RESERVE BANK
OF NEW ZEALAND
TE PŪTEA MATUA

DP2014/03a

Asset markets and monetary policy shocks at the zero lower bound

Edda Claus, Iris Claus and Leo Krippner

August 2016

(First version: July 2014)

JEL classification: E43, E52, E65

www.rbnz.govt.nz

Discussion Paper Series

ISSN 1177-7567

DP2014/03a

Asset markets and monetary policy shocks at the zero lower bound*

Edda Claus, Iris Claus and Leo Krippner†

Abstract

We quantify the responses of United States asset markets to domestic monetary policy shocks and also gauge the usefulness of shadow short rates as a metric across conventional and unconventional monetary policy environments. Our results show that asset market responses to policy shocks have been larger since short term nominal interest rates reached the zero lower bound. While short maturity interest rates no longer provide a useful metric in that environment, appropriately robust shadow short rates are useful over both environments. The increased responses of asset markets in the unconventional period seem due to larger policy shocks rather than a change to their transmission.

* The Reserve Bank of New Zealand's discussion paper series is externally refereed. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the Reserve Bank of New Zealand. They also do not necessarily represent the views of the International Monetary Fund (IMF), its Executive Board, its management, or IMF policy. We thank Anny Chen, Evelyn Truong, anonymous referees, and participants of seminars at the Bank of England and Wilfrid Laurier University for valuable comments.

† Edda Claus: Wilfrid Laurier University, Department of Economics, School of Business and Economics, 75 University Avenue West, Waterloo, Ontario, N2L 3C5, Canada. Email: eclaus@wlu.ca. Iris Claus: Reserve Bank of Fiji Building, Pratt Street, GPO Box 172, Suva, Fiji. Email: iclaus@imf.org. Leo Krippner: Economics Department, Reserve Bank of New Zealand, 2 The Terrace, PO Box 2498, Wellington, New Zealand. Email: Leo.Krippner@rbnz.govt.nz.

ISSN 1177-7567

Non-technical Summary

We investigate the response of US asset prices to monetary policy surprises (shocks) over the period February 1996 to January 2016, which covers periods of monetary policy operated by conventional and unconventional means. In that context, we also gauge the usefulness of shadow short rate estimates as a common measure of the stance of monetary policy across conventional and unconventional periods.

Central banks conventionally conduct monetary policy by setting a policy interest rate, which sets the benchmark for other interest rates and investment returns in the economy. Following the 2007-09 global financial crisis, policy interest rates dropped to unprecedented near-zero levels in many economies, including the United States. But policy rates can't freely be set materially lower than zero, because the availability of physical currency effectively offers an alternative risk-free investment at an interest rate of zero.

To provide further monetary stimulus beyond a near-zero policy rate alone, central banks turned to unconventional policies. For example, the US Federal Reserve implemented direct lending to specific short term credit markets, large scale purchases of interest rate securities to increase the monetary base, and explicit guidance on future policy rates.

In our analysis, we identify monetary policy shocks using monetary policy announcement days, where the common variability of asset prices movements is larger than the usual variability on non-policy days. The representative asset prices we use are the 90 day treasury rate, the 10 year treasury rate, corporate bond prices, the gold price, equity prices, real estate investment trust prices, and the US dollar / British pound exchange rate.

We find that asset prices respond to tightening monetary policy shocks in conventional and unconventional periods as one would anticipate; i.e. higher rates and lower prices. The exception is the 90 day rate in the unconventional period, which falls and is therefore notably deficient as a monetary policy indicator.

We then replace the 90 day rate with a shadow short rate (SSR) series. The SSR is estimated from yield curve data and it can freely take on negative values to reflect intermediate and longer maturity interest rates being lower than expected if a near-zero policy rate prevailed in the absence of unconventional policy measures.

The SSR response is as anticipated across both the conventional period and unconventional periods, and it matches the 90 day rate response in the conventional period. Hence, the SSR provides a useful indicator of the stance of conventional and unconventional monetary policy, as suggested previously by central bankers and academics.

We find that US asset markets have reacted more strongly to monetary policy shocks since the Federal Reserve began to employ unconventional monetary policy actions from late 2008. Our results indicate this is more likely due to larger monetary policy shocks rather than a change in the transmission of those shocks to asset markets.

Central banks should therefore be suitably cautious about unconventional policy actions and communications, or risk larger responses to interest rates, exchange rates, and asset markets. As a practical example, we note the large response in the wake of the 2013 comments on reducing the QE3 asset purchase program (the so-called "taper tantrum"), while financial markets subsequently settled on comments that any tapering would be gradual, and policy rate increases would be some way off.

1 Introduction

In this paper we investigate the response of US asset markets to domestic monetary policy shocks over the period February 1996 to January 2016 which, as we discuss further below, covers periods of monetary policy operated by conventional and unconventional means. In that context, we also gauge the usefulness of using shadow short rate (SSR) estimates as a common monetary policy metric across conventional and unconventional periods.

Understanding the impact of monetary policy shocks is crucial for central banks to conduct monetary policy effectively because changes in interest rates, exchange rates, and asset prices affect the decisions of firms, households, banks, and investors. If unconventional monetary policy actions affect asset markets differently, stabilization of economic activity and inflation may require central banks to adjust their policy responses accordingly.

While the institutional details differ from country to country, central banks conventionally conduct monetary policy by setting the interest rate at which they lend and receive high powered money (also known as outside money or monetary base) with the inter-bank market and by buying and selling short term debt securities to target short term nominal interest rates around that setting. Short term nominal interest rates reached the zero lower bound in several countries, including the United States, when central banks responded to the 2007-09 financial crisis with aggressive monetary easing. But when nominal interest rates reach zero, conventional monetary policy cannot lower interest rates further because the availability of physical currency effectively offers a risk-free investment at a zero rate of interest, which is more attractive than central bank deposits or buying securities that offer a negative interest rate.[1]

To provide further monetary stimulus beyond a zero policy rate, central banks turned to unconventional policies. For example, unconventional actions undertaken by the United States, the euro area, Japan, and the United Kingdom included direct lending to specific short term credit markets, large scale purchases of long term assets to increase the monetary base, and explicit guidance on future policy rates; see Fawley and Neely (2013) for a comparison of the unconventional monetary easing programs of the Federal Reserve, the European Central Bank, the Bank of Japan, and the Bank of England.

Typically, to quantify the effects of monetary policy shocks, event study analysis building on Kuttner (2001) has been used. The assumption in event studies is that monetary policy surprises have an immediate impact on short term interest rates, and therefore observed changes in a given short term market interest rate on monetary policy event days should provide a gauge of monetary policy shocks. In turn, regressing the change in the price of an asset on the change in the short term interest rate should obtain a consistent estimate of the impact of monetary policy shocks on the price of that asset. However, event study analysis is severely complicated in unconventional monetary policy environments because short term rates at or near zero can no longer move freely to proxy policy shocks. In

[1] Occasional minor exceptions are due to institutional features, such as the overhead costs of holding and transacting in physical currency, market liquidity, idiosyncratic supply and demand shocks for specific interest rate securities, and periods where high quality fixed interest securities are purchased during times of market turbulence. Japan, the United States, the euro area, Sweden, and Switzerland are examples of countries that have realized slightly negative interest rates historically and / or at present.

addition, the immediate responses in short term interest rates may be prone to some initial overreaction; see Thornton (2014).

An alternative to event studies is a narrative approach proposed by Romer and Romer (1989 and 2004), who derive monetary policy shocks from intended changes in monetary policy around meetings of the Federal Open Market Committee (FOMC).[2] However, the difficulty with this approach is that it can lead to unreasonably large monetary policy shocks; see Claus and Dungey (2012).

A third approach, which we apply in this paper, is to use a latent factor model, where monetary policy shocks are identified through heteroskedasticity in daily data on policy versus non-policy days; see Rigobon and Sack (2004) and Craine and Martin (2008). We first estimate a latent factor model using only observable variables to quantify the response of asset markets to monetary shocks in conventional and unconventional periods. We consider the response of a range of representative asset prices that are important to the economy from different perspectives, including the 90 day treasury rate, the 10 year treasury rate, corporate bond prices, the gold price, equity prices, real estate investment trust (REIT) prices,[3] and the US dollar / British pound exchange rate.

To gauge the usefulness of shadow short rates to proxy monetary policy shocks over both conventional and unconventional monetary policy periods, we then replace the 90 day rate with an SSR series. SSRs are an estimated monetary policy metric that can freely take on negative values to reflect a near zero policy rate plus unconventional policy actions. Hence, SSRs have been proposed as a metric for quantitative monetary policy analysis and for monitoring the stance of unconventional monetary policy; see Bullard (2012), Krippner (2013), and Wu and Xia (2016). SSRs are estimated from yield curve data and negative values therefore essentially reflect the degree to which intermediate and longer maturity interest rates are lower than would be expected if a zero policy rate prevailed in the absence of unconventional policy measures. The benchmark SSR that we use in this paper is estimated with Krippner's (2015a) shadow / lower bound model.[4]

Figure 1 plots our benchmark SSR estimate together with the federal funds target rate (FFTR), which is the US central bank's policy rate, and a measure of the size of the Federal Reserve's balance sheet; Federal Reserve liabilities as a percent of gross domestic product.[5] From slightly before and since the near zero policy rate setting in December 2008, the Federal Reserve employed its balance sheet to provide a range of unconventional monetary policy actions, such as large scale asset purchases, targeted asset purchases, and liquidity provisions, abbreviated by markets and in this paper as quantitative easing (QE). Note that the Federal Reserve typically announces its intentions for QE programs, and

[2]The FOMC is a committee within the United States Federal Reserve System that sets monetary policy by specifying the short term objective of the central bank's open market operations.

[3]REITs are an investment vehicle for real estate that are comparable to mutual funds. They invest in real estate through property and / or mortgages and often trade on major exchanges like a stock.

[4]The SSR estimates and the MatLab programs used to produce the rates are available at http://www.rbnz.govt.nz/research-and-publications/research-programme/additional-research/measures-of-the-stance-of-united-states-monetary-policy/comparison-of-international-monetary-policy-measures. The SSRs published on the website are updated at the end of each month.

[5]The federal funds rate is the interest rate at which depository institutions trade balances held at the Federal Reserve (federal funds) with each other, usually overnight, on an uncollateralized basis.

markets often react more to the announcements rather than the subsequent realized balance sheet expansion. Another important class of unconventional monetary policy actions not indicated in figure 1 is long term explicit forward guidance on the FFTR, i.e. conditional statements on the likely horizon for which the FFTR would remain near zero.

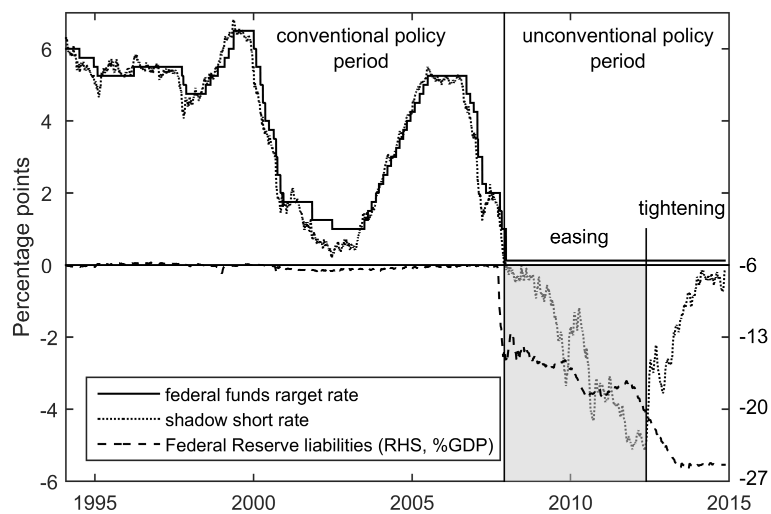

Figure 1: US monetary policy and our benchmark SSR series.

Figure 1 shows that the FFTR and the SSR move closely together when interest rates are unconstrained by the zero lower bound,[6] but they diverge when the FFTR approaches or reaches zero. Hence, a large and persistent divergence developed in late 2008 after the FFTR reached the effective lower bound and the SSR evolved to increasingly negative values to reflect the near-zero policy rate setting plus stimulus through unconventional monetary policy actions. The SSR started rising in May 2013 following signals of reduced unconventional stimulus by the central bank.

Using SSRs to quantify the impact of monetary policy surprises on asset markets for the normal and unconventional monetary policy periods adds a novel aspect to the fast growing literature on unconventional monetary policy. Moreover, using an appropriately robust SSR estimates allows an investigation of whether the size of monetary policy shocks and / or the responses of different asset markets have changed with the transition from operating monetary policy by conventional means to operating at the zero lower bound along with unconventional methods of monetary policy easing.

Our results may be summarized as follows. Using only observable data, we find that the directions of responses of asset prices to monetary policy shocks are the same in conventional and unconventional periods, except for the 90 day rate, and are generally as one would anticipate in principle and in comparison to the related literature. Changes in the 90 day rate are a reasonable measure of monetary policy surprises in normal times, but they are deficient as a measure of monetary policy shocks in the unconventional policy period.

[6]The typically small divergences occur mainly because the yield curve data from which the SSR is estimated reflects the anticipated FFTR path, and hence the SSR generally leads the FFTR cycle. The conventional period divergence is largest around the US deflation scare of 2003.

When we replace the 90 day rate with the Krippner (2015a) SSR, we find that asset price responses to monetary policy shocks are similar to those established with the observable data. The SSR responds similarly to the 90 day rate during normal times and as one would expect in the unconventional period. Compared to the conventional monetary policy period, asset markets have reacted more strongly to monetary policy shocks since the Federal Reserve began to employ unconventional monetary policy actions from late 2008. The results suggest that appropriately robust SSR estimates can provide a useful metric for quantifying monetary policy shocks in unconventional periods, analogous to conventional short term interest rates in normal times.

We therefore proceed to use the Krippner (2015a) SSR estimates as a common monetary policy metric over the conventional and unconventional policy periods to investigate the reason for the larger responses to monetary policy shocks in the unconventional period. Form that perspective, we find that the increased responses are likely due to larger monetary policy shocks rather than a change to the transmission of shocks.

The next section reviews the recent literature on unconventional monetary policy. Section 3 describes the methodology behind obtaining the SSR and compares our benchmark SSR estimate used in the analysis of monetary policy shocks to alternative SSR measures. Section 4 discusses the empirical framework and data used in the estimation of the latent factor model. Section 5 presents the empirical results and the last section offers concluding remarks.

2 Unconventional monetary policy event studies

The effects of asset purchase programs and quantitative easing have been investigated by many authors. In this section we focus on the announcement literature, which examines the effects of monetary policy announcements on asset markets mainly using event study analysis.[7] Event study analysis has been severely complicated by the constraint of the lower bound because short term interest rates at or near zero no longer have the freedom to change and therefore provide a proxy for monetary policy surprises. To investigate the impact of unconventional monetary policy shocks the strategy of event studies typically is to consider a narrow set of announcements that the authors argue are complete surprises.

The impact of quantitative easing policies on medium and long term interest rates has been examined in a number of studies. For example, Krishnamurthy and Vissing-Jorgensen (2011) use event study methodology to evaluate the effects of the Federal Reserve's first two asset purchase programs (QE1 in 2008-09 and QE2 in 2010-11). Specifically they test whether changes on quantitative easing announcement days differ from changes on other days by regressing the daily changes in various yields of interest on dummy variables, which take a value of one if there was a QE announcement on that day or the previous day. Two day changes are considered as some asset prices may have only reacted slowly because of low liquidity at the time. Employing both time series and event study methodology Gagnon, Raskin, Remache, and Sack (2011) gauge the impact of QE1 on longer term

[7] Instead of announcements some researchers investigate the effects of central bank purchases of securities on asset markets; e.g. Meaning and Zhu (2011) and D'Amico and King (2013).

interest rates. Their event study analysis examines changes in interest rates using a one day window around official communications regarding asset purchases, while the time series analysis statistically estimates the impact of the Federal Reserve's asset purchases on the 10 year treasury term premium. Joyce, Lasaosa, Stevens, and Tong (2011), who examine the reaction of asset prices to the Bank of England's QE announcements using event study analysis over a two day window and data from a survey of economists on the total amount of QE purchases expected, obtain quantitatively similar impacts on government yields as Gagnon et al. (2011) for the United States. Swanson (2011) also uses event study analysis and quantifies the potential impact of QE2 by measuring the effect on long term interest rates of the Federal Reserve's 1961 Operation Twist, which was a program similar to QE2.

Beyond interest rate effects, Joyce et al. (2011) examine the effects of quantitative easing on other asset prices (corporate debt and equities) by estimating the expected asset returns of changes in asset quantities. However, they find considerable uncertainty about the size of the impact because of the difficulty in disentangling the impact of monetary policy shocks from other influences. Rosa (2012), Kiley (2014), and Rogers, Scotti, and Wright (2014), who investigate co-movements between long term interest rates and equity prices in the United States in reaction to monetary policy shocks, find an attenuated response in equity prices since the zero lower bound on short term interest rates has been binding. Rosa (2012) uses event study analysis and identifies the surprise component of large scale asset purchase announcements from press reports. The methodology employed by Kiley (2014) is instrumental variable estimation using instruments correlated with the change in the 10 year treasury rate, while Rogers, Scotti, and Wright (2014) use intradaily data around announcement times with 30 and 120 minute windows to identify the causal effect of monetary policy surprises.

Neely (2015) evaluates the effect of QE1 on exchange rates. Using daily data and event study analysis he finds that the US dollar depreciated in response to asset purchase announcements by the Federal Reserve. His estimation period is extended by Glick and Leduc (2013), who compare how the US dollar reacts to changes in unconventional monetary policy compared to conventional monetary policy changes. Monetary policy surprises are identified from changes in interest rate futures prices in a 60 minute window around policy announcements and found to have a significant impact on the value of the US dollar. However, Glick and Leduc (2013) find virtually no response to unconventional monetary policy surprises over a longer window, i.e. a day later.

The effects of other methods of unconventional monetary policy accommodation have not received as much attention in the literature, but Christensen, Lopez, and Rudebusch (2014) offer empirical evidence that central bank lending facilities helped to lower liquidity premiums in markets early in the global financial crisis. Regarding forward guidance, Woodford (2012) provides a summary of the principles by which it can influence financial markets and also an overview of supporting empirical evidence. Femia, Friedman, and Sack (2013) investigate market reaction to forward guidance by focusing on the use of calendar dates and economic thresholds in FOMC statements. To quantify the impact of forward guidance and large scale asset purchases Swanson (2015) estimates the response of financial markets in a 30 minute window around monetary policy announcements using principal components analysis. His results suggest that forward guidance has a limited influence on the 10 year treasury rates and no significant effect on corporate bond yields. In contrast, large scale asset purchases have a large effect on both yields. Moreover, both policies significantly influence medium term treasury rates, equity prices and exchange rates.

We add to the literature on unconventional monetary policy in two respects. First, we use an observable dataset to quantify the impact of all conventional and unconventional monetary policy announcements on a wide range of asset prices. Second, we quantify monetary policy surprises with an appropriately robust SSR. As we detail in the following section, the SSR is consistently estimated over conventional and unconventional monetary policy periods and so it allows us to empirically investigate whether the size of monetary policy shocks and / or the responses of different asset markets have changed. A recent application of a SSR to measure the macroeconomic impact of monetary policy at the zero lower bound is Wu and Xia (2016). However, as we discuss in section 3.4, the Wu and Xia shadow short rate along with other members of its class have some serious shortcomings that we believe make them unsuitable as a metric for monetary policy.

3 Shadow short rate

In this section, we first outline the intuition of the SSR that we subsequently include in our asset price datasets for our empirical analysis of monetary policy shocks. Section 3.2 addresses the robustness of our benchmark SSR series relative to alternative estimates. This is an important consideration for any application of SSR estimates because, as we show, SSR estimates from certain classes of models can be extremely sensitive to small changes in specification. The generic shadow / lower bound model (SLM) framework, the benchmark SLM specification, which is a two factor (i.e. Level and Slope) model for the shadow term structure within the Krippner (2013, 2015a) SLM framework, henceforth the K-ANSM(2), and its estimation are outlined in appendix A.

3.1 SSR intuition

Figure 2 illustrates the concept of obtaining the SSR estimate with the K-ANSM(2) specification, by consistently decomposing the yield curve data into a shadow yield curve and the option effect across conventional and unconventional monetary policy regimes. The option effect accounts for the availability of physical currency, which provides investors with an option to avoid any realizations of negative short maturity interest rates that could otherwise potentially occur at any time up to each given maturity. The shadow yield curve gives the hypothetical interest rates for bonds if physical currency was not available as an alternative investment to negative short maturity rates. The SSR is the shortest maturity rate on the shadow yield curve, and is therefore conceptually analogous to a policy rate except that it can freely adopt positive or negative values.

Panel 1 of figure 2 provides an example of a yield curve constrained by the lower bound, which represents an unconventional monetary policy environment. The SSR is negative, indicating that the stance of monetary policy is more accommodative than a near zero policy rate setting alone. Panel 2 of figure 2 provides an example of yield curve data that is not materially constrained by the lower bound. In this case, the option effect is negligible, and so the SSR and the policy rate are essentially identical. Figure 1, which plotted the time series of the shadow short rate from our benchmark model, showed the close correspondence between the SSR and the federal funds target rate in the conventional monetary policy period.

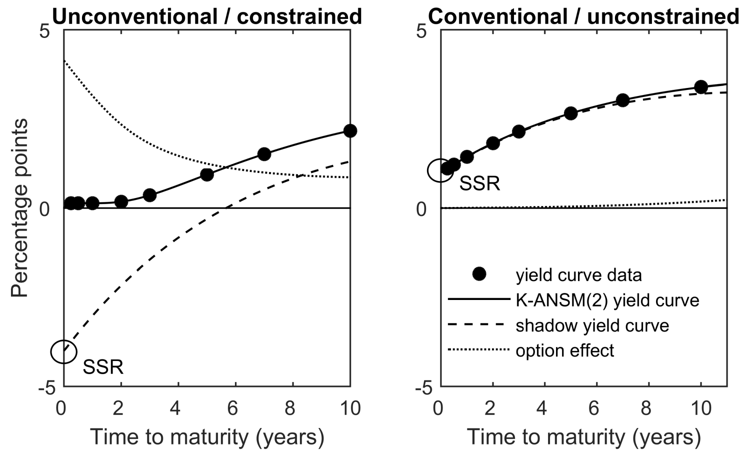

Figure 2: Concept of the shadow yield curve and the SSR implied by the K-ANSM(2) and the actual zero lower bounded yield curve data.

An SSR series, appropriately estimated, is therefore a good candidate metric for the stance of monetary policy across conventional and unconventional monetary policy regimes. However, it is important to emphasize that shadow short rates are not necessarily a perfect monetary policy metric. First, the SSR is not an effective or market interest rate at which economic agents can borrow and lend. Rather, the SSR is a summary measure derived from yield curve data that essentially reflects the degree to which intermediate and longer maturity rates are lower than would be expected if a zero policy rate prevailed in the absence of unconventional policy measures. In that respect, the lower interest rates along the yield curve provide an avenue for additional monetary stimulus and the shadow short rate summarizes that effect. Second, SSRs are estimated quantities that therefore are subject to uncertainties, rather than a unique observable variable.

3.2 Robustness of shadow short rates

Because SSRs are estimated quantities they will be influenced by the model specification and data used to estimate them. Hence, it is important to carefully justify one's modeling and estimation choices, to consider the robustness of SSR estimates from different model specifications and data, and to test the robustness of results in any subsequent applications. This subsection covers the former two aspects, and section 5.4 addresses the latter.

Our first choice is to obtain a benchmark SSR series from a two factor SLM, which we found provides the best trade-off between goodness of fit to our yield curve data and robustness of the SSR estimates. Conversely, one factor SLMs do not fit the data closely, while SSR estimates from three factor SLMs suffer from overfitting, leading the results to be very sensitive to minor specification and data variations. Three factor SSR estimates are also often inconsistent with the evolution of unconventional monetary policy. We illustrate and discuss those issues further below, and refer readers to Krippner (2015a and b) for detailed expositions.

Our second choice is to use a benchmark model with an estimated lower bound parameter. That choice allows for the observation that the lower bound is not strictly zero in practice, which in turn arises from institutional frictions and particular policy framework choices. It also obtains the lower bound value consistent with the yield curve data rather than imposing a calibrated value. However, we show below that our benchmark two factor SSR series is robust to alternative lower bounds that span the practically observed range for short maturity interest rates in the United States, while three factor SSR estimates are not.

Our third choice is to estimate a benchmark model using all benchmark maturity interest rates, spanning 0.25 to 30 years. That choice avoids any data exclusion judgements and makes use of the information from the full yield curve. The term structure literature often uses data only out to 10 years and, as illustrated below, our benchmark SSRs series is also robust to using a maturity span of up to 10 years.

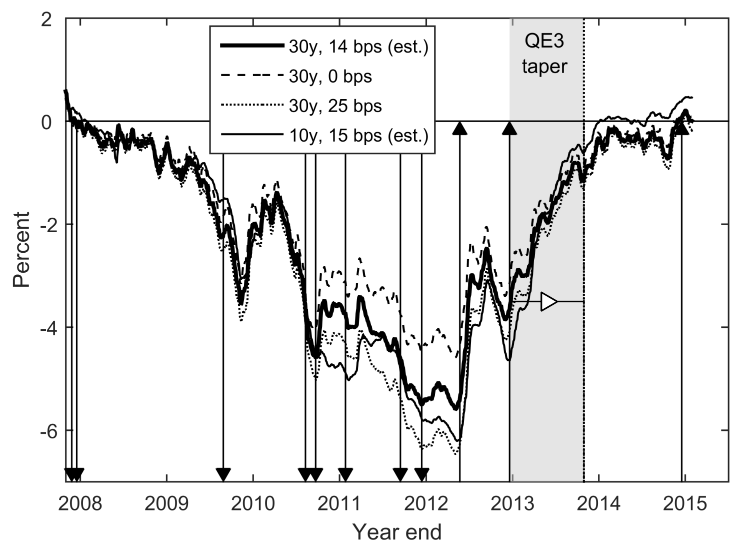

Figure 3: Two factor SSRs with different lower bound parameters.

While we believe our benchmark SSR series provides a suitable metric for quantitative monetary policy analysis, we also show that our results are robust to variations of the K-ANSM(2) specification or estimation. Specifically, figure 3 plots our benchmark daily SSR series along with three alternative K-ANSM(2) SSR series, which are obtained using calibrated lower bound parameters of zero and 25 basis points (bps). The third alternative uses benchmark maturity interest rates spanning 0.25 to 10 years.[8] Despite some magnitude differences, the profiles and dynamics of the shadow short rate series are similar. All of

[8]We focus on the unconventional monetary policy period in figures 3 and 4, where the differences between the series are most material, and so we can highlight the major unconventional monetary policy events. The SSR estimates over the conventional monetary policy period are very similar to each other, being close to the FFTR, as illustrated in figure 1.

the series are also consistent with the evolution of major unconventional monetary policy events, which are listed in table 1 and indicated with down arrows for easings and up arrows for tightenings in figure 3.[9] In addition, all of our SSR series reach negative values of a similar magnitude to the Taylor (1999) rule; i.e. around –4 to –5 percentage points.

Table 1: Major unconventional monetary policy events

Date	Announcement
25/11/2008	QE1 announced (↓)
16/12/2008	Federal funds rate target set to a range of zero to 25 basis points (↓)
27/08/2010	QE2 foreshadowed (↓)
09/08/2011	Calendar forward guidance announced (↓)
21/09/2011	Operation Twist (↓)
25/01/2012	Calendar forward guidance extended (↓)
13/09/2012	QE3 announced and calendar forward guidance extended (↓)
12/12/2012	QE3 extended and unemployment based forward guidance announced (↓)
22/05/2013	QE3 tapering foreshadowed (↑)
18/12/2013	QE3 tapering commenced (↑)
16/12/2015	Federal funds rate target set to a range of 25 to 50 basis points (↑)

Note: ↓ easing, ↑ tightening

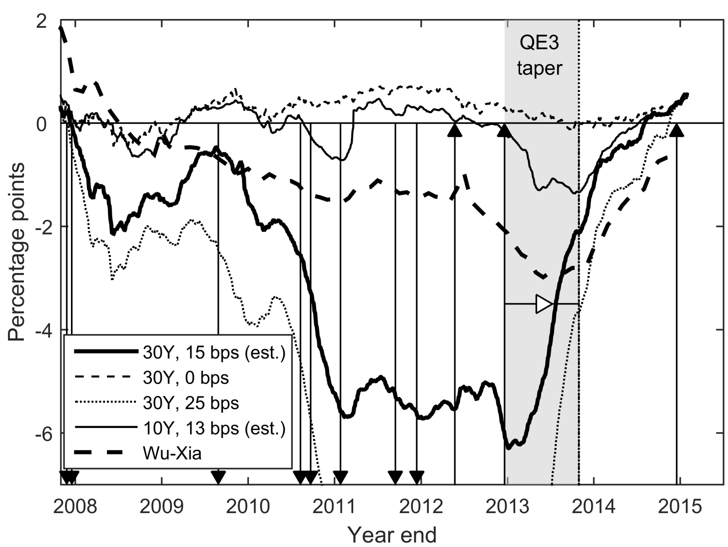

Figure 4: Examples of SSR estimates from three factor SLMs.

Figure 4 illustrates two serious shortcomings of SSR estimates from three factor SLMs, which have been variously documented; see Bauer and Rudebusch (2015), Christensen and Rudebusch (2015), and Krippner (2015b). The series in figure 4 were obtained with a

[9] Krippner (2015b) confirms, using end-month estimates, that correlations of easing / tightening events with declines / increases in K-ANSM(2) shadow short rates are always positive and statistically significant. Conversely, the correlation point estimates are generally negative and always statistically significant for the Wu and Xia (2016) SSR estimates illustrated below.

K-ANSM(3) specification, data out to 10 or 30 years, and estimated or calibrated lower bound parameters.

Regarding the issues, first, the SSR estimates are evidently not robust and small changes to the lower bound parameter markedly alter the profiles and dynamics of the estimated SSR series.[10] Second, SSR estimates from three factor SLMs often evolve counterintuitively relative to the sequence of major unconventional monetary policy events.

Of particular note in this regard is an alternative end-month shadow short rate series from Wu and Xia (2016), which is obtained from a three factor model, slightly different from the K-ANSM(3) specification, yield curve data out to 10 years, and a calibrated lower bound parameter of 25 basis points. The Wu and Xia (2016) SSR estimates indicate a large implied policy easing between May 2013 and May 2014, despite the removal of unconventional monetary accommodation first being foreshadowed in May 2013 and then progressively implemented from December 2013. Specifically, on 22 May 2013 Chair Bernanke, in his testimony on the economic outlook before Congress, signaled the tapering of QE3 stating "(i)f we see continued improvement and we have confidence that is going to be sustained, then we could in the next few meetings, **take a step down in our pace of purchases**."[11] (Emphasis added). Tapering was progressively implemented from January 2014 following the 18 December 2013 FOMC meeting at which "the Committee **decided to modestly reduce the pace of its asset purchases**."[12] (Emphasis added).

4 Empirical framework and data

In this section we outline our latent factor model and the data that underlies the results we report in section 5.

4.1 Latent factor model

The principle behind latent factor models, which are a popular tool in the finance literature, is that they identify monetary policy shocks via heteroskedasticity in daily financial market data between monetary policy event days and non-monetary policy days; see Rigobon and Sack (2004) and Craine and Martin (2008).

In notation, the financial market data on non-monetary policy days may be expressed as the following linear function of common (systematic) and idiosyncratic (diversifiable) factors

$$y_{j,t} = \alpha_j a_t + \delta_j d_{j,t} \tag{1}$$

where $y_{j,t}$ is the demeaned first difference of the financial market variable j at time t for $t = 1, .., T$, a_t is a shock common to all assets and $d_{j,t}$ represents idiosyncratic shocks to $y_{j,t}$.[13]

[10] For ready comparibility, we have deliberately plotted the SSRs on the same scale as for the two factor results. The minimum value of the "30Y, 25 bps" series is –12.4 percent.

[11] https://www.gpo.gov/fdsys/pkg/CHRG-113shrg81472/html/CHRG-113shrg81472.htm

[12] http://www.federalreserve.gov/newsevents/press/monetary/20131218a.htm

[13] Principal component analysis on the data supports the inclusion of just one common factor. The first

The principle of identification through heteroskedasticity is that reactions to monetary policy shocks m_t are in addition to the common and idiosyncratic shocks on non-monetary policy days. Monetary policy days T^{MP} can be exogenously identified so long as central banks make public and explicit monetary policy announcements. In that case, the additional monetary policy factor m_t applies only on monetary policy days

$$y_{j,t} = \alpha_j a_t + \delta_j d_{j,t} + \beta_j m_t \tag{2}$$

where $t \in T^{MP}$, while equation 1 applies on all other days, $t \in T^{OTH}$ and $T^{MP}+T^{OTH} = T$.

All factors, a_t, m_t, and $d_{j,t}$ for $j = 1, ..., N$, where N is the number of assets, are assumed to be independent with zero mean and unit variance. The parameters α_j, δ_j, and β_j are the factor loadings, where β_j is the response of asset j to monetary policy shocks.

Re-writing equations 1 and 2 in matrix form gives

$$Y_t = \Lambda H_t \text{ for } t \in T^{OTH} \text{ and } Y_t = \Lambda H_t + \Phi m_t \text{ for } t \in T^{MP} \tag{3}$$

Y_t is an $(N \times 1)$ vector of $y_{j,t}$, H_t is an $((N+1) \times 1)$ vector of shocks, where the common shock a_t is in the first row and the idiosyncratic shocks are in the remaining N rows. The matrices Λ and Φ contain the factor loadings and Λ is $(N \times (N+1))$ and Φ is $(N \times 1)$. Using the independence assumption and the first and second moment assumptions for the latent factors yields

$$\Omega^{OTH} = \Lambda\Lambda' \text{ and } \Omega^{MP} = \Lambda\Lambda' + \Phi\Phi' \tag{4}$$

where Ω^i with $i = OTH, MP$ is the variance covariance matrix of Y_t. Ω^{MP} applies on the exogenously identified monetary policy days and Ω^{OTH} on all other days. Writing out the first elements of Ω^{MP} gives

$$\Omega^{MP} = \begin{bmatrix} \alpha_1^2 + \delta_1^2 + \beta_1^2 & & \\ \alpha_1\alpha_2 + \beta_1\beta_2 & \alpha_2^2 + \delta_2^2 + \beta_2^2 & \\ \vdots & & \ddots \\ \cdots & \cdots & \end{bmatrix} \tag{5}$$

Ω^{OTH} is analogous with $\beta_j = 0$ for all j.

The latent factor model is estimated using generalized method of moments (GMM) techniques where the model's theoretical second moments in equation 4 are matched to the data moments. In the case of an overidentified model, which occurs when $N \geqslant 6$, the Hansen (1982) method for combining the generated moment conditions with the number of parameter estimates is implemented; see Claus and Dungey (2012) for details.[14]

principal component for all of our empirical specifications explains at least 81 percent or more of the sample variance.

[14] In the empirical application below, we use the identity matrix as the weighting matrix as the inverse of the variance covariance matrix leads to a loading of close to zero for the 10 year treasury rate idiosyncratic factor in the latter part of the sample period. This is likely a reflection of the binding lower bound for short term nominal interest rates over the sample period. Using equal weights is not expected to bias the results. In fact Altonji and Segal (1996) show that equal weights are generally optimal in small samples. Although the total sample size is large, the number of policy days is relatively small.

4.2 Data

We estimate the latent factor model separately for the US conventional and unconventional monetary policy periods. The conventional period is from 1 February 1996 to 12 September 2008, when short term interest rates were comfortably above the zero lower bound. The beginning of this period is determined by the availability of real estate investment trust data discussed further below, and it is also not long after January 1994 when the Board of Governors of the Federal Reserve began making explicit monetary policy announcements on scheduled days, which allows the exogenous identification of monetary policy days T^{MP}. The end of the conventional period is immediately prior to the bankruptcy of Lehman Brothers, which was announced during the weekend. The unconventional period is from 15 September 2008, the Monday after the bankruptcy of Lehman Brothers, to 28 January 2016, which is the end of our sample.[15]

We obtain information on monetary policy days from the Federal Reserve Board's website. We include all policy announcement days (see Kuttner 2001 and Gürkaynak, Sack, and Swanson 2005) as well as days of the Chair's semi-annual monetary policy report to Congress (see Rigobon and Sack 2004).[16] We also identified 25 November 2008, 1 December 2008, and 22 May 2013 as monetary policy announcement days. 25 November 2008 marks the beginning of QE1. The 25 November 2008 press release was followed by a speech on 1 December 2008 by Chair Bernanke, in which he stated that "the Fed could purchase longer-term treasury or agency securities on the open market in substantial quantities". On 22 May 2013 Chair Bernanke signaled the tapering of QE3 in his testimony on the economic outlook before Congress. In addition, during the period of unconventional monetary policy we included as announcement days speeches by the Chair at the Annual Economic Symposium in Jackson Hole. Our identification of unconventional monetary policy days is in line with Rogers, Scotti and Wright (2014). The full period includes 221 monetary policy days $\left(T^{MP} = 221\right)$ and 4,590 all other days $\left(T^{OTH} = 4,590\right)$. The conventional period has 135 monetary policy days and 3,157 all other days, and the unconventional period has 86 monetary policy days and 1,433 all other days.

Regarding the daily financial market data, we have chosen a wide range to broadly represent various perspectives of financial markets. We include the benchmark 90 day treasury rate as the observable short maturity rate, and the benchmark 10 year treasury constant maturity rate as a long term government-risk rate. We include the gold fixing price at 10:30 AM (London time) in the London bullion market in US dollars, shifted forward by one day to account for time zone differences. For equity prices we use the Standard & Poor's (S&P) 500 stock price index. We include corporate bond prices by calculating a bond price index from Moody's seasoned Aaa corporate bond yields.[17] For

[15] Our unconventional period therefore includes a short period at the beginning and end where the target range for the FFTR was not zero to 0.25 percent, which was set in 16 December 2008 and raised to a 0.25 to 0.50 percent range on 16 December 2015. However, those periods may also be regarded as unconventional, because liquidity measures were implemented in the wake of the bankruptcy of Lehman Brothers, QE1 was announced on 25 November 2008, and the Federal Reserve expressly maintained a hugely expanded balance sheet after raising the FFTR target range on 16 December 2015.

[16] During 2003 the Chair delivered three monetary policy testimonies to Congress.

[17] Corporate bond yields could be used directly; it does not change our results, except that higher yields

real estate investment trust prices we use the Wilshire US real estate securities total market index, which are total market returns (including reinvested dividends) of publicly traded real estate equity securities. Finally, we include a representative exchange rate in our data set, i.e. the New York close mid rate for the US dollar / British pound exchange rate (an increase [decrease] in the exchange rate indicates a depreciation [appreciation] of the US dollar). The latter is sourced from Bloomberg, while the remainder of the data is sourced from the Federal Reserve Economic Database (FRED) on the Federal Reserve Bank of St. Louis website.

For the variables described above, we calculate demeaned first differences over the conventional and unconventional periods for estimating the latent factor model. The first differences are calculated directly for the interest rate data, and as changes in the logarithm of the level for the asset prices and the exchange rate.

The alternative dataset replaces the 90 day treasury rate with the SSR estimates that we have already discussed in section 3.2. The yield curve data used to obtain those estimates is sourced from Bloomberg.

5 Empirical results

In this section, we present and discuss a series of results obtained from our datasets and the latent factor model. We focus in particular on the responses to monetary policy shocks, to see how they may have changed between the conventional and unconventional periods of monetary policy, and also to assess the usefulness of the SSR as a monetary policy metric.

Hence, section 5.1 discusses the monetary policy responses for the 90 day rate and SSR datasets over the conventional and unconventional monetary policy periods, section 5.2 discusses differences and changes in monetary policy responses, and section 5.3 discusses normalized monetary policy responses.

5.1 Monetary policy responses

Table 2 reports the estimated responses to monetary policy shocks. The parameter estimates (with standard errors in parentheses) are the responses to a one standard deviation tightening monetary policy shock. The interest rate responses are in basis points and the asset price responses are in percentage points. Note that all our estimation results are symmetric, and so imply opposite movements in the variables for an easing monetary policy shock, but we discuss the tightening perspective. Appendix B reports the full sets of results for each period, including the common and idiosyncratic responses and the estimated standard errors underlying our indications of statistical significance.

The first column of table 2 shows the results for the conventional period with the 90 day rate dataset. These estimates provide a useful point of comparison for the other results, because changes in short term interest rates have often been used to proxy monetary policy shocks in event studies. The signs of the responses are as one would expect from a tightening

would equate to lower prices.

monetary policy shock. That is, the 90 day and 10 year interest rates increase,[18] asset prices decrease, and the exchange rate appreciates. However, the responses are only statistically significant for the 90 day and 10 year interest rates and equity prices.

Table 2: Monetary policy response estimates

	Period 1		Period 2	
	90 day	SSR	90 day	SSR
Short rate	3.265 **	1.474 **	-0.227 **	2.123 *
	(0.199)	(0.306)	(0.137)	(0.148)
10 year treasury rate	2.999 **	3.525 **	8.191 **	8.174 **
	(0.209)	(0.198)	(0.086)	(0.086)
Corporate bond prices	0.238	-0.100	-0.890 **	-0.648 **
	(0.254)	(0.358)	(0.142)	(0.153)
Gold price	-0.118	-0.263	-0.752 **	-0.700 **
	(0.268)	(0.356)	(0.134)	(0.151)
Equity prices	-0.518 **	-0.482 *	-0.423 **	-0.569 **
	(0.269)	(0.355)	(0.151)	(0.157)
REIT prices	-0.183	-0.018	-0.771 **	-0.935 **
	(0.269)	(0.358)	(0.158)	(0.158)
Exchange rate	-0.052	-0.185	-0.321 **	-0.360 **
	(0.268)	(0.357)	(0.137)	(0.152)

Period 1: Conventional monetary policy, 1 February 1996 to 12 September 2008.
Period 2: Unconventional monetary policy, 15 September 2008 to 28 January 2016.
90 day: The short rate is the 90 day treasury rate.
SSR: The short rate is the shadow short rate.
Level of significance: ** 5 percent, * 10 percent.

The second column shows that the responses with the SSR dataset in the conventional period are similar to the 90 day rate dataset results. This indicates that SSR changes offer similar information with respect to monetary policy shocks as 90 day rates, although the magnitude of the SSR response is smaller than for the 90 day rate. The difference is not surprising; the SSR is estimated from the full yield curve and therefore SSR changes reflect a wider set of information, including the effect of actual and expected policy rate changes for longer horizons, than the 90 day rate.

From the third column, for the unconventional period with the 90 day rate dataset, it is clear that changes to the 90 day rate are now seriously deficient as a monetary policy metric. The response to a monetary policy shock is opposite in sign and an order of magnitude smaller than in the conventional period. Hence, changes to the 90 day rate should not be used as a measure of monetary policy shocks during the unconventional period. Of course, that recommendation and the results should not come as a surprise, because it is

[18] Monetary policy shocks also influence the slope of the yield curve, because the 90 day rate responds more than the 10 year rate.

readily apparent from even casual observation that movements in 90 day rates have been constrained by the lower bound in the unconventional period.

Nevertheless, despite the 90 day rate performing poorly, the responses to monetary policy shocks for the other variables all remain as expected. That is, the 10 year rate increases, asset prices fall, and the exchange rate appreciates. Indeed, the responses are now all larger (apart from equity prices) and all are statistically significant. We test the significance of the differences in the following section, and confirm the results without the 90 day rate in section 5.4. Our result for the exchange rate is counter to that of Glick and Leduc (2013) who find virtually no effect of unconventional monetary policy surprises on the value of the US dollar over one day.

The fourth column shows that, in the unconventional period, the SSR response to monetary policy shocks remains similar to the conventional period, in sign, magnitude, and statistical significance. The responses of the remaining variables are similar to the responses for the 90 day rate dataset in the unconventional period. These results suggest that, unlike the 90 day rate, changes to the SSR have the potential to be used as a metric for monetary policy shocks in both the conventional and unconventional periods. The latter reflects that SSRs can continue to move freely in the unconventional period, which is the underlying principle of shadow / lower bound term structure models.

5.2 Differences in monetary policy responses

Table 3 reports a series of differences between the estimated responses to monetary policy shocks from table 2. The standard errors and levels of significance are obtained from a Monte Carlo simulation that we require to obtain the results in section 5.3, and which we will detail there.

The first column of table 3 shows that, for the 90 day rate dataset, the responses to monetary policy shocks have increased from the conventional period to the unconventional period. For example, the response of the 10 year rate increases by around 5 basis points, which is statistically significant. This result is consistent with earlier findings that quantitative easing influences longer term interest rates (e.g. Krishnamurthy and Vissing-Jorgensen 2011 and Gagnon, Raskin, Remache, and Sack 2011). The responses of corporate bond prices, the gold price, and REIT prices are also larger in magnitude by statistically significant amounts. Similarly the exchange rate responds more strongly, but the difference is not statistically significant. The attenuated response of equity prices in the unconventional period is consistent with Rosa's (2012) and Kiley's (2014) results, although our result is insignificant and the point estimate of the change is opposite in our SSR results. Note that the change in the response for the 90 day rate is large and significant, but that mainly reflects its deficiencies as a monetary policy metric in the unconventional period, as discussed in the previous section.

The second column shows that the 10 year rate, asset price, and exchange rate responses in the conventional period are similar whether the 90 day rate or SSR datasets are used. That is, the difference in the 10 year rate response is only marginally significant at the 10 percent level, and the remaining differences are all insignificant. The SSR response is smaller than the 90 day rate response, as already discussed in the previous section, but otherwise the SSR performs similarly to the 90 day rate as a monetary policy metric in normal times.

The third columns shows that, for the unconventional period, the SSR results are also similar to those using the 90 day rate. The only significant difference is between the 90 day rate and SSR responses, which reflects that the former no longer provides a useful monetary policy metric in the unconventional period.

Table 3: Monetary policy response differences

	Period 2 90 day less Period 1 90 day	Period 1 SSR less Period 1 90 day	Period 2 SSR less Period 2 90 day	Period 2 SSR less Period 1 SSR
Short rate	-3.492 **	-1.791 **	2.350 **	0.649 *
	(0.240)	(0.364)	(0.200)	(0.338)
10 year treasury rate	5.192 **	0.527 *	-0.017	4.649 **
	(0.228)	(0.290)	(0.121)	(0.217)
Corporate bond prices	-1.128 **	-0.338	0.242	-0.548
	(0.289)	(0.438)	(0.213)	(0.385)
Gold price	-0.634 **	-0.144	0.052	-0.438
	(0.300)	(0.444)	(0.201)	(0.389)
Equity prices	0.095	0.036	-0.146	-0.087
	(0.306)	(0.451)	(0.218)	(0.385)
REIT prices	-0.588 *	0.165	-0.164	-0.917 **
	(0.308)	(0.450)	(0.224)	(0.389)
Exchange rate	-0.269	-0.133	-0.039	-0.175
	(0.299)	(0.443)	(0.205)	(0.387)

Period 1: Conventional monetary policy, 1 February 1996 to 12 September 2008.
Period 2: Unconventional monetary policy, 15 September 2008 to 28 January 2016.
90 day: The short rate is the 90 day treasury rate.
SSR: The short rate is the shadow short rate.
Level of significance: ** 5 percent, * 10 percent.

The SSR provides a consistent monetary policy metric over both the conventional and unconventional policy periods. It therefore can be used to assess the changes in responses to monetary policy shocks between the two periods. The fourth column contains these results. All responses are larger in the unconventional period than the conventional period, although only the SSR, 10 year rate, and REIT price responses are significantly larger. The latter results are interesting because those variables relate closely to the type of securities targeted by the Federal Reserve in the QE programs. QE2, Operation Twist, and QE3 involved purchases of US treasury bonds, hence influencing the 10 year rate and the SSR estimated from yield curve data, while REITs are related to mortgage-backed securities which were purchased in QE1 and QE3. The increased response for REITs may also reflect their sensitivity to interest rates through two channels. First, a decline in interest rates during the unconventional monetary policy period lowered the discount rate for expected future net income, thereby producing a present value effect. Second, the decline in interest rates also lowered the cost of borrowing for real estate investment vehicles, which are typically highly leveraged, thereby producing a net income effect.

5.3 Normalized monetary policy responses

The results from the previous section indicate that the response to monetary policy shocks has been larger in the unconventional period compared to the conventional period. A related question is: how much of the increased response can be attributed to larger monetary policy shocks versus a larger transmission of similar sized shocks? To provide an indication, table 4 reports the monetary policy responses normalized with respect to the SSR as a proxy for monetary policy shocks. As background, the literature often assumes, reasonably, that monetary policy shocks are the dominant factor for changes to financial market prices on monetary policy days, and that the change in the short rate provides a metric for the monetary policy shock. These assumptions may be reflected in our model by setting $\alpha_1 = \delta_1 = 0$ in equation 2, obtaining $y_{1,t} = \beta_1 m_t$, and therefore the monetary policy shock series as proxied by changes to the SSR is

$$m_t = \frac{y_{1,t}}{\beta_1} \tag{6}$$

Substituting equation 6 into equation 2 for the remaining elements, i.e. $j \neq 1$, and taking the first derivative with respect to the monetary policy shock y_1 yields the normalized response of asset j to a one basis point monetary policy surprise as proxied by the change in the SSR

$$\frac{\partial y_j}{\partial y_1} = \frac{\beta_j}{\beta_1} \tag{7}$$

We report the standardized responses for the 10 year rate, asset prices, and the exchange rate respectively for the conventional and unconventional monetary policy period in columns 1 and 2 of table 4.

To obtain standard errors and levels of significance for the normalized results, we use a Monte Carlo simulation. Specifically, we simulate 10,000 responses using the estimated parameters and associated covariance matrices from the original estimations (i.e. those underlying table 2 and the full results in appendix B), calculate the associated normalized responses with respect to the SSR response for each simulation, and then calculate the 5 and 10 percent levels of significance from the resulting distribution. The reason for using this method is to appropriately allow for the non-normal distribution that results from dividing one random variable by another. However, for brevity we summarize the distribution using the standard errors reported in the tables, rather than the actual percentiles used to determine the levels of significance.

The first three columns of table 4 show the normalized results for the responses reported in table 2, apart from those for the 90 day rate dataset in the unconventional period.[19] The results in terms of signs and significance are similar to those reported in table 1. The main difference is that for the SSR dataset in the conventional period, only the 10 year rate response remains significant.

Table 4: Normalized monetary policy responses

	Period 1 90 day	Period 1 SSR	Period 2 SSR	Period 2 SSR less Period 1 SSR
Short rate	1	1	1	0
10 year treasury rate	0.919 **	2.392 **	3.850 **	1.459
	(0.104)	(1.086)	(0.476)	(1.145)
Corporate bond prices	0.073	-0.068	-0.305 **	-0.237
	(0.092)	(0.428)	(0.12)	(0.438)
Gold price	-0.036	-0.178	-0.330 **	-0.152
	(0.094)	(0.437)	(0.125)	(0.452)
Equity prices	-0.159 *	-0.327	-0.268 **	0.059
	(0.098)	(0.463)	(0.143)	(0.480)
REIT prices	-0.056	-0.012	-0.440 **	-0.428
	(0.095)	(0.431)	(0.169)	(0.459)
Exchange rate	-0.016	-0.125	-0.170 **	-0.044
	(0.095)	(0.434)	(0.118)	(0.446)

Period 1: Conventional monetary policy, 1 February 1996 to 12 September 2008.
Period 2: Unconventional monetary policy, 15 September 2008 to 28 January 2016.
90 day: The short rate is the 90 day treasury rate.
SSR: The short rate is the shadow short rate.
Level of significance: ** 5 percent, * 10 percent.

The final column of table 4 shows the difference in the normalized responses for the SSR dataset between the conventional and unconventional periods. All of these differences are insignificant, which suggests that the response to a monetary policy shock of a given size has not changed from the conventional to the unconventional period. In other words, we find no evidence that the transmission of monetary policy into financial markets has changed. By implication then, the larger responses in the unconventional period appear to be due to an increase in the size of monetary policy shocks.

[19] The results for the 90 day unconventional dataset are not reported, given the deficiencies discussed earlier. In addition, the 90 day response distribution of –0.227 (0.137) spans zero with relatively high probability, which would make any normalizations highly variable.

5.4 Robustness checks

This section discusses the findings from robustness checks. We do not report the detailed results due to space considerations, but they are available on request.

The first robustness check is to assess whether the results are different if no short rate is used in the estimation, otherwise one might legitimately question if the results are due to the invalid use of the 90 day rate in the unconventional period or the use of the SSR estimates rather than observed data. When using just the 10 year rate and the remaining financial market variables, we find substantially similar responses to monetary policy shocks as those reported in section 5.1. The main difference is that the responses of equity prices are no longer significant in both periods, and the exchange rate response is not significant in the unconventional period. The change in responses, the normalized responses, and the change in normalized responses are also similar to the results reported in the previous section. However, the confidence intervals of the latter are wider than for our SSR results.

The second robustness check is to use the three alternative SSR estimates, which were plotted in figure 3 and obtained from two factor SLMs with different lower bounds and data. For the SSR series estimated from benchmark maturity interest rates spanning 0.25 to 30 years, we find substantially similar responses to monetary policy shocks as those reported in section 5.1. The results are similar when using SSRs estimated from interest rates spanning 0.25 to 10 years, except the SSR responses to monetary policy shocks are smaller, and the response is insignificant in the conventional period. That result reflects the use of less information than when the full yield curve is used to obtain the SSR estimates.

The third robustness check is to assess SSR estimates from three factor SLMs as a monetary policy metric described in section 3.4.[20] Analogous to the three factor SSR estimates themselves being counterintuitive, we found counterintuitive negative responses of the SSR to tightening monetary policy shocks. However, the responses of the 10 year rate, asset prices, and the exchange rate were similar to the results reported in section 5.1.

In summary, our robustness checks generally support our findings that the responses of financial market variables to monetary policy shocks have increased from the conventional to the unconventional period, and the increases appear due to larger monetary policy shocks rather than a change in the transmission of shocks. Furthermore, the robustness checks show that all K-ANSM(2) SSR datasets obtain similar SSR responses to monetary policy shocks over both conventional and unconventional monetary policy periods and the responses are consistent with movements in the 10 year rate, asset prices, and the exchange rate. Appropriately robust two factor SSR estimates appear to be good monetary policy metrics for monitoring and quantitative analysis over conventional and unconventional policy periods. Conversely, SSR estimates from three factor SLMs are overly sensitive in the unconventional policy period, due to overfitting, and they respond counterintuitively to monetary policy shocks. Hence, we recommend that SSR estimates from three factor SLMs should not be used as a monetary policy metric.

[20] We have not tested our findings with the Wu and Xia (2016) SSR series, because they are end of month estimates and we require daily estimates for our high frequency analysis. However, with reference to the discussion in section 3.2, we expect that our results and recommendations noted here will generally apply to three-factor SSR series.

6 Conclusion and policy implications

The global financial crisis and the subsequent "great recession" of 2008-09 required unprecedented monetary easing by central banks around the world. The US Federal Reserve responded initially by lowering its policy rate, the federal funds rate, to near zero levels. Having exhausted that conventional means of monetary policy easing by late 2008, the Federal Reserve also implemented unconventional monetary policy measures, e.g. asset purchases and forward guidance on policy rates, to provide additional stimulus.

In this paper we quantified the response of US asset markets to monetary policy shocks during the conventional and unconventional monetary policy periods and, in that context, assessed the usefulness of a shadow short rate as a common metric across those periods. We first established with observable datasets that the responses of interest rates, asset prices, and the exchange rate to monetary policy shocks all became significant in the unconventional period, and increased from the conventional to the unconventional period. Furthermore, we found significant changes in the response of the 10 year rate, corporate bond prices, the gold price, and real estate investment trust prices.

We found, as expected, that the 90 day rate no longer provides a useful metric for monetary policy shocks in the unconventional period. However, we showed that appropriately robust SSR estimates provide a useful monetary policy metric across conventional and unconventional monetary policy periods, because they can freely take on negative values to reflect a near zero policy rate plus unconventional policy actions. In particular, SSR estimates respond consistently with the other financial market variables to monetary policy shocks.

Finally, we provided evidence that the increased response of asset markets appears due to larger monetary policy shocks in the unconventional period, rather than changes in the transmission of shocks. The associated policy implication is that central banks should be aware of potentially larger financial markets responses to surprise monetary policy announcements in the prevailing unconventional period relative to previous experience in the conventional period, and that can potentially be mitigated by using more cautious statements. As a practical example, we note the large response in the wake of Chair Bernanke's 22 May 2013 comments on tapering the QE3 asset purchase program (the so-called "taper tantrum"). Subsequent comments from Federal Open Market Committee (FOMC) members settled financial markets with caution that any tapering would be gradual, and any subsequent normalization of the policy rate would be some way off.

A Overview of the shadow / lower bound framework

In this appendix, we outline the generic shadow / lower bound (SLM) framework, our benchmark SLM specification, and the estimation.

A.1 Generic SLM framework

The concept of SLMs was originally introduced in Black (1995) and is based on the lower bound mechanism

$$\underline{\mathrm{r}}(t) = \max\left[\mathrm{r}(t),\ \mathrm{r}_{\mathrm{LB}}\right] \tag{8}$$

where $\mathrm{r}(t)$ is the SSR that can freely adopt negative values, and $\underline{\mathrm{r}}(t)$ is the lower bounded or actual short rate which is constrained to a minimum value of the lower bound parameter r_{LB}.[21] Unfortunately, the direct application of Black's (1995) framework with any dynamic process to represent the SSR is relatively intractable and examples are generally limited; e.g. Bomfim (2003) and Kim and Singleton (2012). However, Krippner (2015a) derives a framework with a Gaussian affine term structure model (GATSM) process for the SSR that closely approximates the Black (1995) framework and is much more tractable, for any number of factors. Wu and Xia (2016) derive the discrete time equivalent.[22] The key result in both derivations is the closed form analytic expression for lower bounded forward rates $\underline{\mathrm{f}}(x_t, \tau)$

$$\underline{\mathrm{f}}(x_t, \tau) = \mathrm{r}_{\mathrm{LB}} + \left[\mathrm{f}(x_t, \tau) - \mathrm{r}_{\mathrm{LB}}\right] \cdot \Phi\left[z(x_t, \tau)\right] + \omega(\tau) \cdot \phi\left[z(t, \tau)\right] \tag{9}$$

with

$$z(x_t, \tau) = \frac{\mathrm{f}(x_t, \tau) - \mathrm{r}_{\mathrm{LB}}}{\omega(\tau)} \tag{10}$$

where τ is the time to maturity, and $\Phi[\cdot]$ and $\phi[\cdot]$ are respectively the unit normal cumulative density and density functions. The shadow forward rate function $\mathrm{f}(x_t, \tau)$ and volatility function $\omega(\tau)$ are dependent on the model specification in terms of the state variables x_t and their associated parameters, which we discuss below. Equation 9 is the basis for the measurement equation when estimating shadow / lower bound models because it provides model results that can be compared to yield curve data.

The state equation is obtained from the vector Ornstein-Uhlenbeck process that the state variables follow under the physical $\mathbb{P}$ measure, i.e.

$$x_t = \theta + \kappa\left[\theta - x_{t-1}\right] + \sigma \tag{11}$$

[21] The shadow yield curve and the option effect arise directly from this decomposition of the lower bounded short rate into the SSR and the physical currency option pay-off, i.e. $\underline{\mathrm{r}}(t) = \max\{\mathrm{r}(t), \mathrm{r}_{\mathrm{LB}}\} = \mathrm{r}(t) + \max\{0, -[\mathrm{r}(t) - \mathrm{r}_{\mathrm{LB}}]\}$. If $\mathrm{r}(t) > \mathrm{r}_{\mathrm{LB}}$, the option pay-off $\max\{0, -[\mathrm{r}(t) - \mathrm{r}_{\mathrm{LB}}]\}$ is zero, and $\underline{\mathrm{r}}(t) = \mathrm{r}(t)$ If $\mathrm{r}(t) < \mathrm{r}_{\mathrm{LB}}$, the option pay-off is $-\mathrm{r}(t) + \mathrm{r}_{\mathrm{LB}}$, and $\underline{\mathrm{r}}(t) = \mathrm{r}_{\mathrm{LB}}$. Note that non-zero lower bounds typically prevail in practice due to institutional frictions and policy framework choices. Short maturity rates and market expectations of their evolutions may therefore be non-zero, and so the shadow / lower bound model should try to appropriately account for those non-zero expectations on the yield curve data; see Krippner (2015a) for a complete discussion.

[22] Krippner (2015a), Christensen and Rudebusch (2015) and Wu and Xia (2016) show that the approximation is within a maximum of less than 6 basis points for the 10 year maturity (and less for shorter maturites), and within 14 basis points for the 30 year maturity; see Krippner (2015a).

where x_t is the $N \times 1$ vector of state variables with a long run value of θ, a mean reversion matrix κ and a volatility matrix σ.[23] The linear market price of risk specification $\Pi(t) = \gamma + \Gamma x_t$ provides the risk adjusted $\mathbb{Q}$ measure process for the state variables, which is analogous to equation 11 with $\tilde{\kappa} = \kappa + \Gamma$ and $\tilde{\theta} = \tilde{\kappa}^{-1}(\kappa\theta - \gamma)$. The state variables x_t and parameters $\tilde{\kappa}$, $\tilde{\theta}$, and σ define closed form analytic expressions for $\mathrm{f}(x_t, \tau)$ and $\omega(\tau)$ which, together with the parameter $\mathrm{r_{LB}}$, define the closed form analytic expression $\underline{\mathrm{f}}(x_t, \tau)$ in equation 9.

Once the shadow / lower bound model is estimated, with a suitable non-linear Kalman filter, the SSR point estimate is

$$\mathrm{r}(t) = a_0 + b_0' x_t \tag{12}$$

which is the zero maturity rate on the estimated shadow forward rate or interest rate curve. SSRs can freely take on negative values and a negative SSR can, in principle, be interpreted as a combination of a near zero policy rate setting plus unconventional policy actions (e.g. quantitative easing, forward guidance, etc.) that is more accommodative than a near zero policy rate setting alone.

A.2 Benchmark specification and estimation

Our benchmark shadow / lower bound model uses the two factor arbitrage free Nelson and Siegel (1987) model as the shadow yield curve within the Krippner (2015a) framework, which we denote the K-ANSM(2). Section 3 of the main text explains why we chose the K-ANSM(2) specification, in the context of alternative specifications that we and others have considered.

The K-ANSM(2) shadow forward rate specification is

$$\mathrm{f}(x_t, \tau) = L_t + S_t \cdot \exp\left(-\tilde{\phi}\tau\right) + \mathrm{VE}(\tau) \tag{13}$$

where L_t and S_t are respectively the Level and Slope state variables, $\tilde{\phi}$ is the mean reversion parameter for the Slope state variable, and the shadow term structure volatility effect $\mathrm{VE}(\tau)$ is

$$\mathrm{VE}(\tau) = \sigma_1^2 \cdot \frac{1}{2}\tau^2 - \sigma_2^2 \cdot \frac{1}{2}\left[G\left(\tilde{\phi}, \tau\right)\right]^2 + \rho\sigma_1\sigma_2 \cdot \tau G\left(\tilde{\phi}, \tau\right) \tag{14}$$

where σ_1 and σ_2 are the annualized standard deviations of Level and Slope innovations, ρ is the correlation of the innovations, and

$$G(x, \tau) = \frac{1 - \exp(-x\tau)}{x};\ G(x, 0) = 1 \tag{15}$$

The SSR volatility function $\omega(\tau)$ is

$$\omega(\tau) = \sqrt{\sigma_1^2 \cdot \tau + \sigma_2^2 \cdot G\left(2\tilde{\phi}, \tau\right) + 2\rho\sigma_1\sigma_2 \cdot \tau G\left(\tilde{\phi}, \tau\right)} \tag{16}$$

[23] All parameter vectors and matrices should be taken as being conformable to x_t.

Using these specifications within equation 9, and allowing for a non-zero estimated lower bound parameter $\mathrm{r_{LB}}$ defines model lower bounded forward rates $\underline{\mathrm{f}}(x_t, \tau)$. We numerically integrate $\underline{\mathrm{f}}(x_t, \tau)$ as follows

$$\underline{\mathrm{R}}\,(x_t, \tau) = \frac{1}{\tau} \int_0^{\tau} \underline{\mathrm{f}}\,(x_t, \tau)\ \mathrm{d}\tau \tag{17}$$

to obtain model interest rates $\underline{\mathrm{R}}(x_t, \tau)$ so that we can estimate the model using interest rate data. The measurement equation is

$$\underline{\mathrm{R}}\,(x_t, \tau) = \underline{\mathrm{R}}\,(t, \tau) + \eta_t \tag{18}$$

where $\underline{\mathrm{R}}(t, \tau)$ is the yield curve data for time to maturity τ and η_t is the estimated residual. The standard deviations of residuals are specified to be homoskedastic, as in Bauer and Rudebusch (2015) and Wu and Xia (2016). The data we use are daily zero coupon interest rates with maturities of 0.25, 0.5, 1, 2, 3, 5, 7, 10 and 30 years. These are overnight indexed swap (OIS) rates, which are from derivative contracts that settle on the realized federal funds rate, from 6 January 2006 (when the full set of yield curve data is first available) to 28 January 2016 (the latest observation at the time of the analysis). We use government rates as a proxy for OIS rates from 31 January 1995 (the start of the Bloomberg data set) to 5 January 2006. Note that we pro-rata the splicing of the two data sets over the first year of their overlap to ensure there is no possibility of any artificially induced changes to the shadow short rate estimates around the splice date.

We estimate the K-ANSM(2) using the iterated extended Kalman filter as detailed in Krippner (2015a). The iterated extended Kalman filter allows for the non-linearity of the measurement equation, which arises because $\mathrm{f}(x_t, \tau)$ and $\underline{\mathrm{R}}(x_t, \tau)$ are non-linear function of the Level and Slope state variables (due to the normal probability functions). The result is an estimated set of parameters and state variables $L(t)$ and $S(t)$. For the K-ANSM(2), $a_0 = 0$ and $b_0' = [1, 1]$, so the SSR is given by

$$\mathrm{r}\,(t) = L_t + S_t \tag{19}$$

B Full estimation results

This appendix provides the full estimation results that underlie the summaries reported in the main text.[24]

All tables show the parameter estimates (with standard errors in parentheses) of the common shock, the idiosyncratic shocks, and the monetary policy shock for the two interest rates, the four asset prices, and the exchange rate. These are reported in basis points for the interest rates and in percentage points for the asset prices and the exchange rate, and they should be interpreted as the estimated responses to a one standard deviation monetary policy shock.

[24] Estimation results for the entire sample period are available upon request.

Table A1: 90 day rate / conventional policy (1-Feb-1996 to 12-Sep-2008)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
90 day treasury rate	1.363 **	-5.512 **	3.265 **
	(0.281)	(0.106)	(0.199)
10 year treasury rate	2.843 **	5.143 **	2.999 **
	(0.474)	(0.273)	(0.209)
Corporate bond prices	-1.543 **	0.000	0.238
	(0.192)		(0.254)
Gold price	-0.160	-0.933 **	-0.118
	(0.239)	(0.381)	(0.268)
Equity prices	0.363 *	1.093 **	-0.518 **
	(0.245)	(0.348)	(0.269)
REIT prices	0.307	-1.107 **	-0.183
	(0.242)	(0.330)	(0.269)
Exchange rate	-0.137	0.484	-0.052
	(0.242)	(0.733)	(0.268)

Level of significance: ** 5 percent, * 10 percent

Table A2: SSR / conventional policy (1-Feb-1996 to 12-Sep-2008)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
SSR	1.741 **	2.515 **	1.474 **
	(0.155)	(0.167)	(0.306)
10 year treasury rate	5.729 **	0.000 **	3.525 **
	(0.087)	(0.000)	(0.198)
Corporate bond prices	-0.541 **	1.832 **	-0.100
	(0.163)	(0.198)	(0.358)
Gold price	-0.077	0.929 **	-0.263
	(0.162)	(0.383)	(0.356)
Equity prices	0.241 *	-1.134 **	-0.482 *
	(0.162)	(0.328)	(0.355)
REIT prices	0.164	-1.144 **	-0.018
	(0.163)	(0.310)	(0.358)
Exchange rate	-0.065	-0.483	-0.185
	(0.163)	(0.734)	(0.357)

Level of significance: ** 5 percent, * 10 percent

Table A3: 90 day rate / unconventional policy (15-Sep-2008 to 28-Jan-2016)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
90 day treasury rate	0.308 *	-3.680 **	0.227 *
	(0.206)	(0.098)	(0.137)
10 year treasury rate	2.850 **	5.164	-8.191 **
	(0.455)		(0.086)
Corporate bond prices	-0.857 **	0.000	0.890 **
	(0.195)		(0.142)
Gold price	0.083	0.000	0.752 **
	(0.204)		(0.134)
Equity prices	1.580 **	0.000	0.423 **
	(0.168)		(0.151)
REIT prices	1.963 **	-2.444 **	0.771 **
	(0.315)	(0.299)	(0.158)
Exchange rate	0.282 *	0.615	0.321 **
	(0.315)	(0.587)	(0.137)

Level of significance: ** 5 percent, * 10 percent

Table A4: SSR / unconventional monetary policy (15-Sep-2008 to 28-Jan-2016)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
SSR	1.467 **	2.835 **	2.123 **
	(0.208)	(0.164)	(0.148)
10 year treasury rate	5.074 **	-3.030 **	8.174 **
	(0.670)	(1.135)	(0.086)
Corporate bond prices	-0.839 **	-0.325	-0.648 **
	(0.179)	(1.161)	(0.153)
Gold price	-0.062	-1.289 **	-0.700 **
	(0.164)	(0.277)	(0.151)
Equity prices	1.038 **	1.075 **	-0.569 **
	(0.194)	(0.391)	(0.157)
REIT prices	1.225 **	2.861 **	-0.935 **
	(0.210)	(0.162)	(0.158)
Exchange rate	0.181	0.642	-0.360 **
	(0.210)	(0.557)	(0.152)

Level of significance: ** 5 percent, * 10 percent

References

[1] Altonji, J. G. and L. M. Segal (1996). Small sample bias in GMM estimation of covariance structures. *Journal of Business and Economic Statistics* 14(3), 353–366.

[2] Bauer, M. and G. Rudebusch (2015). Monetary policy expectations at the zero lower bound. *Federal Reserve Bank of San Francisco Working Paper* 2013-18, Federal Reserve Bank of San Francisco.

[3] Black, F. (1995). Interest rates as options. *Journal of Finance* 50(7), 1371–1376.

[4] Bomfim, A. (2003). "Interest rates as options:" Assessing the markets' view of the liquidity trap. *Federal Reserve Board of Governors Working Paper* 2003-45, Federal Reserve Board of Governors.

[5] Bullard, J. (2012). Shadow Interest Rates and the Stance of U.S. Monetary Policy. Speech at the Annual Conference, Olin Business School, Washington University in St. Louis, 8 November 2012.

[6] Christensen, J., J. Lopez, and G. Rudebusch (2014). Do central bank lending facilities affect interbank lending rates? *Journal of Business and Economic Statistics* 32(1), 136–151.

[7] Christensen, J. and G. Rudebusch (2015). Estimating shadow-rate term structure models with near-zero yields. *Journal of Financial Econometrics* 13(2), 226–259.

[8] Christensen, J. and G. Rudebusch (2016). Modeling yields at the zero lower bound: Are shadow rates the solution? In E. Hillebrand and S. J. Koopman (ed.), *Dynamic Factor Models* (Advances in Econometrics, Volume 35). Emerald Group Publishing Limited, 75–125.

[9] Claus, E. and M. Dungey (2012). US monetary policy surprises: Identification with shifts and rotations in the term structure. *Journal of Money, Credit and Banking* 44(7), 1547–1557.

[10] Craine, R. and V. L. Martin (2008). International monetary policy surprise spillovers. *Journal of International Economics* 75(1), 180–196.

[11] D'Amico, S. and T. B. King (2013). Flow and stock effects of large-scale treasury purchases. *Journal of Financial Economics* 108(2), 425–448.

[12] Fawley, B. W. and C. J. Neely (2013). Four stories of quantitative easing. The Federal Reserve Bank of St Louis *Review* 95(1), 51–88.

[13] Femia, K., S. Friedman, and B. Sack (2013). The effects of policy guidance on perceptions of the Fed's reaction function. *Federal Reserve Bank of New York Staff Reports* 652, Federal Reserve Bank of New York.

[14] Gagnon, J., M. Raskin, J. Remache, and B. Sack (2011). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking* 7(1), 3–43.

[15] Glick, R. and S. Leduc (2013). The effects of unconventional and conventional U.S. monetary policy on the dollar. *Federal Reserve Bank of San Francisco Working Paper Series* 2013-11, Federal Reserve Bank of San Francisco.

[16] Gürkaynak, R. S., B. Sack, and E. T. Swanson (2005). Do actions speak louder than words? The response of asset prices to monetary policy actions and statements. *International Journal of Central Banking* 1(1), 55–93.

[17] Joyce, M. A. S., A. Lasaosa, I. Stevens, and M. Tong (2011). The financial market impact of quantitative easing in the United Kingdom. *International Journal of Central Banking* 7(3), 113–161.

[18] Hansen, L. P. (1982). Large sample properties of generalized method of moments estimators. *Econometrica* 50(4), 1029–1054.

[19] Kiley, M. (2014). The response of equity prices to movements in long-term interest rates associated with monetary policy statements: Before and after the zero lower bound. *Journal of Money, Credit and Banking* 46(5), 1057–1071.

[20] Kim, D. and K. Singleton (2012). Term structure models and the zero bound: An empirical investigation of Japanese yields. *Journal of Econometrics* 170(1), 32–49.

[21] Krippner, L. (2013). Modifying Gaussian term structure models when interest rates are near the zero lower bound. *Economics Letters* 118(1), 135–138.

[22] Krippner, L. (2015a). *Zero Lower Bound Term Structure Modeling: A Practitioner's Guide*. Palgrave Macmillan.

[23] Krippner, L. (2015b). A comment on Wu and Xia (2015), and the case for two-factor shadow short rates. *Centre for Applied Macroeconomic Analysis Working Paper* 48/2015, Australian National University.

[24] Krishnamurthy A. and A. Vissing-Jorgensen (2011). The effects of quantitative easing on interest rates: Channels and implications for policy. *Brookings Papers on Economic Activity* Fall, 215–265.

[25] Kuttner, K. N. (2001). Monetary policy surprises and interest rates: Evidence from the Fed funds futures market. *Journal of Monetary Economics* 47(3), 523–544.

[26] Meaning, J. and F. Zhu (2011). The impact of recent central bank asset purchase programmes. *BIS Quarterly Review* December, 73–83.

[27] Neely, C. J. (2015). Unconventional monetary policy had large international effects. *Journal of Banking and Finance* 52(March), 101–111.

[28] Nelson, C. and A. Siegel (1987). Parsimonious modelling of yield curves. *Journal of Business* 60(4), 473–489.

[29] Rigobon, R. and B. Sack (2004). The impact of monetary policy on asset prices. *Journal of Monetary Economics* 51(8), 1553–1575.

[30] Rogers, J. H., C. Scotti, and J. H. Wright (2014). Evaluating asset-market effects of unconventional monetary policy: A multi-country review. *Economic Policy* 29(80), 749–799.

[31] Romer, C. D. and D. Romer (1989). Does monetary policy matter? A new test in the spirit of Friedman and Schwartz. *NBER Macroeconomics Annual* 4, 121–170.

[32] Romer, C. D. and D. Romer (2004). A new measure of monetary shocks: Derivation and implications. *The American Economic Review* 94(4), 1055–1084.

[33] Rosa, C. (2012). How "unconventional" are large-scale asset purchases? The impact of monetary policy on asset prices. *Federal Reserve Bank of New York Staff Reports* 560, Federal Reserve Bank of New York.

[34] Swanson, E. T. (2011). Let's twist again: A high-frequency event-study analysis of operation twist and its implications for QE2. *Brookings Papers on Economic Activity* Spring, 151–188.

[35] Swanson, E. T. (2015). Measuring the effects of unconventional monetary policy on asset prices. *NBER Working Paper Series* 21816, National Bureau of Economic Research.

[36] Taylor, J. B. (1999). A historical analysis of monetary policy rules. In J. B. Taylor (ed.), *Monetary Policy Rules*. University of Chicago Press, 319–348.

[37] Thornton, D. L. (2014). The identification of the response of interest rates to monetary policy actions using market-based measures of monetary policy shocks. *Oxford Economic Papers* 66(1), 67–87.

[38] Woodford, M. (2012). Methods of Monetary Policy Accommodation at the Interest-rate Lower Bound. *Jackson Hole Symposium Speech*.

[39] Wu, J. C. and F. D. Xia (2016). Measuring the macroeconomic impact of monetary policy at the zero lower bound. *Journal of Money, Credit and Banking* 48 (2–3), 253–291.