The Welfare Gains from Macro-Insurance Against Natural Disasters

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Abstract

This paper uses a dynamic optimization model to estimate the welfare gains that a small open economy can derive from insuring against natural disasters with catastrophe (CAT) bonds. We calibrate the model by reference to the risk of earthquakes, floods and storms in developing countries. We find that the countries most vulnerable to these risks would find it optimal to use CAT bonds for insurance only if the cost of issuing these bonds were significantly smaller than it is in the data. The welfare gains from CAT bonds range from small to substantial depending on how insurance affects the country's external borrowing constraint. The option of using CAT bonds may bring a welfare gain of several percentage points of annual consumption by improving external debt sustainability. These large gains disappear if the country can opportunistically default on its external debt.

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1 Introduction

Countries can insure themselves against the macroeconomic consequences of natural disasters in several ways. They can accumulate foreign assets as precautionary savings to be spent in the event of disasters. They can rely on crisis loans, aid and relief from the international community. Finally, they can take insurance, for example with catastrophe (CAT) bonds. Natural disasters is one of the risks that can be insured with a minimal degree of moral hazard as its occurrence is exogenous to the insuree's actions.[1] Although the market for insurance instruments against natural disasters has developed significantly, it remains small relative to the potential demand for insurance.

This paper measures the welfare gains from macroeconomic insurance against natural disasters. We use a dynamic optimization model of a small open economy populated by a representative agent. The agent's income may be reduced by natural disasters. We assume that the agent may issue noncontingent debt as well as CAT bonds whose principal is extinguished in the event of a natural disaster. We investigate the conditions under which the representative agent finds it optimal to issue CAT bonds and the implied welfare gains. In particular we derive closed-form expressions for upper bounds on the cost of insurance (the pure risk premium on CAT bonds) such that the country chooses to insure in the short run and in the long run.

The model is then calibrated by looking at the average impact of natural disasters (earthquakes, floods and storms) on growth in a sample of developing countries. We find that only the largest disasters have a significant impact on growth but that this impact is large. A large disaster lowers growth by 4 percent for one year and induces a permanent fall in the level of output (which exhibits no tendency to catch up with the pre-disaster trend). The probability of such a large disaster is between 2 and 5 percent per year for the most exposed countries.

The main results from our calibrated model are as follows. First, we find that the country is willing to issue CAT bonds if and only if the pure risk premium on CAT bonds is smaller than a fraction of a percentage point. By contrast, the available empirical evidence suggests that the pure risk premium on CAT bonds is between 1 and 4 percent. It may not seem surprising, then, that we see little issuance of CAT bonds in the data.

Second, we estimate the welfare gains from CAT bonds assuming that they can be issued at a zero risk premium—as an upper bound for the welfare gains that could be reaped from developing large and liquid markets for catastrophe insurance. We find that these welfare gains are generally moderate, although they may be substantial under some conditions. The welfare gains come from two channels. The first benefit from insurance is to smooth the country's income. We find this benefit to be fairly small—it amounts to a fraction of a percentage point of annual consumption.

The second, more indirect, benefit from insurance is that it may allow the country to borrow more. In the baseline version of our model we assume that the country can issue nondefaultable debt subject to a limit on the fraction of its output that it can pledge in repayment to foreign lenders. With noncontingent debt the maximum amount that the

[1] Moral hazard may distort preventive policies to mitigate the impact of disasters (for example, the effectiveness of antiseismic building codes). This type of moral hazard can be addressed by making the insurance contract contingent on measurable exogenous characteristics of the disaster rather than on its impact.

country can promise to repay with certainty is the maximum amount that it would repay in the worst case scenario where it is hit by a natural disaster in every period in the future. By contrast with CAT bonds the country can promise to repay amounts that are contingent on whether there is a disaster or not, and can promise to repay more if there is no disaster. As a result, the option to issue CAT bonds improves debt sustainability.[2] Under our benchmark calibration, CAT bonds allow the country to increase its external borrowing from about 30 percent of GDP to more than 60 percent of GDP. The resulting welfare gain is substantial and can amount to the equivalent of a several percentage points of consumption if the representative agent is impatient. This result is however sensitive to how the country's external borrowing constraint is modeled. If (perhaps more realistically) the borrowing constraint is determined by the risk that the country opportunistically default on its debt, CAT bonds have a relatively small impact on the country's borrowing constraint and on welfare.

This paper is at the intersection of several lines of literature. This paper is related, first, to the branch of the literature on risk management that focuses on insurance against natural disasters. This literature addresses issues faced by the actors in the financial and insurance industry, such as the optimal design and pricing of CAT bonds, or their complementarity with or substitutability to insurance contracts. For example, Härdle and Cabrera (2010) examine the calibration of a CAT bond for earthquakes sponsored by the Mexican government. Borensztein, Cavallo and Valenzuela (2009) show how catastrophic risk insurance can improve the sustainability of government debt in the case of Belize. Lee and Yu (2007) examine how a resinsurance company can increase the value of a reinsurance contract and reduce its default risk by issuing CAT bonds. Barrieu and Loubergé (2009) point out that downside risk aversion and ambiguity aversion may have contributed to the limited success of CAT bonds. Cummins (2008) and Cummins and Mahul (2009) provide facts about the CAT bonds markets that will be useful to calibrate our model.

This paper is more closely related to contributions that estimate the welfare gains from financial innovations in dynamic optimizing models of a small open economy hit by macroeconomic shocks. For example, Borensztein, Jeanne and Sandri (2013) quantify the welfare gains from hedging instruments for commodity exporters subject to commodity price risk. Caballero and Panageas (2008) show, in the context of a dynamic general equilibrium model, how optimal hedging strategies can help a country to save on precautionary savings against sudden stops in capital flows. Hatchondo and Martinez (2012) study the welfare gains from introducing GDP-indexed bonds in an optimizing model of sovereign debt and default. This paper is the first, to our knowledge, to provide estimates of the welfare gains from catastrophe insurance in a stochastic dynamic optimizing model of a country exposed to the risk of natural disasters.

Barro (2009) finds that the welfare cost of rare disasters is very large, amounting to about 20 percent of average annual income. We find that the welfare gains from insurance against natural disasters are much smaller. The difference begs explanation. The first reason is that our natural disasters have a significantly smaller economic impact than the economic disasters in Barro's study. The natural disasters in our sample are associated with a permanent fall in

[2]Interestingly, this benefit occurs even if the country chooses not to issue CAT bonds in equilibrium. The mere knowledge that it could is sufficient to relax the external borrowing constraint.

output of about 4 percent, whereas Barro's economic disasters lead to a 29 percent permanent fall in output on average. Second, Barro assumes Epstein-Zin preferences with a larger level of risk aversion than we do here. As a result, the welfare cost of the natural disaster risk is equivalent to a permanent consumption loss of 1.3 percent in our model, much lower than in Barro's. Furthermore the potential welfare gains from CAT bonds are smaller than the welfare loss from disasters for two reasons. First, CAT bonds allow countries to smooth their expenditures against falls in income caused by the disasters but they do not remove the income risk itself. Second, CAT bonds are not introduced in a vacuum but in a situation where countries can already insure by borrowing and lending abroad. Our estimates capture the welfare gains that CAT bonds bring on top of precautionary savings.

The paper is structured as follows. Section 2 presents some stylized facts about the impact of natural disasters on output and growth. Section 3 presents the baseline model. Section 4 calibrates the model and measures the welfare gains from CAT bonds. Section 5 presents two extensions of the model and section 6 concludes.

2 Stylized Facts

Natural disasters have important human and economic consequences. Although it is known that these events typically involve huge output losses in their immediate aftermath, especially in developing countries, there is little research on whether the output losses are fully recovered.[3]

Economic theory offers competing hypotheses as to the possible long-run impact of natural disasters on output and growth. Neoclassical growth models a la Solow (1956) would predict lower growth at the time of a disaster that reduces the stock of capital, followed by higher growth rates as the economy reverts to its trend. The loss of life associated with the natural disaster may reduce output permanently if the disaster has a permanent impact on population, but it does not necessarily reduce output per capita. Models rooted in a Shumpeterian view of recessions would predict that the output collapse in the aftermath of a catastrophic event may unleash the forces of creative destruction in the economy, cleansing it of inefficient firms, and leading to higher productivity and growth.[4]

By contrast, some endogenous growth theories would support the view that natural disasters induce a permanent fall in the level of output. For example, Martin and Rogers (1997) show that if future benefits of learning by doing are not fully internalized by economic agents, then recessions are periods in which opportunities for acquiring experience are forgone.[5]

[3] Rasmussen (2004) documents that of the more than 6,000 natural disasters recorded during 1970-2002, three-fourths of the events and 99 percent of the people affected were in developing countries. At the macroeconomic level, the paper finds that large natural disasters produce a median reduction in same-year GDP growth of 2.2 percentage points. Raddatz (2007) and Loayza and Christiansen (2009) find that natural disasters have an adverse short-run impact on output dynamics. Noy (2009) finds that a disaster of similar relative magnitude has a much larger macroeconomic impact in developing countries than in advanced economies. Cavallo et al. (2013) emphasize the role of political instability in the causal impact of natural disasters on growth. See Cavallo and Noy (2011) for a survey of this literature.

[4] See, for example, Caballero and Hammour (1994).

[5] The channel could also involve financial frictions. Barlevy (2003) shows that credit constraints could have a negative effect on aggregate productivity during downturns via an allocation effect. Firms with relatively

This suggests that whether output losses are fully recovered in the aftermath of natural disasters is an empirical question. In order to address it, we pursue an event study approach, taking advantage of the fact that natural disasters are purely exogenous events from the point of view of the affected country.

Our source of data for natural disasters is EM-DAT, an online emergency disaster database sponsored by the United States Agency for International Development (USAID) and the Center for Research on the Epidemiology of Disasters (CRED).[6] The EM-DAT database has worldwide coverage, and contains data on the occurrence and effects of natural disasters from 1900 to the present.[7]

CRED defines a natural disaster as a situation or event that overwhelms local capacity, necessitating a request for external assistance. For a disaster to be entered into the EM-DAT database at least one of the following criteria must be fulfilled: (1) 10 or more people reported killed; (2) 100 or more people reported affected; (3) declaration of a state of emergency; or (4) call for international assistance.[8] Since these criteria may select relatively small events of little macroeconomic significance, we identify the largest events by using somewhat arbitrary thresholds. For concreteness, we focus on three types of natural disasters: earthquakes, floods and storms. These are by and large the most common events and the ones with best data availability in the dataset. For this subsample of 4,640 events in the period 1970-2008, we measure the disaster's magnitude by the associated rate of mortality—the percentage of the population killed by the disaster as a share of the previous year's population. The summary statistics for our sample of disasters are reported in Table 1. The mortality rate is equal to 0.0028 percent on average but exceeded 0.4 percent in the 1972 Nicaragua earthquake.[9]

Table 2 in the appendix reports the 50 largest disasters in the database (above the 95th percentile of the distribution of the mortality rate) between 1970 and 2008. These are the relatively large, catastrophic and rare events that we want to isolate in this study. The top 20 (top 30) disasters correspond to disasters that are more than 0.5 standard deviations (1 standard deviation) above the average mortality rate in the sample.

It can be readily observed that the episodes cover all regions of the world, although the incidence is clearly biased towards small developing economies. Naturally, the more lenient the rule to qualify as large disaster, the less severe the event in our analysis sample will be, and the less likely are we to detect any impact on GDP per capita.

Having determined the sample of events, the next step is to trace the evolution of real GDP per capita following a disaster. To do so, we follow the event-study methodology in Cerra and Saxena (2008) based on the average behavior of the level of real GDP per capita

high productivity, but which are credit-constrained and therefore cannot face recessions successfully, may be forced to exit the market. Shedding of high productivity firms could be productivity-decreasing at the aggregate level.

[6]Available online at http://em-dat.net.

[7]The database is compiled from various sources, including UN agencies, non-governmental organizations, insurance companies, research institutions and the press.

[8]These disasters can be hydro-meteorological disasters including floods, wave surges, storms, droughts, landslides and avalanches; geophysical disasters (earthquakes, tsunamis and volcanic eruptions); and biological disasters covering epidemics and insect infestations (these are less frequent).

[9]The 2010 Haiti earthquake is reported to have led to between 150,000 and 200,000 casualties, i.e., between 1.7 and 2.2 percent of the population.

General Statistics	
Sample	1970 - 2008
Number of countries	196
Number of disasters (a)	4,640
Disaster types:	
Earthquakes	561
Floods	2,200
Storms	1,879
Mortality Rate (Deaths per million of inhabitants)	
Mean	28.03
Median	1.76
Standard deviation	213.55
Maximum	4,046.04
Minimum	0.01
95th percentile	60.99
99th percentile	439.08
Notes: (a) The number of disasters is the total number of events before yearly aggregation.	
Source: Authors' calculations based on EM-DAT database.	

Table 1: Summary Statistics.

for the selected episodes.[10]

Figure 2 shows the average level of real GDP per capita in a 12-year window centered around the event.[11] In order to take averages across countries, we normalize the level of output per capita to 1 in the year of the event. The figure compares the average behavior of real GDP per capita for the top-50, top-30 and top-20 disasters discussed above. We also include the pre- and post-disaster trends to emphasize the difference. The results show that there is a break in the pre- and post-disaster trends for the top-20 and top-30 disasters. The output drop in the year of the disaster is equal to about 2 percentage points for the top-30 disasters and about 4 percentage points for the top-20 disasters respectively. While the intercepts of the pre- and post-disaster trend lines are different, the slopes are not, suggesting the output loss is indeed permanent.

Another way of analyzing the data is by focusing on the average growth rates in real GDP per capita before and after the event. Here, rather than rescaling and indexing countries' GDP per capita series, we compute the average cross-county growth rates of real GDP per capita for every year. We look at the pre- and post-disaster averages to test if there are significant differences. Figure 3 presents the results. It shows that while there is a significant drop in growth rates in the year of the event (in the range of 2 to 4 percent), the ensuing recovery is not large enough to catch up with the pre-disaster trend. In particular, the pre- and post-disaster growth averages are not statistically different (if anything, the post-crisis growth rates are smaller).

Overall, the evidence suggests that natural disasters make growth fall by 2 to 4 percent in the year of the disaster and there is little evidence that output catches up to the pre-disaster trend afterwards. This is consistent with Hamilton's (1989) view of economic fluctuations, where output is modeled as a stochastic trend that undergoes Markov switching between positive and negative drift rates. Since the regime switch occurs in the growth rate of the permanent component of output, a negative state results in output loss that is persistent. After a collapse, output resumes growth with a positive drift, but remains on a parallel path below the original trend.

While the results are robust, it is worth stressing that they relate to a narrow subset of events, which by construction are large and rare. However, this is precisely the set of events that we want to focus as the benefits of insurance are probably less compelling for more frequent and moderate events, especially if insurance comes with sizeable transaction or other fixed costs. Moreover, in two recent papers (Barro, 2006, 2009) Robert Barro has shown that the occurrence of infrequent economic disasters has much larger welfare costs than economic fluctuations of less amplitude. Barro estimated that, for the typical advanced economy, the welfare cost associated with large economic disasters such as those experienced in the twentieth century (wars, economic depressions, financial crises) amounted to about 20 percent of annual GDP, while normal business cycle volatility only amounted to about 1.5 percent of GDP. For developing countries, which usually suffer from a larger propensity to disasters of all types, and of larger magnitude than in advanced economies, these events should have an even greater effect on the welfare of the average citizen.

[10] The data for real GDP per capita comes from the World Development Indicators and covers most countries in the world for the period 1960-2007. As a robustness check, we have used PPPP-adjusted data from the Penn World Tables but the results do not change.

[11] The results are not sensitive to the length of the window.

3 The Model

Our analysis is based on a stochastic dynamic optimizing model of a small open economy that is populated by a representative infinitely-lived consumer. The country's GDP can be negatively affected by a natural disaster, and the representative consumer can insure himself against this risk by issuing CAT bonds.

3.1 Assumptions

We consider a small open economy producing populated by a representative infinitely-lived consumer. There is one homogeneous good that is consumed at home and abroad. The representative consumer maximizes his utility

$$U_t = E_t \sum_{i=0}^{\infty} \beta^i \frac{C_{t+i}^{1-\gamma}}{1-\gamma}. \tag{1}$$

The representative consumer receives a stochastic endowment denoted by Y_t (the country's output). We will assume throughout that the output growth factor,

$$G_t = \frac{Y_t}{Y_{t-1}},$$

follows a stochastic Markov process. In order to better focus on the consequences of natural disasters, we abstract from real business cycle fluctuations and assume that domestic output grows at a constant rate in normal times (when there is no disaster). In light of the evidence reviewed in the previous section, we assume that a natural disaster lowers the growth rate for one period. Thus, we assume a two-state process: the economy is either in normal times (state $s = n$) or is hit by a natural disaster (state $s = d$). The growth factor is equal to G_n in normal times and to $G_d < G_n$ if there is a natural disaster. The probability that the economy will be in state s in the following period is constant and denoted by π_s, with $\pi_n + \pi_d = 1$.

The representative consumer invests in, or issues, two types of one-period bonds: noncontingent bonds and CAT bonds. The country's budget constraint is,

$$C_t + qB_t + q^c B_t^c = Y_t + B_{t-1} + \mathbb{1}_{s_t=n} \cdot B_{t-1}^c, \tag{2}$$

where B_t and B_t^c are the period-t country's investment in noncontingent bonds and in CAT bonds respectively, and q and q^c are their prices, assumed to be constant. The indicator variable $\mathbb{1}_{s_t=n}$ captures the fact that the CAT bond is repaid only if there is no disaster. The price of CAT bonds is lower than that of noncontingent bonds, $q^c \leq q$, because of the risk of disaster as well as premia that may be due to the investors' risk aversion, the complexity or illiquidity of CAT bonds, or to transaction costs.

The consumer's holding of noncontingent bonds, B_t, can be interpreted as the country's international reserves, unless it is be negative, in which case $-B_t$ is the country's external debt. The country can insure itself against the risk of disaster by issuing CAT bonds, i.e., by setting a negative value for B_t^c. We assume for now that bonds are default-free, which means that noncontingent bonds are always repaid and that CAT bonds are repaid if there is no disaster.

The model is flexible enough to capture various ways in which CAT bonds are used to provide insurance in the real world. A typical structure is one in which the investors purchase a safe bond, such as a U.S. Treasury bond, for the desired amount of coverage and deposit it with a special purpose vehicle (SPV) institution. The investors collect the interest on the bond plus the insurance premium that is paid by the insured party while the disaster does not occur. If the disaster strikes, however, their claim is extinguished while the SPV sells the bond and transfers the funds to the insured. This arrangement reproduces an insurance contract in which the insured party pays a premium to the insurer in good times against the promise of a compensation in bad times. It is captured by the model if one assumes that the country invests the proceeds of the CAT bond issuance in noncontingent bonds, $qB_t = -q^c B_t^c$, so that in period $t+1$ the country receives B_t if there is a disaster but pays $B_t \left(\frac{q}{q^c} - 1\right)$ to foreign investors if there is no disaster.[12]

The cost of insurance against disasters can be measured as the expected excess return that the country pays on its CAT bonds. We assume that investors receive a positive expected excess return on CAT bonds,

$$rx = \frac{\pi_n}{q^c} - \frac{1}{q} \geq 0. \tag{3}$$

This expected excess return is equal to zero in the limit case where foreign investors are risk-neutral (or the natural disaster risk is completely diversifiable) and there are no administrative cost or illiquidity premium associated with CAT bonds. Any departure from these assumptions should lead to a positive level of rx.

In order to derive the country's natural borrowing constraint, we assume that consumption cannot fall below a fraction of output,

$$C_t \geq (1-\eta)Y_t, \tag{4}$$

where η is the maximum share of domestic output that can be pledged in repayment to foreign creditors. This constraint could reflect limits on the political feasibility of repressing domestic consumption to repay foreign investors. It implies that the maximum net repayment flow from the country to its creditors is equal to a fraction η of the country's output.

3.2 Complete markets

In this section we show that because the risk is limited to two states , non-contingent bonds and CAT bonds span the same allocations as complete asset markets. The equivalence with complete asset markets will be useful to derive the equilibrium and characterize its main properties.

To introduce complete markets, let us assume that instead of CAT bonds, agents can trade Arrow securities that make state-contingent payments in the following period.[13] Then

[12] Alternatively, the country could decide to pay the insurance premium in period t rather than period $t+1$, by setting $B_t = -B_t^c$.

[13] The allocations that can be achieved in this way are the same as with an Arrow-Debreu structure with complete markets in dated contingent claims all traded at time 0.

the country's budget constraint becomes

$$C_t + \sum_{s'=n,d} \pi_{s'} m_{s'} B_{s',t} = Y_t + B_{s_t,t-1}, \tag{5}$$

where $B_{s_t,t-1}$, the security's payoff, is contingent on the state at time t, and m_n and m_d are the stochastic discount factors for evaluating the present value of next-period payoffs in states n and d respectively.

By comparing (2) and (5) one can see that the allocation with CAT bonds is equivalent to the allocation with contingent Arrow securities if and only if,

$$q = \pi_n m_n + \pi_d m_d, \tag{6}$$

$$q^c = \pi_n m_n, \tag{7}$$

that is, if CAT bonds are priced with the same pricing kernel as the Arrow securities.[14] In this case the same allocation can be achieved by holding B in non-contingent bonds and B^c in CAT bonds, or by holding $B_d = B$ and $B_n = B + B^c$ in contingent securities.

Given q and q^c, it is always possible to find m_n and m_d that satisfy equations (6) and (7). Hence the model with CAT bonds has a dual representation as a model with complete asset markets. This is stated more formally in the proposition below.

Proposition 1 *The model with non-contingent bonds and CAT bonds is equivalent to a model with a complete set of one-period contingent Arrow securities valued with the stochastic discount factors:*

$$m_n = \frac{q^c}{\pi_n}, \tag{8}$$

$$m_d = \frac{q - q^c}{\pi_d}. \tag{9}$$

Proof. See discussion above. Expressions (8) and (9) are obtained by solving for m_n and m_d in equations (6) and (7). ■

For the issuing country the cost of insurance comes from the expected excess return that must be paid to foreign investors on CAT bonds. We have assumed in (3) that this excess return is nonnegative, or equivalently that the CAT bonds have a lower price than the actuarially fair level. Using (3), (6) and (7), the expected excess return on CAT bonds can be expressed in terms of the stochastic discount factors,

$$rx = \frac{\pi_d \left(m_d/m_n - 1 \right)}{q}. \tag{10}$$

The condition $rx \geq 0$ is equivalent to assuming $m_d \geq m_n$. That is, CAT bonds yield a positive expected excess return in the dual model with complete markets if and only if foreign investors value cash more in disaster states than in non-disaster states.

[14] These relationships would have to hold by arbitrage if agents had access to frictionless markets for the four types of bonds.

It is conventional to define the "natural borrowing constraints," in this type of models, as the maximum amount that the country can borrow with a zero probability of default. The natural borrowing constraints are straightforward to derive in the dual model with contingent securities. First we assume that,

$$\Phi \equiv \pi_n m_n G_n + \pi_d m_d G_d < 1. \tag{11}$$

This condition is the stochastic analog of the Golden Rule which requires (under perfect foresight) that the growth rate be smaller than the interest rate. Condition (11) is necessary for the representative consumer to have a well-defined intertemporal budget constraint.

Then we have the following proposition.

Proposition 2 *The natural borrowing limits on the country's state-contingent external debt are given, for $s' = n, d$, by,*

$$\forall t, \quad B_{s',t} \geq \underline{b}_{s'} Y_t,$$

where.

$$\underline{b}_{s'} \equiv -\frac{\eta G_{s'}}{1-\Phi}. \tag{12}$$

Proof. See Appendix. ■

The natural borrowing constraint is the maximum amount of external debt that the country can credibly promise to repay with certainty, given that it cannot pledge more than a fraction η of its output in repayment to foreigners (see equation (4)). Because pledgeable income is proportional to output, so is the natural borrowing constraint. The country can promise a higher repayment contingent on the normal state than contingent on a disaster ($\underline{b}_n < \underline{b}_d$).

The natural borrowing constraints can be transposed to the model with CAT bonds as follows,

$$\begin{aligned} B_t &\geq \underline{b}_d Y_t, \\ B_t + B_t^c &\geq \underline{b}_n Y_t, \end{aligned}$$

where $\underline{b}_d$ and $\underline{b}_n$ are given by (12). There is one constraint for noncontingent bonds and another (less strict) constraint for the sum of noncontingent bonds and CAT bonds.

A property that will turn out to be important for the following results is that the natural borrowing constraint for noncontingent bonds depends on whether CAT bonds are available. In the absence of CAT bonds the natural borrowing constraint must ensure that the country can repay its debt under all circumstances, including the worst-case scenario in which growth is low in every period in the future. The natural borrowing constraint then becomes,

$$\begin{aligned} B_t &= \sum_{i=1}^{+\infty} q^i \left(C_{t+i} - Y_{t+i}\right), \\ &\geq -\eta \sum_{i=1}^{+\infty} q^i Y_{t+i}. \end{aligned}$$

The first equation is the country's intertemporal budget constraint and the inequality in the second equation comes from (4). For the probability of default to be zero, this inequality has to be satisfied even in the worst-case scenario where the growth rate would be low in all the subsequent periods, so that $Y_{t+i} = (G_d)^i Yt$. Hence one must have $B_t \geq \underline{b} Y_t$ where $\underline{b}$ is given by,

$$\underline{b} = -\eta \frac{G_d}{1 - qG_d}. \tag{13}$$

Note that

$$\underline{b} > \underline{b}_d,$$

that is, the natural borrowing constraint on noncontingent debt is less strict if the country can issue CAT bonds, or to put it differently, the country can issue more noncontingent debt provided it can also issue CAT bonds. This is true even if the country does not issue CAT bonds in equilibrium—the mere possibility that it could do so out of equilibrium is sufficient.

The intuition is that CAT bonds allow the country to pledge more domestic output in repayment to foreign lenders, because more output can be promised in the nondisaster state than in the disaster state. This implies that the country can issue more noncontingent debt because it will be better able to roll over this debt in the future by issuing CAT bonds. This is true irrespective of the cost of issuing CAT bonds because what counts for the natural borrowing constraint is the country's ability to repay subject to (4), not its willingness to repay.[15]

3.3 Equilibrium

We derive the equilibrium in the dual model with contingent securities. The consumer's problem is made stationary by normalizing all variables by output. Normalized variables are denoted with lower-case letters, for example $b_t = B_t/Y_t$. It will be convenient to define as a state variable the country's current resources in period t,

$$X_t = Y_t + B_{s_t,t-1}, \tag{14}$$

that is, the representative consumer's current income plus his beginning-of-period external assets.

The normalized Bellman problem for the consumer can then be written,

$$v(x) = \max_{b_n, b_d} \left\{ \begin{array}{c} \frac{1}{1-\gamma} \left(x - \sum_{s'=n,d} \pi_{s'} m_{s'} b_{s'} \right)^{1-\gamma} + \beta \sum_{s'=n,d} \pi_{s'} G_{s'}^{1-\gamma} v(x') \\ + \sum_{s'=n,d} \pi_{s'} \lambda_{s'} \left(b_{s'} - \underline{b}_{s'} \right) \end{array} \right\}, \tag{15}$$

where $\lambda_{s'}$ are the costate variables for the borrowing limits and the transition equation for current resources is given by $x' = 1 + b_{s'}/G_{s'}$.

[15] The results are different if the country's willingness to repay is limited, as we will see in section 5.1.

The equilibrium can be characterized by three policy functions, $c(x)$, $b_n(x)$ and $b_d(x)$, giving respectively consumption and the country's portfolio of contingent securities as functions of current resources. The equilibrium policy functions can solved for numerically using a simple extension of Carroll's (2006) endogenous grid points method, as shown in Appendix B. This equilibrium can then be "translated" into the equilibrium of the model with CAT bonds by setting $b(x) = b_d(x)$ and $b^c(x) = b_n(x) - b_d(x)$.

One question is whether the country finds it optimal to insure against natural disasters. Issuing CAT bonds means $B^c < 0$, or equivalently $B_d > B_n$, i.e., the country's debt burden is reduced by a natural disaster. We adopt a slightly more demanding criterion, which is that the country's debt-to-GDP ratio (and not only its debt level) is reduced by a natural disaster:

Definition 3 *The country uses CAT bonds for insurance in period t if it issues enough CAT bonds to reduce its debt-to-GDP ratio in a disaster,*

$$b_t^c < \min\left[0, \left(\frac{G_n}{G_d} - 1\right) b_t\right]. \tag{16}$$

The country issues CAT bonds if $b^c < 0$. In addition, the definition above requires that if the country issues noncontingent debt ($b < 0$), then it also issues an amount of CAT bonds that is high enough to reduce the ratio of total debt to GDP in a disaster. This requirement can be written as $-b/G_d < -(b + b^c)/G_n$, which, together with $b^c < 0$, is equivalent to the condition given in Definition 3. We choose this criterion because it gives a simple necessary condition on the cost of insurance for insurance to be observed in equilibrium, as stated below.

Proposition 4 *The country uses CAT bonds for insurance in any period t only if,*

$$m_d G_d^{\gamma} < m_n G_n^{\gamma}, \tag{17}$$

or equivalently, if the excess return on CAT bonds is lower than a threshold,

$$rx < rx^* \equiv \frac{\pi_d}{q}\left[\left(\frac{G_n}{G_d}\right)^{\gamma} - 1\right]. \tag{18}$$

Proof. See Appendix. ■

The representative consumer wants to insure against natural disasters but insurance is costly. When the cost of insurance is too high the consumer prefers not to issue CAT bonds, and may even want to hold them ($b^c > 0$) if the excess return on CAT bonds is high enough. Proposition 4 provides an upper bound on the cost of insurance for the country to be willing to ensure in any period t.[16]

[16] A realistic constraint on the consumer's problem is $b^c \leq 0$, because it is unlikely that nonresidents would be willing to issue CAT bonds at a discount. Condition (18) can then be interpreted as a condition for the market for CAT bonds to exist, or at least to exceed a fraction $G_n/G_d - 1$ of the noncontingent bonds issued by the country.

Condition (18) is necessary for CAT bonds to be used for insurance but it is not sufficient. We can derive a condition that is both necessary and sufficient but it holds only in the long run. We shall say that the country insures in the long run if the probability that it issues CAT bonds for insurance in the future does not go to zero as the time horizon goes to infinity, i.e.

$$\lim_{t\to+\infty} \Pr\left\{ b_t^c < \min\left[0, \left(\frac{G_n}{G_d} - 1\right) b_t\right]\right\} \neq 0.$$

A condition that is both necessary and sufficient for the country to insure in the long run is stated in the following proposition.

Proposition 5 *The country uses CAT bonds for insurance in the long run if and only if,*

$$m_d G_d^\gamma < \beta < m_n G_n^\gamma, \tag{19}$$

or equivalently, if the excess return on CAT bonds is lower than a threshold,

$$rx < \min\left(\frac{\pi_n}{q - \beta\pi_d G_d^{-\gamma}}, \frac{G_n^\gamma}{\beta}\right) - \frac{1}{q}. \tag{20}$$

Proof. See Appendix. ■

Compared to Proposition 4 this result adds a condition about the discount factor β, which should be neither too high not too low. The intuition is as follows. First, a consumer who is "too patient" ($\beta \geq m_n G_n^\gamma$) prefers to insure by accumulating large amount of international reserves rather than by issuing CAT bonds. One can show that the ratio of reserves to GDP, b_t, grows without bound, a result that is reminiscent of the well-known result in the precautionary savings literature that consumption and financial wealth grow without bound if the consumer's psychological discount rate is smaller than the interest rate. "martingale result" in the precautionary savings literature.[17] Furthermore, if insurance is costly ($rx > 0$) the consumer would like to hold some of his external assets in the form of CAT bonds, i.e., the country wants to be long rather than short on CAT bonds.[18]

Second, if the representative consumer is "too impatient" ($\beta \leq m_d G_d^\gamma$) his overriding concern is to borrow rather than insure. Recall that the consumer's natural borrowing constraints are,

$$\begin{aligned} b_t &\leq \underline{b}_d, \\ b_t + b_t^c &\leq \underline{b}_n. \end{aligned}$$

The second equation shows that there is a borrowing limit for the sum of noncontingent debt and CAT bonds. Thus issuing CAT bonds may reduce the quantity of noncontingent debt that the country can issue, as well as the net proceeds from borrowing since CAT bonds sell for a lower price than noncontingent debt. An impatient country issues as much noncontingent debt as possible, $b_t = \underline{b}_d$, and then the extra amount of CAT bonds that

[17] The condition $\beta < m_n G_n^\gamma$ is the analog of what Carroll (2008) calls the "impatience condition" in his model with incomplete markets

[18] This and the other claims made to explain Proposition 5 can be found in the proof of the proposition.

γ	G_n	G_d	π_d	η	q	β
2	1.02	0.98	0.02	0.02	1.05^{-1}	1.04^{-1}

Table 2: Benchmark Calibration

can be sold to foreign investors after the country's capacity to issue noncontingent bonds has been exhausted, $b^c = \underline{b}_n - \underline{b}_d$. But in this case the CAT bonds are issued not so much for insurance as a source of extra borrowing. Furthermore they amount to a small share of noncontingent debt and they (equal to $G_n/G_d - 1$ in the long run).

4 Quantitative Results

4.1 Calibration

The benchmark calibration is given in Table 2. The value for relative risk aversion, $\gamma = 2$, is standard in the literature. The growth rate is equal to 2 percent in normal times and falls to minus 2 percent when a natural disaster occurs. This is consistent with the average fall in growth observed in the "top-20 disasters" (see Figure 2 and 3). A disaster thus reduces the level of output by 4 percent forever, implying a loss in the present discounted value of the country's income amounting to 136 percent of GDP.[19]

The probability of disaster is set to 2 percent per year. This probability is calibrated by reference to the sample of disasters listed in Table 2. For the 37 countries that are listed in Table 2, the unconditional probability of having a top-20 disaster (with a mortality rate above one standard deviation) was 1.39 percent per year between 1970 and 2008.[20] The in-sample probability of "top-20" disaster was 5.13 percent for the four countries that had two such disasters between 1970 and 2008 (Honduras, Solomon Islands, Vanuatu, Dominican Republic). Thus a plausible range of variation for the probability of disaster is between 1 and 5 percent. Our benchmark calibration of π_d is at the lower end of this interval.

We assume that the riskless interest rate is equal to 5 percent. We assume that the country cannot pledge more than 2 percent of domestic output in repayment to foreign creditors. This is a low value but it still allows the country to issue a fairly large amount of external debt. If insurance were costless (so that $m_n = m_d = q$), equation (12) would imply $\underline{b}_n = -0.6954$ and $\underline{b}_d = -0.6682$, i.e., the country's external noncontingent debt can reach 66.8 percent of its output.

Finally, we assume that the consumer's discount rate is 4 percent. Because $\beta > q$ the consumer's desire to borrow comes from the expected growth in his income.

[19] The expected PDV of the country's income, V, satisfies $V = Y + q[(1-\pi)G_n + \pi G_d]V$, implying, with the parameter values of Table 2, $V = 34.1 \cdot Y$. A 4 percent fall in Y thus reduces V by 136.4 percent of Y.

[20] In the full sample of 196 countries this unconditional probability is reduced to 0.26 percent. However, this lower probability is obtained by averaging the high-risk countries listed in Table 2 with a large number of low-risk countries that did not have a large disaster. We are interested here in the high-risk countries for which insurance is likely to be most beneficial.

4.2 Cost of macro-insurance

We have not yet calibrated the cost of insurance rx. The evidence in Cummins (2008) and Cummins and Mahul (2009) suggests that the expected excess return rx exceeds 1 percent, sometimes by a large margin. Cummins and Mahul (2009) report that the average ratio of premium to expected loss declined from about 6 in 2001 to about 2 in 2005 as the market for CAT bonds developed, before it increased in response to the 2005 hurricane season. Under our benchmark calibration, the expected annual loss is 2 percent (the probability of a natural disaster) and a ratio of 2 means that CAT bonds delivered an excess return of 2 percent. If the excess return is proportional to the expected loss it could be smaller for CAT bonds that have a lower disaster risk. For example, Cummins (2008) reports that a CAT bond issued by the Mexican government in 2006 (at a time when the cost of insurance was low) had an expected annual loss of 0.96 percent and a spread over LIBOR of 2.35 percent. This implies, in the context of our model, a cost of insurance of $rx = 2.35 - 0.96 = 1.39$ percent. The updated evidence presented in Cummins (2012) suggests that the cost of insurance was still in excess of 1 percent as of 2011. Since the expected annual loss varies between 1 and 2 percent for most CAT bonds, it seems reasonable to assume a lower bound of 1 percent for the cost of insurance rx.

However for the parameter values in Table 1 the maximum value of rx consistent with using CAT bonds for insurance in the short run, given by equation (18), is $rx^* = 0.17\%$. The maximum value consistent with using insurance in the long run, given by (20), is 0.11%. Thus condition (18) is violated in the data, by a wide margin. The observed cost of insurance seems too large by a factor ten for countries to be willing to issue CAT bonds for insurance. It may not seem surprising, then, that we see little issuance of CAT bonds in the data.

This begs the question of why the cost of macro-insurance against natural disasters is so high in the real world. The model with complete markets, in which this cost comes entirely from the fact that investors value liquidity more in the disaster state, is unlikely to give a plausible explanation. Investors may value liquidity more in the disaster state, but not to an extent that can explain the observed excess return on CAT bonds. Expression (10) should imply a cost of insurance that is small, because the probability of a disaster π_d is small, and the premium put on liquidity in the disaster state, $m_d/m_n - 1$, should not be very large either. First, the risk of natural disasters in developing countries is not very large for the global investor community (at least at current levels of insurance) and second, this risk is not very correlated with other insured risks.

The high expected excess return rx is more likely to be due to complexity and illiquidity premia or administrative costs that are not taken into account by a model with frictionless complete asset markets.[21] It is important to keep these frictions in mind if one wants to understand the potential welfare benefits of policies that reduce the cost of macro-insurance through CAT bonds.[22]

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[21] The presence of administrative costs does not invalidate the equivalence between the model with CAT bonds and the model with complete assets markets insofar as the optimal behavior of the small open economy is concerned. This behavior depends on the level of the expected excess return on CAT bonds, not on whether this level reflects a pure risk premium or other causes.

[22] See Froot (2001) and Cummins and Mahul (2009) for discussions of the market imperfections that may contribute to restrict the supply and raise the cost of catastrophe insurance.

Some of these costs might be reduced, raising the question of the welfare gains that might be thus obtained. In the next section we compute the welfare gains from CAT bonds when rx is low enough for the country to insure.

4.3 Welfare gains from macro-insurance

We first assume that insurance is costless ($rx = 0$). Figure 4 shows how b and b^c vary with current resources x. When its resources are low the country must borrow, and issues mostly noncontingent debt because issuing CAT bonds is costly in terms of current consumption (however it still issues a small fraction of its debt in the form of CAT bonds). When the country's resources are high it accumulates reserves and issues substantial amounts of CAT bonds. For example the country issues 43.6 percent of its GDP in CAT bonds when its international reserves amount to 50 percent of its GDP.

To see the amount of CAT bonds that the country issues *on average*, we ran simulations of the model for 10,000 periods and computed the average level of b and b^c (excluding the first thousand periods). Figure 5 shows how the average levels of noncontingent and CAT bonds vary with the cost of insurance rx when rx stays low enough to be consistent with long-term insurance (i.e., lower than 0.1%). It appears that even when insurance is costless ($rx = 0$) the average amount of CAT bonds is relatively small, about 6.5 percent of GDP or one tenth of the noncontingent debt. The reason is that the representative consumer is relatively impatient and prefers to borrow rather than insure in the long run. The average amount of CAT bonds decreases with the cost of insurance, to 2.9 percent of GDP when $rx = 0.1$ percent, while noncontingent debt increases. As a result the debt reduction implied by a disaster is much smaller than the loss in the country's present discounted value of income that is caused by the disaster (which amounts to 136.4 percent of the country's GDP).

Next, we look into the welfare gains from introducing CAT bonds. As is standard in the literature, we express the welfare gains from insurance as the equivalent increase in consumption starting from an equilibrium without insurance, i.e.,

$$\alpha(x) = \left(\frac{v(x)}{\widetilde{v}(x)}\right)^{1/(1-\gamma)} - 1,$$

where $\widetilde{v}(x)$ is the level of welfare in the economy without CAT bonds, and x is the level of resources when CAT bonds are introduced. Figure 6 shows the variations of α with x.

The welfare gains from CAT bonds are relatively large. They decrease with the current level of resources, from about 0.9 percent of consumption when current resources are at their minimum to about one half of this level when current resources amount to about four times GDP. The average welfare gain from introducing CAT bonds (based on the same simulations as for Figure 5) is about 0.85 percent of consumption if rx is small enough for the country to issue CAT bonds in the long run. This is significantly larger than most measures of the welfare cost of the business cycle even for developing countries.[23] To illustrate the size of the welfare gains from macroinsurance with a different metrics, introducing CAT bonds yields

[23] Lucas (1987) estimated the welfare gain from eliminating the business cycle in advanced economies at one-tenth of a percent of consumption. Pallage and Robe (2003) have found business cycle fluctuations to be more costly in developing countries than in advanced economies because their economies are more volatile.

the average welfare gain as a one-time wealth transfer amounting to about 16 percent of GDP.

The welfare gains from CAT bonds are significant but they come primarily from the relaxation of the natural borrowing constraint. By equation (13) the natural borrowing constraint in the absence of CAT bonds is $\underline{b} = -0.294$. That is, the ability to issue CAT bonds allows the country to increase it maximal issuance of noncontingent debt from 29.4 percent to 66.8 percent of GDP.

To understand better the nature of the welfare gains, we look how the economy responds to the introduction of CAT bonds. Figure 7 shows the path for the stocks of noncontingent debt and CAT bonds as well as the current account balance (all in share of GDP) assuming that the country can issue CAT bonds from period 0 onwards. It is assumed that the country is in the steady state with $b = \underline{b}$ before the introduction of CAT bonds, and that no disaster is observed before or after the introduction of CAT bonds. In period 0 the country issues about 30 percent of its GDP in CAT bonds and use the proceeds first to reduce its stock of noncontingent debt by about 20 percent of GDP and second to finance a current account deficit amounting to 10 percent of GDP. The reason is that the country is far from its borrowing limit for noncontingent debt (which has suddenly been relaxed by the introduction of CAT bonds) and uses the spare room to both consume and insure more. The initial reaction, however, is reversed in the following periods: the country starts to reduce its stock of CAT bonds and switches back to noncontingent debt, as the desire to borrow increasingly dominates the insurance motive. In the long run (which is reached in seven years) the country issues only a relatively small stock of CAT bonds—about 6 percent of its GDP, less than one tenth of its stock of noncontingent debt.

Most of the gain comes from relaxing the external debt constraint, which leads to a temporary consumption boom. If one shuts off this channel, the welfare gains from consumption smoothing are much smaller. One can shut off the balance sheet channel by assuming that the borrowing limit for noncontingent debt is not relaxed by the introduction of CAT bonds, i.e., it remains (13). Then the residual welfare gains from CAT bonds do not exceed 0.04 percent of consumption.[24]

4.4 Sensitivity analysis

This section presents some sensitivity analysis of the welfare gains from CAT bonds with respect to the main model parameters. We assume $rx = 0$ throughout. The first sensitivity exercise is with respect to the discount factor β. Figure 8 shows the variations of the average level of noncontingent bonds and CAT bonds with β, for values of β in the interval implied by condition (19). For β smaller than 0.98 the borrowing motive dominates and the consumer issues mostly noncontingent debt. This is the case that we have seen under the benchmark calibration. But when β exceeds 0.98 the consumer start to switch the composition of his balance sheet, being short on CAT bonds and long on noncontingent debt. As discussed following Proposition 5 this is because the insurance motive dominates the borrowing motive

[24]These welfare gains are even smaller than the welfare cost of the business cycle for developing countries. Remember, however, that the insurance is against a risk that occurs very rarely (with probability 2 percent per period), and that the risk is covered only partially (the country receives less than 10 percent of its GDP whereas the cost of the disaster in terms of intertemporal income is in excess of 100 percent of GDP.)

and the consumer insures by issuing CAT bonds to finance a stock of reserves. When β is close to the upper bound implied by condition (19) the country issues CAT bonds to finance a stock of reserves and these gross positions can be very large.

Figure 9 shows the variations of the welfare gain from CAT bonds with β. The solid line shows the total welfare gain whereas the dashed line represents the welfare gains from insurance only (computed by assuming that the borrowing constraint on noncontingent bonds is not relaxed by CAT bonds). The total welfare gains decrease with β because most of the gains come from relaxing the borrowing constraint, and these gains are smaller when the consumer is more patient. The welfare gains from insurance remain relatively small, even when β is larger than 0.98 and the country issues large amounts of CAT bonds.

We also performed sensitivity analysis with regard to the other parameters of the model. The results are not reported here but a summary follows. Increasing risk aversion strengthens both the borrowing motive and the insurance motive. It does not have a significant impact on the average stocks of noncontingent and CAT bonds, which are already close to the maximum levels under the benchmark calibration. The welfare gains from CAT bonds increase with risk aversion (to about 3.5 percent of consumption if $\gamma = 10$) but this comes primarily from the relaxation of the borrowing constraint on noncontingent debt. The welfare gains from insurance increase with risk aversion but do not exceed 0.2 percent of consumption if γ remains below 10.

The average composition of the debt is not very sensitive to the disaster probability π_d. The welfare gains from CAT bonds decrease with the risk of a disaster, as the country derives less benefits from a looser external credit constraint if disasters are more likely. The welfare gain from insurance increases with the probability of a disaster but remain small (they do no exceed 0.04 percent of consumption even if the disaster probability is 5 percent instead of 2 percent).

5 Extensions

We present in this section two extensions of the baseline model. The first extension assumes that the country can default opportunistically on its external debt. The second extension introduces a nontradable good in the baseline model.

5.1 Defaultable debt

We analyze in this section an extension of the model where the country can default on its external debt. Like in much of the literature on sovereign debt, the government is assumed to default in an opportunistic way, if and only defaulting raises domestic welfare. The question is how relaxing the assumption of commitment to repay changes the welfare gains from macro-insurance.

We consider the dual model with complete markets and assume that in every period t the country can default on its state-contingent liabilities. A default means that the country's external liabilities are reduced by a fraction h (the haircut). The country's normalized liabilities before default amount to $1 - x_t$ at the beginning of period t, and a default raises the country's normalized current resources from x_t to $x_t + h(1 - x_t)$. This is the benefit of defaulting. But defaulting may be costly, for example because it cuts off the country from access to international financial markets or because of an output loss. For simplicity we model the cost of defaulting in period t as a penalty that reduces the country's welfare by $d \cdot Y_t^{1-\gamma}$, where d is an exogenous positive parameter. Since the borrowing constraint is now determined by the country's willingness to repay we do not need to set an exogenous limit on the fraction of output that the country can pledge to foreign lenders. We accordingly set $\eta = 1$.

Like in the dynamic optimization literature on sovereign default (Aguiar and Gopinath (2006), Arellano (2008)) there is a threshold in current resources, x^*, such that the country defaults if and only x_t is lower than x^*. The default threshold is the level that makes the country indifferent between defaulting and not defaulting,

$$v^R(x^*) = v^R(x^* + h(1 - x^*)) - d,$$

where $v^R(\cdot)$ is normalized welfare conditional on repayment.

The threshold x^* is the same in the disaster state as in the non-disaster state. Since $x_t = 1 + b_{s_t,t-1}/G_{s_t}$ the level of x^* determines default thresholds for the contingent bonds as follows,

$$\underline{b}_s = G_s(x^* - 1). \tag{21}$$

In equilibrium the country never borrows more than this default threshold since this would imply a sure default conditional on the realization of state s. This is a difference with the models of default on non-contingent debt such as Arellano (2008) in which default can occur in equilibrium. Once debt is contingent, it is possible to avoid default by keeping debt below the default threshold for each state. Thus the model with default implies the borrowing constraint,

$$b_{s,t} \geq \underline{b}_s,$$

where $\underline{b}_s$ is given by (21). One can easily see that the borrowing constraint given by (21) is the same as the natural borrowing constraint in the baseline model, given by (12), if $\eta = (1 - \Phi)(1 - x^*)$. Hence the equilibrium in the model with defaultable debt is the same as in the baseline model for suitably chosen values of η and x^* (or d). This is stated in the following proposition.

Proposition 6 *The equilibrium in the model with defaultable debt is the same as in the baseline model if the share of pledgeable output is given by,*

$$\eta = (1 - \Phi)(1 - x^*),$$

where x^* is the default threshold.

Proof. See discussion above. ■

The model with defaultable debt is isomorphous to the baseline model. For any default cost d, there is a level of η (and for any η there is a level of d) that makes the two models equivalent. Hence the results derived for the baseline model, such as Propositions 4 and 5, also apply to the model with defaultable debt.

The two models differ, however, in the welfare gains from CAT bonds. In the absence of CAT bonds the borrowing constraint for noncontingent debt is still given by (21). The level of the default threshold x^* depends in general on whether CAT bonds are available but it is not clear a priori whether CAT bonds increase or decrease x^*, and so whether they relax or restrict the borrowing constraint for noncontingent debt. Another difference is that without CAT bonds the country might default on its debt if there is a disaster. Defaultable debt provides a form of insurance against natural disasters, but it is rather different from CAT bonds. The level of insurance is determined by the level of debt and by the haircut. The cost of insurance is not the excess return rx but the cost of defaulting d. It is not clear a priori how these various effects affect the welfare gains from CAT bonds.

To estimate the welfare gains from CAT bonds in the model with defaultable debt, we assume $rx = 0$ and $d = 0.3$. This value of d implies $x^* = 0.3534$ in the model with defaultable debt and CAT bonds, which is equivalent to the baseline model with $\eta = 0.019$ (a value that is close to the level of 0.02 assumed in the benchmark calibration).[25] The other parameters are the same as in the benchmark calibration (Table 2).

We then estimate the welfare gain from introducing the CAT bonds in the model with defaultable debt. Figure 10 shows the variations with the discount factor β of the average welfare gain from introducing CAT bonds into the model with defaultable debt (based on the same simulations as for Figure 5, 8 and 9). Figure 10 is the analog of Figure 9 for the model with defaultable debt. We observe that with defaultable debt the welfare gains from CAT bonds are much smaller than the total welfare gains in the baseline model (the solid line in Figure 9), and of the same order magnitude as the welfare gains from insurance only (the dashed line in Figure 9). The reason is that with defaultable debt CAT bonds have a relatively small impact on the default threshold. We find that CAT bonds lower the default threshold, and so enhance the country's ability to borrow, but only by a small amount (x^* is reduced by less than 0.006 for the range of values of the discount factor considered in Figure 10). In the absence of CAT bonds the country is able to insure against disasters through default (default occurs only when there is a disaster and the probability of a default conditional on a disaster is always larger than 80 percent for the parameter values considered in Figure 10).

5.2 Real exchange rate

We now assume that the representative consumer consumes a tradable good and non-tradable good, and receives exogenous endowments of both goods, Y_{Tt} and Y_{Nt}. External debt is denominated in tradable good. The consumption index is given by,

$$C = \left[\sigma^{1/\theta} C_T^{(\theta-1)/\theta} + (1-\sigma)^{1/\theta} C_N^{(\theta-1)/\theta}\right]^{\theta/(\theta-1)}.$$

We assume that the growth rate is the same for the endowments in tradable good and in nontradable good. Thus the ratio Y_N/Y_T is constant: we normalize it to $(1-\sigma)/\sigma$, so that the relative price of the two goods would stay equal to 1 if the representative consumer

[25] The model with defaultable debt is resolved using an extension of the endogenous gridpoint method along the same lines as in Villemot (2012). Details are available upon request to the authors.

consumed the endowments. We denote with lower-case letters the level of the variables normalized by tradable output, e.g. $c_{Tt} = C_{Tt}/Y_{Tt}$, $c_{Nt} = C_{Nt}/Y_{Tt}$. Then the price of the tradable good in terms of nontradable good, denoted by p_t, satisfies,

$$p_t = c_{Tt}^{\theta}.$$

This is a measure of the real exchange rate (a real appreciation corresponds to an increase in p).

The equilibrium can then be solved for like before, the main difference being that the marginal utility of consuming the tradable good which appears in the Euler equation can be written in normalized form,

$$\frac{\partial c}{\partial c_T} c^{-\gamma} = \sigma^{\frac{1-\gamma}{\theta-1}} c_T^{-1/\theta} \left(c_T^{\frac{\theta-1}{\theta}} + \frac{1-\sigma}{\sigma} \right)^{\frac{1-\gamma\theta}{\theta-1}}.$$

We assume that the country can pledge a fraction η of tradable output in repayment to foreign creditors, i.e., equation (4) applies to the consumption and the output of tradable good. Our benchmark calibration for the revised model is $\sigma = 0.3$ and $\theta = 1$. The rest of the calibration is the same as in Table 2 and we assume insurance is costless ($rx = 0$).

We summarize below the properties of the extended model with two goods (details are available upon request). The impact of a disaster on the real exchange rate depends on whether CAT bonds are available. Without CAT bonds, a disaster reduces the relative consumption of tradable good and so depreciates the real exchange rate. By contrast with CAT bonds, a disaster reduces the consumption of nontradable good more than the consumption of tradable good and the real exchange rate appreciates on impact. The welfare gains from CAT bonds are smaller than in the benchmark model as these bonds insure only the tradable component of total consumption. These gains increase with the elasticity of substitution between the two goods, and are the same as in the benchmark model if the two goods are perfectly substitutable. Overall, introducing a real exchange rate into the baseline model does not substantially affect the main results.

6 Conclusion

We have measured the welfare gains from insurance against natural disasters in a small open economy populated by a representative consumer. The evidence suggests that large disasters have a permanent effect on the level of output and so entail a large loss of intertemporal income. Insurance yields two kinds of welfare gains in our model: first, it smoothes domestic income and consumption and second, it allows the country to issue a larger quantity of default-free debt. There is a trade-off between these two benefits since issuing more debt means that debt is less state-contingent and there is less income smoothing. We find that the welfare gains from insurance may be large (and amount to several percentage points of annual consumption) for the countries that use CAT bonds primarily as a way of borrowing more rather than smoothing income and consumption.

There are two important caveats to the conclusion that CAT bonds may yield large welfare gains. First, countries will avail themselves of CAT bonds only if the pure risk premium is much smaller than it is in the data. Second, most of the gains—when they are large—come from relaxing the country's external borrowing constraint rather than from insurance per se, and the existence of these gains depend on how the constraint on the country's pledgeable income is modeled. CAT bonds can significantly relax the external borrowing constraint in our baseline model, where it is assumed that the country can pledge a fixed fraction of its output in repayment to foreigners. These large gains disappear if we assume instead that the country can opportunistically default on its external debt.

The approach taken in this paper relies on a specific definition of insurance against natural disasters. Macroeconomic insurance against natural disasters serves the same purpose as car insurance for individuals: it insures against the income loss caused by the accident. Our model does not capture the fact that insurance might reduce the output cost of a disaster, for example by allowing the country to reconstitute more quickly the physical or human capital lost in the disaster. It also does not take into account certain welfare costs of disasters that may be large in practice—such as the emotional disutility associated with injuries or deaths caused by the disaster.

The model could be extended in several directions. First, it could include productive capital and international financial frictions (a natural disaster might destroy a fraction of the domestic capital stock and at the same time hamper capital inflows to finance investment). Finally, one would like to endogenize the cost of insurance. We have assumed in this paper that CAT bonds yielded a constant premium above non-contingent bonds but other assumptions could be made, for example that the premium increases with the risk in the CAT bonds or with the quantity of bonds issued. This could be studied in a general equilibrium model that would also encompass the supply of insurance.

APPENDICES

Appendix A. Proofs of the Propositions

Proof of Proposition 2

For period $t+1$ the budget constraint (5) can be written,

$$B_{s_{t+1},t} = C_{t+1} - Y_{t+1} + E_{t+1}\left(m_{s_{t+2}} B_{s_{t+2},t+1}\right).$$

Iterating forward and using $C \geq (1-\eta)Y$ as well as the transversality condition then gives,

$$\begin{aligned} B_{s_{t+1},t} &= C_{t+1} - Y_{t+1} + E_{t+1}\left[\sum_{i=1}^{+\infty}\left(\prod_{j=1}^{i} m_{s_{t+1+j}}\right)\left(C_{t+1+i} - Y_{t+1+i}\right)\right], && (22)\\ &\geq -\eta\left\{Y_{t+1} + E_{t+1}\left[\sum_{i=1}^{+\infty}\left(\prod_{j=1}^{i} m_{s_{t+1+j}}\right) Y_{t+1+i}\right]\right\}. && (23) \end{aligned}$$

One can then show by forward induction that,

$$E_{t+1}\left[\left(\prod_{j=1}^{i} m_{s_{t+1+j}}\right) Y_{t+1+i}\right] = \Phi^i Y_{t+1},$$

where Φ is defined in (11). Hence (23) can be rewritten,

$$B_{s_{t+1},t} \geq -\frac{\eta G_{s_{t+1}}}{1-\Phi} Y_t.$$

This is the second equation in Proposition 2**. Q.E.D.**

Proof of Proposition 4

The first-order conditions of problem (15) are:

$$\begin{aligned} m_n c(x)^{-\gamma} &= \beta G_n^{-\gamma} c\left(1 + \frac{b_n}{G_n}\right)^{-\gamma} + \lambda_n, && (24)\\ m_d c(x)^{-\gamma} &= \beta G_d^{-\gamma} c\left(1 + \frac{b_d}{G_d}\right)^{-\gamma} + \lambda_d. && (25) \end{aligned}$$

Using $b = b_d$ and $b^c = b_n - b_d$, the condition $b^c < \left(\frac{G_n}{G_d} - 1\right) b$ can be rewritten in terms of the state-contingent payments in the complete markets model as,

$$\frac{b_d}{G_d} > \frac{b_n}{G_n}.$$

It follows that the credit constraint for the disaster state cannot be binding ($\lambda_d = 0$), so that dividing (24) by (25) gives,

$$\frac{m_n G_n^\gamma}{m_d G_d^\gamma} = \frac{c\left(1+\frac{b_n}{G_n}\right)^{-\gamma} + \lambda_n G_n^\gamma}{c\left(1+\frac{b_d}{G_d}\right)^{-\gamma}} > 1,$$

which implies (17). Then using (10) gives (18). **Q.E.D.**

Proof of Proposition 5

We first show that if condition (19) is violated the country does not use CAT bonds for insurance in the long run. First assume that $\beta \geq m_n G_n^\gamma$. The Euler equations at time t are,

$$\begin{aligned} m_n\, c_t^{-\gamma} &= \beta G_n^{-\gamma} c_{nt+1}^{-\gamma} + \lambda_{nt}, \\ m_d\, c_t^{-\gamma} &= \beta G_d^{-\gamma} c_{dt+1}^{-\gamma} + \lambda_{dt}, \end{aligned}$$

where c_{st+1} denotes normalized consumption in the following period conditional on state s. Using $\beta \geq m_n G_n^\gamma > m_d G_d^\gamma$ this implies $c_{nt+1} \geq c_t$ and $c_{dt+1} > c_t$, so that consumption increases over time. Hence there is a time after which the credit constraint is no longer binding, after which $\lambda_{nt} = \lambda_{st} = 0$ and consumption grows at a positive rate that depends on the state. It follows that c_t grows without bound, and so does b_{st} for $s = n, d$ since in state s, $c_t = c\left(1 + b_{st-1}/G_s\right)$. Once the economy is unconstrained the Euler equations imply that b_{nt} and b_{dt} satisfy,

$$\frac{\beta}{m_n G_n^\gamma} c\left(1+\frac{b_n}{G_n}\right)^{-\gamma} = \frac{\beta}{m_d G_d^\gamma} c\left(1+\frac{b_d}{G_d}\right)^{-\gamma}. \tag{26}$$

Consider a value of current income x that is large enough that the credit constraints are never binding in the future. Then one can write consumption as a linear function of current income, $c(x) = a_0 + a_1 x$ (closed-form expressions for coefficients a_0 and a_1 can be derived, but these expressions do not matter for the proof). Using this expression in equation (26) gives

$$a_0 + a_1\left(1 + b_{dt}/G_d\right) = \left(\frac{m_n}{m_d}\right)^{1/\gamma} \frac{G_n}{G_d}\left[a_0 + a_1\left(1 + b_{nt}/G_n\right)\right].$$

Taking the limit when both b_{nt} and b_{dt} go to infinity gives,

$$\lim_{t\to+\infty} \frac{a_0 + a_1\left(1 + b_{dt}/G_d\right)}{a_0 + a_1\left(1 + b_{nt}/G_n\right)} = \frac{G_n}{G_d} \lim_{t\to+\infty}\left(\frac{b_{dt}}{b_{nt}}\right) = \frac{G_n}{G_d}\left(\frac{m_n}{m_d}\right)^{1/\gamma},$$

from which it follows that $\lim_{t\to+\infty}\left(b_{dt}/b_{nt}\right) = \left(m_n/m_d\right)^{1/\gamma}$.

Going back to the model with noncontingent bonds and CAT bonds, $b = b_d$ implies that the country accumulates foreign reserves without bound, and $b^c = b_n - b_d$ implies that the ratio of CAT bonds to noncontingent bonds converges to,

$$\lim_{t\to+\infty} \frac{b_t^c}{b_t} = \lim_{t\to+\infty} \frac{b_{nt}}{b_{dt}} - 1 = \left(\frac{m_d}{m_n}\right)^{1/\gamma} - 1 \geq 0.$$

This means that in the long run the country *holds* a positive level of CAT bonds and so does not insure. (In the limit case where insurance is costless, $m_d = m_n$ the country does not hold or issue CAT bonds in the long run.) Hence $\beta \geq m_n G_n^\gamma$ implies that the country does not insure in the long run.

Second, assume $\beta \leq m_d G_d^\gamma$. Then the Euler equations show that consumption decreases over time and that in the long run the constraints $b_{st} \geq \underline{b}_s$ are binding for both states. Then $b_t^c = \left(\frac{G_n}{G_d} - 1\right) b_t$ so that condition (16) is not satisfied. We conclude that if (19) is violated the country does not use CAT bonds for insurance in the long run.

Next we show that if condition (19) is satisfied the country uses CAT bonds for insurance in the long run. The Euler equations imply that whether or not $\lambda_n = 0$, one has $\frac{b_d}{G_d} > \frac{b_n}{G_n}$. This implies $b^c < \left(\frac{G_n}{G_d} - 1\right) b$. It remains to show that $b^c < 0$ in order to prove that the country uses CAT bonds for insurance. To do this note that $b^c = b_n - b_d < (1 - G_d/G_n)\, b_n$ has the same sign as b_n. Since c_t and b_{nt} strictly decrease until $b_{nt} = \underline{b}_n$ in the normal state there is a strictly positive probability that b_{nt} is negative for any future t. This proves that (19) is both necessary and sufficient for insurance in the long run.

Finally, using (8)-(9) and (3), condition (19) can be rewritten as (20). **Q.E.D.**

Appendix B. Endogenous grid point method with contingent securities

We show how the endogenous grid point can be generalized to the case with state-contingent securities. With non-contingent bonds, the endogenous grid point method determines the policy functions by iterating on the Euler equation. Iteration k starts with consumption function $c_k(\cdot)$. For each level of end-of-period asset b taken from an exogenous grid, one computes $\beta E c'^{-\gamma}$ using function $c_k(\cdot)$. The Euler equation then gives current consumption c and the budget constraint gives current resources $x = c + qb$. By doing this for each b in the exogenous grid, one obtains two "endogenous grids" for x and c, which can then be used to construct a new function $c_{k+1}(\cdot)$. The iteration is stopped when a fixed point for the consumption function has been achieved with a sufficient degree of precision.

With state-contingent securities the first-order conditions of problem (15) are:

$$m_{s'} c(x)^{-\gamma} = \beta G_{s'}^{-\gamma} c\left(1 + b_{s'}(x)/G_{s'}\right)^{-\gamma} + \lambda_{s'}(x), \quad s' = n, s \tag{27}$$

$$\lambda_{s'}(x)\left[b_{s'}(x) - \underline{b}_{s'}\right] = 0, \quad s' = n, s. \tag{28}$$

The endogenous grid point method can be transposed to the case with state-contingent securities by using the state-contingent payments $b_{s'}$ instead of b. This raises the question of which state s' should be used to define the exogenous grid for $b_{s'}$. It is most convenient to use the state for which the credit constraint $b_{s'} \geq \underline{b}_{s'}$ is the "least binding", in the sense that if the constraint binds for that state then it binds for the other state. Under condition (17) the least binding state is state d and so we use that state to define the exogenous grid.

We now describe the iteration method used to solve for the equilibrium in the model with contingent securities. First, we define a grid for b, $\boldsymbol{b} = (b_1, \ldots, b_I)$ with $b_1 = -\eta/(1 - \Phi)$, and a grid for x, $\boldsymbol{x} = 1 + \boldsymbol{b}$.

We define a grid for b_d, $\boldsymbol{b_d} = G_d \boldsymbol{b}$. The iteration starts with a consumption function $c_k(\cdot)$.

Consider $b_{di} \in \boldsymbol{b_d}$. If $i > 1$ the credit constraint is not binding for state d, so that the Euler equation (27) for state d maps b_{di} into the consumption level,

$$c_i = \left(\frac{m_d}{\beta}\right)^{1/\gamma} G_d c_k \left(1 + \frac{b_{di}}{G_d}\right). \tag{29}$$

One can also map b_{di} into b_{ni} by taking the ratio of the Euler equations for state d and n, which implies

$$c_k \left(1 + \frac{b_{ni}}{G_n}\right) = \left(\frac{m_d}{m_n}\right)^{1/\gamma} \frac{G_d}{G_n} c_k \left(1 + \frac{b_{di}}{G_d}\right) \tag{30}$$

if the implied value of b_{ni} is larger than $\underline{b}_n$, and $b_{ni} = \underline{b}_n$ otherwise. Finally one can map b_{di} into x_i by using

$$x_i = c_i + \pi_n m_n b_{ni} + \pi_d m_d b_{di}. \tag{31}$$

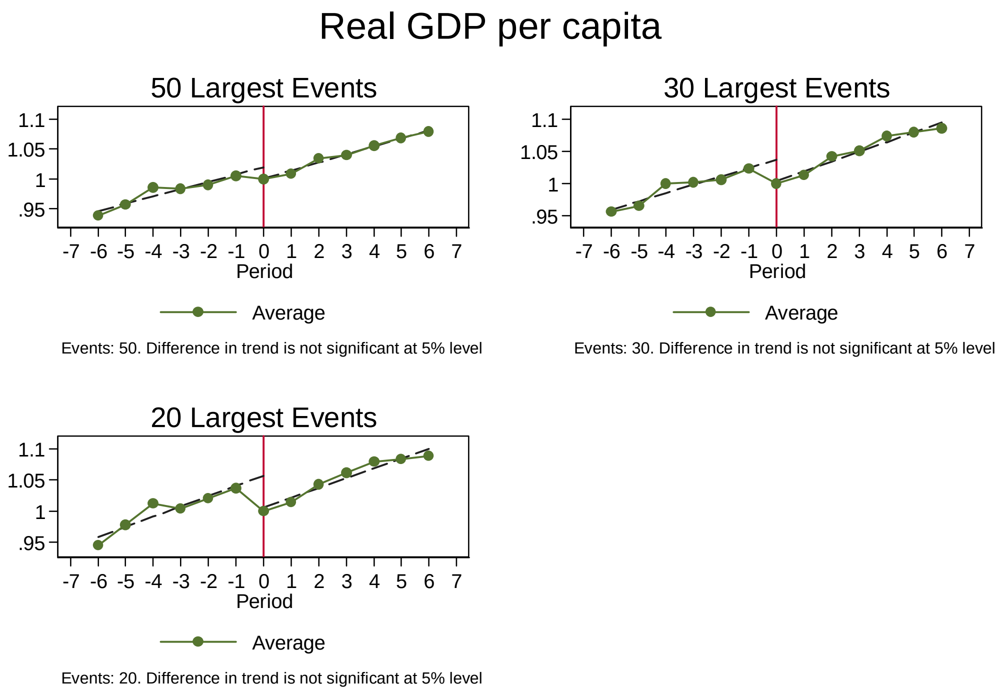
By interpolating the endogenous grids $(x_i)_{i=1,\dots,I}$ and $(c_i)_{i=1,\dots,I}$ one obtains a new consumption function $c_{k+1}(\cdot)$. For x low enough that the credit constraints are binding for both states the consumption function is given by $c_{k+1}(x) = x - \pi_n m_n \underline{b}_n - \pi_d m_d \underline{b}_d$.

Ranking	Country	year	Main event type (a)	Number of killed	Rate by million of inhabitants
1	Nicaragua	1972	Earthquake	10,000	4,046.04
2	Guatemala	1976	Earthquake	23,000	3,707.14
3	Honduras	1974	Storm (tropical cyclone)	8,000	2,733.23
4	Honduras	1998	Storm (tropical cyclone)	14,600	2,506.46
5	Sri Lanka	2004	Earthquake (tsunami)	35,405	1,838.93
6	Solomon Islands	1975	Earthquake (tsunami)	200	1,075.60
7	Iran, Islamic Rep.	1978	Earthquake	25,045	707.64
8	Haiti	2004	2 Storms and 2 floods	5,434	603.47
9	Vanuatu	1997	Earthquake (tsunami)	100	568.38
10	Dominica	1979	Storm (tropical cyclone)	40	554.40
11	Pakistan	2005	Earthquake	74,032	486.86
12	Papua New Guinea	1998	Earthquake (tsunami)	2,182	439.08
13	Grenada	2004	Storm (tropical cyclone)	39	372.80
14	Solomon Islands	1986	Storm (tropical cyclone)	101	371.57
15	Bhutan	2000	General flood	200	368.06
16	Maldives	2004	Earthquake	102	356.50
17	Vanuatu	1987	Storm (tropical cyclone)	48	355.11
18	St Lucia	1988	Storm (tropical cyclone)	45	350.19
19	Dominican Republic	1979	Storm (tropical cyclone)	1,432	252.75
20	Tajikistan	1992	Flood	1,346	248.41
21	Vanuatu	1999	Earthquake	44	241.19
22	Djibouti	1994	General flood	145	241.15
23	El Salvador	1986	Earthquake	1,100	230.65
24	Iran, Islamic Rep.	1972	Earthquake	5,117	174.33
25	Solomon Islands	1977	Earthquake	34	170.29
26	Bangladesh	1985	Storm (tropical cyclone)	15,155	154.48
27	Philippines	1976	Earthquake	6,405	152.43
28	Puerto Rico	1985	Flood	500	149.51
29	Haiti	1994	Storm	1,122	148.73
30	Algeria	1980	Earthquake	2,635	144.74
31	St Lucia	1990	Storm (tropical cyclone)	18	136.16
32	Thailand	2004	Earthquake (tsunami)	8,372	134.76
33	Mexico	1985	Earthquake	9,500	128.53
34	St. Kitts and Nevis	1998	Storm (tropical cyclone)	5	122.73
35	El Salvador	1982	Flood	520	112.12
36	Oman	1977	Storm (tropical cyclone)	107	111.10
37	Solomon Islands	2007	Earthquake (tsunami)	52	107.43
38	Philippines	1991	Storm (tropical cyclone)	6,153	100.50
39	Turkey	1976	Earthquake	3,846	96.09
40	Cape Verde	1984	Storm (tropical cyclone)	29	94.88
41	Comoros	1983	Storm (tropical cyclone)	33	93.45
42	Guatemala	1982	Flood	640	89.02
43	Iran, Islamic Rep.	1981	2 Earthquakes	3,458	88.39
44	Fiji	1979	Storm (tropical cyclone)	53	87.14
45	Swaziland	1984	Storm (tropical cyclone)	53	85.52
46	Italy	1980	Earthquake	4,689	83.26
47	El Salvador	1998	Storm (tropical cyclone)	475	81.04
48	Samoa	1991	Storm (tropical cyclone)	13	80.58
49	Honduras	1993	Flood	413	79.95
50	Bhutan	1994	Flash flood and Storm	39	74.65

Notes: (a) In cases where there are more than one type of event (for example, one earthquake and one flood), if the severity of one of them is considerable greater than the others, the main event type just reports the more severe of them.

Source: Authors' calculations based on EM-DAT database.

Figure 1: Table 2. Largest Disasters



Source: Authors' calculations based on data from WDI and EM-DAT databases.

Figure 2: Natural Disasters and Output

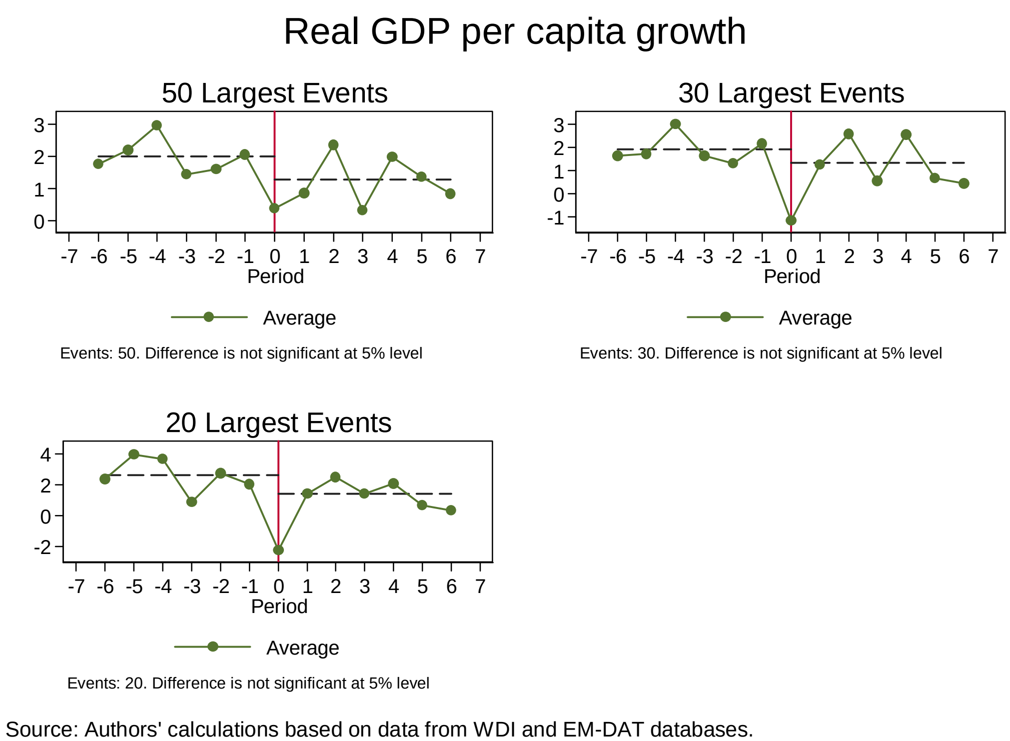


Figure 3: Natural Disasters and Growth

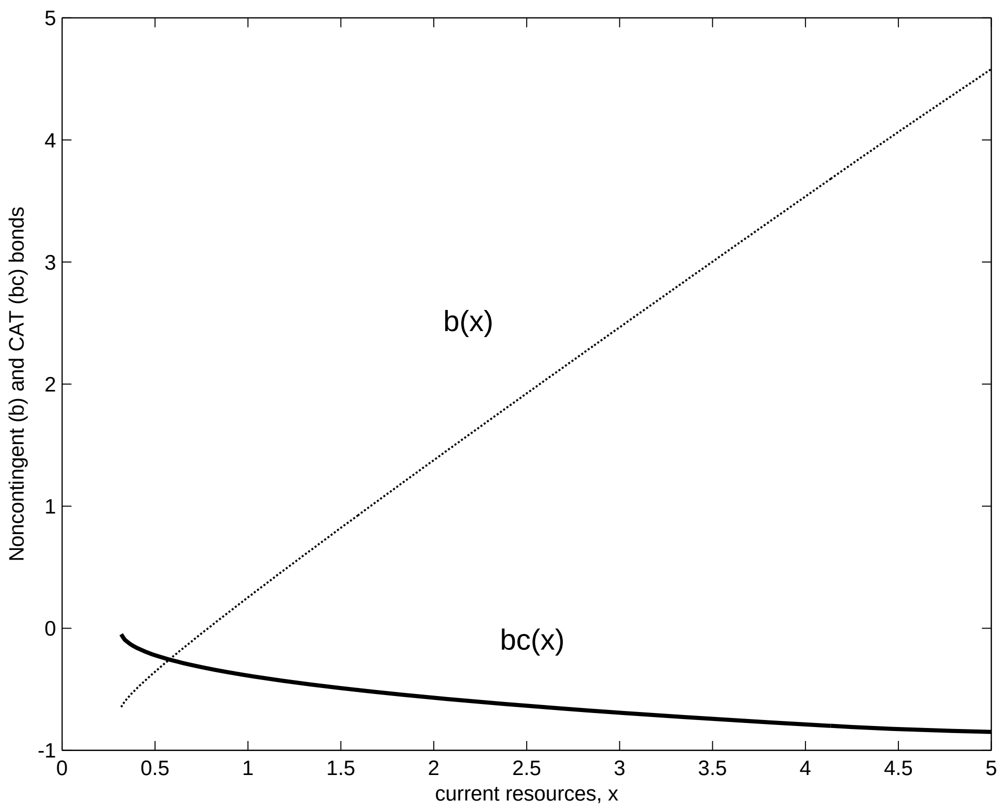


Figure 4: Variations of noncontingent and CAT bond holdings (b and b^c) with current resources (x)

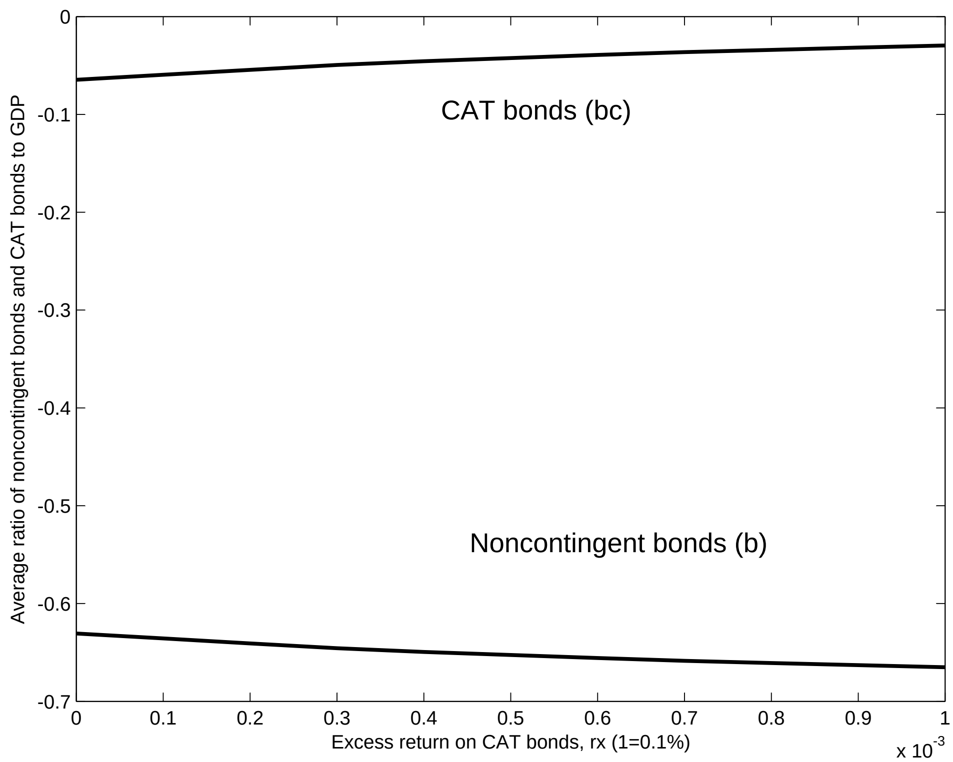


Figure 5: Variations of average levels of noncontingent and CAT bond holdings (b and b^c) with cost of insurance (rx)

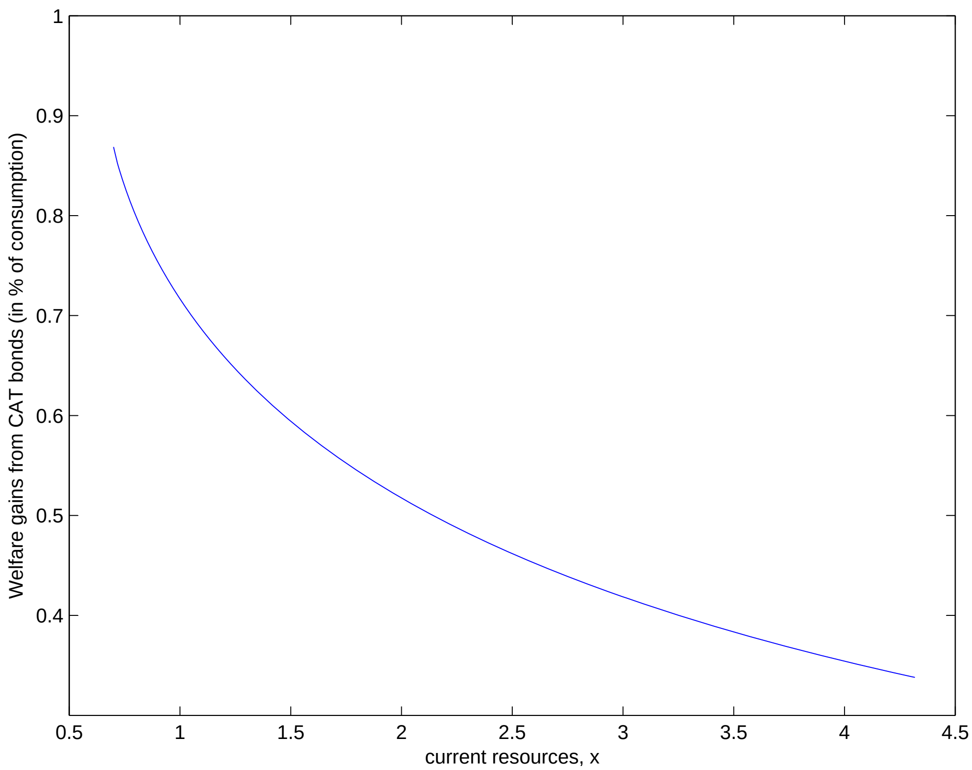


Figure 6: Variations of welfare gains from CAT bond in % of consumption (α) with current resources (x)

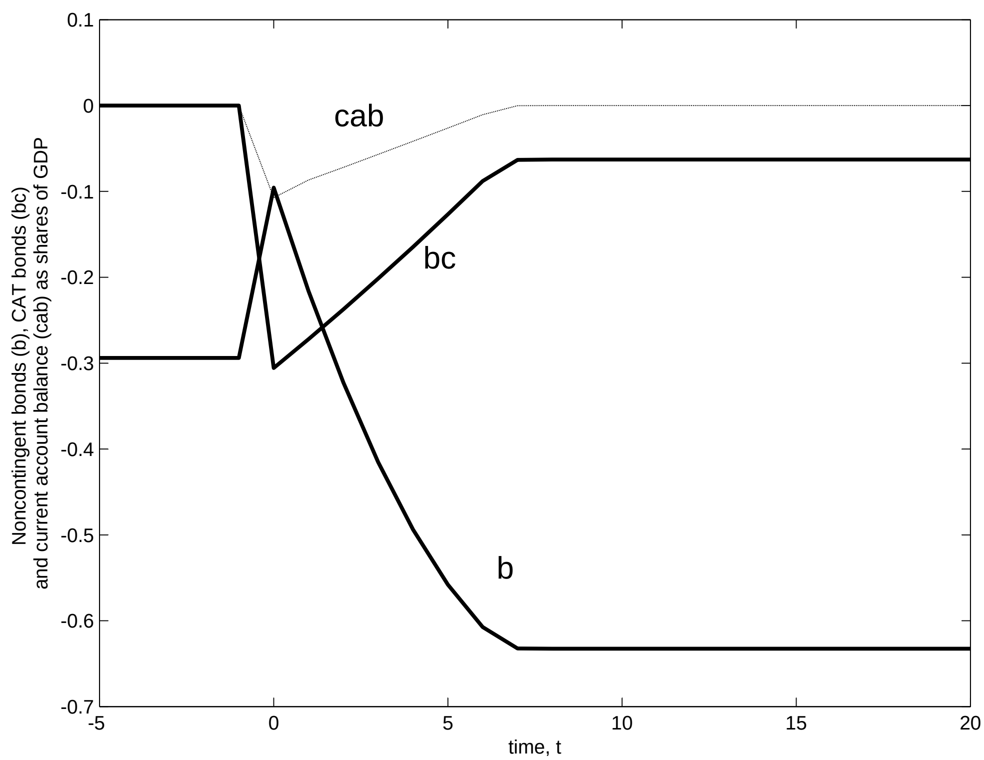


Figure 7: Response of noncontingent debt (b), CAT bonds (b^c) and current account balance (cab) to introduction of CAT bonds

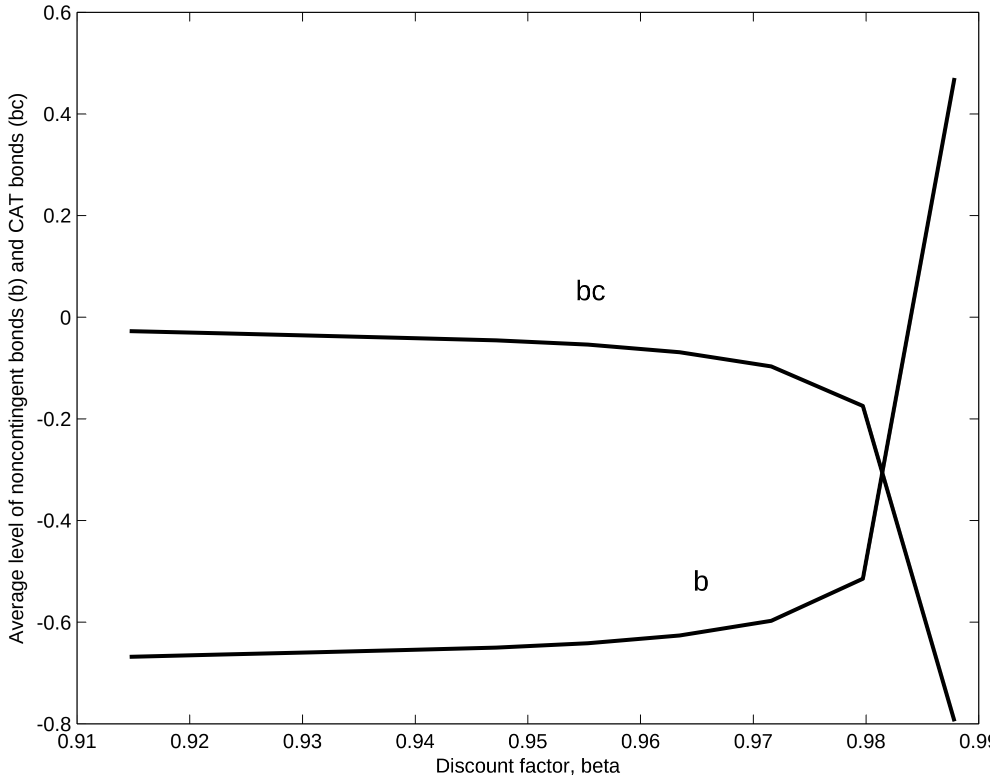


Figure 8: Variation of average stocks of noncontingent bonds (b) and CAT bonds (b^c) with discount rate (β)

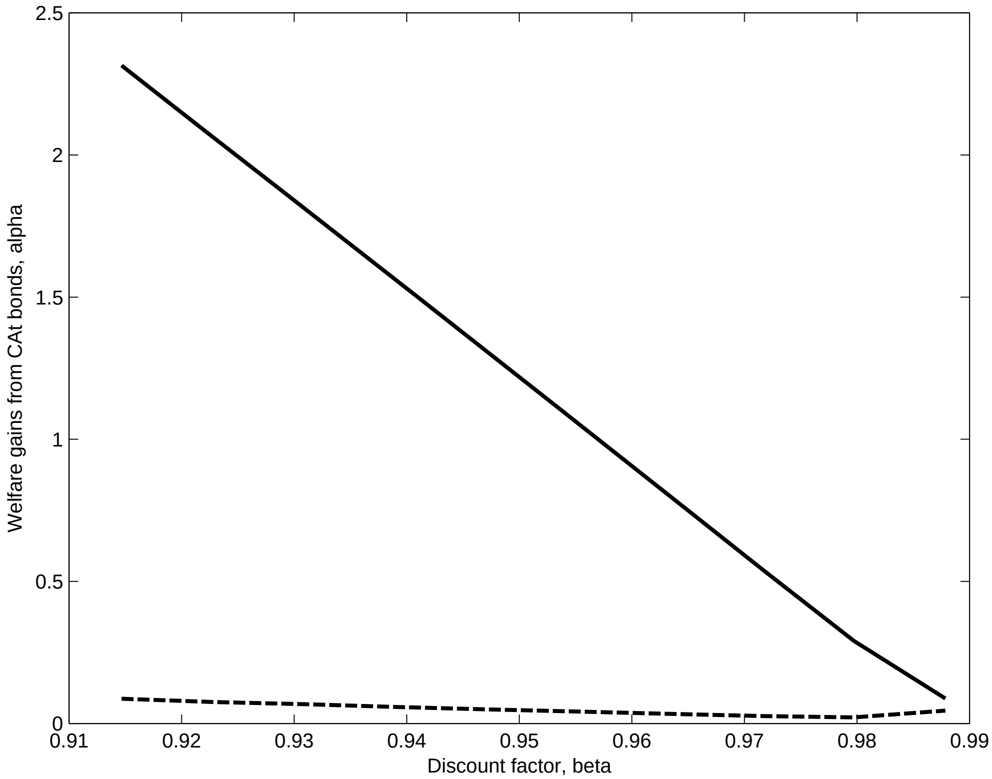


Figure 9: Variation of welfare gain from CAT bonds (α) with discount rate (β): total (solid line) and insurance only (dashed line)

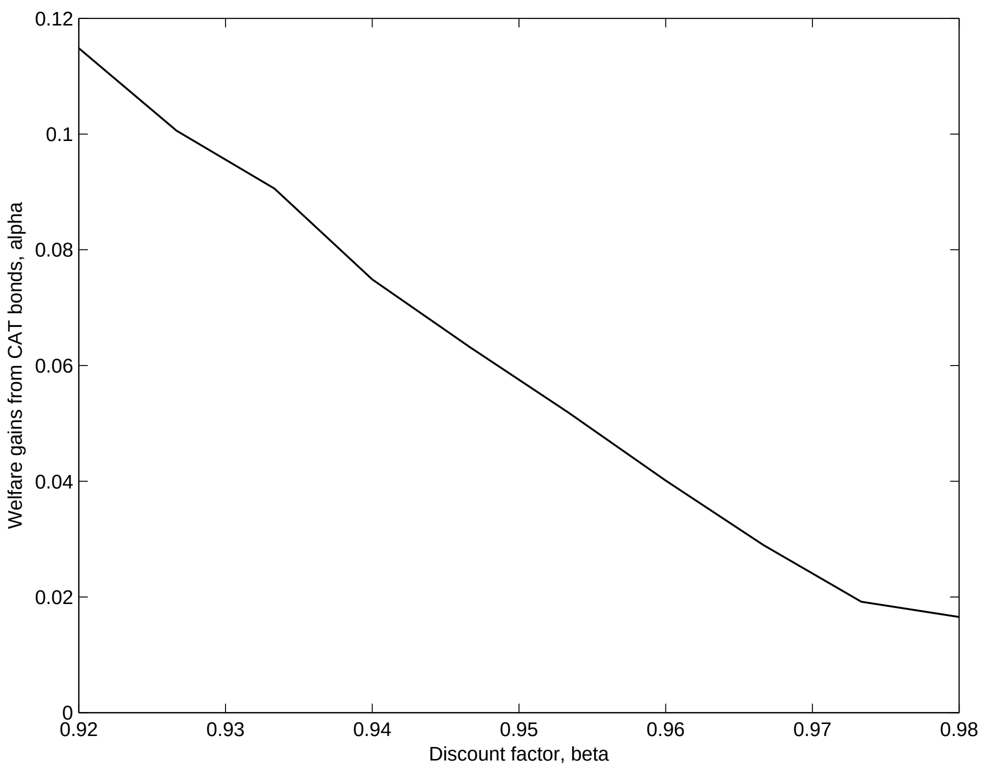


Figure 10: Variation of welfare gain from CAT bonds (α) with discount rate (β) in the model with defaultable debt

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