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Liquidity Effects of Quantitative Easing on Long-Term Interest Rates*

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Abstract

This paper argues that the expansion in reserves following recent quantitative easing programs of the Federal Reserve may have affected long-term interest rates through liquidity effects. The data lends some support for liquidity effects, in that reserves were negatively correlated with long-term yields at the zero lower bound. Estimates suggest that between January 2009 and 2011, 10-year US Treasury yields fell 46-85 basis points as a result of liquidity effects. The liquidity effect is separate from the portfolio balance effect of the change in the public supply of Treasury bonds, which is estimated to have reduced yields by another 20 basis points during that period.

JEL: E43; E52; E58

Keywords: Quantitative Easing; Reserves; Liquidity Effect; Long-Term Interest Rates; Zero Lower Bound; Monetary Policy; Portfolio Balance

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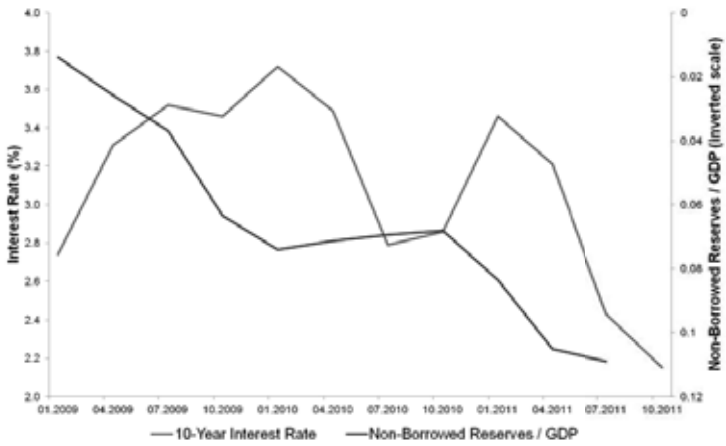
1 Introduction

An increase in the money supply is usually expected to reduce short-term interest rates. This phenomenon, known as the liquidity effect, finds empirical support in the literature. It is commonly held that when short-term interest rates reach the zero lower bound (ZLB), the liquidity effect disappears. This is because the short-term liquid assets typically bought in open market operations (OMO) form a perfect substitute for money when short-term interest rates are at zero. However, banks also demand and hold long-term assets with strictly positive yields. OMOs in long-term bonds could hence still have a liquidity effect. The increase in zero-yielding reserves associated with the purchases of longer term bonds in OMOs at the ZLB, induces banks to search for a higher return on their assets. They hence raise their demand for positive yielding medium to longer-term assets, such as government bonds. The higher demand for these assets, in turn, reduces their yield. In this way, an increase in reserves should be related to lower long-term yields at the ZLB.

Figure 1: Non-Borrowed Reserves and Long Term Yields at the ZLB, Quarterly, 2009-2011



That the large scale asset purchases conducted by the Federal Reserve at the ZLB may have been transmitted to yields through such liquidity effects has been overlooked. Chart 1 shows how non-borrowed reserves held with the Federal Reserve, and long-term Treasury yields, moved in the same overall direction during the recent ZLB period. There could be many reasons for these variables to have been correlated during that period. One candidate is that the relationship is partly causal.

Instead of focusing on the effect of reserves, the currently very active literature has fo-

cussed on the effect of the assets purchased in these operations. Thus, the expansion in reserves during the past years came about partly through outright purchases of Treasury bonds. When the central bank buys a government bond, it augments the asset side of its balance sheet with this bond, and augments the liability side with the corresponding amount of reserves. The liquidity effect is the impact of an expansion of the central bank's liabilities on bond yields, irrespective of the type of asset the central bank buys. The previous literature argues that the change on the asset side of the balance sheet, i.e. the outright purchase of a specific asset, such as a specific maturity government bond, constitutes the main channel through which quantitative easing influences the yield on this bond, as the quantity of the purchased bond in the market changes.

In this paper, we lay out the argument for why liquidity effects may have been at work, and take a first look at the data to offer some initial empirical support for the hypothesis that liquidity effects constitute an additional and potentially important transmission channel, increasing the overall impact of the asset purchases on long-term rates. Specifically, we add reserves to a standard regression specification for the 10-year Treasury yield used for testing for supply effects. We allow the effect of reserves on yields to differ between the present ZLB period and the pre-ZLB period in this regression.

We find that (i) the realized yield on the 10-year Treasury bond has been lower during the recent ZLB period than what the standard regression used for testing for supply effects predicts and (ii) adding non-borrowed reserves in percent of GDP to the regression results in a significantly negative effect of reserves on yields at the ZLB. The estimated correlation between reserves and yields suggest that yields were 46-85 basis points lower during the ZLB period due to liquidity effects of the monetary expansion. This liquidity effect is in addition to the supply effect, meaning that the overall impact of the asset purchases at the ZLB was larger.

The next section offers some theoretical considerations regarding how central bank asset purchases might affect the yield of bonds through liquidity effects as well as supply effects. The empirical investigation of liquidity effects is set up in the subsequent section. The final section concludes.

2 How Do Central Bank Asset Purchases Affect Interest Rates?

How should we expect a change in commercial banks' reserves held at the Fed to affect long-term interest rates, and how important has the effect been during the ZLB period of quantitative easing (QE) programs? To see this, consider three assets: reserves M with zero yield, a short-term treasury bill A with yield r_A, and a long-term treasury bond B with yield r_B.

The recent literature on the effects of QE on long-term yields have focused on the impact of changes in the quantity B, i.e. Fed's purchases of long-term bonds and government supply of Treasuries, on r_B, which is referred to as portfolio balance or supply effect, as well as on the signaling effect which is not discussed here (see next Section). This approach is based on portfolio balance models incorporating different assets with imperfect substitutability through financial frictions. In these models, a change in the relative supply of A and B affects their relative yield. Thus, in a portfolio balance model with market imperfections, such as segmented markets and assumptions of preferred habitat, a central bank purchase of an asset must increase the price of the asset in question, in order to make market participants accept holding less of the respective asset.[1] Hence, the yield of the asset falls. Recent empirical research, such as Kuttner (2006), Gagnon et al. (2010), Greenwood and Vayanos (2010a), Hamilton and Wu (2010), Neely (2010), and D'Amico and King (2011), shows that central bank purchases of specific assets influence their yields through so-called supply effects.

This socalled supply effect relates to the asset side of the central bank's balance sheet. The models do not incorporate the equivalent increase in the liabilities side of the balance sheet, namely reserves. The effect of changes in reserves, or liquidity effect, has been addressed in frameworks that have modeled the private sector's choice between reserves, M, and a short-term bond, A. In practice, the liquidity effect arises from the fact that the portfolios of banks involved in OMOs include more reserves than before the sale of assets to the central bank. A higher level of reserves is empirically found to be related to a fall in short-term interest rates, in normal times. Specifically, the liquidity effect has been found to reduce short-term interbank deposit rates such as the Federal funds rate in the US, and short-term government bond yields; see for example Cochrane (1989), Gordon and Leeper (1994), Christiano and Eichenbaum (1995), Christiano and Eichenbaum (1992a), Hamilton

[1] Recent examples of preferred-habitat models include Hamilton and Wu (2010) or Greenwood and Vayanos (2010a).

(1997), Bernanke and Mihov (1998), Carpenter and Demiralp (2008), Thornton (2008), Hagedorn (2009), or Judson and Klee (2010). Liquidity effects have been modeled using segmented market assumptions. Examples of such models are Grossman and Weiss (1983), Christiano and Eichenbaum (1992b), Lucas (1990), or Dotsey and Ireland (1995). In line with a cash-in-advance constraint, a central bank's lump sum monetary injection cannot immediately be used as transaction balances by the private agents receiving the injection. It therefore pushes up the price of the alternative asset available to market participants.

In practice, the mechanisms in models of the liquidity effect are similar to the ones at work in the portfolio balance approach. In fact, liquidity effects can be thought of as supply effects of reserves. The only differences are the purpose of asset holdings, and the types of frictions. Banks, holding more reserves after an OMO, seek to trade some of these additional reserves for positive yielding assets. Given that the yield on reserves M is fixed at zero, the higher demand for A and B should put upward pressure on the price of both of these assets and thus reduce their yields, in contrast to the supply effect which only pertains to the yields of the specific asset bought in the OMO or to its close substitutes. Indeed, Cochrane (1989) finds that liquidity effects influence the entire yield curve. An important difference between supply and liquidity effects is that while the former suggest a long term link between the supply of an asset and its yield, liquidity effects suggest a link between reserves and interest rates which is temporary. The reason is that an increase in reserves will only affect yields as long as it is in excess of required reserves. But with time, higher excess reserves transform into increased bank credits, which in turn reduce excess reserves (turn excess reserves into required reserves). This is in line with the empirical literature. For example, Christiano and Eichenbaum (1992a) and Christiano and Eichenbaum (1995) find temporary liquidity effects in short rates lasting from one to 20 quarters.

Both the supply effect and the liquidity effect rely on imperfect asset substitutability and should be addressed jointly in the same framework. This would allow for an evaluation of the total effect of QE on long-term yields. Tobin (1958) has suggested a portfolio analysis with money and bonds of different maturities. Andres et al. (2004) provided a theoretical framework including these assets. To understand how the different effects of an OMO can be combined, consider again the three assets M, A and B. A supply effect occurs when the supply of B changes, for example when the government pays back some long-term debt. In this case, the yield r_B decreases. A liquidity effect occurs as a result of a change in the supply of reserves M, for example through a "helicopter drop" of reserves on banks. In this case, the

"yield" of reserves compared to the yield of other assets has to change. With zero or a low and fixed interest on reserves, this will put downward pressure on the yields of both assets A and B.

In normal times, during an OMO, the central bank (CB) buys A with M, thus the supply and the liquidity effect both put downward pressure on r_A, and the liquidity effect puts downward pressure on r_B. Note that we isolate here the supply and liquidity effect from the Fisher effect which can drive yields in the other direction. At the ZLB, when the CB buys B with M, both the supply and liquidity effect put downward pressure on r_B. The yield on the short-term bill, r_A, can be pushed down by the liquidity effect, if it is not already at the ZLB. It is often argued that there cannot be liquidity effects at the ZLB, when A has a zero yield like M. But the total supply of zero-yielding assets M and A increases relative to B when the CB buys B in OMO, putting downward pressure on r_B in addition to the supply effect. Finally, note that in the case of the current maturity extension program "Operation Twist II", the CB buys B and sells A. In that case there is no liquidity effect which would put downward pressure on both r_A and r_B, as the amount of reserves remain constant. Supply effects put downward pressure on r_B and upward pressure on r_A.

3 An empirical assessment

As argued above, a central bank asset purchase directly from the market is transmitted through at least three different channels, namely the supply effect, the liquidity effect and through signalling. Signalling effects occur because a central bank asset purchase may signal something about the central bank's intentions for future monetary policy, and hence, the future short term interest rate path. We hence need a research design which allow us to distinguish these three effects. The following sections present how we approach these issues conceptually and econometrically.

3.1 Identifying liquidity effects

If market participants are informed about asset purchases by the central bank in advance - as has been the case for all three recent large scale asset purchase programs (LSAP) - and if market participants have perfect and complete information, and hence know the impact of these purchases on yields through supply and liquidity effects, then this impact should be discounted immediately at announcement. In contrast, there should be no effect on yields when the transactions actually take place under these assumptions. A number of studies estimating the supply effects of the Fed's asset purchases have hence looked for announcement effects

on yields, using event studies techniques. In order to identify portfolio balance effects from signalling effects at announcement, such studies divide the long-term Treasury yield into a term premium and the expected future short rates using econometric term structure models. Supply effects affect the term premium whereas signalling effects should only affect expected future short rates (see for example Bauer and Rudebusch (2011) and the first part of the analysis in Gagnon et al. (2010). Neely (2010) is an exception).

The event study approach does not allow for an identification of liquidity effects. This is because both liquidity and supply effects affect the term premium at the ZLB. Their individual effects hence cannot be identified by simply investigating the reaction of the term premium. There are other problems with the use of event studies in this context. One is that the breakdown between the expected future short rates and the term premium turns out to be very uncertain, and dependent on the type of term structure model estimated, see for example Bauer and Rudebusch (2011). Another problem is that the assumption of complete and perfect information of market participants, which is necessary for interpreting the effect of an announcement on yields as containing information about supply and liquidity effects, might be too strong.

Instead, we take a different approach to identification and note that if market participants do not have perfect and complete information, then there is room for some of the liquidity and supply effects of planned transactions to materialize when the actual transactions take place. Signalling effects, on the other hand, should only be present at announcement times. In the time series dimension, what matters for the supply effect is the total supply of the asset in question, i.e. the total supply of Treasury bonds available to the public. This supply has been affected by the Fed's purchases during the LSAP, but it has also - and to an even higher degree - been affected by the Treasury's net issuance of new bonds. For this reason, the public supply of Treasurys has had a source of independent variation, and its correlation with reserves is actually quite small. If there is an effect of reserves on long-term treasury yields when controlling for the public supply of Treasurys, then it should be possible to interpret this effect as a liquidity effect, as separate from a supply effect.

3.2 Methodology and Data

We take as a starting point the time series approach employed by Gagnon, Raskin, Remache and Sack (2010) to assess supply effects in a regression of long-term treasury yields. We add

reserves to the regression in order to see if these help explain variation in long-term yields at the ZLB. The effect of reserves is allowed to differ between the pre-ZLB and the ZLB periods. The sample ranges from February 1990 to January 2011. The regressions are carried out in weekly frequency, yielding 112 observations for the ZLB period and 1096 observations for the entire sample. The few explanatory variables for which data is in lower frequency are linearly interpolated (see appendix for details). The baseline regression equation takes the following form:

$$i_t^{(10y)} = \alpha + \beta_1 \cdot D_t^{pre-ZLB} R_{t-1} + \beta_2 \cdot D_t^{ZLB} R_{t-1} + \beta_3 D_t^{ZLB} + \delta X_t + u_t. \tag{1}$$

$i_t^{(10y)}$ denotes the average daily yield on 10-year US Treasury bonds over the week following $t-1$.[2] R_{t-1} denotes the level of non-borrowed reserves held with the Fed at date $t-1$, in percent of GDP.[3] Reserves are thus effectively lagged one week. $D_t^{pre-ZLB}$ and D_t^{ZLB} are dummy variables for the pre-ZLB and the ZLB period, respectively. X_t contains the control variables described below. We define the ZLB to start in mid December 2008, when the Federal funds target rate was lowered to 0.25%. The interaction of reserves with these dummies allows the liquidity effect to differ between normal times and at the ZLB. The level of the ZLB-dummy is included to capture a change in the interest rate level during the ZLB period due to factors that cannot be fully accounted for by the explanatory variables.

The supply of Treasury securities to the public in percent of nominal GDP is included to capture supply effects. Treasury supply is measured as the total supply minus the Fed's holdings of Treasury securities, as reported in the System Open Market Account (SOMA). We include all maturities above one year in order to account for the transmission of changes in the supply of Treasury bonds to other maturities through substitution effects.[4] Since changes in the maturity structure of the total supply could matter for the supply effect on longer yields, we also control for the average maturity of Treasury bonds.[5]

[2] All control variables for which data is available on a daily basis enter in averages over the week following $t-1$.

[3] We use the percentage of GDP to make reserves comparable in specification to the specification of the Treasury supply, see below. It should be mentioned that the results obtained in this paper are not driven by changes in GDP. When carrying out the regressions using nominal reserves, all results remain.

[4] See for example D'Amico and King (2011) on the substitution effects between different maturity Treasury bonds.

[5] Hamilton and Wu (2010) provide data on total and public supply of Treasury securities for each maturity. Gagnon et al. (2010) additionally subtract holdings of foreign official agencies, which is not done in the present analysis.

The Federal funds target rate is included to account for the current interest rate level. Both reserves and the long-term yields may have been driven by weakening economic conditions and resulting changes in expected future monetary policy during the ZLB period. To account for expected future short term interest rates, and hence, expected future monetary policy path, we include the expected change in the 1-year rate one year ahead (see appendix for details). The unemployment gap and the inflation rate of core CPI are additionally included to capture the effect of current economic conditions and the business cycle. Backus and Wright (2007) show that the term premium is countercyclical because risk appetite tends to be larger in booms than during busts. We hence expect the unemployment gap to be positively related to the yield, since we control for changes in the expected future path of short-term rates. The 6-month realized volatility of the Treasury yield itself is included to take account of uncertainty about expectations which may boost the demand for safe assets.[6] Uncertainty about inflation expectations may affect longer-term interest rates through its effect on the term premium. To control for this uncertainty, we include the interquartile range of long-term inflation expectations obtained from the Michigan Survey of Consumers.

In additional robustness tests, inflation expectations from the Cleveland Fed are used to run the regression on the real long-term yield. The regression is also run for the term spread between 10-year and the 3-month interest rate, as well as for the nominal and real 5-year rates. Moreover, we control for announcement effects by including two dummies. The first is an event dummy that captures the Fed's announcements related to future monetary policy, i.e. the LSAP programs (QE1 and QE2). The particular events are listed in Table 7 in the appendix. The choice of the specific events which would increase the market's expectation of future asset purchases is in line with recent case studies, e.g. Gagnon et al. (2010) and Neely (2010). The second dummy is a Jackson Hole dummy, taking the value one from the date of the famous speech (27th August 2009) and until the end of the sample. There is a widespread belief that with Bernanke's speech at Jackson Hole, the entire effect of QE2 was immediately priced in, so that the actual purchases following the announcement had no effect on yields anymore.

[6] The choice of the volatility measure is inconsequential for our results. We run the same regressions using the logarithm of the VIX instead of the realized volatility, with no change to the findings.

3.3 Results

Table 1 presents the results of the pre-crisis regression mimicking the sample used in the previous literature on supply effects. The first column reports the results excluding both

Table 1: Pre-Crisis Regression Results

Dependent Variable: $i_t^{(10y)}$				
Sample	1990/02 to 2008/06		1990/02 to 2008/06	
	Coefficient	t-stat	Coefficient	t-stat
c	-0.810*	-1.661	-1.474***	-2.932
FFTR	0.579***	9.346	0.476***	6.815
Expected Change in 1-Year Rate	-0.069	-0.316	0.220	0.985
Unemployment Gap	0.914***	7.765	0.583***	4.078
Core CPI Inflation	0.545	1.622	0.887***	2.825
Inflation Disagreement	0.065	0.479	0.177	1.297
Realized Volatility	0.127	0.223	-0.141***	-0.260
Average Maturity	0.012***	7.132	0.011**	6.099
Treasury Supply	-	-	0.052***	2.355
Adjusted R^2	0.8534		0.8610	
Number of Obs	961		961	

Both reserves and the Treasury supply are measured in percent of GDP.

Newey West standard errors (12 lags). ***, **, * denote significance at the 1, 5, and 10% levels

the supply of Treasury securities to the public and reserves. The second column reports the results when the Treasury supply is added. The results are similar to those in the recent literature. Specifically, the size of the supply effect is very close to the estimate in Gagnon et al. (2010).[7]

[7]The coefficients on the other explanatory variables deviate somewhat from those found in Gagnon et al. (2010). The main reason is that our sample is slightly shorter because of the lack of access to Treasury supply data before 1990.

How well does this specification perform for the ZLB period? We compute out-of-sample fitted values for the 10-year Treasury yield during the subsequent ZLB period and compare it to the actual outcome for the yield, based on the regression results reported in Table 1. Figure 2 shows that both specifications suggest a yield that is considerably higher than the actual yield during the ZLB. Adding Treasury supply to the equation slightly lowers the error and brings down the fitted value. The deviation of the fitted value from the realized yield during this period remains large, suggesting that factors not contained in these regressions were depressing long-term yields when short-term yields hit the ZLB.[8]

We then include the most recent data for the ZLB period, and run the same specification on the entire sample through January 2011, reported in the first column of Table 2. The parameter estimates generally change. The expected change in short-term interest rates becomes highly significant and carries the expected sign. Non-borrowed reserves are added to the regression in the second column of Table 2. The parameter estimates of other control variables now return to values and significance levels found for the pre-crisis sample, suggesting that it is important to take into account reserves during the ZLB period. The dummy capturing a shift in the level at the ZLB is negative, but not significant. The parameter estimates of all other control variables, except for realized volatility and inflation disagreement, are significant. Signs are according to expectation. Non-borrowed reserves turn out to be highly significant and negative at the ZLB, but not significantly different from zero during normal times.[9]

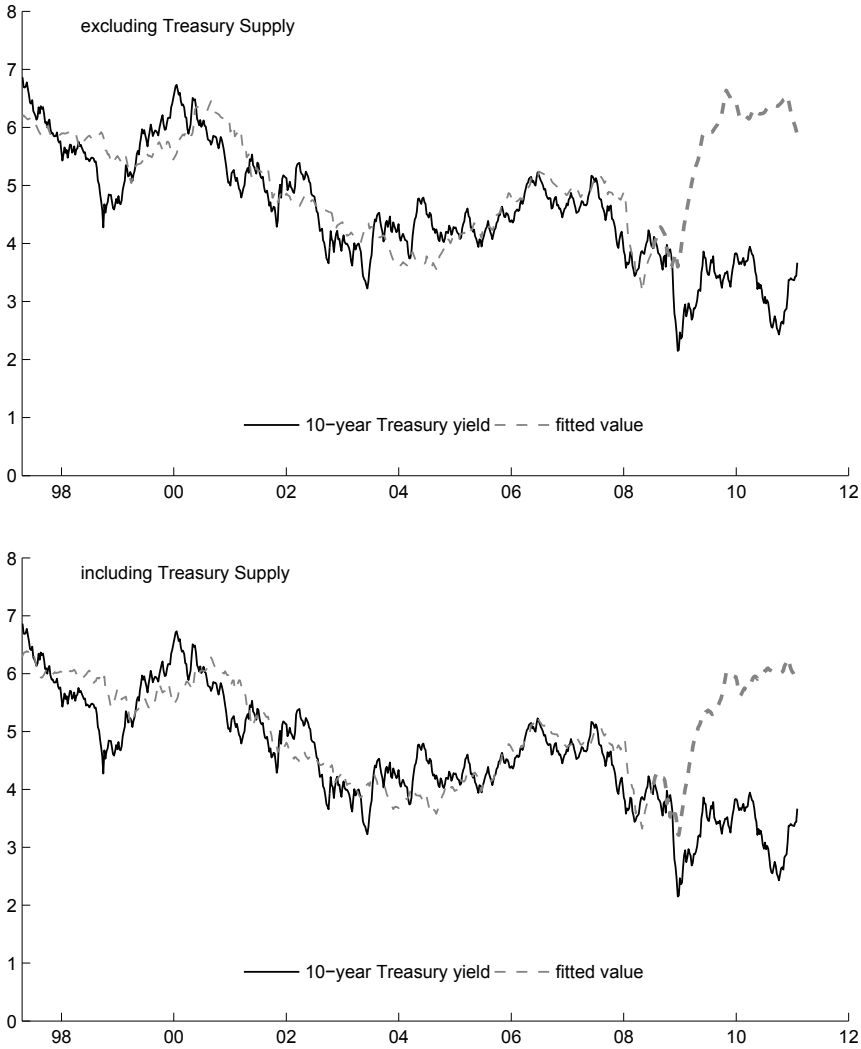
Are the estimated liquidity effects quantitatively meaningful? Table 3 shows the implied contributions of each variable to the change in the level of the 10-year Treasury yield between January 2009 and January 2011.

The first column reports the change in the respective variable during our ZLB sample, that is, from January 2009 to January 2011. The second column shows the coefficient estimates from the main regression (the second column of Table 2). The third column of Table 3 shows how much the 10-year yield is estimated to have changed as a result of the change in the respective explanatory variable during our ZLB sample period. In addition to the public Treasury supply, Table 3 reports the contributions of the total Treasury supply and the Fed's

[8] This finding does not depend, and is not driven by, the unemployment gap, although a large part of the increase in the fitted value for the interest rate at the ZLB is due to the sharp rise in unemployment.

[9] The results do not depend on the exact sample. When we exclude average maturity, which allows to estimate the regression through April 2011, the main conclusions remain.

Figure 2: In- and Out-of-Sample Fitted Values for 10-Year Yield



The fitted values in the upper and the lower panel correspond to the coefficient estimates in the first and second column of Table 1, respectively. the actual 10-year Treasury yield is represented by the solid black line. The fitted values are computed using the estimates of the respective sample size as indicated in each graph. The red dashed line indicates the fitted values within the sample of the estimates. The fat red dashed line depicts the fitted values for the period after the estimation sample ends.

purchases of Treasury securities separately.

The results suggest that both the supply effect and the liquidity effect of the Fed's purchases have reduced long-term yields between January 2009 and January 2011. The point

Table 2: Regression Results including non-borrowed Reserves

Dependent Variable: $i_t^{(10y)}$				
Sample	1990/01 to 2011/01		1990/01 to 2011/01	
	Coefficient	t-stat	Coefficient	t-stat
c	-3.183***	-6.873	-1.515***	-3.084
FFTR	0.412***	6.431	0.522***	8.192
Expected Change in 1-Year Rate	1.101***	4.385	0.483**	2.105
Unemployment Gap	-0.111	-1.049	0.527***	4.296
Core CPI Inflation	1.271***	4.740	0.707**	2.473
Inflation Disagreement	0.468***	3.202	0.205	1.583
Realized Volatility	-0.301	-0.659	-0.182	-0.357
Average Maturity	0.012***	6.539	0.011***	5.819
Treasury Supply	0.075***	3.279	0.044**	2.265
Reserves $\cdot D_t^{pre-ZLB}$	-	-	0.078	0.419
Reserves $\cdot D_t^{ZLB}$	-	-	-0.341***	-2.731
D_t^{ZLB}	-	-	0.005	0.108
D_t^{Lehman}	-	-	-0.280	-1.110
Adjusted R^2	0.8604		0.8888	
Number of Obs	1096		1096	

Both reserves and the Treasury supply are measured in percent of GDP.

Newey West standard errors (12 lags). ***, **, * denote significance at the 1, 5, and 10% levels; $D_t^{pre-ZLB}$ up to Dec-2008; D_t^{ZLB} Jan-2009 to end; D_t^{Lehman} Jun-2008 to Dec-2008

estimate for reserves suggests that the 2.5 percentage points increase in reserves to GDP between January 2009 and January 2011 was associated with a fall in the level of the long yield by roughly 85 basis points.[10] The point estimate for the Treasury supply suggests an additional fall in yields of about 19 basis points on account of supply effects. During the ZLB period, the US Treasury issued a considerable amount of new debt with more than one year maturity. In terms of nominal GDP, the total Treasury supply has increased 19 percentage points. The regression results thus suggest that this would have translated into an increase in long-term yields of 85 basis points. The Fed's purchases of Treasury securities thus only partially alleviated the supply effect of these new issues by approximately one quarter. The combined supply and liquidity effects suggest that the Fed lowered long-term yields by approximately 104 basis points during this time period. These estimates lie at the upper end of

[10] Note that the main part of the increase in reserves took place in the late autumn of 2008. The effect of this increase is not taken into account here.

Table 3: Contributions to the Change in Yield from Jan-2009 to Jan-2011

	2009/01 to 2011/01		
	Change	Estimated Coefficient	Contribution
$i_t^{(10y)}$	1.201	-	-
FFTR	0.000	0.522	0.000
Expected Change in 1-Year Rate	0.571	0.483	0.276
Unemployment Gap	1.620	0.527	0.853
Core CPI Inflation	0.238	0.707	0.168
Inflation Disagreement	0.100	0.205	0.021
Realized Volatility	-0.225	-0.182	0.041
Average Maturity	46.248	0.011	0.487
Public Supply	14.591	0.044	0.646
Total Supply	18.975	0.044	0.840
Fed Holdings	4.384	-0.044	-0.194
Reserves	2.489	-0.341	-0.849

The coefficients correspond to the last column in Table 2. Both the supply measures and reserves are measured in percent of GDP.

the range found in the recent literature. Reviewing recent results, Hamilton and Wu (2010) summarize that estimated supply effects have ranged between 17 to 48 basis points. This range refers to the Fed's LSAP of $400 billion. More recent papers find slightly larger effects. D'Amico and King (2011), for example, find an overall effect of the Fed's $300 billion Treasury purchases of about 50 basis points on the level of the yield curve, and Krishnamurthy and Vissing-Jorgensen (2011) find - through different channels - an overall effect of quantitative easing in excess of 100 basis points.

3.4 Robustness

In theory, liquidity effects should affect the real rate, whereas the nominal part of the yield may pull in the opposite direction due to Fisher effects. The first column of Table 4 hence shows the results for the real 10-year interest rate.[11]

[11] The monthly inflation expectations from the Cleveland Fed are derived from financial market prices and yields. This means that their measurement error is correlated with yields. Therefore, adding inflation expectations as an explanatory variable creates the problem that a large amount of noise enters the yield and inflation index products, which cannot be assigned to changes in expectations or real developments, but rather to liquidity, herding, trading behaviors, etc. Part of this noise enters the expectations measure,

Table 4: Robustness Check I: Real Yield and Term Spread

Dependent Variable:	$i_t^{(10y)} - E_t[\pi^{(10y)}]$		$i_t^{(10y)} - i_t^{(3m)}$	
Sample	02/1990 to 01/2011		02/1990 to 01/2011	
	Coefficient	t-stat	Coefficient	t-stat
c	-1.752***	-5.290	-1.348***	-3.173
FFTR	0.322***	7.502	-0.389***	-6.973
Expected Change in 1-Year Rate	0.452***	2.840	0.826***	4.561
Unemployment Gap	0.262***	2.970	0.373***	3.558
Core CPI Inflation	0.498**	2.401	0.646***	2.038
Inflation Disagreement	0.162*	1.844	0.243**	1.987
Realized Volatility	0.023	0.067	0.190	0.472
Average Maturity	0.006***	4.611	0.009***	5.741
Treasury Supply	0.034***	2.643	0.035**	2.090
Reserves $\cdot D_t^{pre-ZLB}$	0.039	0.283	-0.052	-0.488
Reserves $\cdot D_t^{ZLB}$	-0.178**	-2.236	-0.183*	-1.848
D_t^{ZLB}	-0.001	-0.003	-0.370	-0.644
D_t^{Lehman}	-0.226	-1.261	0.629***	3.566
Adjusted R^2	0.8523		0.8871	
Number of Obs	1096		1096	

Both reserves and the Treasury supply are measured in percent of GDP.

Newey West standard errors (12 lags). ***, **, * denote significance at the 1, 5, and 10% levels; $D_t^{pre-ZLB}$ up to Dec-2008; D_t^{ZLB} Jan-2009 to end; D_t^{Lehman} Jun-2008 to Dec-2008

Both the liquidity effect and the supply effect remain highly significant. Assuming that there are both liquidity effects and Fisher effects at work, the liquidity effect should be even stronger for the real yield. However, the estimated size of the liquidity effect is considerably reduced for the real yield, suggesting that inflation expectations did not increase due to higher liquidity.

As argued in Section 2, liquidity effects could potentially affect other parts of the yield curve, as long as yields are positive. To see if this has been the case, we regress the 5-year yield

depending on how the noise affects yields and prices. The measurement error of an explanatory variable leads to a bias in all parameter estimates. We have no prior of which direction the bias takes. Moreover, if the measurement error is correlated with the dependent variable, the problem of an omitted variable bias arises. Measurement error of a dependent variable, however, does not lead to biased estimates as long as the measurement error is not correlated with the explanatory variables in the regression (see Greene, 1993). Hence, moving the measurement error to the left side of the regression eliminates the problem.

Table 5: Robustness Check II: 5-Year Treasury Yield

Dependent Variable:	$i_t^{(5y)}$		$i_t^{(5y)} - E_t[\pi^{(5y)}]$	
Sample	02/1990 to 01/2011		02/1990 to 01/2011	
	Coefficient	t-stat	Coefficient	t-stat
c	-1.629***	-3.219	-1.640***	-4.590
FFTR	0.616***	9.175	0.375***	8.133
Expected Change in 1-Year Rate	0.059	0.229	0.026	0.141
Unemployment Gap	0.483***	3.608	0.182*	1.426
Core CPI Inflation	0.560*	1.782	0.331	0.515
Inflation Disagreement	0.118	0.855	0.052	0.858
Realized Volatility	-0.521	-0.912	-0.322	-0.816
Average Maturity	0.010***	4.934	0.005***	3.582
Treasury Supply	0.042*	1.958	0.034**	2.364
Reserves $\cdot D_t^{pre-ZLB}$	0.093	0.530	0.080	0.658
Reserves $\cdot D_t^{ZLB}$	-0.453***	-3.285	-0.313***	-3.384
D_t^{ZLB}	0.691	0.879	0.952*	1.791
D_t^{Lehman}	-0.535**	-2.062	-0.443**	-2.487
Adjusted R^2	0.9040		0.8753	
Number of Obs	1096		1096	

Both reserves and the Treasury supply are measured in percent of GDP.

Newey West standard errors (12 lags). ***, **, * denote significance at the 1, 5, and 10% levels; $D_t^{pre-ZLB}$ up to Dec-2008; D_t^{ZLB} Jan-2009 to end; D_t^{Lehman} Jun-2008 to Dec-2008

on the explanatory variables in column 1 of Table 5. The results suggest that the liquidity effect on the 5-year yield is greater than on the 10-year yield. The second column of Table 5, reporting the estimates for the real 5-year yield, shows that liquidity effects are estimated to be smaller for the real yield also at shorter maturity.

Table 6: Robustness Check III: Announcement Effects

Dependent Variable: $i_t^{(10y)}$				
Sample	1990/02 to 2011/01		1990/02 to 2011/01	
	Coefficient	t-stat	Coefficient	t-stat
c	-1.500***	-3.052	-1.588***	-3.182
FFTR	0.519***	8.184	0.497***	7.546
Expected Change in 1-Year Rate	0.460**	2.035	0.424**	1.981
Unemployment Gap	0.529***	4.315	0.504***	3.946
Core CPI Inflation	0.699**	2.449	0.754***	2.659
Inflation Disagreement	0.207	1.593	0.197	1.500
Realized Volatility	-0.157	-0.311	-0.134	-0.265
Average Maturity	0.011***	5.849	0.011***	6.102
Event Dummy	-0.369**	-2.547	-	-
Jackson Hole Dummy	-	-	−0.728***	-2.671
Treasury Supply	0.044**	2.234	0.051**	2.494
Reserves $\cdot D_t^{pre-ZLB}$	0.107	0.567	0.071	0.386
Reserves $\cdot D_t^{ZLB}$	-0.348***	-2.837	-0.285**	-2.434
D_t^{ZLB}	0.078	0.110	-0.178	-0.272
D_t^{Lehman}	-0.240	-0.973	-0.246	-1.003
Adjusted R^2	0.8893		0.8921	
Number of Obs	1096		1096	

Both reserves and the Treasury supply are measured in percent of GDP.

Newey West standard errors (12 lags). ***, **, * denote significance at the 1, 5, and 10% levels;

$D_t^{pre-ZLB}$ up to Dec-2008; D_t^{ZLB} Jan-2009 to end; D_t^{Lehman} Jun-2008 to Dec-2008

As argued in Section 2, the Fed's purchases of Treasury bonds may have signalled something about the Fed's future monetary policy intensions, notably how long the Fed intends to keep interest rates low. There is no reason to believe that such signalling effects would be correlated with the times of the Fed's actual asset purchases (as opposed to the announcement times of these). As a further robustness check, we nevertheless include the two announcement dummies mentioned in Section 3.2. The first column of Table 6 shows that a significant announcement effect indeed exists in the data. The Jackson Hole dummy is included in column 2 of Table 6, and shows that this was an important date for government bond yields. The liquidity effect is robust to the inclusion of these dummies.

Moreover, there is a potential source of endogeneity in the regressions. While the quantity

and time frame for the Fed's purchases of assets during the LSAPs were determined and announced in advance, the speed of the Fed's actual purchases could slightly vary across days, depending on market liquidity. Specifically, the Fed sought to purchase more assets during days of lower market liquidity, where yields tended to be slightly higher. Conversely, relatively less assets were bought on days with high market liquidity. If the influence of market liquidity on the Fed's asset purchases has been sufficiently strong, we might expect changes in reserves to be related to higher interest rate levels, and this could bias the parameter estimate on reserves downward. In line with the empirical literature on the effectiveness of foreign exchange interventions, Hamilton and Wu (2010) address similar endogneity problems by relating a forecast of the Treasury yield to changes in Treasury supply. As we are mainly concerned with qualitative results, we note that this source of endogeneity would tend to bias the parameter estimate for reserves downward, suggesting that the parameter estimate is on the conservative side.

Finally, and most importantly, a concern with the regression reported in Table 2 is the high persistence and near-unit root dynamics of the dependent and some of the explanatory variables. This raises the question of whether the significant correlations represent causality or are simply spurious. As a first pass at addressing this issue, we use the spread between the 10-year Treasury yield and the 3-month Libor (henceforth the term spread) as dependent variable. In contrast to the 10-year yield, the term spread does not exhibit a trend over the sample period (see 5), and while still persistent, it can be accepted borderline stationary depending on the type of unit-root test used. The concern about spurious results is hence mitigated, but not eliminated. The second column in Table 4 presents the regression results for the term spread. Although smaller in size, there is still a significantly negative liquidity effect during the ZLB period. Moreover, when using the term spread between the 5-year and the 3-month interest rates, the coefficient is larger in absolute terms and significant at the 1% level. From January 2009 to January 2011, the 3-month Treasury yield increased by 3.5 basis points. Hence, the estimation of liquidity effects on the term spread suggests that liquidity brought down the 10-year yield by 46 basis points during the period in question.

Simply running the specification used in the paper in first differences leads to the significantly negative parameter estimates only when the December 2008 is included in the ZLB sample, and insignificant estimates otherwise. Thus, we cannot conclude that the estimated empirical association between reserves and yields represents causality in the strict sense. However, for the first differences to yield significant results, it is necessary to specify the dynamics

right. We would need to specify how long it takes for changes in reserves to lead to changes in interest rates, and how long we should expect such interest rate effects to last. Neither the theoretical nor the empirical literature offers clear guidance as to what these time lags and persistence should be. Christiano and Eichenbaum (1992) find liquidity effects in the quarter after the expansion takes place, and lasting for nearly 20 quarters, while more recent papers find very short-term liquidity effects of changes in reserves (see for example Seth and Carpenter, 2006). Furthermore, it is reasonable to believe that the time it takes reserves to affect interest rates, and the persistence of the effect, could be variable and perhaps endogenous to economic circumstances. However, the short time period at the ZLB does not permit us to estimate a VAR in first differences with a substantial number of lags to capture such variable liquidity effects.

Concluding on robustness, the evidence is not conclusive and the risk of spurious correlations remains. But the data does not reject that liquidity effects have been at play as a transmission mechanism of the Fed's asset purchases on long term interest rates. Long term interest rates were lower than what the portfolio balance effects of changes in the supply of Treasury bonds alone can account for, and the correlation of the levels of interest rates with the level of reserves during the ZLB period suggests that liquidity effects could have been a possible cause of the lower level of the long-term interest rate observed at the ZLB. However, more data are needed to establish whether causality in fact runs from reserves to interest rates.

4 Conclusion

This paper argues that at the ZLB, the large scale asset purchases carried out by the Federal Reserve may have had liquidity effects due to increases in reserves as well as portfolio balance effects of the changes in the supply of Treasurys outstanding to the public. Failing to take into account such liquidity effects could lead to an underestimation of the impact of the large scale asset purchase programs on long-term government bond yields. While correlation is not causality, preliminary evidence suggests that reserves and yields were indeed correlated during the ZLB period, and that this correlation points to economically important effects. Thus, liquidity effects may have reduced long-term yields by 46 to 85 basis points due to the increase in reserves of about 2.5 percentage points of GDP between January 2009 and January 2011.

One upshot of these results is that when liquidity is drained from the banking system in the future, this could lead to a more important increase in long-term yields than expected if only supply effects are considered.

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A The Data

The analysis uses weekly data. Both the data on non-borrowed reserves and on the Fed's holdings of Treasury securities are available as end-of-Wednesday levels. We hence define the beginning of a week as Thursday and the end as Wednesday. For the data available on a daily basis, we compute one-week averages of the daily data on a weekly frequency. Thus, given $t-1$ corresponds to a Wednesday, then

$$i_t = \frac{1}{5}\sum_{s=0}^{4} i_{t+s} \quad \text{for} \quad \{i_t, i_{t+5}, \ldots\} \tag{2}$$

The data available only at a lower frequency are linearly interpolated, matching the monthly observation with the last week's observation of the month. Accordingly, Figures 3 to 5 depict the final data entering the regressions.

The 5-year and 10-year Treasury bond yields are from Datastream. Real 5-year and 10-year yields are constructed using the Fisher equation and data on inflation expectations at the two horizons from the Federal Reserve Bank of Cleveland.[12]

The Federal Funds target rate (FFTR) is retrieved from the FRED (DFEDTAR). It starts in 1982, but is discontinued after 2008. We therefore link it with recent data from Bloomberg.

Core CPI inflation is retrieved from the BIS. The unemployment gap is measured as the difference between the monthly unemployment rate retrieved from Datastream and the Congressional Budget Office's estimate of the NAIRU.[13] As in Gagnon et al. (2010), long-run inflation disagreement is measured as the interquartile range of 5- to 10-year ahead inflation expectations, as reported by the Michigan Survey of Consumers.[14] The six-month realized daily volatility is computed using a rolling 24-week window of the 10-year Treasury yield.

Gagnon et al. (2010) use the Eurodollar slope as a proxy for interest rate expectations. They use the difference between the implied rates on Eurodollar futures contracts settling approximately two-years and one-year ahead. We approximate the 2-year-ahead Eurodollar

[12]The Cleveland Fed's data on inflation expectations can be downloaded from `http://www.clevelandfed.org/research/data/inflation_expectations/index.cfm`.

[13]The CBO's estimate of the NAIRU can be downloaded from `http://www.cbo.gov/doc.cfm?index=12039`.

[14]This data can be downloaded from `http://www.sca.isr.umich.edu/main.php`.

rate by the implied 1-year forward rate from 2-year and 3-year Treasuries. Similarly, we approximate the 1-year-ahead Eurodollar rate by the implied 1-year forward rate from 1-year and 2-year Treasury yields. The expectations hypothesis defines the 2-year and the 3-year Treasury yields as follows.

$$1 + i_t^{(2y)} = \left(1 + i_t^{(1y)}\right)\left(1 + E_t i_{t+1}^{(1y)}\right) \tag{3}$$

$$1 + i_t^{(3y)} = \left(1 + i_t^{(2y)}\right)\left(1 + E_t i_{t+2}^{(1y)}\right) \tag{4}$$

The expected 1-year rate one year and two years ahead are thus

$$E_t i_{t+1}^{(1y)} = \frac{1 + i_t^{(2y)}}{1 + i_t^{(1y)}} - 1, \quad \text{and} \tag{5}$$

$$E_t i_{t+2}^{(1y)} = \frac{1 + i_t^{(3y)}}{1 + i_t^{(2y)}} - 1. \tag{6}$$

To get the expected change of the 1-year rate one year ahead, we use the difference between the two, i.e. $E_t i_{t+2}^{(1y)} - E_t i_{t+1}^{(1y)}$.

For the Treasury supply, we use the data provided by Hamilton and Wu (2010)[15] as well as data directly retrieved from the SOMA.[16] Hamilton and Wu provide data on total Treasury supply and on Treasury supply to the public, calculated as total supply minus Fed holdings. The periodicity of their data is monthly. Since the SOMA provides weekly data as of Wednesdays, we compute the public supply ourselves. Unfortunately, the data from the SOMA starts only as of end 2002. Therefore, we extend the public Treasury supply series backwards by linking it with the total Supply, which starts in February 1990. Treasury supply enters the regressions in percent of nominal GDP. The average maturity of total outstanding Treasury bonds is also provided by Hamilton and Wu (2010). It states the average maturity of debt held by the public, measured in weeks.

Weekly non-borrowed reserves are computed by subtracting total borrowings (TOTBORR) from total reserves held with the Fed (WRESBAL). Both are published by the FRED. In line with the Treasury supply, reserves enter the regressions in percent of nominal GDP.

[15] Hamilton and Wu (2010) provide their data on the Treasury supply from `http://econ.ucsd.edu/~jingwu/zlb_data.html`.

[16] The data on the Factors Affecting Reserve Balances (H.4.1) is published by the Board of Governors of the Federal Reserve System and can be downloaded from `http://www.federalreserve.gov/datadownload/Choose.aspx?rel=H41`, Table 2.

Business cycle measures are taken from different sources. First, the unemployment gap [fill in]. The real growth rate of output (Gross Domestic Production) is from the International Financial Statistics database of the IMF. The output gap is taken from the BIS.

Finally, the dummy variable of events controls for announcement effects. The dates listed in Table 7 are included. A more detailed description of these events is given in Gagnon et al. (2010) and Neely (2010).

Table 7: Events with Potential Announcement Effects

25 Nov 2008	initial LSAP announcement
01 Dec 2008	Bernanke's announcement of possible purchase of long-term Treasury securities
16 Dec 2008	FOMC statement: expansion of LSAPs
28 Jan 2009	FOMC statement: expansion of LSAPs
18 Mar 2009	FOMC statement: purchases of "up to" $300 billion of long-term Treasury securities
12 Aug 2009	FOMC statement: drop of "up to" language; gradual slowing or purchases
23 Sep 2009	FOMC statement: drop of "up to" language; gradual slowing or purchases
04 Nov 2009	FOMC statement: purchase of around $175 billion of agency debt
27 Aug 2010	Bernanke's speech at Jackson Hole
10 Aug 2010	FOMC statement: Reinvestment to keep reserve balances steady
21 Sep 2010	FOMC statement: keep policy of reinvesting
03 Nov 2010	FOMC statement: keep reinvesting and expanding purchases of long-term Treasury securities

B Charts and Tables

Figure 3: Dependent Variables

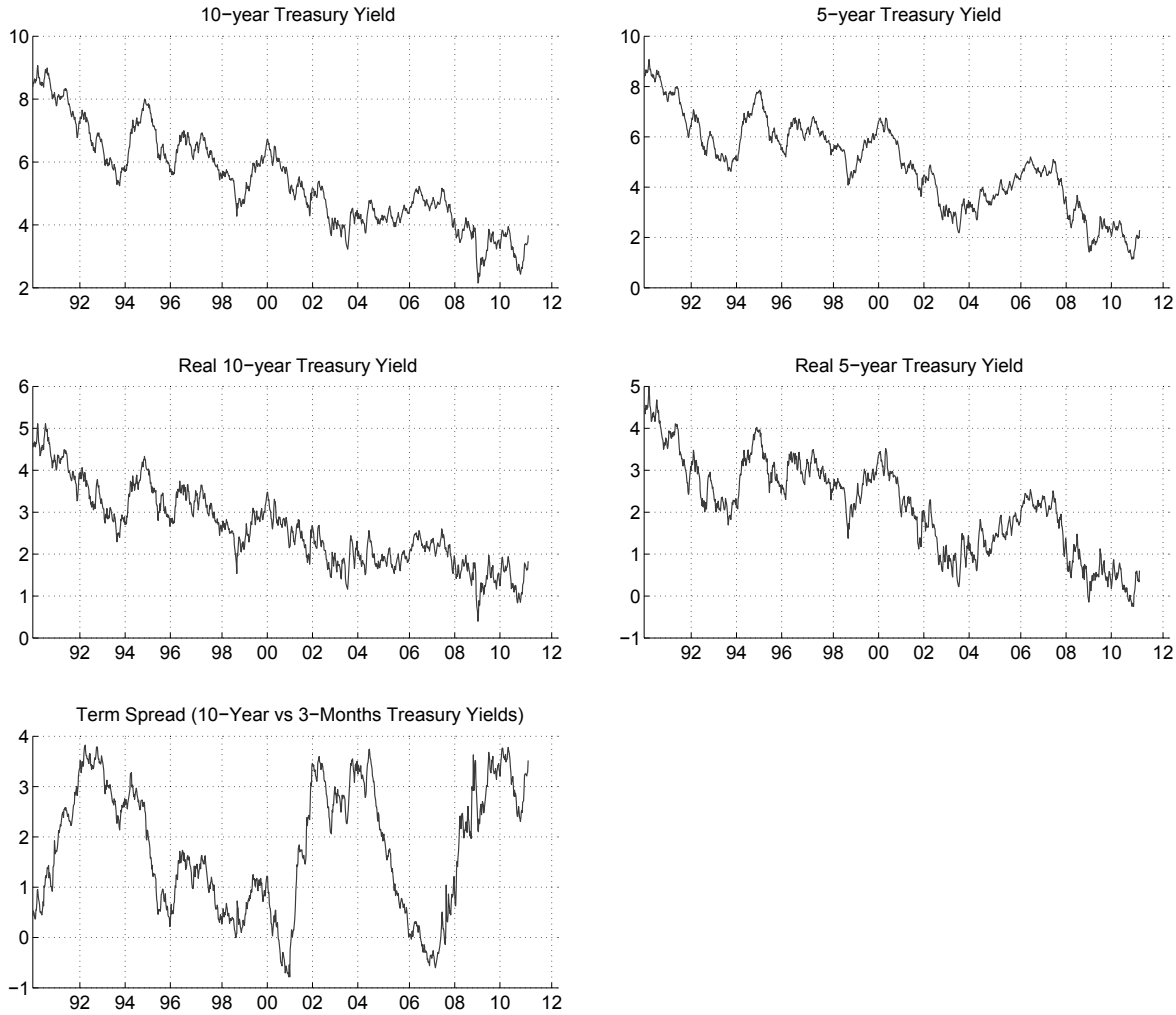


Figure 4: Regressors - Part I

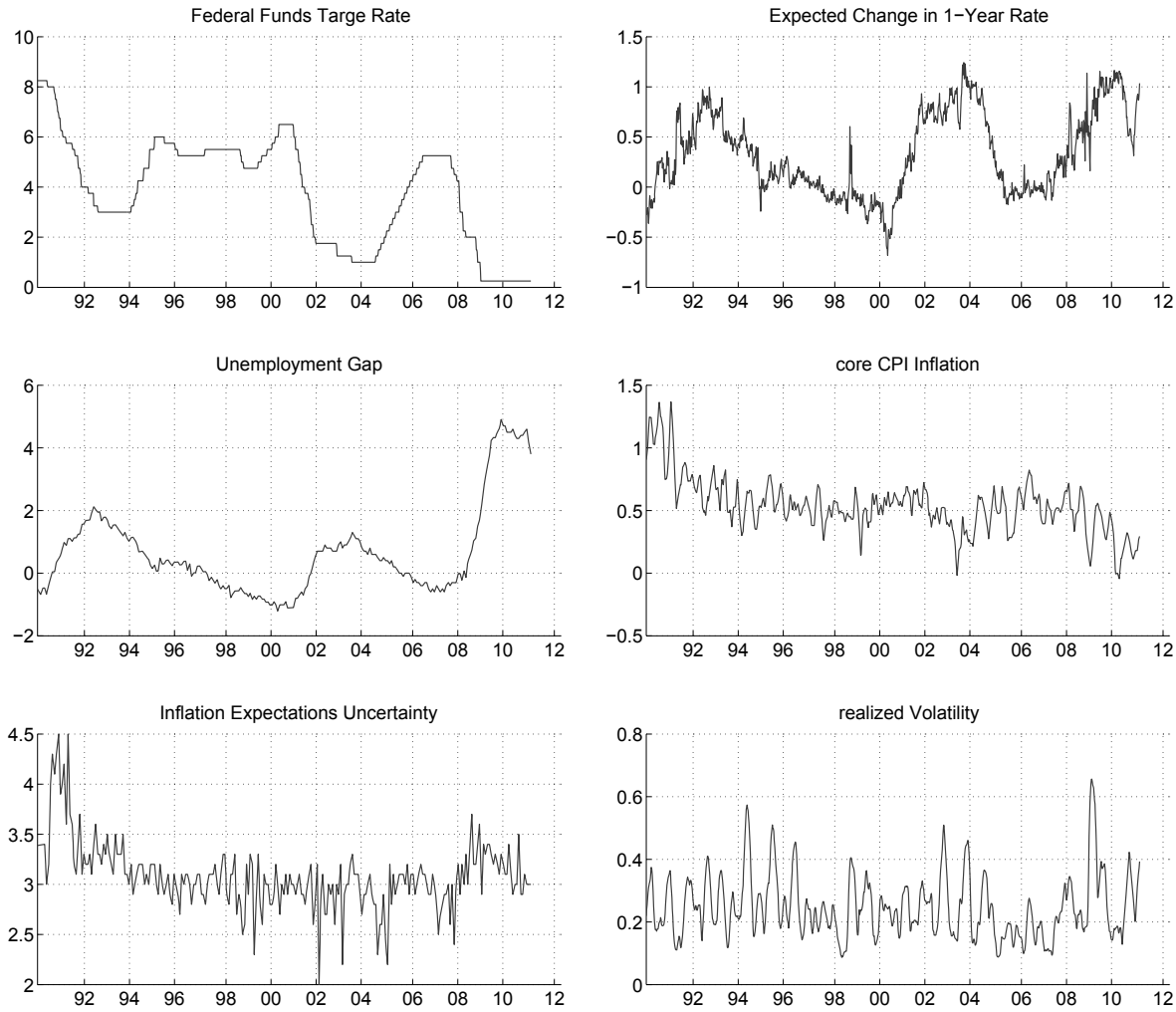
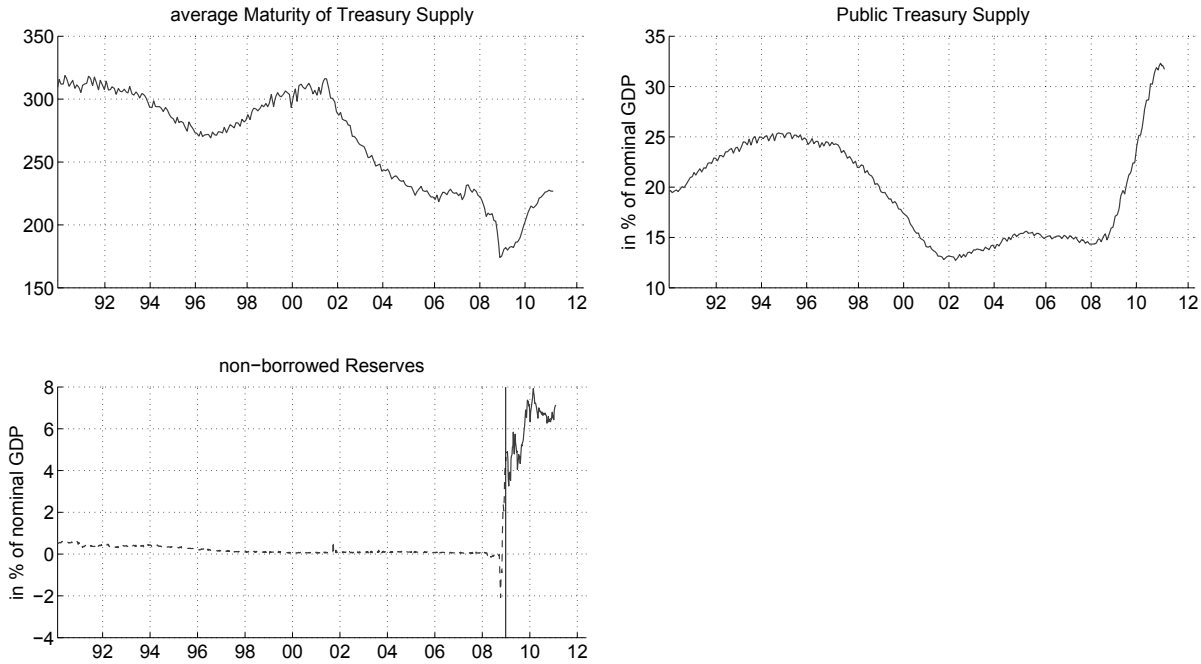


Figure 5: Regressors - Part II



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