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International Reserves: Precautionary versus Mercantilist Views, Theory and Evidence*

by

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Abstract

This paper compares the importance of precautionary and mercantilist motives in accounting for the hoarding of international reserves by developing countries, and provides a model that quantifies the welfare gains associated with optimal self insurance against sudden stops and capital flight. The variables associated with the mercantilist motive, while statistically significant, can only account for a small part of reserve accumulation. A more conspicuous variable is the degree of capital account liberalization, boding well for precautionary motives as they are strengthened by international capital flows. Further evidence of precautionary motives is provided by the strength of variables reflecting two past financial crises in Mexico and Asia. Overall, the empirical results suggest that precautionary motives played a more prominent role behind reserve accumulation by developing countries. We then investigate the micro foundation of precautionary demand in an open, emerging market economy where banks finance long-term projects with short-term deposits, following Diamond and Dybvig (1983). A large precautionary demand for international reserves—self-insurance against sudden stop—arises when liquidity shocks can force a premature closing of long-term projects and impose large output costs on the economy. We show that the welfare gain from the optimal management of international reserves is of a *first*-order magnitude, reducing the welfare cost of liquidity shocks from a *first*-order to a *second*-order magnitude.

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A speech by Mervyn King, Governor of The Bank of England, New Delhi, 20 February 2006

> "…following the Asian crisis of the late 1990s it was likely that countries might choose to build up large foreign exchange reserves in order to be able to act as a "do it yourself" lender of last resort in US dollars."

Keynes versus Bernstein on the role of International Reserves, 24 September 1943

> "Bernstein took the US Treasury part. Bernstein insisted that, beyond the drawing right guaranteed by the gold subscription, the Fund would supply foreign currencies at its discretion, having the power to refuse supply `if its resources were being abused'. Keynes `doubted whether this proposal would meet his objections. The real function of reserves is to give confidence and Mr. Bernstein's proposals seemed to cut at the root of confidence.'" Robert Skidelsky (2000, page 312), *John Maynard Keynes: Fighting for Freedom, 1937-1946*, Penguin Putnam, New York.

1. **Introduction and summary**

This paper has two goals: quantifying the relative importance of alternative views explaining international reserves accumulation, and modeling precautionary demand for international reserves, viewing it as self-insurance against costly output contractions induced by sudden stops and capital flight. This model is used to provide welfare evaluation of the costs and benefits of hoarding reserves, and the optimal size of precautionary demand.

The 1997-8 crisis in East Asia led to profound changes in the demand for international reserves, increasing over time the hoarding by affected countries. Several salient features of the 1997-8 crisis may provide clues to the changing attitude towards international reserves. First, the magnitude and speed of the reversal of capital flows throughout the 1997-8 crisis surprised most observers. While the 1994 Tequila crisis induced the market to expect similar crises in Latin America, most viewed East Asian countries as being less vulnerable to the perils associated with "hot money."[1] This presumption followed from the prevalent pre-1997 view -- East Asian countries were more open to international trade, had sounder overall fiscal policies, and had stronger growth performance than Latin American countries. In retrospect, the crisis exposed hidden vulnerabilities of East Asian countries, forcing the market to update the probability of

[1] See Calvo (1998), Calvo and Mendoza (2000) and Edwards (2004) for further discussion on sudden stops of short-term capital flows.

sudden stops affecting all countries. The crisis also led to sharp output and investment contractions, credit crunches, and—in several countries—to full-blown banking crises.[2] Finally, most affected countries went through tough adjustments, reversing the output contraction and resuming growth within several years. While a few countries flirted with capital controls, within two to three years most countries retained or increased their financial integration.

The above observations suggest that hoarding international reserves can be viewed as a precautionary adjustment, reflecting the desire for self-insurance against exposure to future sudden stops. This view, however, faces a well-known contender in a modern incarnation of mercantilism: international reserves accumulations triggered by concerns about export competitiveness. This explanation has been advanced by Dooley, Folkerts-Landau and Garber (2003), especially in the context of China. They interpret reserves accumulation as a by-product of promoting exports, which is needed to create better jobs, thereby absorbing abundant labor in traditional sectors, mostly in agriculture. Under this strategy, reserves accumulation may facilitate export growth by preventing or slowing appreciation. Some view the modern mercantilist approach as a valid interpretation for most East Asian countries, arguing that they follow similar development strategies. This interpretation is intellectually intriguing, especially in the broader context of the "Revived Bretton Woods system," yet it remains debatable. Some have pointed out that high export growth is not the new kid on the block -- it is the story of East-Asia during the last fifty years. Yet, the large increase in hoarding reserves has happened mostly after 1997. This issue is of more than academic importance: the precautionary approach links reserves accumulation directly to exposure to sudden stops, capital flight and volatility, whereas the mercantilist approach views reserves accumulation as a residual of an industrial policy, a policy that may impose negative externalities on other trading partners.

Figure 1 suggests that the past decade provided a ripe environment for precautionary motive to intensify. The upper panel shows the average ratios of reserves to GDP (in percent), calculated for 28 emerging-market economies and for 23 advanced economies (the lists in the appendix). From the early or mid-1990s, the average reserve ratio of emerging markets took a visibly different path from that of advanced economies. Being the simple average of the ratios for each country, this reflects the sharp rise in the ratios in most countries, and not the

[2] See Kaminsky and Reinhart (1999) and Hutchison and Noy (2002) for further discussion on the output costs associated with sudden stops.

developments restricted to a handful of large emerging markets.[3] The lower panel shows the index of capital account liberalization (Edwards, 2005), aggregated for the two country groups and normalized to their 1980 values. The index rose for both country groups, but rose much more sharply for the emerging-market group, roughly coinciding with the pickup in the reserve-to-GDP ratio of emerging markets. While not constituting sufficient evidence on its own, this comparison suggests that financial market developments—entailing stronger precautionary motive—may have been a critical factor behind the reserve accumulation since the early 1990s.

For a more systematic examination, we augment previous econometric specifications of international reserves by adding two sets of variables. The first set deals with factors associated with mercantilist motives: lagged export growth and deviations of national price levels from the trend based on income levels. The second set of variables captures precautionary demand: the degree of capital account liberalization, and adjustment in the aftermath of unanticipated sudden-stop crises (represented by dummy variables). Specifically, two crucial events were the 1994 Mexican crisis and the 1997 East Asian crisis. Both happened at times of greater financial integration, promoted by relaxing capital controls.

Our results provide only a limited support for the mercantilist approach. While the variables associated with the mercantilist motive are statistically significant, their economic importance in accounting for reserves hoarding is dwarfed by other variables. Specifically, trade openness, measured by the GDP share of imports, and crisis variables are playing a much more important role in accounting for reserves accumulation than variables that can reflect mercantilist motives. Moreover, across all specifications, a key variable accounting for the large hoarding of international reserves by emerging markets is the degree of capital account liberalization: a more liberal capital account regime is found to have increased sizably the amount of international reserves. This by itself constitutes evidence in favor of the precautionary view, for capital account liberalization will boost the precautionary motive more than the mercantilist motive. This result applies to all countries, including China. Indeed, inspecting the magnitude of country-specific dummies reveals that China is not an outlier in the level of reserves.

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[3] Rodrik (2006) presents a similar figure of patterns of reserves-to-GDP ratio for emerging and developed countries, calculated over a longer period since 1960 for a slightly different grouping of countries. He concludes that emerging markets over-invested in the costly strategy of reserve accumulation and under-invested in capital-account management policies to reduce their short-term foreign liabilities.

Overall, the empirical results of Section 2 are in line with the precautionary demand. Yet, the precautionary demand approach has not been endorsed uniformly. Skeptical views point out that the sheer magnitude of reserves accumulated by East Asian countries seems excessive once attention is paid to the opportunity costs of reserves. In order to deal with these concerns, we provide in Section 3 a simple model characterizing and quantifying the welfare gains attributed to hoarding reserves in the presence of exposure to external liquidity shocks. The model extends the literature dealing with the demand for bank reserves in the closed economy to the important, yet less studied open-economy context.[4] Specifically, we consider a country exposed to international liquidity shocks, which in turn can cause liquidation and consolidation of investment. A key postulate of the analysis is that, short of having a credible international lender of last resort, hoarding international reserves is among the few options allowing developing countries to reduce the output costs of sudden stops. While hoarding international reserves has its opportunity cost, we identify circumstances where the welfare gain from hoarding reserves is of a first-order magnitude, leading to potentially large precautionary demand for reserves.

The earlier literature focused on using international reserves as part of the management of an adjustable-peg or managed-floating exchange rate regime [Frenkel (1983), Edwards (1983); see Flood and Marion (2001) for a literature review]. To our knowledge, our paper is the first econometric attempt to evaluate the relevance of the mercantilist approach in the aftermath of the 1997 crisis [see Aizenman and Marion (2003); Edison (2003); and Aizenman, Lee and Rhee (2004) for earlier empirical analysis of related issues]. The model advanced in Section 3 contributes to the growing literature linking international reserves with sovereign risk and limited access to the global capital market. Past literature has considered precautionary motives for hoarding international reserves needed to stabilize fiscal expenditure in countries with limited taxing capacity and sovereign risk [see Aizenman and Marion (2004)].[5] Insurance perspectives

[4] See Bryant (1980); Diamond and Dybvig (1983) and Prisman, Solvin and Sushka (1986) for earlier literature dealing with optimal reserves (liquidity) policy in a closed economy.

[5] The precautionary demand modeled in this paper supplements the precautionary demand stemming from fiscal considerations. For example, one may argue that the prospect of unification of North and South Korea [or a conflict in the worst-case scenario] may explain part of the hoarding of international reserves by Korea. Yet, we may qualify this argument by noting that one expects the US and the OECD countries to provide the credit needed to finance the unification (or the conflict). This argument, however, does not extend to the case of a sudden stop and capital flight. As the 1997 crisis illustrated, external finance at times of sudden stops is not forthcoming without stringent conditions and is frequently limited due to moral hazard considerations.

of international reserves applying the option pricing theory are provided in Lee (2004). The model in this paper is more closely related to the literature viewing international reserves as output stabilizers [see Ben-Bassat and Gottlieb (1992), Aizenman, Lee and Rhee (2004), García and Soto (2004), and Jeanne and Ranciere (2006)]. Our paper adds to this literature by providing an explicit model of financial intermediation and adjustment subject to liquidity shocks, where hoarding international reserves emerges as part of the optimal financial intermediation.

As our focus is on developing countries, we assume that all financial intermediation is done by banks, relying on debt contracts. Specifically, we consider the case where investment in a long-term project should be undertaken prior to the realization of liquidity shocks. Hence, shocks may force costly liquidation of earlier investments, thereby reducing output. We solve the optimal demand for deposits and international reserves by a bank that finances investment in long-term projects. The bank's financing is done using callable foreign deposits, which exposes the bank to liquidity risk. Macro liquidity shocks stemming from sudden stops and capital flights cannot be diversified away.[6] In these circumstances, hoarding reserves saves liquidation costs, potentially leading to large welfare gains, and these gains hold even if all agents are risk neutral. In this framework, deposits and reserves are complements – higher volatility of liquidity shocks will increase both the demand for reserves and deposits. The optimal hoarding of reserves to accommodate more volatile liquidity shocks reduces the output cost of these shocks from *first*-order to *second*-order magnitude.

2. **International Reserves: Evidence**

The mercantilist view focuses on hoarding international reserves in order to prevent or mitigate appreciation, with the ultimate goal of increasing export growth. Hence, we expect that reserves hoarding provoked by mercantilist concerns should be associated with higher export growth rate, and with a depreciated real exchange rate relative to the fundamental PPP real exchange rate. In order to control for export growth, we constructed a three-year moving average of the growth rate of real exports (called EX Growth in tables), lagged two years in the regression. We used lags to avoid contemporaneous endogeneity, but also present the result of using the contemporaneous value of this variable.

[6] The recent history of Argentina provided a vivid illustration of the limited ability to diversify away liquidity shocks. In the mid-1990s Argentina negotiated contingent commercial credit lines in an attempt to provide external insurance against liquidity shocks. These lines, however, dried up as Argentina approached the crisis.

Our "fundamental" PPP real exchange rate is defined as the fitted value from the regression of national price levels on the relative income—the PPP-based real per-capita income relative to the United States. Our choice is motivated by the classic Penn effect, ascertained on numerous occasions for the post-war era.[7] For our sample, the effect is confirmed in the estimates reported in Table 1, which included year-specific constants to address the fact that national price levels are constructed for comparison across space rather than across time. The deviations from the "fundamental" PPP value (PL Deviation) are measured by the residuals of this regression.[8] If a country accumulates reserves to achieve a depreciated real exchange rate relative to the fundamental PPP value, a negative correlation will emerge between the reserves and PL Deviation. In contrast, a positive correlation will arise if a country with an over-appreciated exchange rate tends to accumulate international reserves in an effort to slow the pace of appreciation. The actual correlation will be determined by the prevailing tendency among countries in the sample.

The next set of variables attempts to capture the developments with external financial markets. The degree of capital account liberalization is captured by the variable (K Account) constructed by Edwards (2005), which measures the degree of liberalization in a finer grid than most existing measures. Related, the effects of two important crises, the 1994 Mexican and the 1997-8 East-Asian crises, are captured by applying a dummy variable to each crisis [CRMEXEM: 1 since 1995, 0 before; CRASIAEM: 1 since 1998, 0 before] for emerging markets. In addition, we control for the log of population (Population); log of percent import share (Openness); exchange rate volatility (ER Volatility); and the log of the terms of trade index(ToT). The estimating equation, which allows for country-specific constants, is summarized as follows.

$$\begin{aligned}\text{R-to-Y}_{it} = {} & \beta_{0i} + \beta_1 \text{Population}_{it} + \beta_2 \text{Openness}_{it} + \beta_3 \text{ER Volatility}_{it} \\ & + \beta_4 \text{EX Growth}_{it} + \beta_5 \text{PL Deviation}_{it} + \beta_6 \text{K Account}_{it} + \beta_7 \text{ToT}_{it} \\ & + \beta_8 \text{Crisis Dummies} + \varepsilon_{it}\end{aligned}$$

[7] See Kravis (1984) for a classic reference on PPP, and Samuelson (1994) for the apt expression "Penn effect."
[8] We regard this as a robust measure of exchange rate misalignment, rather than the best or complete measure which hardly exists. Frenkel (2006) also used this measure of misalignment, interpreting the Penn effect as caused by the Balassa-Samuelson effect.

We refer readers to the appendix for detailed description of data, and only discuss the choice of sample countries and sample period here. We selected 53 countries with decent data availability, encompassing traditional advanced economies, emerging markets, and several large developing countries. The latter two groups were combined into one group which we call emerging markets for convenience in the rest of the paper. Hong Kong and Singapore were excluded from most regressions. For the sample period, Hong Kong often had reserves exceeding 40 percent of its GDP and maintained a currency board system for many years, and Singapore had reserves exceeding 80 percent of its GDP. They both are clear outliers and were excluded from the primary sample, while we later present the results of regression for the sample that included them. Indeed, their inclusion brings about 20 percentage-point increase in the fit of the regression, confirming the disproportionate influence of the two out of 53 countries. In regressions that included capital account liberalization index, Luxemburg and Taiwan were excluded owing to the absence of the index, thereby leading to the sample of 49 countries in many regressions. The sample period of all regressions is 1980-2000. Prior to 1980, too many observations were missing and we could not cover a broad spectrum of countries.[9] The sample ends in 2000 because the key variable (K Account) is available until 2000.

Before turning to the regression results, the objective of our empirical strategy may need clarification. We do not claim that our specification can definitively uncover the causality that underlay the accumulation of international reserves over the past two decade for the sample of countries which went through very diverse experiences in terms of economic growth, structural transformation, and policy reform. Rather, we turn to the data looking for relatively robust correlations that guide our thinking, which emerge clearly by the end of this section.

The representative regressions are presented in Table 2. The first three columns were estimated for the sample of 49 countries, and the last two columns were estimated for the subsample that excluded the advanced economies. For each group, three regressions are presented which differ by crisis dummy variables used. Columns I and IV include no crisis dummies, while columns II and V include crisis dummies for Mexican and Asian crises [CRMEXEM and CRASIAEM]. Columns III and VI include crisis dummies that are narrowest in scope, by restricting them to emerging markets in Latin America and Asia only. For example,

[9] The results of regressions for post-1975 sample are available from the authors upon request. Main results remain identical, despite limited data availability.

variables CRASIALA and CRASIAAS are equal to 1 in years since 1998 for emerging markets in Latin America and Asia, respectively, while remaining equal to 0 for emerging markets outside Asia and Latin America as well as for all advanced economies.

Columns II and V show that crisis variables are statistically significant whether for the whole sample or the subsample of emerging markets. However, when crisis dummies are broken down for Asia and Latin America (columns III and VI), it is clear that the Asian crisis had a disproportionately large effect on Asian emerging markets. In contrast, the Mexican crisis does not appear to have had a statistically strong effect on emerging markets in the two regions, implying that it had a stronger effect on emerging markets outside these two regions (Russia, for example), when compared with the statistically significant coefficient in columns II and V.

Population and openness have statistically significant positive coefficients, while the price level deviation has a significant negative coefficient. The negative coefficient of the price level deviation lends support to the interpretation that countries accumulate international reserves to keep the exchange rate depreciated. The coefficient of export growth is statistically significant in all cases for the subsample of emerging markets, while for the whole sample, it is statistically significant only when Asia-specific crisis dummy is used.

The terms of trade are statistically significant with the expected sign for the whole sample, but not for the subsample that excludes advanced economies. The coefficient on the terms of trade declines both in numerical magnitude and in statistical significance when advanced countries are excluded from the sample, suggesting that the terms of trade fluctuations are partly absorbed through reserves in advanced economies but not in emerging-market economies. The exchange rate volatility is statistically significant only when Asia-specific crisis dummy is used, whether for the whole sample or for the subsample.

Strikingly consistent result is found for capital account liberalization. In all six columns—and in other cases not reproduced in the paper—the coefficient on capital account liberalization is positive and statistically significant. Combined with the statistically significant coefficients on crisis dummies, this implies that capital market developments are a robust factor behind the recent build-up in international reserves, if not the single most important factor.

Table 3 reports several variations intended to check robustness. Columns I and IV reports a regression that directly includes the relative per-capita income and national price level. These are conceptually equivalent to columns II and V of Table 2, and confirm that the relative income

affects reserves largely via national price levels, when combined with the fact that the relative income is not statistically significant when included together with the price level deviation (results not reproduced here but available upon request).

Columns II and V in Table 3 use the contemporaneous value of export growth variable, in case our use of two-lagged variable understates the strength of this channel. In comparison to Table 2, the use of contemporaneous values weakens the statistical significance and numerical magnitude of the coefficient on export growth. Columns III and VI of Table 3 drop the capital account liberalization index and the terms of trade from the regression, to check if they tend to weaken the mercantilist channel, reflected in export growth and price level deviation. On the contrary, the capital account liberalization index and the terms of trade are found to strengthen the coefficients of export growth and price level deviation.

Table 4 reports the results of regressions based on the sample that includes Hong Kong and Singapore. The fit of regression jumps from 0.7 (in Tables 2 and 3) to 0.9, reflecting the fact that Hong Kong and Singapore are prominent outliers in their reserves-to-GDP ratios. Otherwise, the basic patterns in Tables 2 and 3 are confirmed. Capital account liberalization is strongly positively correlated with the reserve build-up across all specifications. And the strength of mercantilist channel reflected in export growth and price level deviation is buttressed by the inclusion of variables associated with financial market developments.

The comparison among Tables 2, 3 and 4 shows that the results in Table 2 do not systematically understate the strength of mercantilist channel, at least not by including our controls associated with external financial-market developments (capital account liberalization index, in particular). We will thus use the results of Table 2 (column II) to assess the likely magnitude of various channels in explaining the recent accumulation of reserves in several emerging markets.

Figure 2 attempts to compare the role of various factors in accounting for the accumulation of reserves since 1990 for four emerging markets—Chile, Mexico, China, and Korea—that have been often scrutinized in terms of large reserve accumulation or its central role in a crisis (Mexico). The ratio of reserve to GDP (R_Y) is the percentage change since 1990; for example, Korea's reserves rose by about 15 percentage points of GDP between 1990 and 2000. Other variables are presented in terms of their contribution to the change in this ratio of reserves to GDP since 1990, calculated by multiplying the coefficient estimates of column II of Table 2

and the changes of each corresponding regressor since 1990. For ease of discussion and presentation, the contributions are grouped into four categories. The mercantilist factor comprises the effects of export growth and price level deviation. The precautionary factor comprises the effects of capital account liberalization and two crisis dummies. The external factor comprises the effects of the exchange rate volatility, terms of trade, and openness, while the domestic factor captures the effect of population growth. In all four countries, the most conspicuous factor for reserve accumulation is the precautionary factor, while the mercantilist and external factors played some roles. To consider China and Korea, the external factor appears to have played a bigger role than the mercantilist factor in China, while the opposite applies to Korea.

Figure 3 provides a more detailed comparison of the contribution of each variable from another angle. It plots the effect of an increase in the value of each variable by one standard deviation, with the standard deviation of each variable calculated across countries in years 1990, and 2000. Population effect is not included, because its magnitude dwarfs those of all others and because the cross-country dispersion of population hardly changes over the years. Among the mercantilist variables, the price level deviation plays a more important role in explaining the reserves/GDP ratio, but the combined effect of mercantilist factors does not exceed, in magnitude, the effect of openness or any one of the precautionary factors. And by construction, the dispersion of crisis variables is absent in 1990.[10]

Figure 4 plots the distribution of the country specific effects (column II of Table 2), in terms of the deviation of country-specific constants from the average across all countries. Note that China's country specific effect is a large negative, implying that China's apparently large reserves do not make it an outlier in the context of the cross country panel comparison over the 1980-2000 period. One such country is Cyprus, which has a country specific effect close to two standard deviations above the average.[11] Considering the magnitude of negative country-specific coefficient for China, reserve accumulation of additional 15 percentage points of GDP—which is

[10] Unlike other variables, the terms of trade is a time-series index whose value is based on a particular base year (1995 in our data). Hence, the cross-country dispersion in it captures the cross-country dispersion in changes of the terms of trade relative to the base year.

[11] In regressions of Table 4 that includes Hong Kong and Singapore, Singapore easily dominates all others in the magnitude of its country-specific constant. It should come as no surprise for a country with reserves of more than 80 percent of GDP.

what happened since 2000—would still keep China's reserves at a level fully consistent with the reserve-accumulation patterns of our sample countries.

To take stock of the results from the viewpoint of a horse race between the mercantilist and precautionary views of international reserves, the precautionary motive played a more visible role in the accumulation of reserves than the mercantilist motive. Variables associated with the precautionary motive were statistically significant across a broad spectrum of specifications, while variables associated with the mercantilist motive often lost statistical significance. The quantitative magnitude of the combination of all mercantilist variables was also comparable to the quantitative magnitude of one of several precautionary variables. At the very minimum, we could identify the likely effect of precautionary motive more easily and strongly than the likely effect of mercantilist motive.

3. **The model**

We construct a minimal model to explain the self insurance offered by international reserves in mitigating the output effects of liquidity shocks. The structure of the model is akin to Diamond and Dybvig (1983) -- investment in a long term project should be undertaken prior to the realization of liquidity shocks.[12] Hence, the liquidity shock may force costly liquidation of the earlier investment, reducing second period output. As our focus is on developing countries, we assume that all financial intermediation is done by banks, relying on a debt contract. We simplify further by assuming that there is no separation between the bank and the entrepreneur – the entrepreneur is the bank owner, using it to finance the investment. The time line is summarized in Figure 5. At the beginning of period 1, risk neutral agents deposit D in banks, which in turn use D to finance long term investment, K_1, and hoarding reserves, R. A liquidity shock, with the aggregate value of Z for the borrowing economy, materializes at the end of period 1, after the commitment of capital. A liquidity shock exceeding reserves induces a pre-mature liquidation of Z - R. Output increases with the capital invested at the beginning of period

[12] Our model follows the tradition of Bryant (1980) or Diamond and Dybvig (1993) in that the source of liquidity shock lies with the lender, rather than the borrower (Holmstrom and Tirole, 1998). However, our model assumes away the market equilibrium among lenders (be it the risk of runs or the difficulty of the decentralized provision of liquidity). Abstracting from the question whether market-based liquidity insurance is available, we focus on the implication of large adjustment cost—including but not restricted to the liquidation cost—on the demand for reserves as self-insurance. In a similar vein, no distinction is made between the private sector and the monetary authorities which maintain the stock of international reserves.

one, K_1, and declines with liquidation at a rate that depends on the adjustment cost, θ. Assuming a Cobb-Douglas production function, the second period output is

$$(1) \qquad Y_2 = [K_1 - (1+\theta)MAX\{Z - R, 0\}]^{\alpha}; \quad \text{where} \quad 0 \le \theta < 1, \text{ and } \alpha < 1.$$

Recalling that $K_1 = D - R$, the net capital after liquidation is:

$$(2) \qquad K_2 = \begin{cases} D - R - (1+\theta)(Z - R) = D - Z - \theta(Z - R) & \text{if} \quad Z > R \\ D - R & \text{if} \quad Z \le R \end{cases}$$

It is convenient to normalize the liquidity shock by the level of deposits, denoting the normalized shock by z:

$$(3) \qquad Z = zD; \qquad 0 \le z < \tau \le 1, \text{ and density } f(z).$$

Depositors are entitled to a real return of r_D on the loan that remains deposited for the duration of investment.[13] Assuming agents' subjective discount rate is ρ, competitive intermediation implies that

$$(4) \qquad \int_0^{\tau} (1-z) f(z) dz = \frac{(1+r_D)\int_0^{\tau} (1-z) f(z) dz}{1+\rho} \quad \Rightarrow \quad r_D = \rho.$$

Net reserves held until period 2 are assumed to yield a return of r_f. We denote the marginal liquidity shock associated with liquidation by z^*, $z^* = R/D$. The expected second period surplus [i.e., net income after paying depositors] is:

[13] The possibility that the outcome of investment is not large enough to meet the promised rate of return is discussed later. To preview, this possibility does not affect the main conclusion of our analysis, because of the assumption of risk neutrality.

$$E[\Pi] = \int_0^{z^*} (D-R)^{\alpha} f(z)dz + \int_{z^*}^{\tau} (D - Z - \theta[Z-R])^{\alpha} f(z)dz + (1+r_f)\int_0^{z^*} [R - Z] f(z)dz - (1+\rho)D\int_0^{\tau} (1-z) f(z)dz. \quad (5)$$

It is the sum of the expected output, plus the income associated with reserves net of liquidation, minus the repayment to depositors who get a return of ρ on the net deposit position, $D - Z$. Applying (3) and the definition of the z*, we re-write the expected surplus as

$$E[\Pi] = D^{\alpha}\left[\int_0^{z^*} (1-z^*)^{\alpha} f(z)dz + \int_{z^*}^{\tau} (1 - z - \theta[z - z^*])^{\alpha} f(z)dz\right] + D\left[(1+r_f)\int_0^{z^*} (z^* - z) f(z)dz - (1+\rho)\int_0^{\tau} (1-z) f(z)dz\right]. \quad (5')$$

The FOC determining the optimal demand for international reserves is, using the envelope theorem,

$$0 = D^{\alpha-1}\left[-\alpha(1-z^*)^{\alpha-1}\int_0^{z^*} f(z)dz + \theta\int_{z^*}^{\tau} \alpha(1 - z - \theta[z - z^*])^{\alpha-1} f(z)dz\right] + (1+r_f)\int_0^{z^*} f(z)dz. \quad (6)$$

This condition is equivalent to:

$$[MP_{K_1} - (1+r_f)] \cdot \Pr[Z < R] = \theta E[MP_K \mid Z > R], \quad (7)$$

where MP_{K_1} is the marginal productivity of capital, and $\Pr[Z < R]$ is the probability that the liquidity shock is below the level of reserves. The expected opportunity cost of holding reserves is equalized to the expected precautionary benefit of holding reserves.

Figure 6 plots the final output (the solid line) as a function of liquidity shock, z, drawn for a given initial investment and reserves hoarding. For liquidity shocks below z*, output is

flat, independent of the realized liquidity shock. A liquidity shock above z* requires costly downward adjustment of capital, reducing thereby final output. A marginal increase of the initial reserves position will shift the output line in two different directions. First, hoarding extra dollar reserves reduces the initial capital by one dollar, reducing output for liquidity shocks below z*; shifting the output line downward for z < z* (the downward shift equals MP_{K_1}). Extra dollar reserves implies, however, lower deadweight loss associated with liquidation, shifting thereby the output line to the right for z > z* . The decrease in output associated with extra dollar reserves is depicted in Figure 6 by the shaded area below the old production curve, for z < z*. Similarly, the increase in output associated with the extra dollar reserves correspond to the shaded area to the right of the old production curve, for z > z*. The expected net gain in production from holding reserves corresponds to the difference between the two shaded areas, properly weighted by f(z), as well as the expected gross income attributed to extra dollar reserves. Optimal reserves, which satisfy equation (7), maximize the overall expected gain.

The first order condition characterizing optimal deposit can be rewritten as:

$$0 = \alpha D^{\alpha-1}\left[\int_0^{z^*}(1-z^*)^{\alpha-1} f(z)dz + \int_{z^*}^{\tau}(1-z-\theta[z-z^*])^{\alpha-1}(1-z[1+\theta])\, f(z)dz\right] - \{(1+r_f)\int_0^{z^*} z f(z)dz + (1+\rho)\int_0^{\tau}(1-z) f(z)dz\} \tag{8}$$

We first consider the case with small shocks to gain the basic insight for the welfare gains associated with reserves. In the absence of uncertainty, the optimal level of deposits (D_0^*), and the resultant surplus (Π_0) are:

$$D_0^* = \left[\frac{\alpha}{1+\rho}\right]^{1/(1-\alpha)}; \qquad \Pi_0 = (1+\rho)D_0^*\frac{1-\alpha}{\alpha}. \tag{8'}$$

Suppose that the liquidity shocks are either zero or z_0, with probability half each, and $\rho = r_f$. If reserves are set to zero, and deposits at D_0^*, the expected surplus is

$$(9) \qquad E[\Pi]_{|R=0} = \frac{\left[D_0^*\right]^\alpha - (1+\rho)D_0^*}{2} + \frac{\left[D_0^*(1-(1+\theta)z_0)\right]^\alpha - (1+\rho)D_0^*(1-z_0)}{2}.$$

Applying (8') to (9), the first order approximation of the expected surplus can be reduced to

$$(9') \qquad E[\Pi]_{|R=0} \cong \Pi_0 - \theta\frac{z_0(1+\rho)D_0^*}{2}.$$

Liquidity shocks have a first order adverse effect on expected surplus. In the absence of the insurance provided by reserves, liquidation induces a deadweight loss equal to the adjustment cost, θ, times the expected liquidation. This result is not affected if we allow the optimal adjustment of deposits: the envelope theorem implies that such an adjustment would have only second order effects.[14]

In a two states of nature case, perfect stabilization can be achieved by hoarding reserves equal to the liquidity shock: $R = z_0 D_0^*$; adjusting deposits to $D = (1+z_0)D_0^*$, thereby setting the stock of capital at $K_1 = D_0^*$. If the liquidity shock materializes, R would provide the needed liquidity, preventing costly output adjust. If the shock is nil, there would no need to use R. The assumption that $\rho = r_f$ implies that the cost of this insurance is zero. Consequently, [15]

$$(9'') \qquad E[\Pi]_{|R=z_0 D_0^*} = \Pi_0$$

---

[14] This follows from the observation that $\frac{d\,E[\Pi]_{|R=0}}{d\,z_0} \cong \frac{\partial\,E[\Pi]_{|R=0}}{\partial\,D}\frac{d\,D}{d\,z_0} + \frac{\partial\,E[\Pi]_{|R=0}}{\partial\,z_0} = \frac{\partial\,E[\Pi]_{|R=0}}{\partial\,z_0}$

(recall that the FOC determining deposits is $\frac{\partial\,E[\Pi]_{|R=0}}{\partial\,D} = 0$).

[15] With more than two states of nature, R would be preset at the ex-ante efficient level, providing full insurance for liquidity shocks below z*, and partial insurance above. While there is no way to insure complete stabilization, one expects large welfare gain from setting R at the ex-ante efficient level relative to the case of R = 0.

This simple example suggests that liquidity shocks have a first order welfare effects in the absence of reserves, and that hoarding reserves can reduce the cost of liquidity shocks from first to second order magnitude. We confirm this conjecture by a detailed simulation of the case where liquidity shocks follow a uniform distribution, $f(z) = 1/\lambda; \lambda = \tau < 1$. Figure 7 plots the association between volatility and the reserves/deposit ratio for the case where the level of deposit is kept at the level of equation (8'). The reserves ratio increases with the volatility. Allowing for the optimal adjustment of D according to equation (8), it follows that $\frac{dD}{dR}_{|R=0} > 0$. The increase in D is needed to mitigate the costly drop in output induced by reserves accumulation, and is needed to keep the planned capital at the optimal level.[16] Table 5 traces the impact of higher volatility for the case where both reserves and deposits are adjusting optimally, contrasting it to the case where reserves are set to zero [the last two columns]. Specifically, the first four columns report the optimal reserves/deposit ratio, deposits, reserves and expected surplus as a function of volatility, assuming that R and D are adjusted optimally. The last two columns report D and expected surplus for case where R is zero, and only D is adjusted optimally.

Discussion:

In the absence of reserves, the volatility has first order effects on output: increasing volatility from zero to 0.6 reduces expected surplus by about 15%. Hoarding the optimal level of reserves reduces the cost of volatility into a second order magnitude, about 3%. Hence, optimal reserves have a first order welfare effect, increasing the expected surplus by about 12% relative to the case of zero reserves. Accomplishing this gain requires relatively large reserves, about half of the deposit level for the case where $\lambda = 0.6$. The effect of volatility with optimal reserves hoarding is to increase both deposits and reserves, while keeping the level of planned capital K_1 almost constant.

Our discussion assumed so far that the limited liability constraint does not bind: that is,

[16] Recalling (2), higher R reduces the stock of capital in states of nature where $Z < R$ by ΔR, but increases the stock of capital in states of nature where $Z > R$ by $\theta \Delta R$.

(10) $D^{\alpha}(1-z-\theta[z-z^*])^{\alpha} > D(1+\rho)(1-z)$ for all z.

Indeed, it can be verified that the limited liability constraint is not binding in the simulation reported in Table 5. We now show that our main results are not dependent on these parametric assumptions. The limited liability constraint would bind if $D^{\alpha}(1-z-\theta[z-z^*])^{\alpha} < D(1+\rho)(1-z)$ in some states of nature, which may hold for large enough volatility and adjustment cost. We denote the contractual interest rate on deposits in the presence of binding liability constraint by ρ_d, and by $\tilde{z}$ the threshold liquidity shock associated with zero surplus: [17]

(11) $D^{\alpha}(1-\tilde{z}-\theta[\tilde{z}-z^*])^{\alpha} = D(1+\rho_d)(1-\tilde{z})$.

For liquidity shocks above this threshold, we assume that depositors are paid a fraction ϕ of the output, $0 \le \phi \le 1$.[18] Note that binding limited liability constraint implies that depositors are exposed to the downside risk associated with large liquidity shock. Hence, depositors would demand a high enough deposit interest rate ρ_d to compensate for the exposure. For risk neutral depositors, the equilibrium interest rate is determined by the following brake even condition:

(12) $(1+\rho)D\int_0^{\tau}(1-z)f(z)dz = (1+\rho_d)D\int_0^{\tilde{z}}(1-z)f(z)dz + \phi\int_{\tilde{z}}^{\tau}(D(1-z-\theta[z-z^*])^{\alpha} f(z)dz$

where the threshold $\tilde{z}$ is determined by (11). Consequently, the expected surplus is:

---

[17] Note that for $\frac{1+\theta z^*}{1+\theta} = z$, output is zero, and the bank would default. Hence, a sufficient condition for the limited liability constraint to bind is $\frac{1+\theta z^*}{1+\theta} < \lambda$. Equation (11) implies, however, that $\tilde{z} < \lambda$, and the limited liability constraint may bind even if $\frac{1+\theta z^*}{1+\theta} > \lambda$.

[18] The conventional closed-economy assumption is $\phi = 1$. The case where $\phi < 1$ can capture the presence of repatriation risk, where the banks pays foreign creditors only a fraction ϕ of output for $z > \tilde{z}$, or the efficiency loss associated with debt restructuring.

$$E[\Pi] = D^{\alpha}\left[\int_0^{z^*}(1-z^*)^{\alpha} f(z)dz + \int_{z^*}^{\tilde{z}}(1-z-\theta[z-z^*])^{\alpha} f(z)dz\right] - (1+\rho_d)D\int_0^{\tilde{z}}(1-z) f(z)dz +$$

$$(1-\phi)\int_{\tilde{z}}^{\tau}(D(1-z-\theta[z-z^*])^{\alpha} f(z)dz + D(1+r_f)\int_0^{z^*}(z^*-z) f(z)dz =$$

(13)

$$D^{\alpha}\left[\int_0^{z^*}(1-z^*)^{\alpha} f(z)dz + \int_{z^*}^{\tau}(1-z-\theta[z-z^*])^{\alpha} f(z)dz\right] +$$

$$D\left[(1+r_f)\int_0^{z^*}(z^*-z) f(z)dz - (1+\rho)\int_0^{\tau}(1-z) f(z)dz\right].$$

Note that (13) is *identical* to the expected surplus in the base case of the previous section, (5'). With risk neutral agents, binding limited liability constraint changes the deposit interest rate, without changing the entrepreneur's expected surplus and investment patterns.[19]

4. **Concluding remarks**

Our study has outlined a procedure that helps to identify the contributions of precautionary and mercantilist motives to the hoarding of international reserves. Applying it to 1980-2000, we found that variables associated with trade openness and exposure to financial crises are both statistically and economically important in explaining reserves. In contrast, variables associated with mercantilist concerns are statistically significant, but economically insignificant in accounting for the patterns of hoarding reserves. These results hold for most countries, including China. We provided a model that shows that precautionary demand is consistent with high levels of reserves. We close the paper with qualifying remarks. As is the case with all empirical studies, more accurate and updated data may modify the results. Our empirical study does not imply that the hoarding of reserves by countries is optimal or efficient. Making inferences regarding efficiency would require having a detailed model and much more information, including an assessment of the probability and output costs of sudden stops, and the opportunity cost of reserves. Our study reveals, however, that existing patterns of growing trade openness and greater exposure to financial shocks by emerging markets go a long way towards accounting for the observed hoarding of international reserves.

[19] This result holds because we assumed the absence of enforcement and monitoring costs, and that all agents are risk neutral.

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Data Appendix: Definitions of the regression variables

The sources of data are the International Financial Statistics and the World Economic Outlook Database (both the IMF), World Development Indicator (World Bank), and Penn World Table.

Reserves: international reserves holdings minus gold, measured in U.S. dollars.
R to Y: ratio of reserves to the dollar value of nominal GDP, in percent.
Population: log of population
Openness: log of percent import share
EX Growth: three-year moving average of the growth rate of real exports (log change), lagged two years in the regression.
EX Volatility: exchange rate volatility, calculated from the monthly exchange rate against the U.S. dollar.
Income: log of per-capita real GDP, PPP based.
Relative Income: Income of each country relative to that of the United States.
Price Level: national price levels (measured in U.S. dollars), obtained from the Penn World Table and the World Development Indicator.
PL Deviation: residual from the regression of Price Level on Relative Income.
K Account: Index of capital account liberalization, constructed by Edwards (2005).
ToT: log of the terms of trade index.

CRMEXEM: dummy variable for the period after the Mexico crisis, applied to developing and emerging market countries.
CRASIAEM: dummy variable for the period after the Asian crisis, applied to developing and emerging market countries.
CRMEXEMLA: dummy variable CRMEXEM, applied only to Latin America
CRMEXEMAS: dummy variable CRMEXEM, applied only to Asia
CRASIAEMLA: dummy variable CRASIAEM, applied only to Latin America
CRASIAEMAS: dummy variable CRASIAEM, applied only to Asia

Regressions of Tables 2, 3, and 4 all include country-specific constant terms. The primary sample for Table 2 comprises 49 countries that include advanced and emerging-market economies as well as several major developing economies. They are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States, Cyprus, Israel, Korea, Argentina, Brazil, Chile, Colombia, Czech Republic, Hungary, Indonesia, Malaysia, Mexico, Pakistan, Peru, Philippines, Poland, Russia, South Africa, Thailand, Turkey, Venezuela, Algeria, China, Croatia, Egypt, India, and Morocco.

Four countries were not included in the above sample of 49 countries for varying reasons. Luxembourg and Taiwan Province of China were excluded owing to the absence of capital account liberalization indexes. They were included in Table 3, and the first column of Table 1. Hong Kong SAR and Singapore were excluded because their reserves exceeded 40 and 80 percent of GDP in many sample years, respectively, constituting outliers that spuriously improve the fit of the regressions. They were included in Table 4 and the second column of Table 1.

Table 1. Penn Effect
(1980-2000)

	I	II
Constant	2.16 **	2.17 **
	(0.04)	(0.04)
Relative Income	0.56 **	0.55 **
	(0.01)	(0.01)
Year Dummies		
1980-C	0.22	0.22
1981-C	0.12	0.12
1982-C	-0.03	-0.03
1983-C	-0.09	-0.09
1984-C	-0.14	-0.14
1985-C	-0.20	-0.19
1986-C	-0.07	-0.08
1987-C	0.01	0.01
1988-C	0.06	0.05
1989-C	0.03	0.03
1990-C	0.08	0.08
1991-C	0.02	0.02
1992-C	0.03	0.03
1993-C	-0.01	-0.01
1994-C	0.02	0.02
1995-C	0.09	0.09
1996-C	0.08	0.09
1997-C	0.02	0.02
1998-C	-0.05	-0.04
1999-C	-0.07	-0.07
2000-C	-0.15	-0.14
Adj. R squared	0.77	0.77
Cross-section	51	53

Statistically significant at 5 percent (**), and 10 percent (*).

Table 2. Reserves to GDP
(1980-2000)

	All Countries			EM Countries		
	I	II	III	IV	V	VI
Population	14.99 **	6.97 **	13.46 **	15.02 **	7.31 **	15.02 **
	(1.59)	(1.90)	(1.76)	(2.04)	(2.53)	(2.28)
Openness	4.13 **	2.51 **	3.64 **	6.26 **	4.47 **	6.04 **
	(0.70)	(0.72)	(0.72)	(0.91)	(0.96)	(0.94)
ER Volatility	-0.04	-0.04	-0.06 **	-0.05	-0.05	-0.06 *
	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)	(0.04)
EX Growth	1.67	1.74	4.70 *	6.15 *	5.69 *	9.65 **
	(2.68)	(2.59)	(2.63)	(3.48)	(3.37)	(3.40)
PL Deviation	-3.15 **	-3.84 **	-2.27 **	-3.16 **	-4.17 **	-2.11 **
	(0.74)	(0.72)	(0.74)	(0.96)	(0.95)	(0.96)
K Account	5.57 **	5.44 **	5.77 **	4.51 **	4.13 **	4.88 **
	(0.98)	(0.95)	(0.96)	(1.41)	(1.37)	(1.37)
ToT	4.32 **	4.26 **	4.08 **	1.72	1.37	1.83
	(0.84)	(0.82)	(0.83)	(1.24)	(1.21)	(1.21)
CRMEXEM		2.10 **			1.71 **	
		(0.54)			(0.67)	
CRASIAEM		2.54 **			2.43 **	
		(0.57)			(0.67)	
CRMEXAS			-0.68			-1.65 *
			(0.81)			(0.96)
CRMEXLA			-0.66			-1.23
			(0.84)			(0.99)
CRASIAAS			6.17 **			6.02 **
			(0.96)			(1.12)
CRASIALA			-1.15			-1.38
			(1.02)			(1.19)
Adj. R squared	0.70	0.72	0.72	0.70	0.72	0.72
Cross-section	49	49	49	27	27	27

Statistically significant at 5 percent (**), and 10 percent (*).
All regressions included country fixed effects.

Table 3. Reserves to GDP: Alternative Specifications
(1980-2000)

	All Countries			EM Countries		
	I	II	III	IV	V	VI
Population	7.54 **	7.04 **	11.38 **	8.07 **	7.35 **	12.53 **
	(1.95)	(1.90)	(2.03)	(2.60)	(2.53)	(2.82)
Openness	2.93 **	2.58 **	3.41 **	4.67 **	4.58 **	4.89 **
	(0.72)	(0.71)	(0.86)	(0.96)	(0.96)	(1.19)
ER Volatility	-0.03	-0.04 **	-0.07 *	-0.04	-0.06 *	-0.08 *
	(0.03)	(0.03)	(0.04)	(0.04)	(0.04)	(0.05)
EX Growth	2.53		2.02	6.56 *		4.91
	(2.62)		(3.04)	(3.40)		(4.16)
EX Growth (Contemporaneous)		-0.58			2.88	
		(2.65)			(3.44)	
PL Deviation		-3.85 **	-1.05		-4.16 **	-2.73 **
		(0.72)	(0.80)		(0.95)	(1.12)
Relative Income	2.09 **			3.38 **		
	(0.98)			(1.27)		
PL	-2.29 **			-2.81 **		
	(0.68)			(1.01)		
K Account	3.72 **	5.46 **		4.30 **	4.01 **	
	(0.84)	(0.96)		(1.42)	(1.38)	
ToT	3.72 **	4.23 **		0.68	1.28	
	(0.84)	(0.82)		(1.27)	(1.21)	
CRMEXEM	2.17 **	2.10 **	1.79 **	1.66 **	1.70 **	1.22
	(0.56)	(0.54)	(0.64)	(0.70)	(0.67)	(0.81)
CRASIAEM	2.13 **	2.53 **	2.46 **	1.94 **	2.51 **	2.35 **
	(0.58)	(0.58)	(0.66)	(0.68)	(0.68)	(0.80)
Adj. R squared	0.72	0.72	0.73	0.72	0.72	0.72
Cross-section	49	49	51	27	27	28

Statistically significant at 5 percent (**), and 10 percent (*).
All regressions included country fixed effects.

Table 4. Reserves to GDP: Including Hong Kong and Singapore
(1980-2000)

	I	II	III	IV	V
Population	13.03 **	15.05 **	16.79 **	22.37 **	18.07 **
	(2.07)	(2.13)	(2.14)	(1.69)	(1.89)
Openness	1.81 **	2.39 **	2.31 **	3.64 **	2.80 **
	(0.81)	(0.91)	(0.90)	(0.79)	(0.79)
ER Volatility	-0.06 *	-0.07 *	-0.07 *	-0.06 *	-0.09 **
	(0.03)	(0.04)	(0.04)	(0.04)	(0.03)
EX Growth	-0.48	0.11	1.10	-1.07	3.74
	(2.86)	(3.19)	(3.18)	(2.96)	(2.86)
PL Deviation	-3.06 **	-0.77	-2.18 **	-2.18 **	-1.08
	(0.82)	(0.85)	(0.88)	(0.84)	(0.82)
K Account	3.03 **			3.03 **	3.96 **
	(1.05)			(1.09)	(1.04)
ToT	5.00 **		5.96 **	5.07 **	4.39 **
	(0.92)		(1.06)	(0.95)	(0.91)
CRMEXEM	2.13 **	1.83 **	1.63 **		
	(0.59)	(0.66)	(0.66)		
CRASIAEM	3.18 **	3.01 **	3.09 **		
	(0.62)	(0.68)	(0.67)		
CRMEXAS					0.62
					(0.82)
CRMEXLA					-1.01
					(0.93)
CRASIAAS					7.23 **
					(0.96)
CRASIALA					-1.35
					(1.13)
Adj. R squared	0.91	0.88	0.88	0.90	0.91
Cross-section	51	53	52	51	51

Statistically significant at 5 percent (**), and 10 percent (*).
All regressions included country fixed effects.

Table 5: Volatility, reserves and expected surplus.

λ	z* = R/D	D	R	E[Π]	$E[\Pi]_{\mid R=0}$	$D_{\mid R=0}$
0	0	0.15	0	0.35	0.35	0.15
0.2	0.15	0.17	0.026	0.35	0.34	0.16
0.4	0.3	0.2	0.06	0.345	0.325	0.17
0.6	0.46	0.26	0.12	0.34	0.3	0.18

The simulation values are $\alpha = 0.33;\quad \theta = 0.5;\quad \rho = 0.2;\quad r_f = 0.02$.

Figure 1. Reserve Holdings and Capital Account Liberalization

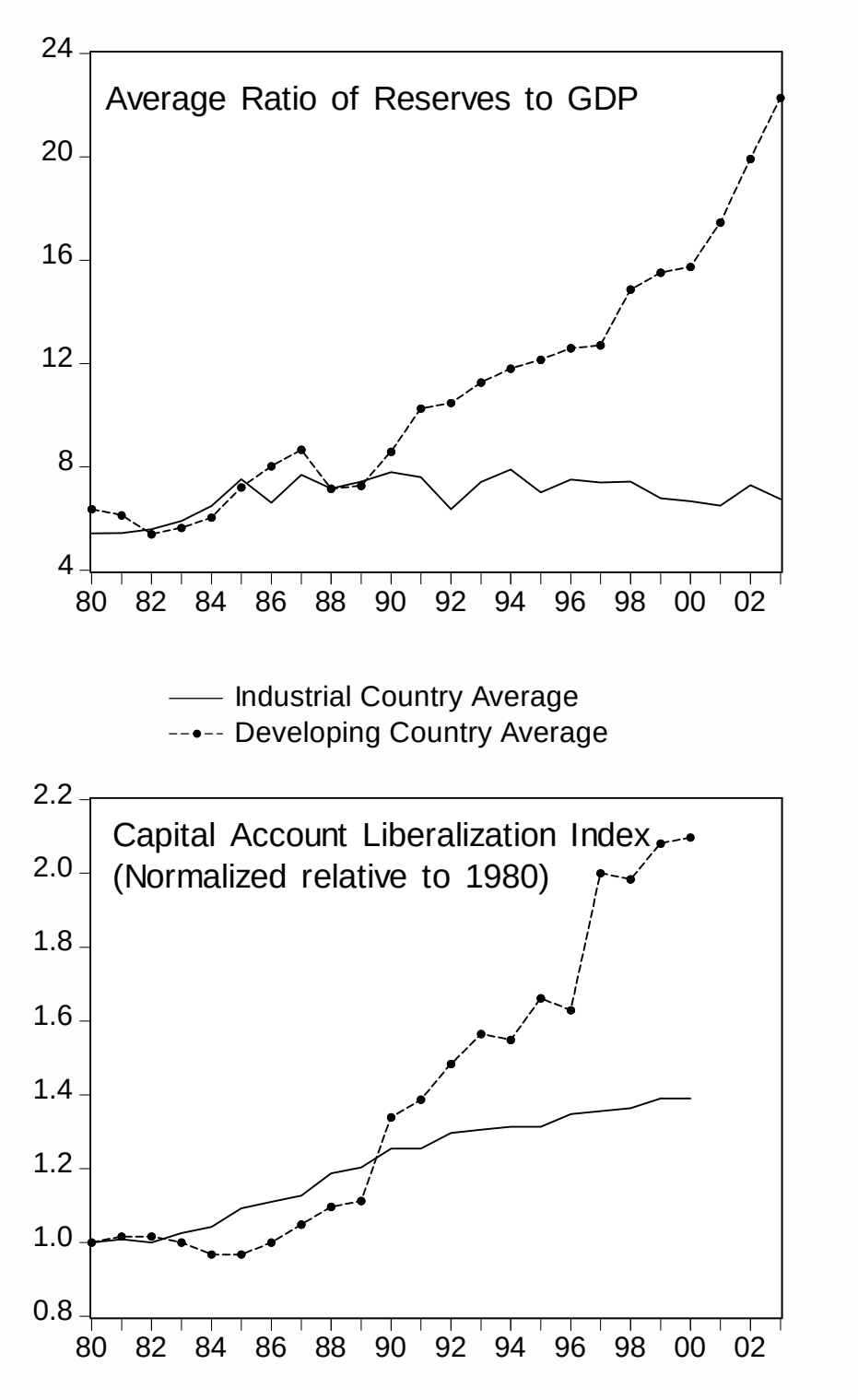


Figure 2. Reserves to GDP for Four Countries—Changes since 1990

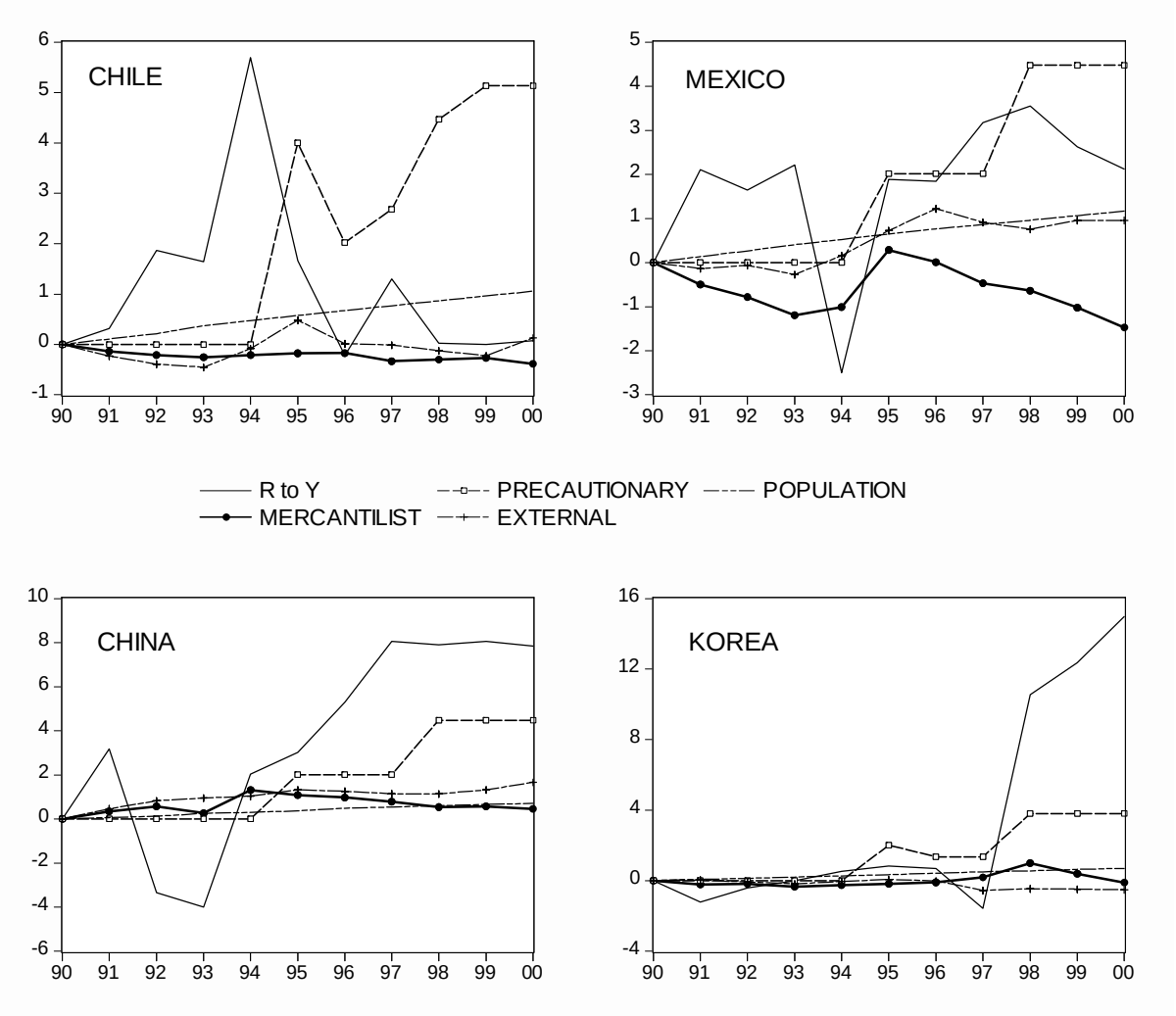


Figure 3. Contribution of Each Variable to Reserves-to-GDP Ratio

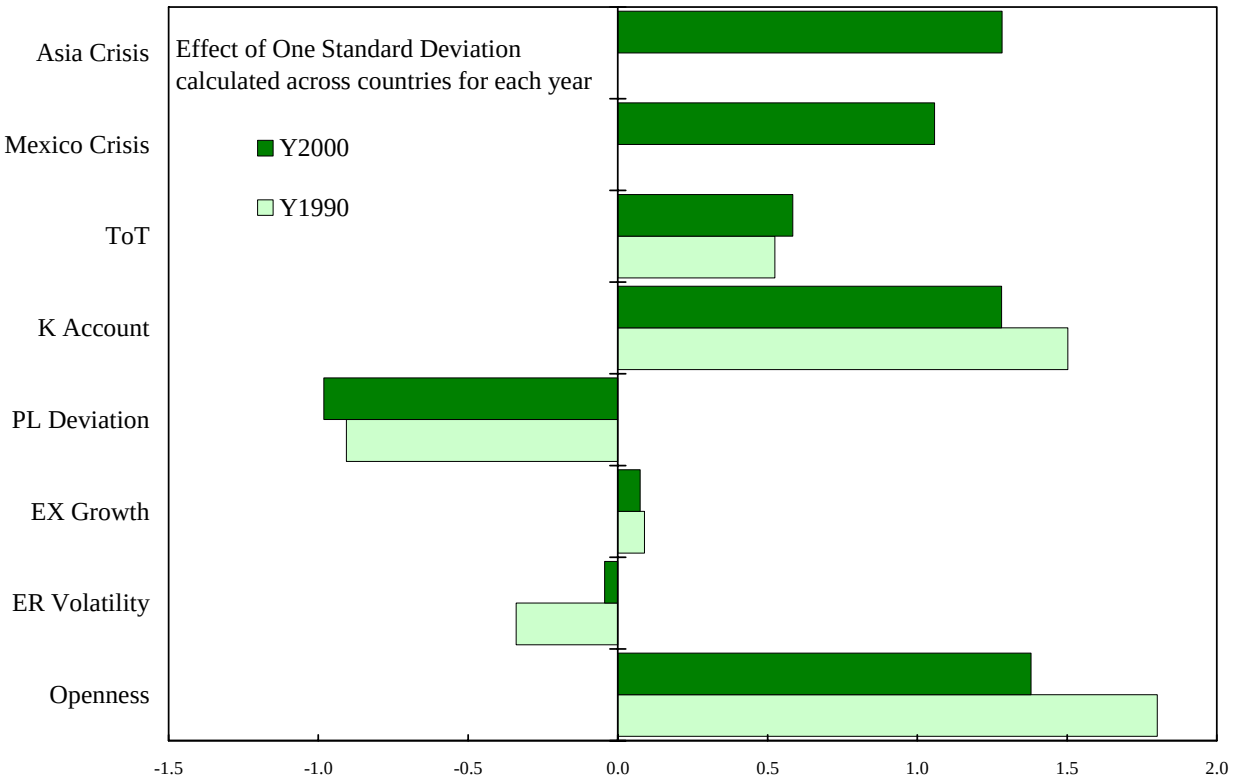


Figure 4. Country Specific Effects

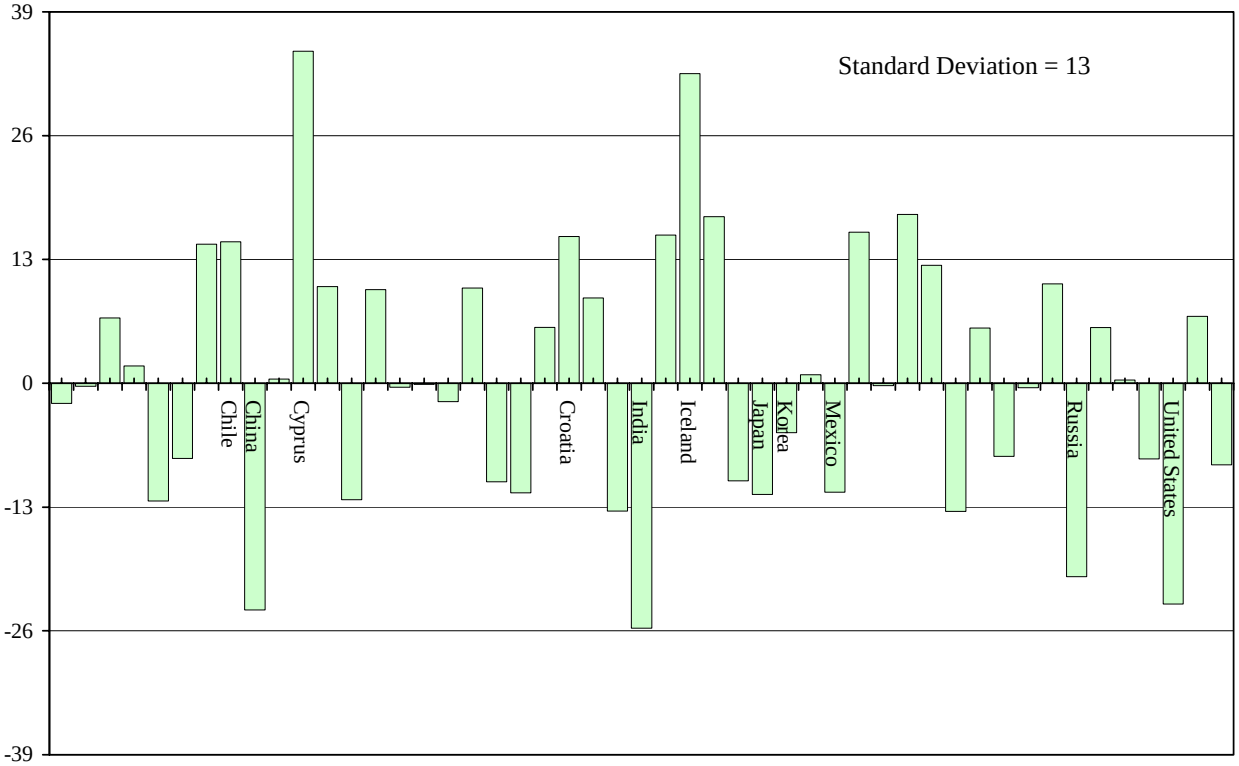
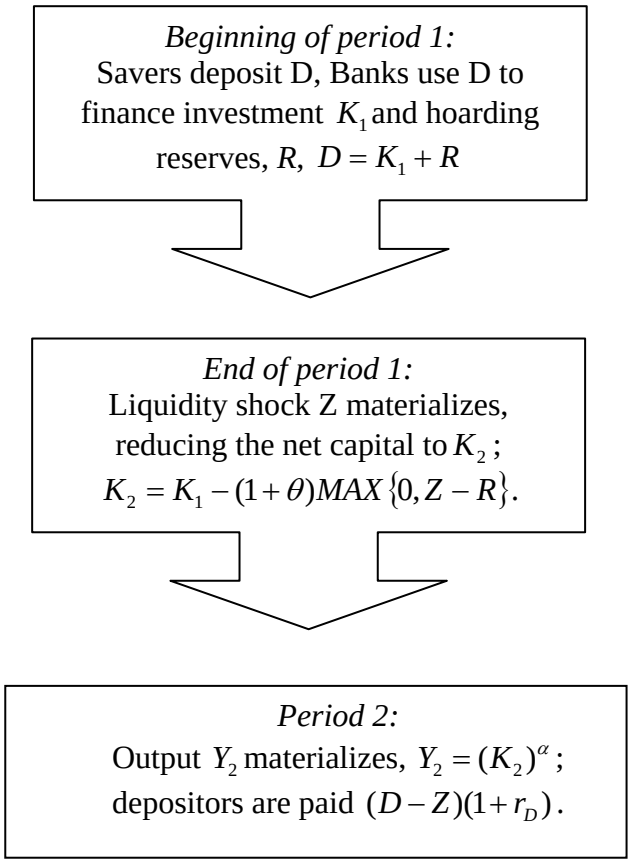


Figure 5:
The time line



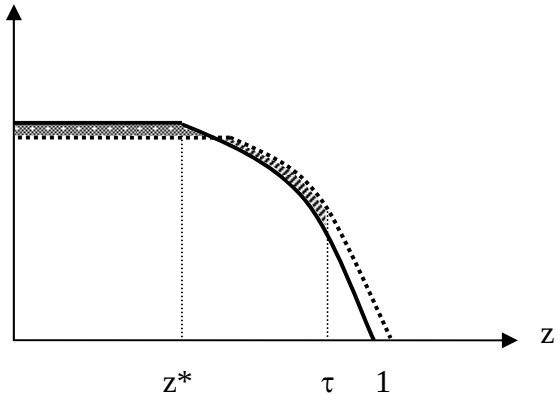


Figure 6
Liquidity shocks, reserves deposit ratio and output

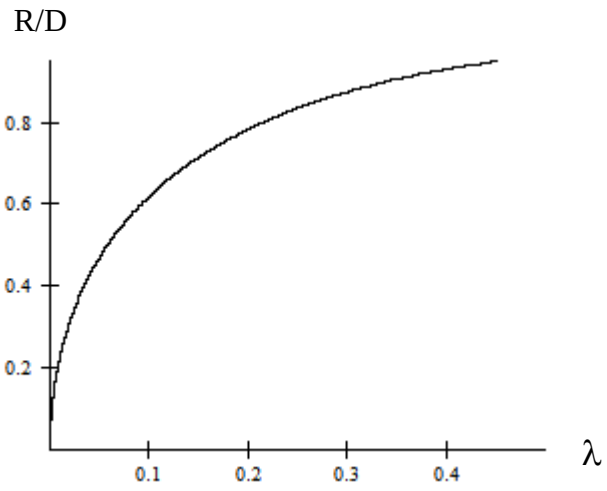


Figure 7
Volatility and R/D ratio, constant D.
The simulation values are $\alpha = 0.33$; $\theta = 0.5$; $\rho = 0.2$; $r_f = 0.02$; $D = D_0^* = 0.15$