Liquidity Effects at the Zero Lower Bound*

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Abstract

Liquidity effects reduce short-term interest rates during normal times. This paper shows that at the zero lower bound, liquidity effects have shifted to the longer end of the yield curve. Estimates for US data suggest that the expansion in reserves has reduced the 10-year US Treasury yield by some 85 basis points since January 2009. The supply effect of the Fed's purchases of long-term Treasury securities reduced the yield by another estimated 19 basis points. The empirical analysis controls for the interest rate level, changes in the expected future policy path, the business cycle, and several measures of uncertainty. The results are robust to announcement effects of the Fed on future policy as well as to changes in inflation expectations. Liquidity is also shown to impact on the term spread and on the 5-year yield.

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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 OMOs in longer-term assets 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 long-term 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. While this liquidity effect on long-term yields could, in principle, be present in normal times as well as at the ZLB, it can be expected to be stronger at the ZLB due to portfolio shifts from short-term toward longer-term assets with a strictly positive yield.

We test the hypothesis of liquidity effects at the ZLB by regressing the 10-year US Treasury bond yield on non-borrowed reserves, allowing the effect of reserves on yields to differ between the present ZLB period and the pre-ZLB period. 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. However, a currently very active 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. To focus on the liquidity effect, we control for such supply effects by including the total supply of Treasury securities available to the public in our regressions.

We find that (i) when running the regression without non-borrowed reserves as an explanatory variable, the realized yield on long-term Treasury securities has been lower during the recent ZLB period than what the regression predicts; (ii) reserves have had a significantly negative effect on long-term interest rates only after the short-term interest rate reached the ZLB. The estimates suggest that yields were brought down by 85 basis points during the ZLB period due to liquidity effects of the monetary expansion. The results are robust to controlling for the announcement effects of the QE programs, safe haven effects, macroeconomic variables and the supply effect. Moreover, we reach the same conclusions for the 5-year Treasury yield, for the real 5- and 10-year yields, as well as for the term spread between the 10-year and the 3-month yield.

The next section lays out the possible mechanisms through which large scale monetary expansions might affect the yield of bonds, in normal times and at the ZLB. An empirical test of the hypothesis of liquidity effects at the ZLB is set up in the subsequent section, which also presents the results. The final section concludes.

2 How Do Central Bank Asset Purchases Affect Interest Rates?

When a central bank injects liquidity, it does so by buying an asset from a reserve-holding bank, and by crediting the account of that bank with reserves. Hence, the increase in reserves can affect the price of the purchased asset in two separate ways: the supply effect and the liquidity effect. The supply effect arises from the change in the remaining supply of that asset in the market. The liquidity effect arises from the associated increase in central bank money (reserves) used to finance the purchase.

The supply effect relates to the asset side of the central bank's balance sheet. In a portfolio balance model with market imperfections, such as segmented markets and assumptions of preferred habitat, the price of the asset in question must increase 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 influences their yields through so-called supply effects.

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

Portfolio rebalancing in turn implies that the yields of surrounding maturities might also fall, potentially extending the fall in yields further on both sides. How far out the yield curve is smoothed by arbitrageurs depends on risk aversion and other preferences of the agents There are other potential effects of outright purchases on the market price of the specific asset bought. One of these is an increase in market liquidity of the specific asset. The liquidity referred to here is to be distinguished from the bank liquidity that is due to reserves, and hence, from the liquidity effect described below. The enhanced market liquidity of a specific asset can affect the price of that asset, as shown e.g. by Krishnamurthy and Vissing-Jorgensen (2011) and D'Amico and King (2011). The US Treasury market is highly liquid, so we ignore market liquidity for the remainder of this paper.

The liquidity effect is related to the liabilities' side of the central bank balance sheet. It arises from the fact that the portfolio of banks involved in OMOs includes 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 interest rates. 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), Hamilton (1997), Bernanke and Mihov (1998), Carpenter and Demiralp (2008), Thornton (2008), Hagedorn (2009), or Judson and Klee (2010). The literature is vague on how liquidity effects might work in practice. Liquidity effects have been modeled using segmented market assumptions. Examples of such models are Grossman and Weiss (1983), Christiano and Eichenbaum (1992), 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. How the mechanism actually works in practice, where banks are the receivers of monetary injections through OMOs, is not well understood. One way liquidity effects might work is the following: banks, holding more reserves after an OMO, seek to trade some of these additional reserves for positive yielding assets. Assuming market imperfections of the same sort as those assumed for a supply effect to exist, the higher demand would put upward pressure on the price of these assets and thus reduce their yields. The class of assets affected by this liquidity effect depends on bank's choices. This is different from 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 affects the entire yield curve.

The central bank's actions and announcements may also affect yields through changes in expectations, the associated portfolio rebalancing, or the Fisher effect. On the one hand, expansionary monetary policy may raise inflation expectations, which, contrary to the liquidity effect, would raise longer nominal yields. It is usually argued that the Fisher effect of a monetary expansion, working through inflation expectations, dominates the liquidity effect at the longer end of the yield curve, leading the literature to typically look for liquidity effects at the short end of the yield curve. On the other hand, the announcement of an asset purchase may signal that the central bank is concerned about the economic outlook, which would reduce inflation expectations. Such announcement effects do not directly depend on whether the economy is at the ZLB.

2.1 In Normal Times

Expansionary monetary policy is normally conducted in short-term assets, typically in Treasury bills. Thus, the supply effect causes the yields on Treasury bills to fall. This effect is spread out to near-by maturities by portfolio rebalancing and arbitrage, so that the level of the yield curve falls at short maturities. The outright purchase augments banks' reserve balances held with the Fed. As reserves carry no yield, banks will want to spend (some of) their excess reserves on non-zero yielding assets. Hence, the liquidity effect will cause the yields of the demanded assets to fall. How the yield curve is affected depends on the banks' portfolio optimization choices.

2.2 At the Zero Lower Bound

OMOs have recently been carried out in a wider range of assets, such as long-term government bonds, asset backed securities, agency debt, or commercial certificates. Under the standard assumptions of the portfolio balance model, the supply effect reduces the yields of the long-term assets bought by the Fed, or close substitutes thereof. The literature, for example Clouse et al. (2003), often argues that there is no liquidity effect at the ZLB, based on one of three assumptions. The first assumption is that OMOs are exclusively conducted in assets which are of short maturity, safe, and liquid, such as short-term government debt. The second assumption is that there is only one interest rate in the economy, i.e. there is no term structure in the model. Hence, all safe and liquid assets serve as perfect substitutes for money at the ZLB. The third assumption, often made in the DSGE literature, is that the Fisher effect discussed above dominates any liquidity effects at the longer end. It is straightforward to see that the first two assumptions do not hold. Whether the third is a reasonable assumption is an empirical question, pointed out in Christiano and Eichenbaum (1992, 1995). During the ZLB period, OMOs raised banks' reserve balances, without reducing other money-equivalent zero-yielding assets. The relative amount of short-term assets in banks' portfolios hence increased, which allows for a liquidity effect. Since short-term liquid and safe assets do not offer a positive yielding alternative to reserves at the ZLB, banks are likely to start bidding up the prices of longer-term assets, such as long-term government bonds.[2] Long-term yields would thus fall.

To conclude, the supply effect, the Fisher effect as well as other announcement effects do not change in the way they affect long-term yields as a consequence of the economy hitting the ZLB. The liquidity effect, however, moves from the short to the longer end of the yield curve as the ZLB is reached.

3 An Empirical Investigation of US Data

As argued above, we need a research design which allow us to distinguish between the liquidity effect in normal times and at the ZLB, and to disentangle liquidity effects from supply effects and from effects of changes in expectations about the future outlook and the future monetary policy stance. The following sections present how we approach these issues econometrically.

3.1 Methodology and Data

We take an empirical approach following the one employed by Gagnon, Raskin, Remache and Sack (2010) to assess supply effects, and set up a regression for the long-term US treasury yield.[3] We add reserves in order to measure liquidity effects, and a few other relevant explanatory variables. We also use more recent data that 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

[2]Krishnamurthy and Vissing-Jorgensen (2010) show how long-term government bonds can, to some degree, be seen as alternatives to holding liquidity, in that they provide liquidity and safety to a similar extent as money.

[3]In theory, both the liquidity and the supply effect should impact on the term premium of the long-term interest rate. Gagnon et al. (2010) therefore base their main findings on regressions of the term premium, and use the nominal yield regressions only as control regressions. However, the term premium is unobservable, and estimations thereof come with high uncertainty, especially for the period of the recent financial crisis. We hence prefer to use the long nominal yield directly; as a robustness check, we run the regression for the term spread.

which data is only available in lower frequency are linearly interpolated (see appendix for details). The baseline regression equation takes the following form:

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

$i_t^{(10y)}$ denotes the average daily yield on 10-year US Treasury bonds over the week following $t-1$.[4] R_{t-1} denotes the level of non-borrowed reserves held with the Fed at date $t-1$. Reserves are thus lagged, which mitigates potential endogeneity issues. $D^{pre-ZLB}$ and D^{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.

As controls, we include the supply of Treasury securities to the public, in percent of nominal GDP, 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 the supply to the public, rather than the Fed's holdings and the total supply separately, because the supply effect is related to the supply available in the market. Moreover, 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.[5] 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.[6]

The Federal funds target rate is included to account for the general interest rate level. To account for expected future short term interest rates, and hence, expected future monetary policy path, we additionally 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

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

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

[6] 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.

included to capture the effect of the business cycle.[7] 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.[8] 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 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. Then, 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 program, QE1, and QE2. The particular events are listed in Table 7 in the appendix. The choice of dates is in line with recent case studies, particulary with 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 the 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.

3.2 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 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 similar to the estimate in Gagnon et al. (2010).[9]

How well does this specification perform for the ZLB period? To test the model, we com-

[7]Backus and Wright (2007), for example, show that the term premium is countercyclical because risk appetite tends to be larger in booms than during busts.

[8]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.

[9]The coefficients on the other explanatory variables deviate substantially 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.

Table 1: Pre-Crisis Regression Results

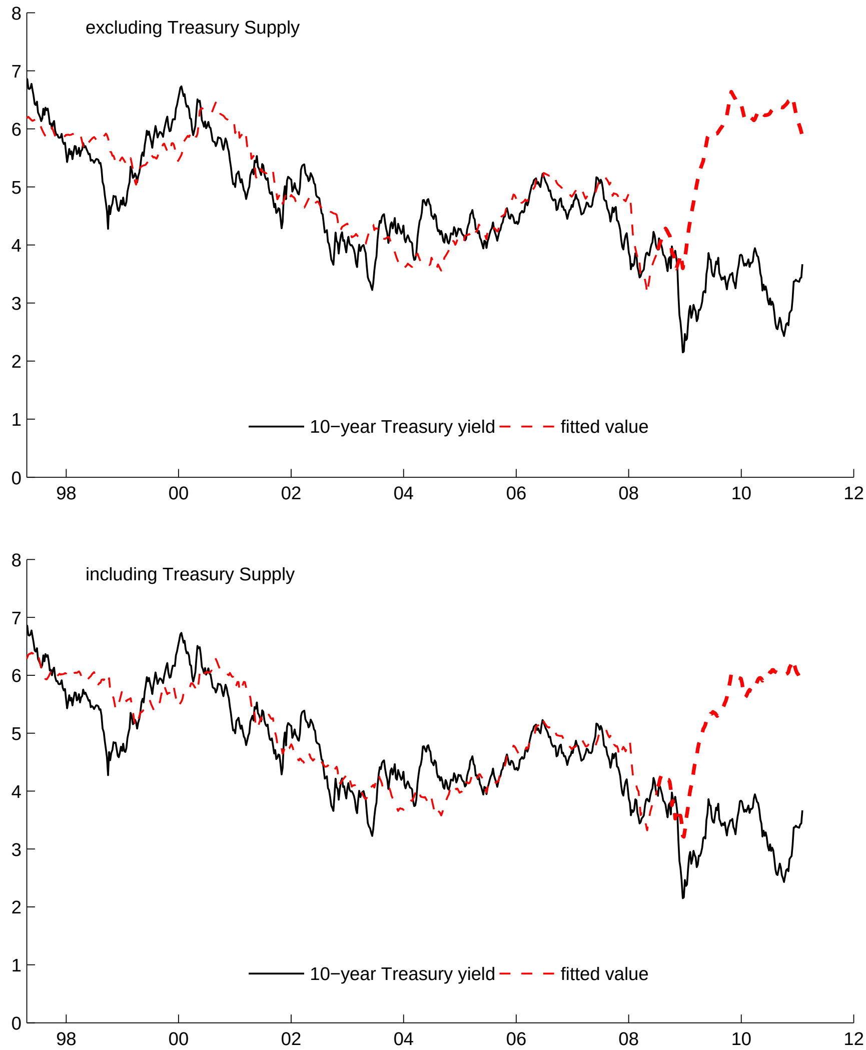
Dependent Variable: $i_t^{(10y)}$				
Sample	1990/02 to 2008/06		1990/02 to 2008/06	
	Coefficient	t-stat	Coefficient	t-stat
c	-0.810*	-1.661	-1.474***	-2.932
FFTR	0.579***	9.346	0.476***	6.815
Expected Change in 1-Year Rate	-0.069	-0.316	0.220	0.985
Ugap	0.914***	7.765	0.583***	4.078
Core CPI	0.545	1.622	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	

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

pute 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 1 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. However, the deviation of the fitted value from the true yield remains large, suggesting that factors not contained in these regressions were depressing long-term yields when short-term yields hit the ZLB.

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 which are more in line with those 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, with the

Figure 1: 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.

exception of the significantly positive unemployment gap. This matches the findings of the previous literature quite well and will not be discussed further here. Non-borrowed reserves turn out to be highly significant and negative at the ZLB, but not significantly different from

Table 2: Regression Results including non-borrowed Reserves

Dependent Variable: $i_t^{(10y)}$				
Sample	1990/01 to 2011/02		1990/01 to 2011/02	
	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
Ugap	-0.111	-1.049	0.527***	4.296
Core CPI	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 $\cdot D^{pre-ZLB}$	-	-	0.078	0.419
Reserves $\cdot D^{ZLB}$	-	-	-0.341***	-2.731
D^{ZLB}	-	-	0.005	0.108
D^{Lehman}	-	-	-0.280	-1.110
Adjusted R^2	0.8604		0.8888	
Number of Obs	1096		1096	

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

zero during normal times.[10] The results thus suggest that liquidity effects of the Fed's asset purchases contributed to driving long-term yields down as short-term interest rates reached the ZLB.

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. The first column reports the change in the respective variable from January 2009 to January 2011. The second column shows the coefficient estimates from the main regression shown in 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. In addition to the public Treasury supply, Table 3 reports the contributions of the total Treasury

[10] 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.

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

	2009/01 to 2011/01		
	Change	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
Ugap	1.620	0.527	0.853
Core CPI	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.

supply and the Fed's purchases of Treasury securities separately.

The results suggest that both the supply effect and the liquidity effect of the Fed's purchases have contributed to the low level of long-term yields during the ZLB. The point estimate for reserves suggests that the increase in reserves has reduced the level of the long yield by roughly 85 basis points since early 2009. 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. These estimates lie at the upper end of 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.

3.3 Robustness

In theory, what matters for the economy is the real rather than the nominal yield. Moreover, we expect liquidity effects to affect the real part of the yield, whereas the nominal part may pull in the opposite direction and raise yields, if the Fed's asset purchases boost inflation expectations. The first column of Table 4 shows the results for the real 10-year interest rate.[11]

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
Ugap	0.262***	2.970	0.373***	3.558
Core CPI	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 $\cdot D^{pre-ZLB}$	0.039	0.283	-0.052	-0.488
Reserves $\cdot D^{ZLB}$	-0.178**	-2.236	-0.183*	-1.848
D^{ZLB}	-0.001	-0.003	-0.370	-0.644
D^{Lehman}	-0.226	-1.261	0.629***	3.566
Adjusted R^2	0.8523		0.8871	
Number of Obs	1096		1096	

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

[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 problems. 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, depending on how the noise affects yields and prices. The measurement error of an explanatory variable

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. A possible reason for this is that the OMOs signalled a weakening economic outlook that actually lowered inflation expectations.

Non-stationarity of the nominal and real interest rates could lead to spurious regression results. This should not be an issue for the term spread, however. The second column in Table 4 presents the results for the term spread as the dependent variable. Although smaller

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
Ugap	0.483***	3.608	0.182*	1.426
Core CPI	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 $\cdot D^{pre-ZLB}$	0.093	0.530	0.080	0.658
Reserves $\cdot D^{ZLB}$	-0.453***	-3.285	-0.313***	-3.384
D^{ZLB}	0.691	0.879	0.952*	1.791
D^{Lehman}	-0.535**	-2.062	-0.443**	-2.487
Adjusted R^2	0.9040		0.8753	
Number of Obs	1096		1096	

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

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.

in size, there is still a significantly negative liquidity effect during the ZLB period. From January 2009 to January 2011, the 3-month Treasury yield increased by 3.5 basis points. Hence, the estimation suggests that liquidity brought down the 10-year yield by 46 basis points.

Liquidity effects could potentially affect other parts of the yield curve, as long as yields are positive. As a robustness test, we therefore regress the 5-year yield on the explanatory variables in column 1 of Table 5. The results suggest that the liquidity effect on the 5-year yield is both stronger and larger 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
Ugap	0.529***	4.315	0.504***	3.946
Core CPI	0.699**	2.449	0.754***	2.659
Inflation Disagreemet	0.207	1.593	0.197	1.500
Realized Volatility	-0.157	-0.311	-0.134	-0.265
Avg 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 $\cdot D^{pre-ZLB}$	0.107	0.567	0.071	0.386
Reserves $\cdot D^{ZLB}$	-0.348***	-2.837	-0.285**	-2.434
D^{ZLB}	0.078	0.110	-0.178	-0.272
D^{Lehman}	-0.240	-0.973	-0.246	-1.003
Adjusted R^2	0.8893		0.8921	
Number of Obs	1096		1096	

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

As argued in Section 2, the Fed's purchases of Treasury bonds might affect interest rates through announcement effects on the expected future path of monetary policy. Announcement effects should be partially picked up by the expected change in the 1-year interest rate one year ahead, included as control in the baseline specification. As a further robustness check, we include the two announcement dummies mentioned in Section 3.1. 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 indeed an important date, if not an important speech, for government bond yields. The liquidity effect remains significantly negative and of largely the same size. The liquidity effect is thus robust to controlling for announcement effects.

4 Conclusion

Monetary expansions are often found to have liquidity effects on short-term interest rates. This paper shows that at the ZLB, the liquidity effect of OMOs has moved to the longer end of the yield curve, thereby reducing long-term government bond yields. The results are robust to controlling for supply effects of outright OMOs as well as announcement effects, changes in the expected future short-term interest rate and other control variables. The parameter estimate suggests that the increase in non-borrowed reserves since the onset of the ZLB period brought down the long-term Treasury yield by an estimated 85 basis points. Reserves did not have significant effects on long yields in the pre-ZLB period before January 2009.

One upshot of these results is that when liquidity is drained from the banking system in the future, this could lead to an increase in long-term yields even if the drainage of liquidity is not the result of a sale of long-term Treasury bonds.

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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 2 to 4 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.

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[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.

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

Figure 2: Dependent Variables

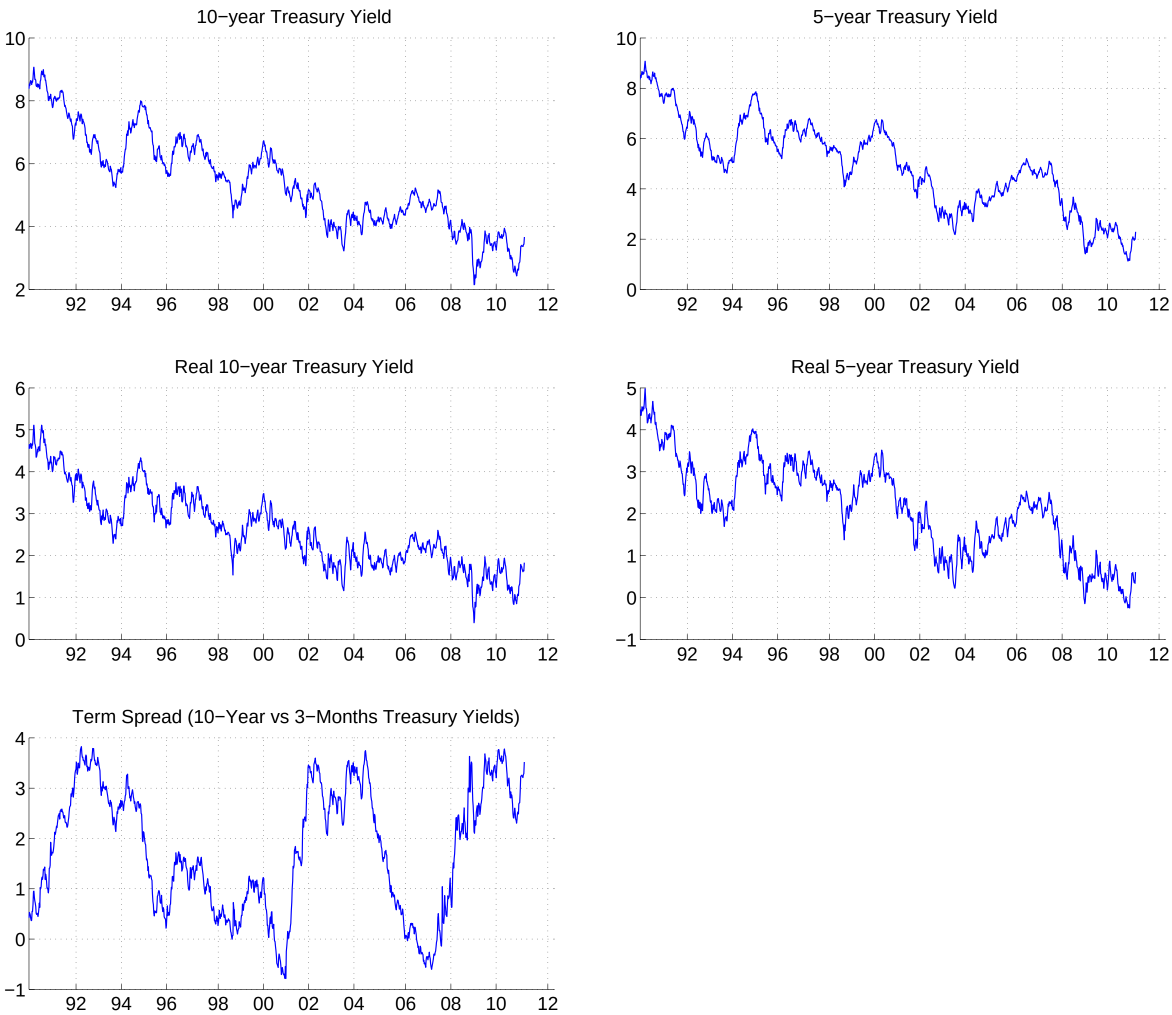

Figure 3: Regressors - Part I

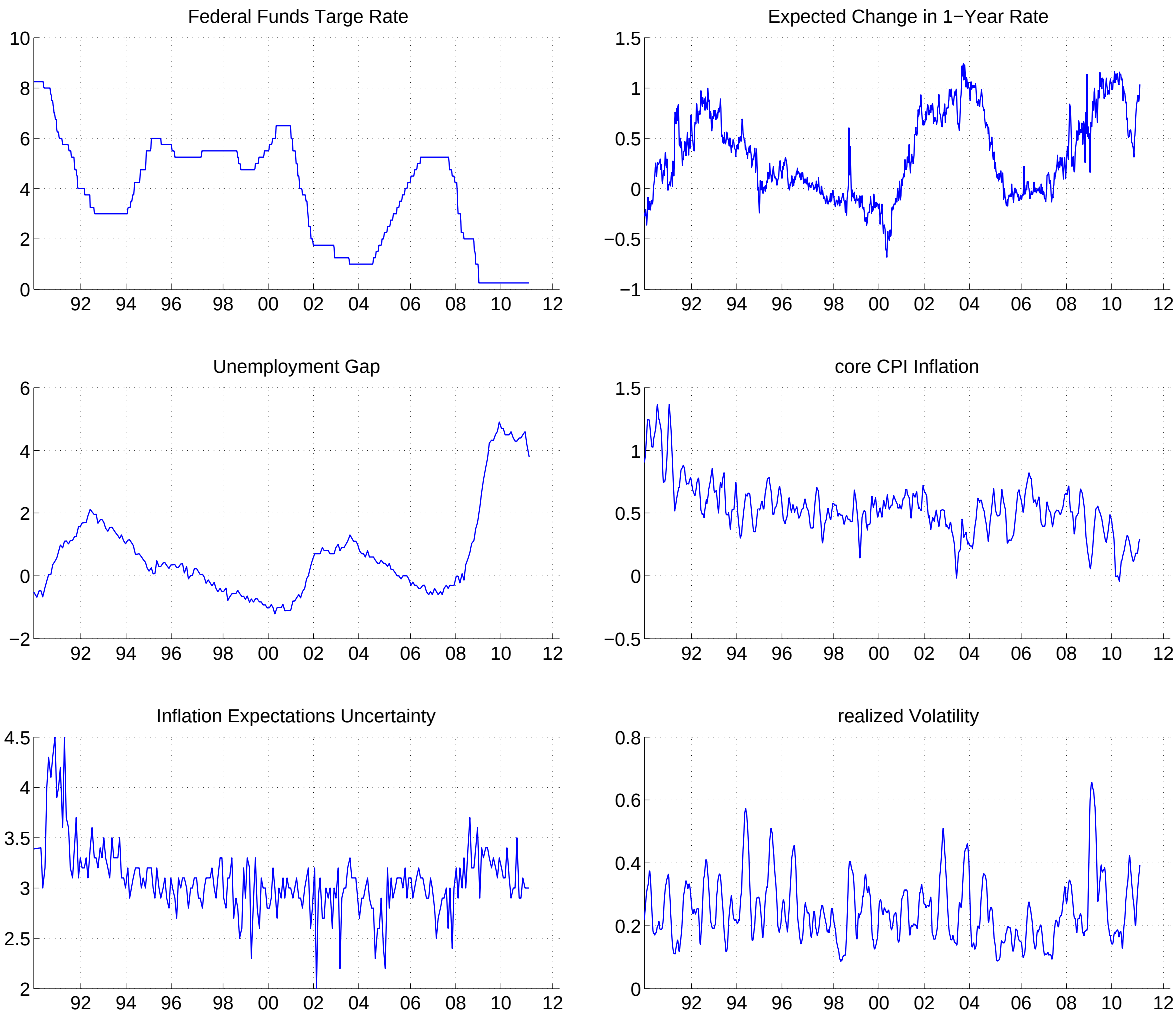

Figure 4: Regressors - Part II