A contribution to the study of the economic causes and consequences of climate change:

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

Integrated assessment models (IAMs) typically ignore the impact of climate change on economic growth. These models assume that the shocks caused by climate change impacts dissipate and have no persistence at all, affecting only the period when they occur. Persistence of shocks is a stylized fact of most macroeconomic time series and it provides a mechanism that could justify much 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 original scaling method in most IAMs can be interpreted as assuming an autonomous, costless, extremely large and effective reactive adaptation capacity.

7.1 Introduction

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 sectors such as agriculture, energy, human health, water and coastal resources, human settlements and ecosystems, sea level rise and 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., 2.5ºC; see Nordhaus and Boyer, 2000; 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

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global impacts expected for a particular increase in global annual mean surface temperatures. For the purposes of this chapter it is important to notice that: 1) in general, the damage functions are calibrated based on static comparisons between current climate conditions and a prescribed warming scenario such as doubling of atmospheric CO2 or a specific period of time in the future (e.g., the 30 years average climate conditions centered in 2050; Hitz and Smith, 2004; Parry et al., 1999) and 2) although the impacts in IAMs are a function of time, the damage functions of most IAMs provide only static comparisons between no-warming and warming scenarios, leaving out all impact dynamics. As such, the scaling method pioneered by Nordhaus (1992a,b; see also Nordhaus and Boyer, 2000) and thereafter used in most of the current IAMs implicitly assume that shocks on the economy have no persistence at all.

The level of persistence of climate shocks in the economy is unknown. However, some studies have suggested that these shocks tend to persist in time and only gradually dissipate. Tol and Fankhauser (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).[20]

The long-term impact of extreme events on economic growth has been addressed in the literature leading to opposite results. Skidmore and Toya (2002), by means of a (static)

[20] Dell et al. (2014) survey the empirical literature on the economic impact of climate change.

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 to be similar (e.g., Tol, 2011; Fankhauser and Tol, 2005).

In this chapter we undertake an empirical approach for testing the sensitivity of current IAMs to different levels of persistence of shocks. Due to the general lack of data on the observed impacts of climate change, we use both arbitrary values of persistence as well as estimates of the observed persistence of GDP to general shocks, and assume that the direct impacts of climate change can be interpreted as such shocks. Given the high level of aggregation of sectors and variety of impacts in IAMs, it can be argued that the observed persistence of GDP may provide a acceptable representation of the dynamics of the aggregated climate change impacts in the economy. Furthermore, as shown in this chapter, similar levels of persistence to that of observed GDP are implied by the economic growth model in DICE —although its effects are vanished by the chosen integration step— as well as in FUND.

The chapter is structured in six sections. In section 7.2, 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; Perron 1997; Kim and Perron, 2009). Section 7.3 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 scaling method, and to the persistence imparted by the economic growth models in DICE/RICE. In section 7.4 of this chapter, 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. Section 7.5 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 when a persistence similar to the observed one is chosen, the economic impacts of climate change are considerably larger in comparison to the "zero persistence" implied by the original scaling method that is common to most of the available IAMs and that therefore the costs presented in the literature could be seriously underestimated. Section 7.6 concludes and presents a summary of our findings.

7.2 How persistent are shocks in 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".

In this section we investigate the persistence of shocks in 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. Figure D1 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[21] (ADF; Dickey and Fuller, 1979; Said and Dickey, 1984) which consist in estimating the regression:

$$y_t = \mu + \beta t + \alpha y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta y_{t-i} + \varepsilon_t \qquad (7.1)$$

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). Table D1, 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 estimates the half-life (i.e., the time that takes for a unit shock to dissipate by 50%) ranges from 5 to 23 years.

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 D1 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, the simple scaling method, which ignores these dynamic effects, could provide a very poor estimation of the potential economic impacts of climate change, or of any other type of shock, for that matter.

However, as can be seen in Figure D1, 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 and the estimates of SAR could be biased towards unity if these structural changes are

[21] Because of the obvious trending behavior of the series plotted in Figure D1 we only consider the ADF specification that includes a constant and a linear trend.

ignored (Perron, 1989). It is therefore important to test if the results shown in Table D1 are affected by the presence of structural changes.

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 D2) 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 D2 shows that, once the occurrence of a break in the trend function is allowed, 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 D1, now ranging from 0.46 to 0.90 with a mean of 0.70, indicating that once structural breaks are accounted for, the persistence of GDP is considerably lower. To exemplify the difference in the persistence of a shock that could be expected from the estimates in Tables D1 and D2, consider the case of the GDP of the twelve largest economies in Western Europe. Without trend break, a unit shock would produce a CIR of 25.57[22]; with trend break, the accumulated response would be 1.85. Note however that both of these long-run accumulated responses are considerably larger that 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 in the scaling method 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 AR(p) models implied in Tables D1 and D2 to simple AR(1) models with the first order

[22] That is assuming that the true value of the first order autoregressive coefficient is 0.965 and not 1, although the unit root test in Table D1 indicates that this estimate is not different form the unity. If the coefficient true value is 1, the long-run response would be equal to infinity.

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.

Figure 7.1 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 the scaling method used in IAMs is not supported by the observed data. Furthermore, it is important to note that results in Figure 7.1 and the CIR values in Tables D1 and D2 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 Figure 7.1.

The next sections illustrate the relevance of including the memory of GDP series when estimating the potential impacts of climate change in a (dynamic) IAM context.

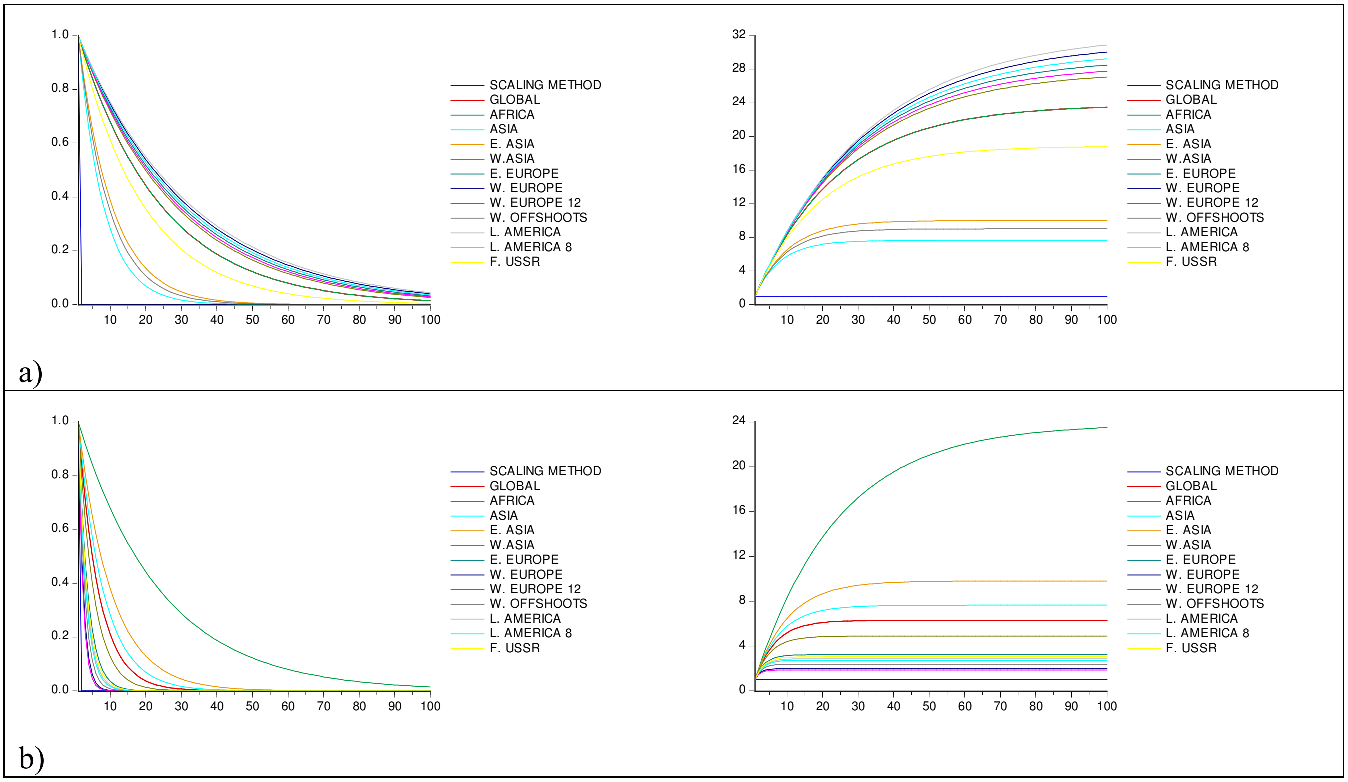

Figure 7.1. Impulse response (left) and accumulated impulse response (right) functions of AR(1) models with the SAR estimates shown in Table D1 (panel a) and in Table D2 (panel b) .

7.3 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 most commonly used to assess the economic impacts of climate change.

7.3.1 PAGE

The impact functions of PAGE2002 can be expressed as follows:

$$I_{t,d,r} = \mu_{d,r}\left(\frac{\Delta T_{t,r}}{2.5}\right)^{\beta} Y_{t,r} \qquad (7.2)$$

$$D_{t,r} = \gamma_t \pi_t Y_{t,r} \tag{7.3}$$

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; $\Delta T_{t,r}$ 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 (7.3) 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 (7.2) and (7.3).

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

7.3.2 FUND

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.

7.3.3 DICE

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

$$\Omega_t = 1/[1 + D_t] \quad (7.4)$$

$$D_t = \theta_1 T_t + \theta_2 T_t^{\,2} \quad (7.5)$$

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.

The model dynamics impart a certain level of persistence to shocks in GDP. Output Q_t is determined by a Solow growth model[23] specified with a Cobb-Douglas production function of the form:

$$Q_t = A_t K_t^{\gamma} L_t^{1-\gamma} \quad (7.6)$$

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:

$$K_t = (1-\delta) K_{t-1} + I_{t-1} = (1-\delta) K_{t-1} + \sigma Y_{t-1} \quad (7.7)$$

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. That is, population is:

[23] 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.

$$L_t = L_0 \exp\left(\int_0^t g_t^{pop}\right) \tag{7.8}$$

$$g_t^{pop} = g_0^{pop} \exp\left(-\kappa_t^{pop}\right) \tag{7.9}$$

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

$$A_t = A_0 \exp\left(\int_0^t g_t^A\right) \tag{7.10}$$

$$g_t^A = g_0^A \exp\left(-\kappa_t^A\right) \tag{7.11}$$

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 $\beta_t = (1-\gamma)\left(g_t^{pop} + g_t^A + \delta\right)$. The convergence coefficient β relates to persistence as $\beta_t = \left(1-\alpha_t^*\right)$, 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 $\alpha^* = 0.916$, quite similar to those shown in Tables 7.1 and 7.3. 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 dynamics. As such, the combination of the damage functions in DICE and the specification of the economic growth model impose a practically zero persistence of climate change impacts *within* the 10-year time step but (reasonably) an almost zero persistence *between* 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 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

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

(7.12)

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

$$\alpha = \frac{1-\Theta_t^{\gamma}}{1-\Omega_{t-1}} = \frac{1-\left[1-\delta(1-\Omega_{t-1})\right]^{\gamma}}{1-\Omega_{t-1}} \approx \delta\gamma \qquad (7.13)$$

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 7.2.

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[24]. 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, α=1 (or conversely, β=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 observed evidence shown above and with the empirical evidence reported in the econometrics literature.

7.4 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 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:

$$I_t = \vartheta_1 \left(\frac{\Delta T_t}{2.5} \right)^{\vartheta_2} Y_t + \alpha I_{t-1} \qquad (7.14)$$

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

where I represents the economic impacts at time t, ΔT is the increment in temperature with respect to its preindustrial value and ϑ_1 and ϑ_2 are parameters. The 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 1.1ºC to 2.6ºC, which is similar to the likely range of the RCP4.5 scenario for the end of this century (IPCC, 2013a). Temperature is assumed to increase linearly. All estimates presented were produced by means of simulation experiments of 5,000 realizations and the time-step was chosen to be one year.

Figure 7.2 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 (α=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 α=0.5 is close to the 95th percentile for α=0, and for values of 0.8 and 1 this estimate is much larger that the 95th percentile. Also note that the confidence intervals grow with α.

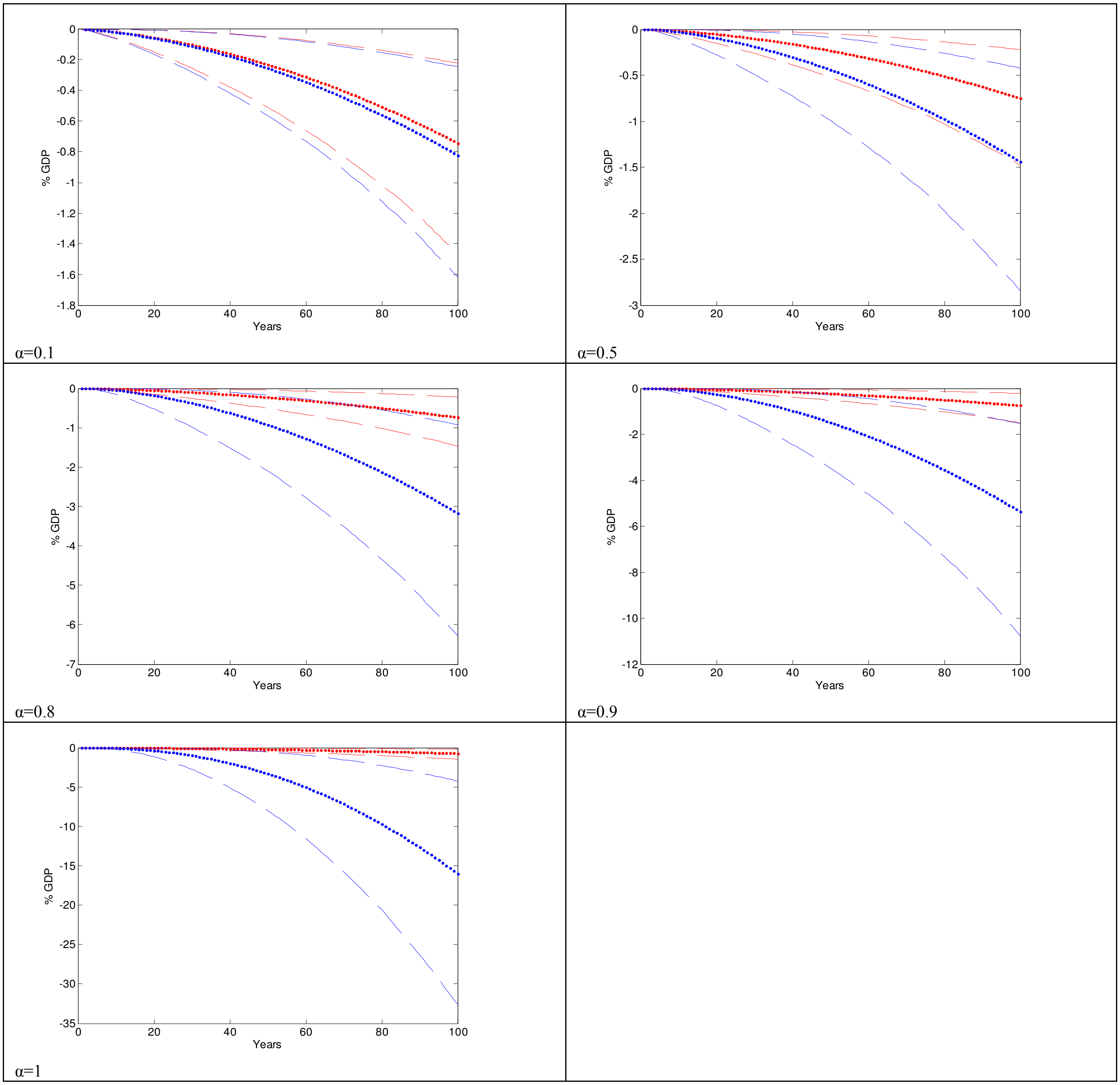

Figure 7.2. Impacts as percent of GDP for different values of parameter α. Dotted lines represent the mean, while the dashed ones the 5th and 95th percentiles. Red lines were produced using α=0, while blue lines use positive values of α.

Table 7.1 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 α=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 α=0.5, the mean value increases to 11.01% of GDP, with a range of 2.44% to 24.00% of GDP. These values are about 90% larger than the estimates that were obtained using α=0 (as in the scaling method). Losses increase very rapidly for higher values of α: for α=0.8 and α=1, the losses become about 300% and 1500% larger, respectively, compared to the α=0 estimates. An important feature of these results is that they are not sensitive to the discount rate that is chosen.

Table 7.1. Present value of the total climate change economic impacts over a century as a percentage of the GDP in year one.

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

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

7.5 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[25] 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 D3.

The increase in global temperature at the end of the century is represented by an uniform distribution covering a range from 1.1ºC to 2.6ºC and 2.6ºC to 4.8ºC in the case of the RCP4.5 and RCP8.5 respectively (WGI-IPCC, 2007). The regional weights for scaling

[25] Note that world estimates here are simply the sum of the results for the seven regions in Table D3.

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[26]. The regional GDP scenarios used for the RCP8.5 are those of the A2r which has the same underlying scenario drivers[27] (van Vuuren, 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, 2011). The discount rate is 4%.

Tables 7.2 and 7.3 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 D2. 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, these estimates become about four times larger when the impacts are allowed to show a similar persistence to that of observed GDP series. For the world and all regions with the exception of Western 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 (Figure 7.3). 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

[26] 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.
[27] See http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome#rcpinfo

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.

Table 7.2. Estimates of global and regional climate change impacts under the RCP4.5 emissions scenario and for different values of α.

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

Table 7.3. Estimates of global and regional climate change impacts under the RCP8.5 emissions scenario and for different values of α.

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

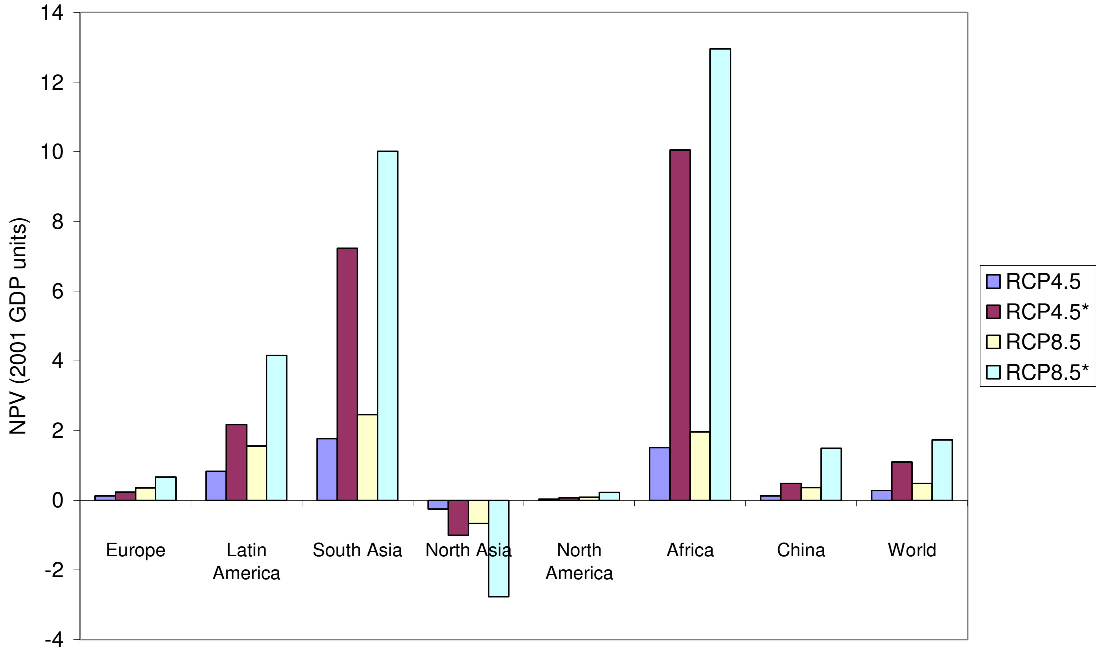

Figure 7.3. Estimates of global and regional climate change impacts under the RCP4.5 and RCP8.5 emissions scenarios and for different values of α. * indicates the use of the regional persistence estimates based on Table D2.

7.6 Conclusions

The long persistence of shocks is a stylized fact of macroeconomic and financial time series. This has been studied at length particularly for GDP series as shown by the economics and econometrics literature. Nevertheless, this relevant characteristic has been ignored or seriously underestimated in most of the IAMs that are available.

The exact level of persistence and dynamics of climate change impacts is unknown, and the lack of data on impacts prevents its estimation; instead, we assume that climate change shocks are like other shocks. Nevertheless, economic growth theory and models indicate 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 of GDP time series that is not supported by the observed data nor by economic growth theory. Furthermore, the zero persistence assumption 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.

In this chapter, the impact functions and parameterizations of the PAGE2002 are used to produce simulations experiments that allow to explore the importance of the persistence of climate change shocks in future 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 when this parameter is chosen to be similar to the observed sum of the autoregressive coefficients, estimates of the present value of the costs of climate change are about four times larger than when the persistence or shocks is ignored, as occurs when using the original scaling method. These results are not sensitive to the discount rate that is used.

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. Results are dramatically different with respect to the estimates that are produced ignoring the persistence of shocks. Including the persistence of shocks not only leads to larger and 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. This chapter presents an easy to implement approach for incorporating the persistence of shocks to IAM to estimate the potential economic costs of climate change.

Appendix D

Table D1. Results of standard ADF tests applied to the natural logs of annual GDP data and CIR values.

Region	k	$\hat{\mu}$	$\hat{\beta}$	$\hat{\alpha}$	$\tau(\hat{\alpha})$	CIR
Global	1	0.68 [1.79]	0.0014 [1.54]	0.958	-1.71	23.81
Africa	1	0.54 [1.59]	0.0014 [1.49]	0.958	-1.53	23.81
Asia	1	1.84 [2.43]	0.0069 [2.37]	0.869	-2.38	7.63
Eastern Asia	2	1.08 [1.94]	0.0038 [1.93]	0.900	-1.90	10.00
Western Asia	2	0.46 [1.67]	0.0013 [1.16]	0.964	-1.54	27.78
Eastern Europe	1	0.43 [2.06]	0.0007 [1.59]	0.966	-2.01	29.41
Western Europe	0	0.51 [2.20]	0.0003 [0.66]	0.968	-1.97	31.25
Western Europe (12)	0	0.55 [2.36]	0.0004 [0.73]	0.965	-2.14	28.57
Western Offshoots	1	1.63 [1.65]	0.0035 [1.40]	0.889	-1.61	9.01
Latin America	1	0.44 [1.54]	0.0009 [1.09]	0.969	-1.44	32.26
Latin America (8)	1	0.46 [1.54]	0.0097 [1.06]	0.967	-1.42	30.30
Former USSR	2	0.74 [2.60]	0.0008 [1.73]	0.947	-2.57	18.87

*, ** indicate statistical significance at 10% and 5% levels, respectively. The lag length k was chosen using the Schwarz Information Criterion (BIC).

Table D2. Tests for a unit root with a one-time break in the trend function and CIR values.

Series	Model	T_b	W	$\hat{\alpha}$	$t_{\alpha}\left(\hat{\lambda}_{tr}^{AO}\right)$	CIR
Global	II	1973	5.08[a]	0.841	-2.02 (1)	6.29
Africa	III	1983	2.59	0.958	--	23.81
Asia	II	1974	0.18	0.869	--	7.63
Eastern Asia	III	1994	4.11[b]	0.898	-2.42 (0)	9.80
Western Asia	II	1976	6.24[a]	0.795	-2.26 (0)	4.88
Eastern Europe	III	1990	3.33[c]	0.690	-2.53 (0)	3.23
Western Europe	II	1973	339.48[a]	0.495	-3.28 (1)	1.98
Western Europe (12)	II	1972	118.43[a]	0.460	-3.83[c] (1)	1.85
Western Offshoots	II	1972	3.27[a]	0.580	-3.08 (1)	2.38
Latin America	III	1982	7.94[a]	0.650	-4.24[a] (0)	2.86
Latin America (8)	III	1982	7.48[a]	0.632	-4.19[a] (0)	2.72
Former USSR	III	1992	4.70[b]	0.671	-2.27 (0)	3.04

Model II allows a one-time change in the slope of the trend function; Model III permits both a one-time change in the slope and in the intercept of the trend function. W is the Perron-Yabu test statistic. A 5% trimming was used for the Perron-Yabu test. $t_{\alpha}\left(\hat{\lambda}_{tr}^{AO}\right)$ is the Kim and Perron (2009) unit root test statistic. Lag length is given in parenthesis (selected via BIC). a, b, c denote statistical significance at the 1%, 5% and 10% respectively.

Table D3. Concordance of regions.

PAGE2002	Regions in this study
Europe	Europe
Eastern Europe and Former Soviet Union	North Asia
USA	North America/OECD
China	China
India	South Asia
Africa	Africa
Latin America	Latin America
Other OECD	North America/OECD

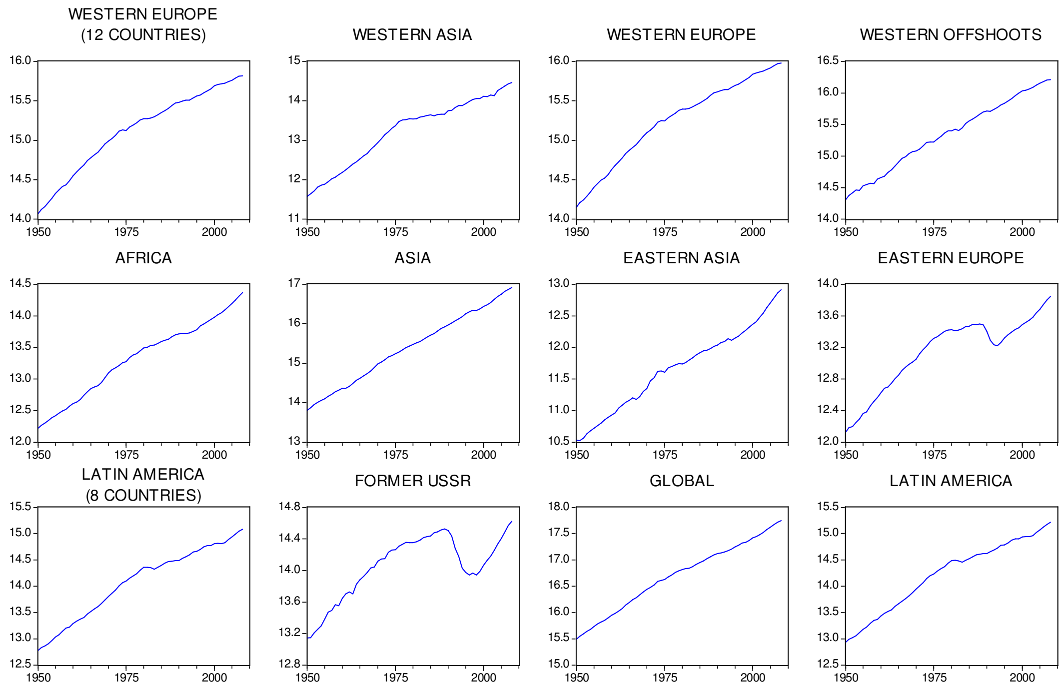

Figure D1. Natural logs of annual GDP data for the selected regions