The Optimal Level of International Reserves For Emerging Market Countries: a New Formula and Some Applications*

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Abstract

We present a model of the optimal level of international reserves for a small open economy seeking insurance against sudden stops in capital flows. We derive a formula for the optimal level of reserves, and show that plausible calibrations can explain reserves of the order of magnitude observed in many emerging market countries. However, the buildup of reserves in emerging market Asia seems in excess of the level that would be implied by an insurance motive against sudden stops (estimated by reference to historical experience).

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1 Introduction

The recent buildup in international reserves in emerging market countries has revived old debates about the appropriate amount of reserves for an open economy. It has been argued that many emerging market countries accumulated reserves as a form of self-insurance against capital flow volatility, the danger of which was learned the hard way in the international financial crises of the 1990s (Aizenman and Marion, 2003; Stiglitz, 2006).[1] Against this backdrop, there has been surprisingly little work trying to quantify the level of reserves that can be justified as an insurance against capital flow volatility.

This paper contributes to fill this gap with a model and some calibrations. The model features a representative consumer in a small open economy who may lose access to external credit (a sudden stop). The consumer can smooth domestic consumption in sudden stops by entering insurance contracts with foreign investors, or equivalently, by financing a stock of liquid reserves with contingent debt. The model yields a closed-form expression for the welfare-maximizing level of reserves. The optimal level of reserves depends in an intuitive way on the probability and the size of the sudden stop, the consumer's risk aversion, and the opportunity cost of holding the reserves. We also present various extensions of the basic model, including one in which reserves have benefits in terms of prevention (they reduce the probability of a sudden stop), and one in which the opportunity cost of holding reserves is endogenous.

With our formula in hand, we then explore the quantitative implications of the model using data on a sample of sudden stops in emerging market countries. Our estimates of the optimal level of reserves are relatively sensitive to parameters that are relatively difficult to measure, such as their opportunity costs or their benefits in terms of crisis prevention. However, we find that for plausible values of the parameters the model can explain reserves-to-GDP ratios of the order of magnitude observed in emerging market countries over the past decades. For a coefficient of constant relative risk aversion of 2 (a standard value in the real business cycle literature), our model predicts a reserves-to-GDP ratio of 9 percent, which is close to the average reserves-to-GDP ratio observed in a group of 34 middle-income countries over the period 1975-2003. The calibrated version of the basic model can also account for the recent reserves increase in some emerging market countries. However, the recent build-up of reserves in emerging market Asia seems in excess of what would be implied by an insurance motive against sudden stops. Rationalizing such high levels of reserves in Asia would require the

[1] Another view is that the reserves buildup is the unintended consequence of policies that maintain large current account surpluses (Dooley et al, 2004; Summers, 2006).

anticipation of crises with an output cost of unprecedented size.

Our paper contributes to a long line of literature on reserves adequacy. The first cost-benefit analyses of the optimal level of reserves were developed in the 1960s and the 1970s, when the focus was mainly on the current account (Heller, 1966). The main insights from that literature were later formalized in variants of the Baumol-Tobin inventory model in which the stock of reserves is being depleted by a stochastic current account deficit (see, e.g., Frenkel and Jovanovic, 1981, and Flood and Marion, 2002, for a review). The optimal level of reserves can be derived as a simple closed-form expression involving the volatility of the reserves-depleting process, the opportunity cost of holding reserves, and the fixed costs of depleting and rebuilding the reserves stock. One problem with this framework is that it is a highly reduced form with no well-defined welfare criterion.

Following (with a substantial lag) a more general trend in macroeconomic theory, the recent literature on reserves adequacy has taken the welfare of the representative agent as the criterion to maximize. Two recent papers derive the optimal level of reserves in a welfare-based calibrated model, as we do here.[2] Durdu et al (2007) present some estimates of the optimal level of precautionary savings accumulated by a small open economy in response to business cycle volatility, financial globalization, and the risk of sudden stop. They conclude that financial globalization and the risk of sudden stop may be plausible explanations of the observed surge in reserves in emerging market countries.[3] The model presented here is one of insurance, rather than precautionary savings, and from this point of view is more directly comparable to that of Caballero and Panageas (2007). Those authors calibrated a dynamic general equilibrium model in which the country that is vulnerable to sudden stops can invest in conventional reserves (fixed income foreign assets) as well as more sophisticated assets whose payoffs are correlated with sudden stop arrivals. They find that the gains from the optimal hedging strategies can be substantial. Both Durdu et al (2007) and Caballero and Panageas (2007) solve their models numerically, whereas we strive, in this paper, to obtain closed-form expressions for the optimal level of reserves.

Policy analysts often assess reserves adequacy using simple rules of thumb, such as maintaining reserves equivalent to three months of imports, or the "Greenspan-Guidotti rule" of

[2] Other papers present stylized models that are useful to illustrate the basic trade-offs involved in the choice of optimal reserves, but do not lend themselves to the kind of quantitative exercises that we present in this paper (Aizenman and Marion, 2003; Aizenman and Lee, 2005; Miller and Zhang, 2006).

[3] They find that the risk of sudden stops can explain an increase in the country's foreign assets amounting to 20 percent of GDP. In an earlier contribution, Mendoza (2002) found that a shift from perfect credit markets to a world with sudden stops increases the average foreign assets-to-GDP ratio by 14 percentage points.

full coverage of short-term external debt. The Greenspan-Guidotti rule is a natural benchmark of comparison for our estimates, which are also based on the idea that reserves help countries deal with a sudden stop in short-term debt inflows. We find that the optimal level of reserves suggested by our model may be close to the Greenspan-Guidotti rule for plausible calibrations of the model, although it could be significantly higher or lower.

The paper is structured as follows. Section 2 presents a model yielding a simple formula for the optimal level of reserves. Section 3 calibrates the model, and compares the model predictions and the data. Section 4 concludes.

2 An Insurance Model

We first present the assumptions of the model (section 2.1), and derive a closed-form expression for the optimal level of reserves (section 2.2). We then show that this model can be reinterpreted as one of balance sheet management in which the reserves are financed by contingent debt (section 2.3). The following sections present some extensions of the basic model.

2.1 Assumptions

We consider a small open economy in discrete infinite time $t = 0, 1, 2, \ldots$. There is one single good which is consumed domestically and abroad.[4] The economy follows a deterministic path that may be disturbed by sudden stops in capital inflows. The only source of uncertainty in our model is the risk of sudden stop.

The domestic economy is populated by a representative infinitely-lived consumer, who is subject to the budget constraint,

$$C_t = Y_t + L_t - (1 + r)L_{t-1} + Z_t, \tag{1}$$

where Y_t is domestic output, L_t is external debt, and Z_t is a transfer resulting from a "reserve insurance contract" (to be described later). The interest rate r is constant and the representative consumer does not default on her external debt.

We assume that there is a constraint on the quantity of output that can be pledged in repayment to foreign creditors. The debt is fully repaid in period $t + 1$ only if,

$$(1 + r)L_t \leq \alpha_t Y^n_{t+1}, \tag{2}$$

[4] Issues related to the real exchange rate will be treated in section 2.5.

where Y^n_{t+1} is trend output in period $t+1$ (to be defined shortly) and α_t is a time-varying parameter that captures the pledgeability of output.[5] We assume that both α_t and Y^n_{t+1} are known in period t, implying that debt issued in t is default-free if condition (2) is satisfied. The stringency of the country's external borrowing constraint can change over time, generating the possibility of sudden stops. The time variation in α_t could be interpreted, for example, as exogenous changes in the level of sanction that foreign creditors can impose on a defaulting country, or in the domestic political determinants of the country's willingness to repay its foreign debt.[6] For the purpose of this model we simply take it as exogenous.

The economy can be in two states: the normal—or non-crisis—state (denoted by n), or in a sudden stop (denoted by s). In normal times output grows at a constant rate g and pledgeable output is a constant fraction of output,

$$Y^n_t = (1+g)^t Y_0, \tag{3}$$

$$\alpha^n_t = \alpha. \tag{4}$$

We assume that if there is a sudden stop, output falls by a fraction γ below trend, and pledgeable output falls to zero:

$$Y^s_t = (1-\gamma) Y^n_t, \tag{5}$$

$$\alpha^s_t = 0. \tag{6}$$

The assumption that pledgeable output falls to zero, rather than a positive level, is a matter of normalization. The external debt that is rolled over does not contribute to the sudden stop and therefore plays no interesting role in our model.

We assume that it takes a certain number of periods θ for the economy to go back to its trend path after a sudden stop. If a sudden stop occurs at time t, output and pledgeable output catch up with the trend levels over the time interval $t+1, t+2, ..., t+\theta$, and the economy is back in the n-state at time $t+\theta+1$. We define the time interval $[t, t+\theta]$ as a "sudden stop episode". Thus in a given period t the economy could be in one of $\theta+2$ states: the normal state, $s_t = n$, or in one of the $\theta+1$ substates corresponding to the different periods of a sudden stop episode, $s_t = s^0$, $s^1, ..., s^\theta$.

[5] Constraint (2) can be justified by contractual enforcement problems—a limit on the country's output that can be seized by foreign creditors, or on the default cost that creditors can impose on the debtor country—or by agency problems (see Tirole, 2005, for a review of the possible theoretical underpinnings in a corporate finance context). This type of constraint has been extensively used in international finance, in particular to model sudden stops in capital flows (see, e.g., Mendoza, 2002; Rancière, Tornell and Westermann, 2008).

[6] See Guembel and Sussman (2005) for a model in which a country's willingness to repay foreign debt is endogenous to domestic political economy factors.

The dynamics of output and external credit in a sudden stop episode starting at date t are given by,

$$Y^s_{t+\tau} = (1 - \gamma(\tau))Y^n_t, \tag{7}$$

$$\alpha^s_{t+\tau} = \alpha(\tau), \tag{8}$$

where $\gamma(\cdot)$ and $\alpha(\cdot)$ are exogenous functions of $\tau = 0, 1, ..., \theta$. By (5) and (6) we have $\gamma(0) = \gamma$ and $\alpha(0) = 0$. We assume that the economy catches up with the trend path in a monotonic way, in the sense that $\gamma(\tau)$ and $\alpha(\tau)$ are both non-negative, and respectively decreasing and increasing in τ. We further assume that at the end of the sudden stop episode the consumer has regained the same level of access to external credit as before the sudden stop, $\alpha(\theta) = \alpha$.

Given our focus on insurance against sudden stops (rather than business cycle fluctuations), we streamline the model by assuming that the only source of uncertainty is the risk of a sudden stop. We denote by π_t the probability in period t that a sudden stop occurs in the following period. At the end of a sudden stop episode the economy goes to state n with certainty.

Sudden stops reduce the representative consumer's welfare in two ways. First, they perturb the consumption path around the trend level, which decreases the consumer's welfare if her elaticicity of intertemporal substitution of consumption is finite. Second, sudden stops reduce the consumer's intertemporal income because of the fall in domestic output. This is illustrated in Figure 1, which shows the paths of output, external debt and domestic consumption in a sudden stop episode under the assumption that the borrowing constraint (2) is always binding and that there is no insurance. Consumption falls sharply at the time of the sudden stop under the cumulative impact of the fall in output and of the capital outflow, and then recovers as foreign capital flows back in.

We assume that the representative consumer can smooth her consumption in a sudden stop by entering into a "reserves insurance contract" with specialized foreign investors. A contract signed at time t stipulates contingent payments from the investor to the consumer at time $t + 1$. More formally, a contract (R_t, x_t) specifies that the transfer is given by

$$Z^n_{t+1} = -x_t R_t, \tag{9}$$

if there is no sudden stop, and by

$$Z^s_{t+1} = (1 - x_t)R_t, \tag{10}$$

if there is a sudden stop. In words, the consumer pays an insurance premium $x_t R_t$ in both states of the world, but receives a transfer R_t if there is a sudden stop. We assume $x_t < 1$, so that the insurance contract transfers purchasing power from the n-state to the s-state. The insurance premium x_t is taken as exogenous for now—it will be endogenized in sections 2.3 and 2.4.

To close the model we need to specify the consumer's intertemporal objective function. We assume that the consumer maximizes her welfare,

$$U_t = E_t \left(\sum_{i=0,\ldots,+\infty} (1+r)^{-i} u\left(C_{t+i}\right) \right), \tag{11}$$

where the flow utility function has a constant relative risk aversion $\sigma \geq 0$,

$$u(C) = \frac{C^{1-\sigma}}{1-\sigma}, \quad \sigma \neq 1 \tag{12}$$

and $u(C) = \log(C)$ for $\sigma = 1$. We assume $r < g$ so as to keep the consumer's intertemporal income finite.

The equilibrium can be defined as follows. Denoting the state of the economy by S_t, we are looking for two state-contingent decision rules, $\widetilde{L}(S_t)$ and $\widetilde{R}(S_t)$, that maximize the consumer's welfare (11) under the constraints (1)-(2). Obviously the consumer has no reason to insure during a sudden stop episode (since there is no risk), so $\widetilde{R}(S_t) = 0$ if the economy is in a sudden stop episode.

2.2 A formula for the optimal level of reserves

The consumer's insurance problem is fairly simple—and can be solved in closed form—if the borrowing constraint (2) is always binding. We first derive a formula for the optimal level of reserves under the assumption that (2) is always binding, and then derive a set of conditions that are sufficient for this assumption to be satisfied in equilibrium. Note that if (2) is binding, the country maintains, in normal times, a constant ratio of short-term debt to GDP, given by

$$\lambda = \frac{L_t^n}{Y_t^n} = \frac{1+g}{1+r}\alpha. \tag{13}$$

The optimal level of reserves maximizes the expected utility of period $t+1$ consumption,

$$R_t = \arg\max (1-\pi_t) u(C_{t+1}^n) + \pi_t u(C_{t+1}^s), \tag{14}$$

where C_{t+1}^n and C_{t+1}^s are given by (1), in which only the terms in Z depend on the reserves level R_t, whereas the terms in L results from the binding borrowing constraint (2). Thus the first-order condition is

$$(1-\pi_t) u'(C_{t+1}^n) \frac{\partial Z_{t+1}^n}{\partial R_t} + \pi_t u'(C_{t+1}^s) \frac{\partial Z_{t+1}^s}{\partial R_t} = 0,$$

which, using (9) and (10), can be rewritten,

$$\pi_t(1-x_t)u'\left(C^s_{t+1}\right) = (1-\pi_t)x_t u'\left(C^n_{t+1}\right). \tag{15}$$

The left-hand-side is the probability of a sudden stop times the marginal utility of reserves conditional on a sudden stop. The right-hand-side is the probability of no sudden stop times the marginal cost of reserves conditional on no sudden stop.

This first-order condition can be manipulated to obtain a closed-form expression for the optimal level of reserves. First, let us denote by p_t the price of a normal-times dollar in terms of a sudden-stop dollar,

$$p_t = \frac{u'\left(C^n_{t+1}\right)}{u'\left(C^s_{t+1}\right)}. \tag{16}$$

This variable measures the extent of insurance provided by reserves. If $p_t = 1$, domestic consumption is the same whether or not there is a sudden stop (full insurance). If $p_t < 1$, consumption is lower in a sudden stop (partial insurance). The first-order condition (15) says that when reserves are set optimally, this price should be equal to,

$$p_t = \frac{x_t^{-1}-1}{\pi_t^{-1}-1}. \tag{17}$$

The country's demand for insurance increases with the probability of sudden stop π_t and decreases with the premium x_t. The country fully insures if the insurers are risk-neutral ($x_t = \pi_t$). From now on we assume that $x_t \geq \pi_t$, implying that $p_t \leq 1$.

The optimal level of reserves is given in the following proposition.

Proposition 1 *If the external credit constraint (2) is always binding, the optimal level of reserves-to-GDP ratio $\rho_t \equiv R_t/Y^n_{t+1}$ is given by,*

$$\rho_t^* = \frac{\lambda+\gamma-\left(1-\frac{(r-g)\lambda}{1+g}\right)\left(1-p_t^{1/\sigma}\right)}{1-x_t\left(1-p_t^{1/\sigma}\right)}, \tag{18}$$

where λ is the ratio of short-term debt to GDP, γ is the output loss in the first period of the sudden stop, and p_t is given by (17).

Proof. The terms in Y, L and Z can be substituted out from (1) using (2) as an equality, (3), (4), (5), (6), (9), (10), and (13),

$$\begin{aligned} C^n_{t+1} &= Y^n_{t+1} + \frac{\alpha}{1+r}Y^n_{t+2} - \alpha Y^n_{t+1} - x_t R_t, \\ &= Y^n_{t+1}\left(1 - \frac{r-g}{1+g}\lambda - x_t\rho_t\right), \end{aligned} \tag{19}$$

and

$$
\begin{aligned}
C^s_{t+1} &= Y^s_{t+1} - \alpha Y^n_{t+1} + (1 - x_t) R_t, \\
&= Y^n_{t+1} \left(1 - \gamma - \frac{1+r}{1+g} \lambda + (1 - x_t) \rho_t \right). \qquad (20)
\end{aligned}
$$

The formula then results from simple manipulations of these two equations and the first-order condition $p_t (C^s_{t+1})^{-\sigma} = (C^n_{t+1})^{-\sigma}$. ■

Equation (18) is our formula for the optimal level of reserves. The optimal level of reserves responds in an intuitive way to changes in its determinants. First, it increases (more than one for one) with the level of short-term debt, λ, and with the output cost of a sudden stop, γ. Second, the optimal level of reserves is also increasing with the probability of a sudden stop, π_t, and the level of domestic risk aversion, σ. To see this, one can rewrite (18) as,

$$
\rho^*_t = \lambda + \gamma - \frac{1}{(1 - p_t^{1/\sigma})^{-1} - x_t} \left(1 - \frac{r-g}{1+g} \lambda - x_t (\lambda + \gamma) \right), \qquad (21)
$$

which is increasing in $p_t^{1/\sigma}$. Thus, an increase in π_t (or in σ, given that $p_t \leq 1$) raises $p_t^{1/\sigma}$ and leads to an increase in ρ^*_t. An increase in the premium x_t decreases the demand for insurance p_t, but also decreases the net supply of insurance, $(1 - x_t)\rho_t$, so that the net impact on reserves is ambiguous in general.

How does our formula relate to the Greenspan-Guidotti rule? This rule says that the ratio of the reserves to short-term debt should be equal to 1, that is,

$$
\rho = \lambda.
$$

One can see from (21) that the Greenspan-Guidotti rule corresponds to full insurance if a sudden stop does not reduce output ($p = 1$, $\gamma = 0$). In general, however, the optimal level of reserves could be larger or smaller than the Greenspan-Guidotti rule. It could be larger because the full insurance level of reserves, $\rho^* = \lambda + \gamma$, must also cover the fall in output associated with the sudden stop. It could be smaller because insurance is costly so that the country will not, in general, fully insure.

We conclude this section with a set of conditions that are sufficient for (2) to be always binding in equilibrium.

Lemma 2 *The borrowing constraint (2) is binding at all times if the following inequalities are satisfied:*

$$
\forall t, \quad (1+g)^\sigma \geq \frac{1 - \pi_t}{1 - x_t}, \qquad (22)
$$

$$
\forall \tau = 1, ..., \theta, \quad \alpha(\tau) - \alpha(\tau - 1) \leq g \left(1 - \gamma - \frac{r-g}{1+r} \alpha \right), \qquad (23)
$$

$$\gamma(1) \leq \frac{1}{1+g}\left(g + \frac{r-g}{1+r}\alpha\right) + \frac{1+g}{1+r}\alpha(1). \tag{24}$$

Proof. See the appendix. ■

Condition (22) ensures that the credit constraint (2) is binding in normal times.[7] Conditions (23) and (24) ensure that the credit constraint (2) is also binding during sudden stop episodes. Condition (23) says that foreign capital should not flow back to the country too quickly after a sudden stop—otherwise it might be optimal for the consumer to save a fraction of the capital inflows. We will show in section 3 that the conditions of Lemma 2 are satisfied for plausible values of the parameters.

2.3 The opportunity cost of reserves

The literature on reserves generally defines the opportunity cost of reserves by reference to marginal substitutions in the country's balance sheet. Reserves can be used to repay external liabilities, and the opportunity cost of reserves is defined as the difference between the interest rate paid on the country's liabilities and the lower return received on the reserves (Edwards, 1985; Garcia and Soto, 2004; Rodrik, 2006). We now show that our insurance model can be reinterpreted in those terms, conditional on certain assumptions about the menu of available assets and liabilities. This interpretation will be useful to calibrate the model in section 3.

The reserves insurance contract is easy to replicate if the domestic consumer can issue liabilities whose payoff is contingent on the occurrence of a sudden stop. Let us assume that the representative consumer does not have access to the insurance contracts described above, but can issue debt whose principal is repaid only if there is no sudden stop. One unit of this debt issued in period t has a face value of 1, and yields $1 + r + x_t$ if there is no sudden stop in period $t + 1$, and $r + x_t$ if there is a sudden stop. Variable x_t, thus, is now defined as the interest rate spread on the consumer's external debt. The consumer sells this debt to foreign investors at a unitary price of 1 and invests the proceeds in reserves that yield the riskless interest rate r. Denoting by R_t the number of securities issues in period t, the net payoff for the consumer in period $t + 1$ is

$$(1 + r)R_t - (1 + r + x_t)R_t = -x_t R_t \text{ if no sudden stop in } t + 1,$$
$$(1 + r)R_t - (r + x_t)R_t = (1 - x_t)R_t \text{ if sudden stop in } t + 1.$$

The payoffs are exactly the same as those of the insurance contract, given by (9) and (10). Thus, the country can replicate the insurance contract by holding a stock of reserves that

[7] The fact that the constraint is binding means that there is no precautionary savings, in part because the reserves insurance contracts provide a substitute to such savings.

is financed by debt with contingent default, and the insurance premium x_t is equal to the interest rate spread on this debt.

This is reminiscent of Edwards' (1985) measure of the opportunity cost of reserves as the spread between the interest rate on the country's long-term external debt and the return on its reserves.[8] The model suggests, however, that the interest rate spread x_t overestimates the true opportunity cost of reserves. To see this, note that the expected payoff of the contingent security is given by,

$$(1-\pi_t)(1+r+x_t)+\pi_t(r+x_t)=1+r+\delta_t,$$

where the difference between the spread and the default probability,

$$\delta_t = x_t - \pi_t, \tag{25}$$

is the expected excess return, or pure risk premium. If foreign investors were risk-neutral this term would be equal to zero in equilibrium, but it is in general positive because of foreign investors' risk aversion.

Using (25) to substitute out x_t from (17) gives an expression for the extent of insurance in equilibrium,

$$p_t = 1 - \frac{\delta_t}{(1-\pi_t)(\pi_t+\delta_t)}.$$

The right-hand side is equal to 1 if $\delta_t = 0$ and is decreasing in δ_t. There is less than full insurance, therefore, only to the extent that δ_t is strictly positive. The cost of insurance, thus, should be measured by the pure risk premium δ_t, rather than the full spread $x_t = \pi_t + \delta_t$, which is generally used in the empirical literature on international reserves. The default risk premium π_t is a fair compensation for the risk that the country will not repay, and does not represent an opportunity cost of holding reserves in the same sense as δ_t.

2.4 The supply of insurance

The cost of insurance, δ_t is equal to the pure risk premium coming from the risk aversion of foreign investors (plus possibly a transaction cost). We now endogenize the pure risk premium by assuming that the insurance is provided by a pool of foreign "insurers".

We assume that the insurance is provided by overlapping generations of foreign insurers. The generation born at t consumes in period $t+1$. Each insurer born at t is endowed with

[8] The contingent debt has an average duration of $1/\pi > 1$, which is longer than the maturity of the short-term bonds held as reserves.

w_{t+1} in period $t+1$ and consumes $w_{t+1} - z_{t+1}$, where z_{t+1} is the transfer from the insurance contract with the representative consumer, given by

$$\begin{aligned} z_{t+1} &= -x_t r_t \text{ if no sudden stop,} \\ z_{t+1} &= (1 - x_t) r_t \text{ if sudden stop,} \end{aligned}$$

where r_t is the supply of reserves per insurer. Assuming that w_{t+1} is known in period t, the supply of insurance per insurer is solution to the problem,

$$\max_{r_t} (1 - \pi_t) v_t (w_{t+1} + x_t r_t) + \pi_t v_t (w_{t+1} - (1 - x_t) r_t),$$

where $v_t(\cdot)$ is the utility function of an insurer born at t. If $v_t(\cdot)$ is CRRA with time-varying risk aversion σ_t^*, the first-order condition is,

$$(w_{t+1} + x_t r_t)^{-\sigma_t^*} = p_t (w_{t+1} - (1 - x_t) r_t)^{-\sigma_t^*}.$$

Solving for r_t then implies the aggregate supply schedule,

$$\rho_t = \frac{N_t r_t}{Y_{t+1}^n} = \omega_t \frac{1 - p_t^{1/\sigma_t^*}}{1 - (1 - p_t^{1/\sigma_t^*}) x_t}, \tag{26}$$

where N_t is the number of insurers born at t and $\omega_t = N_t w_{t+1} / Y_{t+1}^n$ is the ratio of foreign insurers' total wealth to domestic output. Using $x_t = \pi_t + \delta_t$ and (17), equation (26) defines a supply function for reserves,

$$\rho_t = \rho_t^s (\pi_t, \delta_t).$$

If the country is a price-taker in the market for reserves,[9] its demand $\rho^d(\pi_t, \delta_t)$ is given by (18), and market equilibrium implies,

$$\rho^d(\pi_t, \delta_t) = \rho_t^s(\pi_t, \delta_t). \tag{27}$$

The comparative statics for the joint determination of ρ_t and δ_t are shown in Figure 2. A decrease in the wealth or risk appetite of foreign insurers increases the risk premium and lowers the equilibrium level of reserves (the equilibrium moves from point A to point B). The impact of an increase in the probability of sudden stop is more ambiguous, because it affects both sides of equation (27). The supply of insurance decreases at the same time as demand increases (the equilibrium moves from point A to point C). The risk premium δ_t increases, but the equilibrium level of insurance ρ_t could go up or down. Thus it is no longer necessarily true that a more risky country (with higher π) holds more reserves.

[9] The country would be a price-taker if it belongs to a large class of similar countries, or if the insurance is subscribed by atomistic residents.

2.5 Real exchange rate

We now consider valuation effects caused by a real exchange rate depreciation at the time of the sudden stop. Let us assume that the country's external liabilities and reserves are denominated in foreign currency. Then the budget constraint of the representative consumer (1) is replaced by,

$$C_t = Y_t + Q_t \left(L_t - (1+r)L_{t-1} + Z_t \right),$$

where Q_t is the real exchange rate at time t. We assume that the real exchange rate is constant (and normalized to 1) in normal times, and depreciates by ΔQ at the time of the sudden stop,[10]

$$Q_t^n = 1,\ Q_t^s = 1 + \Delta Q.$$

As shown in the appendix, the formula for the optimal level of reserves is now given by,

$$\rho_t^* = \frac{\lambda + \gamma - \left(1 - \frac{(r-g)\lambda}{1+g}\right)(1 - p_t^{1/\sigma}) + \frac{1+r}{1+g}\lambda \Delta Q}{1 - x_t(1 - p_t^{1/\sigma}) + (1 - x_t)\Delta Q}, \tag{28}$$

where p_t is given by,

$$p_t = \frac{x_t^{-1} - 1}{\pi_t^{-1} - 1}(1 + \Delta Q). \tag{29}$$

The impact of the real depreciation on the optimal level of reserves is *a priori* ambiguous. On one hand, the cost of insurance falls (since the value of reserves in terms of domestic consumption increases at the time of the sudden stop) and the size of the balance-of-payments shock increases (since external debt is in foreign currency), with both effects contributing to increase the demand for insurance. On the other hand, the same level of insurance can be achieved with less reserves. The sign and size of the net effect are explored in section 3.

2.6 Crisis prevention

Our model has focused so far on the benefits of reserves in terms of crisis mitigation (reducing the welfare cost of a crisis). An additional benefit of reserves might be to instill confidence in the economy and thus reduce the probability of a sudden stop (Ben Bassat and Gottlieb, 1992; Garcia and Soto, 2004). We show in this section how the model can be extended to incorporate the benefits of reserves in terms of crisis prevention.

The prevention benefits of reserves can be captured, in reduced form, by writing the probability of a sudden stop as a decreasing function $\pi(\rho)$ of the reserves ratio,

$$\pi_t = \pi(\rho_t). \tag{30}$$

[10] For simplicity, ΔQ is assumed to be exogenous to the level of reserves.

This is a generalization of the previous model, which corresponds to the special case where function $\pi(\cdot)$ is constant.

As shown in the appendix, one possible interpretation of the reduced form (30) is a model of self-fulfilling debt rollover crises a la Cole and Kehoe (2000). The key assumptions are that: (1) the country's pledgeable output falls if there is a debt rollover crisis; and (2) the lending decisions are taken by a large number of uncoordinated lenders. Then we show that if the level of reserves falls short of a threshold ($\rho < \overline{\rho}$), a good equilibrium in which foreign lenders roll over their claims coexists with a bad equilibrium in which they don't. The strategic complementarity behind the equilibrium multiplicity is that an individual investor who fails to lend contributes to reduce the pledgeability of the country's output for all the other lenders. A self-fulfilling debt rollover crisis could be triggered by a sunspot variable that coordinate lenders on the bad equilibrium. Since the stochastic process for the sunspot is essentially arbitrary—and could depend on the level of reserves—the shape of function $\pi(\cdot)$ is indeterminate in the range of multiplicity $[0, \overline{\rho}]$.[11]

Coming back to the general formulation of the problem with crisis prevention, the question is how the optimal level of reserves ρ^* changes in the benchmark model when the probability of a sudden stop is given by (30) rather than a fixed exogenous level π. We show in the appendix that although closed-form expressions can no longer be obtained, ρ^* is the solution to a relatively simple fixed-point problem that can be solved numerically. We will estimate the quantitative impact of this effect in a calibrated version of the model.

2.7 Other extensions

The model lends itself to a number of other extensions, which we discuss briefly as a way of concluding this section. For example, we could assume that the real devaluation, ΔQ, is a decreasing function of the level of reserves ρ (as would be the case if reserves are used to defend the domestic currency in a sudden stop). Similarly, a larger stock of reserves could be used to mitigate the output cost of a crisis, γ (as assumed by Garcia and Soto, 2004) or the size of the sudden stop, λ. Then if π remains exogenous the optimal level of reserves, ρ^*, maximizes

$$(1-\pi)u\left(1-\frac{r-g}{1+g}\lambda - x\rho\right)+\pi u\left(1-\gamma(\rho)-(1+\Delta Q(\rho))\frac{1+r}{1+g}\lambda(\rho)+(1+\Delta Q(\rho))(1-x)\rho\right),$$

where $\Delta Q(\cdot)$, $\gamma(\cdot)$ and $\lambda(\cdot)$ are decreasing functions that capture (in reduced form) the endogeneity of those variables.

[11] One could use a model with heterogeneous beliefs a la Morris and Shin (1998) to endogenize π as a function of a public signal on the level of reserves. See Kim (2007) for a model of reserves along those lines.

In addition, if π is endogenous to ρ (like in section 2.6) and δ is endogenous to π (like in section 2.4), then δ becomes endogenous to and decreasing in ρ. The opportunity cost is then decreasing with the level of reserves, which presumably brings in an additional motive for holding reserves (Hauner, 2005; Levy-Yeyati, 2006).

3 Calibration

We now explore the quantitative implications of the model with some calibrations. We first construct a benchmark calibration by reference to the average sudden stop in our sample and present some sensitivity analysis (subsections 3.1 and 3.2). We then discuss the extent to which our insurance model can account for the recent reserves buildup in emerging market countries (subsection 3.3).

3.1 Benchmark calibration

The behavior of the model economy is determined by 7 parameters: the probability of a sudden stop π, the output loss γ, the ratio of short-term debt to GDP λ, the return on reserves r, the premium δ, and the risk-aversion parameter σ. Our benchmark calibration is given in Table 1.

Parameters π, γ and λ are calibrated by reference to a sample of sudden stops in 34 middle-income countries over 1975—2003. For this purpose we decompose domestic absorption as the sum of domestic output, the financial account, income from abroad, and reserves decumulation:

$$A_t = Y_t + KA_t + IT_t - \Delta R_t, \tag{31}$$

where KA_t is the financial account, IT_t the income and transfers from abroad, and $\Delta R_t = R_t - R_{t-1}$ is the change in reserves.[12] A sudden stop is an abrupt fall in the financial account, KA_t, which, other things equal, reduces domestic absorption. The impact of the sudden stop on domestic absorption could be amplified by a concomitant fall in domestic output, Y_t, or mitigated by a fall in reserves, ΔR_t.

To see the correspondance between the national accounting identity (31) and the model, note that the consumer's budget constraint (1) can be written (in a sudden stop with $L_t = 0$

[12] The financial account (formerly called the capital account) is a measure of capital inflows. Domestic absorption is the sum of domestic (private and public) consumption and investment. Equation (31) results from the GDP identity $Y_t = A_t + TB_t$, where TB_t is the trade balance, and the balance of payments identity, $CA_t + KA_t = \Delta R_t$, where $CA_t = TB_t + IT_t$ is the current account balance.

and $Z_{t-} = (1 - x_{t-1})R_{t-1})$,

$$\underbrace{C_t}_{A_t} = \underbrace{(1-\gamma)Y_t^n}_{Y_t} + \underbrace{(-L_{t-1})}_{KA_t} + \underbrace{(-rL_{t-1} - x_{t-1}R_{t-1})}_{IT_t} - \underbrace{(-R_{t-1})}_{\Delta R_t}.$$

Thus, it is possible to infer the size of the shocks to the economy in a sudden stop (λ and γ) from the empirical behavior of the terms on the right-hand side of equation (31).

In line with Guidotti et al (2004), we identify a sudden stop in year t if the ratio of capital inflows to GDP, $k_t \equiv KA_t/Y_t$, falls by more than 5 percent relative to the previous year,

$$\text{sudden stop in year } t \ \Leftrightarrow k_t < k_{t-1} - 5\%.$$

The countries in our sample and the years in which they had a sudden stop are reported in Table 2.[13] Reassuringly, our criterion captures many well-known crises (Mexico 1995; Korea, Thailand and the Philippines in 1997; Argentina 2001).

Figure 3 shows the average behavior of domestic absorption and the contribution of the various components on the right-hand-side of equation (31) in a five-year event window centered around a sudden stop.[14] Real output is normalized to 100 in the year prior to the sudden stop. The income and transfers from abroad are not shown because they are small and do not vary much in a sudden stop.

We observe a large fall in capital inflows in the year of the sudden stop, amounting to about 10 percent of the previous year's output. This is not surprising since a large fall in the financial account is the criterion that was used to identify sudden stops. More interestingly, we see that most of the negative impact of the financial account reversal on domestic absorption is offset by a fall in reserve accumulation. Thus, domestic absorption falls by less than 3 percent of GDP on average in the year of the sudden stop—much less than capital inflows. This evidence is consistent with the view that emerging market countries accumulate reserves in good times so as to be able to decumulate them, thereby smoothing domestic absorption, in response to sudden stops.

[13] Our sample includes the countries classified as middle-income by the World Bank, plus Korea. It excludes major oil producer countries, for which a large change in the price of oil could be misinterpreted as a sudden stop. Capital inflows are measured as the deficit in the Current Account minus the accumulation of Reserves and Related Items in the IMF's *International Financial Statistics* (IFS). Exceptional financing and IMF loans are counted as reserves rather than capital inflows.

[14] Figure 3 is based on the events that occurred after 1980, excluding the sudden stops that occurred inside the five-year window of a previous sudden stop. The data for the financial account, the change in reserves and the income and transfers come from the IFS database. They are converted from current US dollar to constant local currency units using the nominal exchange rate vis-a-vis the US dollar and the local GDP deflator index. The data for real GDP and the real GDP deflator come from the World Bank's *World Development Indicators*.

Coming back to the calibration, the unconditional probability of a sudden stop is 10.2 percent per year, which is rounded to $\pi = 0.1$ in the calibration. Parameter λ was calibrated as the average level of $(k_{t-1} - k_t)$ over our sample of sudden stops, which is close to 10 percent. Looking at the ratio of short-term external debt to GDP would give similar values. This ratio is equal to 8.2 percent on average in our sample according to the World Bank's *Global Development Finance* (GDF) data set, and to 11.7 percent according to the Bank of International Settlements (BIS) database.[15]

We calibrated the output cost of a sudden stop by looking at the average difference between the GDP growth rate the year prior to the sudden-stop and the growth rate the first year of the sudden stop. We find that the GDP growth rate falls by 4 percent on average in the first year of a sudden stop, and by 9 percent if we restrict the sample to the sudden stops in which output fell. We set γ to 6.5 percent, the average between the low and the high estimates. This is consistent with the output cost of sudden stops estimated in the literature.[16]

The opportunity cost of holding reserves is often measured, in the literature, as the difference between the interest rate that the country pays on its long-term external debt and the return on its reserves. If one assumes for simplicity that the reserves are denominated in US dollars, the opportunity cost of reserves for country j in year t is given by,

$$\delta_t(j) = r_t^l(j) - r_t^s(us),$$

where $r_t^l(j)$ is the interest rate on the country j's long-term dollar debt, and $r_t^s(us)$ is the US short-term interest rate. This can also be written as the sum of the US term premium plus the spread on the country's long-term debt,

$$\delta_t(j) = \underbrace{r_t^l(us) - r_t^s(us)}_{\text{US term premium}} + \underbrace{r_t^l(j) - r_t^l(us)}_{\text{country spread}}.$$

Our model suggests a similar approach to the calibration of δ, but with the caveat that the country spread should only include the *pure* risk premium and not the default risk premium.

The US term premium, measured as the differential between the yield on 10-year US Treasury bonds and the Federal Funds rate, was equal to approximately 1.5 percent on average

[15] One source of discrepancy is that the definition of short-term debt is based on original maturity in the GDF data but on residual maturity in the BIS data. The two data sets also differ by their country coverage.

[16] The estimates in the literature tend to be somewhat larger, but they refer to the cumulated output loss over several years. Hutchison and Noy (2006) find that the cumulative output loss in a sudden stop is around 13 to 15 percent of GDP over a three-year period. Becker and Mauro (2006) find an expected output cost of 16.5 percent of GDP.

over the period 1990—2005.[17] The second component (the pure risk premium on emerging market debt) has been found to be relatively small in the literature. Based on estimates of the average ex-post returns on emerging market bonds and loans over the period 1970-2000, Klingen, Weder and Zettelmeyer (2004) find that the pure risk premium is approximately zero. Using a different approach, Broner, Lorenzoni and Schmukler (2007) find risk premia on emerging markets bonds ranging from 0 to 1.5 percent in the period 1993-2003.[18] Based on this discussion, we set δ to 1.5 percent in the benchmark calibration of the model, and allow δ to vary in a relatively wide interval, from 0.25 percent to 5 percent in the sensitivity analysis.

Finally, the risk-free short-term dollar interest rate r is set at 5 percent. The growth rate g is set at 3.3 percent, the average real GDP growth rate in our sample of middle-income countries over 1975—2002 (excluding sudden-stop years). The benchmark risk-aversion and its range of variation are standard in the growth and real business cycle literature.

One can check that condition (22) is satisfied for the benchmark calibration. Condition (23) is also satisfied provided that debt does not flow back to the country too quickly after a sudden stop. If we assume a linear specification $\alpha(\tau) = \tau\alpha/\theta$, this condition is satisfied if a sudden stop episode lasts at least 4 years ($\theta \geq 4$). Finally, condition (24) is satisfied provided that the output deviation from trend is lower than 6 percent of GDP after the first period of the sudden stop. This condition is satisfied if $\gamma(\tau)$ decreases linearly during a sudden stop episode.

3.2 Sensitivity analysis

Based on our formula for the optimal level of reserves, equation (18), the benchmark calibration implies an optimal level of reserves of 9.1 percent of GDP, or 91 percent of short-term external debt. This is close to the ratio of reserves to GDP observed in the data over 1975-2003 (11 percent on average, a level that can be explained by the model if the risk aversion parameter is raised from 2 to 2.75). However, this is significantly lower than the level observed in the most recent period, especially in Asia. It would be interesting to know what changes in the parameters would be required to increase the optimal level of reserves. The remainder of this section explores the sensitivity of our results to parameter values.

Figure 4 shows how the optimal level of reserves depends on: the level of short-term debt

[17] This measure is not adjusted for fluctuations in the expected US rate of inflation over the sample period. See Rudebusch, Sack and Swanson (2007) for a review of the possible approaches to estimating the US term premium.

[18] Broner et al (2007) find that the pure risk premium can increase to much higher levels in times of crisis. But the appropriate measure of δ is the level of the risk premium in non-crisis times (when the country insures itself against a crisis).

(or size of sudden stop), λ; the probability of sudden stop, π; the risk premium, δ; and the degree of risk aversion, σ. In each case, we contrast the level of reserves computed using our model with the one implied by the Greenspan-Guidotti rule. Several interesting results emerge. First, the Greenspan-Guidotti rule provides a good approximation to the variation of the optimal level of reserves with the level of short-term debt. The optimal ratio of reserves to short-term debt remains in the 90 to 100 percent range if the size of the sudden stop exceeds 10 percent of GDP.[19]

Second, the optimal level of reserves is quite sensitive to the probability of sudden stop, π, the premium δ, and the risk aversion parameter, σ. This offers an interesting contrast with the Greenspan-Guidotti rule, which does not depend at all on these parameters. Doubling the probability of sudden stop from 5 percent to 10 percent more than doubles the optimal level of reserves, from 3.6 percent to 9.1 percent of GDP. Increasing δ from 1.5 percent to 3 percent reduces the optimal reserve-to-GDP ratio from 9.1 percent to 2.8 percent. A shift in risk-aversion from 1 to 4 increases the optimal level of reserves from 2.1 percent to 12.7 percent of GDP. However, because the optimal level of reserves is a strongly concave function of σ, increasing risk-aversion has a milder impact for σ larger than 4.

Figure 5 shows the sensitivity of our estimates to the changes in the model considered in sections 2.4, 2.5 and 2.6. The upper-left panel of Figure 5 explores the implications of making the cost of insurance δ endogenous. Those estimates are based on the model presented in section 2.4, assuming that the wealth of foreign insurers amounts to one half of domestic output ($\omega = 0.5$). The panel shows how the optimal level of reserves varies with the (exogenous) probability of sudden stop π for two different levels of σ^*. For the sake of comparison, the dashed line shows the optimal level of reserves when δ is exogenous (it is the same as in the upper-right panel of Figure 4). It is interesting to see that with an endogenous cost of insurance, ρ^* becomes essentially invariant with regard to π, a result that does not seem to depend on σ^*. Thus, the model extension with endogenous δ predicts that a country's level of reserves is not very sensitive to its vulnerability to a sudden stop.

The upper-right panel of Figure 5 shows how the optimal level of reserves increases with the size of the real exchange rate depreciation in a sudden stop (ΔQ). This effect is quantitatively significant, with a 10 percent depreciation (close to the level observed in the data) increasing the optimal level of reserves by approximately 4 percent of GDP above the benchmark.

[19] This is not true, however, for small sudden stops: the optimal level of reserves is equal to zero if short-term debt amounts to less than 2.5 percent of GDP. This is because the marginal benefit of smoothing domestic absorption varies in proportion with the size of the sudden stop, whereas the marginal cost of holding reserves is constant.

Next, we look at crisis prevention, based on the analysis in section 2.6. The impact of crisis prevention crucially depends on the specification of function $\pi(\rho)$. First, we could assume (in line with the model of self-fulfilling crisis presented in the appendix), that the economy is vulnerable to sudden stops if and only if its reserves do not cover its short-term debt. That is, $\pi(\cdot)$ is a step function,

$$\begin{aligned}\pi(\rho) &= \pi \text{ if } \rho < \lambda, \\ \pi(\rho) &= 0 \text{ if } \rho \geq \lambda.\end{aligned}$$

Then the country will never find it optimal to set reserves in excess of short-term debt since the extra reserves yield no benefit once the probability of sudden stop has been reduced to zero (the Greenspan-Guidotti rule corresponds to full insurance in terms of crisis prevention). A simple numerical exercise shows that if the other parameter values are set to their benchmark values, the Greenspan-Guidotti rule is indeed optimal provided that the probability of sudden stop π is larger than 1 percent.[20]

Another approach to calibrating function $\pi(\cdot)$ relies on the empirical literature on early warning indicators of crisis, which has estimated probit equations of the type,

$$\pi = F\left(b - a\frac{\rho}{\phi}\right), \tag{32}$$

where ϕ is the denominator of the reserves-coverage ratio (e.g., if the denominator is short-term debt, $\phi = \lambda$), and $F(\cdot)$ is the cdf of a standard normal law. In this specification, the probability of a crisis is a smoothly decreasing function of the reserve ratio.

The lower panels of Figure 5 show the optimal level of reserves when the prevention benefits are specified like in (32). For the purpose of the sensitivity analysis, we used a range of $[0, 0.3]$ for the crisis prevention parameter a, which is consistent with probit regressions for the probability of currency crisis (Jeanne, 2007).[21] To illustrate, if the crisis prevention parameter is at the upper end of the range ($a = 0.3$), doubling the ratio of reserves to short-term debt from 1 to 2 reduces the probability of a sudden stop from 10 to 6 percent.

The lower-left panel of Figure 5 shows how the optimal level of reserves ρ^* varies with the

[20] This is based on the assumption that δ is exogenous and equal to 1.5 percent. If δ is endogenous like in section 2.4, then it is equal to zero for $\rho \geq \lambda$ (since there is no risk). In this case the Greenspan-Guidotti rule is always optimal, irrespective of π.

[21] The literature tends to find that reserves have prevention benefits for currency crises, but not for sudden stops. See Berg et al (2005) for a recent review on early warning indicators of currency crises. By contrast with currency crises, Calvo et al (2004), Frankel and Cavallo (2004) and Jeanne (2007) do not find that reserves have a statistically significant effect of reducing the probability of sudden stop.

crisis prevention parameter a.[22] Parameter b was set to $F^{-1}(0.1)$, so that $a = 0$ corresponds to the benchmark model. The optimal level of reserves increases markedly with a, and reaches a maximum of 34.4 percent of GDP for $a = 0.25$. The relationship between a and ρ^* is non-monotonic, as a low probability of sudden stop can be achieved with less reserves for higher levels of a .

The lower-right panel of Figure 5 shows how the optimal level of reserves varies with parameter b, for $a = 0.15$. The range of variation of b makes π increase from 5 percent to 15 percent when reserves are equal to short-term debt. The optimal level of reserves is always larger than 20 percent of GDP and can exceed 30 percent of GDP. The figure also shows that more vulnerable countries (with higher b) tend to accumulate more reserves, like in the case without prevention (upper-right panel of Figure 4).

Finally, we also explored the impact of assuming that reserves reduce the output cost of a sudden stop (making γ a decreasing function of ρ). We assume that $\gamma = 0.065 - a(\rho/\lambda)$ and calibrate coefficient a by reference to the literature on balance-of-payments crises. A 100 percent increase in the reserves-to-short-term debt ratio has been found to lower the output cost of a currency crisis by 0.25 percent of GDP by De Gregorio and Lee (2003), and by 1.7 percent of GDP by Rodrik and Velasco (1999). We find that De Gregorio and Lee's estimate increases the optimal level of reserves from 9.1 percent to 10.1 percent of GDP in the benchmark calibration of our model, whereas Rodrik and Velasco's estimate implies a larger increase in the optimal level of reserves, to 14.9 percent of GDP.

3.3 The recent buildup in emerging market reserves

There has been a large buildup in the reserves of emerging market countries, especially in Asia where the average ratio of reserves to GDP exceeded 30 percent in 2006 (Figure 6).[23] As noted in the introduction, this buildup has sometimes been interpreted in terms of self-insurance against the risk of sudden stops in capital flows, although it could be due to other causes. We now explore how far one can go in explaining the recent buildup using our insurance framework.

Prima facie, the level of reserves in Latin America seems broadly consistent with the benchmark calibration of our model, but the same is not true for Asian emerging market

[22] The optimal level of reserves was computed using the numerical method presented in the appendix. To compute the optimal level of reserves under prevention one also needs to calibrate how the economy converges back to trend in a sudden stop episode. We assume linear paths: $\alpha_s(\tau) = (\tau/\theta)\alpha$ and $\gamma_s(\tau) = (1 - \tau/\theta)\gamma$, with $\theta = 5$.

[23] The sample of countries is the same as in the previous section.

countries. In fact, since 2000 the average reserves-to-GDP in Asia has exceeded the full insurance level $\lambda + \gamma$, which is equal to 16.5 percent of GDP in our benchmark calibration. Can extensions of our model account for the Asian reserves buildup? One could think, for example, of the extension with crisis prevention, which can predict optimal levels of reserves in excess of 30 percent of GDP. To explore this question we first look at probit estimates of the probability of a sudden stop in our sample of countries.

Probability of sudden stop: cross-country estimates

The probability of a sudden stop is estimated as a function of a country's economic fundamentals by running a probit estimation of the probability of sudden stops in our sample of 34 middle income countries over 1980-2004. Our preferred specification is reported in Table 3. The explanatory variables have been selected using a general-to-specific approach, starting from a set of more than 20 potential regressors.[24] All the explanatory variables are averages of the first and second lags, and are thus predetermined with respect to the sudden stop. The results are robust to the inclusion of time effects and fixed effects.

We find that the probability of a sudden stop increases with the level of real appreciation (measured as the deviation in the real exchange rate from a Hodrick-Prescott trend), the ratio of public debt to GDP, and the country's openness to financial flows (measured by the absolute value of gross inflows as a share of GDP) (regression 3.1). The last determinant suggests that the vulnerability to sudden stops rises with the degree of international financial integration. Interestingly, we found that trade openness did not significantly affect the probability of a sudden stop when financial openness was included as an explanatory variable. Our estimation remains robust when different combination of time and fixed effects are introduced in the specification (regressions 3.2, 3.2, and 3.4). Finally, we tried various reserves adequacy ratios and did not find any significant negative impact on the probability of a sudden stop, in accordance with the results previously obtained in the literature. Importantly, thus, our estimates of the probability of sudden stop are exogenous to the accumulation of reserves.

Figure 7 shows the evolution of the probability of sudden stop in Latin America and in Asia according to our preferred specification (without fixed effects). Interestingly, the probability of sudden stop increased in Latin America from 1997 to 2003, which, according to our insurance model, could explain why reserves have increased too. In fact, the upper-right panel of Figure 4 shows that both the level and variations in the Latin American reserves-to-GDP ratio between 1997 and 2003 can be explained by the benchmark model. In contrast, the probability of sudden stop declined in Asia after a peak that was reached at the time of

[24] The regressors are listed in Table 4.

the 1998 crisis. This probability also declined in Latin America after 2004.

Puzzles

The large buildup in Asian reserves since 1998 (and the continuing buildup in Latin America since 2004) may seem puzzling from the point of view of our insurance model, since the probability of sudden stop was going down during that period. Can variants of the benchmark model account for the reserves buildup?

First, the model with crisis prevention can explain levels of reserves of the order of magnitude recently observed in Asia (lower panels of Figure 5). But there are several problems with this explanation. First, we do not find evidence that reserves have prevention benefits in our probit estimates. Second, even if crisis prevention benefits existed, the countries that are more vulnerable to sudden stops should hold more reserves (lower-right panel of Figure 5), i.e., reserves should be higher in Latin American than in Asia.

The data suggest that more risky countries do not hold more reserves: we do not observe a significant and positive cross-country correlation between our probit estimates of the probability of sudden stop and the ratio of reserves to GDP. This is consistent with the model presented in section 2.4, in which more risky countries were deterred from taking more insurance because of its higher cost (higher-left panel of Figure 5). In that model, however, the cross-country differences in the level of reserves would have to come from different expectations about the size or output cost of a sudden stop (λ and γ).[25] One can compute the "implied γ" for each country, as the level of the output cost of a crisis that is required for the insurance model to explain the level of reserves observed in a given year. Based on this approach, we find that the model can explain the level of Asian reserves in 2005 only if one assumes that the expected output cost of a sudden stop exceeds 30 percent of GDP.

We have calibrated γ in reference to the typical size of the financial account reversal during a sudden-stop. One could argue that while the accumulation of reserveswas excessive to cope with "standard" sudden stops in East Asia, it was appropriate to insure against a large global financial crisis such as the one that started in 2007-08. Obstfeld, Shambaugh and Taylor (2008) suggest that, in a financially integrated world, a financial crisis can result in a significant share of M2 being converted in foreign currency. This could justify a much higher value for γ and explain the level of reserves observed in Asia.

On balance, it seems relatively difficult to account for the recent pattern of reserves accumulation in EMEs using our model of insurance.[26] The emerging market economies that

[25] By contrast, increasing the risk aversion parameter cannot raise the optimal level of reserves above the full insurance level, $\lambda + \gamma$. Thus, risk aversion cannot explain the post-crisis buildup in emerging Asia's reserves.

[26] Similar conclusions have been reached in IMF (2003) and Becker et al (2007). IMF (2007, chapter II) uses

insured themselves the most are Asian countries that seem to need this insurance the least. The Asian crisis may have led to an upward revision of the size of the sudden stop or of the output loss resulting from sudden stops. Although this revision seems implausibly large (in view of historical experience) for actual accumulation to be consistent with the model, the Asian reserves build-up might be justifiable ex post by the current crisis.

4 Concluding Comments

This paper derives a simple formula for the optimal level of international reserves, based on the assumption that reserves provide insurance allowing countries to smooth domestic absorption against the disruption induced by a sudden stop in capital flows associated with a fall in output.

We find that a plausible calibration of the model can account for the average level of reserves in emerging market countries since 1980, but not for the recent accumulation in Asia. There are, obviously, other explanations for this accumulation. For example, a number of authors argue that the reserves buildup in Asia is the unintended consequence of policies that maintain large current account surpluses (see, e.g., Summers, 2006; Dooley et al, 2004). If one takes this view, our framework could help to assess the fraction of the public sector's foreign assets that should be held as liquid reserves for the sake of insurance against volatile capital flows, rather than invested with a longer-term perspective in "sovereign wealth funds". From this point of view, the main contribution of this paper should be viewed as normative rather than positive.

It would be interesting to look at issues related to the collective management of reserves. What would be the benefits of reserve-pooling arrangements between emerging market countries? What are the consequences, for reserve accumulation and domestic welfare, of an institution such as the IMF that relaxes the external credit constraint of emerging market countries in a crisis? These questions could be analyzed using a multi-country extension of the framework presented in this paper.

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our model to assess the adequacy of international reserves in Latin American countries.

TECHNICAL APPENDIX

A1. Proof of Lemma 2

The external credit constraint (2) is binding in normal times if the marginal utility of consumption remains higher than the expected marginal utility of consumption in the next period, that is if

$$u'(C_t^n) > (1-\pi_t)\ u'(C_{t+1}^n) + \pi_t\ u'(C_{t+1}^s).$$

Using (15) this condition can be rewritten,

$$u'(C_t^n) > \frac{1-\pi_t}{1-x_t} u'(C_{t+1}^n),$$

and using the CRRA specification (12), as well as the fact that consumption grows at rate g before the sudden stop, we obtain (22).

During a sudden stop episode, the consumption path is deterministic and the external credit constraint (2) is binding if consumption increases over time. For a sudden stop starting at time t this means

$$C_t \leq C_{t+1} \leq ... \leq C_{t+\theta} \leq C_{t+\theta+1}$$

An expression for $C_{t+\tau}$ can be derived, for $\tau = 1, ..., \theta+1$, by using (1) with $Z_t = 0$, substituting out the terms in L with (2) as an equality, and equations (3) and (7),

$$\begin{aligned} C_{t+\tau} &= Y_{t+\tau}^s + \frac{\alpha(\tau)}{1+r} Y_{t+\tau+1}^n - \alpha(\tau-1) Y_{t+\tau}^n, \\ &= \left(1 - \gamma(\tau) + \frac{1+g}{1+r}\alpha(\tau) - \alpha(\tau-1)\right) Y_{t+\tau}^n. \end{aligned} \tag{33}$$

This formula also applies for $\tau = \theta + 1$ if we define $\gamma(\theta+1) = 0$ and $\alpha(\theta+1) = \alpha(\theta) = \alpha$.

Using (33) the inequality $C_{t+\tau} \leq C_{t+\tau+1}$ can be written, for $t = 1, ..., \theta$,

$$\left(1 - \gamma(\tau) - \frac{r-g}{1+r}\alpha(\tau) + \alpha(\tau) - \alpha(\tau-1)\right) \leq$$
$$(1+g)\left(1 - \gamma(\tau+1) + \frac{1+g}{1+r}\left(\alpha(\tau+1) - \alpha(\tau)\right) - \frac{r-g}{1+r}\alpha(\tau)\right).$$

Since $\alpha(\tau+1) - \alpha(\tau) \geq 0$ and $\gamma(\tau+1) \leq \gamma(\tau)$ this inequality is necessarily satisfied if,

$$\left(1 - \gamma(\tau) - \frac{r-g}{1+r}\alpha(\tau) + \alpha(\tau) - \alpha(\tau-1)\right) \leq (1+g)\left(1 - \gamma(\tau) - \frac{r-g}{1+r}\alpha(\tau)\right),$$

or

$$\alpha(\tau) - \alpha(\tau-1) \leq g\left(1 - \gamma(\tau) - \frac{r-g}{1+r}\alpha(\tau)\right),$$

which in turn is true if (23) is satisfied (because $\gamma(\tau) \leq \gamma$ and $\alpha(\tau) \leq \alpha$). Note that under the linear specification $\alpha(\tau) = \frac{\tau}{\theta}\alpha$, condition (23) implies a lower bound on the duration of a sudden stop episode,

$$\theta \geq \frac{1}{g} \frac{(1+r)\lambda}{(1+g)(1-\gamma) - (r-g)\lambda},$$

(where we used (13) to substitute out α).

Finally, we show that $C_t \leq C_{t+1}$. Since $C_t = C_t^s \leq C_t^n$ it is sufficient to show that $C_t^n \leq C_{t+1}$. Using $C_t^n = \left(1 - \frac{r-g}{1+r}\alpha - x_{t-1}\rho_{t-1}\right) Y_t^n$, and (33) with $\tau = 1$ and $\alpha(0) = 0$, this is necessarily true if

$$1 - \frac{r-g}{1+r}\alpha \leq (1+g)\left(1 - \gamma(1) + \frac{1+g}{1+r}\alpha(1)\right),$$

which is condition (24).

A2. The case with a real exchange rate depreciation

The consumer's problem is now,

$$\rho_t = \arg\max (1-\pi_t)u(C_{t+1}^n) + \pi_t u(C_{t+1}^s),$$

subject to,

$$C_{t+1}^n = Y_{t+1}^n \left(1 - \frac{r-g}{1+g}\lambda - x_t\rho_t\right),$$

$$C_{t+1}^s = Y_{t+1}^n \left(1 - \gamma - (1+\Delta Q)\frac{1+r}{1+g}\lambda + (1+\Delta Q)(1-x_t)\rho_t\right).$$

The first-order condition remains $p_t(C_{t+1}^s)^{-\sigma} = (C_{t+1}^n)^{-\sigma}$ with p_t now given by (29). Manipulations of the first-order condition then give equation (28).

A3. A model with self-fulfilling sudden stops

We present an extension of the model with self-fulfilling crises a la Cole and Kehoe (2000). Like in that paper, the equilibrium multiplicity is based on the fact that the pledgeability of the country's output is endogenous to the country's ability to roll over its external debt. This leads to an equilibrium with self-fulfilling creditor runs.

Let us assume that the debt coming due at t can be repaid with normal-times fiscal resources[27] ηY_t^n, plus the proceeds of the new debt, L_t, and the payment on the reserves insurance contract, Z_t. Thus the country can roll over its external debt at t if,

$$(1+r)L_{t-1} \leq \eta Y_t^n + L_t + Z_t.$$

[27] This term could be interpreted as the fiscal resources that can be mobilized for sovereign debt repayment when the economy is not under the pressure of a crisis. Parameter η is lower than α, the amount of resources that the creditors can extract from the country following a default.

There is a debt roll-over "incident" if this condition is not satisfied. A debt roll-over incident is a necessary but not sufficient condition for a full-fledged sudden stop associated with an output loss. We assume that the country can draw on the reserves contract if there is a debt roll-over incident, and that this problem becomes a full-fledged sudden stop only if the country does not have enough reserves to repay all the outstanding creditors. In this case, there is a sudden stop as defined in section 2.1: both output and pledgeable output fall in the following periods. Thus, we have

$$(1+r)L_{t-1} \leq \eta Y_t^n + L_t + (1-x_{t-1})R_{t-1} \Rightarrow \alpha_{t+1} = \alpha \ , \tag{34}$$

$$(1+r)L_{t-1} > \eta Y_t^n + L_t + (1-x_{t-1})R_{t-1} \Rightarrow \alpha_{t+1} = 0. \tag{35}$$

We assume that the normal-times level of fiscal resources is high enough to roll over $L_t = \lambda Y_t^n$ if there is no incident, i.e.

$$\eta \geq \alpha \frac{r-g}{1+r}. \tag{36}$$

This ensures that there is an equilibrium with no roll-over incident and no sudden stop. There could be a sudden stop, however, because of a *self-fulfilling* fall in L_t. An important difference with the benchmark model is that the pledgeability of period-$t+1$ output is now endogenous to the levels of reserves (R_{t-1}) and external credit (L_t) available in period t. Like before, we assume that the outstanding creditors can recover a fraction of output αY_t^n in payment of their claims $(1+r)L_{t-1}$, so that the consumer does not default on her outstanding debt in a sudden stop.

We now turn to the determination of L_t. We assume that there is a mass 1 of identical atomistic lenders indexed by $i \in [0,1]$. In each period t, lender i decides to roll over his claim at the riskless interest rate r, or not. Lender i's action is represented by the dummy variable $\kappa_t(i)$ (equal to 1, if he lends, and to 0 if he does not). Thus, we have

$$L_t = \int_0^1 \kappa_t(i) di \ \lambda Y_t^n.$$

The sequence of events and actions in period t is as follows. First, the lenders decide their actions $\kappa_t(i)$, $i \in [0,1]$. This determines the level of L_t and whether there is a debt roll-over incident or not. If there is no incident, the representative consumer rolls over her debt with all the lenders who accept to do so. If there is an incident, the representative consumer draws on the reserves contract and repays the outstanding creditors if possible. If this is not possible, then the debt rollover problem degenerates into a full-fledged sudden stop.

In equilibrium, a given creditor i rolls over his claim as long as pledgeable output remains high,

$$\alpha_{t+1} = \alpha \Rightarrow \forall i,\ \kappa_t(i) = 1, \tag{37}$$

$$\alpha_{t+1} = 0 \Rightarrow \forall i,\ \kappa_t(i) = 0. \tag{38}$$

The potential for multiplicity, then, is clear from (34)-(35) and (37)-(38). There may be an equilibrium in which no creditor rolls over his claim. This equilibrium exists if the left-hand side of (35) is satisfied when $L_t = 0$, that is if $\alpha > \eta + (1 - x_{t-1})\rho_{t-1}$, or (for constant x),

$$\rho_{t-1} \leq \overline{\rho} \equiv \frac{\alpha - \eta}{1 - x}, \tag{39}$$

where $\overline{\rho}$ is the full-insurance level of reserves in terms of crisis prevention. It could be smaller or larger than λ (because of (36) and $x \geq 0$). If condition (39) is satisfied, a self-fulfilling sudden stop could occur following the realization of a sunspot variable coordinating market participants on the bad equilibrium. The probability of a self-fulfilling sudden stop is indeterminate, and could be a function of the level of reserves, $\pi_{t-1} = \pi(\rho_{t-1})$. The only restrictions on function $\pi(\cdot)$ is that it should satisfy condition (39) for all values of ρ for which $\pi(\rho)$ is not equal to zero, with $x = \delta + \pi(\rho)$.

A4. Computing the optimal level of reserves in the case with crisis prevention

We show how to solve for the optimal level of reserves when they have benefits in terms of crisis prevention, i.e., the probability of a sudden stop is a decreasing function of the reserves-to-GDP ratio, $\pi_t = \pi(\rho_t)$. We divide the value functions by $(Y^n)^{1-\sigma}$ (which makes the problem stationary), and denote with tilde the normalized value functions. We have,

$$\rho^* = \arg\max \left(\widetilde{V}(\rho) \equiv (1 - \pi(\rho))\widetilde{U}^n(\rho) + \pi(\rho)\widetilde{U}^s(\rho) \right), \tag{40}$$

where

$$\widetilde{U}^n(\rho) \equiv u\left(1 - \frac{r-g}{1+g}\lambda - (\pi(\rho) + \delta)\rho\right) + \frac{(1+g)^{1-\sigma}}{1+r}\widetilde{V}(\rho^*), \tag{41}$$

$$\begin{aligned} \widetilde{U}^s(\rho) = u\left(1 - \gamma - \frac{1+r}{1+g}\lambda + (1 - \pi(\rho) - \delta)\rho\right) + \\ \sum_{\tau=1}^{\theta} \left(\frac{(1+g)^{1-\sigma}}{1+r}\right)^{\tau} u\left(1 - \gamma(\tau) + \lambda(\tau) - \frac{1+r}{1+g}\lambda(\tau - 1)\right) + \left(\frac{(1+g)^{1-\sigma}}{1+r}\right)^{\theta+1} \widetilde{U}^n(\rho^*). \end{aligned} \tag{42}$$

This is a fixed-point problem in the pair $(\widetilde{V}(\rho^*), \rho^*)$, which can be solved by iterations. The iteration mapping $(\widetilde{V}_k^*, \rho_k^*)$ into $(\widetilde{V}_{k+1}^*, \rho_{k+1}^*)$ is as follows. Define the value functions $\widetilde{U}_{k+1}^n(\cdot)$ and $\widetilde{U}_{k+1}^s(\cdot)$ using (41) and (42) with $\widetilde{V}(\rho^*) = \widetilde{V}_k^*$. Then derive the new pair $(\widetilde{V}_{k+1}^*, \rho_{k+1}^*)$ as respectively the maximand and solution to problem (40).

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Table 1. Calibration Parameters

Parameters	Baseline	Range of Variation
Size of Sudden Stop	$\lambda = 0.10$	[0, 0.3]
Probability of a Sudden Stop	$\pi = 0.10$	[0, 0.25]
Output Loss	$\gamma = 0.065$	[0, 0.2]
Potential Output Growth	$g = 0.033$	
Term Premium	$\delta = 0.015$	[0.0025, 0.05]
Risk Free Rate	$r = 0.05$	
Risk Aversion	$\sigma = 2$	[1, 10]

Source: Authors' calculations using data from International Financial Statistics and Federal Reserve Board.

Table 2. Countries and Years of Sudden Stops

Country	Dates of Sudden Stops
ARGENTINA	1989; 2001; 2002
BOLIVIA	1980; 1982; 1983; 1994
BOTSWANA	1977; 1987; 1991; 1993
BRAZIL	1983
BULGARIA	1990; 1994; 1996; 1998,2003
CHILE	1982; 1983; 1985; 1991; 1995; 1998
CHINA,P.R.: MAINLAND	
COLOMBIA	
COSTA RICA	
CZECH REPUBLIC	1996; 2003
DOMINICAN REPUBLIC	1981; 1993; 2003
ECUADOR	1983; 1986; 1988; 1992; 1999; 2000
EGYPT	1990; 1993
EL SALVADOR	1979
GUATEMALA	
HONDURAS	1998; 2000
HUNGARY	1994; 1996
JAMAICA	1983; 1985; 1986; 1988; 2002; 2003
JORDAN	1976; 1979; 1980; 1984; 1989; 1992; 1993; 1998; 2001
KOREA	1986; 1997
MALAYSIA	1984; 1987; 1994; 1999
MEXICO	1982; 1995
MOROCCO	1978; 1995
PARAGUAY	1988; 1989; 1995; 2002
PERU	1983; 1984; 1998
PHILIPPINES	1983; 1997
POLAND	1988; 1990
ROMANIA	1988
SOUTH AFRICA	1985
SRI LANKA	
THAILAND	1982; 1997; 1998
TUNISIA	
TURKEY	1994; 2001
URUGUAY	1982; 2002,2004

The sample includes the countries classified as middle-income by the World Bank, plus Korea, and minus major oil-producing countries. A country-year observation is identified as a sudden stop if the ratio of capital inflows to GDP falls by more than 5 percent, where capital inflows are measured as the current account deficit minus reserves accumulation (source IFS).

Table 3. Probit Estimation of the Probability of a Sudden Stop, 1980-2004

	(3.1)	(3.2)	(3.3)	(3.4)
Real Effective Exchange Rate Overvaluation	2.33	2.29	2.42	2.32
(Deviation from HP-Trend)	(2.78)**	(2.55)*	(2.77)**	(2.43)*
Public Debt / GDP	0.65	0.66	0.80	0.93
	(2.81)**	(2.52)*	(2.04)*	(1.82)
Financial Openness	8.88	9.98	8.10	9.41
(|Gross Inflows|/GDP)	(5.74)**	(5.82)**	(4.24)**	(4.29)**
Intercept	-2.17	-1.85	-2.03	-2.00
	(13.07)**	(5.66)**	(3.80)**	(2.60)**
Observations	706	706	543	543
Pseudo R^2	0.10	0.16	0.11	0.14
Time Effects	No	Yes	No	Yes
Country Fixed Effects	No	No	Yes	Yes

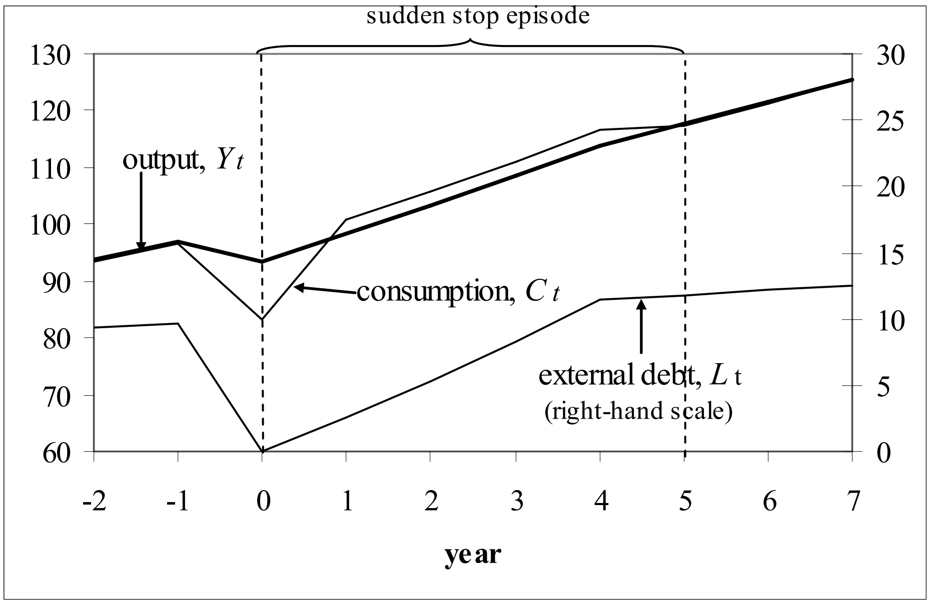
Note: All explanatory variables are taken as average of first and second lags. Absolute value of z statistics in parentheses. * means significant at 5%; ** means significant at 1%

Table 4. List of Variables Used in Regression Analysis

Variables	Source
Debt	
Lag of Real Public Debt to Real GDP	GDF/WDI (2006)
Lag of Short Term Debt to Real GDP	GDF/WDI (2006)
Stock of Reserves	
Total Reserves minus Gold (line 1l.d) / GDP	IFS (2006)
Balance of Payments	
Current Account (line78ald)	IFS (2006)
Reserves and Related Assets (line 79dad)	IFS (2006)
Exchange Rate	
Second Lag Exchange Rate Regime Dummies	Reinhart and Rogoff (2004)
Lag of Real Effective Exchange Rate Deviation from HP trend	
Trade	
Lag of Openness to Trade, (X+M)/GDP	WDI (2006)
Lag of Term of Trade Growth	IFS (2006)
Index of Current Account Openness	Quinn and Toyoda (2006)
US Interest Rate	
Interest Rate of T-bill	IFS (2006)
Change in the Interest Rate of T-bill	IFS (2006)
Financial Development	
Stock Market Capitalization over GDP	Beck and Levine (2005)
Stock Market Total Value Traded over GDP	Id.
Private Credit of the Banking Sector over GDP	Id.
Liquid Liabilities of the Banking Sector over GDP	Id.
Business Cycles	
Average of First and Second Lags of Real GDP Growth	WDI (2006)
Average of First and Second Lags of Real Credit Growth	IFS (2006) and Lane and Milesi-Ferretti (2006)
Financial Account Openness	
Lag of Absolute Gross Inflows / GDP	IFS (2006)
Lag of Sum of Absolute Gross Inflows and Absolute Gross Outflows / GDP	IFS (2006)
Stocks of Foreign Assets and Foreign Liabilities	
Lag of Net Foreign Assets / GDP	Lane and Milesi-Ferretti (2006)
Lag of Stock of Foreign Liabilities / GDP	
Lag of Stock of Debt Liabilities / Stock of Liabilities	
Lag of Stock of FDI / Stock of Liabilities	Lane and Milesi-Ferretti (2006)
Governance	
Lag of Law and Order Index	ICRG (2005)
Lag of Government Stability Index	ICRG (2005)
Others	
Ratio of Foreign Liabilities to Money in the Financial Sector	IFS (2006)

Databases: International Financial Statistics (IFS), Global Development Finance (GDF), World Development Indicators (WDI), International Country Risk Guide (ICRG)

Figure 1. Output, External Debt and Consumption in a Sudden Stop



Source: authors' computations. The figure shows the path of domestic output, consumption (left-hand scale) and external debt (right-hand scale) in a sudden stop episode starting in period 0 and lasting 5 periods. Trend output is normalized to 100 in the period of the sudden stop. The parameter values are those of the benchmark calibration given in Table 1.

Figure 2. Demand and supply of insurance. Comparative Statics.

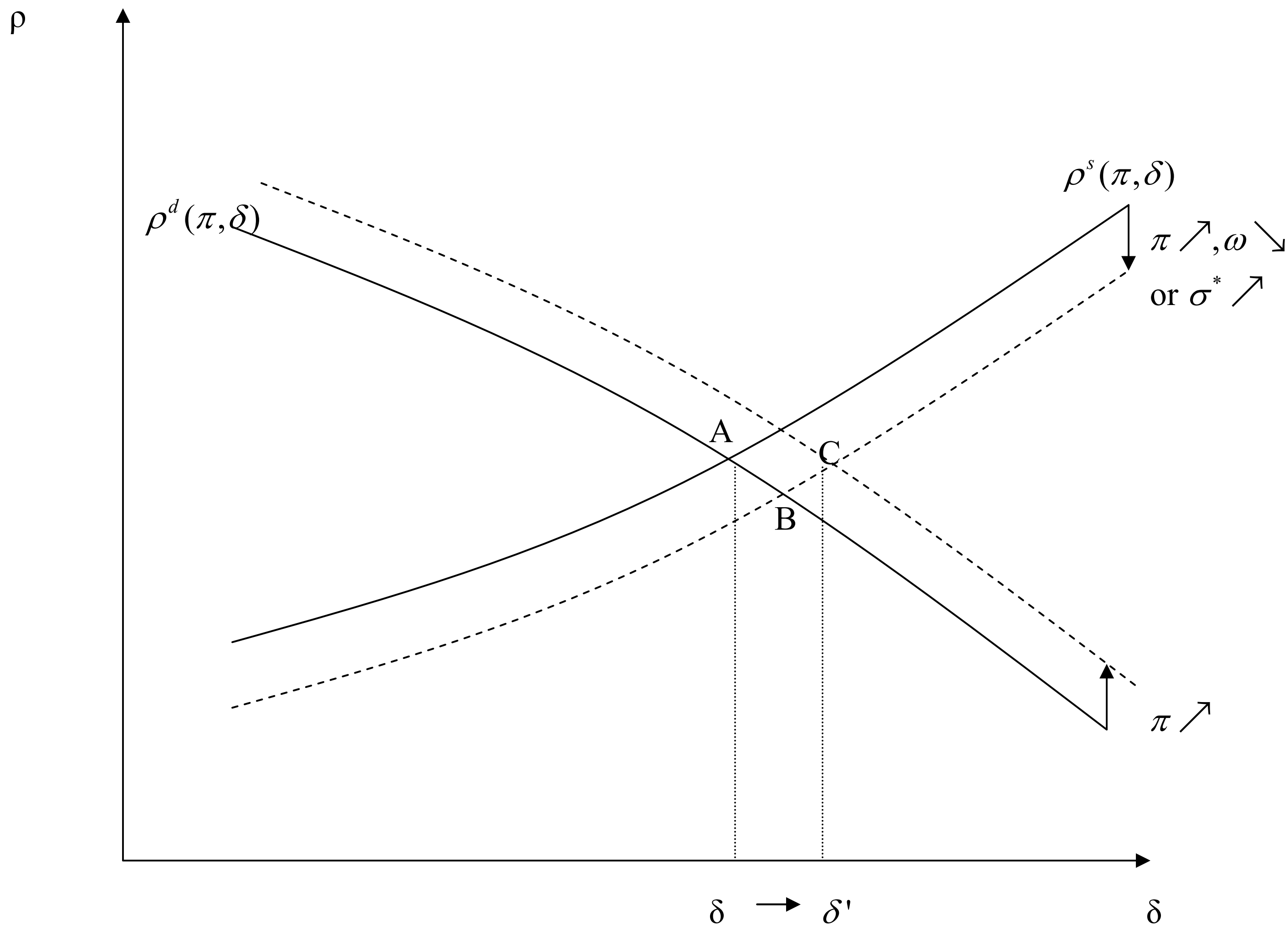
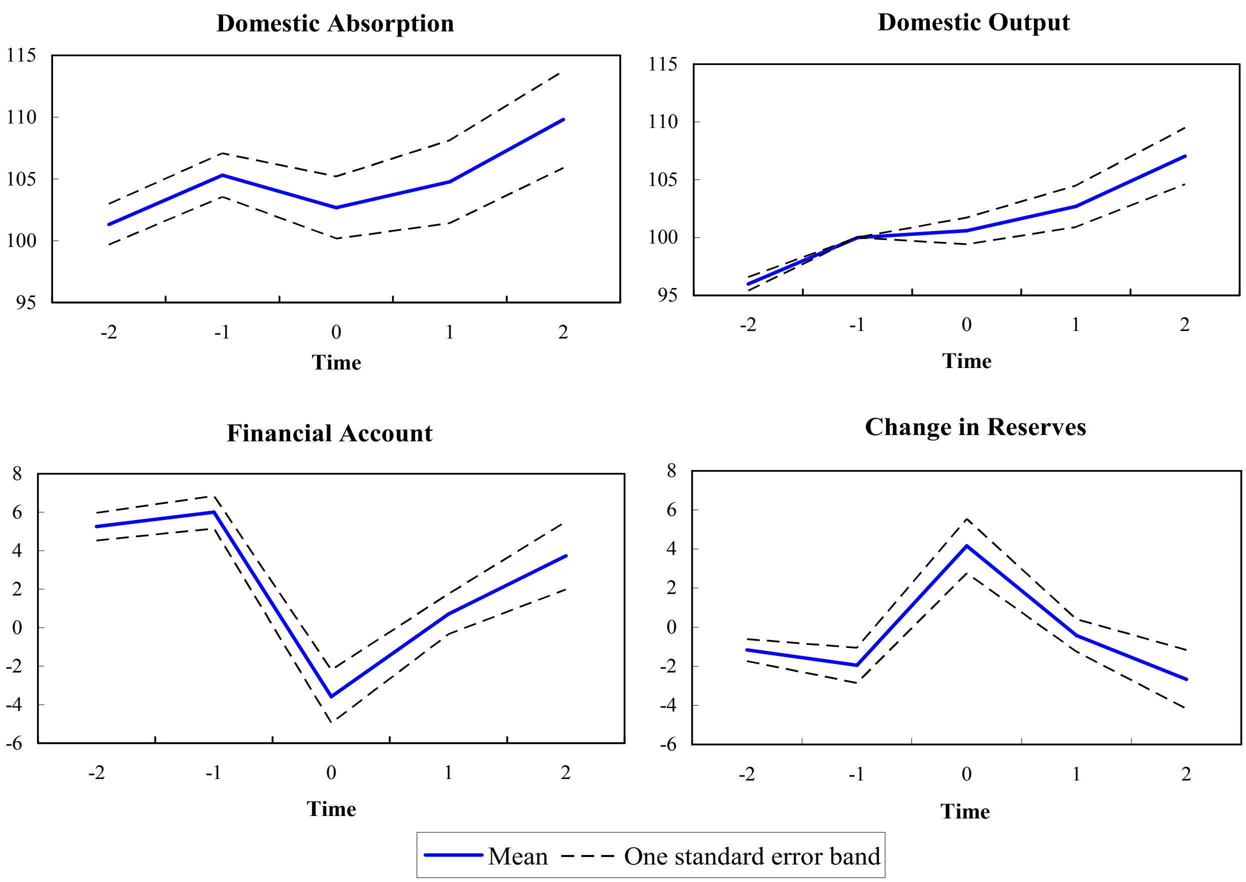
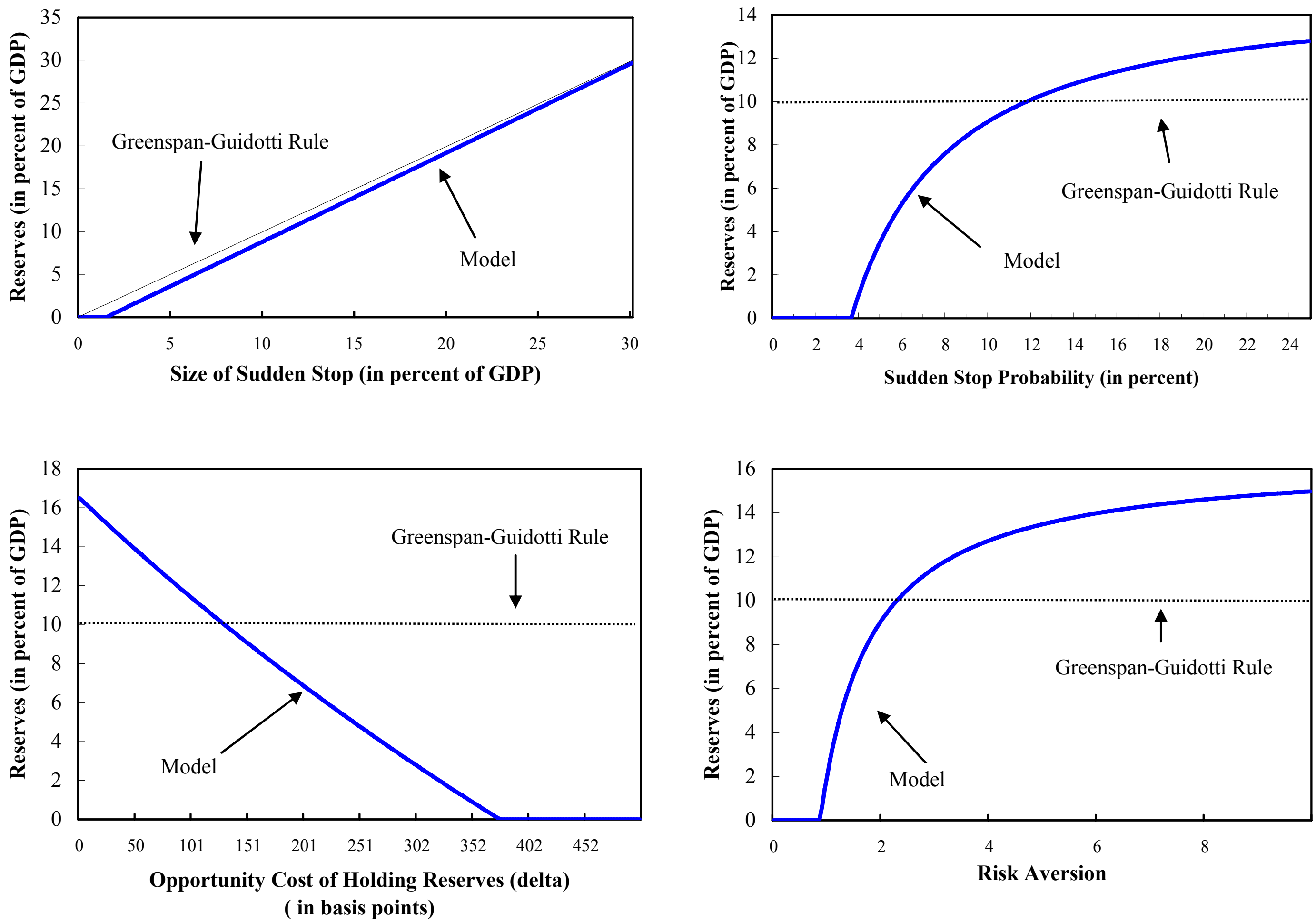


Figure 3. Domestic Absorption and International Reserves in Sudden Stops, 1980-2003



Source: Authors' computations based on International Financial Statistics and World Development Indicators.
Note: The five year event window is centered around a sudden stop occurring at time zero. The list of countries and sudden-stop years is given in Table 1. The events that occurred before 1980 or inside the five-year window of the previous sudden stop were excluded. Domestic Absorption and Domestic Ouput are expressed in percentage points of real GDP in the year before the sudden stop. The financial account and the change in reserves are expressed in percentage points of GDP. A positive level of "Change in Reserves" corresponds to a loss of reserves.

Figure 4. Optimal Ratio of Reserves to GDP: Basic Model



Source: Authors' calculations.

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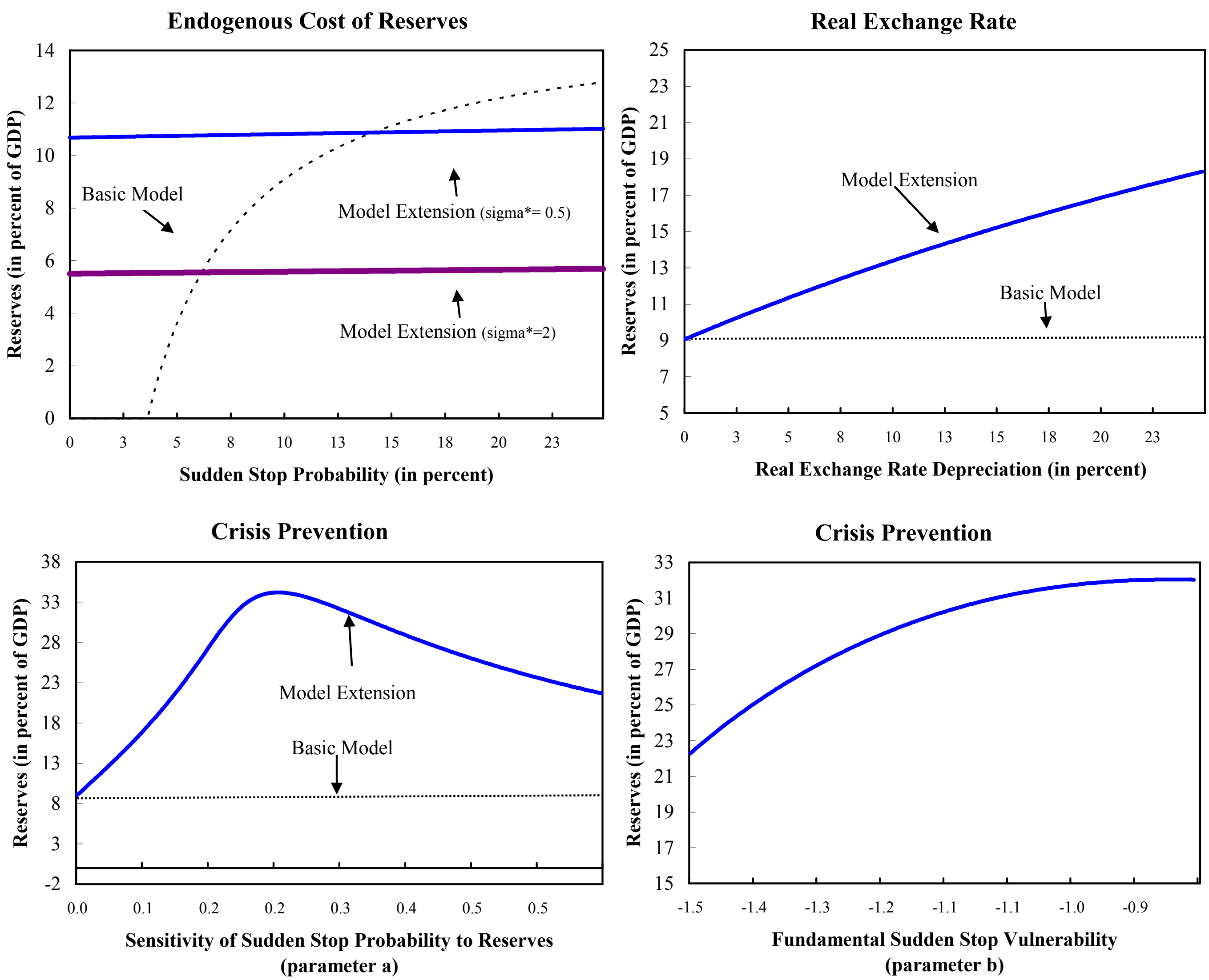
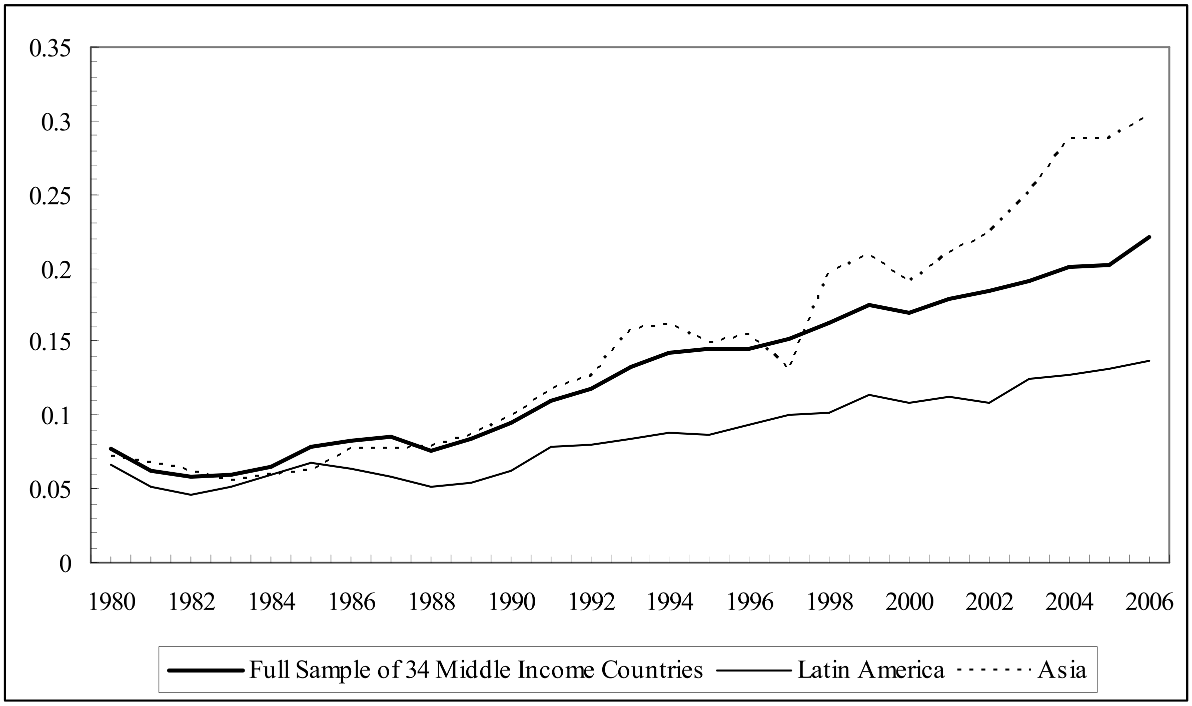
Figure 5. Optimal Ratio of Reserves to GDP: Model Extensions



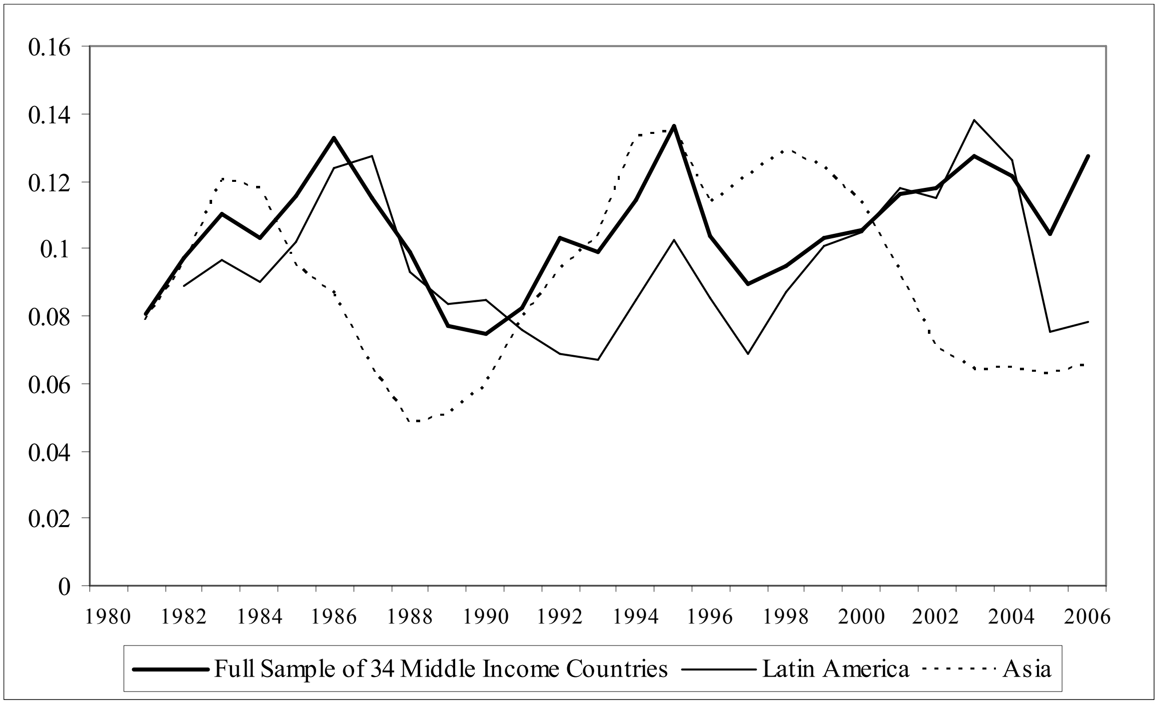
Source: Authors' calculations.

Figure 6. International Reserves as a Share of GDP, 1980-2006



Source: Authors' computations based on International Financial Statistics and World Development Indicators.
Note: For each country group, the data refer to unweighted cross-country averages.

Figure 7. Estimated Probability of a Sudden Stop, 1980-2006



Source: Authors' computations based on International Financial Statistics and World Development Indicators.
Note: The probability of a sudden stop for each country and each year is computing by using the estimates of the probit model presented on Table 3, Regression 3.1. For each country group, the data refer to unweighted cross-country averages.