Swiss Unconventional Monetary Policy: Lessons for the Transmission of Quantitative Easing

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Abstract

We analyze the financial market reaction to announcements by the Swiss National Bank (SNB) regarding its unconventional monetary policy initiatives in response to the European sovereign debt crisis. Since these actions included an expansion of bank reserves without any purchases of long-term securities, this episode provides novel insights on the transmission mechanism of quantitative easing. Using dynamic term structure models, we decompose the response of Swiss government bond yields into changes to expectations about future short-term interest rates and term premiums. We find that the declines in yields following the announcements of the reserve expansions reflected reduced term premiums. This suggests that expansions of reserves by themselves can give rise to a portfolio balance effect.

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1 Introduction

After lowering conventional policy rates to near their effective zero lower bound by early 2009, a number of major central banks engaged in large-scale asset purchases—frequently referred to as quantitative easing (QE)—to provide further monetary stimulus through unconventional means. The stated aims of such purchases differ slightly across countries, but usually involve reducing long-term interest rates, either broadly or in specific markets. Whether QE programs have reduced long-term interest rates—and through what channels—has become the topic of a large and growing literature.

This literature has focused on two main channels: namely a signaling channel, which works through changing market expectations about future monetary policy (see, e.g., Christensen and Rudebusch 2012 and Bauer and Rudebusch 2013); and a portfolio balance channel arising from changes in the supply available in the market of the assets that the central bank has purchased (see, e.g., Gagnon et al. 2011 and Krishnamurthy and Vissing-Jorgensen 2011).[1] Bernanke and Reinhart (2004), however, point out that portfolio balance effects of QE programs can arise through an additional reserves channel. Namely, the increase in the supply of reserves may put upward pressure on asset prices more broadly. When the central bank buys specific securities in large quantities and pays for these by issuing central bank reserves, both channels can work simultaneously. This is the case for all three QE programs conducted by the Federal Reserve since 2008, and for the Bank of England's asset purchase programs. Both central banks conducted QE by buying large quantities of safe and liquid long-term bonds in exchange for newly issued reserves.[2] The implication is that the effects of QE programs on long-term yields documented in the previous empirical literature can derive both from the portfolio balance effect of the reduced relative supply of long-term bonds and from the increased supply of central bank reserves. The effects of these two different channels cannot be separately identified.

This paper investigates the unconventional policies conducted by the Swiss National Bank (SNB) in August 2011. While these policies had many features similar to the Federal Reserve and the Bank of England QE programs, both its background and nature differed in important ways. These allow for a new empirical perspective on the transmission of QE to interest rates. With the standard policy rate constrained by its zero lower bound, the SNB introduced a set of unconventional monetary policies in response to the strongly appreciating Swiss franc exchange rate at the time.[3] These policies comprised three consecutive expansions of bank

[1] See also Joyce et al. (2011), Thornton (2012), and Neely (2013) for discussions.

[2] There is one exception, namely the Federal Reserve's "Maturity Extension Program" (MEP) that operated from September 2011 through 2012. This program involved purchases of more than $600 billion of long-term Treasury securities (defined as bonds with more than six years to maturity) financed by selling an equal amount of shorter-term Treasuries (defined as bonds with less than three years to maturity). Thus, the MEP represents a case of sizable purchases and sales of securities without any change in the amount of reserves. This contrasts with the Swiss National Bank program we study, which features the opposite combination. See Cahill et al. (2013) and Li and Wei (2013) for analysis of the Fed's MEP.

[3] The appreciation of the Swiss franc was, in part, caused by flight-to-safety pressures arising from the

reserves held as sight deposits at the SNB. The expansions were large and carried out within a few weeks, making the program unprecedented in terms of both its size and how quickly it was implemented.[4] Most importantly for our analysis, the policies were announced as, and centered around, an expansion of reserves rather than around purchases of specific securities. Moreover, the expansions were achieved without any purchase of long-term debt securities. In particular, the program left the supply of long-term government bonds—as well as the supply of close substitutes—unchanged. The expansion of reserves therefore cannot have affected Swiss long-term bond yields through a direct portfolio balance effect arising from changes in the available market supply of long-term bonds.

The question we are interested in is whether the SNB's expansion of reserves in August 2011 affected long-term Swiss government bond yields, and through which channels. We document that yields of long-term Swiss government bonds *did* respond, and we argue that this would primarily have happened through three channels. The first is the portfolio balance effect derived from an expanded supply of reserves held by banks, as emphasized by Bernanke and Reinhart (2004). The second is a possible portfolio balance effect related to the assets that the SNB purchased to achieve the reserve expansions. Given the short maturity of these assets, we argue that direct substitution effects are at most negligible. As a consequence, this channel is unlikely to have been important for long-term yields. Third, as with other QE programs, the SNB announcements could have produced signaling effects.

To separate these channels, we follow the literature and use term-structure modeling combined with an event study approach similar to Christensen and Rudebusch (2012, henceforth CR), who investigate the response of U.S. and U.K. government bond yields to their respective unconventional policy initiatives. Applying a dynamic term structure model (DTSM) to Swiss Confederation bond data allows us to decompose, in real time, long-term yield changes into changes to expected short rate and term premium components. The expected short rate component is then associated with monetary policy expectations, while portfolio balance effects are associated with the term premium. A drawback of this approach for evaluating the effects of QE programs—for which we have no remedy—is that the term premium incorporates all portfolio balance effects and does not allow us to separate the effect of reserves from the effect of the reduced market supply of the assets purchased. For the same reason, these two portfolio balance effects have not been separated in event studies of the U.S. and U.K. QE programs. However, we note that, given the nature of the assets purchased by the SNB, these are far less likely to have yielded portfolio balance effects on long-term yields than the U.S. and U.K. programs.

With estimated changes in term premiums and monetary policy expectations in hand, we

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sovereign debt crises in peripheral euro-area countries.

[4]By early September 2011, the SNB's balance sheet had expanded by an amount equal to 30 percent of Swiss GDP.

evaluate and compare the responses around the SNB announcements.[5] We find that long-term Swiss Confederation bond yields dropped by a total of 28 basis points in the aftermath of the three SNB announcements of reserve injections.[6] We also find that this drop was predominantly reflected in the term premium, suggesting portfolio balance effects. To our knowledge, this is the first paper, using data on unconventional monetary policies in the aftermath of the global financial crisis, to show that an expansion of reserves can have significant portfolio balance effects on long-term bond yields in the absence of long-term bond purchases. Given the nature of the SNB reserve expansions, we conclude that the most likely driver of the identified portfolio balance effects were the reserve expansions themselves, rather than the reduced supply of the assets that the SNB bought. By contrast, we find signaling effects were less important in the long-term bond market. However, signaling likely played a central role in driving the very short end of the Swiss yield curve into negative territory in connection with the announcements.

Regarding the relative importance of signaling versus portfolio balance effects, our findings are similar to those reported by CR in their analysis of the U.K. QE program, where portfolio balance effects are found to be the dominating factor in the yield response. We speculate that this could be linked to the fact that neither the U.K. QE program nor the SNB announcements studied here were accompanied by any type of forward guidance that could have affected bond investors' expectations about future monetary policy. This contrasts with findings for the U.S. QE program, where both CR and Bauer and Rudebusch (2013) report evidence of significant signaling effects consistent with the forward guidance provided by the FOMC.[7] If so, this would suggest that the effect of central bank unconventional policies may depend crucially on central bank communication policies, as also emphasized by CR.

The findings could also have implications for the exit from QE programs based on long-term bond purchases. To reduce the risk of strong abrupt portfolio balance effects on long-term interest rates, that unwinding these QE programs could have, it may not be sufficient for the central bank to keep the bonds on its balance sheet, while draining reserves from the banking system. Depending on the tools used, draining reserves could have portfolio balance effects on long-term yields. And again, the communication strategy could make a material difference for the outcome.

The remainder of the paper is structured as follows. The next section describes the context and details of the SNB's expansions of reserves in August 2011. In Section 3, we

[5]Gagnon et al. (2011), CR, and Bauer and Rudebusch (2013) are among the previous studies that provide DTSM decompositions of the U.S. experience with unconventional monetary policies. Mirkov and Sutter (2013) also use DTSMs to analyze both the U.S. and Swiss experience with such policies, but they do not make a real-time event study like ours.

[6]Relative to the yield on the ten-year Swiss Confederation bond of 1.33 percent on the eve of the first announcement, 28 basis points represent a significant drop.

[7]At first, in December 2008, the Federal Reserve introduced the formulation that its target rate would be exceptionally low for "some time." In March 2009, the language in FOMC statements was changed to state that an exceptionally low target rate would be required for "an extended period of time" before explicit forward guidance was given starting with the FOMC statement in August 2011.

take a first look at the data and discuss in more detail how we expect the expansion of reserves to have affected interest rates. Section 4 introduces our empirical term structure models, details our sample of Swiss Confederation bond yields, and describes how we use the models to extract short-term interest rate expectations and term premiums from bond yields. Section 5 contains the model-based analysis of the market reaction around the SNB announcements, while Section 6 concludes. Appendices contain additional empirical results and technical formulas.

2 The SNB's Expansion of Reserves in August 2011

In normal times, the SNB ensures price stability by setting a target range for a representative short-term money market interest rate, the three-month CHF LIBOR, and by steering market rates toward this target through short-term repo operations with banks. The exchange rate is floating under normal circumstances. This policy framework reached its limit in March 2009 when, in response to developments related to the financial crisis, the SNB reduced its target rate to what was considered its effective lower bound. Further monetary policy easing continued to be desirable, but a complicating factor was the persistent strengthening of the Swiss franc due to sustained safe-haven pressures starting in late 2008, see Figure 1(a). The appreciation added considerable downward pressure on Swiss consumer prices despite the reduction in interest rates.

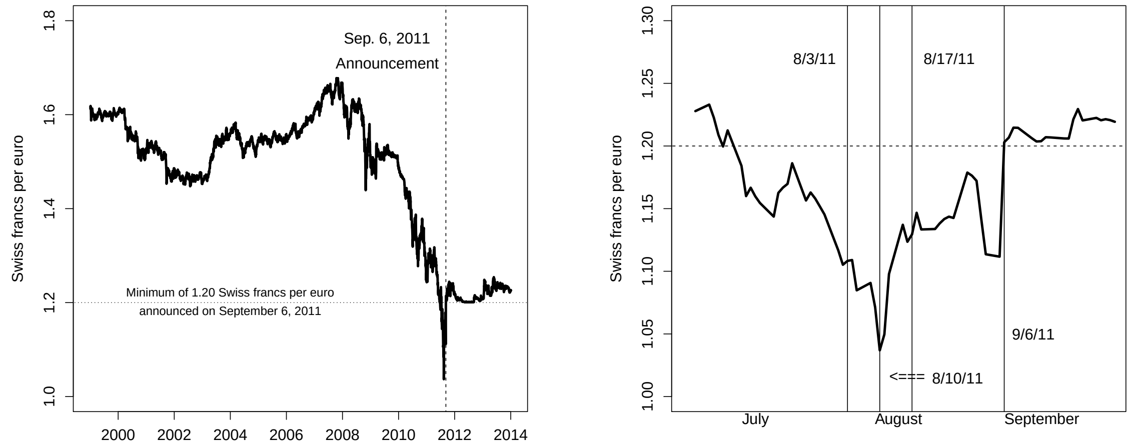
As the interest rate tool was no longer available, the SNB instead adopted a number of unconventional policies. In March 2009, these included foreign exchange interventions to prevent further appreciation, extension of the maturity for repo operations, and a relatively small, targeted, and short-lived bond purchase program.[8]

As economic prospects temporarily improved, the bond purchase program was discontinued by the end of 2009, and exited in 2010, and foreign exchange interventions were officially discontinued in the summer of 2010. By that time, however, the foreign exchange interventions had resulted in a substantial expansion of the SNB's balance sheet and central bank reserves. A large part of these reserves were gradually absorbed starting in 2010, through reverse repo operations and the sale of short-term SNB bills.[9] The exchange rate continued to appreciate however, and in 2011 the flaring up of the European debt crisis compounded woes and resulted in increasing deflation risks in Switzerland. Headline inflation was already very low, hovering around 0.5 percent at the time.

Against this background, the SNB introduced new unconventional policy measures in August and September 2011. First, on August 3, the SNB announced that it would further narrow the target range for the three-month CHF LIBOR to 25 basis points (the lower end of the range was already at zero), and that it would aim at the lower end of that range. At the

[8]See Kettemann and Krogstrup (2014) for an overview and analysis of the impact of this program.

[9]SNB bills are short-term debt securities with maturities up to one year issued by the SNB.



(a) From 1999 to 2014.

(b) Summer of 2011.

Figure 1: **The Exchange Rate between the Swiss Franc and the Euro.**
Panel (a) shows the daily movements in the exchange rate between the Swiss franc and the euro since 1999. Panel (b) shows the daily movements around the four 2011 SNB unconventional policy announcements, indicated with solid black vertical lines. In both panels, the minimum exchange rate level of 1.20 announced on September 6, 2011, is shown with a dotted black horizontal line. Source: SNB.

same time, it announced that it would significantly increase its supply of liquidity to Swiss money markets.[10] Specifically, the SNB would expand banks' sight deposits (i.e., central bank reserves) from CHF 30 billion to CHF 80 billion.[11] This reserve expansion was to be achieved by buying back SNB bills from the markets, by not rolling over maturing SNB bills, and by allowing reverse repos with banks to expire. The intended mix of these operations was not announced and could only be observed ex post. Figure 1(b) shows that the exchange rate appreciation briefly paused, but quickly resumed following this first announcement.

One week later, on August 10, the SNB announced that it would again expand reserves, this time by a further CHF 40 billion. This announcement also stated explicitly that the liquidity expansions were intended to push down money market interest rates, thereby making the Swiss franc less attractive against other currencies. To achieve the second expansion quickly, the SNB would, in addition to the previous types of operations, also conduct short-term foreign exchange swaps (primarily of one week maturity).[12] The exchange rate reversed

[10]See the press release at http://www.snb.ch/en/mmr/reference/pre_20110803/source/pre_20110803.en.pdf.

[11]Banks' sight deposits are equivalent to central bank reserves. Approximately 300 banks hold sight deposits at the SNB. Sight deposits are non-interest bearing and readily available for payment transactions and represent legal payment instruments. Banks also hold sight deposits as a liquidity reserve and in order to fulfill the statutory minimum reserve requirements. The SNB directly influences the aggregate amount of sight deposits, and hence the liquidity in the Swiss franc money market, through its money market operations. Total SNB sight deposits also include deposits held by the Swiss government and a smaller number of nonbank financial institutions.

[12]See the press release at http://www.snb.ch/en/mmr/reference/pre_20110810/source/pre_20110810.en.pdf.

No.	Date	Announcement description
I	Aug. 3, 2011, 8:55 a.m.	Target range for three-month CHF LIBOR lowered to 0 to 25 basis points. In addition, banks' sight deposits at the SNB will be expanded from CHF 30 billion to CHF 80 billion.
II	Aug. 10, 2011, 9:05 a.m.	Banks' sight deposits at the SNB will rapidly be expanded from CHF 80 billion to CHF 120 billion.
III	Aug. 17, 2011, 8:55 a.m.	Banks' sight deposits at the SNB will immediately be expanded from CHF 120 billion to CHF 200 billion.
	Sep. 6, 2011, 10:00 a.m.	The SNB announces a minimum exchange rate for the Swiss franc to the euro of 1.20 francs per euro and is prepared to buy foreign currency in unlimited quantities to defend it.

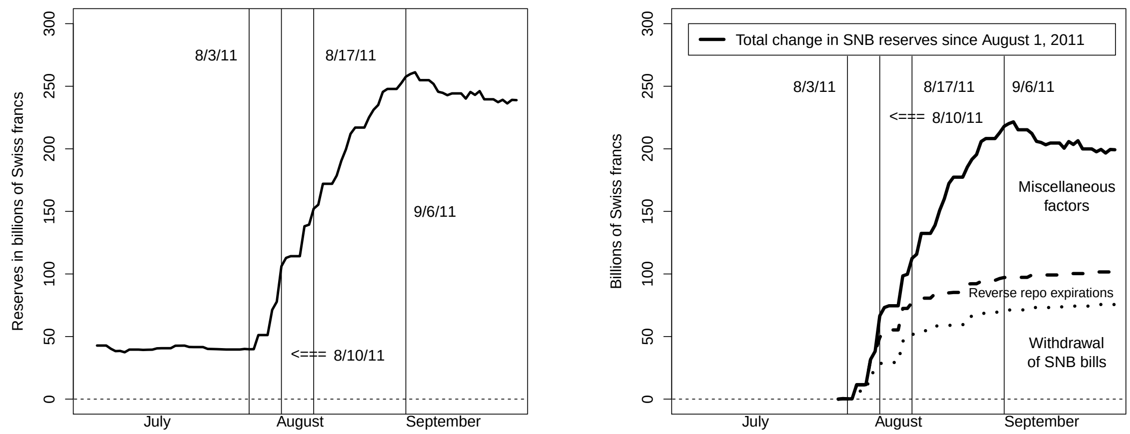
Table 1: **SNB Policy Announcements in August and September 2011.**

course and briefly depreciated following this announcement. The depreciation was not considered sufficient, however, and on August 17, the SNB announced it would raise reserves further, by CHF 80 billion. This expansion would take the total level of reserves to roughly CHF 200 billion.[13] It would be implemented through the same means as the second expansion.

The exchange rate response was again muted, and in the weeks that followed, the exchange rate appreciation resumed. Therefore, on September 6, the SNB announced the adoption of a minimum exchange rate for the Swiss franc of 1.20 francs per euro, and stated its willingness to buy foreign currency in unlimited quantities to defend it.[14] The exchange rate immediately moved to 1.20 and has remained at or above this threshold since.

Our focus is on the three expansions of reserves announced in August 2011 (events I-III in Table 1). The sum of these reserve expansions amounted to CHF 170 billion, or about 30 percent of Swiss GDP in 2011. In comparison, the U.S. aggregate QE programs have yet to reach such a magnitude.[15] Figure 2 shows the reserve expansions and their main counterparts on the SNB balance sheet. A large part was achieved by repurchasing SNB bills and allowing the shorter maturity SNB bills to mature without new issuance. The total volume of outstanding bills was reduced by CHF 66 billion in August alone. By the end of 2011, outstanding bills had been reduced by nearly CHF 100 billion. Expiration of reverse repos amounted to CHF 26 billion in August, after which all reverse repo operations had expired. Liquidity-increasing repos were subsequently carried out, but these contributed only a small part of the overall reserve expansion. The largest part of the expansions was achieved

[13]See the press release at http://www.snb.ch/en/mmr/reference/pre_20110817/source/pre_20110817.en.pdf.
[14]See the press release at http://www.snb.ch/en/mmr/reference/pre_20110906/source/pre_20110906.en.pdf.
[15]As of the end of 2013, the Federal Reserve's balance sheet totaled $4.1 trillion or about 25 percent of U.S. GDP.



(a) Total SNB reserves.

(b) Decomposition of changes in reserves.

Figure 2: **Expansion of Reserves and its Counterparts on the SNB Balance Sheet.** Panel (a) shows the daily total SNB reserves in billions of Swiss francs around the four SNB unconventional policy announcements shown with solid black vertical lines. Panel (b) decomposes the changes in total SNB reserves since August 1, 2011, into (i) withdrawal of SNB bills (through expiration or repurchases), (ii) reverse repo expirations, and (iii) miscellaneous residual factors that include outright foreign currency purchases and foreign exchange swaps. Source: SNB.

through other measures, most notably foreign exchange swaps. As SNB bills were increasingly bought back during the rest of 2011, a corresponding part of the foreign exchange swaps were allowed to expire.

For our event study analysis in Section 5 to be valid, at least part of these measures must have been unexpected when they were announced. First of all, the three announcements followed unscheduled meetings of the SNB's Governing Board.[16] Still, there was plenty of discussion in the Swiss media and a certain level of pressure from political and interest groups to enact exchange rate measures to counter what was seen as an unsustainable and unacceptable appreciation in the spring and early summer of 2011. The public called for a floor or peg for exchange rates, or for interventions to reverse the exchange rate trend. Moreover, there was speculation about the SNB introducing negative interest rates, and for good reason. The SNB had responded to a strongly appreciating exchange rate in the 1970s by introducing negative interest rates on foreign bank deposits, before finally introducing an exchange rate floor to the German mark in 1979. By contrast, public debate did not include possible liquidity expansions. This magnitude of reserve expansion had not been used before as a policy tool by the SNB, nor had it ever been publicly discussed as a possible means to counter exchange rate appreciation pressures during this episode. Hence, the contents of the first announcement on August 3 came arguably as a complete surprise.

[16]The SNB normally releases its monetary policy statements on a scheduled quarterly basis in mid-March, mid-June, mid-September, and mid-December.

The SNB stated clearly in each of the announcements that it continued to view the strength of the Swiss franc as unacceptably high, and that further measures would be forthcoming if the actions already taken did not have the intended effect. Hence, market participants probably expected the SNB to take further measures at each stage of the process. However, the exact timing, nature, and extent of the responses were never foreseeable. Furthermore, the sheer size of the announced liquidity expansions also seems to have been unexpected, particularly for the two later announcements. We conclude that the three announcements of expansions of reserves can be treated as at least partial surprises to the markets and, therefore, we can draw inferences from the financial market reaction to the announcements.

3 Transmission to Long-Term Interest Rates

In this section, we show that the announcements of the SNB's reserve expansions were associated with drops in Swiss long-term interest rates, and we offer some theories about possible transmission channels.

In prior research, Ranaldo and Rossi (2010) studied the response of various Swiss financial assets to SNB monetary policy announcements (both scheduled and unscheduled). They found that, in general, the bond market shows the strongest reaction to such events. This motivates our focus on the Swiss Confederation bond market to provide the clearest reading of investors' reactions to the SNB announcements.

Figure 3 shows the movements of the daily ten-year Swiss Confederation bond yield during the summer and fall of 2011, and the dates of the three announcements of reserve expansions as well as the date the exchange rate floor was introduced. The ten-year yield is based on bond market data, which is collected each morning between 9:00 a.m. and 11:00 a.m. Because the announcements were made around 9:00 a.m., which is around the time the bond market data is collected, we look for an effect both on the day of the announcement and the day after (see more discussion of the appropriate event window in Section 5).[17] The yield was already on a downward trend due to strong global safe-haven pressures and high risk aversion when the first announcement was made. During the weeks of the three announcements, however, the drop in the yield seems to have accelerated. Yields, moreover, invariably fell following all three announcements. The drop of a few basis points in the yield following the first announcement was within the standard deviation of two-day yield changes during the sample period (about 5 basis points). However, the change in the yield following the second announcement was slightly above. Moreover, the yield drop was particularly strong in connection with the final announcement of the most substantial increase in reserves. The ten-year yield fell by 20 basis points between the morning of the day before and the morning of the day after that

[17] Using high-frequency intraday data, Ranaldo and Rossi (2010) find that the Swiss bond market may take up to 30 minutes to respond to regular monetary policy announcements. This raises the likelihood even further that a one-day event window would not be able to capture the full bond market reaction.

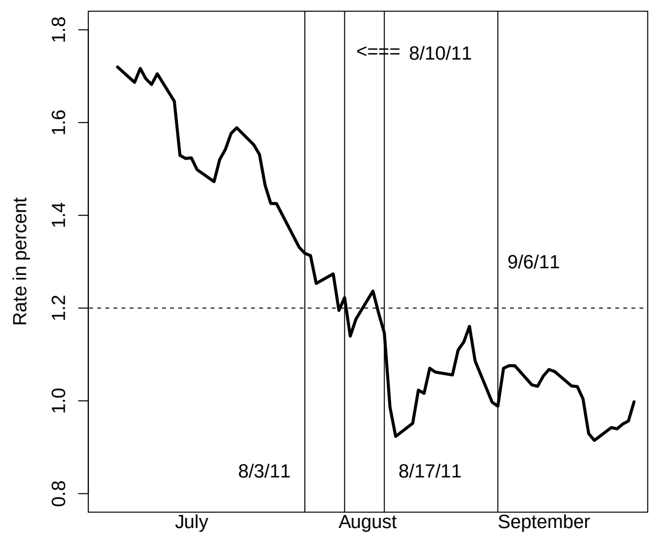


Figure 3: **Ten-Year Swiss Confederation Bond Yield.**
Illustration of the movements in the ten-year Swiss Confederation bond yield around the SNB policy announcements in August and September 2011, shown with solid black vertical lines. Source: SNB.

announcement, amounting to four standard deviations of two-day changes in that yield over our sample period.[18] At the third announcement, there was largely no reaction of the exchange rate. Given the very different reactions of Confederation bond yields and the exchange rate, it is unlikely that the movements in yields were driven by exchange rate changes.[19] The drop in the Swiss Confederation bond yields in connection with the announcement on August 17, 2011, also does not seem to have been driven by yields of foreign government bonds, such as German Bunds or U.S. Treasuries. Foreign long-term government bond yields also fell on those days, but not exceptionally and not to the same extent as Swiss Confederation bond yields. Still, for robustness, we attempt to account more formally for changes in foreign yields later on.

Through which channels could these announcements have reduced long-term yields? To structure our thoughts, note that the yield of a bond can be written as consisting of a risk-neutral part that represents the expected future short interest rates until maturity, and a term premium, according to:

[18]For the entire sample period since 1998, only one two-day change was larger than that observed on August 17. That extreme event took place on November 20, 2008, in connection with the Lehman Brothers bankruptcy. At that time, the ten-year yield fell 29 basis points over two days.

[19]Note that, if the measure announced on August 17, 2011, led market participants to believe more strongly that the SNB would take measures to induce the exchange rate to depreciate in the future, we should have expected to see an increase in the yield to compensate for the expected depreciation risk according to interest rate parity conditions.

$$y_t^j(\tau) = RN_t(\tau) + TP_t^j(\tau),$$

where t is time, j is the specific issuer, and τ is time until maturity. $RN_t(\tau)$ is the risk-neutral component of the yield that is identical for all bonds independent of the issuer. The term $TP_t^j(\tau)$ captures macro risks such as uncertainty regarding the growth and inflation outlook, changes in overall risk aversion, issuer-specific risks such as the risk of default of the issuer in question, and premiums due to special preferences for the bond in question relative to other bonds in the market in the presence of market imperfections.

Following the decomposition of the yield into these two components, the effect of the expansion of reserves can be divided into two broad categories, namely policy signaling effects and portfolio balance effects. The former affect the risk-neutral component of the yield, while portfolio balance effects are specific to the security, and hence affect the term premium. We discuss each of these types of effects below in the context of the Swiss reserve expansions in August 2011.

3.1 Policy Signaling Effects

Policy signaling affects the risk-neutral part of the yield, $RN_t(\tau)$. Thus, the announcements of the expansion of reserves could have changed the market view of how the SNB intended to set short-term interest rates in the future, that is, for how long the SNB intended to keep the short-term policy rate at the zero lower bound, and how quickly it would increase that rate after exiting the zero lower bound. If the announcements in August 2011 indicated that the SNB was more concerned about the subdued outlook for inflation than previously perceived, we should expect measures of average expected future short-term policy interest rates to fall in response to the announcements. In the empirical analysis in Section 5, we find that such signaling effects were very small in connection with the announcements of reserve expansions. Other studies (e.g., Joyce et al. 2011) explore money market data to shed some initial light on signaling effects of QE program announcements. In the following, we also take a quick look at Swiss money market rates around the August 2011 announcements and offer our interpretation, as the very strong reaction of short money market rates to announcements attracted a lot of attention at the time. But keep in mind that Swiss money market data have not been well suited for such purposes since the outbreak of the global financial crisis because liquidity has been low.

Figure 4 plots the development in select short-term Swiss franc term overnight indexed swap (TOIS) rates. Changes in TOIS rates are usually taken to represent good proxy measures for changes in expected future short-term interest rates.[20] The depicted rates dropped by

[20]TOIS quotes are collected around 11 a.m. on each business day. We would ideally want to investigate long-term Swiss franc TOIS rates, which would reflect the expected policy path over a longer horizon. However, traded TOIS contracts with long maturities are few and the market for such contracts developed only recently and is not liquid. For this reason, we consider TOIS rates of the more liquid part of the market with maturities

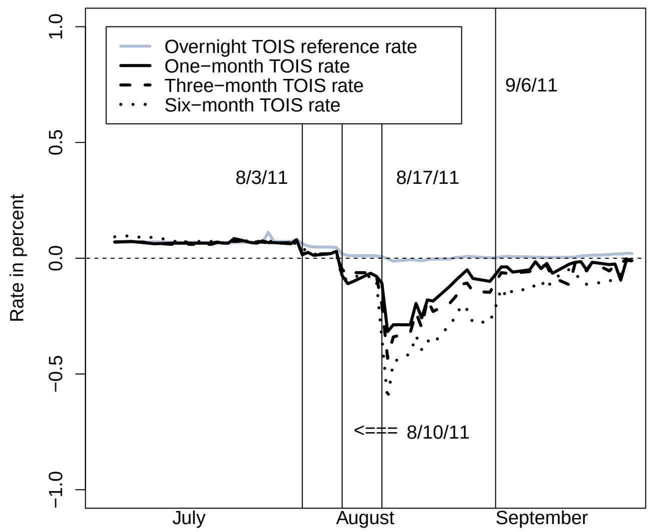


Figure 4: **Swiss TOIS Rates.**
Illustration of the movements in the overnight TOIS reference rate and the one-, three-, and six-month TOIS rates around the four SNB unconventional policy announcements shown with solid black vertical lines. Source: SNB.

between 30 and 70 basis points and turned negative in the weeks following the first announcement. The strongest reaction came after the third announcement, when the three-month TOIS rate fell 17 basis points to -0.24 percent within a few hours of the announcement, and a further 22 basis points the following day, reaching its lowest point ever of -0.46 percent. To put this reaction into perspective, a change of 22 basis points in the three-month TOIS rate amounts to seven standard deviations of its daily variation since records began in 2000. The SNB's intermediate aim of pushing down money market rates through reserve expansions clearly was very successful.

A negative three-month TOIS rate means that the counterparty paying the floating rate is willing to pay a fixed rate (for example 0.46 percent) for a three month period for the right to also pay the floating overnight rate to the counterparty. This only makes sense if there is a possibility that the overnight rate could turn negative during the next three months. As already discussed, the financial press at the time indeed speculated on the possibility that the SNB might introduce negative interest rates. It is therefore likely that investors placed a much higher probability on the SNB introducing negative interest rates after having observed that the SNB was prepared to take steps like those announced in August 2011.

We consider these strong dips into negative territory to represent a short-term expectation,

up to six months.

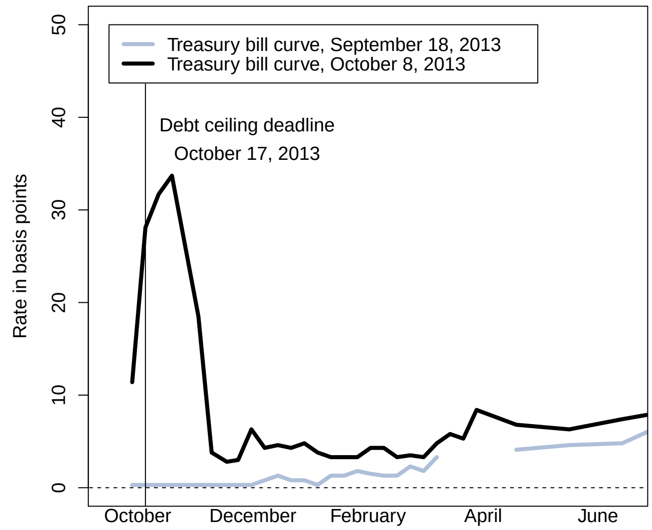


Figure 5: **U.S. Treasury Bill Curve ahead of the U.S. Debt Ceiling Deadline.** Illustration of the U.S. Treasury bill curve on October 8, 2013, a few days before the official debt ceiling for the U.S. federal government would be breached. For comparison the Treasury bill curve on September 18, 2013, is shown. Source: Bloomberg.

that is, market participants may have attached increased probability to the SNB imposing negative interest rates, but once negative interest rates were imposed, they did not expect those rates to last very long. We hence do not consider the drops in rates to imply signaling effects for long-term yields. Our reasons for this interpretation are provided in the following.

First, market participants were expecting the SNB to take crisis measures, rather than seek to loosen the overall monetary policy stance. A crisis measure such as negative interest rates, if effective, should only affect expected short rates in the very near term (during the crisis), making any effect on longer-term interest rates very small. One parallel would be the market reaction around the approaching debt ceiling deadline for the U.S. federal government in October 2013. Unlike the Swiss case where we can only speculate about what type of scenarios investors were fearing, the U.S. debt ceiling debacle presents a tangible risk of default at a specific, known time. This makes it useful for comparison. Figure 5 shows yields on outstanding U.S. Treasury bills on two days, one several weeks before the official deadline and one just days before it. Bills that would mature immediately after the debt ceiling deadline were seriously affected, while bills with maturities further in the future barely responded. Apparently, investors expected that, even if a technical default were to happen, it would be short-lived—measures would be taken to solve the problem. The key takeaway is that rather extreme priced expectations for near-term events can exist with no material implications for medium- and long-term expectations. We suspect that we are observing an example of this in the Swiss money market reaction following the SNB announcements in August 2011.

Second, the rapid reversal in the rates after August 17, 2011, implies that the net decline from the end of July through September is much smaller and more consistent with the variation observed in the Swiss Confederation bond market that our empirical model-based analysis in Section 5 relies upon. Third, the TOIS rate reactions as a sign of changes in expected future short rates are not confirmed by the monthly Consensus survey. This survey suggests that the biggest decline in short-rate expectations occurred between the July 11, 2011, and August 8, 2011, surveys, that is, in response to the first announcement that also included a lowering of the target range for the three-month CHF LIBOR. The September and October 2011 surveys show more muted responses.

To conclude, short-term money market data suggest that the announcements of expansions in reserves certainly had strong signaling effects in the very short end of the yield curve. Whether or not such signaling effects were also strong drivers of the drop in long-term interest rates in response to the announcements is assessed in Section 5, where the evidence suggests that this was not the case. Rather, the drop in long rates seems to have been driven by portfolio balance effects, which we turn to next.

3.2 Portfolio Balance Effects

Portfolio balance effects are related to the relative supply of assets in the market. Theoretical research shows that when markets are segmented through, for example, preferred habitat behavior by investors, a change in the relative market supply of an asset may have an effect on its relative price (see Tobin 1969 and Vayanos and Vila 2009). According to such theories, for market participants to be willing to hold more of an asset that has increased in relative supply, the relative price of this asset will have to fall, or its expected return relative to those of other assets will have to increase. We note that a portfolio balance effect of reserves is all the more likely for the reason that reserves clearly fulfill the requirement of segmented markets. Only banks with accounts at the central bank can hold reserves, and in aggregate, banks have to hold any increase in the total supply of reserves.

Portfolio balance effects depend on market supplies of different assets. The initial impact of the SNB's operations on market supplies of assets was to reduce short-term SNB bills, repo collateral, and short-term foreign exchange, and to increase central bank reserves held by banks. Figure 6 illustrates the composition of the subset of bank assets related to their operations in Switzerland on a yearly basis. The light blue area indicates the substantial increase in banks' reserve holdings in 2011. This impact is very similar to the impact of the large-scale purchases of long-term bonds conducted by the Federal Reserve and the Bank of England in their respective QE programs, with an important difference. As already pointed

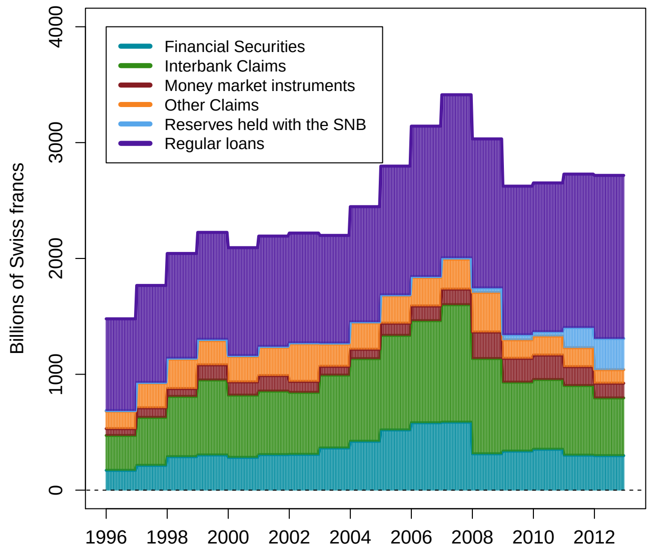


Figure 6: **Swiss Bank Assets.**
Illustration of the assets held by Swiss banks over the period from 1996 to 2012 broken down into six categories: (1) Financial Securities (trading and banking book), (2) Interbank Claims, (3) Money market instruments and liquid assets other than central bank reserves, (4) Other Claims, (5) Reserves held with the SNB, and (6) regular loans. Source: SNB.

out, the large-scale asset purchase programs of the Federal Reserve and the Bank of England reduced the market supply of long-term bonds directly, and this direct reduction is usually credited as the main driver of the portfolio balance effects from those purchases on long-term interest rates. The SNB's program did not reduce the supply of long-term bonds in the market. If it nevertheless had portfolio balance effects on long-term interest rates, this must have been indirectly through the reduced supply of Swiss franc collateral or short-term SNB bills, or through the increase in central bank reserves held by banks.[21]

We are not aware of a suitable model of bank portfolio choice that would allow us to derive predictions regarding which asset prices would change as a result of reserve expansions. Instead, to clarify how we think about the portfolio balance effect of the reserve expansions, we take the example of SNB purchases of SNB bills from nonbanks. The other types of reserve expanding operations conducted by the SNB would have very similar effects.[22] SNB bills are

[21] We do not consider whether dominant changes in short-term foreign exchange affected the price of government bonds, as the foreign exchange changes related to the SNB operations were minuscule relative to the foreign exchange market.

[22] When the SNB buys SNB bills directly from reserve holding banks, this has the effect of replacing one short-term liquid asset—SNB bills—with another—reserves. It is not clear that such a transaction would have much effect on banks' overall portfolio choice. However, in the case of the QE programs conducted by the Federal Reserve, the findings of Carpenter et al. (2013) suggest that assets were mainly purchased from the nonbank sector. Unfortunately, we do not have detailed statistics on the ultimate counterparties to the SNB's

short-term liquid assets, which are arguably very close, if not perfect, substitutes for reserves. However, the fact that SNB bills can be traded and held outside the banking sector means that the market for these assets is much less segmented than the market for reserves. When the SNB bought SNB bills from nonbank financial institutions, this operation reduced the institutions' holdings of SNB bills and increased their holdings of bank deposits. The balance sheet of the correspondent banks at the same time expanded with the equivalent amount of reserves on the asset side and the equivalent amount of deposits on the liability side. We associate the effect on the balance sheet of the nonbank counterparties with supply effects or portfolio balance effects arising from reductions in the market supply of the purchased assets.

First, the portfolio shifts of the SNB's nonbank counterparties resulting from the transaction with the SNB would imply a shift of credit risk within the counterparties' short-term liquid portfolios, from sovereign risk (SNB bills) to bank risk (deposits with the correspondent bank). Meanwhile, duration risk would remain largely unchanged. This could have affected the demand for short-term safe assets. However, given that the economy was at the zero bound, the impact on short-term interest rates would have been muted. It is not clear whether and how such a supply effect could in turn have affected nonbanks' demand for long-term bonds. This would depend on the substitutability between short-term and long-term safe assets. We know very little about this substitutability, but find it unlikely that the difference in maturity of the two assets would not play a strongly differentiating role. Moreover, during the period in 2010 when SNB bills were sold unannounced in large quantities into the market to absorb reserves, no correlation is detected between the yield on the ten-year Confederation bond and the volume of outstanding SNB bills.[23] We hence conclude that any indirect supply effect of the SNB asset purchases on long-term bonds would likely be second order. Similar considerations could be made for the examples of SNB purchases of foreign exchange swaps and repos.[24] This contrasts with a situation in which the SNB bought long-term sovereign bonds instead of SNB bills. In that case, both duration and credit risk would have changed in the counterparty's balance sheet. This would likely have resulted in increased demand for long-term sovereign bonds leading directly to supply effects.

operations.

[23]We tried many different specifications of regressions of the ten-year Confederation bond yield on the outstanding volume of SNB bills, including levels and first differences, with different lags and with a number of different controls. The benchmark sample used was daily data in the year 2010, but samples including 2009 and late 2008 and with weekly and monthly frequency were also tested. Results are available upon request. It is not clear what information such regressions convey, however, as they are not able to capture the moment when changes in the amount of outstanding SNB bills become expected or known to the markets—at which point a price effect should materialize and might discount, and hence nullify, possible price effects from actual volume changes. This is the rationale for using event study techniques in this paper.

[24]Regarding repo collateral, the relatively small reductions in repo collateral associated with the reserve expansions are unlikely to have increased demand for long-term Swiss franc bonds in August 2011. The reason is that the general collateral basket for Swiss franc repos comprises foreign currency collateral, making the pool from which to draw such collateral much larger than Swiss franc bonds. The Swiss secured lending market usually functions in an environment with scarcity of Swiss franc-denominated collateral. Partly as a result of this scarcity, there is broad availability and acceptance of collateral denominated in foreign currency for Swiss repo operations.

Second, the correspondent banks of the counterparties to the SNB's operations would have seen their reserve holdings, as well as their balance sheets, increase. This would imply a relative increase in the safe liquid short-term portfolio, and a related lower average return on assets.[25] If correspondent banks viewed their portfolios as optimized before the operation, the post-operation portfolios would have contained too much short-term liquid safe assets or reserves. This could have induced a reallocation away from reserves. But all banks cannot reduce their reserve holdings at the same time, as pointed out in Krogstrup et al. (2012). Hence, the price of reserves would have to adjust to make banks as a group content to hold the extra reserves. According to portfolio balance theory, for banks to be willing to hold an increased amount of reserves relative to other assets, the relative price of reserves would have to fall. Since reserves by their nature always have a fixed nominal price of one, serving also as a numeraire, the average price level of other bank assets would have to increase. Crucially, the existence of a portfolio balance effect of reserves depends on the segmentation of reserve markets, that is, only banks can hold reserves. If banks could sell their reserves to nonbanks, it is not clear that this effect would remain. It is also important to stress that the reserve effect is independent of the types of assets bought by the central bank when injecting reserves, in particular it could be at work when a central bank buys long-term government bonds.

The lack of appropriate models for investigating these effects also means that we do not have clear theoretical predictions regarding which assets would be affected by this bank portfolio balance effect of reserves. But we note that, in principle, all securities held by banks in their financial asset portfolios could have been affected. This includes all types of fixed-income securities, stocks, assets denominated in foreign currency, commodities, and the exchange rate.[26] If a longer horizon were allowed for, it also includes bank loans, given that reserve requirements have not been constraining bank lending in Switzerland. To limit our focus and make our study comparable to the existing literature assessing the effects of QE programs, however, we consider only Swiss long-term Confederation bonds in our empirical examination. One reason why banks are likely initially to have increased their demand for Swiss Confederation bonds when they received the reserve injections is that such bonds are liquid, safe, and benefit from a zero risk weight for calculating regulatory risk-weighted assets. Risk weights arguably represented an important balance sheet constraint for bank portfolio choice in recent years. We also note that the size of the reserve expansions in 2011 on banks' balance sheets was large relative to both the size of the entire Swiss Confederation bond market (around CHF 100 billion in recent years) and banks' holdings of these (about CHF

[25] Perhaps average funding costs would also change due to the relative increase in deposits. This could also affect bank portfolio behavior. According to the Modigliani-Miller theorem, however, funding costs should not change following a change in the structure of funding.

[26] Neely (2013) investigates the importance of a similar channel for the transmission of U.S. QE programs to the exchange rate and foreign government bond yields. For the same reasons, the expansions in SNB reserves could have affected the yields on other foreign assets in addition to the exchange rate, if such foreign assets are in limited supply relative to the increase in reserves.

11 billion of these were held by banks in Switzerland in 2011).[27] Hence, even if only a small proportion of the reserve injections in 2011 resulted in higher bank demand for Confederation bonds, the effect on the relatively small Confederation bond market could have been substantial.

The empirical literature on portfolio balance effects from changes in reserves is scarce. There are no event studies of QE programs focusing on the effect of reserves. Two related papers, Krogstrup et al. (2012) and Mirkov and Sutter (2013), empirically investigate the association between reserves and long-term yields in connection with post-financial crisis unconventional monetary policies in the United States and Switzerland. They find tentative evidence of a correlation, which suggests that those reserve expansions might have had portfolio balance effects. Another related paper is Ennis and Wolman (2012), who investigate the inter-depository institutions' allocation of holdings of central bank reserves following the Federal Reserve's QE programs. They find that reserves held by U.S. depository institutions were redistributed from the banks that initially received the injections to banks that did not, at least after late 2009. This finding would seem to suggest that U.S. banks were not content with the initial increase in their individual holdings of excess reserves following QE and hence responded by seeking to reallocate their portfolios. In turn, this could have had asset price implications.

To conclude, portfolio balance effects flowing from the SNB's expansions of reserves could have affected the yields of Swiss long-term Confederation bonds through the increase in central bank reserves. We cannot exclude that long-term yields could also have been affected indirectly by the reduced supply of SNB bills and repo collateral. All these effects would show up in the term premium component of yields on government bonds; we cannot separate them empirically. However, we do not expect portfolio balance effects from a reduced supply of SNB bills and repo collateral to have been important. We next turn to the data. As portfolio balance effects tend to be discounted by market participants when expectations about future changes to market quantities occur, we look for portfolio balance effects as well as signaling effects when the SNB announced its reserve expansions, using an event study methodology. For this, we need to decompose the yield on Swiss Confederation bonds into a component capturing changes in expectations of future short-term policy rate decisions, and a residual term premium component that captures changes in risk perceptions as well as issuer-specific risk and features such as portfolio balance effects. To achieve this, we turn to term structure modeling of Swiss Confederation bond yields.

[27] Foreign banks with sight deposits at the SNB could have held additional Confederation bonds. Data on Confederation bond supply and bank holdings are available in the annual Swiss National Bank publications "Banks in Switzerland" and "Swiss Financial Accounts."

4 Empirical Term Structure Models

In this section, we first describe how bond yields can be decomposed into a short-rate expectations component and an associated term premium component. Second, we introduce the specific class of Gaussian term structure models used in the empirical analysis. Third, we detail the Swiss government bond yield data set used in model estimation.[28] We end the section by describing the model selection procedure we use to find a favored specification and documenting the favored model's performance.

4.1 Decomposing Yields with Affine Models

Assessing whether unconventional central bank policy actions affect yields through lower policy expectations or lower term premiums requires an accurate model of expectations for the instantaneous risk-free rate r_t and the term premium. For simplicity, we focus on decomposing $P_t(\tau)$, the price of a zero-coupon bond at time t that has a single payoff, namely one unit of currency, at maturity $t+\tau$. Under standard assumptions (see Cochrane 2001 and the references therein), this price is given by

$$P_t(\tau) = E_t^P\Big[\frac{M_{t+\tau}}{M_t}\Big],$$

where the stochastic discount factor, M_t, denotes the value at time t_0 of a claim at a future date t, and the superscript P refers to the actual, or real-world, probability measure underlying the dynamics of M_t.

We follow the usual reduced-form empirical finance approach that models bond prices with unobservable (or latent) factors, here denoted as X_t, and the assumption of no residual arbitrage opportunities.[29] We assume that X_t follows an affine Gaussian process with constant volatility and dynamics in continuous time given by the solution to the following stochastic differential equation (SDE):

$$dX_t = K^P(\theta^P - X_t)dt + \Sigma dW_t^P,$$

where K^P is an $n \times n$ mean-reversion matrix, θ^P is a $n \times 1$ vector of mean levels, Σ is an $n \times n$ volatility matrix, and W_t^P is an n-dimensional Brownian motion. The dynamics of the stochastic discount function are given by

$$dM_t = -r_t M_t dt + \Gamma_t' M_t dW_t^P,$$

[28] Mirkov and Sutter (2013) and Söderlind (2010) are among the previous studies to analyze Swiss yields using Gaussian term structure models.

[29] Ultimately, of course, the behavior of the stochastic discount factor is determined by the preferences of the agents in the economy, as in, for example, Rudebusch and Swanson (2011).

and the instantaneous risk-free rate, r_t, is assumed affine in the state variables

$$r_t = \delta_0 + \delta_1 X_t,$$

where $\delta_0 \in \mathbf{R}$ and $\delta_1 \in \mathbf{R}^n$. The risk premiums, Γ_t, are also assumed affine

$$\Gamma_t = \gamma_0 + \gamma_1 X_t,$$

where $\gamma_0 \in \mathbf{R}^n$ and $\gamma_1 \in \mathbf{R}^{n\times n}$.

Duffie and Kan (1996) show that these assumptions imply that zero-coupon yields are also affine in X_t:

$$y_t(\tau) = -\frac{1}{\tau}A(\tau) - \frac{1}{\tau}B(\tau)'X_t,$$

where $A(\tau)$ and $B(\tau)$ are given as solutions to the following system of ordinary differential equations

$$\begin{aligned} \frac{dB(\tau)}{d\tau} &= -\delta_1 - (K^P + \Sigma\gamma_1)'B(\tau), \quad B(0) = 0, \\ \frac{dA(\tau)}{d\tau} &= -\delta_0 + B(\tau)'(K^P\theta^P - \Sigma\gamma_0) + \frac{1}{2}\sum_{j=1}^{n}\left(\Sigma'B(\tau)B(\tau)'\Sigma\right)_{j,j}, \quad A(0) = 0. \end{aligned}$$

Thus, the $A(\tau)$ and $B(\tau)$ functions are calculated *as if* the dynamics of the state variables had a constant drift term equal to $K^P\theta^P - \Sigma\gamma_0$ instead of the actual $K^P\theta^P$ and a mean-reversion matrix equal to $K^P + \Sigma\gamma_1$ as opposed to the actual K^P.[30] The difference is determined by the risk premium Γ_t and reflects investors' aversion to the risks embodied in X_t.

Finally, we define the term premium as

$$TP_t(\tau) = y_t(\tau) - \frac{1}{\tau}\int_t^{t+\tau} E_t^P[r_s]ds. \quad (1)$$

That is, the term premium is the difference in expected returns between a buy-and-hold strategy for a τ-year Treasury bond and an instantaneous rollover strategy based on the risk-free rate r_t.[31]

4.2 The Empirical Affine Model

In order to use the theoretical framework introduced in the previous section to analyze the market reaction to the SNB announcements, we need empirical yield curve models introduced and analyzed in this section.

The specific DTSMs we consider are arbitrage-free Nelson-Siegel (AFNS) representations

[30] The probability measure with these alternative dynamics is frequently referred to as the risk-neutral, or Q, probability measure since the expected return on any asset under this measure is equal to the risk-free rate r_t that a risk-neutral investor would demand.

[31] Note that a Jensen's inequality term has been left out for the rollover strategy in this definition.

that follow Christensen, Diebold, and Rudebusch (2011, henceforth CDR), with three state variables, $X_t = (L_t, S_t, C_t)$. These are characterized by the following system of stochastic differential equations under the risk-neutral Q-measure:[32,33]

$$\begin{pmatrix} dL_t \\ dS_t \\ dC_t \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda & -\lambda \\ 0 & 0 & \lambda \end{pmatrix} \left[\begin{pmatrix} \theta_1^Q \\ \theta_2^Q \\ \theta_3^Q \end{pmatrix} - \begin{pmatrix} L_t \\ S_t \\ C_t \end{pmatrix} \right] dt + \Sigma \begin{pmatrix} dW_t^{L,Q} \\ dW_t^{S,Q} \\ dW_t^{C,Q} \end{pmatrix}, \quad \lambda > 0.$$

In addition, the instantaneous risk-free rate is defined by

$$r_t = L_t + S_t.$$

CDR show that this specification implies that zero-coupon bond yields are given by

$$y_t(\tau) = L_t + \Big(\frac{1 - e^{-\lambda\tau}}{\lambda\tau}\Big) S_t + \Big(\frac{1 - e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\Big) C_t - \frac{A(\tau)}{\tau}, \tag{2}$$

where the factor loadings in the yield function match the level, slope, and curvature loadings introduced in Nelson and Siegel (1987). The final yield-adjustment term, $A(\tau)/\tau$, captures convexity effects due to Jensen's inequality.[34]

The maximally flexible specification of the AFNS model has P-dynamics given by[35]

$$\begin{pmatrix} dL_t \\ dS_t \\ dC_t \end{pmatrix} = \begin{pmatrix} \kappa_{11}^P & \kappa_{12}^P & \kappa_{13}^P \\ \kappa_{21}^P & \kappa_{22}^P & \kappa_{23}^P \\ \kappa_{31}^P & \kappa_{32}^P & \kappa_{33}^P \end{pmatrix} \left[\begin{pmatrix} \theta_1^P \\ \theta_2^P \\ \theta_3^P \end{pmatrix} - \begin{pmatrix} L_t \\ S_t \\ C_t \end{pmatrix} \right] dt + \begin{pmatrix} \sigma_{11} & 0 & 0 \\ \sigma_{21} & \sigma_{22} & 0 \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix} \begin{pmatrix} dW_t^{L,P} \\ dW_t^{S,P} \\ dW_t^{C,P} \end{pmatrix}. \tag{3}$$

The AFNS models are estimated with the standard Kalman filter, where equation (2) is the measurement equation, while equation (3) is the transition equation; see CDR for technical details.

4.3 The Swiss Government Bond Yield Data

In this section, we describe the yield data derived from Swiss Confederation bonds and used in the empirical analysis.

The specific Swiss bond yields analyzed in this paper are zero-coupon yields constructed

[32] As discussed in CDR, with a unit root in the level factor under the pricing measure, the model is not arbitrage-free with an unbounded horizon; therefore, as is often done in theoretical discussions, we impose an arbitrary maximum horizon.

[33] Following CDR, we identify this class of models by fixing the θ^Q means under the Q-measure at zero without loss of generality.

[34] The model is completed with a risk premium specification that connects the factor dynamics to the dynamics under the real-world P-measure. It is important to note that there are no restrictions on the dynamic drift components under the empirical P-measure beyond the requirement of constant volatility. To facilitate empirical implementation, we use the essentially affine risk premium introduced in Duffee (2002).

[35] As noted in CDR, the unconstrained AFNS model has a sign restriction and three parameters less than the standard canonical three-factor Gaussian DTSM.

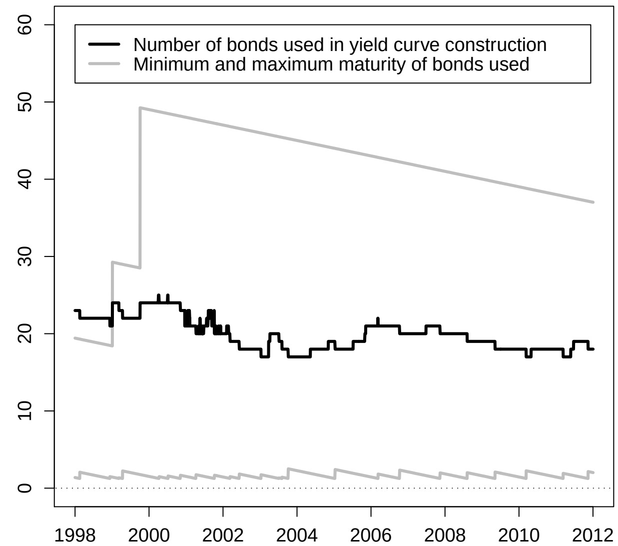


Figure 7: **Statistics for Bonds Used in Yield Curve Construction.**
Illustration of the number of bonds used in the construction of the daily Swiss government zero-coupon bond yield curve as well as their minimum and maximum maturity. The sample covers the period from January 9, 1998, to December 30, 2011.

using a smooth discount function based on the Svensson (1995) yield curve:[36]

$$y(\tau) = \beta_0 + \frac{1 - e^{-\lambda_1 \tau}}{\lambda_1 \tau}\beta_1 + \Big[\frac{1 - e^{-\lambda_1 \tau}}{\lambda_1 \tau} - e^{-\lambda_1 \tau}\Big]\beta_2 + \Big[\frac{1 - e^{-\lambda_2 \tau}}{\lambda_2 \tau} - e^{-\lambda_2 \tau}\Big]\beta_3.$$

For each business day, this function is fitted to price a set of observed Swiss Confederation bond prices. Figure 7 shows the number as well as the shortest and longest maturity of the bonds used in the daily estimation of the discount function over the sample period we analyze. As demonstrated by Gürkaynak, Sack, and Wright (2007), this model fits pools of U.S. Treasury bond prices extremely well. By implication, the zero-coupon yields derived from this approach should constitute a very good approximation to the true underlying Swiss government zero-coupon yield curve over the maturity range covered by the underlying pool of bonds. Using the fitted values of the four coefficients, $(\beta_0(t), \beta_1(t), \beta_2(t), \beta_3(t))$, and the two parameters, $(\lambda_1(t), \lambda_2(t))$, we obtain zero-coupon bond yields with six maturities: one, two, three, five, seven, and ten years to maturity. The summary statistics are provided in Table 2, while Figure 8 illustrates the constructed time series of the one-, two-, five-, and ten-year Swiss government zero-coupon bond yields. First, we note the upward sloping term structure on average. Second, we note that short- and medium-term yields are more volatile than long-

[36]These are computed daily by SNB staff.

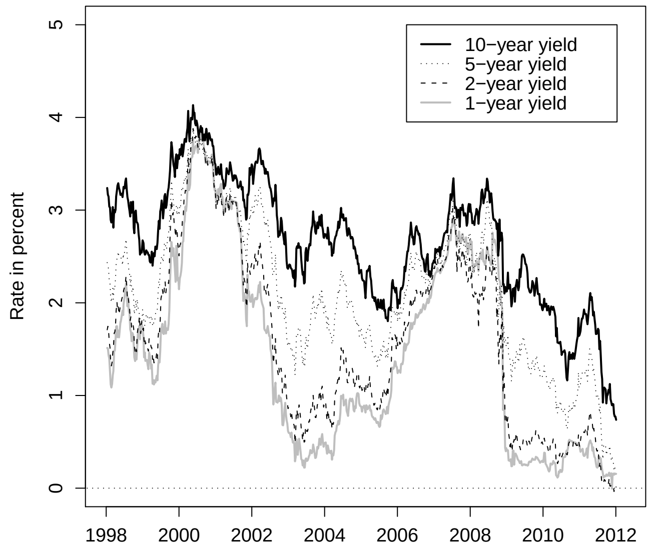


Figure 8: **Time Series of Swiss Government Bond Yields.**
Illustration of the weekly Swiss government zero-coupon bond yields covering the period from January 9, 1998, to December 30, 2011. The yields shown have maturities in one year, two years, five years, and ten years, respectively.

Maturity (months)	Mean (percent)	Std. dev. (percent)	Skewness	Kurtosis
12	1.46	1.03	0.44	2.01
24	1.62	0.96	0.34	2.17
36	1.78	0.90	0.21	2.25
60	2.10	0.79	0.00	2.46
84	2.36	0.72	-0.15	2.68
120	2.65	0.67	-0.33	2.84

Table 2: **Summary Statistics for the Swiss Government Bond Yields.**
Summary statistics for the sample of weekly Swiss government zero-coupon bond yields covering the period from January 9, 1998, to December 30, 2011, a total of 730 observations.

term yields. We emphasize that these are stylized facts shared by both U.S. Treasury and U.K. gilt yield data.

Researchers have typically found that three factors are sufficient to model the time-variation in the cross section of U.S. Treasury bond yields (e.g., Litterman and Scheinkman, 1991). Here, we observe a similar phenomenon for our sample of Swiss government bond yields.[37] Indeed, 99.89 percent of the total variation is accounted for by three factors. Table 3 reports the eigenvectors that correspond to the three first principal components of the

[37]The reported statistical properties are for the weekly sample. Similar properties are obtained for the daily sample used later.

Maturity in months	Loading on		
	First P.C.	Second P.C.	Third P.C.
12	0.49	0.60	-0.60
24	0.47	0.25	0.35
36	0.44	0.01	0.52
60	0.38	-0.26	0.20
84	0.34	-0.42	-0.13
120	0.30	-0.58	-0.44
% explained	95.03	4.37	0.49

Table 3: **Eigenvectors of Principal Components in Swiss Government Bond Yields.** The loadings of yields of various maturities on the three first principal components are shown. The final row shows the proportion of all bond yield variability accounted for by each principal component. The data consist of weekly Swiss government zero-coupon bond yields covering the period from January 9, 1998, to December 30, 2011, a total of 730 observations.

sample. The first principal component accounts for 95.0 perent of the variation in the Swiss government bond yields, and its loading across maturities is uniformly positive. Thus, like a level factor, a shock to this component changes all yields in the same direction irrespective of maturity. The second principal component accounts for 4.4 percent of the variation in these data and has sizable positive loadings for the shorter maturities and sizable negative loadings for the long maturities. Thus, like a slope factor, a shock to this component steepens or flattens the yield curve. Finally, the third component, which accounts for 0.5 percent of the variation, has a hump-shaped factor loading as a function of maturity, which is naturally interpreted as a curvature factor. This motivates our use of the Nelson and Siegel (1987) model with its level, slope, and curvature factors for modeling this sample of Swiss government bond yields, even though we emphasize that our estimated state variables are *not* identical to the principal component factors discussed here.[38]

4.4 Model Selection

Before describing our model selection procedure, we point out up front that we use the pre-crisis part of our sample, that is, the period from January 1998 to January 2008, to find appropriate specifications of the AFNS model framework introduced earlier. This avoids the shocks and noise from the crisis and makes our model validation truly a real-time exercise.

To select the best-fitting specification of the AFNS model's real-world dynamics, we first build on the findings in CDR and limit the Σ volatility matrix to be diagonal. Then, to determine the appropriate specification of the mean-reversion matrix K^P, we use a general-to-specific modeling strategy that restricts the least significant parameter in the estimation to zero and then re-estimates the model. This strategy of eliminating the least significant coefficients is carried out down to the most parsimonious specification, which has a diagonal

[38] A number of recent papers use principal components as state variables, Joslin, Singleton, and Zhu (2011) is an example.

Alternative specifications	Goodness-of-fit statistics				
	$\log L$	k	p-value	AIC	BIC
(1) Unrestricted K^P	19,463.57	22	n.a.	-38,883.14	-38,789.47
(2) $\kappa^P_{12} = 0$	19,462.82	25	0.2207	**-38,883.64**	-38,794.23
(3) $\kappa^P_{12} = \kappa^P_{23} = 0$	19,461.25	24	0.0764	-38,882.50	-38,797.35
(4) $\kappa^P_{12} = \kappa^P_{23} = \kappa^P_{21} = 0$	19,460.20	23	0.1473	-38,882.40	-38,801.50
(5) $\kappa^P_{12} = \ldots = \kappa^P_{32} = 0$	19,458.57	22	0.0710	-38,881.14	-38,804.50
(6) $\kappa^P_{12} = \ldots = \kappa^P_{13} = 0$	19,456.32	21	0.0339	-38,878.64	**-38,806.26**
(7) $\kappa^P_{12} = \ldots = \kappa^P_{31} = 0$	19,450.41	20	0.0006	-38,868.82	-38,800.70

Table 4: **Evaluation of Alternative Specifications of the AFNS Model.**
There are seven alternative estimated specifications of the AFNS model of Swiss government bond yields with the unrestricted 3-by-3 K^P matrix being the most flexible. Each specification is listed with its maximum log likelihood value ($\log L$), number of parameters (k), the p-value from a likelihood ratio test of the hypothesis that it differs from the specification above with one more free parameter, and the information criteria (AIC and BIC). The sample is weekly from January 9, 1998, to January 4, 2008, a total of 522 observations.

K^P matrix. The final specification choice is based on the values of the Akaike and Bayes information criteria as per Christensen et al. (2010, 2014) and CR.[39] The summary statistics of the model selection process are reported in Table 4. The Akaike information criterion is minimized by specification (2), while the Bayes information criterion is minimized by specification (6), that is, the preferred specifications of the mean-reversion matrix K^P are given by

$$K^P_{AIC} = \begin{pmatrix} \kappa^P_{11} & 0 & \kappa^P_{13} \\ \kappa^P_{21} & \kappa^P_{22} & \kappa^P_{23} \\ \kappa^P_{31} & \kappa^P_{32} & \kappa^P_{33} \end{pmatrix} \quad \text{and} \quad K^P_{BIC} = \begin{pmatrix} \kappa^P_{11} & 0 & 0 \\ 0 & \kappa^P_{22} & 0 \\ \kappa^P_{31} & 0 & \kappa^P_{33} \end{pmatrix}.$$

Due to the lack of any established benchmark model for Swiss government bond yields, we choose to compare the selected AFNS models to relevant alternative AFNS models. Specifically, we include the unconstrained AFNS model in equation (3), which is the AFNS model closest to the canonical $A_0(3)$ model of Dai and Singleton (2000), as well as the most parsimonious independent-factor AFNS model favored by CDR. Also, we consider the AFNS model with diagonal Σ volatility matrix, but unrestricted K^P mean-reversion matrix, which is the starting point for our model selection procedure, in addition to the specification favored by CR for U.S. data with the K^P matrix given by[40]

$$K^P_{CR} = \begin{pmatrix} \kappa^P_{11} & 0 & 0 \\ \kappa^P_{21} & \kappa^P_{22} & \kappa^P_{23} \\ 0 & 0 & \kappa^P_{33} \end{pmatrix}.$$

[39]See Harvey (1989) for further details.

[40]This model nests the AFNS specification CR favored for U.K. gilt yields, which has the additional restriction $\kappa^P_{21} = 0$. For this reason we do not include that model in the analysis.

Forecasting method	Six-month forecast		One-year forecast		Two-year forecast	
	Mean	RMSE	Mean	RMSE	Mean	RMSE
Random walk	33.55	79.33	62.37	113.65	71.26	123.57
Unconstrained AFNS model	-1.54	60.86	44.62	73.67	80.63	93.56
Unrestricted K^P AFNS model	22.28	63.40	72.80	85.43	110.27	116.27
Indep.-factor AFNS model	11.80	60.18	51.96	72.89	78.46	90.14
CR AFNS model	29.35	67.88	80.94	93.03	118.82	124.77
Preferred AIC AFNS model	21.60	62.83	71.48	83.23	107.97	113.27
Preferred BIC AFNS model	13.82	61.00	54.31	73.97	80.22	91.15

Table 5: **Summary Statistics for Policy Target Rate Forecast Errors.**
Summary statistics of the forecast errors—mean and root mean-squared errors (RMSEs)—of the three-month CHF LIBOR one and two years ahead. The forecasts are weekly starting on January 4, 2008, and running until December 30, 2011, a total of 209 forecasts for all three forecast horizons. All measurements are expressed in basis points.

4.5 Model Fit and Forecast Performance

In this section, we first use our AFNS models to forecast the three-month CHF LIBOR, which is the rate targeted by the SNB in its conventional monetary policy. The goal is to find a final favored specification of the AFNS model class for Swiss yields. Second, we describe the preferred model's fit and other empirical characteristics.

To begin, we use the specific AFNS models identified in the previous section to forecast the three-month CHF LIBOR six months, one year, and two years ahead on a weekly basis over the period from January 4, 2008, until December 30, 2010.[41] As the three-month CHF LIBOR has been the target policy rate of the SNB since 1998, this exercise can shed light on the ability of the various AFNS models to deliver reasonable policy expectations—a prerequisite for a model to deliver reliable term premium estimates given the conditional expectation in the definition of the term premium (see equation (1)). The summary statistics for the forecast errors relative to the subsequent realizations of the three-month CHF LIBOR are reported in Table 5, which also contains the forecast errors obtained using a random walk assumption. We note the strong forecast performance of the preferred AFNS model according to the BIC. In the remainder of the paper, we will refer to this specification as the preferred AFNS model.[42]

Figure 9 compares the forecasts at the one-year horizon from the preferred AFNS model to the corresponding mean from the Consensus Forecasts survey and to the subsequent realizations of the three-month CHF LIBOR. Since late 2008 the model has generated one-year-ahead short rate forecasts that have systematically been a bit above the subsequent realizations. This suggests that bond investors never anticipated the period of the zero inter-

[41] The model output used in the forecast exercise is the model-implied three-month yield.

[42] Unreported results for Diebold and Mariano (1995) tests of forecast accuracy show that the preferred AFNS model's short rate forecasts are statistically significantly more accurate than the random walk at all three forecast horizons. However, among the AFNS models, the preferred model's performance is not, in general, statistically superior to that of the other models.

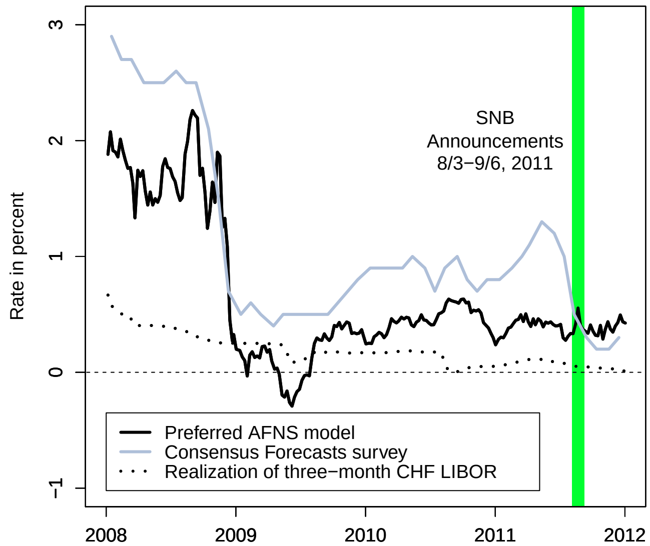


Figure 9: **Forecasts of the Three-Month CHF LIBOR.**
Illustration of the forecasts of the three-month CHF LIBOR one year ahead from the preferred AFNS model. For comparison the mean one-year-ahead forecast from the Consensus Forecasts survey is also shown. Subsequent realizations of the three-month CHF LIBOR are included, so at date t, the figure shows forecasts as of time t and the realization from t plus one year. The model forecast data and the realizations are weekly covering the period from January 4, 2008, to December 30, 2011, while the Consensus Forecast survey is monthly covering the period from January 14, 2008, to December 31, 2011.

est rate policy to be as long as it turned out to be.[43] This is also consistent with the evidence from the Consensus Forecasts survey of professional forecasters.

Table 6 reports the estimated parameters for the preferred AFNS model. We note the usual pattern from applications of AFNS models to U.S. data, namely that the level factor is the most persistent factor and has the lowest volatility, while the curvature factor is the least persistent and most volatile factor. As in studies of U.S. yields, the slope factor has dynamic qualities in between the two other factors in terms of persistence and volatility. Furthermore, the estimated mean parameters in θ^P accord well with the estimated paths of the three state variables. In particular, the negative values for θ_2^P and θ_3^P are consistent with the average negative values of the slope and curvature factors needed to generate the typically upward sloping yield curve.

As for the fit of the preferred AFNS model, Table 7 contains the summary statistics for

[43]In unreported results, we analyze whether this outcome could be caused by finite-sample bias in the estimation of the model's mean-reversion P-dynamics, i.e., the K^P matrix. Specifically, we followed the approach described in CR of imposing a near-unit-root property on the AFNS level factor. However, we did not obtain better forecast performance for any of the specifications studied. As a consequence, we proceed without any adjustments to the original model estimates.

K^P	$K^P_{\cdot,1}$	$K^P_{\cdot,2}$	$K^P_{\cdot,3}$	θ^P		Σ
$K^P_{1,\cdot}$	0.2140	0	0	0.0461	$\Sigma_{1,1}$	0.0048
	(0.1717)			(0.0075)		(0.0003)
$K^P_{2,\cdot}$	0	0.2922	0	-0.0301	$\Sigma_{2,2}$	0.0093
		(0.2793)		(0.0125)		(0.0003)
$K^P_{3,\cdot}$	3.6067	0	2.1144	-0.0186	$\Sigma_{3,3}$	0.0194
	(1.1275)		(0.4898)	(0.0118)		(0.0007)

Table 6: **Parameter Estimates of the Preferred AFNS Model.**
The estimated parameters of the K^P matrix, the θ^P vector, and the Σ matrix for the AFNS model preferred according to BIC. The associated estimated λ is 0.2726 (0.0045) with maturity measured in years. Estimated standard deviations of the parameter estimates are given in parentheses. The maximum log likelihood value is 19,456.32.

Maturity	Preferred AFNS model		
in months	Mean	RMSE	$\widehat{\sigma}_\varepsilon(\tau_i)$
12	-4.78	13.51	13.64
24	-0.12	1.20	1.96
36	0.55	2.04	2.29
60	0.06	0.60	0.92
84	-0.39	1.14	1.44
120	0.00	0.00	2.24

Table 7: **Summary Statistics for the Fitted Errors.**
The mean and root mean squared error of the fitted errors of the Swiss government bond yields across six different maturities are shown. Also reported are the estimated measurement error standard deviations for each maturity. All numbers are measured in basis points. The data are weekly covering the period from January 9, 1998, to January 4, 2008.

its fitted yield errors. We note that it delivers a very good fit as indicated by the low root mean-squared fitted errors (RMSE), and its fit is almost without bias, on average, as the mean errors are very close to zero across the entire maturity range.

In terms of the parameter restrictions imposed on the K^P mean-reversion matrix in the preferred AFNS model, we can test their significance relative to the corresponding AFNS model with an unrestricted K^P matrix using standard likelihood ratio tests. As shown in Figure 10, the parameter restrictions have been statistically insignificant for most sample cutoff dates. Thus, our preferred AFNS model is flexible enough to capture the relevant information in the data throughout this period. The figure also shows the LR tests of the parameter restrictions in the more parsimonious independent-factor AFNS model, which appears to be too tightly parameterized as its parameter restrictions are never supported by the data at conventional significance levels independent of the sample cutoff date.

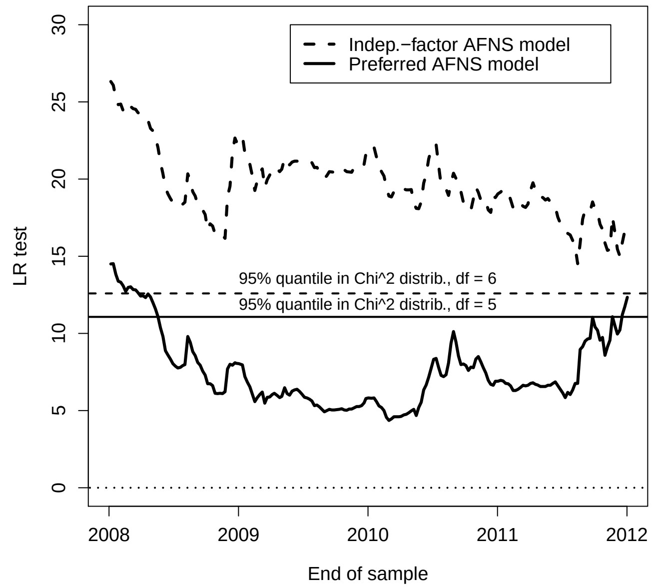


Figure 10: **Likelihood Ratio Tests of Parameter Restrictions in AFNS Models.** Illustration of the value of likelihood ratio tests of the restrictions imposed in the independent-factor and preferred AFNS models relative to the AFNS model with unrestricted K^P matrix and diagonal Σ matrix. The analysis covers weekly re-estimations from January 4, 2008, to December 30, 2011, a total of 209 observations, while the full data set used in the estimation covers the period from January 9, 1998, to December 30, 2011.

5 Event Analysis

In this section, we use the estimates of expected future short-term interest rates and term premiums from the empirical term structure models to assess the different channels of transmission of the SNB announcements onto Swiss long-term yields.

5.1 Responses of Swiss Long-Term Yields to the SNB Policy Announcements

As already touched on earlier, we use a two-day window as the baseline for the event study. This is a rather broad window, but it is necessary given that the yield data we investigate is collected in the morning around the time that the announcements were made. By looking at the change between the morning of the day before the announcement and the morning on the day after the announcement, we allow enough time—a minimum of 24 hours, but no more than 26 hours after the announcement—for market participants to factor new information into prices. A two-day window is in line with the recommendations of the literature. Specifically, Joyce and Tong (2012) study windows for event studies of the impact on long-term yields of QE programs in the U.K. and conclude a two-day window is optimal. Moreover, results

Event		Maturity					
		1-year	2-year	3-year	5-year	7-year	10-year
I	Aug. 2, 2011	30	17	24	65	100	133
	Aug. 4, 2011	26	12	20	61	98	131
	Change	**-4**	**-5**	**-5**	**-4**	**-3**	**-2**
II	Aug. 9, 2011	26	13	14	47	83	119
	Aug. 11, 2011	21	8	10	43	79	114
	Change	**-5**	**-5**	**-5**	**-4**	**-4**	**-6**
III	Aug. 16, 2011	19	8	13	49	84	119
	Aug. 18, 2011	18	8	7	32	64	99
	Change	**0**	**0**	**-6**	**-17**	**-21**	**-20**
Total net change		**-9**	**-10**	**-15**	**-25**	**-28**	**-28**

Table 8: **Two-Day Response of Swiss Government Bond Yields on SNB Announcement Dates.**
The table reports the two-day response of the six Swiss government bond yields used in model estimation around the SNB announcement dates. All numbers are measured in basis points.

reported in Appendix A show that for all three announcements, the one-day responses are rather small. This suggests that most of the information was either received or digested after the recording of the bond prices used in the construction of the yield data. A broad event window comes at the risk of including some non-event related news. However, this could be less problematic in the current context than, say, in the U.S. and U.K. analysis of CR because macroeconomic news releases are less frequent in Switzerland.

Though widely used for lack of better alternatives, event studies represent an imperfect technique for assessing the impact of a policy on market rates. These imperfections should be kept in mind when interpreting the findings. First, we have no clear measures of what was expected before each announcement, so, following CR, we have to assume that the entire announcement was a complete surprise. Given the discussions in Sections 2 and 3 of expectations around the time of the announcements, this assumption is likely to result in some degree of underestimation of the interest rate response, as market participants may have anticipated some action. Also, a two-day event window may be too short to capture all of the announcements' effects—again, perhaps biasing the estimated size of these effects downward. On the other hand, short event windows may capture an exaggerated initial market response that is unwound over time as market makers and investors adjust. Finally, other news may have been released during the event window that significantly affected interest rates and obscured the effects we are trying to assess. Although we believe that a majority of the interest rate movements we examine reflected new information from the announcements, at the very least our results provide a benchmark to compare with alternative ways of extracting market reactions.

Table 8 shows the two-day response of the Swiss government bond yields to the announcements. As noted in Section 3, there is a clear negative yield response, on net, to the

Event	Model	Decomposition from models			Ten-year yield
		Avg. target rate next ten years	Ten-year term premium	Residual	
I Aug. 3, 2011	Unconstrained AFNS	-5	2	1	**-2**
	Unrestricted K^P AFNS	-2	-1	1	
	Indep.-factor AFNS	-3	-1	1	
	Preferred AFNS	**-2**	**-1**	**1**	
II Aug. 10, 2011	Unconstrained AFNS	-3	-2	-1	**-6**
	Unrestricted K^P AFNS	0	-4	-1	
	Indep.-factor AFNS	1	-5	-1	
	Preferred AFNS	**1**	**-5**	**-1**	
III Aug. 17, 2011	Unconstrained AFNS	0	-20	0	**-20**
	Unrestricted K^P AFNS	4	-23	-2	
	Indep.-factor AFNS	-1	-17	-2	
	Preferred AFNS	**0**	**-19**	**-2**	
Total net change	Unconstrained AFNS	-8	-19	0	**-28**
	Unrestricted K^P AFNS	2	-28	-2	
	Indep.-factor AFNS	-3	-23	-2	
	Preferred AFNS	**-1**	**-25**	**-2**	

Table 9: **Decomposition of Two-Day Responses of Ten-Year Yield.**
The decomposition of two-day responses of the ten-year Swiss government bond yield on three SNB announcement dates into changes in (i) the average expected target rate over the next ten years, (ii) the ten-year term premium, and (iii) the unexplained residual based on empirical AFNS models of Swiss government bond yields. All changes are measured in basis points.

announcements with long-term yields declining about twice as much as their shorter-term counterparts. Figure 11 shows the result of the decomposition of ten-year Swiss government bond yields since 2008. Over the period from August 1, 2011, to the date of the introduction of the exchange rate floor on September 6, 2011, the observed ten-year government bond yield declined 35 basis points. According to our preferred AFNS model, policy expectations as reflected in the estimated average expected short rate over the next ten years only declined 4 basis points, while the ten-year term premium account for 31 of the 35 basis point yield decline, or 89 percent. However, the key question is to what extent the announced reserve expansions by the SNB are the driver of these yield changes. This would be more likely if these changes in yields take place in immediate response to the announcements.

To get at that question, we use the AFNS models, now estimated at daily frequency, to decompose the response of the Swiss government bond yields to the SNB announcements into three components:

(i). the response of the estimated average expected short rate until maturity;

(ii). the response of the term premium defined as the difference between the model fitted yield and the average expected short rate; and

(iii). a residual that reflects variation not accounted for by the model.

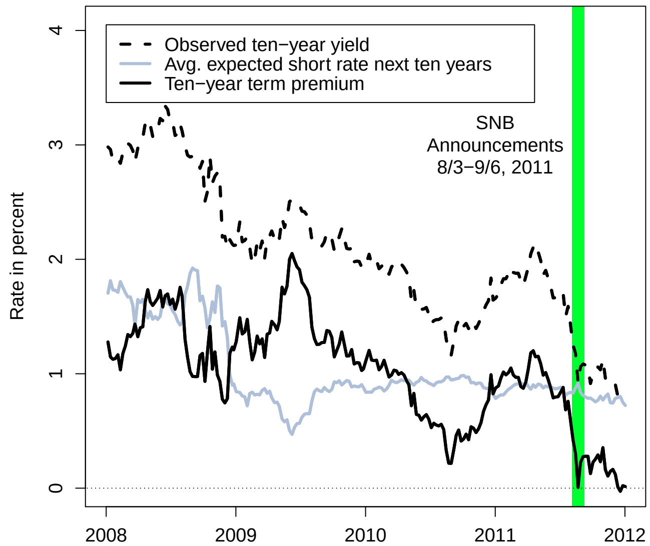


Figure 11: **Decomposition of Ten-Year Yield.**
Illustration of the decomposition of the variation of the ten-year Swiss government bond yield into (i) estimated average expected short rate until maturity forecasted and (ii) the term premium defined as the difference between the observed government bond yield and the average expected short rate based on the preferred AFNS model of Swiss government bond yields.

Table 9 contains the results of decomposing the two-day ten-year yield responses based on our empirical AFNS models.[44] Despite the differences in statistical fit and forecast performance documented earlier, the models agree on what drove yield changes on announcement dates. Three of the four models, including our preferred specification, indicate that policy expectations were only revised marginally lower in response to the announcements, so that most of the yield declines are associated with declines in term premiums. In support of the model results, we also note that all four models indicate that short rate expectations declined around the first announcement on August 3, 2011, when the target range for the three-month CHR LIBOR was lowered from an upper bound of 75 basis points to an upper bound of 25 basis points. Importantly, this is the main evidence of any notable signaling effect that we detect in our analysis.

Still, changes in the term premium could reflect factors other than portfolio balance effects. In particular, term premium changes could also result from changes in risk perceptions, safe haven demand, market liquidity or changes in foreign term premiums. We address this next.

[44]The one-day response decompositions are reported Appendix A.

5.2 Analysis of the Term Premium Change

We argue in this section that while other factors could have contributed to pushing term premiums lower in the wake of the SNB's announcements of reserve expansions, the reserve expansions remain the most likely direct driver of these declines.

The SNB announcements of reserve expansions in August 2011 came at a time of substantial market upheaval, high volatility, and flights to safety. Could the SNB announcements *per se* have resulted in heightened risk perceptions, simply because they were so unusual and dramatic? If so, this might have triggered two effects that could have affected the term premium on Swiss government bonds. First, a higher perceived future risk attached to the macroeconomic outlook would have pushed the term premium up. If anything, the presence of such effects would imply that the portfolio balance effect has been even larger than suggested by the estimated decline in the term premium.

Conversely, higher risk perceptions could have increased the flight to safety from risky assets and into Swiss Confederation bonds. This would have shown up as a fall in the term premium on such bonds through the portfolio balance effect of the increase in demand. We cannot control for such a possibility as the term premium contains all portfolio balance effects and does not allow us to discriminate between their different sources. Stock market implicit volatilities, which usually are a good measure of risk aversion in the markets, did increase in the days following the final reserve expansion announcement in particular. However, they did not increase abnormally, and based on historical correlations that cannot account for the strong drop in yields on those days. Moreover, strong safe-haven pressures in Switzerland tend to be accompanied by a strengthening of the Swiss franc. But the exchange rate either remained unchanged or slightly depreciated in the two-day windows around the three announcements.

5.2.1 Controlling for Foreign Developments

Another possibility, as already discussed earlier, is that foreign developments drove the drops in the term premium. The Swiss fixed-income markets can be significantly affected by foreign developments, in particular from the U.S. and the euro area, and we need to adjust the results reported so far for any effects arising from those channels before we can make any final assessment about the effects of the SNB's unconventional policies on Swiss yields.

In pursuing that objective, we make the simplifying assumption that the Swiss policy actions had a minimal, if any, effect on foreign market activity. This allows us to treat the yield changes abroad, and decompositions thereof, as purely exogenous variables. Furthermore, for simplicity, we limit our focus to the U.S. and euro-area government bond markets, widely regarded as the two most liquid fixed-income markets in the world.

For the United States, instead of using the estimated ten-year term premium generated by CR's preferred U.S. Treasury model, we choose to rely on its shadow-rate model equivalent analyzed in Christensen and Rudebusch (2013).[45] As explained in Christensen and Rudebusch (2013), the shadow-rate modeling approach allows us to preserve the Gaussian factor dynamics, while we obtain bond yields that respect the zero lower bound. The authors document that this aspect matters for modeling U.S. Treasury yields in the most recent period.[46]

Without an established benchmark term premium model for the euro area, we went through a model selection analysis similar to the one described for the Swiss yields using German government bond yields,[47] which we consider representative for the euro area over the period of interest. This work led us to a preferred AFNS model for German yields with P-dynamics given by[48]

$$\begin{pmatrix} dL_t \\ dS_t \\ dC_t \end{pmatrix} = \begin{pmatrix} 10^{-7} & 0 & 0 \\ 0 & \kappa_{22}^P & \kappa_{23}^P \\ 0 & 0 & \kappa_{33}^P \end{pmatrix} \left[\begin{pmatrix} 0 \\ \theta_2^P \\ \theta_3^P \end{pmatrix} - \begin{pmatrix} L_t \\ S_t \\ C_t \end{pmatrix} \right] dt + \begin{pmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{pmatrix} \begin{pmatrix} dW_t^{L,P} \\ dW_t^{S,P} \\ dW_t^{C,P} \end{pmatrix}.$$

This specification is identical to the AFNS specification CR preferred for their analysis of U.K. gilt yield responses to the Bank of England's QE programs.

Figure 12 shows the ten-year term premium from our preferred AFNS model for Swiss yields and compares it to the estimates of the foreign term premiums.

Now, to establish the dynamic relationship between these various term premium estimates, we focus on the period from January 3, 2008, to June 30, 2011, that is before the SNB announcements. As reported in Table 10, the correlation between both the Swiss and euro-area ten-year term premium and the Swiss and U.S. ten-year term premium was -10.9 percent over this period. Using five-year term premiums gives similar results. Thus, in general, the connection between Swiss and foreign term premiums appears to be relatively weak.

5.2.2 Controlling for Market Liquidity

Since economic theory suggests that part of the term premium could be a premium investors require for assuming the liquidity risk of Swiss Confederation bonds, we want to control for liquidity effects in our analysis.

To capture variation in the liquidity of the Swiss Confederation bond market, we use the average bid-ask spread of all available Confederation bonds weighted by the outstanding notional of each bond.[49] Figure 13(a) shows the weighted average bid-ask spread of Swiss

[45] As Christensen and Rudebusch (2013) only consider weekly data, we estimate the shadow-rate model on the updated sample of daily Treasury yields used in CR.

[46] It is not obvious that we would want to enforce a lower yield bound for either the Swiss or the German bond yields also analyzed, mainly because in both of these samples yields have actually been well below zero for intermediate maturities for extended periods in recent years. Hence, in these cases, a standard Gaussian modeling approach appears to be fully warranted.

[47] The data are publicly available on the website of the German Bundesbank.

[48] The results leading to this conclusion are available from the authors upon request.

[49] The data are based on SNB staff's own calculations.

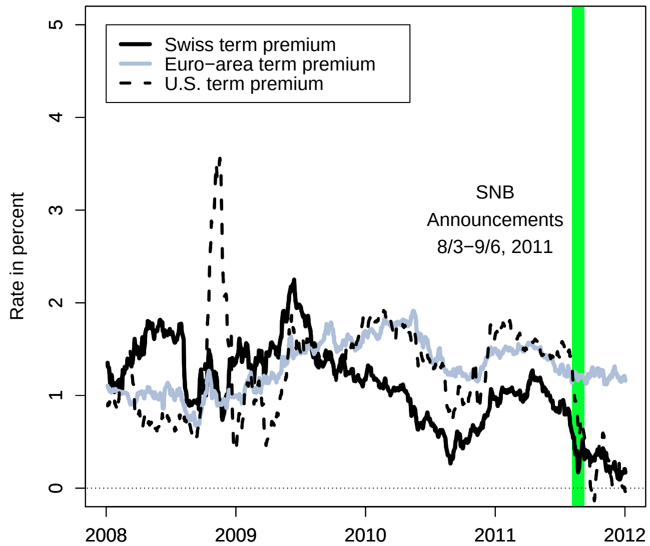


Figure 12: **Swiss and Foreign Ten-Year Term Premiums.**
Illustration of ten-year Swiss, U.S., and euro-area term premiums. The source of each is detailed in the main text. The data cover the period from January 3, 2008, to December 30, 2011.

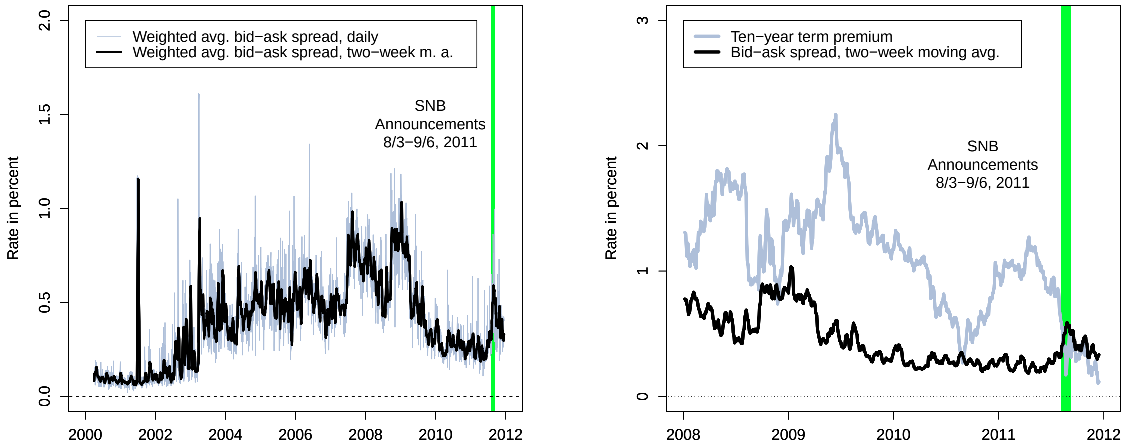
Correlation	Five-year term premiums		
	Swiss	Euro	U.S.
Swiss	1	0.039	-0.134
Euro		1	0.404
U.S.			1

Correlation	Ten-year term premiums		
	Swiss	Euro	U.S.
Swiss	1	-0.109	-0.109
Euro		1	0.447
U.S.			1

Table 10: **Pairwise Correlations of Term Premiums.**
The table contains the pairwise correlations between the estimated five- and ten-year term premiums from the Swiss, U.S., and euro-area models described in the main text. The sample is daily from January 3, 2008, to June 30, 2011, a total of 854 observations.

confederation bonds from April 3, 2000, to December 12, 2011.[50] Since the raw daily series is very volatile, we also show the smoothed two-week moving average that we use in the subsequent regression analysis. Figure 13(b) compares the bid-ask spread to the ten-year Swiss term premium estimate from our preferred model. For the period from January 4, 2008, to August 5, 2011, that is, up until the last day before the first SNB announcement,

[50]This was the sample made available to us.



(a) Bid-ask spread since April 2000.

(b) Bid-ask spread and term premium.

Figure 13: **Bid-Ask Spread and Ten-Year Term Premium.**
Panel (a) shows the daily weighted average bid-ask spread in the Swiss Confederation bond market over the period from April 3, 2000, to December 12, 2011. Also shown is the smoothed two-week moving average. The data is based on SNB staff's own calculations. Panel (b) compares the smoothed two-week moving average of the bid-ask spread series to the daily Swiss term premium estimate from our preferred model for the period where both are available. In both panels, the period containing the four SNB unconventional policy announcements is indicated with a green bar. Source: SNB.

the correlation between the term premium and the smoothed bid-ask spread was 43.3%. This is indication of a positive connection between the two series. Thus, both on economic and statistical grounds, we want to control for the impact of this measure of market liquidity on our conclusions.

5.2.3 Regression Analysis

To quantify the dynamic relationship between the Swiss term premiums and the controlling measures described in the previous sections, we run simple ordinary least squares regressions. The results are reported in Table 11. Overall, the R^2s are somewhat low, but all coefficients are statistically significant. Furthermore, there is a difference in the dynamic interaction with the foreign risk premiums. Increases in U.S. term premiums tend to put downward pressure on Swiss term premiums. By contrast, Swiss and euro-area term premiums tend to move in the same direction, possibly due to the geographical proximity and the close economic ties between Switzerland and the core euro-area countries. Finally, the coefficients of the bid-ask spread that serves as a proxy for market liquidity has the expected positive sign, which indicates that Swiss term premiums tend to go up when market liquidity deteriorates and bid-ask spreads increase.

Next, we want to use the estimated statistical relationships to control for outside effects

Coef.	Swiss term premium	
	Five-year	Ten-year
β_0	-0.0033***	-0.0016
	(-5.032)	(-1.612)
β_{Euro}	0.9909***	0.7275***
	(15.04)	(11.80)
$\beta_{U.S.}$	-0.3328***	-0.1842***
	(-10.17)	(-7.315)
$\beta_{bid-ask}$	1.2644***	1.3846***
	(19.08)	(18.64)
Adj. R^2	0.3172	0.2992

Table 11: **Regressions of Swiss Term Premiums on Foreign Term Premiums.** The table shows the results of regressing five- and ten-year Swiss term premiums from the preferred AFNS model on the matching term premiums from the euro area and the U.S. described in the main text in addition to the smoothed measure of bid-ask spreads in the Confederation bond market. The sample is daily from January 3, 2008, to June 30, 2011, a total of 854 observations. T-statistics are reported in parentheses. * means significant at the 5 percent level, ** means significant at the 1 percent level, while *** means significant at the 0.1 percent level.

Event	Model	Decomposition from models			Ten-year yield
		Avg. target rate next ten years	Ten-year term premium	Residual	
I Aug. 3, 2011	Euro-area model	1	5	-4	2
	U.S. model	4	-16	-3	-15
II Aug. 10, 2011	Euro-area model	-7	0	1	-6
	U.S. model	7	-4	14	16
III Aug. 17, 2011	Euro-area model	-9	-3	-4	-15
	U.S. model	6	-17	-7	-18
Total net change	Euro-area model	-15	3	-6	-19
	U.S. model	16	-37	4	-16

Table 12: **Decomposition of Two-Day Responses of Foreign Ten-Year Yields.** The decomposition of two-day responses of ten-year foreign government bond yields on three SNB announcement dates into changes in (i) the average expected target rate over the next ten years, (ii) the ten-year term premium, and (iii) the unexplained residual based on empirical DTSMs as described in the main text. All changes are measured in basis points.

before we make a final conclusion. To that end, Table 12 summarizes the decompositions of the two-day responses of foreign ten-year government bond yields around the time of the three SNB announcements. Based on the statistical relationship reported in Table 11, the adjustment for the foreign two-day net response is $0.7275 \cdot 2.76 - 0.1842 \cdot (-36.68) + 1.3846 \cdot 11.09 = 24.12$ basis points, of which 8.76 basis points arise from changes in foreign term premiums and 15.36 basis points derive from the spike in bid-ask spreads. This suggests that the effect from the controlling factors would actually have pushed up the Swiss ten-year term premium around the SNB announcements. For robustness, we repeat the analysis using one-day responses instead. This produces an adjustment of $0.7275 \cdot 5.54 - 0.1842 \cdot (-17.76) +$

$1.3846 \cdot 4.33 = 13.30$ basis points with a fairly even split of 7.30 basis points from the foreign developments and 6.00 basis points from the deterioration in Swiss bond market liquidity. Thus, the conclusion remains that foreign and market liquidity influences have tended to offset some of the declines in the Swiss term premiums that we estimate.[51] Overall, this gives us confidence in our results in that it suggests that, if anything, we are likely to underestimate the term premium effects of the SNB policy announcements.

6 Conclusion

In the rapidly growing literature on the effects of QE on financial markets, two channels have received the most attention, the signaling channel and the portfolio balance effect of changes in the market supply of the purchased assets. In this paper, we emphasize that another source of portfolio balance effects may be important, notably the potential portfolio reallocation effect arising from the mere expansion of excess reserves that is a defining part of any QE program.

To obtain evidence on the latter channel, we study the unconventional monetary policy initiatives undertaken by the SNB in the late summer of 2011 to counter the negative spillover effects from the intensifying European sovereign debt crisis. The design of the SNB's policy response provides a unique data set that could shed light on the question at hand. In particular, in contrast to the QE programs conducted in the United States and the United Kingdom, the policy response of the SNB included an unprecedented expansion of excess reserves within a very short period of time *without* any outright purchases of domestic long-term securities.

To understand the transmission through which the expansion of reserves had an impact, we employ standard event study techniques and the estimation of dynamic term structure models for Swiss Confederation bond yields to analyze the market reaction around the days the SNB announced these policy initiatives. The modeling approach allows us to decompose the observed yield changes into a component that represents expectations for future short rates, that is, a monetary policy expectations component, and an associated risk or term premium component. We find that 70 percent or more (depending on the model specification) of the drop in yields in response to the SNB announcements reflect declines in term premiums. Only the first announcement on August 3, 2011, which included a lowering of the upper bound for the three-month CHF LIBOR, is associated with any notable signaling effect. These findings are robust across model specifications. Also, we obtain similar results when we focus on five-year yields. Furthermore, when we control for the variation in foreign term premiums at the time of the SNB announcements, the results suggest that, if anything, we are underestimating the term premium effects of the announcements.

To summarize, we provide evidence suggesting that the Swiss expansions of reserves in

[51] In Appendix B, we repeat this analysis for the five-year maturity and obtain very similar results.

August 2011 reduced long-term interest rates through portfolio balance effects, even though no long-term debt securities were bought as part of these initiatives. We conclude that the expansion of reserves themselves, and perhaps to a lesser extent, the resulting reduced supply of SNB bills and repo collateral, had portfolio balance effects on long-term interest rates. To our knowledge, this paper is the first to document that part of the transmission channel of QE programs onto long-term interest rates may derive from a portfolio balance effect through the expansion of reserves.

In comparing our results to those reported elsewhere for the U.K. and U.S. QE programs, we find stronger similarities with the U.K. experience regarding the relative importance of signaling versus portfolio balance effects. The difference between the U.K. and Swiss experiences on one side and the U.S. experience on the other could be linked to the fact that neither the U.K. QE program nor the SNB announcements studied here were accompanied by any type of forward guidance that could have implications for bond investors' expectations about future monetary policy, unlike the U.S. program. This would suggest that the effect of central bank unconventional policies may depend crucially on central bank communication policies, as also emphasized by Christensen and Rudebusch (2012). Furthermore, the structure of financial markets likely matter for the magnitude of the portfolio balance effects of reserve expansions. In that regard, the Swiss Confederation bond market is much less deep and liquid than the enormous market for U.S. Treasury securities, and for that reason it might be easier to detect such effects in the Swiss context. Finally, the size and pace of implementation are likely to matter, and the SNB program was truly unique in both respects. This complicates comparisons to other QE programs as well as any assessment of the probable effects of winding down QE programs, which inevitably reduces the amount of outstanding reserves. Thus, more research is needed to better understand the financial market impact of changes in central bank reserves.

Event		Maturity					
		1-year	2-year	3-year	5-year	7-year	10-year
I	Aug. 2, 2011	30	17	24	65	100	133
	Aug. 3, 2011	28	12	20	63	99	132
	Change	**-2**	**-4**	**-4**	**-2**	**-1**	**-1**
II	Aug. 9, 2011	26	13	14	47	83	119
	Aug. 10, 2011	21	4	10	50	88	122
	Change	**-5**	**-9**	**-5**	**3**	**4**	**3**
III	Aug. 16, 2011	19	8	13	49	84	119
	Aug. 17, 2011	17	7	12	48	82	115
	Change	**-1**	**-1**	**0**	**-1**	**-2**	**-4**
Total net change		**-9**	**-14**	**-9**	**0**	**1**	**-3**

Table 13: **One-Day Response of Swiss Government Bond Yields on SNB Announcement Dates.**
The table reports the one-day response of the six Swiss government bond yields used in model estimation around three SNB announcement dates. All numbers are measured in basis points.

Event	Model	Decomposition from models			Ten-year yield
		Avg. target rate next ten years	Ten-year term premium	Residual	
I Aug. 3, 2011	Unconstrained AFNS	-4	2	0	**-1**
	Unrestricted K^P AFNS	-2	0	1	
	Indep.-factor AFNS	-2	1	1	
	Preferred AFNS	**-2**	**0**	**1**	
II Aug. 10, 2011	Unconstrained AFNS	-2	5	0	**3**
	Unrestricted K^P AFNS	-2	5	0	
	Indep.-factor AFNS	0	3	0	
	Preferred AFNS	**-1**	**4**	**0**	
III Aug. 17, 2011	Unconstrained AFNS	1	-5	-1	**-4**
	Unrestricted K^P AFNS	0	-3	-2	
	Indep.-factor AFNS	-2	0	-2	
	Preferred AFNS	**-1**	**-1**	**-2**	
Total net change	Unconstrained AFNS	-4	2	-1	**-3**
	Unrestricted K^P AFNS	-4	2	-2	
	Indep.-factor AFNS	-4	3	-2	
	Preferred AFNS	**-4**	**2**	**-2**	

Table 14: **Decomposition of One-Day Responses of Ten-Year Yield.**
The decomposition of one-day responses of the ten-year Swiss government bond yield on three SNB announcement dates into changes in (i) the average expected target rate over the next ten years, (ii) the ten-year term premium, and (iii) the unexplained residual based on empirical DTSMs of Swiss government bond yields. All changes are measured in basis points.

Appendix A: Decomposition of One-Day Yield Responses

In this appendix, we provide the decomposition of the one-day responses based on our empirical models of Swiss government bond yields. Table 13 contains the one-day changes in the six bond yields used in model estimation, while Table 14 reports the results from the model decompositions of the one-day response of the ten-year yield around the SNB announcements.

Event	Model	Decomposition from models			Five-year yield
		Avg. target rate next five years	Five-year term premium	Residual	
I Aug. 3, 2011	Unconstrained AFNS	-5	2	0	**-2**
	Unrestricted K^P AFNS	-2	0	0	
	Indep.-factor AFNS	-3	1	0	
	Preferred AFNS	**-2**	**0**	**0**	
II Aug. 10, 2011	Unconstrained AFNS	-2	5	0	**3**
	Unrestricted K^P AFNS	-2	5	0	
	Indep.-factor AFNS	-1	4	0	
	Preferred AFNS	**-1**	**4**	**0**	
III Aug. 17, 2011	Unconstrained AFNS	2	-3	0	**-1**
	Unrestricted K^P AFNS	0	-1	0	
	Indep.-factor AFNS	-2	1	0	
	Preferred AFNS	**-2**	**1**	**0**	
Total net change	Unconstrained AFNS	-5	5	0	**0**
	Unrestricted K^P AFNS	-5	4	0	
	Indep.-factor AFNS	-6	6	0	
	Preferred AFNS	**-5**	**5**	**0**	

Table 15: **Decomposition of One-Day Responses of Five-Year Yield.**
The decomposition of one-day responses of the five-year Swiss government bond yield on three SNB announcement dates into changes in (i) the average expected target rate over the next five years, (ii) the five-year term premium, and (iii) the unexplained residual based on empirical DTSMs of Swiss government bond yields. All changes are measured in basis points.

Appendix B: Decomposition of Five-Year Yield Responses

In this appendix, we provide the decomposition of the one- and two-day responses of the five-year Swiss government bond yield based on our empirical models of the Swiss government bond yield curve. Table 15 contains the decompositions of the one-day changes, while Table 16 reports the results from the model decompositions of the two-day changes. Furthermore, Table 17 summarizes the decompositions of the two-day responses of foreign five-year government bond yields around the time of the three SNB announcements.

Based on the regression results reported in Table 11, the adjustment at the five-year maturity for the two-day net response of the foreign term premiums and the market liquidity measure is $0.9909 \cdot 1.97 - 0.3328 \cdot (-21.11) + 1.2644 \cdot 11.09 = 23.00$ basis points with 8.98 basis points derived from changes in foreign term premiums, while 14.02 basis points is associated with the spike in bid-ask spreads in the Swiss Confederation bond market. Thus, the conclusion remains that the effect from foreign term premiums and the deterioration in market liquidity would actually have pushed up the Swiss five-year term premium around the SNB announcements. For robustness, we repeat the analysis using one-day responses instead. This produces an adjustment of $0.9909 \cdot 5.45 - 0.3328 \cdot (-10.76) + 1.2644 \cdot 4.33 = 14.46$ basis points with 8.98 basis points associated with foreign developments, while 5.47 basis points derive from the weakening in Swiss bond market liquidity conditions. Thus, the conclusion remains the same, namely that accounting for spillovers from foreign term premiums and market liquidity measures would actually push in the direction of observing smaller term premium declines, if not outright term premium increases.

Event	Model	Decomposition from models			Five-year yield
		Avg. target rate next five years	Five-year term premium	Residual	
I Aug. 3, 2011	Unconstrained AFNS	-6	2	0	**-4**
	Unrestricted K^P AFNS	-3	-1	0	
	Indep.-factor AFNS	-3	0	0	
	Preferred AFNS	**-3**	**-1**	**0**	
II Aug. 10, 2011	Unconstrained AFNS	-4	0	0	**-4**
	Unrestricted K^P AFNS	0	-4	0	
	Indep.-factor AFNS	1	-5	0	
	Preferred AFNS	**1**	**-5**	**0**	
III Aug. 17, 2011	Unconstrained AFNS	-1	-16	0	**-17**
	Unrestricted K^P AFNS	5	-22	0	
	Indep.-factor AFNS	0	-17	0	
	Preferred AFNS	**1**	**-18**	**0**	
Total net change	Unconstrained AFNS	-10	-14	0	**-25**
	Unrestricted K^P AFNS	2	-27	0	
	Indep.-factor AFNS	-2	-23	0	
	Preferred AFNS	**-1**	**-24**	**0**	

Table 16: **Decomposition of Two-Day Responses of Five-Year Yield.**
The decomposition of two-day responses of the five-year Swiss government bond yield on three SNB announcement dates into changes in (i) the average expected target rate over the next five years, (ii) the five-year term premium, and (iii) the unexplained residual based on empirical DTSMs of Swiss government bond yields. All changes are measured in basis points.

Event	Model	Decomposition from models			Five-year yield
		Avg. target rate next five years	Five-year term premium	Residual	
I Aug. 3, 2011	Euro-area model	1	6	1	7
	U.S. model	3	-10	-1	-7
II Aug. 10, 2011	Euro-area model	-9	0	0	-9
	U.S. model	7	-2	7	11
III Aug. 17, 2011	Euro-area model	-9	-3	0	-12
	U.S. model	5	-9	-2	-6
Total net change	Euro-area model	-17	2	1	-14
	U.S. model	15	-21	4	-2

Table 17: **Decomposition of Two-Day Responses of Foreign Five-Year Yields.**
The decomposition of two-day responses of five-year foreign government bond yields on three SNB announcement dates into changes in (i) the average expected target rate over the next five years, (ii) the five-year term premium, and (iii) the unexplained residual based on empirical DTSMs as described in the main text. All changes are measured in basis points.

Appendix C: Analytical Formulas for Policy Expectations and Term Premiums in the Preferred AFNS Model

In this appendix, we derive the analytical formulas for policy expectations and term premiums within the preferred AFNS model of Swiss Confederation yields.

For a start, we note that the term premium is defined as

$$TP_t(\tau) = y_t(\tau) - \frac{1}{\tau}\int_t^{t+\tau} E_t^P[r_s]ds.$$

In the preferred AFNS model, as in any AFNS model, the instantaneous short rate is defined as

$$r_t = L_t + S_t,$$

while the specification of the P-dynamics is given by

$$\begin{pmatrix} dL_t \\ dS_t \\ dC_t \end{pmatrix} = \begin{pmatrix} \kappa_{11}^P & 0 & 0 \\ 0 & \kappa_{22}^P & 0 \\ \kappa_{31}^P & 0 & \kappa_{33}^P \end{pmatrix} \left[\begin{pmatrix} \theta_1^P \\ \theta_2^P \\ \theta_3^P \end{pmatrix} - \begin{pmatrix} L_t \\ S_t \\ C_t \end{pmatrix} \right] dt + \begin{pmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{pmatrix} \begin{pmatrix} dW_t^{L,P} \\ dW_t^{S,P} \\ dW_t^{C,P} \end{pmatrix}.$$

Thus, the mean-reversion matrix is given by

$$K^P = \begin{pmatrix} \kappa_{11}^P & 0 & 0 \\ 0 & \kappa_{22}^P & 0 \\ \kappa_{31}^P & 0 & \kappa_{33}^P \end{pmatrix}.$$

Its matrix exponential can be calculated analytically and is given by

$$\exp(-K^P\tau) = \begin{pmatrix} e^{-\kappa_{11}^P\tau} & 0 & 0 \\ 0 & e^{-\kappa_{22}^P\tau} & 0 \\ -\kappa_{31}^P \frac{e^{-\kappa_{11}^P\tau} - e^{-\kappa_{33}^P\tau}}{\kappa_{33}^P - \kappa_{11}^P} & 0 & e^{-\kappa_{33}^P\tau} \end{pmatrix}.$$

Thus, the conditional mean of the state variables is

$$\begin{aligned} E_t^P[X_{t+\tau}] &= \theta^P + \begin{pmatrix} e^{-\kappa_{11}^P\tau} & 0 & 0 \\ 0 & e^{-\kappa_{22}^P\tau} & 0 \\ -\kappa_{31}^P \frac{e^{-\kappa_{11}^P\tau} - e^{-\kappa_{33}^P\tau}}{\kappa_{33}^P - \kappa_{11}^P} & 0 & e^{-\kappa_{33}^P\tau} \end{pmatrix} \begin{pmatrix} L_t - \theta_1^P \\ S_t - \theta_2^P \\ C_t - \theta_3^P \end{pmatrix} \\ &= \begin{pmatrix} \theta_1^P + e^{-\kappa_{11}^P\tau}(L_t - \theta_1^P) \\ \theta_2^P + e^{-\kappa_{22}^P\tau}(S_t - \theta_2^P) \\ \theta_3^P - \kappa_{31}^P \frac{e^{-\kappa_{11}^P\tau} - e^{-\kappa_{33}^P\tau}}{\kappa_{33}^P - \kappa_{11}^P}(L_t - \theta_1^P) + e^{-\kappa_{33}^P\tau}(C_t - \theta_3^P) \end{pmatrix}. \end{aligned}$$

In order to get back to the term premium formula, we note that the conditional expectation of the instantaneous short rate process is:

$$\begin{aligned} E_t^P[r_s] &= E_t^P[L_s + S_s] \\ &= \theta_1^P + e^{-\kappa_{11}^P(s-t)}(L_t - \theta_1^P) + \theta_2^P + e^{-\kappa_{22}^P(s-t)}(S_t - \theta_2^P). \end{aligned}$$

Now, we integrate the expected short rate over the time interval from t to $t+\tau$ as in the definition of the term premium:

$$\begin{aligned} \int_t^{t+\tau} E_t^P[r_s]ds &= \int_t^{t+\tau} \Big(\theta_1^P + e^{-\kappa_{11}^P(s-t)}(L_t - \theta_1^P) + \theta_2^P + e^{-\kappa_{22}^P(s-t)}(S_t - \theta_2^P) \Big) ds \\ &= (\theta_1^P + \theta_2^P)\tau + (L_t - \theta_1^P) \int_t^{t+\tau} e^{-\kappa_{11}^P(s-t)} ds + (S_t - \theta_2^P) \int_t^{t+\tau} e^{-\kappa_{22}^P(s-t)} ds \\ &= (\theta_1^P + \theta_2^P)\tau + (L_t - \theta_1^P) \Big[\frac{-1}{\kappa_{11}^P} e^{-\kappa_{11}^P(s-t)} \Big]_t^{t+\tau} + (S_t - \theta_2^P) \Big[\frac{-1}{\kappa_{22}^P} e^{-\kappa_{22}^P(s-t)} \Big]_t^{t+\tau} \\ &= (\theta_1^P + \theta_2^P)\tau + (L_t - \theta_1^P) \frac{1 - e^{-\kappa_{11}^P\tau}}{\kappa_{11}^P} + (S_t - \theta_2^P) \frac{1 - e^{-\kappa_{22}^P\tau}}{\kappa_{22}^P}. \end{aligned}$$

The relevant term to go into the term premium formula is the average expected short rate

$$\frac{1}{\tau} \int_t^{t+\tau} E_t^P[r_s]ds = \theta_1^P + \theta_2^P + (L_t - \theta_1^P) \frac{1 - e^{-\kappa_{11}^P\tau}}{\kappa_{11}^P\tau} + (S_t - \theta_2^P) \frac{1 - e^{-\kappa_{22}^P\tau}}{\kappa_{22}^P\tau}.$$

The final expression for the term premium is then given by

$$
\begin{aligned}
TP_t(\tau) &= y_t(\tau) - \frac{1}{\tau}\int_t^{t+\tau} E_t^P[r_s]ds \\
&= L_t + \frac{1-e^{-\lambda\tau}}{\lambda\tau}S_t + \Big(\frac{1-e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\Big)C_t - \frac{A(\tau)}{\tau} \\
&\quad -\theta_1^P - \theta_2^P - (L_t - \theta_1^P)\frac{1-e^{-\kappa_{11}^P\tau}}{\kappa_{11}^P\tau} - (S_t - \theta_2^P)\frac{1-e^{-\kappa_{22}^P\tau}}{\kappa_{22}^P\tau} \\
&= \Big(1 - \frac{1-e^{-\kappa_{11}^P\tau}}{\kappa_{11}^P\tau}\Big)L_t + \Big(\frac{1-e^{-\lambda\tau}}{\lambda\tau} - \frac{1-e^{-\kappa_{22}^P\tau}}{\kappa_{22}^P\tau}\Big)S_t + \Big(\frac{1-e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\Big)C_t \\
&\quad -\Big(1 - \frac{1-e^{-\kappa_{11}^P\tau}}{\kappa_{11}^P\tau}\Big)\theta_1^P - \Big(1 - \frac{1-e^{-\kappa_{22}^P\tau}}{\kappa_{22}^P\tau}\Big)\theta_2^P - \frac{A(\tau)}{\tau}.
\end{aligned}
$$

We now provide the formulas for the decomposition of forward rates in the preferred AFNS model. In AFNS models, in general, the instantaneous forward rate is given by

$$
f_t(\tau) = L_t + e^{-\lambda\tau}S_t + \lambda\tau e^{-\lambda\tau}C_t + A^f(\tau), \tag{4}
$$

where the yield-adjustment term in the instantaneous forward rate function is:

$$
\begin{aligned}
A^f(\tau) &= -\frac{\partial A(\tau)}{\partial\tau} \\
&= -\frac{1}{2}\sigma_{11}^2\tau^2 - \frac{1}{2}(\sigma_{21}^2 + \sigma_{22}^2)\Big(\frac{1-e^{-\lambda\tau}}{\lambda}\Big)^2 \\
&\quad -\frac{1}{2}(\sigma_{31}^2 + \sigma_{32}^2 + \sigma_{33}^2)\Big[\frac{1}{\lambda^2} - \frac{2}{\lambda^2}e^{-\lambda\tau} - \frac{2}{\lambda}\tau e^{-\lambda\tau} + \frac{1}{\lambda^2}e^{-2\lambda\tau} + \frac{2}{\lambda}\tau e^{-2\lambda\tau} + \tau^2 e^{-2\lambda\tau}\Big] \\
&\quad -\sigma_{11}\sigma_{21}\tau\frac{1-e^{-\lambda\tau}}{\lambda} - \sigma_{11}\sigma_{31}\Big[\frac{1}{\lambda}\tau - \frac{1}{\lambda}\tau e^{-\lambda\tau} - \tau^2 e^{-\lambda\tau}\Big] \\
&\quad -(\sigma_{21}\sigma_{31} + \sigma_{22}\sigma_{32})\Big[\frac{1}{\lambda^2} - \frac{2}{\lambda^2}e^{-\lambda\tau} - \frac{1}{\lambda}\tau e^{-\lambda\tau} + \frac{1}{\lambda^2}e^{-2\lambda\tau} + \frac{1}{\lambda}\tau e^{-2\lambda\tau}\Big].
\end{aligned}
$$

The instantaneous forward rate term premium in the preferred AFNS model is then given by

$$
\begin{aligned}
TP_t^f(\tau) &= f_t(\tau) - E_t^P[r_{t+\tau}] \\
&= L_t + e^{-\lambda\tau}S_t + \lambda\tau e^{-\lambda\tau}C_t + A^f(\tau) - \Big(\theta_1^P + e^{-\kappa_{11}^P\tau}(L_t - \theta_1^P) + \theta_2^P + e^{-\kappa_{22}^P\tau}(S_t - \theta_2^P)\Big) \\
&= \Big(1 - e^{-\kappa_{11}^P\tau}\Big)L_t + \Big(e^{-\lambda\tau} - e^{-\kappa_{22}^P\tau}\Big)S_t + \lambda\tau e^{-\lambda\tau}C_t + A^f(\tau) - \Big(1 - e^{-\kappa_{11}^P\tau}\Big)\theta_1 - \Big(1 - e^{-\kappa_{22}^P\tau}\Big)\theta_2.
\end{aligned}
$$

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