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„The dynamics of financial crises and the risk to defend the exchange rate“

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Abstract

Despite major recent advance in the literature on financial crises, the role of central banks as key players and the dynamics of financial crises are still not well understood. Our aim is to contribute to a better understanding by explicitly modeling (A) the strategic options of market participants and policy makers as well as (B) the dynamics of financial crises.

Motivated by stylized facts from our panel of 32 emerging market countries in the period between 1990 and 2005, we analyze a global game in which both speculative traders and the central bank face imperfect information. In case of an attack, the central bank basically faces three alternatives. It can either give in to the speculative attack or it can try to defend its exchange rate regime. If it chooses to defend its currency, the defense can be successful or not.

Immediate devaluations are associated with costs in terms of higher inflation, successful interventions are followed by sluggish growth while unsuccessful interventions result in both high inflation and a recession. Taken together, intervention is risky. If a central bank chooses to defend its currency it can avoid the costs of a devaluation if it succeeds, however, if it fails it faces even higher costs, namely higher inflation and lower growth.

In our global game approach, the strength of the *realized* defensive measures – in contrast to the defensive *potential* – in general does not monotonously increase with the fundamental state. Thus global games attack models need to take into account the difference between the fundamentals themselves – i.e. the strength of the status quo or the

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defensive potential – and the optimal central bank reaction to an attack, i.e. the realized defensive measures.

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1 Motivation and related literature

By opening up their capital markets countries can benefit from a deeper international division of labor. However, the advantages of financial globalization come at a price, in particular more frequent and potentially more severe financial crises (see Tornell and Westermann (2005)). The risks of financial crises have further increased in recent years because of growing global imbalances and international capital flows as well as new financial instruments and large players such as hedge funds. A number of countries, e.g. Mexico (1995), the Asian tiger economies (1997-98), Russia (1998), Brazil (1999), Ecuador (1999-2000) and Turkey (2000) faced sudden and unpredicted severe financial crises. These crises illustrate the large costs of inconsistent policies and the subsequent speculative attacks for both the directly affected countries as well as the international community. While financial crises have become less frequent in recent years, they are likely to recur again, giving rise to the déjà vu so typical for capital markets.

Both the likelihood of currency crises as well as the associated economic and social costs are only partially determined by fundamentals, exogenous shocks, and the strength of attacks. In addition, monetary policy reactions can play a crucial role. If a currency is under speculative pressure the central bank can choose to either defend its exchange rate or to let its currency depreciate.

If the central bank opts to intervene in the exchange market the intervention can either succeed or fail depending on the strength of its defense relative to the scale of the speculative attack. Figure 1 indicates the four distinct outcomes that follow from this interaction between the decisions of speculative traders and policy makers: no crisis, successful defense, immediate depreciation, and unsuccessful defense.

Conventional models of currency crises and speculative attacks do not differentiate between these different types of crises. In particular, there is no approach to our knowledge that accounts for (1) the specific costs of the alternative outcomes of a speculative attack, and (2) the strategic actions of policy makers (e.g. central banks) and investors with respect to incomplete information, information and transmission lags, and inherent dynamics.[3]

[3] The missing distinction between the three alternative outcomes of a speculative attack is also characteristic for empirical analyses. Two types of binary crises definitions are most common. A first crisis definition accounts for sudden and large devaluation (Frankel and Rose (1996) and Bauer et al. (2007)), i.e. it combines and therefore does not differentiate between immediate devaluations and unsuccessful defenses while completely leaving out the case of a successful defense. The second common crisis definition is based on exchange market pressure (Eichengreen et al. (1995) and Prati and Sbracia (2002)) and

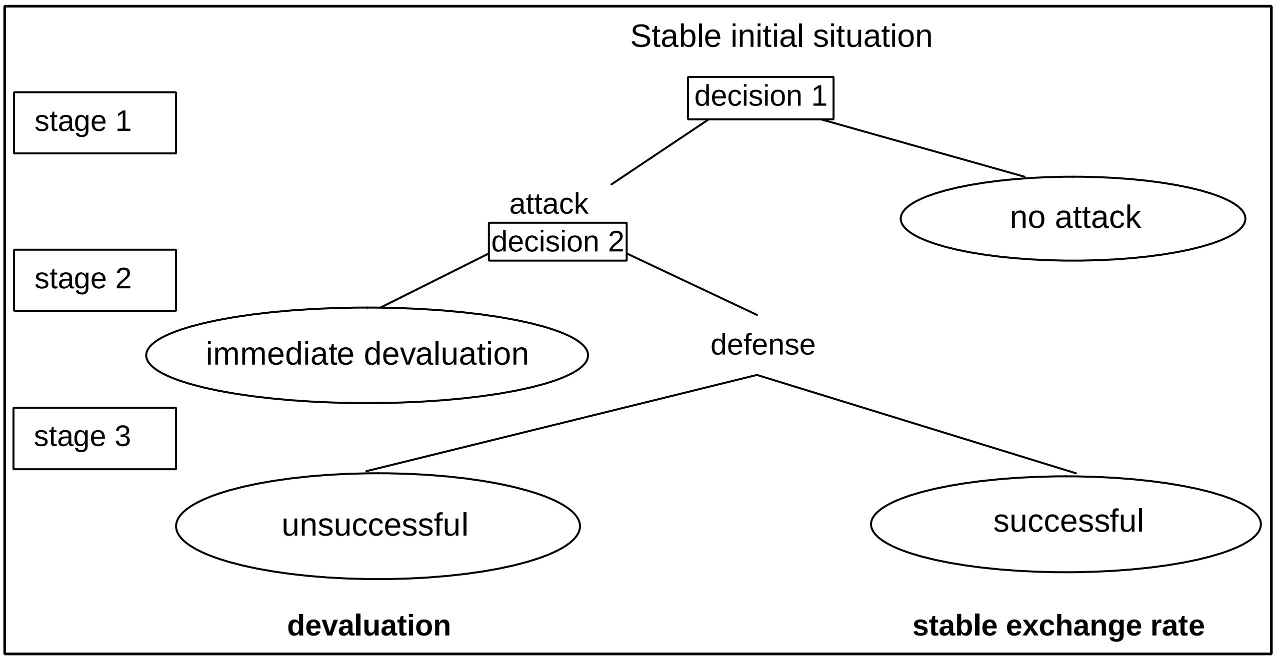


Figure 1: Multi stage decision tree of a simple speculative attack with stylized costs

First, concerning the specific costs an adequate analysis of currency crises should differentiate between the three alternative outcomes following a speculative attack. These three cases have very different economic implications for among others inflation and real growth. As a stylized fact these three types of crises yield quite different economic outcomes in the aftermath of a speculative attack. In a sample of 32 emerging markets countries for the time period between 1990 and 2005 we identify a total of 60 crises with 24 immediate devaluation, 18 successful and 18 unsuccessful exchange rate defenses.[4]

In figure 2, we have normalized the beginning of the crises to period 0 and display average rates of real growth in the 36 months before and after immediate devaluations

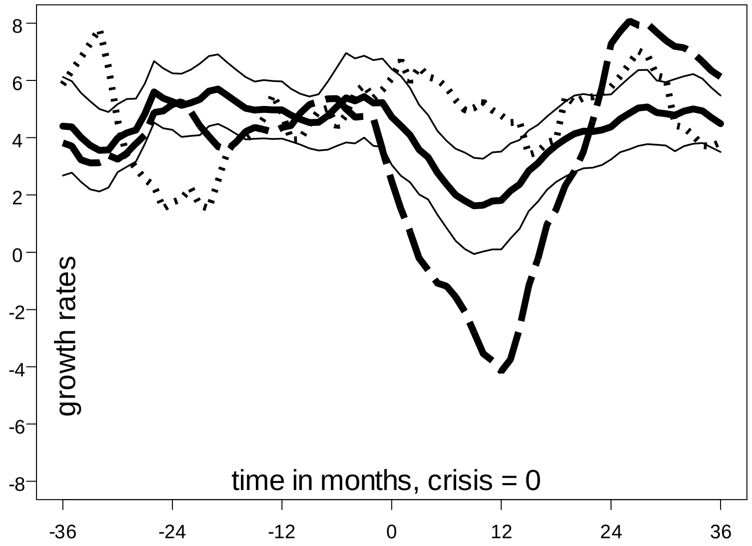
merges all three crises types. In a different approach Eichengreenand Rose (2003) compare the behavior of successful attacks on pegged exchange rates with successful defenses.

[4]In analogy to Frankel and Rose (1996),we define a devaluation as significant, if it is larger than three times the standard deviation of exchange rate changes during the previous 12 months and if the rate of devaluation exceeds 5%. The intervention index (II) which measures the strength of the defensive actions taken by the central bank is the weighted sum of the percentage loss in reserves and the increase in the interest rate. An increase of the intervention index is defined as significant, if it exceeds three standard deviations of the changes during the previous 12 months. The standard deviation weights for the devaluation indicator as well as for the reserve and interest rate changes are calculated for each country and each point in time separately in order to catch country and time specific events.

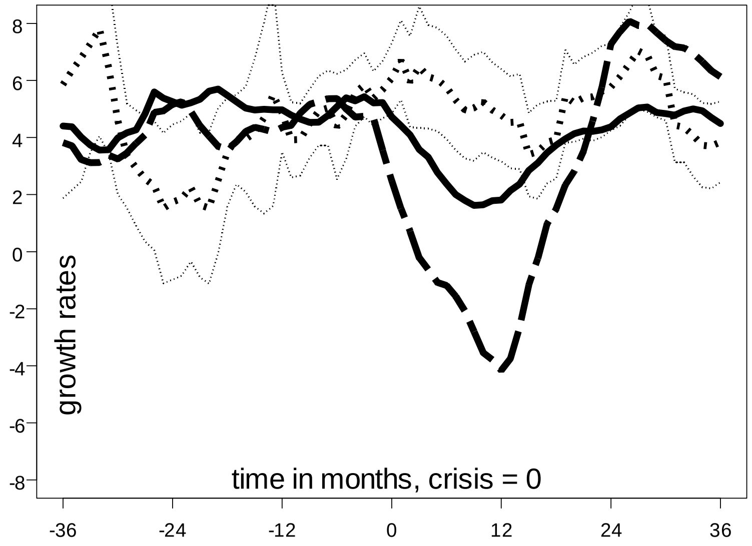
and (un)successful defenses. The average growth rates are shown in each subfigure while subfigures (a) - (c) additionally display one set of confidence intervals each. If the defense is successful (dotted line in figure 2), real growth slows down for about eight months and reaches its pre-crisis rate after 18 months. This drop of the growth rate is significantly different from zero, as can be seen by the confidence interval. In the case of an immediate devaluation (dashed line in figure 2), real growth does not seem to be affected. An unsuccessful attempt to defend the currency (solid line in figure 2) is typically followed by a strong decline in real growth with the growth rate reaching its trough about 12 months after the attack. Two years after the crisis event the rate of real growth returns to the pre-crisis situation while the level of GDP is still lower than in the case of the other two crisis scenarios. Twelve months after the crisis, the confidence band of the unsuccessful defense group lies below both the average pre-crises real growth and the confidence bands of the other two crises types. Thus real growth after a failed defense is not only significantly lower than before the crisis, but it is also significantly lower than growth after a successful defense or an immediate devaluation. It is interesting to note that the development of real GDP before the crisis is very similar for the three subsamples. This could indicate that it is indeed the difference in central bank behavior and not in the state of the economy (at least if measured in growth rates) that is responsible for the difference in real GDP development after the crisis. For a comprehensive empirical analysis other variables such as inflation or real debt should also be taken into account when evaluating the alternative outcomes of speculative attacks.

As a second shortcoming of the literature on currency crises we have pointed out the lack of explicitly modeling the strategic calculus of policy makers which so far is restricted to a black box. The effects of crisis outcomes and the informational position of the agents are only rudimentarily represented by fixed and variable costs. An explicit analysis of the key role of central banks and their influence on the course and the costs of financial crises is still missing. As the decisions of speculative traders and the central bank are tightly interrelated, any partial approach might explain only subgroups of outcomes and cannot solve the associated endogeneity problems.

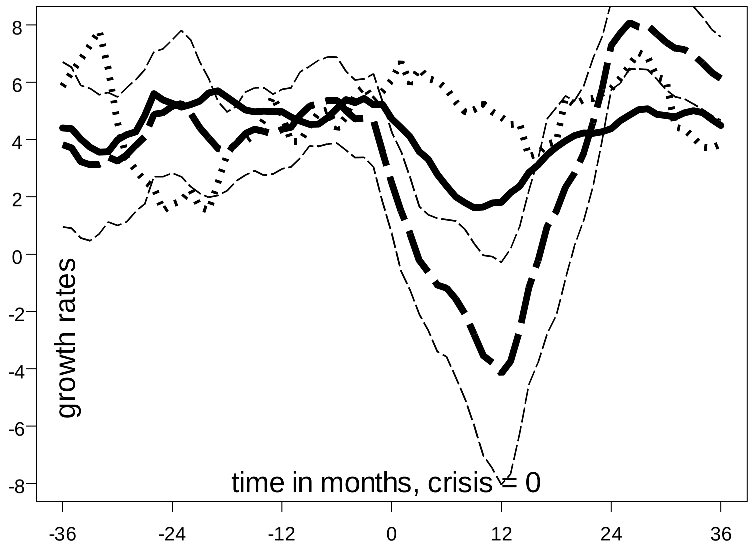
So far currency crises are typically analyzed on basis of static models with dual options, i.e. only subsets of the structure presented in figure 1 are examined. In first generation models (Krugman (1979), Flood and Garber (1984)) a deteriorating shadow exchange rate inevitably induces an attack of rational investors with the central bank mechanically depleting its reserves in an unsuccessful attempt to defend the currency, - the dichotomy "no crisis" vs. "unsuccessful defense". By contrast second generation models (Obstfeld



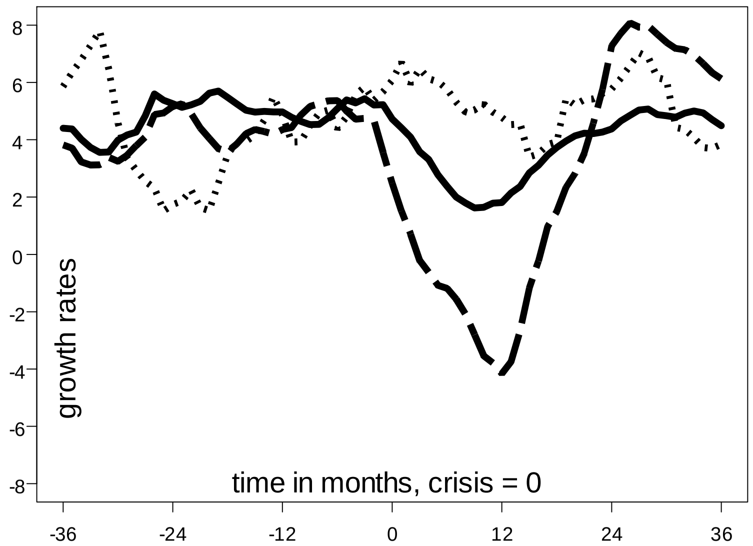
(a) with 95% confidence bands for successful defenses



(b) with 95% confidence bands for immediate devaluations



(c) with 95% confidence bands for unsuccessful defenses



(d) only averages

Figure 2: Robust estimates of crisis type specific growth rates of real GDP: successful defenses: dotted line; immediate devaluations: dashed line; unsuccessful defenses: solid line

(1994)) only differentiate between a "no crisis" situation and an attack followed by an "immediate devaluation" - with the outcome being determined by initial fundamentals and self-fulfilling expectations of the speculators (see Jeanne (2000) for a literature review).

These approaches fail to analyze the empirically most relevant scenarios in which central banks initially try to defend the currency peg but devalue later in the course of an attack. Many currency crises follow this scheme, e.g. Sweden and the United Kingdom during the 1992 EMS crisis and Indonesia and the Philippines during the Asian crisis in 1997/98. In these events central banks initially defended their currency. Apparently, they were unwilling or unable to correctly evaluate the strength and duration of the attack or the associated costs of defending the currency peg. Later in the crisis they revised their assessment and devalued their currency.

While the more recent global game approach, initiated by the seminal work of Morris and Shin (1998), has advanced the understanding of speculative attacks with respect to the informational position of the investors, it still lacks an adequate analysis of central bank behavior. Based on the distribution of private information among the investors global games solve the coordination problem which arises in second-generation models for intermediate fundamental states. This model class analyzes the strategic calculus of traders and the role of different model parameters, e.g. fundamentals, precision of public and private information, and highly leveraged institutions such as hedge funds (e.g. Corsetti et al. (2004)). Morris et al. (2002, 2006) and Svensson (2006) discuss the social value of public information in the sense that more information reduces the likeliness of crises. Bauer (2005) develops a stochastic calculus to apply generalized information structures to these models. Dynamic and multi period models (e.g. Chamley (2003) and Hellwig et al. (2007)) analyze timing, signaling, front running or learning effects. Heinemann et al. (2004) analyze the impact of strategic uncertainty on the decision process and find that global games yield a good description of the results found in their experimental studies.

Our paper contributes to the analysis of currency crises by expanding the standard global game model to incorporate the policy makers' strategic calculus. We build a two stage game with imperfect information which we can solve by backward induction and the typical global game approach. On the one side, the speculative traders simultaneously decide on an attack of the status quo based on private information about the fundamentals. They thereby maximize expected profits with respect to the expected probability and strength of the central bank's defensive action. On the other side, the central bank receives a noisy signal about the attack and chooses the scope of its defensive measures minimizing the expected costs. Costs arise first for the defensive measures itself and secondly if the regime has to be abandoned, i.e. if the attack is stronger than the defensive measures. The optimal central bank reaction for a given attack is to abstain from defensive measures if the attack appears to be very strong, and otherwise to defend the currency with sufficient measures which equal the expected strength of the attack plus some safety margin. Thus the defense only fails if the central bank significantly underestimates the strength and duration of the attack.

This feature also constitutes the main innovation of our approach. In the standard global game literature the fundamentals are set equal to the strength of the status quo, i.e. the defensive potential of the central authority, and as a standard assumption the policy makers tap the full potential in case of an attack and thus the strength of the defense rises with the fundamentals. As we argue below, however, it is not rational for the central bank to always apply the full range of costly defensive measures. Therefore the strength of the *realized* defensive measures – in contrast to the *defensive* potential – never monotonously increases with the fundamental state. We also show that the Morris/Shin assumption cannot be hold by assuming suitable definitions of fundamentals for different crises types.XXX[5]

The global game approach extensively relies on the assumption of monotonously increasing defense, while rational central bank behavior implies a different functional. As we show below, the solution algorithm used in global games may be retained with certain restrictions on the structure of the relative costs of defense and devaluation. Challenging these restrictions in turn puts into question the robustness of the results obtained with the global game formalism.

The next section presents the theoretical model. We first present the standard approach as in Morris and Shin (1998) in Section 2.1. We then expand this model by introducing a strategically acting central bank in Section 2.2, which however still relies on perfect information. In section 2.3, we then relax the assumption of perfect information on the side of the central bank. Section 2.4 describes the equilibrium. The final section concludes.

[5]In a recent paper, ANGELETOS??? models uncertainty about the type of central banker instead of the fundamentals. In this context, the monotonity assumption is jusstified since the central bank type is identified with its willingness to apply defensive measures. However, the type of central banker is idependent from the current state of the economy.

	attack fails ($A < B$)	attack succeeds ($A \geq B$)
attack	-c	1-c
null action	0	0

Table 1: Payoffs of speculative traders

2 The model

2.1 The Global Game approach of Morris and Shin (1998)

The Global Game approach as presented in Morris and Shin (1998) and many thereafter represents a coordination game on the side of the speculative traders in an exchange market. There is a continuum $[0, 1]$ of heterogeneous traders indexed by i which differ only in their private information x_i about the fundamentals θ and are otherwise homogenous.[6] Agents individually and simultaneously decide between two actions: they can either attack the current exchange rate regime or abstain from attacking (null action). Their strategy profile depends on their private information, i.e. $a_i = a(x_i) = \begin{cases} 0 & \text{not attack} \\ 1 & \text{attack} \end{cases}$. The payoff from not attacking ($a_i = 0$) is zero, whereas attacking is costly and the payoff depends on the success of the attack. The attack is successful if and only if the strength of the attack $A = \int_0^1 a_i di$ is larger than the defensive measures B of the central bank. The decision to join the attack ($a_i = 1$) implies costs $c \in (0, 1)$. If the attack succeeds in forcing the regime to change, i.e. to devalue the currency, there is a normalized payoff of one for each trader, who has participated in the attack. Table 1 summarizes the total payoffs.

An agent hence finds it optimal to attack if and only if the expected payoff of attacking is non-negative. This is equivalent to expecting a regime change with probability of at least c. The speculative traders' decisions might be triggered by contagion effects, changes in the fundamentals, and/or expectations which are included in the private signal on the fundamentals.

Since the success of the attack positively correlates with the mass of attacking agents, their actions are strategic complements: the aggregate size of the attack increases with each agent's decision to attack thereby increasing the incentive to attack for all other agents.

[6] Normalizing the weight of the agents eliminates all means referring to the size of the economy under attack.

As noted above, agents have heterogeneous information about the fundamentals θ. Specifically, nature draws the state of the fundamentals θ according to the (improper) distribution function G_N which is common knowledge.[7] Then each trader receives a private signal $x_i = \theta + \varepsilon_i$, where the error term ε_i is distributed according to some commonly known distribution G.[8] Thus the c.d.f. of agent i's posterior distribution about θ is non increasing in his private signal x_i.

Therefore, if the private information is sufficiently precise relative to public information, only one monotone Bayesian Nash equilibrium survives the iterated elimination of dominated strategies.[9] This equilibrium strategy is characterized by a threshold x^*, i.e. $a_i(x_i) = I(x_i < x^*) \begin{cases} 0 & \text{if } x_i \leq x^* \\ 1 & \text{if } x_i < x^* \end{cases}$ .Player „i“ joins the attack, if and only if his private information signals sufficiently bad fundamentals.

For a given state of the fundamentals θ, we therefore have

$$A(\theta) = \int_0^1 a_i di = \int_0^1 I(\theta + \varepsilon_i < x^*) \, di = \int_0^1 I(\varepsilon_i < x^* - \theta) \, di = G(x^* - \theta) \qquad (1)$$

In particular, this implies that the attack is decreasing with the fundamentals.

The defensive measures B taken by the central bank generally may depend on the fundamentals and its information set $\mathfrak{F}_{CB}$, i.e. $B = B(\theta, \mathfrak{F}_{CB})$. In Morris and Shin (1998) the defense follows a mechanic pattern and is simply chosen identical to the state of the fundamentals, i.e. $B = B(\theta, \mathfrak{F}_{CB}) \equiv \theta$. The choice of this function enters the determination of the traders' strategy profile x^*. In the next section, we will relax this assumption and endogenize the central bank reaction.

Finally, the equilibrium condition equates the expected gain from attack and the cost of participation as traders are assumed to be risk neutral

$$E_\theta \left(G(x^* - \theta) \, | x_i = x^* \right) = c. \qquad (2)$$

[7] G_N maz also be implemented in form of an uninformative or improper prior.

[8] A common choice is $G_N = N(z, \frac{1}{\alpha})$ and $G = N(0, \frac{1}{\beta})$ so that the information structure can be parsimoniously parameterized with (α, β, z), the precision of private information as well as the mean and precision of the common prior.

[9] As the decision is binary, monotone strategies, i.e. strategies that are non-increasing in x_i, are threshold strategies where the agent decides to attack if and only if his private signal is lower (or equal) to some threshold x^*.

2.2 Endogenous central bank reaction

In a speculative attack, the decisions of both speculative traders and policy makers should be seen as the result of strategic optimization under incomplete information in a dynamic situation. The global game approach as presented above has drawn attention to the strategic behavior of the traders but completely ignores the strategic behavior on the central bank side. We close this gap in two steps. First, we introduce an endogenous central bank reaction function under full information. While the traders' aim is to maximize their expected profits, the central bank minimizes the expected loss function which incorporates both the costs of defensive measures and the costs of a devaluation. We thereby show, that no matter how the fundamentals are chosen, any simple monotone reaction function cannot represent rational central bank behavior. Secondly, we introduce imperfect information on the side of the central banks to allow for a more realistic setting which includes the empirically and economically most relevant case of unsuccessful defenses.

Figure 1 illustrates the stylized dynamics of a currency crisis with the timing of decisions. Starting from a situation of stable exchange rates, contagion effects, changes in the fundamentals, and/or expectations might trigger (stage 1 decision) speculative traders to initiate an attack or to not enter the market. In case of an attack, the policy maker chooses (stage 2 decision) to either devalue immediately or to defend the exchange rate. This attempt can either be successful, i.e. the exchange rate remains stable, or unsuccessful, i.e. the currency depreciates despite defensive actions. Figure 1 specifies (i) the time line of the crisis as well as (ii) all nodes and outcomes. Of course, if the central bank has full information unsuccessful defenses will not occur.

Our model extends the classical global game models with respect to the fundamentals and the reaction function of the monetary authority. Technically speaking, in typical global game models the fundamentals $\theta \in \mathbb{R}$, often denoted as strength of the regime, are equated with the ability and willingness of the policy maker to defend the exchange rate, i.e. the status quo is abandoned if and only if the measure of agents attacking is greater than or equal to θ. The underlying decision process of the central authority is treated as a black box, however. In our model the reaction function of the central bank is the result of an optimization process of a forward-looking policy maker under incomplete information.[10] Thus, the ability of a central bank, the defensive potential, is different from

[10] While we focus currency crises, the highly stylized theoretical model may well be applied more generally in the context of financial crises (currency crises, debt crises, and bank runs) and political change.

its willingness to tap it. The realized defense is not monotonic in the fundamentals.

2.2.1 Optimal monetary policy

The central bank faces the problem to decide on the optimal extent of costly stabilizing measures given the strength of the attack. Its target to minimize the expected total costs of exchange rate policy. The total costs C depend on the per unit costs of stabilizing measures $\phi(\theta)$ and the degree of stabilization B as well as the costs of a devaluation $R(\theta)$. As both types of costs might depend on the fundamental state θ we get

$$C = \phi(\theta) B + R(\theta) I(A > B)$$

where $I(A > B)$ denotes the indicator function which takes values 1 if $A > B$, i.e. if the attack succeeds, and 0 otherwise.

The costs of a devaluation could include a reputation loss or an increased risk of a debt crises as the real value of the external debt denominated in foreign currency increases. Additionally, this cost function could be seen as the individual cost function of the monetary policy decision maker, e.g. Minister of Finance or Central Bank President, and thus include the personal risk in case of a regime change. In view of the results presented below, the analysis of the resulting principal agent problem appears to be a very interesting topic of future research.

Additionally, a currency crisis with the accompanying devaluation might have positive effects in terms of increased exports and negative effects from higher inflation. We generally assume that the negative effects outweigh the positive aspects for each state of the fundamentals so that there are effective costs. Therefore, for every state of the fundamentals it is optimal to keep the status quo if no attack is to be expected.

As the central bank perfectly observes the strength of the attack A, cost minimizing policy implies either to devalue immediately, i.e. $B = 0$, or to exactly apply the amount of defensive measures necessary to preserve the current state, i.e. $B = A$. Any other policy would imply unnecessary costs either for insufficient or wastly defensive measures. We get a binary outcome

$$C = \begin{cases} \phi(\theta) A & \text{if } B = A \quad \text{no devaluation} \\ R(\theta) & \text{if } B = 0 \quad \text{devaluation} \end{cases} . \tag{3}$$

The central bank will choose to defend the currency if and only if the cost of the defense are less than the cost of the devaluation, i.e. $\phi(\theta) A < R(\theta)$ .Thus

$$B_{opt} = \begin{cases} A & \text{if } A < \frac{R(\theta)}{\phi(\theta)} \\ 0 & \text{else} \end{cases} . \tag{4}$$

We can derive two implications from this solution: Firstly, optimal monetary defense policy is not monotonously increasing in the fundamentals. Secondly, the relative costs of defense to devaluation determine the state of fundamentals for which a defense is optimal.

We know from the previous section that the strength of the attack $A = G(x^* - \theta)$ is decreasing in the fundamentals. In addition, whenever the central bank chooses to defend the current state, the defense will equal the strength of the attack. Therefore, the optimal central bank reaction is either null or in case of a defense, the lower the better the fundamentals are.

The second point is less trivial to analyze. The central bank defends the currency if the costs of the defensive measures are less than the costs of a devaluation, i.e.

$$G(x^* - \theta) < \frac{R(\theta)}{\phi(\theta)}. \tag{5}$$

Now the LHS of equation 5 is monotonously decreasing in θ. Let us assume for a moment that the RHS is increasing in θ, then equation holds for all θ below the intersection of LHS and RHS.[11] We denote the fundamental solving LHS=RHS with $\bar{\theta}$. The central bank successfully defends the currency for all fundamental states better than $\bar{\theta}$ and forbears from defending the regime for all fundamental states worse than $\bar{\theta}$:

$$B_{opt} = \begin{cases} A & \text{if } \theta \in (\bar{\theta}, \infty) \\ 0 & \text{if } \theta \in (-\infty, \bar{\theta}] \end{cases} . \tag{6}$$

The policy reaction function $B_{opt}(\theta)$ is zero until $\bar{\theta}$, then jumps to $G\left(x^* - \bar{\theta}\right)$ and declines to zero again.

We now turn to the incidence of the fundamentals on the costs. It is rather unambiguous that the per unit costs of defensive measures $\phi(\theta)$ are decreasing in the fundamentals

[11] Formally, there would be three possible ranges of θ for which equation 5 holds. Besides the solution $[\bar{\theta}, \infty[$ given above, equation 5 could hold for either all θ or none. Both alternatives are implausible, however. 5 holds for all θ, if $\lim_{\theta \to -\infty} G(x^* - \theta) = 1 < \lim_{\theta \to -\infty} \frac{R(\theta)}{\phi(\theta)}$. This would imply that even in the worst possible state of fundamentals the central banks cost to withstand an attack of all speculators are lower than the cost of a devaluation. 5 holds for no θ, if $\lim_{\theta \to \infty} G(x^* - \theta) = 0 \geq \lim_{\theta \to \infty} \frac{R(\theta)}{\phi(\theta)}$. Since $\frac{R(\theta)}{\phi(\theta)}$ is increasing, this would imply that $R(\theta) \leq 0$ for all θ.I.e. there are no costs but a net gain from devaluation independent from the attack and for all fundamenal states.

since a better of economy is more capable of getting along with interest rate increases or regaining reserves. Arguments are less obvious in terms of the costs of a devaluation. If fundamentals are measured by the fragility of the banking system, e.g., which are based on currency mismatches in the banks' balance sheets, the costs of a devaluation are high but declining if fundamentals are better. If fundamentals are measured by export led growth, net devaluation costs could be increasing in fundamentals, as for higher growth rates the export push from a devaluation is weaker while the other costs (inflation, terms of trade losses, increased real value of foreign denominated debt) remain. If political costs of a devaluation are examined, the reasoning becomes almost arbitrary. One could argue that in bad states a devaluation is adequate and thus imposes low political costs. One could also argue that in bad states a defense is a political success and thus a surrender leads to political costs.

Summarizing, the costs of per unit costs of defensive measures $\phi(\theta)$ are decreasing in the fundamentals, while the costs of a devaluation $R(\theta)$ might be de- or increasing. We thus think the assumption is reasonable that the relative rates of decrease are lower for the costs of the defense, which is equivalent to the assumption that $\frac{R(\theta)}{\phi(\theta)}$ is decreasing in the fundamentals.[12]

The use of different variables to measure the fundamental state of the economy leads to different levels of costs for both alternatives devaluation and defense. The fragility of the banking system, e.g., would lead to a high cost of defensive measures such as interest rate increases. If the fragility is due to currency mismatches rather than maturity mismatches it would also imply high costs of a defense. But for a given choice of fundamentals, the reasoning remains that the costs are lower for better fundamentals.

2.3 Imperfect information of the central bank

2.3.1 Information structure

We now extend the global game approach by adding imperfect information on the central bank side. In our approach, there are two variables, which are not common knowledge, the fundamentals θ and the strength of the attack A. There is an information asymmetry between speculative traders and central bank. While the traders know the calculus of the central bank, they have only noisy information about the fundamental state of the economy. In contrast the central bank knows the fundamental state, but is not able to

[12] $\frac{d}{d\theta}\frac{R(\theta)}{\phi(\theta)} < 0 \Leftrightarrow \frac{d}{d\theta}\left(\log\frac{R(\theta)}{\phi(\theta)}\right) < 0 \Leftrightarrow \frac{R'(\theta)}{R(\theta)} - \frac{\phi'(\theta)}{\phi(\theta)} < 0$

	defense fails $(A \geq B)$	defense succeeds $(A < B)$
no defense $(B = 0)$	$R(\theta)$	impossible
defense $(B > 0)$	$\phi(\theta) B + R(\theta)$	$\phi(\theta) B$

Table 2: Loss of the central bank

exactly monitor the behavior of the speculative traders. Ex ante, the central bank cannot accurately assess the scale of an attack and the endurance of the speculative traders. We separate the sources of uncertainty for traders and central bank thereby simplifying their calculus as to allow closed form solutions. This simplification comes at no prize since it is equivalent to assuming a specific error distribution of the central bank's assessment of the fundamentals.[13]

The central bank is not able to perfectly predict the strength of the attack A. For its defense strategy, it relies on an unbiased estimate $\widetilde{A} = A + \xi_{CB}$ where the noise term ξ_{CB} is distributed according to some distribution G_{CB} and is independent from the signals on the fundamentals.

The model is solved by backward induction. We first determine the optimal reaction of the central bank $B_{opt} = B\left(\widetilde{A}\right)$ as a function of its information on the fundamentals and the strength of the attack. We solve the modified global game where we include the central bank policy function to the speculative traders' behavior. In determining their threshold x^* the optimal central bank behavior is taken into account.

2.3.2 Optimal monetary policy

The central bank faces the problem to decide on the optimal extent of costly stabilizing measures under imperfect information about the attack. It receives a private signal on the strength on the attack $\widetilde{A}$. Its target to minimize the expected total costs of exchange rate policy $C = \phi(\theta) B + R(\theta) I_{A>B}$ implies the following policy function

$$B_{opt} = \arg\min_{B} \left(\mathbb{E}\left(C|\widetilde{A}\right)\right).$$

Table 2 summarizes the potential losses of the central bank.

In addition to our previous assumption that the costs of a defense relative to the cost

[13] The measurement error of central bank and traders are assumed to be independent and the central bank's signal, the strenght of the attack, is a functional of the fundamentals.

a devaluation $\frac{\phi(\theta)}{R(\theta)}$ are non-increasing, we also assume

$$\phi(\theta) < \frac{R(\theta)}{2\sigma} \tag{7}$$

i.e. for any given fundamental θ the costs of the defense are less than the risk adjusted costs of a devaluation.[14] If the expected costs of the stabilizing measures $\phi(\theta)$ are larger than the risk adjusted cost of giving up the currency peg $\frac{R(\theta)}{2\sigma}$, a defense would never be an optimal strategy as the costs of defensive measures would always outweigh its benefits (see Proposition 1).

We now specify the central bank's error distribution. We assume that the central bank's assessment error about the strength of the attack ξ_{CB} is Laplace distributed with standard deviation 2σ, i.e. the density of G_{CB} is given by $g_{CB}(x) = \frac{1}{2\sigma}\exp\left(-\frac{|x|}{\sigma}\right)$. In contrast to distributions like the normal distribution or the uniform distribution, which are commonly used in this literature, the Laplace distribution allows a closed form solution for the optimal monetary policy while still being unimodal and centered around zero, i.e. the likeliness of small errors is higher than that of large estimation errors.

Proposition 1: Given the assumptions on the distribution of the central bank's signals, the expected costs of a defense B are

$$\mathbb{E}_A\left(C|\widetilde{A}\right) = \begin{cases} \phi(\theta)B + \frac{1}{2}R(\theta)\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ \phi(\theta)B + R(\theta)\left(1 - \frac{1}{2}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right)\right) & if \quad B < \widetilde{A} \end{cases}.$$

Proof: Appendix 1

Proposition 2: The optimal reaction function of the central bank is

$$B_{opt} = \begin{cases} \widetilde{A} + \sigma\ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) & if \quad \widetilde{A} < T_{CB} \\ 0 & else \end{cases} \tag{8}$$

where the threshold T_{CB} takes the value $\frac{R(\theta)}{\phi(\theta)} - \sigma\ln\frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma$.

Proof: Appendix 2

The optimal strategy of the central bank is to abstain from defensive measures, if it perceives a signal above the threshold T_{CB} indicating a very strong attack. For estimated attacks stronger than the threshold $T_{CB} = \frac{R(\theta)}{\phi(\theta)} - \sigma\ln\frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma$, the optimal size of

[14] The realization of the devaluation costs is uncertain. The standard deviation of the central bank's measurement error is 2σ.

interventions to fend off the attack are more costly than to give up the status quo without any defense.[15]

If the attack signal $\widetilde{A}$ is below the threshold, the central bank will take defensive measures which do not only offset the expected strength of the attack $\widetilde{A}$ but additionally include some safety cushion $\sigma \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) > 0$ as $\phi(\theta) < \frac{R(\theta)}{2\sigma}$. For a given measurement error ξ_{CB} the central bank abstains from defensive measures for bad fundamentals, i.e. for $\theta < \theta_0(\xi_{CB}) = \inf\left\{\theta : G(x^* - \theta) + \xi_{CB} \leq \frac{R(\theta)}{\phi(\theta)} - \sigma \ln \frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma\right\}$.[16] This approach proves very helpful in understanding the dynamics of the model. It is equivalent to ask the following question: what happens if a central bank over-/underestimates an attack by an error ξ_{CB}. If the central bank underestimates the attack, $\xi_{CB} < 0$, defensive measures are insufficient, if and only if the error is larger than the security margin. If the central bank overestimates the strength of the attack, $\xi_{CB} > 0$, the defense will be successful if the central bank chooses to act. However, in this situation the estimated strength of the attack is more likely to be higher than the threshold keeping the central bank from taking measures.

Finally, we compare the result with the perfect information benchmark. We obtain the optimal central bank reaction function for perfect information from equation (8) by taking the limit $\sigma \to 0$

$$B_{opt}(\sigma = 0) = \begin{cases} A \quad if \quad \phi(\theta) A < R(\theta) \\ 0 \qquad\qquad else \end{cases}. \tag{9}$$

The central bank exactly chooses the necessary amount of defensive measures to counter the attack A, if the costs of these measures $\phi(\theta) A$ are less than the cost of the devaluation, and abstains from taking defensive measures, if its costs would exceed the devaluation loss. As the central bank acts under perfect information on the strength of the attack, the case of an unsuccessful defense does not occur. The threshold in the perfect information case is higher than under imperfect information, as the central bank doesn't face the risk of bearing both costs, defense and regime change, if the defense fails.

[15] For the derivation of this threshold, we assume that the status quo is abandoned if the central bank chooses $B = 0$ regardless of the realized strength of the attack.

[16] Note that the central banks assessment of the strength of the attack is $\widetilde{A} = A + \xi_{CB}$ and $A = G(x^* - \theta)$ (see equation 1).

2.3.3 Speculative traders

The equilibrium in the standard global game (see section 2.1) is characterized by two variables – the threshold x^* and a threshold of the fundamental state $\bar{\theta}$ – which are determined by two equations. However, in our approach a second source of uncertainty is present. The central banks can only imperfectly assess the strength of the attack. The determining equation of the fundamental threshold holds only conditional on the central banks assessment error.

Proposition 3: The attack is successful if and only if $\theta < \bar{\theta}(\xi_{CB})$ where

$$\bar{\theta}(\xi_{CB}) = \sup\{\theta : A(\theta) > B(\theta, \xi_{CB})\} \tag{10}$$

Depending on the central bank's signals, there are four possible situations. First, the signals are such that the attack is underestimated and the attack succeeds for all θ, i.e. $\bar{\theta}(\xi_{CB}) = \infty$. Secondly, the attack is not underestimated, however, defensive measures are too costly given bad fundamentals. Then $\bar{\theta}(\xi_{CB})$ solves the threshold in equation (8). Thirdly, the safety cushion in the central banks defense strategy is not sufficient to offset the underestimation of the strength of the attack for bad fundamentals, i.e. $\bar{\theta}(\xi_{CB})$ solves $A(\theta) = B(\theta, \xi_{CB})$. Fourthly, based on a high estimate of the strength of the attack, the central bank chooses defensive measures that are stronger than the attack for all θ, i.e. $\theta_0(\xi_{CB}) = -\infty$ and $\bar{\theta}(\xi_{CB}) = -\infty$. In appendix 3, we visualize the relation of $\theta_0(\xi_{CB})$ and $\bar{\theta}(\xi_{CB})$ exemplarily.

Proposition 4: The unique threshold x^* is given by

$$\mathbb{E}_{\xi_{CB}}\left(G\left(\theta < \bar{\theta}(\xi_{CB}) \,|x_i = x^*\right)\right) = c \tag{11}$$

The threshold x^* must satisfy the condition stated above. Agent i receiving a signal exactly at the threshold value, i.e. $x_i = x^*$, is indifferent between attacking or not. Therefore the expected payoff given this private information must equal zero or equivalently, the expected probability of a regime change conditional on $x_i = x^*$ must equal the costs of attacking, i.e. using equation (10) $\mathbb{E}_{\xi_{CB}}\left(G\left(\theta < \bar{\theta}(\xi_{CB}) \,|x_i = x^*\right)\right) = c$, which generalizes equation (2).[17]

x^* depends on the cost and information structure of the central bank, i.e. ϕ, R, and σ. If R and ϕ do not depend on θ, θ is a pure sunspot variable, i.e. a coordination device for the speculative traders.

[17] If we apply the above stated common example of normally distributed prior and error distribution, the posterior distribution is $P\left(\theta < \hat{\theta}(\xi_{CB}) \,|x_i = x^*\right) = \Phi\left(\hat{\theta}(\xi_{CB}) - \frac{\alpha}{\alpha+\beta}x^* - \frac{\beta}{\alpha+\beta}z\right)$.

2.4 Equilibrium analysis

2.4.1 Shape of the central bank's optimal reaction function and the global game solution

In the literature on global games, the fundamentals θ usually are identified with the strength of the status quo which implies setting $B(\theta) = \theta$. The fundamentals θ thus represent the defensive potential and policy makers are assumed to always tap the full potential in case of an attack. In contrast to classical global games in our approach, the reaction function of the central bank is not monotonously increasing in θ. We argue that under imperfect information it is rational to adjust costly defensive measures to the size of the expected attack. Therefore the central bank either abstains from defensive measures, if its estimates the necessary defense as too costly or adjusts the extent of its interventions to the estimated strength of the attack, which is *declining* in θ.[18] Therefore the strength of the *realized* defensive measures $B_{opt}(\theta)$ – in contrast to the defensive *potential* – does not always monotonously increase with the fundamental state.

We now discuss the assumption that the costs of a defense relative to the costs of a devaluation $\frac{\phi(\theta)}{R(\theta)}$ are non-increasing. This assumption is a sufficient condition for the application of the iterated elimination of dominated strategies, i.e. the global game solution. Proposition 3 tells us that there is a threshold of the fundamentals $\bar{\theta}(\xi_{CB})$ below which there will be a successful attack, i.e. $\{\theta : A(\theta) > B(\theta, \xi_{CB})\} = \left(-\infty, \bar{\theta}(\xi_{CB})\right)$. However, this result holds if and only if $A(\theta) - B(\theta, \xi_{CB})$ – and therefore $\frac{\phi(\theta)}{R(\theta)}$ – is non-increasing in θ.[19]

This problem is a direct consequence of the shape of the optimal central bank reaction B_{opt}. If the defense measures monotonously increase in the fundamentals (as in the standard models), there is a unique threshold in the fundamentals since $A(\theta)$ is decreasing and $B(\theta)$ is increasing. If the defense measures are not monotonously increasing in the fundamentals (as in this model), there is a unique threshold in the fundamentals if only if we make additional assumptions on the determinants of the central bank reaction function. Thus, for applications of global games to speculative attacks these assumptions need to be addressed.

[18] Since traders actions are strategic complements, the unique monotone Nash equilibrium is a threshold strategy. Traders attack if and only if their private signals are lower than the threshold. As the private signals are distributed around the true fundamentals θ, the less traders receive a signal below their threshold the better the fundamentals are.

[19] $A(\theta) - B(\theta, \xi_{CB}) = -\xi_{CB} - \sigma \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) = -\xi_{CB} + \sigma \ln(2\sigma) + \sigma \ln\left(\frac{\phi(\theta)}{R(\theta)}\right)$

2.4.2 Behavior of the traders

The following subsections derive the main results regarding the influence of various model parameters on the incidence of a currency crisis and the policy reaction function under the assumption that the conditions for uniqueness of the equilibrium are satisfied. Since a devaluation takes place for all fundamental values lower than or equal to $\bar{\theta}(\xi_{CB})$, each change in a parameter that increases $\bar{\theta}(\xi_{CB})$ raises the ex ante probability of a crisis. This in turn allows the traders to act more aggressively, i.e. x^* increases. Increasing $\bar{\theta}(\xi_{CB})$ in this context means that $\bar{\theta}(\cdot)$ increases for at least some values of ξ_{CB} and is not decreasing for any value of ξ_{CB}, i.e. $\bar{\theta}_1(\xi_{CB}) \geq \bar{\theta}_2(\xi_{CB}) \forall \xi_{CB}$. To analyze the reaction of $\bar{\theta}(\xi_{CB})$ to parameter changes, it sufficient to look at B_{opt} and θ_0. The likeliness of a regime change, i.e. $\bar{\theta}(\xi_{CB})$, decreases, if the strength of the defensive action (if taken) increases, i.e. B_{opt} increases, and the area where no defensive action is taken decreases, i.e. θ_0 decreases. Parameters with mixed effects on $\bar{\theta}(\xi_{CB})$ cannot be analyzed in this setting without choosing concrete error distributions and cost functions.

Proposition 5:

The traders behave less aggressive, if the costs of a devaluation increase or the costs of defensive measures decrease.

Proof: Appendix 4

We have $\frac{d\bar{\theta}(\xi_{CB})}{dR} < 0$ and therefore $\frac{dx^*}{dR} < 0$, as well as $\frac{d\bar{\theta}(\xi_{CB})}{d\phi} > 0$ and therefore $\frac{dx^*}{d\phi} > 0$. This proposition shows that the model is consistent. The defense of the central bank becomes stronger (both the use of defensive measures is more intense, if the central bank chooses to defend the regime, and the likeliness of the central bank to take defensive measures grows), if a regime change is more costly or if defensive measure are cheaper for the central bank.

2.4.3 Policy analysis

The strength of the attack depends on the true value of the fundamentals, since $A = G(x^* - \theta)$. Speculative traders attack if they receive a signal lower than their threshold indicating sufficiently bad fundamentals. As the signals are centered around the true value, the share of signals below the threshold decreases if the true value increases. We have $\frac{dA(\theta)}{d\theta} = -g(x^* - \theta) < 0$, i.e. better fundamentals imply weaker attacks.

The policy of the central bank depends on its assessment of the strength of the attack. To infer the influence of a change in the fundamentals on the probability of a regime change, both parts of the defense strategy have to be analyzed: the effect on the defensive action if taken and the likeliness that defensive action is taken.

Strength of defensive action

If the central bank decides to take defensive actions, it chooses $B = \tilde{A} + \sigma \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right)$, i.e. it intervenes more aggressively than is necessary given its estimate of the strength of the attack and applies a security margin against a certain amount of estimation error. The likeliness of a regime change then equals the probability that the cushion is sufficient, i.e. $P\left(\xi_{CB} < -\sigma \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right)\right)$. We have

$$\frac{d}{d\theta}\sigma \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) = \sigma\frac{2\sigma\phi(\theta)}{R(\theta)} \cdot \frac{1}{2\sigma} \cdot \frac{d\frac{R(\theta)}{\phi(\theta)}}{d\theta} = \frac{\sigma\phi(\theta)}{R(\theta)} \cdot \frac{d\frac{R(\theta)}{\phi(\theta)}}{d\theta} > 0.$$

therefore the cushion is increasing in θ and the likeliness of a regime change decreases.

To put it intuitively, for better fundamentals it is easier and cheaper to take defensive measures.

Likeliness that defensive action is taken

The likeliness that defensive action is taken depends on the absolute height of the attack signal, i.e. the sum of realized attack and estimation error, and the central bank threshold. The fundamentals change both, the size of the attack and the threshold. The probability that the central bank acts is

$$P\left(\underbrace{A(\theta) + \xi_{CB}}_{\tilde{A}} < \underbrace{\frac{R(\theta)}{\phi(\theta)} - \sigma \ln \frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma}_{T_{CB}}\right).$$

Now we have

$$\begin{aligned}
\frac{d}{d\theta}A(\theta) &= -g(x^* - \theta) < 0 \text{ and} \\
\frac{d}{d\theta}T_{CB} &= \frac{d}{d\theta}\left(\frac{R(\theta)}{\phi(\theta)} - \sigma \ln \frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma\right) \\
&= \frac{d\frac{R(\theta)}{\phi(\theta)}}{d\theta} - \frac{\sigma\phi(\theta)}{R(\theta)} \cdot \frac{d\frac{R(\theta)}{\phi(\theta)}}{d\theta} = \left(1 - \frac{\sigma\phi(\theta)}{R(\theta)}\right) \cdot \frac{d\frac{R(\theta)}{\phi(\theta)}}{d\theta} > 0,
\end{aligned}$$

since $\frac{\sigma\phi(\theta)}{R(\theta)} < \frac{1}{2}$ (see equation (7)). The threshold increases with better fundamentals as the defensive measures become relatively cheaper.

In addition, the strength of the attack decreases.

For better fundamentals, both effects conjointly raise the likeliness that the central bank takes defensive actions. And if such measures are taken, they are more likely to be successful.

The precision of central bank information

The effects of the precision of central bank information on the behavior of the agents are mixed.

$$\text{Security margin:} \quad \frac{d}{d\sigma}\sigma \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) = \ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) - 1 = \begin{cases} > 0 & if \quad \sigma < \frac{R(\theta)}{2\exp(1)\phi(\theta)} \\ < 0 & if \quad \sigma > \frac{R(\theta)}{2\exp(1)\phi(\theta)} \end{cases}$$

$$\text{Threshold:} \quad \frac{d}{d\sigma}\left(\frac{R(\theta)}{\phi(\theta)} - \sigma \ln \frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma\right) = -\ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) < 0$$

A decrease in the central bank's information quality, i.e. an increase in σ, always decreases the threshold for the estimated attack strength above which no defense action is taken. However, the effect on the size of the defense measures if action is taken depends on the level of information quality. If the central authority is well informed, i.e. σ is small, a decrease of precision is compensated by an increased safety buffer. With decreasing precision the cost -utility ratio of additional safety buffer declines. If the central authority is informed poorly, i.e. σ is large, a further increase leads to a reduction of the safety cushion. As a topic of further research, we intend to specify the informational situation of the speculative traders and relate it to the central bank's information set.

3 Conclusion

While the recent global game literature has considerably improved our understanding of the role investors play in speculative attacks, the role of central banks as key players in and the dynamics of financial crises are still not well understood. We explicitly model the strategic options of market participants and policy makers as well as the dynamics of financial crises. In case of an attack, the central bank basically faces three alternatives. It can either give in to the speculative attack or it can try to defend its exchange rate regime. If it chooses to defend its currency the defense can succeed or fail. Each of these outcomes yields entirely different economic consequences with the case of an unsuccessful defense having the most severe negative growth effects. Therefore, the decision to defend is risky. When defending the exchange rate the central bank might avoid the economic costs of an immediate devaluation, however, at the price of risking an unsuccessful defense which entails the costs of defending a currency and in addition the costs of a devaluation.

In future work we want to extend the empirical analysis and relate our findings to the empirical results found in the literature based on the two standard crisis definitions, namely a significant devaluation and an increase in an exchange market pressure index. Both crisis indicators mix up different types of financial crises, which should be differentiated according to our model. Throughout the analysis our preliminary empirical results are highly sensitive to the types of financial crisis. Indicators which are significant for one type of crises are insignificant for the others and vice versa. Our results thus offer one line of explanation for the well known poor performance of early warning systems and the heterogeneous results in the empirical currency crisis literature. It would be interesting among other extensions to further analyze the costs and benefits of currency crises for the different actors in the economy, e.g. central bank, government, private households and enterprises. In a number of cases governments have been voted out of office after abandoning the fixed exchange rate even though the economy developed quite well after the speculative attack, e.g. Mexico after 1994 or UK after 1992. On the empirical side an important aspect to account for is the endogeneity of the type of currency crisis and the subsequent economic development. Is the (failed) defense itself to be blamed for bad outcomes, or do the underlying fundamentals determine the type of defense the central bank chooses? Likewise in the theoretical model, the additive structure of the cost functions could be generalized to address this endogeneity problem. In addition, a more detailed description of the fundamental process would allow to model timing aspects, to specify preemptive defensive measures of the central bank and to evaluate temporary nominal anchor policies.

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4 Appendix

4.1 Appendix 1

$$\begin{aligned}\mathbb{E}\left(I_{A>B}|\widetilde{A}\right) &= \mathbb{E}\left(I_{\widetilde{A}-\xi_{CB}>B}|\widetilde{A}\right) = \mathbb{E}\left(I_{-\xi_{CB}>B-\widetilde{A}}|\widetilde{A}\right) \\ &= \mathbb{E}\left(I_{\xi_{CB}<\widetilde{A}-B}|\widetilde{A}\right) = \begin{cases} \frac{1}{2}\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ 1-\frac{1}{2}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B < \widetilde{A} \end{cases}\end{aligned}$$

$$\mathbb{E}C = \mathbb{E}\left(RI_{A>B} + \phi B\right) = \begin{cases} \phi B + \frac{1}{2}R\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ \phi B + R\left(1-\frac{1}{2}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right)\right) & if \quad B < \widetilde{A} \end{cases}$$

We see that this function has extrema if and only if $\phi < \frac{R}{2\sigma}$.

4.2 Appendix 2

First order condition

$$\begin{aligned}
\frac{d\mathbb{E}C}{dB} &= \frac{d}{dB}\begin{cases} \phi B + \frac{1}{2}R\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ \phi B + R\left(1-\frac{1}{2}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right)\right) & if \quad B < \widetilde{A} \end{cases} \\
&= \begin{cases} \phi + \frac{d}{dB}\left(\frac{1}{2}\exp\left(\frac{\widetilde{A}-B}{\sigma}\right)R\right) & if \quad B \geq \widetilde{A} \\ \phi - \frac{d}{dB}\left(\frac{1}{2}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right)R\right) & if \quad B < \widetilde{A} \end{cases} \\
&= \begin{cases} \phi - \frac{R}{2\sigma}\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ \phi - \frac{R}{2\sigma}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B < \widetilde{A} \end{cases} \stackrel{!}{=} 0 \\
\Rightarrow \quad B &= \begin{cases} \widetilde{A} + \sigma \ln \underbrace{\left(\frac{R}{2\sigma\phi}\right)}_{>1} > A & if \quad B \geq \widetilde{A} \\ \widetilde{A} - \sigma\ln\left(\frac{R}{2\sigma\phi}\right) & if \quad B < \widetilde{A} \end{cases}
\end{aligned}$$

$$\begin{aligned}
\frac{d^2K}{dB^2} &= \frac{d}{dB}\begin{cases} \phi - \frac{R}{2\sigma}\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ \phi - \frac{R}{2\sigma}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B < \widetilde{A} \end{cases} \\
&= \begin{cases} \frac{R}{2\sigma^2}\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B \geq \widetilde{A} \\ -\frac{R}{2\sigma^2}\exp\left(-\frac{\widetilde{A}-B}{\sigma}\right) & if \quad B < \widetilde{A} \end{cases} = \begin{cases} > 0 & if \quad B \geq \widetilde{A} \\ < 0 & if \quad B < \widetilde{A} \end{cases} \\
&\Rightarrow \begin{cases} Minimum & if \quad B \geq \widetilde{A} \\ Maximum & if \quad B < \widetilde{A} \end{cases}
\end{aligned}$$

For $B < \widetilde{A}$ expected costs increase in B. As $B \geq 0$ we get $B_{opt} = 0$ for $B < \widetilde{A}$.

To find the optimal strategy we first calculate $\mathbb{E}_A\left(C(\cdot)\,|\widetilde{A}\right)$ for $B_{opt} = 0$ and $B_{opt} = \widetilde{A} + \sigma\ln\left(\frac{R}{2\sigma\phi}\right)$

$$\begin{aligned}
\mathbb{E}_A\left(C\left(\widetilde{A}+\sigma\ln\left(\frac{R}{2\sigma\phi}\right)\right)|\widetilde{A}\right) &= \phi B + \frac{1}{2}R\exp\left(\frac{\widetilde{A}-B}{\sigma}\right) \\
&= \phi\left(\widetilde{A}-\sigma\ln\left(\frac{2\sigma\phi}{R}\right)\right) + \frac{1}{2}R\exp\left(\frac{\widetilde{A}-\left(\widetilde{A}-\sigma\ln\left(\frac{2\sigma\phi}{R}\right)\right)}{\sigma}\right) \\
&= \phi\left(\widetilde{A}+\sigma-\sigma\ln\frac{2}{R}\sigma\phi\right) \\
\mathbb{E}_A\left(C(0)\,|\widetilde{A}\right) &= R
\end{aligned}$$

and now compare the two options

$$\begin{aligned}
\mathbb{E}_A\left(C\left(\widetilde{A}+\sigma\ln\left(\frac{R}{2\sigma\phi}\right)\right)|\widetilde{A}\right) &< \mathbb{E}_A\left(C\left(0\right)|\widetilde{A}\right)\\
\phi\left(\widetilde{A}+\sigma-\sigma\ln\frac{2\sigma\phi}{R}\right) &< R\\
\widetilde{A} &< \frac{R}{\phi}-\sigma-\sigma\ln\frac{R}{2\sigma\phi}.
\end{aligned}$$

We find that the expected costs of taking optimal defense measures are lower than the costs of not defending the current regime if and only if the estimated strength of the attack $\widetilde{A}$ is below a threshold $\frac{R}{\phi}-\sigma+\sigma\ln\frac{2}{R}\sigma\phi$. We therefore have

$$B_{opt}=\begin{cases}\widetilde{A}+\sigma\ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) & if \quad \widetilde{A}<\frac{R(\theta)}{\phi(\theta)}-\sigma\ln\frac{R(\theta)}{2\sigma\phi(\theta)}-\sigma\\ 0 & else\end{cases}.$$

4.3 Appendix 3: An example: θ_0 and $\bar{\theta}$

If the central bank assesses the strength A of the attack correctly, i.e. $\xi_{CB}=0$ and $A(\theta)\equiv\tilde{A}(\theta)$, the attack is successful if and only if the central bank abstains from defensive measures, i.e. $\bar{\theta}=\theta_0$.

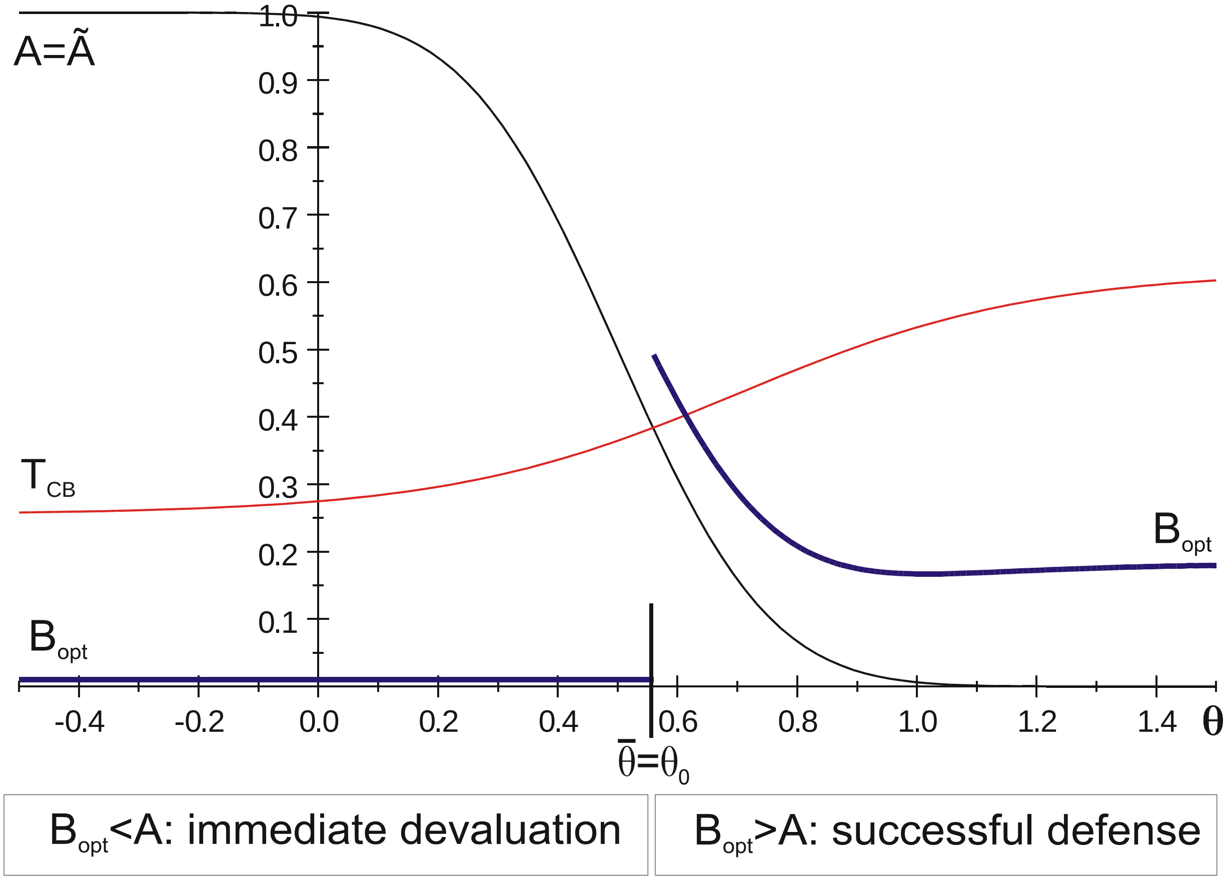

Figure 3: $\xi_{CB} = 0:$ θ_0 is the intersection of $A(\theta)$ (black) and $T_{CB} = \frac{R(\theta)}{\phi(\theta)} - \sigma \ln \frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma$ (red). Further B_{opt} is blue and below $A(\theta)$ if and only if $B_{opt} = 0$, i.e. $\bar{\theta}(\xi_{CB} = 0) = \theta_0(\xi_{CB} = 0)$.

If the central bank underestimates the strength A of the attack, i.e. $\xi_{CB} < 0$ and $A(\theta) > \tilde{A}(\theta)$, there is the possibility that defensive measures are taken but not sufficient to fight the attack. We have $\bar{\theta} < \theta_0$ and three alternative crises outcomes:

1. immediate devaluation for $\theta < \bar{\theta}$
2. unsuccessful defense for $\bar{\theta} < \theta < \theta_0$ and
3. successful defense for $\theta_0 < \theta$

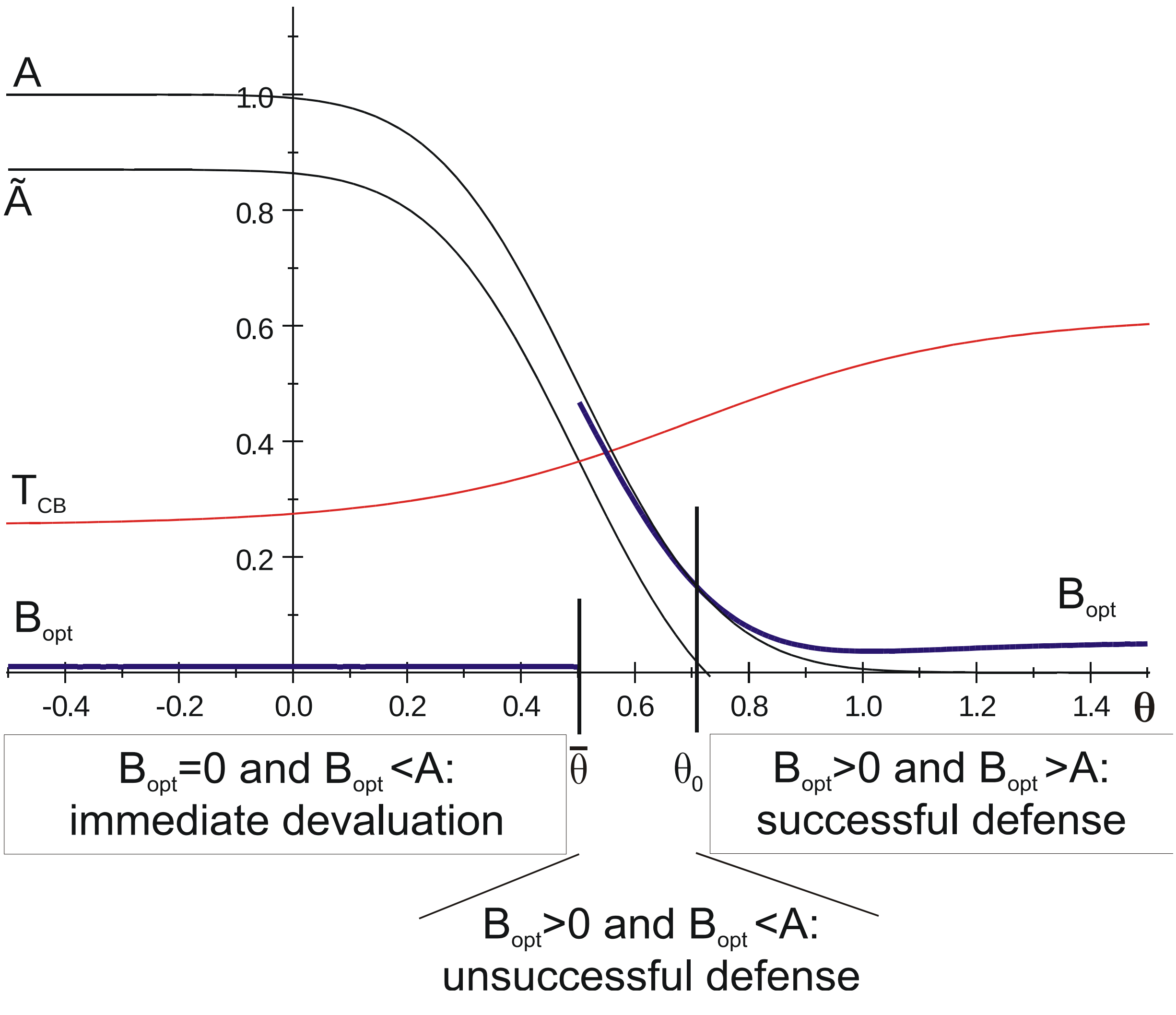

Figure 4: $\xi_{CB} = -0.13$: θ_0 is the intersection of $\tilde{A}(\theta) = A(\theta) + \xi_{CB}$ (lower black) and $T_{CB} = \frac{R(\theta)}{\phi(\theta)} - \sigma \ln \frac{R(\theta)}{2\sigma\phi(\theta)} - \sigma$ (red). Further $\hat{\theta}$ is the intersection of the upper black line (real strength of the attack) and B_{opt}(blue line).

4.4 Appendix 4

1. $B_{opt} = G\left(x^{*}-\theta\right)+\xi_{CB}+\sigma\ln\left(\frac{R(\theta)}{2\sigma\phi(\theta)}\right) \Rightarrow \left(R\uparrow\Rightarrow B_{opt}\uparrow\right)$

$$\theta_0\left(\xi_{CB}\right) = \lim\inf\left\{\theta : \underbrace{G\left(x^{*}-\theta\right)+\xi_{CB}}_{:=LS} \leq \underbrace{\frac{R\left(\theta\right)}{\phi\left(\theta\right)}-\sigma\ln\frac{R\left(\theta\right)}{2\sigma\phi\left(\theta\right)}-\sigma}_{:=RS}\right\}$$

$$\left.\begin{array}{c} R\uparrow\Rightarrow RS\uparrow \\ R\uparrow\Rightarrow x^{*}\downarrow\Rightarrow LS\downarrow \end{array}\right\}\Rightarrow\theta_0\downarrow$$

2. analogously: $\phi\uparrow\Rightarrow B_{opt}\downarrow$

$$\left.\begin{array}{c} \phi\uparrow\Rightarrow RS\downarrow \\ \phi\uparrow\Rightarrow x^{*}\uparrow\Rightarrow LS\uparrow \end{array}\right\}\Rightarrow\theta_0\uparrow$$

4.5 Appendix 5: Country sample

Argentina, Brazil, Bulgaria, Chile, China, Colombia, Czech Republic, Ecuador, Estonia, HongKong, Hungary, India, Indonesia, Korea, Latvia, Lithuania, Malaysia, Mexico, Pakistan, Peru, Philippines, Poland, Russia, Singapore, Slovak Republic, Slovenia, South Africa, Sri Lanka, Taiwan, Thailand, Turkey, Venezuela