacts but only the monetized impacts (e.g., Tol and Fankhauser, 1998), and therefore all impact dynamics can in practice only occur in two parts of IAMs: 1) in their damage functions or 2) through the dynamics of the economic growth model, if included in the IAM. In any case, impact functions in IAMs should be able to represent the most salient features of the dynamics of impacts.

Most economic IAMs represent climate change impacts as aggregated direct shocks to GDP. This makes GDP the variable of interest to study impact dynamics in these models. The level of persistence of climate shocks to GDP is unknown. However, some studies have suggested that these shocks tend to persist in time and only gradually dissipate. Fankhauser and Tol (2005) studied this problem from a theoretical perspective analyzing the dynamic effects of climate change impacts in future welfare by means of economic growth models. They showed that in addition to the direct impacts of climate change, this phenomenon can have important indirect impacts over capital accumulation, the propensity to save and capital-labor ratio due to climate change's potential health effects. Hallegatte (2005, 2007) stresses the importance of considering the climate and economic dynamics (and feedback processes between these two systems) as well as the short-term socioeconomic constraints in determining the long-term costs of climate change. He argues that the impacts associated to these dynamic processes can be larger than those shown in the traditional assessments of the costs of climate change that have been published. The existence of poverty traps has been also pointed out as a potential mechanism that can create persistent effects over economic growth through its impact on demographic and economic dynamics (Tol, 2011; Hallegatte, 2007).

The long-term impact of extreme events on economic growth has been addressed in the literature leading to opposite results. These differences may be explained by the modeling approaches taken and the treatment of temporal dynamics of impacts in particular (Noy, 2009; Raddatz, 2007). Skidmore and Toya (2002), by means of a (static) cross-sectional analysis for the period 1960–1990, conclude that higher frequencies of climatic disasters are positively correlated with higher rates of human capital accumulation, increases in total factor productivity and economic growth. On the contrary, studies based on macroeconomic models have shown that disasters do not increase economic growth and that economic dynamics and constraints can make the overall production loss considerably larger than the direct costs of the disaster (Hallegatte et al., 2007; Hallegatte and Dumas, 2008). Although the study of the effects of disasters in growth offers the large advantage of data availability on the consequences of past events, the effects of climate change over economic growth are far more general and sustained than those of extreme events alone and the dynamics need not be similar (e.g., Tol, 2011; Fankhauser and Tol, 2005; Dell et al., 2014).

A useful way for analyzing the temporal dynamics of a process or system is to study how single shocks (or one-time "pulses") propagate through time using, for example, impulse response functions. A single perturbation is introduced in the equation describing the process of interest (e.g., an impact function) at time t and its effects over the following periods are analyzed. A shock is persistent if its effects take longer to dissipate than the length of the time step. This is how the temporal dynamics of the impact functions in IAMs are investigated in this paper. Different approaches are available for studying persistence in economic variables, notably the classical econometrics approach based on time-series models and the Real Business Cycle (RBC; see King and Rebello,

[1] The baseline GDP scenarios used in climate change studies represent what is expected to occur conditional on a set of assumptions about some determinant factors. Any external perturbation that is imposed to these projections can be interpreted as a shock (for a definition of shock in economics see Black et al., 2009).

2000; Plosser, 1989) which requires calibrating theory-based economic growth models using a selection observed statistics describing the economy. These approaches rely on different methodologies and assumptions, often leading to different estimates of persistence (e.g., Gregory and Smith, 1995; Cogely and Nason, 1995). According to the RBC literature, although most shocks show some degree of persistence, technological (productivity) shocks are the only type of shocks that can reproduce the high persistence of the business cycle. Fankhauser and Tol (2005) and Dietz and Stern (2014) explore the effects of climate change impacts on growth by including an endogenous model for the total factor productivity (TFP). These authors find that climate change impacts, through their effects on productivity, could be highly persistent and lead to estimates of the costs of climate change several times higher than those obtained with original model. In this paper we undertake an empirical approach based on the econometrics literature for investigating the sensitivity of current IAMs to different levels of persistence of shocks.

Due to the general lack of data on the impacts of climate change, the objective of this paper is to assess the importance of the persistence of shocks. We recognize that precise estimates of their persistence are not attainable. We therefore explore a range of arbitrary values of persistence as well as estimates of the observed persistence of GDP to general shocks to illustrate the importance of impact dynamics. Note that the projected costs of climate change based on the estimated persistence values assume that climate change shocks would show a persistence level similar to that of general shocks to GDP. This is uncertain and therefore these results should be interpreted as indicative only. However, it is worth noting that, as shown in this paper, the economic growth model in DICE —although its effects are vanished by the chosen integration step— as well as FUND impact dynamics suggest a level of persistence similar to that estimated here.

This paper first analyzes the observed dynamic impacts of shocks to GDP. It then focuses on the economics dynamics induced by the impacts of climate change. The paper finally illustrates the sensitivity of the estimates of climate change costs to different degrees of persistence. The structure of the paper is as follows. In the second section, the time-series properties of twelve regional GDP time series are investigated by means of a standard unit root test (Dickey and Fuller, 1979; Said and Dickey, 1984) and a unit root test that allows for a one-time structural change in the trend function (Perron, 1989, 1997; Kim and Perron, 2009). The third section analyses the persistence of three of the most commonly used IAMs: DICE/RICE, FUND and PAGE2002. The empirical estimates of persistence are then contrasted to that implied by the impact functions of the selected IAMs, and to the persistence imparted by the economic growth models in DICE/RICE. In the fourth section of this paper, a simple version of the PAGE2002 model (Hope, 2006) is used to conduct a sensitivity analysis varying the degree of persistence in simulated future GDP. The fifth section provides new estimates of the potential costs of climate change at the global and regional scales for the RCP4.5 and RCP8.5 emissions scenarios and different values of persistence. It is shown that the economic impacts of climate change are highly sensitive to different levels of persistence and that they are considerably larger than the "zero persistence" implied by the common specification of the impact functions used in IAMs. Results suggest that the costs presented in the literature could be seriously underestimated. Section six concludes and presents a summary of our findings.

2. How persistent are shocks to GDP?

Output shows a substantial degree of persistence and shocks tend to affect not only current period but a number of periods in the future (e.g., Nelson and Plosser, 1982; Perron, 1989; Kim and Perron, 2009). As stated by Campbell and Mankiw (1987) "much disagreement remains over exactly how persistent are shocks to output. Nonetheless, among investigators using post-war quarterly data, there is almost unanimity that there is a substantial permanent effect". The contribution of persistence from different sectors and types of shocks in aggregated time series has been investigated. It has been shown that while sectors may contribute differently to the persistence of aggregated output, in general persistence at the sectoral level is close to unity and that sector-specific shocks tend to have a more permanent effect on sectoral and aggregate GDP than general macroeconomic shocks (Lee et al., 1992; Pesaran et al., 1993). These results suggest that even if climate change impacts affected only a limited number of sectors, these sector-specific impacts may have a highly persistent effect on aggregate GDP.

In this section we investigate the persistence of shocks to GDP for 12 groups of countries that are similar to those typically included in some IAMs (e.g., PAGE2002, DICE/RICE) for the post-war period (1950–2008). All data was taken from the Maddison database (http://www.ggdc.net/maddison/). The annual GDP time series considered are: global, Africa, Asia, Eastern Asia, Western Asia, Eastern Europe, Western Europe, the 12 countries with the largest economies in Western Europe, Western Offshoots (Australia, New Zealand, Canada and the US), Latin America, the 8 Latin American countries with the largest economies and the countries from the former USSR. Fig. A.1 shows a plot of the natural log of these time series and, as can be seen, all of them show a clear non-stationary behavior with the potential presence of large structural changes in the slope or in the slope and level of the trend function.

In order to investigate the time-series properties of GDP, we first applied the standard Augmented Dickey–Fuller test[2] (ADF; Dickey and Fuller, 1979; Said and Dickey, 1984) which consist in estimating the regression:

$$y_t = \widehat{\mu} + \widehat{\beta}t + \alpha y_{t-1} + \sum_{i=1}^{k} \widehat{\delta}_i \Delta y_{t-i} + \varepsilon_t \quad (1)$$

and testing the null hypothesis of a unit root ($\alpha = 1$) against the alternative hypothesis of trend stationary process ($\alpha < 1$). The coefficient α equals the sum of the autoregressive coefficients (SAR), one of the most commonly used measures of persistence in macroeconomic time series (Oka and Perron, 2011). $\widehat{\mu}$ and $\widehat{\beta}$ are the intercept and slope parameters and Δy_{t-i} are first differenced lagged values added to correct for serial correlation. Table A.1, the null of a unit root cannot be rejected for any of these series at the 10% significance level. The α estimates range from 0.97 to 0.87 with a mean value of 0.94. According to these point estimates the half-life (i.e., the time that takes for a unit shock to dissipate by 50%) ranges from 5 to 23 years.[3]

The cumulative impulse response (CIR) values, estimated as $1/(1-\alpha)$, illustrate how the persistence in GDP can greatly modify the long-run effect of a shock. The CIR values in Table A.1 show that depending on the region, a unit shock would produce a long-run cumulative impact ranging from 7.63 to 32.26 with a mean value of 22.73. Thus, ignoring these dynamic effects, could provide a very

[2] Because of the obvious trending behavior of the series plotted in Fig. A1 we only consider the ADF specification that includes a constant and a linear trend.

[3] This is assuming that the true values of the first order autoregressive coefficient are as shown in Table A1 and not 1, although in most cases the unit root tests indicate that these point estimates are not different form the unity. If the coefficient true value is 1, the effect of shocks would be permanent and the long-run responses discussed below would be equal to infinity. See Clark (2006) and Oka and Perron (2011).

poor estimation of the potential economic impacts of climate change, or of any other type of shock, for that matter.

However, the presence of structural changes in the slope or in both the slope and the intercept of the series is likely in many of the GDP series in Fig. A.1 and the estimates of SAR could be biased towards unity if these structural changes are ignored (Perron, 1989). It is therefore important to test if the results shown in Table A.1 are affected by the presence of structural changes. If this is the case, the estimates of persistence could be biased upwards.

The Kim and Perron (2009) unit root test is applied to further investigate the persistence of these series. The existence of a break was pretested using the Perron and Yabu (2009) procedure for structural change (Table A.2) and results show that the null of no-break in the trend function can be rejected for all series, with the exception of Africa and Asia. Table A.2 shows that, once the occurrence of a break in the trend function is taken into account, the unit root null can be rejected at 5% level for Latin America and the eight largest Latin American economies and at 10% level for the twelve largest economies in Western Europe. The estimated break dates are similar, reflecting the effects of major shocks: the oil price shock of 1973, the 1980s debt crisis, and the disintegration of the USSR in the 1990s. The SAR estimates are considerably lower than those shown in Table A.1, now ranging from 0.46 to 0.90 with a mean of 0.70, indicating that once structural breaks are accounted for, the point estimates of persistence of GDP are considerably lower (although for most of these estimates the existence of a unit root still cannot be ruled out). To exemplify the difference in the persistence of a shock that could be expected from the estimates in Tables A.1 and A.2, consider the case of the GDP of the twelve largest economies in Western Europe. Without taking into account the existence of a trend break, a unit shock would produce a CIR of 25.57; with trend break being taken into account, the accumulated response would be only 1.85. Note however that both of these long-run accumulated responses are considerably larger than those that would be produced under the “no memory” assumed by most IAMs. The CIR values range from 1.85 to 23.81, with a mean of 5.87, suggesting that certainly the lack of persistence commonly assumed in IAMs' impact functions (see Section 3) fails to represent a feature of observed dynamics of GDP shocks that could be quite relevant when assessing the potential costs of climate change.

The integrated assessment modeling approach strives for simplicity, stripping the different systems and components to their most fundamental traits. Following this line of reasoning, we propose a simplification and standardization of the dynamics in the autoregressive model of order p (AR(p)) implied in Tables A.1 and A.2 to simple AR(1) models with the first order autoregressive coefficients equal to the corresponding SAR. Although the dynamics of the impulse response functions of AR(p) models would be more complex, the accumulated long-run responses produce the same CIR values. In this manner, the use of AR(1) models with coefficients equal to the SAR provides an approximation for representing the dynamics of observed GDP series in a simple and compact form in IAMs, fairly conveying the persistence effects to the estimations of the costs of climate change.

Fig. 1 shows the impulse response functions and the accumulated response of a unit shock in the estimated AR(1) models. Panel a) ignores structural breaks, and panel b) does not. As evident from these figures, the dynamics of a shock and the time it takes for its effects to dissipate are very different: shocks dissipate more rapidly in panel b) and the cumulative response is much lower. In any case, the “zero persistence” of shocks to GDP assumed in some in IAMs is not supported by the observed data. Furthermore, it is important to note that results in Fig. 1 and the CIR values in Tables A.1 and A.2 are illustrative but conservative as, according to the results of the ADF and Kim and Perron tests, the unit root hypothesis cannot be rejected for most of the groups of countries and therefore the SAR values are not statistically different from unity. These tests indeed suggest that shocks may have a permanent effect, leading to larger long-run responses than those shown in Fig. 1.

3. Persistence in integrated assessment models

Above, we discuss persistence in GDP data. Here, we turn to persistence in three integrated assessment models: PAGE, FUND, and DICE. These three models are the most commonly used to assess the economic impacts of climate change.

3.1. PAGE

The impact functions of PAGE2002 can be expressed as follows:

$$I_{t,d,r} = \mu_{d,r}\left(\frac{T_{t,r}}{2.5}\right)^{\beta} Y_{t,r} \tag{2}$$

$$D_{t,r} = \gamma_t \pi_t Y_{t,r} \tag{3}$$

where $I_{t,d,r}$ represents the economic impacts in time t, in the sector d ($d = 1,2$; representing the economic and the noneconomic sectors, respectively) and in region r; $T_{t,r}$ is the increment in regional temperature with respect to its preindustrial value; β is the exponent that determines the functional form of the impact function; and $\mu_{d,r}$ are regional parameters to express the percentage of GDP ($Y_{t,r}$) lost for a benchmark warming of 2.5 °C in each impact sector and region. Equation (3) represents the impacts associated to the occurrence of a large-scale discontinuity in the climate system. $D_{t,r}$ represents the economic impacts of a discontinuity at time t and region r; γ_t is the loss if a discontinuity occurs; and π is the probability of occurrence of the discontinuity. The total economic impacts are the sum of Equations (2) and (3).

The equations defining the impact function show that the PAGE2002 impact module has zero persistence: a unit shock at time t in any sector and of any type (e.g., catastrophic events) has no impact on the level or growth rate of GDP at time $t + s$ for $s > 0$.

3.2. FUND

The climate impact module in FUND includes agriculture, forestry, sea level rise, human health, energy consumption, water resources, unmanaged ecosystems, diarrhea, and tropical and extra tropical storms. In FUND, a shock never dissipates. In an absolute sense, the gap between the growth path with and without shock grows with the growth rate of the economy. In a relative sense, the economy with shock is always X% smaller than the economy without shock (see Anthoff and Tol, 2014).

The persistence of climate change shocks in FUND impact functions comes from the dynamic specification of its agricultural and sea level rise impact modules. The equation for estimating the impacts on agriculture due to the rate of climate change is

$$A_{t,r} = \gamma A_{t-1,r} + \varepsilon_t;\ \varepsilon_t = \alpha_r\left(\frac{(T_t - T_{t-1})}{c}\right)^{\beta}$$

where $A_{t,r}$ represents the damage in agricultural production at time t and region r, α_r, β and c are fixed parameters and $\gamma = 0.9$. T_t is global temperature increase over the 1961–1990 period. The value of γ makes climate shocks in agriculture highly persistent, dissipating only after several time steps. The wetland and dryland loss are represented by cumulative equations of the type $C_t = C_{t-1} + u_t$

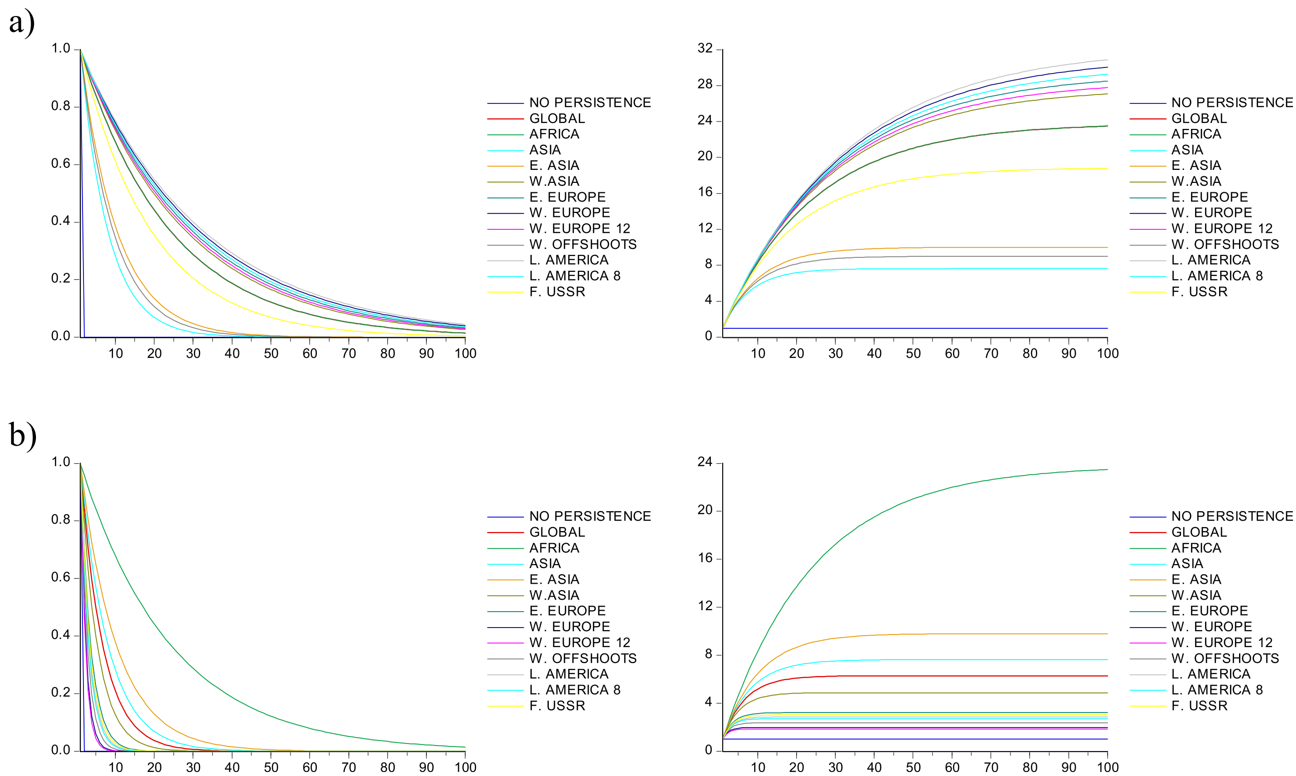

Fig. 1. Impulse response (left) and accumulated impulse response (right) functions of AR(1) models with the SAR estimates shown in Table A.1 (panel a) and in Table A.2 (panel b).

where u_t represents the damages occurring in time t. As such, the impacts of sea level rise have a permanent effect on GDP level.

3.3. DICE

DICE is more complex than PAGE and FUND. The damage function of DICE is as follows:

$$\Omega_t = 1/[1 + D_t] \quad (4)$$

$$D_t = \theta_1 T_t + \theta_2 T_t^2 \quad (5)$$

where D_t represents the climate damage as fraction of output, θ_1 and θ_2 are the parameters of the damage function, T_t is global temperature increase over the 1900 level and Ω_t is the scaling factor for output. Climate change damages in DICE include agriculture, sea level rise, other market sectors, human health, nonmarket amenity impacts, human settlements and ecosystems, and catastrophes. From Equations (4) and (5) it can be seen that, as in the case of PAGE, the impact module of DICE/RICE has zero persistence as any shock at time t has no impact at time $t + s$ for $s > 0$.

However, the model dynamics impart a certain level of persistence to shocks in GDP. Output Q_t is determined by a Solow growth model[4] specified with a Cobb–Douglas production function of the form:

$$Q_t = A_t K_t^{\gamma} L_t^{1-\gamma} \quad (6)$$

where A_t is the total factor productivity, L_t is population, γ is the elasticity of output with respect to capital and K_t is the capital stock which is determined by the equation for capital accumulation:

$$K_t = (1-\delta)K_{t-1} + I_{t-1} = (1-\delta)K_{t-1} + \sigma Y_{t-1} \quad (7)$$

where δ is the depreciation rate, I_t is investment and σ is the savings rate.

Population L_t increases less than exponentially with a rate of growth g_t^{pop} that declines geometrically over time, leading to a stable population in the long-run. Population is given by:

$$L_t = L_0 \exp\left(\int_0^t g_t^{pop}\right) \quad (8)$$

$$g_t^{pop} = g_0^{pop} \exp\left(-\kappa_t^{pop}\right) \quad (9)$$

Total factor productivity is modeled in a similar way to population, using an exponential growth function with a geometrically declining growth rate:

$$A_t = A_0 \exp\left(\int_0^t g_t^A\right) \quad (10)$$

$$g_t^A = g_0^A \exp\left(-\kappa_t^A\right) \quad (11)$$

There are two types of dynamics in a growth model: equilibrium dynamics and disequilibrium dynamics. To start with the latter, the speed of convergence to steady state for the Solow model with a Cobb–Douglas production function is $\beta_t = (1-\gamma)(g_t^{pop} + g_t^A + \delta)$. The convergence coefficient β relates to

[4] There are two versions of DICE, Ramsey and Solow. In the Ramsey model, the impact of climate change barely affects the savings' rate, so that the model, for all practical purposes, is *de facto* Solow.

persistence as $\beta_t = (1-\alpha_t^*)$, where α_t^* measures persistence of shocks (see, for example, Lee et al., 1997; Clark, 2006). The persistence coefficient α^* depends on the elasticity of output γ, the total factor productivity growth rate g_t^A, the population growth rate g_t^{pop} and the depreciation rate δ of capital. Persistence also depends on the length of the time step that is chosen, since the growth rates tend to be larger as the time step becomes larger. For example, using the annual growth rates (instead of decadal) from the DICE base case scenario, the beta convergence coefficient is $\beta_t = (1-0.3)(0.0157+0.0038+0.1) = 0.08$, indicating that every year 8% of the shock would dissipate. The persistence coefficient is then $\alpha^* = 0.916$, quite similar to those shown in Tables 1 and 3. As the length of the time step increases, persistence decreases. In DICE, the time step is 10 years and the persistence is $\alpha^* = 0.04$. The impacts show practically no memory. As such, the combination of the damage functions in DICE and the specification of the economic growth model impose both a practically zero persistence of climate change impacts *within* the 10-year time-step and (reasonably) an almost zero persistence *between* the 10-year time-steps. Note that the damage functions are not calibrated or adjusted in any way to approximate the effects of persistence within the 10-year time steps. As a consequence, results would be different if climate change impacts were estimated yearly, allowing for the persistence effects, and then aggregated in 10 year periods than if the damage function is directly applied using a 10-year step. The time-step length in IAMs is usually chosen for computational convenience and in some cases it even changes for a single model run (e.g., the time-step in PAGE2002 goes from 1 to 10–50 years). The dependence of model results on the time-step that is chosen indicates that, beyond computational convenience, relevant time-series properties of the process being model should be taken into account when choosing an appropriate time-step.

The equilibrium dynamics are as follows. Labor and total factor productivity are unaffected by changes in output. Capital accumulation is, however. Investment falls by a factor Ω, just like output. The equilibrium relationship between capital and output is $K=\sigma Y/\delta$. The scaling factor for capital is

$$\Theta_t = \frac{\sigma\Omega_{t-1}Y_{t-1} + (1-\delta)K_{t-1}}{\sigma Y_{t-1} + (1-\delta)K_{t-1}} = \frac{\sigma\Omega_{t-1}Y_{t-1} + (1-\delta)\frac{\sigma}{\delta}Y_{t-1}}{\sigma Y_{t-1} + (1-\delta)\frac{\sigma}{\delta}Y_{t-1}} = \frac{\Omega_{t-1} + \frac{(1-\delta)}{\delta}}{1 + \frac{(1-\delta)}{\delta}} = 1 - \delta(1-\Omega_{t-1}) \tag{12}$$

That is, if the impact of climate change is 1% (10%), then the scaling factor for output is 0.99 (0.90). If the depreciation rate is 10%, then impact on capital in the next period is 0.1% (1%). The scaling factor for capital is thus 0.999 (0.990). The scaling factor for output in the next period is the scaling factor for capital raised to its elasticity: 0.999^γ (0.990^γ). Persistence is therefore

$$\alpha = \frac{1-\Theta_t^\gamma}{1-\Omega_{t-1}} = \frac{1-[1-\delta(1-\Omega_{t-1})]^\gamma}{1-\Omega_{t-1}} \approx \delta\gamma \tag{13}$$

Consequently, whether we consider the equilibrium or the disequilibrium dynamics of DICE, its persistence is low, much lower than the empirical evidence presented in Section 2.

The differences in persistence, or in the speed of convergence, can also be interpreted more generally. On one hand, the lack of persistence (or a 100% speed of convergence) in DICE and PAGE2002 can be interpreted as assuming that human and natural systems have an autonomous, costless, extremely large and effective reactive adaptation capacity and resilience.[5] The economy, the society in general and nature are assumed to have the capacity to overcome the effects of a shock in a single period of time without affecting their output/state in any future periods, no matter how large the impact may be and without having to invest anything on it. In contrast, $\alpha = 1$ (or conversely, $\beta = 0$) would describe a system with a very limited resilience, being never capable of fully recover from a shock. Values of α close to unity, as in FUND, are broadly in agreement with the empirical evidence reported in the econometrics literature regarding general shocks to GDP.

3.4. Extending IAMs impacts function to include persistence of shocks

In order to further motivate the need to include persistence of impacts in IAMs projections, consider the generic impact function in IAMs (e.g., DICE/RICE and PAGE):

$$I_t = \vartheta_1 T_t^{\vartheta_2} Y_t \tag{14}$$

where I represents the economic impacts at time t, T_t is the increment in temperature with respect to its preindustrial value and ϑ_1 and ϑ_2 are parameters. Note that, as discussed in the introduction, these impact functions are calibrated using comparative static analysis of benchmark estimates of the costs of climate change for a given increase in global equilibrium temperature. The temperature change value does correspond to an equilibrium temperature, however the associated impacts and their costs do not. For example, the benchmark estimates for a 2.5 °C temperature change depict the predicted percent change in GDP in comparison to a baseline scenario (i.e., no climate change) that assumes that all systems are undisturbed, no previous impacts of climate change have occurred. That is, although some this benchmark estimates include the interactions between different sectors, they do not represent long term equilibrium values: time itself and temporal dynamics are absent from these estimates (e.g., Toth, 1998; Fankhauser and Tol, 2005). These impact functions are calibrated to interpolate the costs of climate change for different temperature values only, not for time and therefore a modification is need to take into account temporal dynamics.

As discussed in sections 3.1 and 3.3, Equation (14) imposes that shocks at time t are independent from those in time t-i for any i = 1,2,…, n. That is, the dynamics of impacts are exclusively determined by the dynamics of the driver variable T_t, and it assumes that the systems being impacted have no dynamics of their own.

Table 1
Present value of the total climate change economic impacts over a century as a percentage of the GDP in year one.

α	5th Percentile	Mean	95th Percentile
0	1.28	5.73	12.49
0.1	1.46	6.37	13.72
	(14%)	(11%)	(10%)
0.5	2.44	11.01	24.00
	(91%)	(92%)	(92%)
0.8	5.01	23.18	50.40
	(291%)	(305%)	(304%)
0.9	8.15	37.34	82.97
	(537%)	(552%)	(564%)
1	18.87	90.85	203.94
	(1374%)	(1486%)	(1533%)

Numbers in parenthesis represent the increase (%) in comparison to the estimates produced assuming α = 0.

[5] Resilience here is understood as a system's capacity and speed to recover after the occurrence of a perturbation (see, for example Adger, 2000).

Table 2
Estimates of global and regional climate change impacts under the RCP4.5 emissions scenario and for different values of α.

Region	$\alpha = 0$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.8$	$\alpha = 0.9$	$\alpha = 1$	α	NPV
Europe	0.12	0.13	0.23	0.51	0.84	2.24	0.5	0.23
	(0.03, 0.24)	(0.04, 0.26)	(0.06, 0.45)	(0.14, 1.02)	(0.22, 1.71)	(0.58, 4,60)		(0.06, 0.46)
Latin America	0.83	0.92	1.56	3.51	5.79	14.47	0.65	2.17
	(0.21, 1.78)	(0.23, 2.00)	(0.40, 3.36)	(0.86, 7.64)	(1.36, 12.68)	(3.58, 30.65)		(0.54, 4.77)
South Asia	1.77	1.93	3.33	7.23	11.57	27.06	0.8	7.23
	(0.47, 3.77)	(0.52, 4.07)	(0.89, 7.01)	(1.88, 15.36)	(3.01, 24.43)	(6.82, 55.45)		(1.88, 15.36)
North Asia	−0.25	−0.27	−0.47	−1.01	−1.66	−4.04	0.8	−1.01
	(−0.70, 0.02)	(−0.78, 0.03)	(−1.35, 0.04)	(−2.90, 0.08)	(−4.86, 0.11)	(−11.72, 0.33)		(−2.90, 0.08)
North America	0.03	0.03	0.05	0.12	0.20	0.53	0.6	0.07
	(0.01, 0.07)	(0.01, 0.08)	(0.01, 0.13)	(0.02, 0.30)	(0.03, 0.49)	(0.09, 1.28)		(0.01, 0.16)
Africa	1.51	1.67	2.87	6.25	10.05	24.34	0.9	10.05
	(0.39, 3.21)	(0.43, 3.52)	(0.77, 6.24)	(1.60, 13.40)	(2.55, 21.61)	(5.86, 52.30)		(2.55, 21.61)
China	0.12	0.13	0.21	0.48	0.77	1.97	0.8	0.48
	(0.02, 0.31)	(0.02, 0.33)	(0.03, 0.57)	(0.07, 1.23)	(0.11, 2.09)	(0.28, 5.32)		(0.07, 1.23)
World	0.28	0.30	0.52	1.14	1.85	4.52	–	1.10
	(0.08, 0.56)	(0.08, 0.55)	(0.14, 1.06)	(0.31, 2.33)	(0.49, 3.83)	(1.17, 9.16)		(0.30, 2.27)

Figures denote the number of times of the GDP in year 2001 that the present value of the economic impacts of climate change over this century amounts to. Figures in parenthesis give the 5% and 95% percentiles.

Fig. 1 illustrates the dynamics of single shocks for different values of persistence, including the case of zero persistence case which characterizes Equation (14). It is important to note that if instead of a single shock a sequence of them are introduced to the impact function the conclusions are the same as the dynamics that this function imparts to shocks are determined by its specification, not by the external driver (in this case T_t). The consequences of Equation (14) on the projection of the costs of climate change impacts are: 1) the rate of change in climate is irrelevant for determining the impacts of climate change. According to this equation the impacts of, say, a 3 °C increase in T_t would be the same whether this change in temperatures is reached instantaneously, in 30 or in 200 years. As has been discussed at length in the literature this not a reasonable assumption (e.g., IPCC, 2014); 2) impact functions such as Equation (14) are calibrated using equilibrium temperatures. However, in IAMs these equations are used for transient climate change by simply adding a time subscript matching that of the climate projection. These equations therefore imply that the transient and equilibrium climate change values produce the same impacts; 3) impacts are path independent. The sequence in which climate change shocks occur is irrelevant. In this equation the impacts of a 3 °C increase in T_t would be the same whether the affected system was previously exposed to a larger increase in global temperatures (e.g. 4 °C, 6 °C) than if it was to lower (e.g., 1 °C). However, the impacts of a X°C change are likely to be very different depending on the impacts that have affected the system in the past. These past damages are likely to generate differences in the affected system's resilience, time to recover, residual damages and possibly could have caused permanent or irreparable damages to the system (e.g., Holling, 1973; Denton et al., 2014; Gunderson, 2000; Tol, 1996); 4) Consider the thought experiment consisting in that after reaching 3 °C above current global temperature, the climate system rapidly goes back to its previous equilibrium state. Would the affected system be able to immediately recover its previous state or would it take a certain amount of time for the system go back to its previous state? Even excluding the occurrence of permanent damages, it is very likely that the system that was affected by the 3 °C change would only gradually and slowly recover its previous state (e.g., Holling, 1973; Denton et al., 2014; Gunderson, 2000; Tol, 1996; Hallegatte, 2014; Fankhauser and Tol, 2005; Dell et al., 2012).

As suggested in Section 2, a simple modification of the typical impact function in IAMs that allows for the persistence of shocks in GDP consists in a one-period memory equation with persistence α, such as:

$$I_t = I_t^D + I_t^I = \vartheta_1 T_t^{\vartheta_2} Y_t + \alpha I_{t-1} \quad (15)$$

Table 3
Estimates of global and regional climate change impacts under the RCP8.5 emissions scenario and for different values of α.

Region	$\alpha = 0$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.8$	$\alpha = 0.9$	$\alpha = 1$	α	NPV
Europe	0.35	0.39	0.67	1.45	2.41	5,68	0.5	0.67
	(0.13, 0.64)	(0.15, 0.74)	(0.26, 1.27)	(0.57, 2.77)	(0.93, 4.50)	(2.54, 8.84)		(0.26, 1.27)
Latin America	1.56	1.77	3.05	6.55	10.54	21.03	0.65	4.15
	(0.55, 3.23)	(0.61, 3.55)	(1.07, 6.29)	(2.36, 13.39)	(3.73, 20.73)	(9.67, 31.99)		(1.48, 8.54)
South Asia	2.46	2.72	4.72	10.02	15.86	29.40	0.8	10.02
	(0.89, 4.99)	(0.96, 5.47)	(1.68, 9.52)	(3.61, 20.15)	(5.82, 29.12)	(14.93, 42.41)		(3.61, 20.15)
North Asia	−0.66	−0.73	−1.29	−2.77	−4.42	−11.28	0.8	−2.77
	(−1.83, 0.05)	(−2.09, 0.05)	(−3.72, 0.12)	(−8.07, 0.19)	(−12.87, 0.41)	(−30.86, 0.82)		(−8.07, 0.19)
North America	0.09	0.10	0.18	0.39	0.65	1.69	0.6	0.22
	(0.02, 0.21)	(0.02, 0.23)	(0.04, 0.41)	(0.09, 0.87)	(0.14, 1.43)	(0.38, 3.74)		(0.05, 0.50)
Africa	1.96	2.16	3.72	8.03	12.95	26.82	0.9	12.95
	(0.68, 3.93)	(0.77, 4.33)	(1.29, 7.47)	(2.77, 16.11)	(4.69, 25.34)	(11.64, 41.44)		(4.69, 25.34)
China	0.36	0.40	0.70	1.49	2.47	6.33	0.8	1.49
	(0.06, 0.89)	(0.07, 0.97)	(0.12, 1.70)	(0.28, 3.70)	(0.42, 6.08)	(1.10, 15.39)		(0.28, 3.70)
World	0.48	0.53	0.91	1.96	3.18	6.68	–	1.73
	(0.18, 0.91)	(0.20, 1.00)	(0.35, 1.75)	(0.76, 3.77)	(1.23, 5.80)	(3.21, 10.11)		(0.64, 3.27)

Figures denote the number of times of the GDP in year 2001 that the present value of the economic impacts of climate change over this century amounts to. Figures in parenthesis give the 5% and 95% percentiles.

In this specification, the impacts of climate change consists of two parts. First, there is the direct impact, that is, the new shock imposed by climate change in that year. Second, there is the indirect impact, that is, the aftershocks from past shocks (here conceptualized as persistence in shocks to economic growth). Note that this modification allows to tackle the problems described above: the rate of climate change in previous time steps affects the projected impacts of climate change at time t; the impacts of transient and equilibrium climate change are different; the projected impacts of climate change are path dependent; the effects of climate shocks do not necessarily immediately dissipate.

4. Sensitivity analysis of the estimates of the economic impacts of climate change to different assumptions regarding the persistence of shocks to GDP

In this section, the sensitivity of the estimates of the costs of climate change to different assumptions regarding the memory of GDP is investigated. We use a simple impact function, following PAGE2002, for a hypothetical region with an annual GDP growth of 2.5%, and as discussed in the Section 3.4 we represent the persistence of shocks in GDP by means of a simple one-period memory equation with persistence α. The impact function is as follows:

$$I_t = \vartheta_1 \left(\frac{T_t}{2.5}\right)^{\vartheta_2} Y_t + \alpha I_{t-1} \qquad (16)$$

where I represents the economic impacts at time t, T_t is the increment in temperature with respect to its preindustrial value and ϑ_1 and ϑ_2 are parameters. These parameters are represented by triangular probability distributions parameterized for the European Union as shown in Hope (2006), and the increase in temperature at the end of the century is represented by an uniform distribution covering a range from 1.1 °C to 2.6 °C, which is similar to the likely range of the RCP4.5 scenario for the end of this century (IPCC, 2013). Temperature is assumed to increase linearly. All estimates presented were produced by means of simulation experiments of 5000 realizations and the time-step was chosen to be one year.

Fig. 2 shows the mean (dotted) and 5th and 95th percentiles (dashed) of the percent loss of GDP for different values of the parameter α. The red lines show the estimates produced without considering the persistence of shocks ($\alpha = 0$), while the blue ones present those assuming positive values of α. As can be seen from this figure, for very small values of α (for example 0.1) the differences in the losses in GDP may be negligible but for those that are closer to what the observed memory of GDP is (say, from 0.5 to 1), the differences become very large. For example, the mean economic impact estimated when $\alpha = 0.5$ is close to the 95th percentile for $\alpha = 0$, and for values of 0.8 and 1 this estimate is much larger that the 95th percentile. The variance of the process in (16) is a function α such that the confidence intervals become wider for higher values of this parameter.

Table 1 shows the net present value of the impacts of climate change over 100 years, using a 5% discount rate. The net present value is expressed as a percentage of GDP in year 1. If $\alpha = 0$, the present value of the total impacts would range from 1.28% to 12.49% of initial GDP, with a mean value of 5.73%. If $\alpha = 0.5$, the mean value increases to 11.01% of GDP, with a range of 2.44%–24.00% of GDP. These values are about 90% larger than the estimates that were obtained using $\alpha = 0$ (as in the scaling method). Losses increase very rapidly for higher values of α: for $\alpha = 0.8$ and $\alpha = 1$, the losses become about 300% and 1500% larger, respectively, compared to the $\alpha = 0$ estimates. An important feature of these results is that they are not sensitive to the discount rate that is chosen.

5. Estimates of the economic impacts of climate change under the RCP4.5 and RCP8.5 scenarios and for different values of α

In this section we present estimates of the economic impacts of climate change for the world[6] and for 7 world regions using the impact functions of the PAGE2002 model modified to incorporate the persistence of shocks assuming different values of α. The regions used are similar to those in the PAGE2002 model; see Table A.3.

The increase in global temperature at the end of the century is represented by an uniform distribution covering a range from 1.1 °C to 2.6 °C and 2.6 °C–4.8 °C in the case of the RCP4.5 and RCP8.5 respectively (WGI-IPCC, 2007). The regional weights for scaling the impact functions that were used are those from the PAGE2002 model (see Table 5 in Hope, 2006). Regional estimates of temperature increase were produced using the scaling factors obtained from the emulation of the UKMOHADCM3 General Circulation Model of MAGICC/ScenGen.[7] The regional GDP scenarios used for the RCP8.5 are those of the A2r which has the same underlying scenario drivers[8] (Van Vuuren et al., 2011; Grübler et al., 2007; Nakicenovic et al., 2000). For the RCP4.5 the B1 GDP scenarios were used given their similarities in terms of the resulting forcing (Van Vuuren et al., 2011). The discount rate is 4%.

Tables 2 and 3 present the discounted accumulated impacts of climate change during this century in 2001 GDP units for varying values of α and for the RCP4.5 and RCP8.5, respectively. Results are highly sensitive to the memory parameter α and the uncertainty in the persistence of climate change impacts tends to have a larger effect over the estimated costs than the use of different climate change scenarios. The rightmost two columns of these tables show the estimates of the economic impacts of climate change for the world and for the seven world regions above, choosing values of the α parameter for each region that are similar to those in Table A.2. The present values of the accumulated costs of climate change for the world during this century estimated using the original PAGE2002 impact functions (i.e., $\alpha = 0$) are about 30% and 48% of the 2001 GDP for the RCP4.5 and RCP8.5 scenarios, respectively. However, if for example climate change impacts are assumed to show a persistence similar to general shocks to GDP, these estimates become about four times larger. For the world and all regions with the exception of Europe and North America the accumulated costs of climate change are more sensitive to the persistence parameter than to the climate change scenario that is chosen, even though these scenarios represent large differences in emissions and climate (Fig. 3). As in many other studies of the potential costs of climate change (see, for example, Tol, 2009), regional differences are significant and become larger when the persistence of (positive and negative) shocks is considered: the North Asia region is expected to experience large benefits from climate change; regions such as North America/OECD and Europe would experience small impacts that are likely to be compensated if some adaptation measures are adopted; and for regions such as South Asia, Africa and Latin America climate change could represent a major challenge.

[6] Note that world estimates here are simply the sum of the results for the seven regions in Table A4.

[7] http://www.cgd.ucar.edu/cas/wigley/magicc/; the regional scaling factors are: 1.56 for Europe; 1.39 for Latin America; 1,49 for North America/OECD; 1.30 for Africa; 2.04 for North Asia; 1.33 for South Asia and; 1.45 for China.

[8] See http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome#rcpinfo.

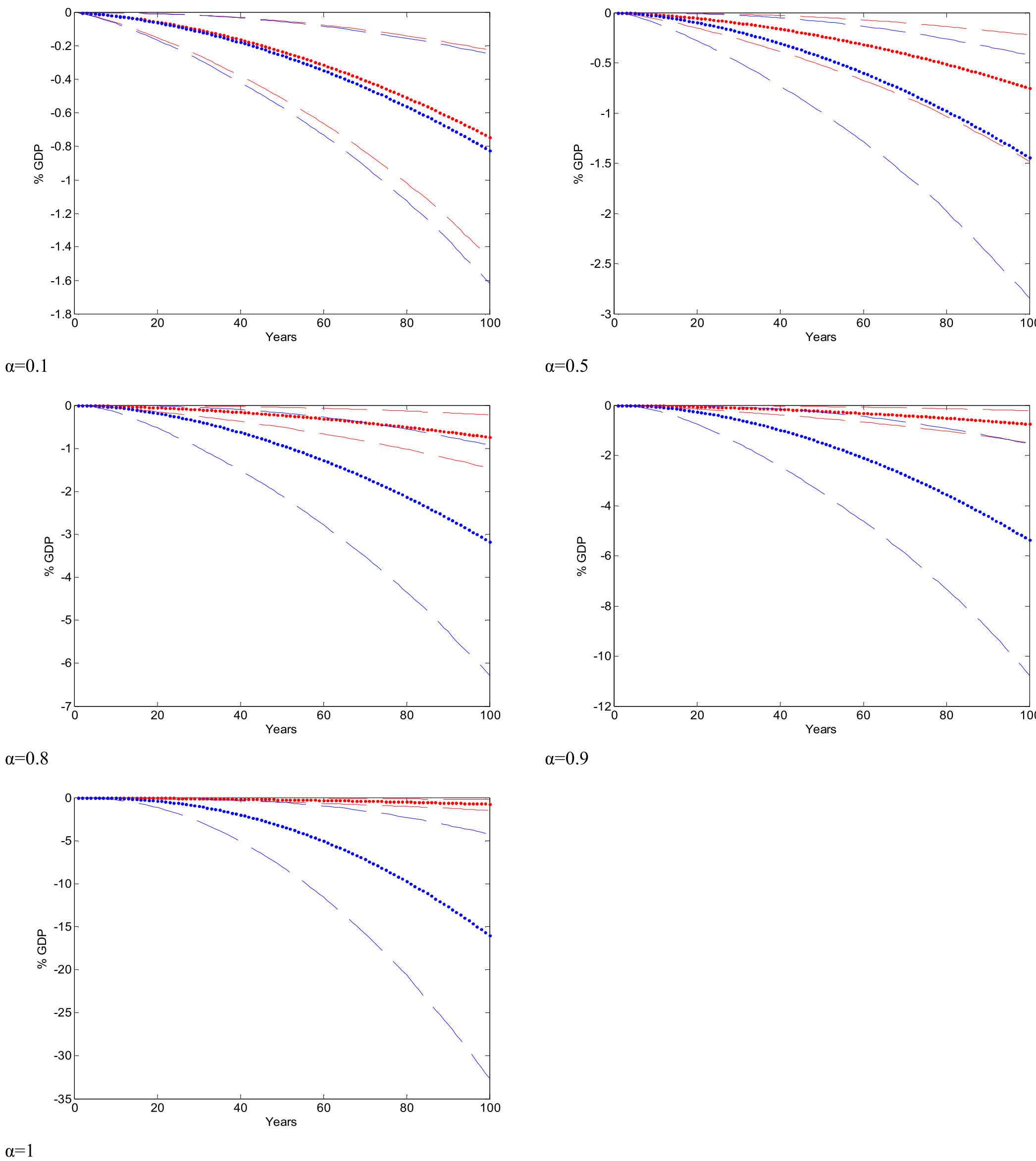

Fig. 2. Impacts as percent of GDP for different values of parameter α. Dotted lines represent the mean, while the dashed ones the 5th and 95th percentiles. Red lines were produced using $\alpha = 0$, while blue lines use positive values of α. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

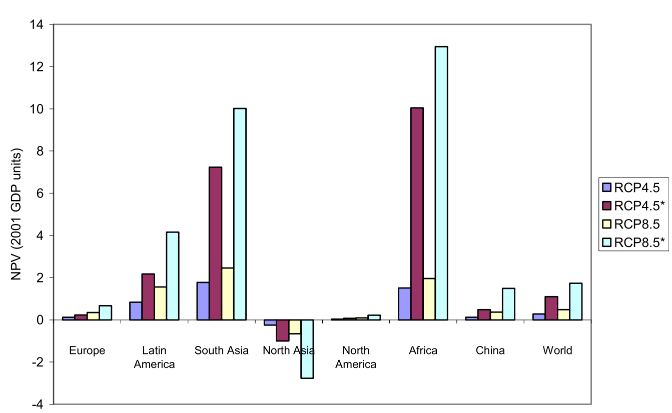

Fig. 3. Estimates of global and regional climate change impacts under the RCP4.5 and RCP8.5 emissions scenarios and for different values of α. * indicates the use of the regional persistence estimates based on Table A.2.

6. Conclusions

The lack of persistence in climate shocks in IAMs is an implicit assumption in most of these models that needs to be spelled out in order to increase the transparency of this models. The exact level of persistence and dynamics of climate change impacts is unknown, and the lack of data on impacts prevents its estimation. However, economic growth theory and models, research on the dynamics of resilience of human and natural systems as well as those of adaptation in the latter (e.g., Denton et al., 2014; Holling, 1973; IPCC, 2014) suggest that some level of persistence is expected from climate change impacts. The "zero persistence" implied by some IAMs is an extreme assumption regarding the memory properties of these systems that can be interpreted as an autonomous, extremely large and effective, costless reactive adaptation and limitless resilience capacities to no matter how large impacts climate change may produce in both human and natural systems.

Given that most of economic IAMs model climate change impacts as an aggregated direct shock to baseline GDP, the dynamics of general shocks to output are investigated and used to compare with those of three of the most commonly used IAMs. On the one hand, the high level of persistence of shocks in macroeconomic and financial time series is a stylized fact that has been studied at length in the economics and econometrics literature. On the other hand, although climate change impacts are treated in IAMs as direct shocks to GDP, the large persistence shown by this variable to general shocks has been ignored or seriously underestimated in most of the available projections. Recognizing that empirical estimates of the persistence of climate shocks cannot be obtained, we present results for a range of persistence values as well as for persistence values similar to those of general shocks to GDP.

Estimates of the economic impacts of climate change under the RCP4.5 and RCP8.5 emissions scenarios are presented for various arbitrary values of the memory parameter and for a set of regionally differentiated values based on the sum of the autoregressive coefficients estimated from the regional observed GDP series. It is shown that the estimates of the costs of climate change are very sensitive to the inclusion of a "memory parameter" and that for values of persistence ranging from moderate to high, the estimates of the present value of the costs of climate change can be dramatically different with respect to the estimates that are produced ignoring the persistence of shocks. These results are not sensitive to the discount rate that is used. Including the persistence of shocks not only can lead to presumably more realistic estimates of the cost/benefits and risks of climate change but also points out that regional differences may be larger than previously estimated.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2015.03.010.

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