International Channels of the Fed's Unconventional Monetary Policy*

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Abstract

Previous research has established that the Federal Reserve large scale asset purchases (LSAPs) have had significant effects on international bond yields. This paper analyzes the channels through which these effects were transmitted. We use dynamic term structure models to decompose yield changes into changes in term premia and expected short rates. The LSAP effects appear to occur mainly through the portfolio balance channel for Japan. In contrast, plausible term structure models imply that the signaling channel also plays a major role in effects on Canadian, Australian, German and American yields. Our results are consistent with the existence of strong signals from U.S. conventional and unconventional policies to yields of Canada, Australia and Germany.

Keywords: monetary policy, zero lower bound, QE, LSAP, signaling, portfolio balance, no arbitrage

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1 Introduction

In response to the extreme credit market disturbances in the fall of 2008, the Federal Reserve both lowered the Federal Funds target to zero and also announced unprecedented bond purchases. The first two purchase announcements, in November 2008 and March 2009, would total $1.725 trillion. These actions were similar to those taken by other central banks, such as the Bank of Japan, the Bank of England and the European Central Bank.

Several groups of researchers have studied various aspects of these asset purchase programs. The event study estimates of Gagnon et al. (2011) and Joyce et al. (2011) establish that the U.S. and U.K. bond market purchase programs had large effects on their respective domestic bond yields. Neely (2010) finds that the U.S. bond purchases had large effects on international bond and foreign exchange markets.

All of the above studies consider domestic effects of financial crisis programs. In addition to influencing U.S. yields, the LSAP could affect international asset prices through either the signaling or portfolio balance (PB) channel. The signaling channel implies that the asset purchases could lead international investors to lower their forecasts for international growth and therefore lead them to expect that central banks would keep interest rates lower than previously expected. On the other hand, the portfolio balance channel implies that a purchase of U.S. assets would tend to push down the real yields on those bonds and the real yields in U.S. goods of other sovereign bonds of similar duration, until a new equilibrium was reached.

A major issue is determining through which channels—liquidity/market functioning (for non-government bonds), signaling or portfolio balance—these asset purchases have effects. The term structure estimates of Gagnon et al. (2011) argue for a large portfolio balance effect, and consider the signaling effects small and negligible. Bauer and Rudebusch (2011) and Christensen and Rudebusch (2012), however, claim a larger role for the signaling channel. They argue that likely half or more of the total impact of the Fed's LSAP announcements is due to the signaling channel.

Neely (2010) argues that the LSAP effects on international yields are consistent with a portfolio balance effect but does not directly evaluate the relative importance of signaling/portfolio balance effects. There has been no serious analysis of the channels by which the asset purchases affect international bond yields. This paper aims to fill that gap by using term structure models to evaluate the relative importance of the signaling/portfolio balance channels in mediating the impact of U.S. asset purchases on international bond yields. As with all of the previous literature, we will consider the QE 1 episode because of the difficulty in isolating changes in market expectations in later episodes.

For each country, we estimate six alternative term structure models that vary in their implied persistence for interest rates. The models fit the data nearly equally well, making it difficult to clearly prefer one over the others. Two models–the UR and EV models—imply very substantial signaling effects for Germany, Australia and Canada. The BC model also implies substantial signaling effects for Canadian yield changes. Strong signaling effects for Germany, Australia and Canada are consistent with the fact that their yield structures have historically reacted strongly to U.S. monetary policy shocks. We prefer the bias-corrected model because this has been shown to accurately recover term premia (Bauer et al., 2012). The results from this model suggest that beyond the U.S., signaling effects have been significant particularly in Canada, in line with the close ties between conventional monetary policy in these two countries.

2 Event study of the Fed's first LSAP program

We apply the widely used event study approach to assess and analyze the impact of the first LSAP program–2008-2009–on yields in the U.S., the U.K., Canada, Japan, Germany, and Australia. FOMC statements and speeches described the motives for these asset purchases in several ways but repeatedly returned to the themes of directly supporting credit markets—especially for housing—to increase the availability and affordability of credit with the ultimate goal of stimulating real activity. That is, the intermediate goal was to reduce medium- and long-term U.S. interest rates.

The LSAP program have consisted of suggestions of possible future purchases, firm statements of planned purchases, including time-frames and quantities, and announcements of purchase slowdowns and a cutback. Because efficient markets should react to news about future asset values, not to expected transactions, the effects of such purchases should occur when market expectations of such purchases change, typically at the purchase announcement.

We have chosen to study the effect of the first rounds of LSAP announcements (2008-2009) on international yield curves because we can more easily isolate the changes in expectations to FOMC announcements and speeches for this first LSAP program.[footnote: Fawley and Neely (2012) describe the circumstances of and motivations for the quantitative easing programs of the Federal Reserve, Bank of England, European Central Bank and Bank of Japan. Fawley, Brett and Christopher J. Neely, Four Stories of Quantitative Easing, unpublished manuscript, FRB St. Louis, June 2012.] Later LSAP programs, such as "QE II," which was announced in November 2010, were partly anticipated before the actual purchase announcement. This partial anticipation makes it hard to evaluate the effect of the actual event. Furthermore, the first LSAP program had by far the largest effects on interest rates.

What events influenced LSAP expectations? Examination of press releases, FOMC member speeches, FOMC statements, and news reports confirms Gagnon et al.'s (2011) assessment that 8 events/announcements associated with the LSAP program had potentially important information: 5 of those events discussed purchases or suggested future purchases; 3 discussed slowing and/or limiting purchases. Table 1 describes the time and information content of those 8 events.

The FOMC announced purchases or suggested possible future purchases 5 times: On November 25, 2008, the Federal Reserve announced purchases of up to $100 billion of GSE debt and up to $500 billion in MBS in response to widening GSE debt spreads and housing-credit market turmoil. On December 1, 2008, Chairman Bernanke cited the limited ability of conventional monetary policy to further influence financial conditions—the Federal funds target was one percent—and mentioned possible purchases of "longer-term Treasury or agency securities on the open market in substantial quantities." The December 16, 2008, FOMC press release said that the Federal Reserve was evaluating the possibility of buying long-term Treasury debt. In addition, the FOMC added the following caveat about the funds rate: "[T]he Committee anticipates that weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time." The January 28th FOMC statement reiterated that the Fed stood ready to buy additional agency and Treasury debt if such actions would help credit market conditions. This failure to actually announce purchases disappointed markets, but the FOMC soon announced such specific plans on March 18, 2009: "The Committee decided today to increase the size of the Federal Reserve's balance sheet further by purchasing up to an additional $750 billion of agency mortgage-backed securities, bringing its total purchases of these securities to up to $1.25 trillion this year, and to increase its purchases of agency debt this year by up to $100 billion to a total of up to $200 billion. Moreover, to improve credit market conditions, the Committee decided to purchase up to $300 billion of longer-term Treasury securities over the next six months." Finally, the caveat about the funds rate was changed to "The Committee anticipates that economic conditions are likely to warrant exceptionally low levels of the federal funds rate for an extended period."

Three announcements caused the public to expect slower or reduced purchases: On August 12, 2009, the FOMC statement announced that the Treasury purchases would be finished by the end of October, rather than September 18, as originally announced.[1] On September 23, 2009, the FOMC statement said that agency debt and MBS purchases would be slowed and finished by the end of 2010Q1, rather than the end of 2009. On November 4, 2009, the FOMC reduced the planned purchase of agency debt from $200 billion to $175 billion.

[1]The August 12, 2009 announcement contained elements that might have increased market purchase expectations. Specifically, the announcement made clear that the full $300 billion in Treasuries would be purchased.

Gagnon et al. (2011) describe the program in some detail, estimating that the $1.725 trillion dollar total debt purchase was 22 percent of the publically held, long-term agency debt, fixed-rate agency MBS, and Treasury securities outstanding as of November 24, 2008, just prior to the first LSAP announcement. This calculation excludes U.S. corporate debt but properly takes a fairly comprehensive view of substitutes for U.S. Treasury debt. Gagnon et al. (2011) report that the Federal Reserve Bank of New York purchased securities across the yield curve, with maturities from 3 months to 30 years, but bought Treasuries most heavily in the 4- to 10-year range, newly issued MBS with 30 year maturities and generally "underpriced" issues. The rate of purchase was fairly steady, but increased (decreased) when liquidity was good (poor).

3 The signaling and portfolio balance channels

Central bank asset purchases can potentially affect asset prices through signaling and portfolio balance (PB) channels, as well as through liquidity and credit risk channels. For non-Treasury securities, the first round of the Fed's LSAPs likely temporarily improved prices by improving the liquidity and market functioning, relieving market stress by providing a consistent source of demand (Gagnon et al., 2011). For corporate bonds, changes in default and credit risk premia probably produced some of the price effects(Krishnamurthy and Vissing-Jorgensen, 2011). For Treasury securities, a market where liquidity is extraordinarily high and credit risk basically absent, we can safely focus on the two major channels through which LSAPs could have affected government bond yields—signaling and portfolio balance.

The signaling channel recognizes that the announcement or execution of an LSAP program by a central bank can affect long-term interest rates by signaling that the policy rate will be lower for longer than previously expected—perhaps due to weaker growth forecasts or a central bank commitment to deviate from usual policy—then the average expected future policy rate will decline and this will reduce the long-term interest rate as borrowers substitute away from long term borrowing to a series of short-term loans.

Portfolio balance effects are theoretically motivated by acknowledging imperfect substitutability between securities of different maturities (as in preferred-habitat models) or between different asset classes. Such market segmentation arguments imply that the total amount and the maturity structure of government securities outstanding affect risk premia in long-term interest rates. If the central bank purchases a quantity of certain types of risk (i.e., duration) investors will demand less compensation to hold the remaining amount of that type of risk and the term premia component of nominal yields will fall.[2] Neely (2010) extends this standard argument to international bond returns.

3.1 Distinguishing the channels

In distinguishing the signaling and PB channels, it is useful to define the n-year yield on a government bond as the sum of expected average overnight rates and the term premium on that bond:

$$y_t^n = n^{-1} \sum_{i=0}^{n-1} E_t r_{t+i} + YTP_t^n = \tilde{y}_t^n + YTP_t^n, \tag{1}$$

where y_t^n is the yield at time t on an n-period bond, r_t is the short-term interest rate (i.e., the policy rate), $\tilde{y}_t^n$ is the average expected overnight rate over the subsequent n periods (also called the "risk-neutral rate"), and YTP_t^n is the yield term premium, which compensates investors in long-term bonds for holding duration risk.

Researchers often identify signaling channel effects with changes in expected overnight rates and the PB channel with changes in the term premia. Bauer and Rudebusch (2011) caution against this simplification, however. A purchase that produces a successful PB effect might also affect expected future overnight rates through its effect on expected growth. Therefore,

[2] In addition to this "duration removal" version of the PB channel, which closely relates to the preferred-habitat model of Vayanos and Vila (2009) and requires the existence of deep-pocketed arbitrageurs that equalize expected returns, some researchers have distinguished additional versions of the portfolio balance channel in which market segmentation goes further. D'Amico et al. (2011) cite a "scarcity" channel, and Bauer and Rudebusch (2011) discuss a "market segmentation" channel.

they suggest that estimated changes in expected future policy rates constitute a lower bound for the importance of the signaling channel's effects.

What has the literature said about the relative importance of signaling and PB effects in international asset purchases? For the U.S., Gagnon et al. (2011) use the Kim-Wright term structure model, swap rates and changes in short bond rates to argue that PB channel effects produced the great majority of the yield changes. Similarly, Joyce et al. (2011) cite swap rates to argue that U.K. bond purchases were also effective through the PB channel. Some other estimates in the literature do not allow for the possibility of signaling effects but consider the extent to which a PB effect can explain the yield changes due to LSAPs in a term structure model(Hamilton and Wu, 2012). However, Bauer and Rudebusch (2011) and Christensen and Rudebusch (2012) claim an important role for the signaling channel for the Fed's LSAPs, plausibly accounting for about 50% of the total impact of LSAPs on long-term Treasury yields. For the LSAPs in the U.K., Christensen and Rudebusch (2012) confirm the importance of the PB channel in explaining the effects on domestic government yields. Neely (2010) documents large effects of the LSAP announcements on international yields. The extent to which signaling and portfolio balance effects can explain these large effects on international yields remains an important open question.

3.2 Signaling predictions

Federal Reserve asset purchase announcements might signal a lower future path of the policy rate for two reasons. First, such announcements can convey to the public that the central bank forecasts weaker inflation and/or slower real growth than the consensus. For a given policy rule, this would then imply lower future policy rates. Second, such announcements could suggest that the central bank will pursue an easier stance of the policy rate for given macroeconomic conditions than what markets previously had anticipated. This could mean either changing the policy rule, or temporarily deviating from normal policy by keeping short-term rates unusually low for a long time.[3]

During the recent period of unconventional monetary policy, the FOMC has to some extent directly signaled its intended future path for the federal funds rate. It has, for example, used four variations of the "extended period" language to hold down expectations of policy rate hikes, eventually being quite explicit and predicting that it would not raise the policy rate until at least late 2014. Two of those FOMC extended period announcements were coincident with the LSAP announcements discussed in this paper:

- December 16, 2008: "In particular, the Committee anticipates that weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time."
- March 18, 2009: "The Committee [...] anticipates that economic conditions are likely to warrant exceptionally low levels of the federal funds rate for an extended period."

Beyond this type of direct signaling, the LSAP announcements themselves can produce signaling effects if the Fed's intention to pursue such unconventional monetary policy itself conveys more downbeat macro forecasts and/or an easier desired stance of policy than was previously anticipated. The unprecedented LSAP announcements might signal a greater willingness to act on the part of Federal Reserve, implying that the economic environment might be more dire and such extraordinary stimulus warranted.

Here we are interested in how the Fed's LSAP announcements lowered international yields. Why might a announcements about a U.S. asset purchase program provide information about the future monetary policy of a foreign central bank? In practice, changes in central bank policy rates tend to be correlated internationally, especially for countries with close economic ties. Central banks tend to respond similarly to common global shocks, e.g., international

[3] A strategy that promises to deviate from normal policy is what Eggertson (2006) refers to as "committing to be irresponsible." Campell et al. (2012) attempt to disentangle FOMC forward guidance into these two categories, which they term Delphic and Odyssean guidance, respectively.

commodity price shocks, and similar business conditions. Further, central banks that desire stable exchange rates might follow another country's monetary policy to avoid swings in the exchange rate. Hence, policy rates in the U.S. and abroad tend to move together. The closeness of the relationship between policy rates across countries naturally varies depending on various country-specific and country-pair-specific factors. Specficially, smaller countries are more likely to take external factors into account when making monetary policy because conditions in large countries, like the United States, affect conditions in smaller trading partners more than the reverse. Therefore, the Federal Reserve has frequently been a first-mover in international interest rate movements, and US monetary policy has influenced monetary policy in other countries to some degree.

Because of the nature of the signaling channel, we predict the foreign signaling effects of U.S. LSAP announcements to be larger for those countries that have historically shown a close relationship with U.S. interest rate policy. To assess this relationship, we regress changes in foreign interest rates on measures of U.S. monetary policy surprises. Since Kuttner (2001), U.S. monetary policy surprises have typically been measured with scaled rate changes of the nearest federal funds futures contract on FOMC meeting dates. Gürkaynak et al. (2005) extend this one-dimensional measure to recognize that the FOMC statement often surprised markets about the intended future path of policy without a surprise about the current target. They construct a "target" and a "path" surprise by rotating the first two principle components of changes in money market rates around FOMC announcements, such that the target factor corresponds to the surprise change in the near-term fed funds futures contract, and the path factor represents the change in near-term interest rates that are uncorrelated with the target surprise. The paper shows that U.S. monetary policy surprises strongly affect long-term yields. Hausman and Wongswan (2011), use a modestly different procedure for constructing target and path surprises to show that U.S. monetary policy surprises also affect foreign yields.[4]

[4]Hausman and Wongswan (2011) identify the target surprise with the standard fed funds target surprise and use the orthogonalized component of 12-month out eurodollar futures contracts to represent the path surprise. They report that orthogonalized and non-orthogonalized path surprises produce very similar results.

To determine the extent to which one might expect U.S. monetary policy shocks to influence foreign interest rates, we further investigate the effects of such shocks on foreign interest rates using the procedure of Gürkaynak et al. (2005) for constructing target and path surprises.[5] In constructing U.S. shocks and foriegn yield changes, we used Tickwrite data on Eurodollar futures prices, Wall Street Journal daily prices for Fed Funds futures contracts through Haver and Bloomberg's FMCs (Fair-Market yield Curves) daily zero-coupon bond yields from actively traded bonds, starting in January 1995 to June 2012. Gürkaynak et al. (2005) publish the timing of FOMC press releases for meetings from January 1994 to April 1999, and Rosa (2012) provides the timing for meetings between May 1999 and June 2011. Our sample consists of 139 policy announcements from February 2, 1995 to March 15, 2011.

Table 2 shows the results from regressing one-day interest rate changes around FOMC days on the path and target surprises associated with the FOMC statement. The path surprises have statistically significant, positive effects on almost all foreign yields, with the exception of three-month UK and Japanese yields. Similarly, target surprises significantly raise Australian, Canadian and German 3-month and 2-year yields. The international effects of U.S. monetary policy are strongest—based on high t-statistics and R^2— on Canadian yields. The effects are weakest for Japan, which has had very low and fairly stable short term interest rates since 1995.

3.3 Portfolio balance predictions

Neely (2010) motivates the study of portfolio balance effects with a mean-variance investor who represents all non-US government/central bank demand for international bonds. The investor chooses an N-vector of portfolio weights at time t (w_t) to maximize the utility function

$$w_t' E r_{t,t+1} - 0.5\gamma w_t' V w_t$$

[5] We obtain similar results with the procedure of Hausman and Wongswan (2011).

where $Er_{t,t+1}$ is the N-vector of expected real returns from period t to $t+1$, V is the $N \times N$ covariance matrix of the asset returns and γ is the investor's coefficient of relative risk aversion. Neely (2010) shows that announcement-time changes in expected real asset returns ($\Delta_t Er_{t,t+1}$) depend on the size of the asset purchases and the covariance between the real returns to U.S. and foreign bonds (V_{1j}):

$$\Delta_t Er_{t,t+1} = -n\gamma 0.22 w_{1,t} V_{1j}, \tag{2}$$

where n denotes the maturity of the bonds, V_{1j} is the $1,j$ element of V, $w_{1,t}$ is the element of w_t that denotes the prior weight on U.S. bonds. Equation (2) uses the estimate of Gagnon et al. (2011) that the 1.725 trillion dollar total debt purchase of the first round of LSAPs was 22 percent of the publicly held, long-term agency debt, fixed-rate agency MBS, and Treasury securities outstanding as of November 24, 2008, just prior to the first LSAP announcement. Thus, the portfolio balance channel's effects on foreign long bonds returns will depend on the covariance between those returns and the returns on US bonds. For more details please refer to Neely (2010).

Which international long bond returns have the largest covariances with those of the United States? To construct real bond returns for the U.S. we use monthly nominal 7-10 year Citigroup bond indices from Bloomberg, daily exchange rates at the New York close from the Federal Reserve's H.10 release and inflation compensation from inflation-indexed and nominal yields for the U.S. from Haver. Using data from January 1985 through April 2010, covariances in monthly 10-year real bond returns in U.S. goods for the U.S. versus Australia, Canada, the UK, Japan and Germany are 3.14, 2.65, 2.41, 2.37 and 3.20 percentage points, respectively.[6] Thus, the portfolio balance channel suggests that a change in the U.S. portfolio weight will have the strongest effect on Australian, Canadian and German returns and the weakest effects on Japanese returns, though the differences are within sampling error.

[6] Australian bond index data begins in October 1993 so the covariance is calculated from that date.

3.4 Summary of predictions

The portfolio balance model and the evidence about the international effects of U.S. monetary policy lead to similar predictions for the relative impact of U.S. LSAP announcements. Historical data on real bond returns suggests that the strongest portfolio balance effects will be on real U.S. goods returns on Canadian and German bonds and the weakest effects will be on real returns (in U.S. goods) on Japanese bonds. The signaling effects of conventional U.S. monetary policy, in turn, predict that the strongest nominal effects on yields will be on those of Canadian bonds and the weakest effects will be on those of Japanese bonds.

We now turn to the model-based decompositions of the effects of U.S. LSAP announcements on foreign yields. As it will turn out, our results will generally be very consistent with the predictions made above. We will show that Australian and Canadian yields exhibited the largest yield changes in response the LSAP announcements, followed by those of UK and Germany, while those of Japan exhibited the smallest response. Furthermore we will show that the signaling channel was relatively important for Canada, the country which has the closest ties to U.S. monetary policy.

4 Model specification and estimation

To analyze the effects of LSAPs on international bond yields, we decompose the changes in government bond yields on the announcement dates into expectations and term premium components with affine term structure models. These models reduce the dimensionality of the yield curve to a low number of risk factors, and impose that the cross-sectional behavior of yields is consistent with their time series dynamics (absence of arbitrage), allowing for a risk adjustment. We estimate such models for each of the six countries separately with daily data on government bond yields.[7]

[7]While it is possible to specify an international term structure model, there are many unresolved issues in this area, which would be complicated by the need to use daily yield data which is sampled at different times. We see the use of individual country-level models as a useful and sufficiently rich modeling framework for our

4.1 Affine term structure models

Dynamic term structure models have three basic ingredients: A time series model for the risk factors, an equation linking the short rate to the risk factors, and a specification of the stochastic discount factor (SDF) that captures the risk pricing. Here we use discrete-time affine Gaussian models, in which (1) the N-vector of risk factors X_t follows a first-order Gaussian VAR,

$$X_{t+1} = \mu + \Phi X_t + \Sigma \varepsilon_{t+1}, \tag{3}$$

where $\varepsilon_t \overset{iid}{\sim} N(0, I_N)$ and Σ is lower triangular; (2) the short rate, r_t, is an affine function of the pricing factors:

$$r_t = \delta_0 + \delta_1' X_t, \tag{4}$$

and (3) the SDF is of the form

$$-\log(M_{t+1}) = r_t + \frac{1}{2}\lambda_t'\lambda_t + \lambda_t'\varepsilon_{t+1},$$

where the risk prices are affine in the risk factors,

$$\Sigma\lambda_t = \lambda_0 + \lambda_1 X_t,$$

for N-vector λ_0 and $N \times N$ matrix λ_1. Under these assumptions X_t follows a first-order Gaussian VAR under the pricing measure $\mathbb{Q}$,

$$X_{t+1} = \mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} X_t + \Sigma \varepsilon^{\mathbb{Q}}_{t+1}, \tag{5}$$

and the prices of risk parameters λ_0 and λ_1 determine how VAR parameters are related under the objective and risk-neutral measures, denoted by $\mathbb{P}$, and $\mathbb{Q}$.[8]

purpose.

[8]Specifically, we have $\mu^{\mathbb{Q}} = \mu - \lambda_0$ and $\Phi^{\mathbb{Q}} = \Phi - \lambda_1$.

Intuitively, one should think of policy expectations (and risk-neutral interest rates) as real-world, $\mathbb{P}$-measure expectations of future values of r_t, and of forward rates (and yields) as risk-adjusted, $\mathbb{Q}$-measure expectations. Hence, the VAR parameters largely determine the properties of short rate expectations, whereas the "cross-sectional" parameters $\mu^{\mathbb{Q}}$ and $\Phi^{\mathbb{Q}}$ govern the behavior of yields and forward rates. The mean-reversion matrices Φ and $\Phi^{\mathbb{Q}}$ determine the persistence of X_t under each measure, i.e., the speed of mean reversion, and hence the variability of expected and forward policy rates.

We take the first three principal components of each country's yield data as the risk factors, and exploit the convenient normalization of Joslin et al. (2011), which makes estimation fast and reliable.[9] Appendix A details the bond pricing and the normalization.

For each country, we will present results for several alternative estimated models that differ by the imposed parameter restrictions and by the estimation method. We prefer this to selecting one preferred model for each country, using some selection criterion, because this would mask model uncertainty—different models with similar statistical fit can have very different economic implications. Therefore we present results from a set of six models that fit the data fairly well among a larger universe of candidate models.

OLS This baseline model is the maximally-flexible specification, estimated using maximum likelihood (ML) as in Joslin et al. (2011). The estimates of the μ and Φ are obtained using OLS. Since there are no restrictions on the risk pricing or VAR parameters, only the time series information in yields is used to estimate the VAR. High persistence of interest rates and the necessarily relatively short sample period produce imprecise estimates of the estimated VAR parameters, and also the small-sample bias that Bauer et al. (2012) discuss. This bias tends make the estimated dynamic system less persistent than the data-generating process. Because estimated mean reversion is too fast, forecasts of future short-term interest rates are too close to their unconditional mean and hence

[9] In particular, it is not necessary to jointly optimize the likelihood function over all model parameters—instead, many parameters can be concentrated out of the likelihood function.

too stable. As a consequence, decompositions of yield changes into expectations and premium components will typically attribute too little of the movements to changing policy expectations. When studying LSAPs using an event study methodology, one would therefore underestimate the importance of the signaling channel. We address this problem in two ways: first we an use alternative estimation method, and second, we estimate various restricted model specifications.

BC This "bias-corrected" model is specified exactly as the OLS model but estimated in a way that adjusts for small-sample bias in the VAR parameters, as in Bauer et al. (2012). The estimation is carried out in two stages: First, we obtain bias-corrected estimates of μ and Φ using the bootstrap, applying the stationarity adjustment of Kilian (1998) to ensure the largest $\mathbb{P}$-eigenvalue is not larger than one. Second, we maximize the likelihood function for given values of the VAR parameters. With less small-sample bias, this estimation procedure tends to make the estimated VAR more persistent, so that short rate forecasts revert more slowly to their unconditional mean.

UR The unit root (UR) specification restricts the VAR parameters to imply a unit root for the first risk factor, and allow some predictability of changes in this factor (the level factor).[10] This model closely corresponds to the "PC-UR" model estimated in Duffee (2011), who shows that this model displays good out-of-sample forecast performance in monthly Treasury yields.[11] For our daily data set, where persistence is significantly higher than in a monthly data set, it is particularly appealing to set the largest root of Φ equal to unity. We reduce estimation uncertainty significantly, and avoid the severe downward bias in the estimated persistence. If anything, persistence is more likely to be overestimated because we impose a unit root, so the resulting decomposition of changes

[10]That is, the first column of Φ is equal to $(1, 0, 0)'$ and the other elements are unrestricted.

[11]One difference between Duffee's and our model is that he does not enforce no-arbitrage by having the loadings of yields on risk factors be unrestricted, whereas we require that these loadings are consistent with no-arbitrage and our factor structure.

in long-term yields can be taken as an upper bound for the importance of changing policy expectations.

EV The restricted-eigenvalue (EV) model is similar to the UR model, with the difference that the largest $\mathbb{P}$-eigenvalue is not set equal to unity, but instead equal to the largest $\mathbb{Q}$-eigenvalue. Joslin et al. (2010) has proposed restricting the largest root of the VAR in this way. As with the UR model, this restriction reduces estimation uncertainty and small-sample bias.

RRP1 This model has restricted risk prices, imposing zero restrictions on λ_1, which determines how risk prices and expected returns vary with the risk factors. Several studies, including Cochrane and Piazzesi (2008), Joslin et al. (2010), and Bauer (2011), have advocated restricting risk prices in estimating dynamic term structure models, in order to reduce the statistical uncertainty and the small-sample bias in the inference about the VAR parameters. When the risk pricing is restricted, the cross-sectional dynamics of interest rates, which are estimated precisely and accurately, can help pin down the VAR parameters. We estimate each model under various possible sets of zero restrictions, and report results for that specification which achieves the highest Akaike Information Criterion (AIC).[12]

RRP2 This model also restricts risk prices. Specifically, the rank of λ_1 is restricted to be two, so that only two linear combinations of X_t drive variations in risk prices. This is in the spirit of Cochrane and Piazzesi (2005), who find that one linear combination of forward rates explains the majority of excess bond returns. As in Joslin et al. (2011) we test restrictions on the rank of λ_1, and find the best fit for the model with rank equal to two.

[12]Notably, specifications with similar fit according to AIC can have vastly different economic implications, and a more encompassing statistical approach would have to take into account this model uncertainty (as in Bauer, 2011).

We estimate all models are estimated using daily zero-coupon yield data from Bloomberg. The sample period is from 1995 to 2009. The yields have maturities three and six months, one through ten years, 15 years, and 20 years. As in most studies that use yield data after the Great Inflation, the length of the data sample is relatively short. The requirement of having the same sample period for all six countries makes this issue even more prevalent. The relatively short available sample makes correcting for small-sample bias and improving efficiency through restrictions on risk prices or VAR parameters particularly important. Our estimation imposes that the VAR is non-explosive under both the objective and risk-neutral pricing measures.

4.2 Summary statistics and economic implications

Table 3 shows summary statistics for the estimated models. The first three column show measures of model fit, the root-mean-square pricing error (RMSE), the log-likelihood function, and the AIC. The models estimate the cross-sectional structure very accurately, with RMSEs between 6 and 9 basis points. For each country, this fit is practically identical across specifications—restrictions on risk prices or VAR parameters essentially do not affect cross-sectional fit. Restricting the model parameters decreases the log-likelihood very little, indicating that VAR/risk price parameters are estimated very imprecisely. Consequently, the AIC is always smallest for one of the restricted models, typically RRP1. Overall, the differences in the AIC are generally small.

Turning to the economic implications of the models for term premium estimation, the next three columns show average levels (in annualized percentage points) of yields, risk-neutral yields, and term premia, for the ten-year maturity. The magnitude of the average ten-year term premium differs quite significantly between models, even for those with identical fit as measured by the AIC. For the U.S., for example, it ranges from 1.9 to 4.3 percent. Columns (7) to (10) consider second moments of daily changes, namely the standard deviation of changes in the actual yield, the risk-neutral yield, and the term premium, as well as the Pearson correlation coefficient between changes in the risk-neutral yield and the term premium. Again, the models imply very different variability and correlation of expectations and term premium components. A typical pattern here is that OLS implies risk-neutral yields that are more stable than for other models, due to the quick mean reversion of short rate forecasts. This often, but not always, implies a term premium that is more variable than for other models.

One can gain some perspective on these results by considering the estimated persistence of the VAR for the risk factors, both under the real-world probability measure $\mathbb{P}$ and under the pricing measure $\mathbb{Q}$. The 9th and 10th columns of the table show measures of persistence under both probability measures: The largest root of the VAR and the impulse response of the level factor to a level shock at the horizon of five years. First, note that the largest $\mathbb{Q}$-eigenvalue is always less than one by construction, but usually rounds to one with six digits of precision. The cross-sectional dynamics are extremely persistent, a result that is driven by the significant variability of long-term interest rates.[13] The persistence measures under $\mathbb{Q}$ vary little across models, because the restrictions do not strongly affect the cross-sectional dynamics. For the time series dynamics, the persistence differs substantially between specifications. The UR and EV models naturally imply the most persistent dynamics. The BC model always has a higher persistence than the OLS model, due to the bias correction which increases persistence. The RRP models do not generally have higher persistence than OLS, as one might have hoped for in light of the arguments in Joslin et al. (2010) and Bauer (2011), hence it is not clear whether these specifications appropriately address the bias problem.

All told, the models differ substantially in their implications for the decomposition of long-term yields into expectations and term premium components. These differences reflect a general problem in the DTSM literature: Small changes in specifications, each in itself statistically plausible, can lead to big differences in economic implications (Kim and Orphanides,

[13]A unit root under $\mathbb{Q}$, as assumed by the arbitrage-free Nelson-Siegel model of Christensen et al. (2011), seems entirely plausible in our data.

2005). In light of this finding, we need to study the effects of LSAPs with a variety of models, which we do in the following.

5 Empirical evidence on international signaling and portfolio balance

In this section, we present and discuss the evidence about the importance of the signaling and portfolio balance channels for the international effects of the Fed's LSAP program.

5.1 Model-free results

In order to provide a model-free overview of the international effects of the Fed's LSAP announcements, Table 4 shows the changes in short-term, medium-term, and long-term yields on the key event days. This parallels some of the analysis in Neely (2010). We can see that the international effects, based on the cumulative changes in long-term yields, were largest in Canada and Germany.

[TBC: discuss this relative to our predictions and to Neely (2010)]

We can get some indication about the importance of the signaling and PB channels based on these model-free results. Since term premia in short- and medium-term interest rates are limited in magnitude, changes in these rates can be interpreted as mostly driven by changes in policy expectations. This approach is often taken in empirical research, e.g., by Hanson and Stein (2012) and also Gagnon et al. (2011).

For now we leave aside the U.K., because there were some important confounding news on the event days that we consider, as will be discussed in more detail below.

The largest decrease in the two-year yield outside the U.S. occurred in Canada, where it decreased by almost as much as the two-year Treasury yield. This by itself indicates that signaling effects were largest in Canada. Our model-based evidence will reinforce this finding.

[TBC: discuss confounding news events in other countries here or else earlier in the paper. E.g., decreases in Canadian 3m yield.]

Naturally, model-free evidence can only go so far in revealing changes in expectations and risk premia, and we now turn to event study results based on our estimated term structure models.

5.2 Model-based decompositions

For each of the six countries, Figure 1 shows a bar plot with the cumulative changes in the ten-year yield as the left-most bar, and the contribution to this change of the expectations component, i.e., the change in the risk-neutral rate. The remainder of the change that is not explained by policy expectations naturally is attributed to changes in the term premium.

The first thing to note is that the decomposition is very sensitive to the model choice. Models with a highly persistent VAR and consequently more volatile risk-neutral rates typically attribute a larger share of the yield decrease to the expectations component.

The OLS model typically attributes a very small part of the yield change to the expectations component. In light of the small-sample bias that was discussed above, this model likely understates the contribution of expectations to yield movements. The BC model typically attributes a larger share of the decrease to the expectations component than the OLS model.

The BC, UR and EV models indicate that signaling plays an important role for the behavior of U.S. and Canadian interest rates. For these models, the point estimate for the decrease in expected short rates explains from one third to two thirds of the total decrease in U.S. and Canadian yields. This result is comforting as Canadian monetary policy probably has the closest relation to U.S. monetary policy. The UR and EV models also imply a large signaling channel for Germany and Australia, with the expectations component equal to about 1/3 to 1/2 of the total change. These findings point to an important role of the signaling channel, paralleling the findings of Bauer and Rudebusch (2011).

The U.K. data show the most pronounced changes in expectations, with the expectations component declining even more than the ten-year yield. This evidence, seemingly indicating a very strong signaling channel of LSAPs for the U.K., however, cannot be taken at face value: The U.K. data are unusual in that important domestic news events, which occurred at the same time as the Fed's LSAP announcements, lowered short-term interest rates and generated significant downward revisions future short-term rates. Specifically, the announcement on December 1, 2008, of the U.K. government that it would back retail deposits lead to substantial decreases in short-term rates and expected future policy rates.

For Australia, Germany and Japan, the results tend to indicate that the changes in expected future short rates were small. While the downward revision of expected short rates obtained using the RW model is still sizable, this is to be expected for a model that imposes absence of mean reversion. The picture that emerges for these countries is one of a dominant portfolio balance channel, and essentially no role for changes in expected short rates.[14]

6 Conclusion

This paper has presented some preliminary results on the relative importance of signaling and portfolio balance channels for the international bond yield effects of Fed large scale asset purchases. We generally find that the BC, UR and EV models imply that expected short rates, and hence the signaling channel of purchase announcements strongly influence on Canadian, Australian and German and U.S. long-term yield changes but have little effect on Japanese rates. In the latter case, changes in the term premia explain almost all of the change in long bond yields.

Our preliminary conclusion is that the close relationship between U.S. and Canadian monetary policy is likely responsible for the LSAP's particularly strong effects on expected Cana-

[14] The OLS and BC models imply increases for risk-neutral yields in Germany, due to the fact that the expected future German short rates were already very low.

dian short rates. The UR and EV models imply that the signaling channel is responsible for 80% of the total change in ten year yields. The signals that the Fed sent through its LSAP announcements about the likely future path of the federal funds rate transmitted to a large extent to expectations about the policy rate in Canada. However, Japanese policy rates are set much more independently from U.S. policy. Hence, it is very plausible that signals about U.S. interest rate policy do not carry over in the same way to Japan. Our results provide a valuable insight into the international linkages of unconventional monetary policy.

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A Affine bond pricing and JSZ normalization

Bond prices are exponentially affine functions of the pricing factors:

$$P_t^m = e^{\mathcal{A}_m + \mathcal{B}_m X_t},$$

and the loadings $\mathcal{A}_m = \mathcal{A}_m(\mu^{\mathbb{Q}}, \Phi^{\mathbb{Q}}, \delta_0, \delta_1, \Sigma)$ and $\mathcal{B}_m = \mathcal{B}_m(\Phi^{\mathbb{Q}}, \delta_1)$ follow the recursions

$$\begin{aligned}
\mathcal{A}_{m+1} &= \mathcal{A}_m + (\mu^{\mathbb{Q}})'\mathcal{B}_m + \frac{1}{2}\mathcal{B}_m'\Sigma\Sigma'\mathcal{B}_m - \delta_0 \\
\mathcal{B}_{m+1} &= (\Phi^{\mathbb{Q}})'\mathcal{B}_m - \delta_1
\end{aligned}$$

with starting values $\mathcal{A}_0 = 0$ and $\mathcal{B}_0 = 0$. Model-implied yields are determined by $y_t^m = -m^{-1}\log P_t^m = A_m + B_m X_t$, with $A_m = -m^{-1}\mathcal{A}_m$ and $B_m = -m^{-1}\mathcal{B}_m$. Risk-neutral yields, the yields that would prevail if investors were risk-neutral, can be calculated using

$$\tilde{y}_t^m = \tilde{A}_m + \tilde{B}_m X_t, \quad \tilde{A}_m = -m^{-1}\mathcal{A}_m(\mu, \Phi, \delta_0, \delta_1, \Sigma), \quad \tilde{B}_m = -m^{-1}\mathcal{B}_m(\Phi, \delta_1).$$

Risk-neutral yields reflect policy expectations over the life of the bond, $m^{-1}\sum_{h=0}^{m-1} E_t r_{t+h}$, plus a convexity term. The yield term premium is defined as the difference between actual and risk-neutral yields, $ytp_t^m = y_t^m - \tilde{y}_t^m$.

Denote by $\hat{Y}_t$ the vector of observed yields on day t. The number of observed yield maturities is J, and in the paper we have $J = 14$. We take the risk factors X_t to be the first $N = 3$ principal components of observed yields. That is, if W denotes the $N \times J$ matrix with rows corresponding to the first three eigenvectors of the covariance matrix of $\hat{Y}_t$, we have $X_t = W\hat{Y}_t$. As is common in the literature, we specify observed yields to include i.i.d. measurement errors, $\hat{Y}_t = Y_t + e_t$., which we take to have equal variance across yields.[15]

We parameterize the model using the canonical form of Joslin et al. (2011). Thus, the free parameters of the model are $r_\infty^{\mathbb{Q}} = E^{\mathbb{Q}}(r_t)$, the risk-neutral long-run mean of the short rate, $\lambda^{\mathbb{Q}}$, the eigenvalues of $\Phi^{\mathbb{Q}}$, and the VAR parameters μ, Φ, and Σ.[16]

[15] Note that because N linear combinations of yields are priced exactly, $We_t = 0$, and there are effectively only $J - N$ independent measurement errors.

[16] To see how $\mu^{\mathbb{Q}}$, $\Phi^{\mathbb{Q}}$, δ_0, and δ_1 are calculated from $(W, \lambda^{\mathbb{Q}}, r_\infty^{\mathbb{Q}}, \Sigma)$ refer to Proposition 2 in Joslin et al. (2011).

Table 1: LSAP announcements

Date	Event	Time	Description	Other significant news
11/25/2008	initial LSAP announcement	8:15a	Federal Reserve announces purchases of up to $100 billion in agency debt and up to $500 billion in agency MBS.	FOMC minutes released on November 24.
12/1/2008	Chairman's speech	1:40p	Chairman Bernanke states that the Federal Reserve "could purchase longer-term Treasury securities [...] in substantial quantities."	Alistair Darling, Chancellor of the Exchequer, promises backing to retail deposits at London Scottish Bank, effectively backing all retail bank deposits in the U.K.. Construction spending and ISM announcements come in weaker than expected. NBER dating committee officially declares a recession.
12/16/2008	FOMC statement	2:15p	Statement indicates that the FOMC is considering expanding purchases of agency securities and initiating purchases of Treasury securities.	Federal funds rate target reduced from 1 percent to a 0-25 bp target range.
1/28/2009	FOMC statement	2:15p	Statement indicates that the FOMC "is prepared to purchase longer-term Treasury securities."	The term asset lending facility (TALF) will be implemented.
03/18/2009	FOMC statement	2:15p	Statement announces purchases "up to an additional $750 billion of agency [MBS]," $100 billion in agency debt, and $300 billion in Treasury securities.	
08/12/2009	FOMC statement	2:15p	Statement drops "up to" language and announces slowing pace for purchases of Treasury securities.	
9/23/2009	FOMC statement	2:15p	Statement drops "up to" language for purchases of agency MBS and announces gradual slowing pace for purchases of agency debt and MBS.	
11/4/2009	FOMC statement	2:15p	Statement declares that the FOMC would purchase "around $175 billion of agency debt."	The Reserve Bank of Australia raises its policy rate by 25 basis points.

Notes: The table describes the 8 events associated with the first round of LSAPs. The columns denote the date of the announcement, the nature of the event, the time of the event (EST), a brief description of the event and a brief description of other possibly significant news events in a 3-day event window from $t-1$ through $t+1$.

Table 2: Conventional U.S. monetary policy and foreign interest rates

Yield		U.S.	Australia	Canada	Germany	Japan	U.K.
three-month	Target	.57	-.01	.22	.08	.01	.06
		(11.69)	(.26)	(4.68)	(2.50)	(.44)	(1.04)
	Path	.03	.05	.06	.02	.01	.01
		(2.04)	(3.56)	(4.96)	(2.54)	(.94)	(.45)
	R^2	50.9%	8.6%	25.5%	8.6%	.8%	.9%
two-year	Target	.40	.14	.16	.14	.03	.08
		(8.06)	(2.49)	(3.55)	(2.99)	(1.16)	(1.42)
	Path	.18	.07	.09	.06	.02	.07
		(13.81)	(4.79)	(7.67)	(4.54)	(2.72)	(4.10)
	R^2	65.3%	17.7%	34.5%	17.9%	6.1%	12.2%
five-year	Target	.28	.06	.02	.08	.02	.03
		(4.31)	(.92)	(.49)	(1.61)	(.63)	(.47)
	Path	.19	.09	.09	.07	.03	.07
		(11.30)	(5.17)	(7.52)	(5.50)	(2.86)	(4.48)
	R^2	51.9%	16.9%	29.5%	19.5%	5.9%	13.0%
ten-year	Target	.14	-.09	-.07	.00	-.02	-.04
		(1.98)	(1.38)	(1.47)	(.11)	(.44)	(.74)
	Path	.16	.10	.08	.06	.03	.07
		(8.75)	(5.45)	(6.58)	(4.86)	(2.73)	(4.21)
	R^2	37.2%	18.8%	25.0%	14.8%	5.3%	11.9%

Notes: The table shows results for regressions of foreign yield changes on U.S. monetary policy surprises as defined by Gürkaynak et al. (2005). The number of observations is 139, corresponding to FOMC statements between February 1, 1995, and March 15, 2011. Numbers in parentheses indicate t-statistics.

Table 3: Model summary statistics

Model	RMSE (1)	LLK (2)	AIC (3)	avg. y (4)	$\tilde{y}$ (5)	TP (6)	vol. Δy (7)	$\Delta\tilde{y}$ (8)	ΔTP (9)	corr (10)	$\mathbb{Q}$-root (11)	$\mathbb{P}$-root (12)	IRF-$\mathbb{Q}$(5y) (13)	IRF-$\mathbb{P}$(5y) (14)	par. (15)
U.S.															
OLS	8.9	604140.7	-1208238	5.2	2.1	3.2	6.6	3.6	5.5	0.0	1	0.999320	0.422992	0.379082	22
BC	8.9	604137.8	-1208232	5.2	3.3	1.9	6.6	7.3	6.7	-0.6	1	0.999996	0.422979	0.875368	22
UR	8.9	604134.9	-1208232	5.2	1.0	4.3	6.6	6.4	3.3	-0.2	1	1.000000	0.422988	1.000000	19
EV	8.9	604134.9	-1208232	5.2	1.0	4.3	6.6	6.4	3.3	-0.2	1	1.000000	0.422988	1.000000	19
RRP1	8.9	604139.5	-1208245	5.2	1.8	3.4	6.6	4.5	5.6	-0.2	1	0.999606	0.422993	0.642429	17
RRP2	8.9	604140.7	-1208243	5.2	2.2	3.0	6.6	3.0	5.5	0.1	1	0.999112	0.423002	0.301651	19
Australia															
OLS	7.5	609090.4	-1218137	6.4	5.0	1.4	7.5	1.0	7.3	0.2	1	0.997077	1.056598	0.014032	22
BC	7.5	609086.8	-1218130	6.4	5.3	1.1	7.5	2.0	7.4	-0.1	1	0.998785	1.056599	0.118838	22
UR	7.5	609083.9	-1218130	6.4	3.9	2.4	7.5	6.0	3.6	0.2	1	1.000000	1.056598	1.000000	19
EV	7.5	609083.9	-1218130	6.4	3.9	2.4	7.5	6.0	3.6	0.2	1	1.000000	1.056597	1.000000	19
RRP1	7.5	609086.4	-1218143	6.4	4.8	1.5	7.5	1.2	6.7	0.7	1	0.997835	1.056597	0.010673	15
RRP2	7.5	609090.2	-1218143	6.4	4.9	1.4	7.5	1.2	7.3	0.1	1	0.997919	1.056597	0.015461	19
Canada															
OLS	7.6	611683.8	-1223324	5.4	2.8	2.6	4.9	1.6	4.4	0.2	1	0.998421	0.842617	0.111749	22
BC	7.6	611677.2	-1223311	5.4	3.5	1.9	4.9	4.3	3.9	-0.3	1	0.999987	0.842613	0.828916	22
UR	7.6	611679.5	-1223321	5.4	1.1	4.3	4.9	6.2	3.3	-0.6	1	1.000000	0.842608	1.000000	19
EV	7.6	611679.5	-1223321	5.4	1.1	4.3	4.9	6.2	3.3	-0.6	1	1.000000	0.842615	1.000000	19
RRP1	7.6	611681.6	-1223329	5.4	2.3	3.1	4.9	3.4	4.6	-0.3	1	0.998788	0.842607	0.189468	17
RRP2	7.6	611683.2	-1223328	5.4	2.6	2.8	4.9	2.4	4.6	-0.1	1	0.998708	0.842611	0.115936	19
Germany															
OLS	6.8	619751.5	-1239459	4.8	2.5	2.3	4.3	1.2	4.2	-0.1	0.999896	0.998008	1.027665	0.057997	22
BC	6.8	619742.8	-1239442	4.8	3.0	1.8	4.3	3.6	4.9	-0.5	0.999896	0.999686	1.027680	0.685034	22
UR	6.8	619746.3	-1239455	4.8	1.4	3.4	4.3	4.1	2.8	-0.3	0.999896	1.000000	1.027675	1.000000	19
EV	6.8	619745.9	-1239454	4.8	1.1	3.7	4.3	3.7	2.9	-0.2	0.999896	0.999896	1.027674	0.876958	19
RRP1	6.8	619749.9	-1239468	4.8	2.6	2.2	4.3	1.1	4.4	-0.2	0.999896	0.998430	1.027668	0.045766	16
RRP2	6.8	619751.3	-1239465	4.8	2.4	2.3	4.3	1.4	4.3	-0.1	0.999896	0.998263	1.027671	0.062645	19
Japan															
OLS	6.3	626601.9	-1253160	1.9	0.2	1.7	4.1	0.1	4.1	0.1	0.999665	0.997500	1.296807	0.027443	22
BC	6.3	626596.7	-1253149	1.9	0.2	1.7	4.1	0.2	4.1	-0.1	0.999665	0.998976	1.296810	0.181060	22
UR	6.3	626587.7	-1253137	1.9	-0.1	2.0	4.1	1.2	3.0	1.0	0.999665	1.000000	1.296820	1.000000	19
EV	6.3	626589.3	-1253141	1.9	-0.2	2.1	4.1	0.8	3.4	1.0	0.999665	0.999665	1.296822	0.655615	19
RRP1	6.3	626600.3	-1253167	1.9	0.2	1.7	4.1	0.1	4.1	0.1	0.999665	0.997137	1.296860	0.022433	17
RRP2	6.3	626600.5	-1253163	1.9	0.2	1.7	4.1	0.1	4.1	0.0	0.999665	0.998803	1.296806	0.135900	19
U.K.															
OLS	7.6	611917.5	-1223791	5.5	2.4	3.0	5.2	5.5	5.1	-0.5	1	0.999877	0.863672	0.292608	22
BC	7.6	611915.3	-1223787	5.5	4.6	0.9	5.2	6.4	5.6	-0.6	1	0.999996	0.863667	0.371266	22
UR	7.6	611910.6	-1223783	5.5	2.6	2.8	5.2	7.0	6.7	-0.7	1	1.000000	0.863667	1.000000	19
EV	7.6	611910.6	-1223783	5.5	2.6	2.8	5.2	7.0	6.6	-0.7	1	1.000000	0.863665	1.000000	19
RRP1	7.6	611915.5	-1223797	5.5	2.1	3.4	5.2	6.7	4.9	-0.6	1	0.999925	0.863658	0.590242	17
RRP2	7.8	610909.0	-1221780	5.5	2.7	2.7	5.3	5.7	6.6	-0.6	1	0.999980	0.868143	0.339585	19

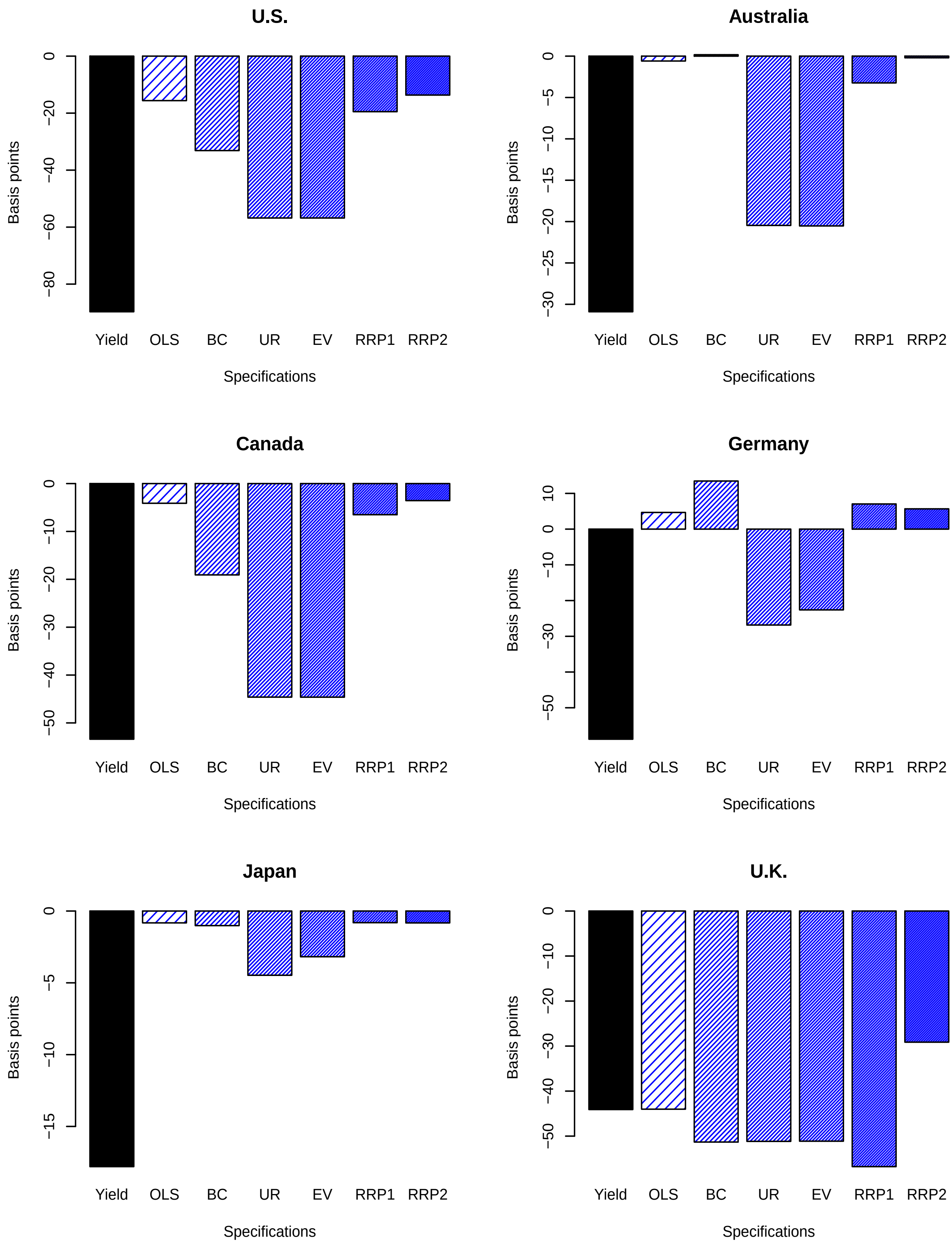
Notes: The first three columns show measures of model fit, namely the root-mean-square pricing error (RMSE) in basis points, the value of the log-likelihood function (LLK), and the AIC. Columns (4) to (6) show, for the ten-year yield, average levels of actual yield, the risk-neutral yield, and the term premium, in annualized percentage points. Columns (7) to (9) show the standard deviation of daily changes in the actual yield, risk-neutral yield, and term premium, in basis points, and column (10) shows the correlation between changes in the risk-neutral yield and the term premium, all for the ten-year yield. Columns (11) and (12) show the largest eigenvalue of Φ and $\Phi^{\mathbb{Q}}$, and columns (13) and (14) show as alternative measures of persistence the value of the impulse response function of the level factor to level shocks, using Φ and $\Phi^{\mathbb{Q}}$, respectively. The last column shows the number of unrestricted parameters in the model (not counting measurement error variances).

Table 4: Effects of LSAP announcements on international yields

	U.S.			Australia			Canada		
	3m	2y	10y	3m	2y	10y	3m	2y	10y
2008/11/25	1.5	-2.4	-23.1	1.2	-0.5	6.1	-6.4	-4.6	-12.4
2008/12/01	0.2	-8.6	-21.6	-4.0	-7.5	-5.3	-10.5	-15.8	-17.0
2008/12/16	1.0	-9.1	-27.6	-3.6	-7.0	-17.9	-17.1	-15.1	-13.0
2009/01/28	5.3	6.9	15.0	-6.4	-4.7	2.8	-7.3	6.1	5.6
2009/03/18	-2.3	-22.6	-50.5	-13.3	-14.3	-28.5	-4.6	-7.0	-23.9
2009/08/12	1.3	0.4	7.9	5.4	4.9	15.8	-2.5	-0.5	3.4
2009/09/23	-0.6	-3.5	-2.5	-1.1	-2.5	-7.2	0.4	0.0	0.0
2009/11/04	-0.1	-1.2	12.7	3.9	5.6	3.3	-1.1	-1.5	3.9
total	6.3	-40.1	-89.7	-17.9	-26.0	-30.9	-49.1	-38.4	-53.4
	Germany			Japan			U.K.		
	3m	2y	10y	3m	2y	10y	3m	2y	10y
2008/11/25	5.7	5.7	-8.2	2.8	1.5	-1.8	-2.8	11.4	-7.3
2008/12/01	-1.2	-0.9	-12.6	-1.0	-3.2	-3.5	-18.1	-25.6	-16.3
2008/12/16	-7.1	-16.7	-14.6	-7.9	-5.7	-7.7	-2.6	-18.0	-16.8
2009/01/28	-0.8	-5.2	-0.3	-0.5	1.0	-2.3	-2.2	-0.7	-0.4
2009/03/18	-2.3	-0.8	-18.5	-6.1	-5.0	-2.0	-7.2	-5.2	-6.9
2009/08/12	0.9	-5.3	-2.8	-0.4	-0.8	-1.7	-0.7	-6.0	0.6
2009/09/23	0.4	-6.2	-6.7	-2.2	-2.9	-3.4	-4.1	-7.2	-5.1
2009/11/04	-0.6	0.0	4.9	0.4	0.9	4.6	0.4	1.4	8.1
total	-5.0	-29.4	-58.8	-14.9	-14.2	-17.8	-37.3	-49.9	-44.1

Notes: The table changes in three-month, two-year, and ten-year yields around the eight key announcement days of the Fed's LSAP program.

Figure 1: Decomposition of changes in the ten-year yield



Notes: The figure shows (in basis points) the cumulative change in the ten-year yield over the eight LSAP announcements under consideration, as well as the contribution of the expectations component to this change, according to each of the seven estimated models.