Estimating Natural Catastrophic Risk Exposure and the Benefits of Risk Transfer in Developing Countries

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Introduction and project description

The decade of the 1990's will be remembered as the most costly to date in terms of natural hazard damage. Yet, during the past decade, enormous progress has been made in understanding the nature and consequences of natural catastrophes. This is a result of the increased use of catastrophe modeling by insurance-industry firms. As a result of this increase of available knowledge, the amount of catastrophe insurance purchased in the world insurance markets has also increased dramatically. For example, in 1997 catastrophic excess of loss coverage (the most common type of catastrophe reinsurance) purchased amounted to USD 52.9 billion. This was an increase of 34% in three years.

Unfortunately, the benefits of this insurance were reaped almost entirely by the developed world. The United States, UK and Japan amounted to 55% of the total. By contrast, developing Asia, which represented half of all the damages caused by natural catastrophes and two-thirds of all the casualties from catastrophic events in 1997, "owned" only 8% of the insurance coverage for catastrophes purchased in the world market. This coverage sufficed to absorb only 13% of the losses incurred. The remainder of these costs fell either to the government or victims, with some limited relief from international aid agencies.

Losses from natural disasters have at least three links to poverty. First, natural disasters hurt poor people directly by disrupting income flows and destroying private assets. Second, natural disasters destroy public infrastructure, with consequent impacts on poverty. Among the projects most at risk are road, irrigation, and electrification projects, which are judged to have the most immediate impacts on rural poverty (World Bank 1994). Third, and less widely known, infrastructure loss and infrastructure replacement lending represent a significant offset to total international development lending and assistance.

Catastrophic events are among the most difficult to insure. Insurance works best for events with high frequency and low severity of events. Catastrophic events are at the opposite extreme, they occur infrequently with devastating impact when they happen. To cope with the ambiguity associated with the impacts of catastrophes, professional risk takers have relied on very sophisticated modeling to help define the risk they are absorbing. These models provide guidance in understanding both the frequency and severity of the consequences of these events on potentially insured assets.

The modeling has had a secondary benefit. It has provided the planning tool for a whole new generation of risk transfer tools. These new tools take the financial risk of catastrophic events and transfer them directly to the capital markets. Through 1998, nearly USD 2.7 billion of these capital market instruments have been issued. Today, the key component of either catastrophe insurance or capital market risk transfer instruments has been good modeling.

Why has the improvement in catastrophic risk management passed by the developing countries of the world, as well as countries in economic transition? A key reason is that proper quantification tools do not exist to explain why ex ante risk transfer would be of benefit to emerging economies vulnerable to catastrophic natural hazard events. For both private and public entities in the developed world, sophisticated tools to measure the likely benefits of catastrophic risk transfer exist.

A primary distinguishing feature of developing countries is that the government is the primary bearer of the costs of catastrophes. Generally, the costs of the catastrophes are borne by the central government as a component of the national budget. The relevant decision maker is thus clear. However, the work necessary to identify, quantify, and price the risk has not been done, and without this work, it is impossible to consider transferring risk.

IIASA has undertaken a research project create a decision-making framework in which the benefits of ex ante risk transfer options for developing countries can be assessed. The first step in this process is to estimate, based on historical data, the present value of future GDP growth which is likely to be sacrificed as a result of natural catastrophes. The second step is to weigh the relative benefits of ex ante versus ex post financing of the costs of catastrophes. By establishing a basis to measure the potential benefits of ex ante risk transfer, it is hoped that a meaningful effort can be undertaken to begin extending the benefits of ex ante risk transfer to developing countries.

Conceptual basis to address problem

Any rational strategy for managing risk of natural catastrophes requires an estimate of risk exposure. The more refined this estimate, the more efficiently the risk can be managed. Even a rough estimate is, however, better than none at all.

Estimating risk exposure is made more difficult by the fact that it is not conceptually simple to define the costs of natural catastrophes (U.S. National Research Council 1999). Most published estimates refer only to direct losses (typically value of capital destroyed), and sometimes refer only to insured direct losses. Total direct and indirect costs of the catastrophe are presumably much greater than direct losses alone. They would include, for example, losses which arise from work interruption. Complicating matters, however, would be a number of effects (many of them operating through prices) which tend to soften the overall impact of a natural catastrophe. For example, while the owners of assets destroyed by the catastrophe suffer a capital loss, owners of similar assets not damaged by the catastrophe enjoy a windfall capital gain. Or, impacts may be highly differentiated by sector, with some sectors (such as construction) enjoying a boom as a result of the catastrophe.

One way of simplifying the estimation of the costs is to ignore short-term impacts, as well as impacts by sector, and concentrate on long-term impacts on potential GDP, which depends only on capital, labor, and technology. The most obvious impacts of natural catastrophes on potential GDP are mediated through the first of these, especially infrastructure. If capital stock destroyed when catastrophe strikes is not replaced, the result is a permanent loss of potential output. However, even at this highly simplified level, there are likely to be some complications. When GDP is reduced by the shock to the capital stock, so is the available pool of savings and (in a closed economy) investment. Thus, ignoring cyclical responses in the form of a short lived post-catastrophe investment boom, net capital formation in the years following a catastrophic loss will be lower than it would have been in the no-catastrophe case.

So far, we have assumed that there is no explicit response, either ex post or ex ante, to catastrophic risk, but this is unlikely to be the case. When natural catastrophe strikes, Government generally has an implicit obligation to replace destroyed infrastructure, and often also to assist private businesses and households to make good their losses. If post-event response diverts resources from capital budgets, damaged capital is made whole, but planned projects go unrealized. The result is, in effect, a transfer of the impact of the catastrophe from one sector of the economy to another. At least conceptually, this case is no different from the case in which there is no post-event response. However, when (as is often the case) diversion from budgeted capital expenditure is not politically feasible, then Government must engage in unexpected borrowing. If this borrowing is carried out in domestic markets, the result will be crowding out of planned private investment. If it is carried out in international capital markets, the result will be increased foreign debt and, most likely, a higher risk premium (which must be paid on all debt, not just debt related to the catastrophe). Ex ante measures, such as hazard mitigation and the purchase of catastrophic insurance, also carry costs, and one of the main purposes of this research effort is to allow the comparison of the costs of ex post and ex ante measures.

In this exploratory analysis, we limit ourselves to impacts of natural catastrophes on potential GDP and concentrate on the three most straightforward impacts:

- costs which arise from destruction of capital stock, whether direct losses in the form of unreplaced infrastructure or indirect losses in the form of resources diverted from other planned investment in order to replace damaged infrastructure,
- costs which arise from unexpected ex post foreign borrowing, and
- costs of ex ante catastrophic risk insurance.

<u>A one-factor model</u>

The simplest sort of growth model is a one-sector Harrod-Domar model, in which economic growth is exclusively a factor of the rate of growth of the capital stock. Let

$$\Delta GDP = \frac{1}{k}\Delta K$$

where *GDP* is gross domestic product , *k* is the capital-output ratio, a fixed parameter, and *K* is the capital stock. Then, assuming investment is funded only by domestic saving, and letting *Cat* be the value of capital stock destroyed by natural catastrophes in a given year,

$$\Delta GDP = \frac{1}{k}[\sigma GDP - Cat]$$

where σ is the saving rate. If we normalize catastrophic losses *Cat* by *K,* then

$$\Delta GDP = \frac{1}{k}[\sigma GDP - cK]$$

where *c* is the proportion of the capital stock destroyed. The economic growth rate is

$$g = \frac{\Delta GDP}{GDP} = \frac{\sigma}{k} - c$$

For given k, economic growth will be more rapid

- the higher the saving rate,
- the lower the capital-output ratio (i.e., the more efficiently capital is translated into output), and
- the lower the proportion of the capital stock destroyed by natural catastrophes in an average year,

all of which is sensible.

In Annex 1, we develop a model which is generalized to cover ex post foreign borrowing, resulting in the formula

$$g = \frac{1}{k}\left(\sigma + a - r\frac{ForDebt}{GDP}\right) - c(1-b)$$

where *ForDebt* is foreign debt, *a* is "autonomous " foreign borrowing (expressed relative to GDP) in an average year, *b* is the proportion of losses due to catastrophes which are replaced by post-event borrowing, *r* is the international interest rate, and we ignore amortization of debt. The important point to note is the non-linearity of the growth rate *g* in *b*. The higher the proportion of catastrophic losses replaced by foreign borrowing, the higher the rate of growth; however, the greater also will be foreign debt and the costs of debt service, which translate into opportunity costs of foregone investment.

<u>IIASA's approach</u>

The simulation work now being done at IIASA is conceptually identical to that presented above, the main difference being that a two-factor (capital and labor) Cobb-Douglas production function is employed instead of the one-factor Harrod-Domar function. This model, described in Annex 2, is solved in a Monte Carlo simulation over a chosen time period (say 30 years) and, in each year of each solution run, the capital stock is shocked downward based on a draw from a probability distribution of catastrophic event losses.[1] The nature of the loss distribution will depend on the event being modeled. The parameterization of this distribution requires the availability of a time-series of catastrophic losses in the country whose risk exposure is being assessed; obviously, the more accurate the data and the longer the time series, the more confidence we can have in the results.

The impact of each catastrophic event shock is to reduce the capital stock and thus output and, as a consequence, wages and profits, which in turn reduces savings and investment.[2] Investment can be adjusted upward subsequent to each shock to reflect replacement investment funded by foreign borrowing, in which case future savings are adjusted downward to reflect interest payments. We assume a one-to-one offset between interest and amortization payments and resources available to finance investment. To model ex ante risk transfer, a catastrophic risk insurance premium is added to annual government expenditure and investment is correspondingly reduced, again making the simple assumption of a one-for-one offset. Following each catastrophic shock non-debt creating capital inflows corresponding to the severity of the catastrophe and the nature of the hypothetical insurance contract are translated into replacement investment. While we have not yet simulated the impact of ex ante mitigation, this should be conceptually simple.[3]

An illustrative single deterministic shock

No response. In this and the following section, we present two illustrative applications. The model has been initialized in the year 1995 on a hypothetical developing country with per capita GDP of $1000, a capital-output ratio of 3.0, and a population of 100 million, which taken together translate into a capital stock of $300 billion. The saving rate (household plus corporate plus government savings) is about 20 percent of GDP. Say that, in year 15 of a 30-year simulation run, a catastrophic event occurs destroying 20 percent of the capital stock. This is a highly extreme event; based on loss distributions that we have examined, it might be on the order of a 1000-year event. The reason for choosing such an extreme event is simply to enhance the visual presentation in Figures 1-3.

As illustrated in Figure 1, if destroyed capital is not replaced, GDP simply returns to the same growth path at a lower level. A number of indices of risk exposure, or of the expected costs of catastrophes, can be calculated. Here, we use the index

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[1] There would be clear advantages to disaggregation of the capital stock to break out infrastructure and refinement of the production function.
[2] An alternative and possibly complementary approach is to define a stochastic multiplier by which GDP is shocked directly. This approach has been utilized, for example, to simulate impacts of climate change on the global economy.
[3] For example, investment could be split into two streams, one consisting of mitigation, which makes no net new contribution to the capital stock but reduces the vulnerability of the capital stock to future disasters. Alternatively, capital could be disaggregated into two stocks, consisting of capital which incorporates mitigation measures and capital which does not.

$$Risk\ \ exposure = \frac{\sum_{t=0}^{0}\left[GDP'(t) - GDP(t)\right]}{\sum_{t=0}^{30} GDP(t)}$$

where the prime superscript refers to shocked GDP.[4] In the no-response case illustrated in Figure 1, we calculate this index to be -0.027 (i.e., risk exposure is about 3 percent of GDP). Note that the more negative the index, the greater the exposure to catastrophic risk. Note also that the index is not time-independent; on the contrary, it is a function of the length of time over which it is calculated and the year in which the catastrophe occurs.[5]

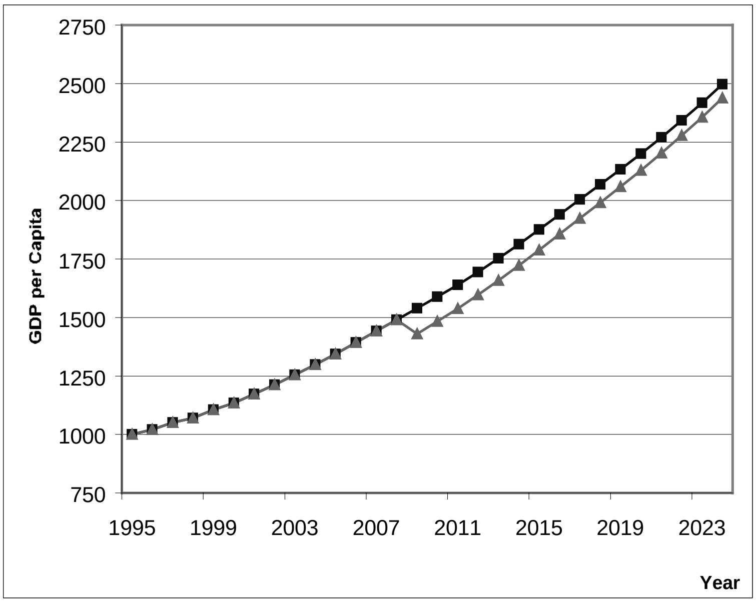

Figure 1. GDP per capita, single deterministic shock with no replacement investment.

[4] There may be political difficulties in adopting an approach which depends on foregone potential GDP. Economic planning exercises are typically done in iterative fashion by adopting a long-run growth target, calculating the required resources under various assumptions, and modifying the target accordingly. An alternative approach to the one used here is to take GDP growth as exogenous and calculate private consumption which must be foregone (or public foreign borrowing which must be undertaken) in order to meet the growth target in the presence of natural catastrophic risk.

[5] A case could be made for introducing a discount rate into the risk index, in which case GDP foregone far in the future would be valued less than GDP foregone in the near future. If a discount rate were introduced, one potential risk index would be the present value of future losses relative to present GDP. An impact of discounting would be to tilt the analysis in favor of post-event borrowing, whose costs may occur far in the future (if at all) as opposed to ex ante insurance or mitigation, whose costs must be borne (with certainty) in the present.

Post-event borrowing from abroad. Now say that the same event occurs, again in Year 15, but that destroyed capital is replaced over five years. First we run the model to produce the scenario illustrated in Figure 1. Then we run the model again assuming that in Years 15-19, investment in the shocked scenario is increased by 0.04 K(15).[6] In other words, direct losses to the capital stock are made good over a five-year period; however, indirect effects are assumed to remain in force. This replacement investment is financed by foreign borrowing, which gives rise to interest costs, which in turn reduces domestic savings available to finance investment.[7]

In Table 1, we show capital stock in years 15 through 30. The column headed "Baseline" gives capital stock assuming no catastrophe occurs. The column headed "Alternative 1" gives capital stock assuming that there is a catastrophe with no replacement investment. The column headed "Alternative 2" gives capital stock assuming that, after the catastrophic shock, there is replacement investment on the basis of foreign borrowing. The interest rate is assumed to be 10 percent and there is assumed to be a one-for-one offset between interest expenditure and domestic resources available for investment.

The resulting path for GDP is shown in Figure 2. In the years immediately following the shock, GDP returns to its baseline path, only to diverge again when repayment of principal commences. If Figure 2 were extended to the right, it would illustrate a slow gradual convergence to baseline.

[6] The catastrophe reduces baseline capital stock by 0.2 K(15); replacement investment over five years would require that investment in each year be higher by 0.2/4 K(15).

[7] We assume that replacement investment is funded by foreign borrowing to avoid the complications which would arise from crowding out in the domestic capital market.

Year	Baseline[1]	Alternative 1[2]	Cat Loss	Replacement Investment	Interest[3] Payments	Amort.[4] Payments	Alternative 2[5]
1995	300.0	300.0					300.0
1996	305.3	305.3					305.3
1997	304.6	304.6					304.6
1998	304.6	304.6					304.6
1999	305.1	305.1					305.1
2000	306.6	306.6					306.6
2001	308.7	308.7					308.7
2002	311.5	311.5					311.5
2003	315.3	315.3					315.3
2004	319.8	319.8					319.8
2005	324.9	324.9					324.9
2006	330.4	330.4					330.4
2007	335.4	335.4					335.4
2008	340.1	340.1					340.1
2009	344.7	275.8	68.9	13.8	1.38		275.8
2010	349.6	284.0		13.8	2.76		296.4
2011	355.5	293.0		13.8	4.14		316.0
2012	362.9	303.1		13.8	5.52		335.1
2013	371.1	314.0		13.8	6.89		353.2
2014	380.1	325.4			6.89	5.50	370.1
2015	389.5	337.2			6.34	5.07	373.5
2016	399.2	349.2			5.84	4.67	372.4
2017	408.9	361.1			5.37	3.95	372.7
2018	418.2	372.8			4.94	3.64	373.9
2019	427.4	384.2			4.54	3.34	376.1
2020	436.6	395.6			4.18	3.08	379.2
2021	446.3	407.4			3.85	2.83	383.7
2022	456.7	419.9			3.54	2.60	389.6
2023	468.3	433.3			3.26	2.42	397.2
2024	481.2	447.8			2.99	2.16	406.5

Table 1. Capital Stock, Single deterministic shock with replacement investment financed by post-event borrowing.

Notes to Table 1

1. Assuming no catastrophic losses.
2. Assuming catastrophe with no replacement investment.
3. Assuming 10 percent interest rate.
4. Assuming 5-year grace period and 8 percent amortization rate.
5. Assuming catastrophic loss and replacement investment.

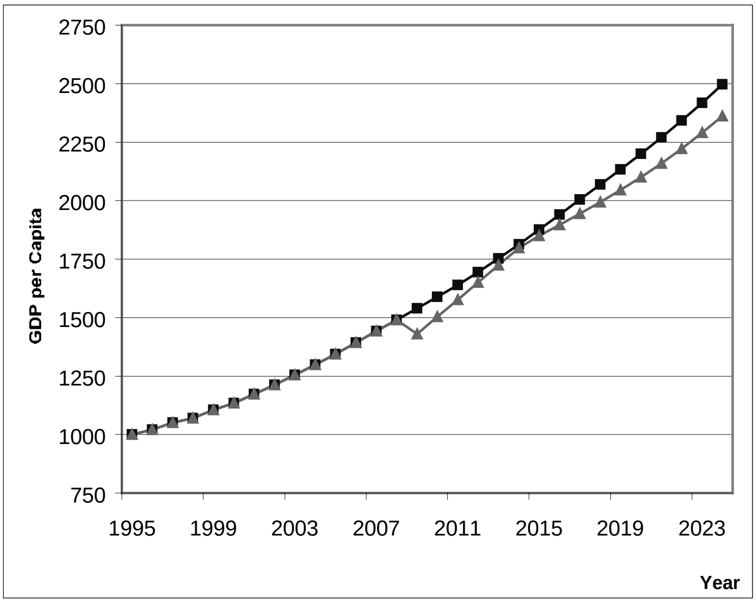

Figure 2. GDP per capita, single deterministic shock with replacement investment by post-event borrowing.

Risk exposure, calculated according to the definition above, is -0.025. It is a function of the size of the catastrophe, when the catastrophe occurs, the length of the period over which it is calculated, the rate of interest on the loan compared to the rate of return on capital in the domestic economy, and the repayment terms of the loan. In this illustrative example, the impact of the post-event borrowing strategy is to reduce risk exposure by two-tenths of a percentage point.

<u>Ex ante catastrophic risk insurance.</u> Table 2 and Figure 3 illustrate the impact of the catastrophe under the assumption that a $60 billion catastrophic risk insurance policy is in place. This policy is assumed to carry a premium rate on line (i.e., premium payments divided by coverage in place) of 2 percent.

The risk exposure index is calculated to be -0.011. While the numbers are only illustrative, they clearly provide a means of comparing alternative risk transfer strategies under alternative assumptions. To the extent that countries' ability to borrow (post-event) in international capital markets may be known, these comparisons may permit the pricing of ex ante risk transfer strategies.

Year	Baseline[1]	Alternative 1[2]	Cat Loss	Replacement Investment	Premium[3] Payments	Alternative 3[4]
1995	300.0	300.0			1.2	300.0
1996	305.3	305.3			1.2	304.1
1997	304.6	304.6			1.2	302.2
1998	304.6	304.6			1.2	301.1
1999	305.1	305.1			1.2	300.7
2000	306.6	306.6			1.2	301.1
2001	308.7	308.7			1.2	302.2
2002	311.5	311.5			1.2	304.2
2003	315.3	315.3			1.2	307.0
2004	319.8	319.8			1.2	310.6
2005	324.9	324.9			1.2	314.9
2006	330.4	330.4			1.2	319.6
2007	335.4	335.4			1.2	323.8
2008	340.1	340.1			1.2	327.7
2009	344.7	275.8	68.9	60.0	1.2	265.3
2010	349.6	284.0			1.2	331.5
2011	355.5	293.0			1.2	336.6
2012	362.9	303.1			1.2	342.9
2013	371.1	314.0			1.2	350.1
2014	380.1	325.4			1.2	357.8
2015	389.5	337.2			1.2	366.1
2016	399.2	349.2			1.2	374.8
2017	408.9	361.1			1.2	383.5
2018	418.2	372.8			1.2	392.0
2019	427.4	384.2			1.2	400.4
2020	436.6	395.6			1.2	409.0
2021	446.3	407.4			1.2	418.0
2022	456.7	419.9			1.2	427.8
2023	468.3	433.3			1.2	438.5
2024	481.2	447.8			1.2	450.4

Table 2. Capital Stock, Single deterministic shock with replacement investment financed by ex-ante risk transfer.

Notes to Table 2

1. Assuming no catastrophe.
2. Assuming catastrophe with no replacement investment.
3. Assuming $60 billion policy and 2 percent premium rate on line.
4. Assuming catastrophic loss and replacement investment.

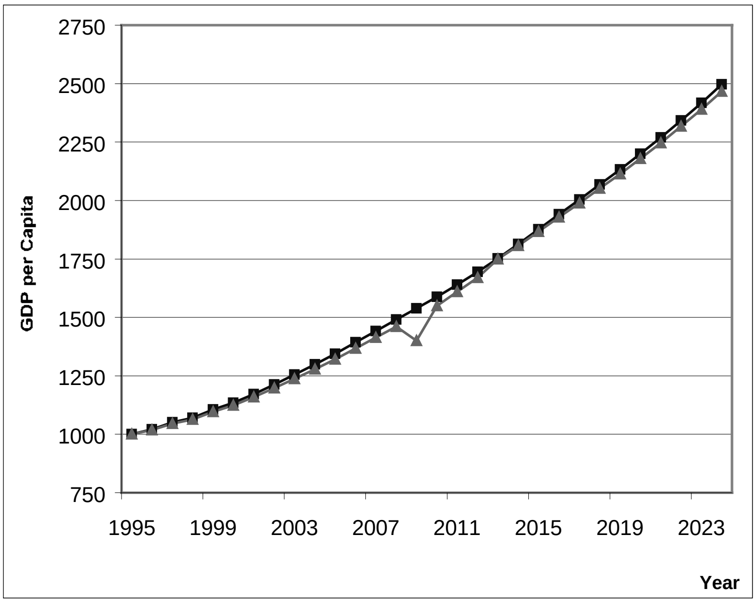

Figure 3. GDP per capita, Single deterministic shock with replacement investment financed by ex-ante risk transfer.

<u>An illustrative stochastic simulation</u>

So far, we have been dealing with a single deterministic shock. Now, we report the results of a Monte Carlo simulation in which, in every year, there is

- a 20 percent chance of an event which destroys 0.2 percent of the capital stock,
- a 5 percent chance of an event which destroys 0.4 percent of the capital stock,
- a 1 percent chance of an event which destroys 6 percent of the capital stock, and
- a 74 percent chance of no event occurring.

These event probabilities and damage estimates were calculated on the basis of 25 years of data on flood losses in a Latin American economy.

The model was initialized on an economy with per capita GDP of $5000, a population of 30 million, and a capital output ratio of 3.0. The model was solved 200 times over a 30-year solution horizon, making a draw from the distribution described above in each year of each solution run.

While still only illustrative, the loss distribution used is roughly in line with the real world, as a result of which losses are too small to illustrate with figures like Figures 1-3. Therefore, we adopt a different approach. In Figure 4, corresponding to the case of no replacement investment, the bars represent the number of solution runs (out of 200) in which the estimated risk exposure index was *less than* the figure on the horizontal axis. The further to the left, the greater the catastrophic losses and the more significant the exposure to catastrophic risk. The frequencies corresponding to the bars are measured along the left-hand vertical axis. The dotted line gives the cumulative probability (estimated on the basis of the 200 solution runs) that the risk index will be less than the figure given on the right-hand vertical axis. In Figure 4, for example, the probability that the risk index will be less than -0.0009 (i.e., risk exposure in excess of about one-tenth percent of GDP) is a bit less than 0.4. The probability that it will be lower than -0.0037 (i.e., risk exposure in excess of about four-tenths of a percent of GDP) is approximately 0.1.

Figure 5 illustrates the results of another 200-run Monte Carlo which used the same loss distribution and assumed post-event borrowing under the same conditions spelled out above in the case of a deterministic shock. Figure 6 illustrates the results of a Monte Carlo simulation assuming ex ante insurance[8]. The greater the probability mass in the right-hand side of the diagram, the lower the retained risk exposure. In this illustrative example, the insurance strategy is the ex ante. By changing assumptions on the insurance premium, it would be possible to find a price at which the country would be indifferent between post-event borrowing on assumed terms and ex ante insurance. Conceptually, then, simulations like these point towards a strategy for pricing insurance contracts and insurance-linked securities, as well as assessing economic tradeoffs between mitigation, ex post response and ex ante risk transfer.

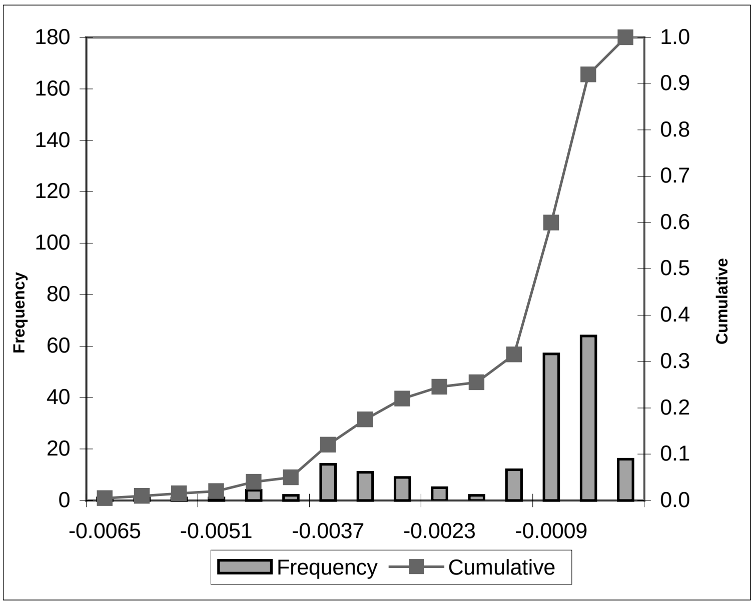

Figure 4. Risk index with no replacement investment

[8] We assume that the entire capital stock is insured with a 20 percent deductible. The premium is calculated as the actuarially fair premium times 1.1. In other words, the annual premium payment is

Premium = [(0.002 x 0.2) + (0.004 x 0.05) + (0.06 x 0.01)] x 1.1 x 0.8 x K(t)

where K(t) is the capital stock in year t. The term in square brackets is the expected annual loss, the 1.1 builds in a ten percent profit wedge, and the 0.8 reflects a 20 percent deductible. The resulting premium is extremely low, which explains why the insurance strategy illustrated in Figure 6 is clearly superior to ex post borrowing strategy.

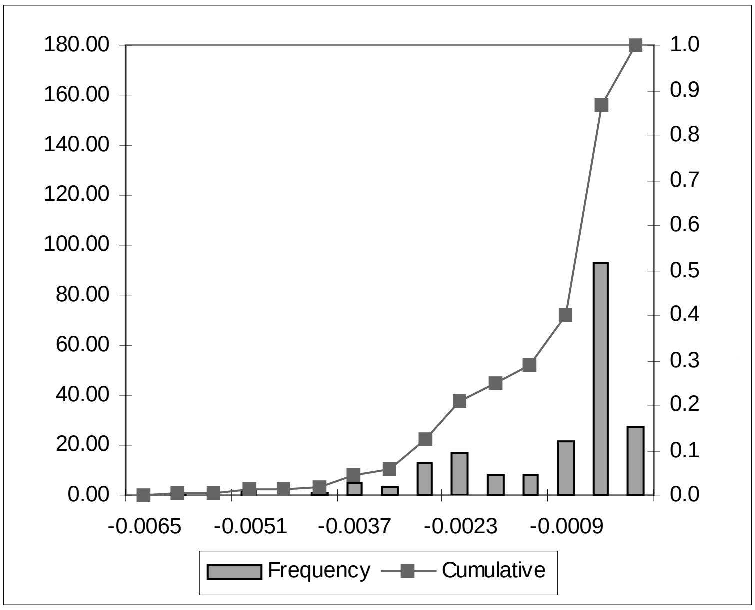

Figure 5. Risk index with replacement investment financed by ex-post borrowing.

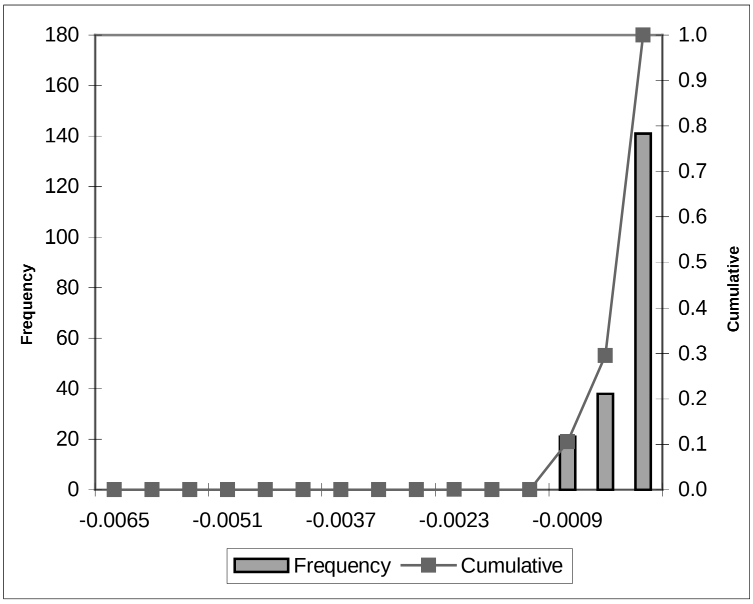

Figure 6. Risk index with replacement investment financed by ex-ante insurance.

Annex 1

A one-sector model with *ex post* foreign borrowing and *ex ante* insurance

If we generalize the model presented in the main text to allow investment to be financed by foreign borrowing in addition to domestic saving, then

$$\Delta GDP = \frac{1}{k}\left[\sigma GDP + \Delta ForDebt - rForDebt - Cat\right]$$

where $\Delta ForDebt$ is foreign borrowing and r is the international interest rate, assumed to be exogenous. This formulation embodies a number of simplifying assumptions:

- foreign capital inflows do not crowd out domestic savings (i.e., every dollar from abroad translates into a dollar of investment expenditure),
- there is no linkage between foreign debt service and the availability of domestic savings,
- we ignore amortization, and
- there is no link between foreign indebtedness and the interest rate; i.e., there is no risk premium.

Normalizing catastrophic losses *Cat* by *K*, then

$$\Delta GDP = \frac{1}{k}\left[\sigma GDP + \Delta ForDebt - rForDebt - cK\right]$$

where c is the proportion of the capital stock destroyed. The economic growth rate is

$$g = \frac{\Delta GDP}{GDP} = \frac{1}{k}\left[\sigma + \frac{\Delta ForDebt - rForDebt - cK}{GDP}\right]$$

Now, in addition to the factors given in the text, economic growth will be more rapid the higher is foreign borrowing and the lower are interest payments on existing foreign debt.

We can express the growth rate as

$$g = \frac{\sigma}{k} - c + \frac{\Delta ForDebt - rForDebt}{K}$$

Let foreign borrowing consist of two components, one "autonomous" or "regular" borrowing component denoted by a bar and foreign borrowing to replace infrastructure damaged by natural catastrophes. If the latter is a proportion *b* of capital losses, then

$$\Delta ForDebt = \overline{\Delta ForDebt} + bcK$$

and

$$g = \frac{\sigma}{k} - c + \frac{\overline{\Delta ForDebt} + bcK - rForDebt}{K}$$

or

$$g = \frac{\sigma}{k} - c(1-b) + \frac{1}{k}\left(\frac{\overline{\Delta ForDebt}}{GDP} - r\frac{ForDebt}{GDP}\right)$$

If autonomous borrowing is constant relative to GDP, say at a value *a*, then

$$g = \frac{\sigma}{k} - c(1-b) + \frac{a}{k} - \frac{r}{k}\frac{ForDebt}{GDP}$$

which may be rearranged to read

$$g = \frac{1}{k}\left(\sigma + a - r\frac{ForDebt}{GDP}\right) - c(1-b)$$

which is the expression given in the text.

Modeling risk exposure with some degree of ex ante risk transfer through the insurance market is conceptually similar. Assume that an annual premium *Prem* is paid in return for catastrophic risk coverage *Cover*. Then

$$\Delta GDP = \frac{1}{k}\left[\sigma GDP - \Pr em + \Delta ForDebt - rForDebt - (Cat - Cover)\right]$$

from which further development of the model would proceed analogously. The modeling of mitigation, catastrophe bonds, etc., within the same context does not present any fundamental conceptual problems.

Annex 2

Model Description

The IIASA model is a neoclassical two-factor multiregional economic-demographic model which, for purposes of this simulation, has been collapsed to a single region. The core of the model is a Cobb-Douglas production function. Gross domestic product (*GDP*) is

$$GDP(t) = \alpha(1+g)^t \left[\sum_a K_a(t)\right]^{\beta} \left[\sum_a L_a(t)\right]^{(1-\beta)}$$

where α is a scaling factor used to initialize the model, g is the average rate of growth of total factor productivity growth between time 0 and t, K_a is capital stock indexed by age a of claimant and L_a is labor force aged a. Based on observed factor-income shares, we assume β =0.33. Rates of return to factors are

$$R(t) = \beta\left[\frac{GDP(t)}{K(t)}\right]$$

$$\overline{Wage}(t) = [1-\beta]\left[\frac{GDP(t)}{L(t)}\right]$$

where R is the gross profit rate, including depreciation and indirect taxes net of subsidies, $\overline{Wage}$ is average (over age groups) employee compensation, and K and L are total capital stock and labor force. Age-specific saving rates and age-specific labor force participation rates are exogenous. Income and outlay corresponding to the OECD national income accounts are generated for households, firms, and government.

The main impact of a downward shock to the capital stock (which we assume to be spread uniformly across all capital) is lower GDP, a higher rate of return to capital, and a reduced real wage rate (i.e., wage rate relative to the rate of return to capital). Net savings (not only savings of households, but corporate and government savings as well) are reduced, leading to lower investment and thus lower net capital formation over and above the exogenous downward shock to capital. These negative feedback effects to investment, capital stock, and household income and savings persist in the years following the catastrophe shock. In this way, the model captures at least some of the indirect and induced impacts of catastrophic losses.

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