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Global Change, Catastrophic Risks and Sustained Economic Growth: Model-based Analysis

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Abstract

This paper analyzes the effects of catastrophes on two types of regions referred to as developed and developing. Economic development of regions is measured in terms of gross domestic product (GDP) per capita and incomes are considered to be the main factor driving demand for ex-ante catastrophe management arrangements. We show that the same magnitude shocks affect regions differently. While a developed country has sufficient resources to cope with catastrophes, the developing may stagnate or even collapse without appropriate catastrophe mitigation measures or external aid that is needed only until sustained growth takes off**.** The analysis relies on a stochastic multi-regional growth model that embeds mechanisms enabling the design of robust strategies ensuring sustained performance of regions under catastrophes at any time that they may occur. Resilience of regions is estimated with respect to the abundance of internal and external resources, e.g., capital labor and catastrophe fund, to adequately confront the shock and to maintain regional growth on a "satisfactory" level.

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About the Authors

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Global Change, Catastrophic Risks and Sustained Economic Growth: Model-based Analysis

Tatiana Ermolieva and Michael Obersteiner

1 Introduction

Global change induced by anthropogenic activities, rapid technological innovations, and creation of densely populated locations with a high concentration of industries and infrastructure increases the vulnerability of modern societies making them more exposed to manmade and natural disasters. "*In the old days, the tools of farming, manufacture, business management, and communication were simple. Breakdowns were frequent, but repairs could be made without calling the plumber, the electrician, the computer scientist — or the accountants and the investment advisers. Today, the tools we use are complex, and breakdowns can be catastrophic, with far reaching consequences. We must be constantly aware of the likelihood of malfunctions and errors*" (Bernstein, 1996).

Impacts of catastrophes cannot be properly evaluated on aggregate levels. For example, aggregate worldwide economic impacts of global change may even be considered as beneficial, whereas some regions and even countries may be wiped out. Disaster occurrences do not discriminate between regions. The forest fires which lasted for several weeks in California in the United States in the last few years and the floods in several parts of Europe remind us of the increasing vulnerability of not only developed but also developing countries. Nevertheless, developing countries are much more severely affected, especially in terms of the loss of lives and the percentage of economic losses in relation to their gross national product (GNP).

Various United Nations studies have shown that 90 percent of disaster victims live in developing countries. The World Bank has stated that losses caused by disasters in developing countries, in terms of percentages of GNP, are 20 times higher than those in developed countries. While the developed world has the financial and technological means to cope with catastrophes, for many developing countries the same magnitude catastrophes cause major shocks and disruptions. In addition, poverty and other factors create conditions for low mitigative and adaptive capacity in most developing countries. Falling disproportionally upon developing countries and the poor persons within all countries, the impacts of global change thereby exacerbate inequalities in welfare, meaning increased poverty, health problems, decreased water quality and supply (Fischer *et al*., 2002).

Coping with catastrophes is a complex problem requiring integrated approaches starting with the analysis of potential region-specific losses, vulnerabilities, internal and external mitigation and adaptation capacities, i.e., productivity, governmental budgets, regional "credibility", income distribution, availability and access to insurance markets, etc. Therefore, modeling of regional, temporal and social heterogeneities involving multiple stakeholders, their goals, constraints and risk indicators becomes a key concern. Evaluation of appropriate ex-ante mitigation and ex-post adaptation measures has to account for complex synergy between these two sets of measures: preventive mitigation measures applied today may essentially reduce costs for coping with a catastrophe if it happens tomorrow.

The way catastrophes are managed induces strong economic path-dependencies. As mentioned by Froot (1997), most losses from disasters, especially in developing regions, are dealt with ex-post by some combination of insurers and re-insurers (and their investors), insured, state and federal agencies and taxpayers *"…with only some of these payments being explicitly arranged ex-ante. This introduces considerable uncertainty about burden sharing into the system, with no particular presumption that the outcome will be fair"*. Recently the Secretary General of the United Nations, Mr. Kofi Annan, noted that "*…we must, …shift from a culture of reaction to a culture of prevention. The humanitarian community does a remarkable job in responding to disasters. But the most important task in the medium and long term is to strengthen and broaden programmes which reduce the number and cost of disasters in the first place. …Prevention is not only more humane than cure; it is also much cheaper"*. This is a principle, which should be acted upon with an increasing sense of urgency.

This paper analyzes the effects of potential catastrophes on two types of regions referred to as developed and developing. It illustrates that ex-ante preventive strategies can be of benefit for both of them. Economic development of regions is measured in terms of GDP per capita and incomes are considered to be the main factor driving demand for ex-ante insurance arrangements. We show that the same magnitude shocks affect regions differently. While a developed country has sufficient resources to cope with catastrophes, the developing may stagnate or even collapse without appropriate catastrophe mitigation measures or external aid that is needed only until the sustained growth takes off (see Ermoliev *et al.*, 2001).

The applied model combines features of IIASA's integrated catastrophic risks management model (Ermoliev *et al.*, 2000) and the stochastic economic-demographic model (MacKellar and Ermolieva, 1999; Westlund *et al.*, 2000). In particular, it allows tracking incomes, consumption, and savings of households by single-year age groups, as well as intergenerational and interregional transfers of resources. Other "actors" in the model are firms, governments and financial intermediaries, including pension systems, banks, insurance, and mutual catastrophe funds. Complex dependencies underlying the model allow for comprehensive analysis of feedbacks between growth, incomes, savings and shocks.

The model embeds mechanisms enabling the design of robust strategies ensuring sustained performance of regions under multiple shocks at any time they occur. It estimates the resilience of regions depending, e.g., on the availability of internal or external (foreign aid) resources, e.g., capital and labor, to adequately confront the shock and to maintain regional productivity on a "satisfactory" level.

The model can specify features (e.g., Ginsburg and Keyzer, 1997) to study more profound effects of catastrophes on global economic growth, i.e., when catastrophes can "move" the markets (see, for example, Manne and Richels, 1992; Nordhaus, 1993).

In this paper ex-ante precautionary measures are represented by a mandatory catastrophe fund which can be easily interpreted as catastrophic insurance. Savings within the fund increase the overall rate of regional savings. A rather general operational framework to the allocations of ex-ante and ex-post measures with an illustration of catastrophic risk management in a particular region is discussed in Ermolieva *et al*. (2003). The ex-ante mechanisms and their efficiency are yet subject to regional constraints. In a society with low incomes it is likely that it cannot be much saved. In this situation it is also unlikely that the government or policy maker can do much to raise precautionary savings (and, thus, investments) or implement insurance schemes (catastrophe fund, contingent credits, etc.). In this case, probable losses, feasible insurance premiums and incomes determine the specific demand and the market of ex-ante measures/insurance. Thus, regional management of catastrophes must consider the following questions. Up to what extent catastrophes can be managed ex-ante and whether these actions are profitable? Up to what extent the management of catastrophes must rely on ex-post risk management measures, such as external borrowing or aid, since these are subject to multiple constraints, e.g., ability of a region to obtain credits, loans, and ability to pay them back? The answer and, thus, the demand in ex-ante measures depends on many factors, namely the exposure of a region to catastrophes, sustainability of the region, governmental budgets, capacities to absorb the losses nation-wide, access to international insurance markets, social and political regimes, historical traditions, etc. (for more discussion, see Froot, 1997; Gilber and Gouy, 1998).

In section 2 we present a stylized economic growth model that illustrates the importance of ex-ante precautionary mechanisms to aid sustainable growth in coping with catastrophes. Section 3 contains a summary description of the two-region economic-demographic growth model. Section 4 describes the shocks applied to the regions. Section 5 illustrates the impacts of these shocks on selected numerical experiments. Finally, section 6 presents some concluding remarks.

2 Sustained Economic Growth and Ex-ante Measures

Traditionally, the major losses from catastrophes, especially in developing regions, are borne by central governments and households (Froot, 1997). This often "unexpectedly" diverts resources from other planned projects and requires "unplanned" borrowing, which introduces considerable uncertainty about burden sharing into the system. This, in general, reduces the ability of a region to repay credits, loans and, thus, to obtain new resources. Ex-ante precautionary savings and loss mitigation measures may significantly improve catastrophe management by reducing "unexpected" costs of post-shock responses.

To better understand the effects of catastrophes on economic growth and the role of ex-ante measures, specifically, mandatory fund/savings, let us consider a stylized model of a "well-behaving" economy described by a two factor, "capital" and "labor", production function $Y = F(K, L)$ with constant returns to scale, $Y = LF(K/L, 1)$, where Y is its output. The economy may be characterized in terms of capital to labor ratio, $k = K/L$, and output to labor ratio, $y = Y/L$, $y = f(k) := F(k, 1)$. For illustrative purposes, output Y is subdivided only into consumption and savings, and savings are equal to investments I. The growth is driven by the accumulation of capital through investments:

$$\frac{dK}{dt} = I - \delta K\,,\ K(0) = K_0\,,\ t > 0\,, \tag{1}$$

where δ, $0 < \delta < 1$, is the capital depreciation rate. Assume further that the investments $I(t)$ are simply a fraction s, $0 < s < 1$, of the output, i.e., $I(t) = sY(t)$, and γ is an exponential growth rate of the population, $\frac{d}{dt}\ln L = \gamma$. We can then rewrite equation (1) in variables k:

$$\frac{dk}{dt} = sf(k) - (\gamma + \delta)k\,,\ k(0) = k_0\,, t > 0\,, \tag{2}$$

or

$$\frac{d}{dt}\ln k = s\frac{f(k)}{k} - \gamma - \delta\,. \tag{3}$$

Assuming constant output to capital ratio, θ, i.e., $y/k = f(k)/k = \theta$, we derive the very influential Harrod-Domar model (Ray, 1998; Sargent, 1987; Solow, 1997) with a constant exponential rate of growth

$$\frac{d}{dt}\ln k = s\theta - \gamma - \delta\,, \tag{4}$$

where the growth of real output $\frac{d}{dt}\ln y(t)$ is the same as the growth of capital stock $\frac{d}{dt}\ln k(t)$. For this reason, the exponential growth of the output is defined by the linear function:

$$\ln y = \ln y_0 + (s\theta - \gamma - \delta)t\,,\ y(0) = y_0\,, t > 0. \tag{5}$$

The deterministic Harrod-Domar model, equation (4), often serves as a building block in regional economic growth control and forecasting models (see Ray, 1998). Two variables are determining the overall rate of growth in the interval: the ability of the economy to save and the productivity of the capital θ. By increasing the rate of savings s or capital productivity θ, it is possible to accelerate the rate of growth.

A catastrophe is a shock to the economy causing depletion of capital and reduction of the growth rate $s\theta - (n + \delta)$ by a random variable $v = v(t, y, \omega)$, where $v(t,y,\omega)$ denotes the impacts of the shock ω at the current $y(t)$. Shocks occur at random time moments T_0, T_1, T_2, …, $T_0 = 0$, $v(0,y,\omega) = 0$. The random intensity v in our model depends on the aggregate level $y(t)$. In realistic versions of the model $v(t,y,\omega)$ is determined by geographical distribution of wealth and shocks as well as other country-specific sources of vulnerability. The accumulation of property values in risk prone areas and sectors of the economy can make significant difference to the probability distributions and the severity of v. Shocks, in general, transform the linear function in equation (5) into a highly nonlinear and discontinuous random function:

$$\ln y(t) = \ln y_0 + (s\theta - \gamma - \delta)t - V(t),\ V(t) = \sum_{t=1}^{N(t)} v_i, \tag{6}$$

where $N(t)$ is a random number of shocks in the interval $[0,t]$, and v_i is the magnitude of the shocks.

Thus, for a given t a positive probability may exist that accumulated random losses exceed accumulated growth

$$(s\theta - \gamma - \delta)t - V(t) \le 0. \tag{7}$$

Equation (7) formalizes the problem of economic growth under catastrophes: values of parameters s, θ, γ, δ have to be appropriately adjusted in order to protect the growth rate. A "gap" between available resources determined by the per capita income and the investment required to achieve the output growth target, e.g., due to "unforeseen" shock, provides the information for the ex-post measures, e.g., borrowing, needed to cover this "gap".

To determine such s, θ, γ, δ that the inequality $(s\theta - \gamma - \delta)t - V(t) > 0$ holds with a given safety level (probability) in each time period t is a challenging task that cannot be achieved analytically or by simple "if–then" analysis, since each of the parameters s, θ, γ, δ is dependent on many other factors, e.g., the distribution of incomes among the population and investments among various sectors of the economy and geographical regions. Also, ex-ante saving decisions may significantly effect levels of shocks v_i, $t = 1 : N(t)$ (e.g., allocated into mitigation), by increasing "structural" resilience of the region and, thus, reduce the demand in ex-post measures. It is important that the ex-ante and the ex-post measures are evaluated not in a one-by-one manner, but considering their synergies.

Besides this, a critical issue arises with the naïve adaptive sequential (intertemporal) adjustments of growth rates. It is evident that the occurrence of a shock in a small interval of length Δt is evaluated by a negligibly small probability $\lambda\Delta t$, but the probability $1 - (1 - \lambda\Delta t)^{T/\Delta t} \approx 1 - e^{\lambda T}$ of a shock in the interval $[0,T]$ is dramatically increasing with T. Therefore, the analysis of the growth rate at time t only for the next interval Δt may not provide a good idea to develop preparedness and loss reduction measures for rare future events. The decisions to control the growth must account for long time horizons and the singularity of the extreme events in order to be prepared for "uncertain" shocks.

The next section outlines a stochastic economic-demographic model that allows analyzing complex feedbacks between economic growth, incomes, savings and shocks and, thus, is able to provide insights into the regional demands in ex-ante mitigation and ex-post adaptation measures.

3 Stochastic Growth Model

Savings enhance economic growth and incomes. Catastrophes deplete capital and, thus, may decrease growth and reduce incomes. Creation of a precautionary catastrophe fund may protect economic growth and incomes, but efficiency of this measure dramatically depends on the timing of random catastrophes. For example, a high consequences 1000 year flood may occur in 5 years or in 300 years. Thus, a catastrophe fund may be beneficial for the current generation only in the first case, and it creates an intergenerational (contingent) transfer in the second case. The need for such an intergenerational "contract" depends also on the extent that the sustained economic growth takes-off at the moment of low probability — high consequence catastrophe (say, related to a global climate change). In this section we briefly outline a model that aims to analyze these complex interdependencies.

The model consists of two major sub-models, namely a catastrophe model and a stochastic dynamic economic-demographic multi-regional model. It combines features of IIASA's integrated catastrophic risks management model (Ermoliev *et al.*, 2000) and the stochastic economic-demographic model (MacKellar and Ermolieva, 1999; Westlund *et al.*, 2000). In particular, it allows tracking incomes, consumption, and savings of households by single-year age groups, as well as intergenerational and interregional transfers of resources. Other "actors" in the model are firms, governments and financial intermediaries, including pension systems, banks, insurance, and mutual catastrophe funds.

The model incorporates moderate disturbances and severe "catastrophic" shocks to regional economies (discussed in section 4). Underlying complex dependencies allow for comprehensive analysis of feedbacks between growth, incomes, savings and shocks.

Production processes are characterized by a Cobb-Douglas production function. It represents, in general, a well behaving economy with perfect convergence properties. Even in the case of such an economy, it may be shown that under persistent shocks and insufficient resources the economy can stagnate and even collapse (Ermoliev *et al.*, 2001; Ray, 1998). In other words, shocks implicitly modify even the "well-behaving" Cobb-Douglas function into a function, which may generate locked-in states without additional growth mitigation efforts. Other forms of production functions, than Cobb-Douglas, can be used as well. Rates of return and wages are endogenous. The capital coefficient in the two-factor Cobb-Douglas production function is set to 0.333 (meaning that the labor coefficient is 0.667) and the total factor productivity growth and depreciation rates are 1 and 5 percent per year, for developed and developing regions, respectively. A special procedure creates age-specific wage-rate profiles. The sources of household income are wages, rents from residential capital, dividends distributed from earnings on capital operated by firms, public social security system benefits, and private pension benefits. All taxation is assumed to occur at the income level.

Capital is either residential or non-residential. The latter is further subdivided into capital operated by private unincorporated enterprises and capital operated by firms, i.e., corporate enterprises. Residential capital is installed entirely in the home region and is held by households directly. Capital operated by corporate enterprises is installed either at home or abroad.

Financial claims on this capital are held on behalf of households by institutions that collect and distribute dividends. These institutions comprise the private pensions system and other financial institutions such as banks and mutual funds. Foreign investment can consist either of portfolio claims or foreign direct investment.

Persons above the age of eligibility for social security benefits are entitled to public pension system benefits calculated on the basis of their years of employment, the number of years they have been retired, the degree of indexation of pension benefits to real wages, and the evolution of wages since their retirement. Private pension system benefits represent the sale of financial assets. The assumption is made that, when wealth is inherited, it is converted to cash, some of which is allocated to consumption and the remainder is allocated among residential or non-residential forms of capital. Consumption comes out of income, out of the proceeds of asset sales, sales of inherited assets and retirement dissaving. Household net saving is the difference between real income and consumption.

Firms operate capital installed at home and abroad; they earn profits and pay out direct taxes and dividends. In the case of portfolio investment abroad, profits are credited to firms in the foreign region; in the case of foreign direct investments, earnings are credited to firms in the home region.

The government consumes a share of GDP, makes interest payments on public-sector debt, collects taxes and social security contributions and pays social security benefits.

For the purposes of these studies the model incorporates regional mandatory catastrophe funds that function similar to catastrophe insurance. Contracts are purchased by households who pay premiums into the fund until the occurrence of a catastrophe. If a catastrophe occurs, damages are covered according to the contracts. Premium rates are collected on an annual basis and are set equal to a percentage (say, 1 percent) of gross annual wage income. In an ideal case, which is beyond the scope of this paper, the premiums should account for regional risk exposure and property values (capital) at risks (Ermoliev *et al*., 2001; Ermolieva *et al*., 2003).

This short summary of the Monte Carlo simulation model illustrates its complexity and rich variety of dynamic interactions between different agents. The model simulates in time random trajectories of different variables, in particular, paths of age-specific per capita GDP, wages, dividends, and consumption. The model allows for designing robust mitigation and adaptation strategies ensuring sustained performance of regions under multiple shocks at any time that they may occur.

4 Generation of Uncertainties: Catastrophe Model

Representation of uncertainties and catastrophic risks in integrated models plays a crucial role in the design of appropriate mitigation and adaptation strategies. In this conceptual model we incorporate moderate temporal irregularities typical for economic growth paths (see, for example, Enders, 1995) and we pay special attention to modeling catastrophic shocks (see Baranov *et al*., 2002; Christensen *et al*., 2002; Walker, 1997).

Climate change catastrophes have spatial patterns and complex non-stationary laws of region-specific temporal occurrences. They bring direct spatial losses and induce location specific response measures. Apart from direct losses, catastrophes cause even higher indirect losses that arise, for example, from business interruptions, damages to transportation and communication networks, etc. The two types of losses are modeled through shocks to the capital and production function: capital depletion corresponds to direct losses and decreased production level corresponds to indirect effects, e.g., due to business interruption.

The following subsections present the model of stochastic baseline together with the model of catastrophes implied in these studies.

4.1 Modeling the Stochastic Baseline

Most economic variables exhibit moderate temporal irregularities (we distinguish them from catastrophic shocks). These disturbances may have periods of higher and lower volatilities, repetitive yearly, decade, millenniums cyclical trend patterns, etc. Regular stochastic components (random events of catastrophic nature are discussed later), while not having well-defined patterns, are still somewhat predictable (Enders, 1995). They are typically represented by econometric models. We imply ARCH-M processes (Westlund *et al*., 2000) to selected parameters, e.g., production function constant term, $A(t)$, to model the mean value of the variable as dependent on its own conditional variance. Specifically, the process is represented by $A(t) = \mu(t) + \varepsilon(t)$, where $\mu(t) = A^* + \delta\, h(t)$, $\delta > 0$, $h(t) = \alpha_0 + \sum_{i=1}^{q} \alpha_i \varepsilon^2(t-i)$ and $\varepsilon(t) \sim N(0, 0.05\beta^*)$. For illustrative purposes $q = 1$, that is the conditional forecast of the variable $A(t)$ is based only on one time period lagged error term. In empirical analysis, the parameters δ , α_0 , and α_i must be econometrically estimated. However, these values may be initialized as $\delta = 1$, $\alpha_0 = 0$, $\alpha_1 = 1$ (see, for example, Enders, 1995), which ensures a reasonable baseline for stochastic dynamics of GDP (and other economic variables) trajectories coherent, e.g., with GDP growth rates from historical data series (see, for example, http://www.nuff.ox.ac.uk/Economics/Growth).

4.2 Catastrophe Generator

In these studies severe shocks to economies are introduced through region-specific "catastrophic" depletion of capital stocks and decrease in GDP levels. Shocks to capital correspond to direct capital losses and decreased production to indirect effects, e.g., due to business interruption.

Occurrences of catastrophic shocks are generated using similar to Gutenberg-Richter dependencies (traditional for modeling earthquakes) connecting the timing of a catastrophe with its magnitude. For example, if n is a number of events of magnitude M, then the law in a simplified form reads as $\log(n) = -Mb$ or $n = 10^{-Mb}$, where value b varies from area to area, but worldwide it is assumed to be $b = 1$ (Christensen *et al.*, 2002). According to recent analysis of market fluctuations and crashes data (Gabaix *et al.*, 2003), power laws similar to Gutenberg-Richter reasonably represent also social and political disasters.

For realistic modeling of catastrophic losses this type of dependencies can be fine-tuned using historical data accounting for severity and potential dependencies of the losses. Such representation of catastrophes may be further modified to include in a more explicit way the "memory" of the events and their endogeneity with respect to implemented policy options.

5 Numerical Experiments

The ability of a region to sustain catastrophes is, to a major extent, determined by the ability of this region to accumulate savings. Can the savings rate be easily manipulated or adjusted to create an adequate protection before or when a catastrophe happens? It depends, in particular, on how much control a policy maker has over the economy. The rate of savings is influenced by other variables, for instance, the overall level of per capita income in the society, not to mention the distribution of incomes among the population. In a society with low incomes sufficient only for subsistent life, it is not likely that much will be saved. It is likely that it will be borrowed to make ends meet. In this situation it is unlikely that the government or policy maker can do much to raise the precautionary savings rate or introduce "full-scale" insurance homogeneous with respect to all fractions of the heterogeneous population.

In the following numerical experiments we illustrate that ex-ante mechanisms may increase regional sustainability against catastrophes — they enhance economic growth by additional savings and investments. These savings/investments may be directly utilized in mitigation measures increasing structural resilience and sustainability of the economy towards catastrophe. Another possibility, considered in the numerical experiments, are regional mandatory catastrophe funds that, in the case of catastrophes, are immediately consumed to rehabilitate damaged economies. Premium rates to these funds are collected on an annual basis and equal to a percentage (say, 1 percent) of gross annual wage income. In an ideal case, which is beyond the scope of this paper, the premiums should account for regional risk exposure and property values (capital) under risks (Ermoliev *et al.*, 2001; Ermolieva *et al.*, 2003).

The experiments will also show that the ex-ante mandatory precautionary savings (insurance) can be introduced only to the extent determined by per capita incomes in such a way that they do not undermine consumption constraints of households (e.g., they should not decrease consumption below, e.g., the subsistence level). Clearly, if saving/premium rates are too high, the consumption will rely on borrowing, which decreases the overall cumulative savings.

In this conceptual model and the numerical experiments we measure the efficiency of ex-ante measures (precautionary savings) in terms of GDP per capita. The model is simulated in a Monte Carlo fashion. Modeling time horizon equals 40 years. In each simulation run and each year "regular" and catastrophic shocks to capital stocks and GDP are administered according to the descriptions in section 4. The results are presented by selected tables and percentile graphs.

5.1 Macroeconomic Aggregates and Stochastic Baseline

The model is calibrated for two regions — developed and developing. In the developed region, the average baseline GDP per capita is initialized at USD 36563 per annum and in the developing region at USD 2103. Forty years of simulation time horizon correspond to the period from 2000 to 2040. Capital to output ratio of the developed region in the baseline is on average equal to 2.6 and for the developing region to 1.7. The dynamics of baseline stochastic macro-aggregates is presented in Tables 1 and 2. Figures 1 and 2 present distributions (histograms) of GDP per capita in the terminal year and the discounted terminal year GDP per capita (with a discount rate of 1.5 percent), respectively. These histograms indicate that baseline distributions of these and other variables are approximately normal. The shapes of the distributions are compact and appear normal, without any indication that the system experiences severe shocks.

5.1.1 Stochastic baseline: developed region

Numerical experiments start with the baseline simulations. Regular disturbances are administered to the production function as described in section 4.1. Table 1 summarizes baseline macro-aggregates. Thus, in the initial year regional GDP per capita is on average equal to USD 36567. Over 40 years of the modeling time horizon, average GDP per capita increases to USD 67232. The uncertainty bounds of the regional indicators are presented by the 5-th and the 95-th percentiles: initial year difference between the 5-th and the 95-th GDP per capita percentiles is 6 percent. Selected jagged trajectories (due to the applied disturbances) of GDP per capita and the dynamics of GDP per capita percentiles are shown in Figures 3 and 4.

5.1.2 Stochastic baseline: developing region

Similar to the developed region, regular disturbances are applied to the developing region. They do not cause severe problems to the production level. Figures 5 and 6 indicate rather narrow uncertainty bounds. The initial year difference between the 5-th and the 95-th GDP per capita percentiles is about 6 percent. The average GDP per capita in the initial year equals USD 2103 and it increases to 4141 in the terminal year. Similar to Figures 1 and 2, Figures 7 and 8 are well shaped without any indication of catastrophic disturbances.

Table 1: Macro-aggregates, selected percentile trajectories.

GDP per capita	**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
5%	35447	38151	41197	44688	47995	51704	55713	60598	64829
50%	36567	39196	42452	46165	49847	53427	57971	62427	67190
95%	37668	40688	43995	47568	51112	55163	59863	64434	69645
Mean	36563	39330	42547	46227	49738	53443	57913	62376	67232
Capital-output ratio									
5%	2.5	2.5	2.6	2.8	3.0	3.1	3.2	3.3	3.4
50%	2.6	2.6	2.7	2.9	3.1	3.2	3.3	3.4	3.5
95%	2.7	2.7	2.8	3.0	3.2	3.3	3.4	3.5	3.6
Mean	2.6	2.6	2.7	2.9	3.1	3.2	3.3	3.4	3.5
Rate of return to capital									
5%	12.4	12.2	11.6	11.0	10.4	10.0	9.7	9.4	9.2
50%	12.8	12.5	12.0	11.4	10.8	10.3	10.0	9.8	9.5
95%	13.2	13.0	12.5	11.8	11.1	10.6	10.4	10.1	9.8
Mean	12.8	12.6	12.1	11.4	10.8	10.3	10.0	9.8	9.5

Table 2: Macro-aggregates, selected percentile trajectories.

GDP per capita	**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
5%	2032	2162	2372	2638	2908	3176	3465	3728	4028
50%	2101	2242	2441	2721	2984	3297	3573	3861	4141
95%	2174	2310	2522	2813	3086	3391	3697	3987	4272
Mean	2103	2240	2444	2721	3984	3286	3572	3859	4141
Capital-output ratio									
5%	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.9	1.8
50%	1.7	1.8	1.8	1.8	1.8	1.8	1.9	1.9	1.9
95%	1.7	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0
Mean	1.7	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.9
Rate of return to capital									
5%	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2
50%	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
95%	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Mean	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8

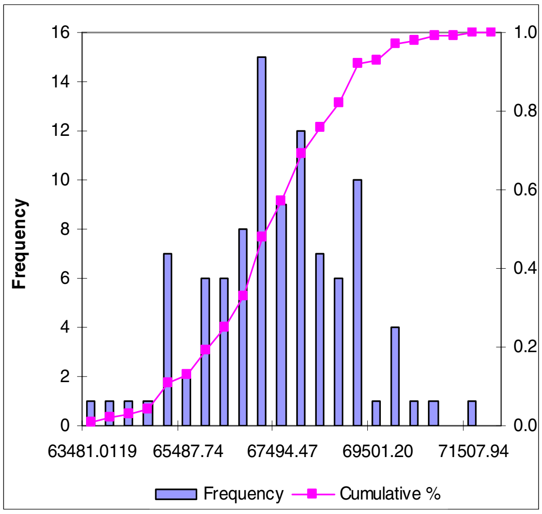

Figure 1: GDP per capita (USD), terminal year.

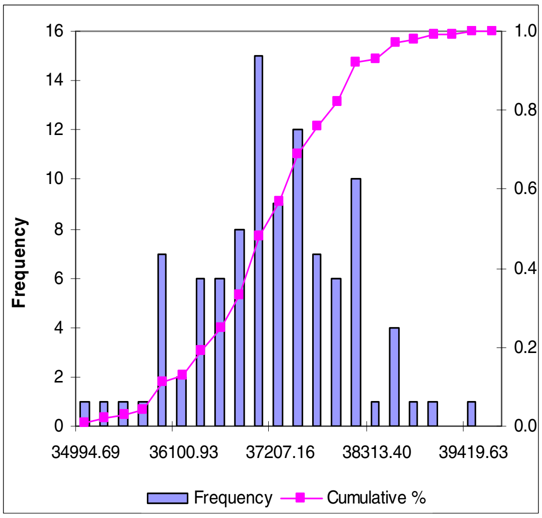

Figure 2: GDP per capita, discounted.

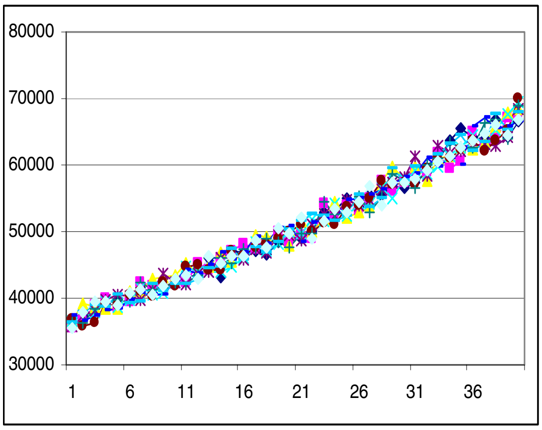

Figure 3: GDP per capita (USD), selected trajectories.

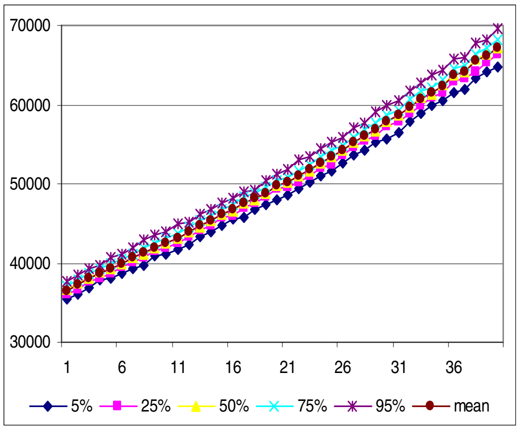

Figure 4: GDP per capita, selected percentiles.

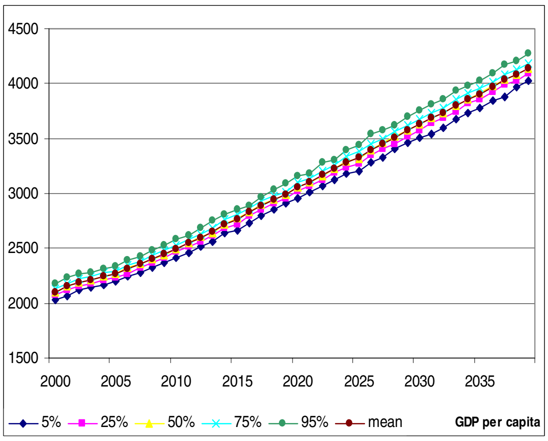

Figure 5: GDP per capita (USD), selected percentiles.

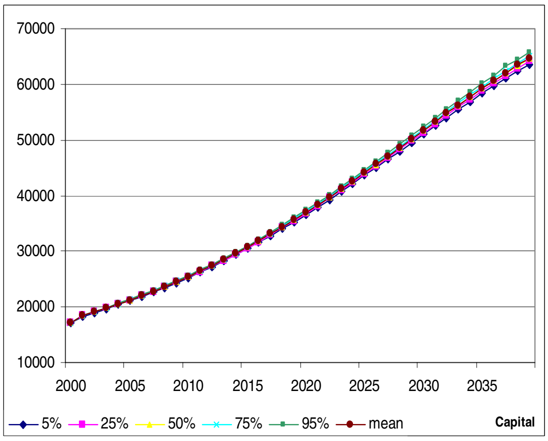

Figure 6: Capital, selected percentiles.

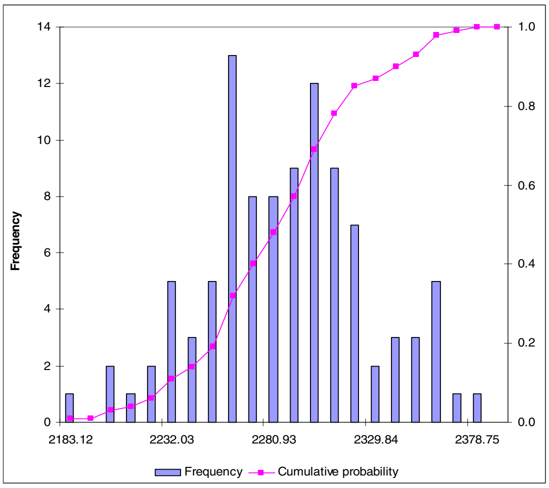

Figure 7: GDP per capita (USD), discounted.

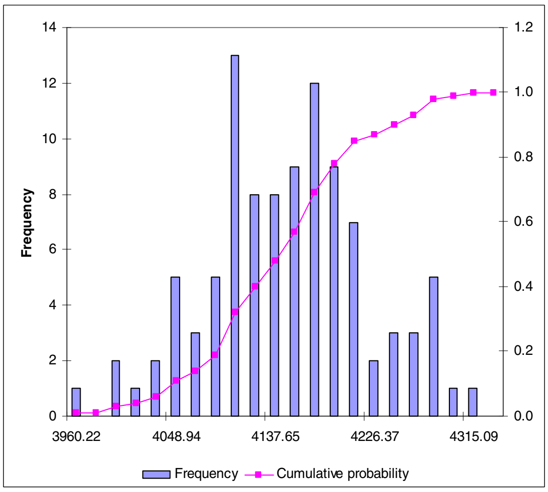

Figure 8: GDP per capita, terminal year.

5.2 Developed Region, Shocks to Capital and Production Function

To illustrate direct and indirect impacts of catastrophes to economies of developed and developing regions, we apply shocks to capital stocks and production functions of these regions.

5.2.1 Shocks to capital stock, no precautionary savings

In this set of experiments shocks are applied to capital stocks of the developed region. Random magnitudes and random time occurrences of the shocks are generated by the models discussed in section 4.2. Histograms of the discounted and of the terminal year GDP per capita, Figures 9 and 10, change shapes (in comparison to the baseline, Figures 1 and 2): distributions are skewed to the left indicating presence of catastrophes. The terminal year average GDP per capita, Tables 1 and 3, decreases in comparison to the baseline by 4.5 percent, from USD 67232 to 64281, which can be regarded as an insignificant change. Selected jagged trajectories and ranges of uncertainties of the GDP per capita percentiles are shown in Figures 11 and 12.

Although catastrophes deplete capital stocks and affect production, growth of the region is sustained due to the internal resilience and sufficient capital and labor resources. In these experiments the average GDP per capita and GDP per capita growth rate do not show drastic deviations from the baseline. Table 3 summarizes the main macroeconomic percentiles.

5.2.2 Shocks to production function, no precautionary savings

The set of experiments illustrates the effects of indirect shocks to the developed region modeled as disturbances to the production function. The shocks to production, similar to capital shocks, are administered at random times and have random magnitudes.

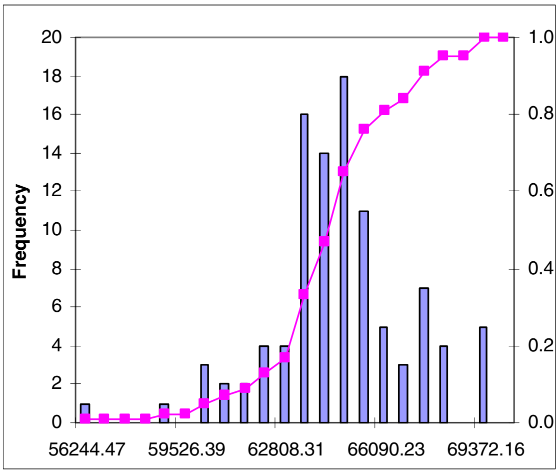

Figure 9: GDP per capita, terminal year.

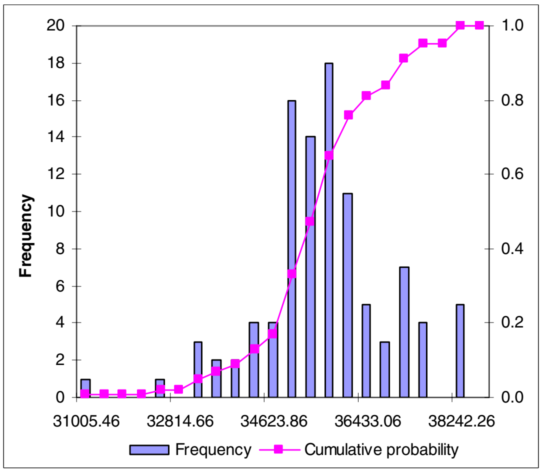

Figure 10: GDP per capita, discounted.

Table 3: Macro-aggregates, selected percentile trajectories.

GDP per capita		**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	5%	32557	34339	37262	40952	44338	47916	52385	56606	60219
	50%	36420	38782	41165	43088	46389	50902	54974	59956	64217
	95%	37745	40344	43492	46911	49785	54436	58583	63227	68087
	Mean	36169	38052	40468	43741	46869	50904	55218	59946	64281
Capital-output ratio										
	5%	2.0	2.0	2.1	2.3	2.5	2.6	2.7	2.9	2.8
	50%	2.6	2.6	2.7	2.5	2.6	2.8	2.9	3.1	3.2
	95%	2.7	2.7	2.8	2.9	3.1	3.2	3.4	3.4	3.5
	Mean	2.5	2.5	2.5	2.6	2.8	2.9	3.0	3.1	3.2
Rate of return to capital										
	5%	12.4	12.2	11.8	11.2	10.6	10.2	9.8	9.7	9.5
	50%	12.8	12.8	12.4	13.4	12.5	11.7	11.3	10.8	10.3
	95%	16.6	16.4	15.4	14.4	13.2	12.5	12.1	11.6	11.7
	Mean	13.2	13.5	13.4	12.9	12.0	11.5	11.1	10.7	10.4

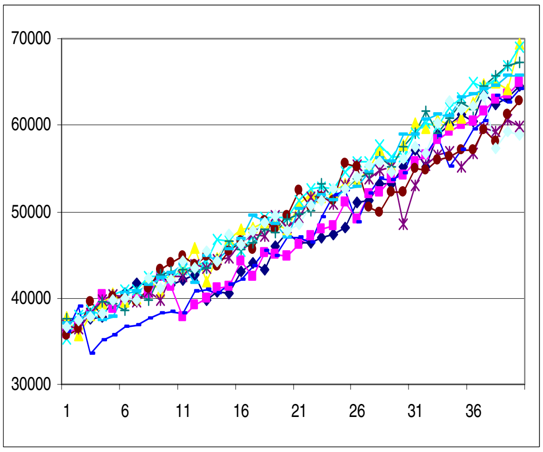

Figure 11: GDP per capita, selected trajectories.

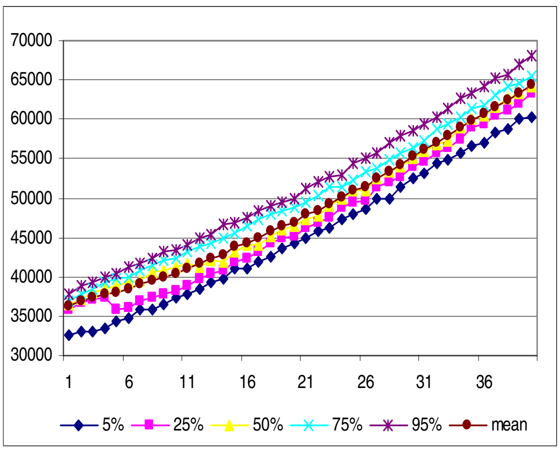

Figure 12: GDP per capita, selected percentiles.

Histograms of the discounted and of the terminal year GDP per capita, Figures 13 and 14, are slightly skewed to the left due to the presence of catastrophes. The terminal year average GDP per capita decreases in comparison to the baseline by only 0.075 percent (Tables 1 and 4). Thus, the indirect effects of catastrophes do not cause severe problems. Figures 15 and 16 show selected jagged trajectories and ranges of uncertainties of GDP per capita percentiles. Table 4 contains a summary of the main macroeconomic indicators. In reality, the effects of direct and indirect shocks cannot be considered separately, as their compound synergies can induce, due to nonlinearities of the system, much higher magnitude disturbances than any individual shock. This requires more sophisticated analysis and will be discussed in the follow-up research.

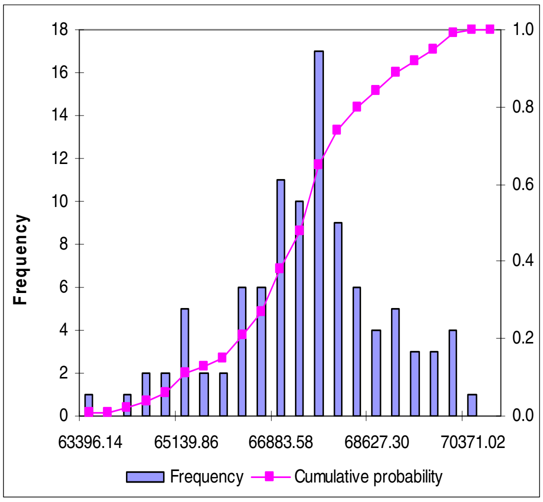

Figure 13: GDP per capita, terminal year.

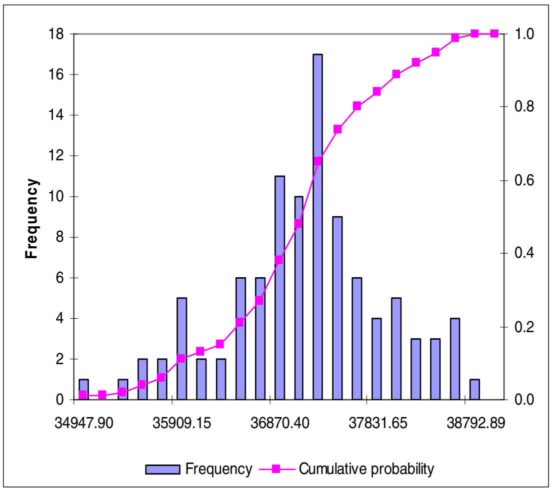

Figure 14: GDP per capita, discounted.

Table 4: Macro-aggregates, selected percentile trajectories.

GDP per capita		**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	5%	33065	37439	40829	44489	47828	51256	55550	60011	64778
	50%	36701	39154	42482	45875	49160	53280	57525	61952	57278
	95%	37744	40301	44158	47505	50418	54669	59129	64045	69523
	Mean	36355	39020	42401	45875	49118	53133	57343	61988	67181
Capital-output ratio										
	5%	2.5	2.5	2.6	2.8	3.0	3.1	3.2	3.2	3.3
	50%	2.6	2.6	2.7	2.9	3.0	3.2	3.3	3.3	3.4
	95%	2.8	2.7	2.8	3.0	3.2	3.3	3.4	3.4	3.5
	Mean	2.6	2.6	2.7	2.9	3.1	3.2	3.3	3.3	3.4
Rate of return to capital										
	5%	11.6	12.1	11.8	11.2	10.5	10.1	9.8	9.6	9.4
	50%	12.9	12.6	12.2	11.5	10.8	10.4	10.1	9.9	9.7
	95%	13.2	13.0	12.7	11.9	11.1	10.8	10.4	10.2	10.0
	Mean	12.7	12.6	12.2	11.5	10.8	10.4	10.1	9.9	9.7

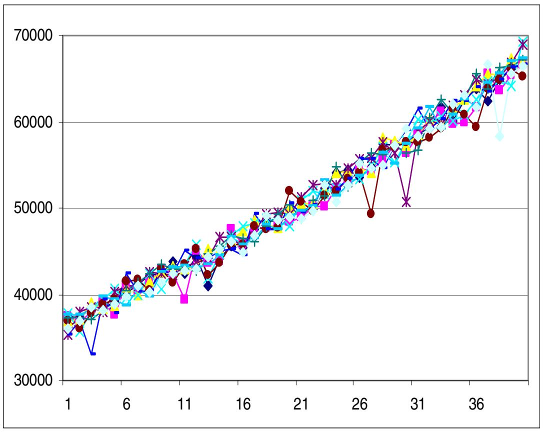

Figure 15: GDP per capita, selected trajectories.

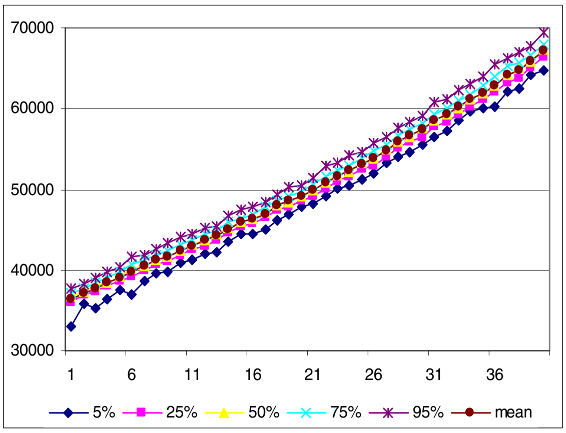

Figure 16: GDP per capita, percentiles.

5.2.3 Shocks to capital and production function, no precautionary savings

Combined shocks to capital stocks and production are also applied at random times and have random magnitudes. Table 5 of macro-aggregates and Figures 17 and 18 show that performance of the region is sustained: the GDP growth rate is not affected and the terminal year GDP per capita, equal to USD 64155, is 4.6 percent lower than in the baseline. Histograms of the regional GDP per capita, Figures 19 and 20, do not show dramatic skewness. Performance of the region under administered shocks does not require extra resources or savings to increase the resilience. However, supplementary savings or investments into mitigation, as demonstrated in section 3, may only be of benefit.

Table 5: Macro-aggregates, selected percentile trajectories.

GDP per capita		**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	5%	29301	32710	36863	40762	44049	47604	52262	56495	60052
	50%	36420	38782	41165	42968	46228	50659	54828	59855	64109
	95%	37745	40344	43492	46911	49785	54436	58583	63227	68087
	Mean	35875	37845	40296	43624	46736	50758	55064	59834	64155
Capital-output ratio										
	5%	2.2	2.0	2.1	2.3	2.5	2.6	2.7	2.8	2.8
	50%	2.6	2.6	2.7	2.5	2.6	2.8	2.9	3.0	3.2
	95%	2.7	2.7	2.8	2.9	3.1	3.2	3.4	3.4	3.5
	Mean	2.5	2.5	2.5	2.6	2.8	2.9	3.0	3.1	3.2
Rate of return to capital										
	5%	12.4	12.2	11.8	11.2	10.6	10.2	9.8	9.7	9.5
	50%	12.8	12.8	12.4	13.4	12.6	11.8	11.3	10.9	10.4
	95%	15.0	16.5	15.5	14.5	13.3	12.6	12.2	11.6	11.8
	Mean	13.0	13.5	13.4	12.9	12.1	11.6	11.1	10.7	10.4

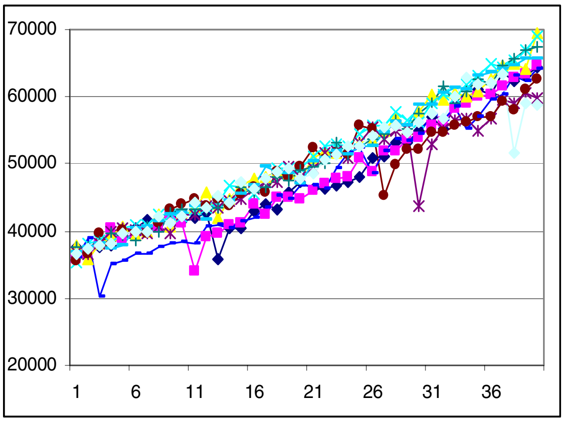

Figure 17: GDP per capita, selected trajectories.

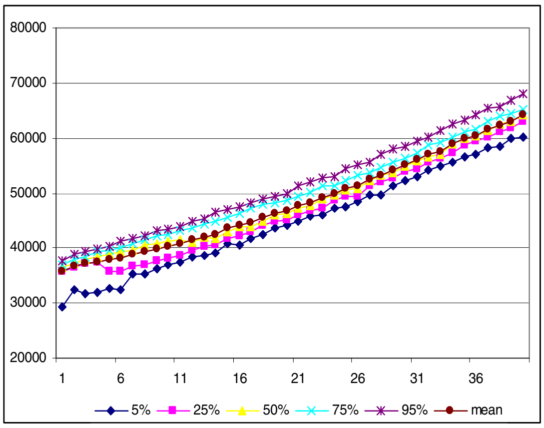

Figure 18: GDP per capita, percentiles.

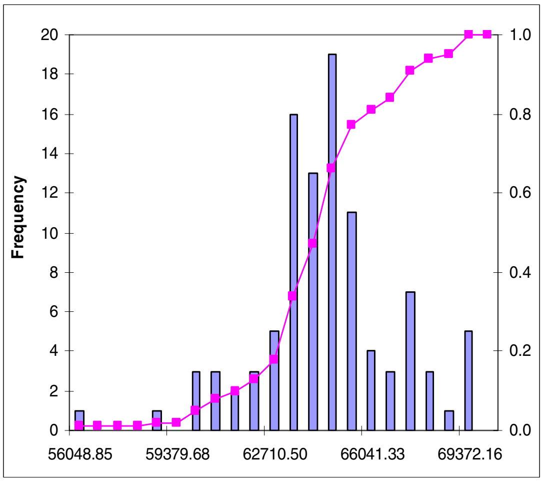

Figure 19: GDP per capita, terminal year.

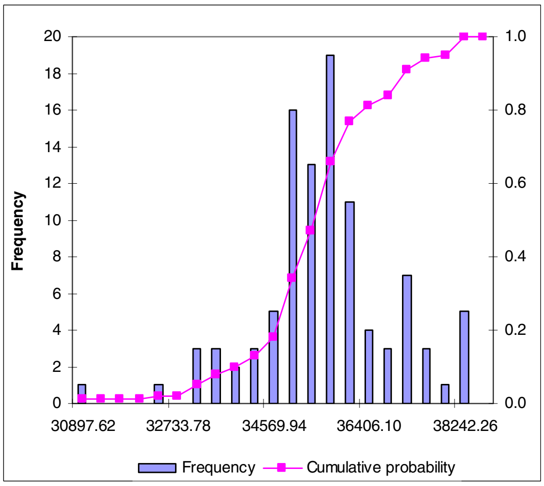

Figure 20: GDP per capita, discounted.

5.3 Developing Region, Shocks to Capital and Production Function

In this section we illustrate that, in contrast to a developed region, a region without abundant resources (capital and labor) and with inefficient production planning can be dramatically affected by the same magnitude catastrophes. Without additional precautionary savings or investments into mitigation the region may experience a rapid decrease of incomes. It may even stagnate and finally collapse. Although the demand in ex-ante measures is high, they can be implemented only up to the extent determined by regional incomes. Income constraints can be taken into account similar to Ermolieva (2005). In the following experiments we apply the same magnitude shocks as for the developed region.

5.3.1 *Shocks to capital, no precautionary savings*

In this set of experiments shocks are administered to capital stocks. Without precautionary savings (or investments into mitigation) the region experiences an essential drop of production level. In comparison to the baseline, GDP per capita decreases from USD 4141 to 3728, which makes a difference of almost 10 percent. Table 6 summarizes the macro-aggregates.

Table 6: Macro-aggregates, selected percentile trajectories.

		1	5	10	15	20	25	30	35	40
GDP per capita										
	5%	2028	2114	2272	2565	2801	3063	3299	3416	3201
	50%	2099	2227	2418	2668	2935	3193	3450	3647	3787
	95%	2175	2308	2520	2791	3067	3352	3602	3925	4097
	Mean	2098	2221	2416	2670	2939	3196	3450	3656	3728
Capital-output ratio										
	5%	1.6	1.6	1.6	1.6	1.6	1.7	1.6	1.5	1.1
	50%	1.7	1.7	1.8	1.8	1.7	1.8	1.7	1.8	1.6
	95%	1.7	1.8	1.8	1.9	1.9	1.9	1.9	1.9	1.8
	Mean	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.7	1.5
Rate of return to capital										
	5%	19.4	18.3	18.0	17.8	17.5	17.6	17.2	17.6	18.1
	50%	19.9	19.0	18.8	18.8	18.9	18.8	19.0	19.3	20.9
	95%	21.2	21.2	20.8	20.4	20.3	19.9	20.7	22.3	30.9
	Mean	20.0	19.2	19.2	19.0	18.9	18.7	18.9	19.5	22.6

Figure 21 presents percentile trajectories of total capital stock. In the outer years, starting from 2025, the 5-th percentile decreases rapidly. This effect stems from the cumulative nature of the capital growth process since catastrophes not only directly deplete capital stock but also indirectly decrease its cumulative capacity by reducing savings and investments. Due to these and other combined effects, as Figure 22 indicates, the overall regional growth slows down and even becomes negative.

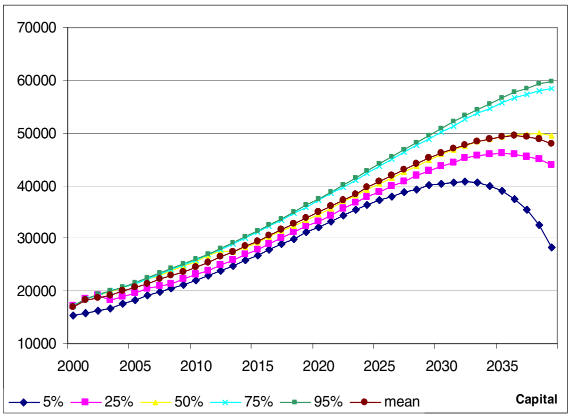

Figure 21: Total capital stock, percentiles.

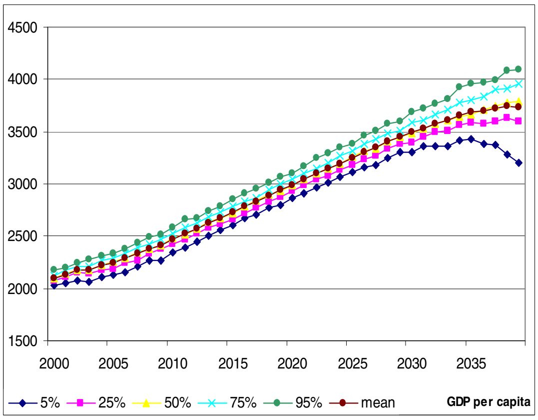

Figure 22: GDP per capita, percentiles.

5.3.2 Shocks to capital, precautionary savings

These experiments illustrate that with additional savings in the mandatory precautionary catastrophic fund (which can also be interpreted as additional investments into mitigation resulting in more efficient regional planning for disasters) the performance of the region under catastrophes improves. The catastrophe fund is used for compensation of damages or, in other words, its reserve is injected into the economy when a catastrophe occurs. In fact, the reserve of the fund operates in the economy all the time increasing the production level. GDP per capita of the terminal year, Tables 2 and 7, in comparison to the baseline changes from USD 4141 to 4055, makes only 2 percent instead of 10 percent change in the experiments without precautionary savings (section 5.3.1).

Table 7: Macro-aggregates, selected percentile trajectories.

		1	5	10	15	20	25	30	35	40
GDP per capita										
	5%	1971	2091	2281	2528	2808	3053	3348	3603	3794
	50%	2106	2217	2397	2653	2916	3204	3502	3812	4063
	95%	2196	2299	2488	2766	3052	3399	3679	3967	4258
	Mean	2102	2210	2398	2650	2923	3200	3510	3803	4055
Capital-output ratio										
	5%	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7
	50%	1.6	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.8
	95%	1.7	1.8	1.8	1.8	1.8	1.9	1.9	2.0	2.0
	Mean	1.6	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.9
Rate of return to capital										
	5%	19.2	18.4	18.4	18.2	17.9	17.3	17.0	16.7	16.4
	50%	20.0	19.2	19.4	19.5	19.2	18.7	18.2	18.0	17.9
	95%	21.8	21.6	21.5	21.2	20.6	19.7	19.5	19.3	19.8
	Mean	20.2	19.6	19.8	19.6	19.1	18.6	18.2	18.0	17.9

Due to higher productivity and the "buffering" of the capital stock by the catastrophe fund reserve, the process of capital accumulation shown in Figure 23 is not as severely affected as in Figure 24.

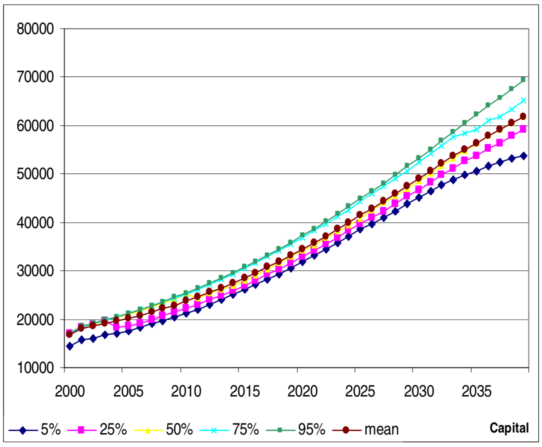

Figure 23: Total capital stock, percentiles.

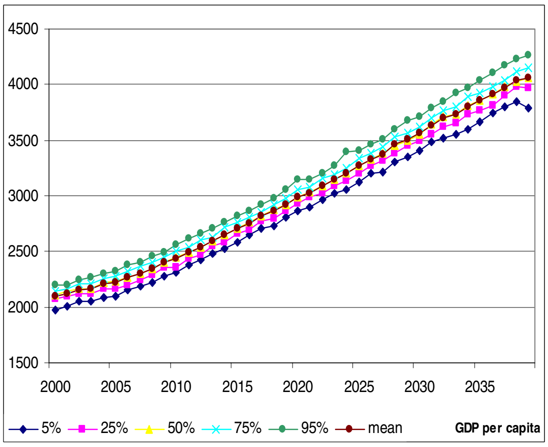

Figure 24: GDP per capita, percentiles.

5.3.3 Shocks to production function, no precautionary savings

Shocks to production of the developing region do not cause significant difficulties and do not, in general, require additional savings. Figure 25 shows the uncertainty bounds of the GDP per capita. It starts from 12 percent difference between the 5-th and the 95-th percentiles in 2000 and in 2040 it decreases to 6.5 percent. Figure 26 shows a slight decline of all percentiles of the total capital stocks in the outer years. Figure 6 of the baseline also shows the same tendencies. Therefore, shocks to production function do not significantly accelerate these effects. The terminal year average GDP per capita decreases in comparison to the baseline by only 3 percent. Thus, indirect effects of catastrophes, as they are introduced in the model, are not a problem even for the developing region. As already mentioned, in reality the effects of direct and indirect shocks cannot be studied separately from each other because of complex linkages and amplifying synergetic effects that these shocks can produce. A summary of macro-aggregates is in Table 8.

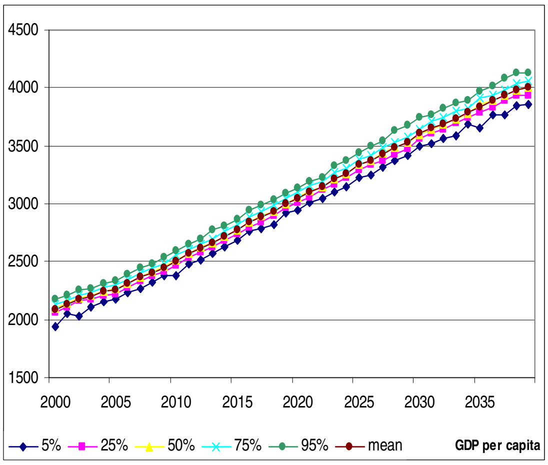

Figure 25: GDP per capita, percentiles.

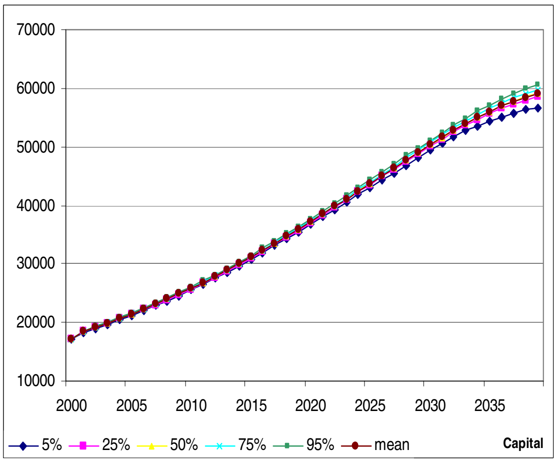

Figure 26: Total capital stock, percentiles.

Table 8: Macro-aggregates, selected percentile trajectories.

GDP per capita		**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	5%	1938	2159	2379	2631	2920	3143	3422	3689	3858
	50%	2095	2242	2454	2714	3003	3264	3533	3776	4003
	95%	2176	2315	2535	2810	3089	3378	3682	3890	4129
	Mean	2089	2241	2450	2716	3002	3255	3530	3785	4001
Capital-output ratio										
	5%	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.7
	50%	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.8
	95%	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9	1.9
	Mean	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.8	1.8
Rate of return to capital										
	5%	18.3	18	18	17.7	17.5	17.1	17.1	17.3	17.6
	50%	19.8	18.7	18.5	18.3	18.1	17.8	17.7	17.8	18.4
	95%	20.6	19.4	19.1	19.0	18.7	18.3	18.4	18.4	19.3
	Mean	19.7	18.7	18.5	18.3	18.1	17.8	17.7	17.8	18.4

5.3.4. Shocks to production function, precautionary savings

These experiments illustrate that additional savings within the consumption constraints (which do not affect the necessary consumption level) can only improve the regional performance under shocks: GDP per capita is steadily increasing, Figure 27 and Table 9. Capital, Figure 28, accumulates at a rate sufficient to take on catastrophes.

Table 9: Macro-aggregates, selected percentile trajectories.

GDP per capita		1	5	10	15	20	25	30	35	40
	5%	1898	2156	2354	2620	2875	3216	3533	3854	4162
	50%	2090	2238	2441	2726	3007	3313	3633	3974	4317
	95%	2165	2297	2507	2808	3104	3418	3741	4066	4436
	Mean	2083	2231	2435	2713	3003	3312	3629	3965	4301
Capital-output ratio										
	5%	1.6	1.7	1.7	1.7	1.8	1.8	1.9	2.0	2.0
	50%	1.7	1.7	1.8	1.8	1.8	1.9	2.0	2.0	2.0
	95%	1.8	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1
	Mean	1.7	1.8	1.8	1.8	1.8	1.9	2.0	2.0	2.1
Rate of return to capital										
	5%	17.9	18.1	17.9	17.7	17.1	16.9	16.3	15.9	15.5
	50%	19.8	18.9	18.6	18.4	17.9	17.4	16.8	16.4	16.1
	95%	20.5	19.4	19.1	19	18.4	17.9	17.5	16.9	16.6
	Mean	19.7	18.8	18.6	18.3	17.9	17.3	16.8	16.4	16.1

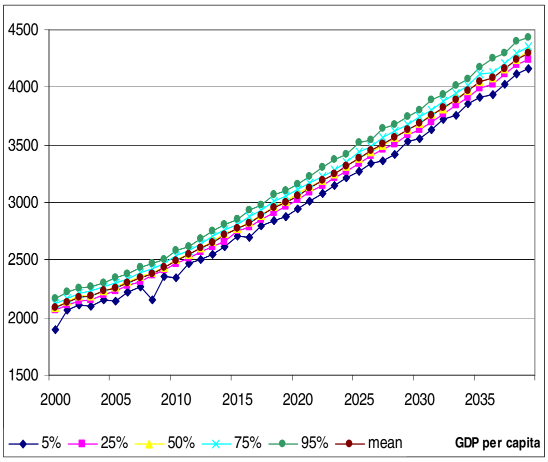

Figure 27: GDP per capita, percentiles.

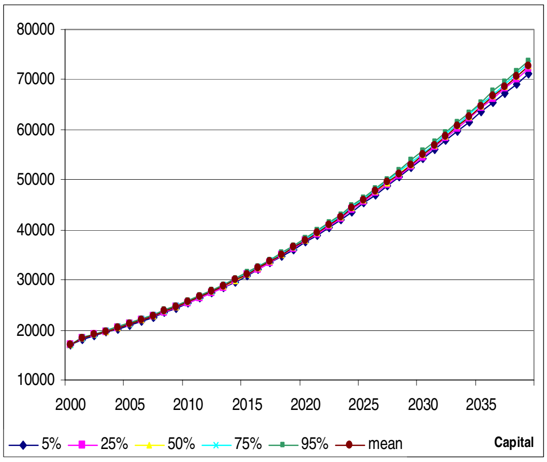

Figure 28: Total capital stock, percentiles.

5.3.5 Shocks to capital and production function, no precautionary savings

These experiments illustrate cumulative effects of shock to capital and GDP. Without precautionary savings, the macro-aggregates, Table 10 and Figures 29 and 30, indicate that the region experiences significant difficulties. Thus, GDP per capita in the terminal year is on average equal to USD 3736, which is 10 percent less than in the baseline. The production level indicates decisively negative growth starting in 2026. Capital accumulation under catastrophes slows down, Figure 30, and in 2019 shows a negative growth.

Figures 31 and 32 show a skewed distribution of regional indicators caused by cumulative affects of shocks and nonlinear responses of the model.

Table 10: Macro-aggregates, selected percentile trajectories.

GDP per capita		**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	5%	1772	2003	2203	2497	2750	2947	3167	3205	2725
	50%	2094	2212	2379	2626	2864	3154	3379	3620	3808
	95%	2170	2303	2509	2774	3010	3352	3634	3916	4273
	Mean	2070	2187	2364	2629	2874	3129	3391	3565	3736
Capital-output ratio										
	5%	1.6	1.5	1.5	1.5	1.5	1.6	1.5	1.2	0.9
	50%	1.7	1.7	1.7	1.7	1.6	1.7	1.7	1.7	1.6
	95%	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9
	Mean	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.6	1.6
Rate of return to capital										
	5%	19.2	18.2	18.2	18.2	17.9	17.4	17.1	17.0	10.5
	50%	19.8	19.1	19.1	20.3	19.9	19.7	19.5	19.8	20.4
	95%	21.0	22.4	21.9	22.0	21.4	21.2	22.4	26.1	29.6
	Mean	20.0	19.6	19.8	20.0	19.6	19.5	19.5	19.9	20.9

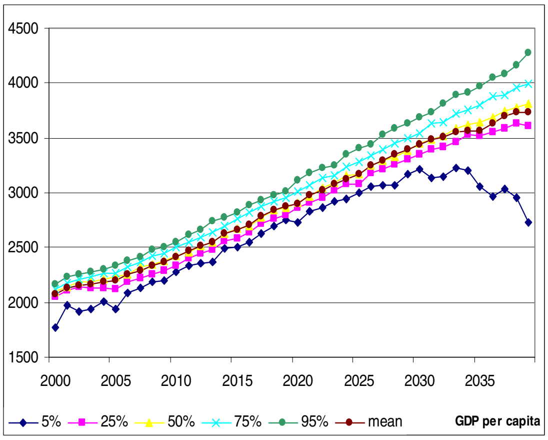

Figure 29: GDP per capita, percentiles.

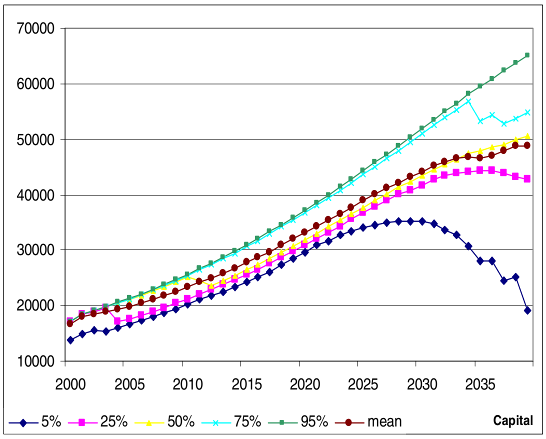

Figure 30: Total capital stock, percentiles.

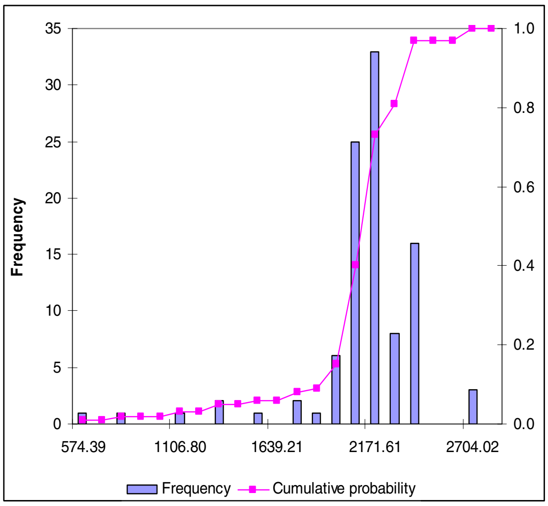

Figure 31: GDP per capita, discounted.

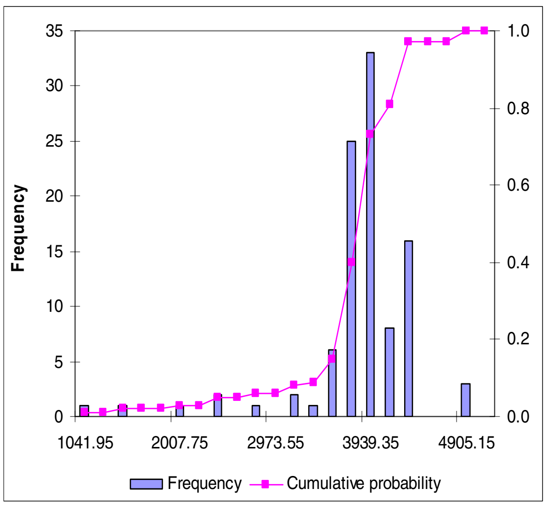

Figure 32: GDP per capita, terminal year.

5.3.6 Shocks to capital and production function, precautionary savings

To improve the performance of the region under shocks, a mandatory catastrophe fund is introduced. The premium rate to the fund equals 1 percent of the households' gross annual wage income. The average GDP per capita in the terminal year is USD 3872 (Table 11), which is 6.2 percent less than in the baseline solution, Table 2, but 3.5 percent higher than in the solution with no precautionary savings, Table 10.

Table 11: Macro-aggregates, selected percentile trajectories.

GDP per capita		1	5	10	15	20	25	30	35	40
	5%	1771	1996	2206	2488	2747	2980	3220	3381	3112
	50%	2093	22065	2369	2616	2858	3161	3410	3683	3912
	95%	2169	2297	2498	2763	3003	3353	3648	3951	4283
	Mean	2070	2180	2357	2618	2869	3156	3420	3665	3872
Capital-output ratio										
	5%	1.6	1.5	1.5	1.5	1.5	1.6	1.5	1.4	0.9
	50%	1.7	1.7	1.7	1.6	1.7	1.7	1.7	1.7	1.7
	95%	1.7	1.8	1.8	1.8	1.8	1.9	1.9	2.0	2.0
	Mean	1.7	1.7	1.7	1.6	1.7	1.7	1.7	1.7	1.6
Rate of return to capital										
	5%	19.2	18.3	18.4	18.3	17.9	17.4	16.9	16.8	16.5
	50%	19.9	19.2	19.3	20.5	20.0	19.6	19.2	19.0	19.1
	95%	21.0	22.5	22.1	22.2	21.4	21.0	21.8	24.1	25.6
	Mean	20.0	19.7	20.0	20.2	19.7	19.4	19.2	19.6	19.1

Figure 33 presents the dynamics of the GDP per capita percentiles, from which we see that in the outer years the lowest 5-th percentile turns down indicating negative economic growth rate. The capital stock trajectories in Figure 34 need better buffering", i.e., higher savings in the catastrophe fund.

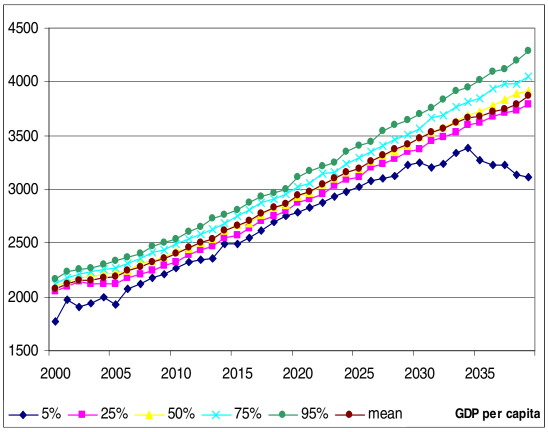

Figure 33: GDP per capita, percentiles.

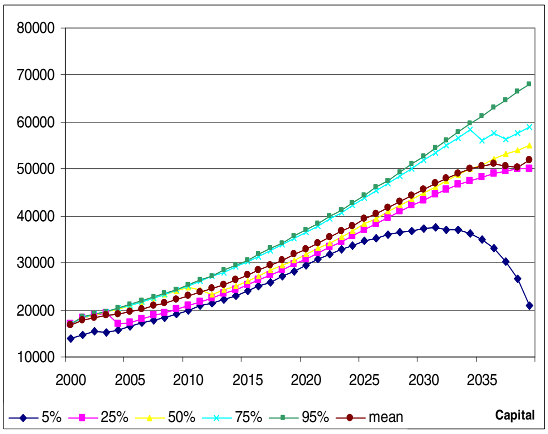

Figure 34: Total capital stock, percentiles.

Histograms of discounted and terminal year GDP per capita in Figures 35 and 36 show significant skewness of the distributions. Histograms of discounted depleted capital, Figure 37, and cumulative discounted premiums, Figure 38, are also very illustrative.

The first shows the amount of capital that the economy lost due to catastrophes. The second shows cumulative discounted premiums. In an ideal case, the two histograms should have the same scales and shapes. This would mean that the total accumulated premiums are sufficient to cover the losses. Here, the collected premiums are not sufficient to restore depleted capital.

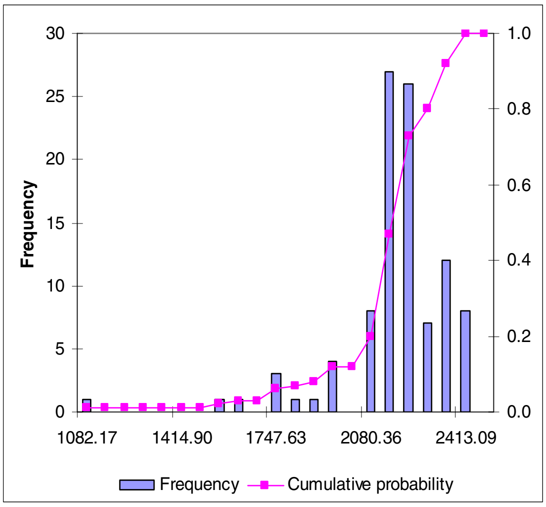

Figure 35: GDP per capita, discounted.

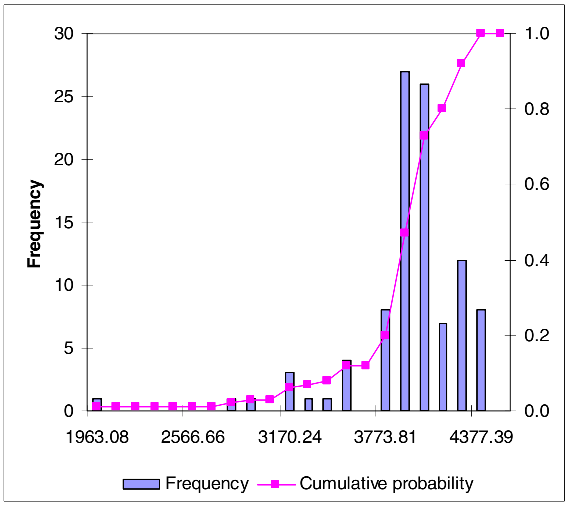

Figure 36: GDP per capita, terminal year.

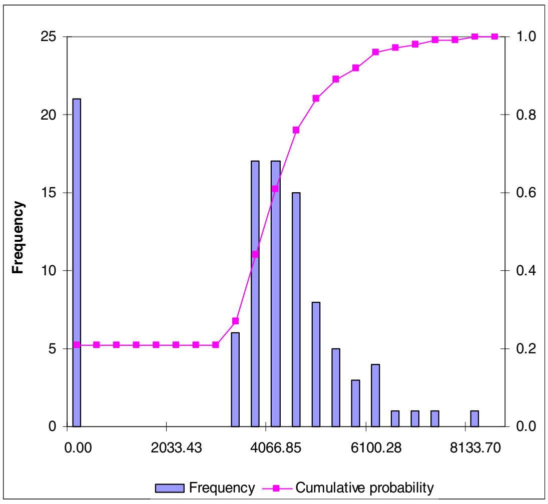

Figure 37: Depleted capital stock, discounted.

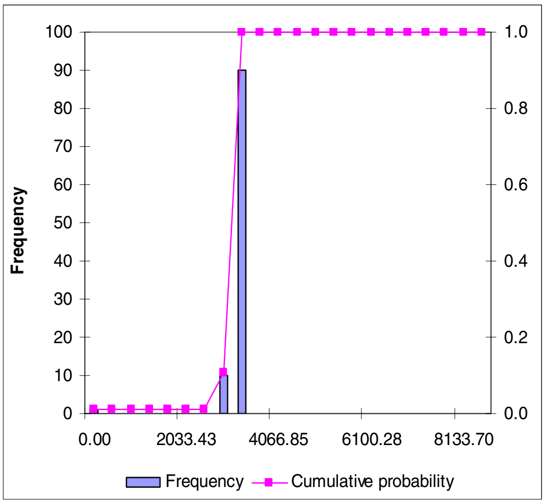

Figure 38: Cumulative premiums, discounted.

A major goal of catastrophic management is to set premiums that ensure appropriate restoration of damages at any time they occur. Minimization of the gap between the collected premiums and the capital (assets and liabilities) needed for recovery is a problem similar to equation (7). It represents a complex challenge for stochastic dynamic optimization, which can be approached similar to, e.g., Ermolieva (2005).

5.3.7 *Shocks to capital and production function, higher precautionary savings*

Previous experiments, section 5.3.6, demonstrated that initial premiums were insufficient to cover the losses. In these experiments we increase the premium rate, setting it equal to 3 percent of annual gross wage income. This measure improves the shapes of percentile trajectories, Table 12, Figures 39 and 40. Histograms of GDP per capita in Figures 41 and 42 gain compact distributions. The gap between the discounted depleted capital, Figure 43, and the discounted cumulative premiums, Figure 44, is, in a sense, minimized.

Table 12: Macro-aggregates, selected percentile trajectories.

GDP per capita		**1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	5%	1879	2094	2282	2543	2797	3082	3348	3566	3791
	50%	2096	2234	2417	2668	2928	3217	3486	3741	4029
	95%	2169	2307	2499	2776	3054	3331	3618	3917	4223
	Mean	2080	2217	2403	2655	2927	3215	3489	3744	4023
Capital-output ratio										
	5%	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.6
	50%	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.8
	95%	1.7	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9
	Mean	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.8
Rate of return to capital										
	5%	19.1	18.1	18.3	18	17.7	17.5	17.1	16.9	17.2
	50%	19.8	19	19	19.1	19	18.7	18.4	18.2	18.6
	95%	20.5	20.6	20.3	20.5	19.9	19.6	19.2	19.6	20.6
	Mean	19.8	19.1	19.2	19.2	18.9	18.6	18.3	18.2	18.7

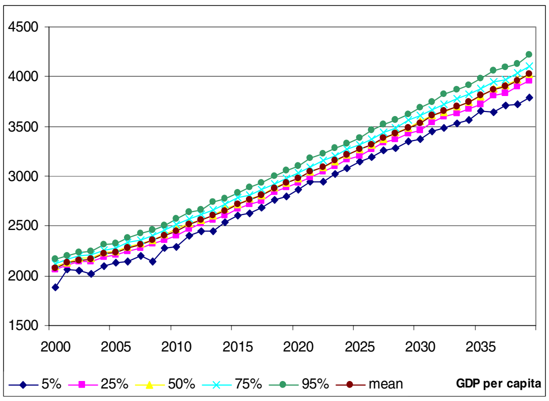

Figure 39: GDP per capita, percentiles.

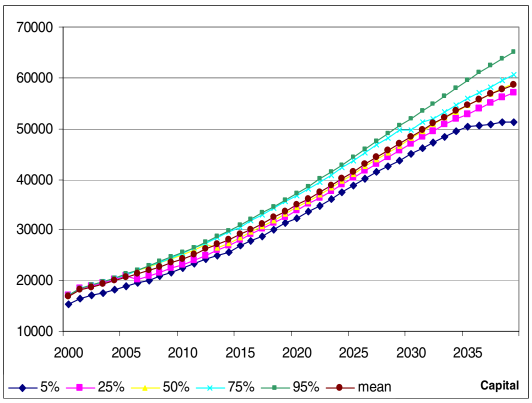

Figure 40: Total capital stock, percentiles.

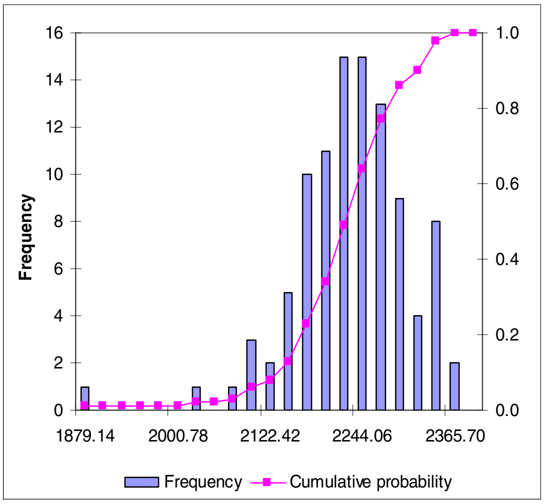

Figure 41: GDP per capita, discounted.

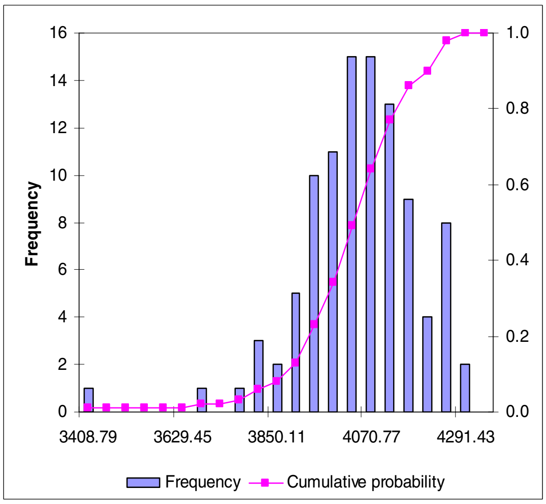

Figure 42: GDP per capita, terminal year.

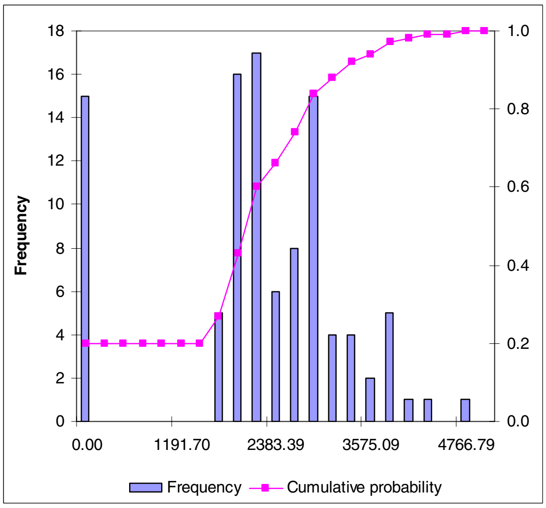

Figure 43: Depleted capital stock, discounted.

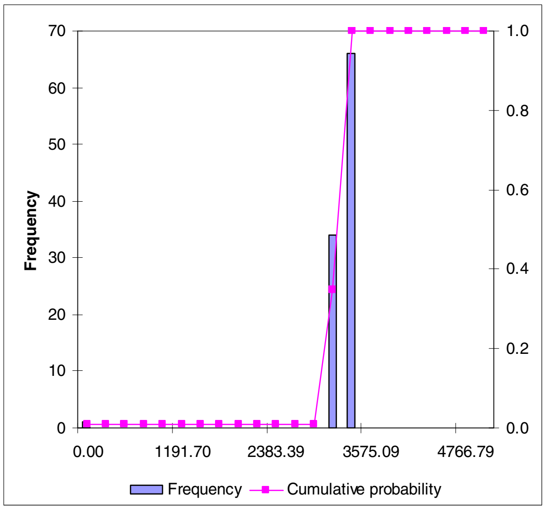

Figure 44: Cumulative premiums, discounted.

6 Conclusions

In this paper we analyze the effects of catastrophic shocks on economic growth of a developed and a developing country/region. Economic development of regions is characterized in terms of GDP per capita. Shocks are introduced as events depleting capital stocks and reducing production levels.

Traditionally, the major part of catastrophic losses especially in developing countries has been managed ex-post through borrowing, external aid or by diverting financial resources from other economic sectors/programs with rather high costs of ex-post catastrophe rehabilitation measures. In this paper, using a conceptual model and numerical experiments, we showed that ex-ante precautionary savings and loss mitigation measures may significantly reduce "unexpected" costs of highly uncertain post-shock responses. These measures, i.e., savings, enhance economic performance and allow maintaining the growth rate necessary to confront catastrophes. The level of precautionary savings is determined by regional incomes: if premium rates of the mandatory fund are too high they can decrease consumption below the subsistent level, turning households from savers into borrowers and thus causing downward effects on overall savings. This is a typical situation for developing regions.

It is a challenging task to evaluate up to what extent catastrophes can be managed ex-ante and up to what extent the management of catastrophes must then rely on ex-post capital measures, such as external borrowing or aid. In these experiments some insights regarding a capacity of a precautionary catastrophe fund were gained through the analysis of regional vulnerability towards catastrophes and regional incomes. In a more general case, it depends also on many other factors, e.g., the spatial distribution of incomes and the distribution of investments among various sectors of the economy and geographical regions. An important aspect of the problem is that the ex-ante savings (investments into mitigation) may significantly affect the levels of shocks and reduce the demand in ex-post measures. Thus, it is important that the ex-ante and the ex-post measures are evaluated accounting for their complex synergies. However, sequential "if–then" analysis of feasible strategies may end up with an unlimited number of scenarios. Moreover, the simulation model does not take explicitly into account the concept of robust strategies relying on goals, constraints and risk indicators of the involved stakeholders. Analysis of the optimal portfolio of regional ex-ante and ex-post measures requires dynamic stochastic optimization techniques (see, for example, Ermoliev *et al.*, 2001, Ermoliev and Wets, 1988) with necessary downscaling procedures (Fischer *et al.*, 2004).

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