Does a Big Bazooka Matter? Central Bank Balance-Sheet Policies and Exchange Rates*

Preliminary work in progress - Do not cite or distribute

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December 28, 2017

Abstract

In this paper we study the effects of unconventional monetary policy (UMP) in the form of increases in central bank balance sheets, focusing on the foreign exchange market as a case study. We explicitly relate the response of the exchange rate and its fundamental determinants to shocks to central bank balance sheets, in order to disentangle the workings of different transmission channels. Using announcements of QE by the ECB and the Federal Reserve predicting future changes in their relative balance sheet, we find that a 1% increase in the ECB balance sheet relative to that of the Fed results in a 1% euro depreciation vis-à-vis the dollar. Since the euro-dollar exchange rate is expected to revert to its baseline after less than a year, changes in expectations of (relative) monetary policy over longer horizons in the future (the "signalling" channel) can hardly contribute to the estimated QE effects on the exchange rate. We find instead that these policies work by impinging on money market conditions, and on frictions in foreign exchange markets, such as failures of covered interest rate parity. Specifically, an ECB expansionary QE shock reduces the short-term euro-dollar interest rate differential, while narrowing the differential between money market euro rates and their "synthetic" counterparts in euro-dollar currency swaps. However, as these two channels basically offset each other in their effects on the exchange rate, we find that currency risk premia account for the bulk of the euro depreciation.

Keywords: Unconventional monetary policy, exchange rates, covered interest rate parity, limits to arbitrage, financial frictions.
JEL-Classification: F42.

*We thank for useful comments and suggestions, without implicating, Ambrogio Cesa-Bianchi, Jordi Galí, Pierre-Olivier Gourinchas, Wouter den Haan, Cho-Hoi Hui, Oscar Jorda, Chris Neely, Barbara Rossi, Mark Watson, Ken West and participants at ESSIM 2017, the 2017 Annual Meeting of the Central Bank Research Association, and the BIS-CEPR-GRU-JIMF International Conference on Exchange Rate Models for a New Era. The views expressed in this paper are our own, and do not reflect those of the European Central Bank or any institution to which we are affiliated.

1 Introduction

Since the onset of the global financial crisis in 2008, central banks around the world have engaged in a number of unprecedented and unconventional monetary policy interventions. In particular, central banks have deployed quantitative easing (QE) measures as an additional policy tool when interest rates reached their lower bound. For instance, Figure 1 shows that the Federal Reserve was early in purchasing sizeable amounts of private and government securities, which resulted in a dramatic expansion of its balance sheet. The ECB initially implemented more modest asset purchase programs, but greatly expanded its provision of liquidity to the banking sector far beyond standard short-term maturities, especially after the second half of 2011. By March 2012, the nominal size of the ECB balance sheet was similar to that of the Federal Reserve. Then, between March 2012 and the start of 2015 the continuous purchases under the Federal Reserve's QE3 program again doubled the Federal Reserve's balance sheet relative to that of the ECB. However, in March 2015 the ECB embarked on a comprehensive program of private and public asset purchases, which returned the size of its balance sheet close to that of the Federal Reserve by the end of 2017.

The exchange rate has been at center stage in the discussion about the effectiveness, transmission channels and the side effects of QE (see, for example, Mantega, 2010; Rajan, 2013; Bernanke, 2015).[1] That monetary policy actions that alter the size of the central bank's balance sheet and thereby the monetary base may affect the international value of a currency is not a new topic, as it has already been discussed in the context of the monetary theory of the exchange rate. And indeed, Figure 1 documents that there has been a correlation between the announcements of QE measures, the relative balance sheet and the US dollar-euro exchange rate. In particular, central banks' balance sheets tended to expand and the exchange rate to depreciate following the announcement of QE measures. These correlations are of course silent about causality, and can thereby not be referred to in order to showcase the effectiveness or transmission channels of QE measures. Against this background, a large literature that is concerned with assessing the effects of QE measures has emerged.[2] However, the bulk of this literature has considered the high-frequency (i.e., daily or intra-day) effects of QE measures, typically by means of event studies that focus on a narrow time window around their announcement. Unfortunately, this approach is not informative regarding the persistence of the effects beyond very short-term horizons after the announcement and the associated transmission channels.

Some work has explored the macroeconomic effects of QE at lower frequencies. Early studies are

[1] In particular in the context of spillovers from QE policies is the exchange rate center stage (Bruno and Shin, 2015a,b).

[2] The literature has become too voluminous to do equal justice to all relevant contributions. For a survey of the literature see Bhattarai and Neely (2016) and Borio and Zabai (2016).

Kapetanios et al. (2012) as well as Baumeister and Benati (2013), who study the effects of QE in the cases of the US and the UK considering monthly VAR models and proxying QE as shocks to the government bond spread. Gambacorta et al. (2014) bring the monthly VAR framework to the panel context for eight advanced economies in order to address the short sample period, proxying QE as shocks to the central bank balance sheet. Weale and Wieladek (2016) also use the central bank balance sheet in order to proxy QE shocks in monthly VAR models, but focus on the US and the UK. Wu and Xia (2016) study the effects of unconventional monetary policy proxied by a shadow federal funds rate in a VAR model for the US. Meinusch and Tillmann (2016) consider a monthly QualVAR in which QE announcements proxy an unobserved propensity for QE for the US. Much less work has so far been done on the euro area. Altavilla et al. (2016) study the effects of the OMT announcements in counterfactual simulations in a VAR framework, calibrating the OMT shock based on the effect on government bond yield spreads estimated in a high-frequency event study. And Boeckx et al. (2017) estimate monthly VAR models, proxying QE shocks by the central bank balance sheet. Most importantly, all of these studies consider the effect of QE on output and inflation. Only Boeckx et al. (2017) investigate in more depth the transmission channels of QE by adding a few variables one at a time to their baseline VAR model. *None* of these studies investigates the effects of QE on the exchange rate, which is surprising given its prominence in the debate about the effectiveness of QE, its transmission channels and spillovers.

Our paper fills this gap. We estimate the effects of QE on the exchange rate at frequencies and time horizons that are relevant for policymakers, and we explore the transmission channels through which these materialise. We focus on the exchange rate of the US dollar against the euro, as the ECB and the Federal Reserve have been carrying out the largest QE programmes after the global financial crisis, and as this is the world's most liquid currency pair. As the dollar-euro exchange rate is a relative price, in our analysis we consider the size of the ECB's balance sheet *relative* to that of the Federal Reserve as well as QE announcements by both the ECB and the Federal Reserve. Our findings suggest that QE measures have large and persistent effects on the exchange rate. For example, our estimates imply that the ECB's APP program which raised the ECB's balance sheet relative to that of the Federal Reserve by 35% between March 2015 and the end of 2016 depreciated the euro vis-à-vis the US dollar by 20%. Regarding the transmission channels, we first find that a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve reduces the euro-dollar short-term money market interest rate differential, reflecting expectations of further monetary policy accommodation in the short term. Second, we find that QE shocks relax limits to arbitrage in foreign exchange markets, as they persistently reduce deviations from CIP. We also find that changes in risk premia in foreign exchange markets play an important role in the transmission of QE shocks to the exchange rate.

We arrive at these conclusions using an empirical approach that draws on elements from several strands of the literature. Borrowing from the news shocks literature (Schmitt-Grohe and Uribe, 2008), we conceive QE measures that are announced in period t as shocks which materialise in period t but which are anticipated by agents to be implemented and to affect central banks' balance sheets only in future periods $t + m$ for $m = 1, 2, \ldots, M$. Borrowing from the literature on fiscal policy shocks (Mertens and Ravn, 2013), we show that while these QE *shocks* are unobserved by the econometrician they can be proxied by future changes in central banks' balance sheets. We consider QE shocks rather than *announcements* as the main variable of interest in our empirical framework, because it allows us to come up with a quantitative assessment of the overall effects of the ECB's and the Federal Reserve's major QE measures on the exchange rate. In particular, our framework allows us to determine an elasticity that reflects the change in the exchange rate that is implied by a change in the relative central bank balance sheet of a given magnitude.

More technically, we estimate the effects of QE shocks on the euro-dollar exchange rate using local projections (Jorda, 2005). We derive a theoretically-consistent local projection regression equation from the standard asset pricing formulation of exchange rate determination, according to which the spot exchange rate is determined by current and future expected fundamentals. Specifically, the local projection regression for the exchange rate at horizon h is implied by the difference between the uncovered interest rate parity conditions for periods $t + h$ and $t - 1$. In order to address the endogeneity of the relative balance sheet — which we use as proxy for the unobserved QE shocks — in the local projection regression equation, we exploit announcements of ECB and Federal Reserve QE measures as instruments in two-stage least squares regressions. Deriving the local projection regression equation from a structural equation for the exchange rate disciplines the empirical specification we bring to the data, for example by pointing to possible sources of endogeneity, guiding the choice of control variables and their timing. We also pay great attention to model specification tests, including instrument validity and power. Finally, we explore a battery of robustness checks related to variations of the identification of QE shocks, various aspects of the regression specification and data frequency.

The paper is organized as follows. In Section 2 we review standard exchange rate determination according to asset pricing theory, and we derive the local projection equation for the exchange rate. Then, in Section 3 we describe the empirical specification of the local projection regression, followed by our results in Section 4. Section 5 presents robustness checks, and Section 6 concludes.

2 An framework for the assessment of the effects of QE on the exchange rate

In this section we motivate the local projection regression equation for the exchange rate that we will use in order to estimate the effects of QE measures. To do so, we first draw on textbook asset pricing theory and review exchange rate determination in the presence of frictions that give rise to deviations from CIP. We then show that the associated uncovered interest rate parity (UIP) condition implies that the value of the spot exchange rate in period t is equal to the undiscounted sum of future expected fundamentals, i.e. expected interest rate differentials, currency risk premia and CIP deviations up to horizon T, as well as the expected exchange rate at horizon T. Finally, we show that we can estimate the effects of QE shocks on the exchange rate based on a theoretically-consistent local projection regression equation derived as the difference between the UIP conditions for periods $t+h$ and $t-1$.

2.1 Exchange rate determination and CIP deviations

Consider an investor whose relevant nominal discount factor is expressed in US dollars ("American" investor), $\mathcal{D}_t^{\$}$.[3] Under standard conditions, the relation between $\mathcal{D}_t^{\$}$ and the one-period nominally risk-free US dollar nominal interest rate $R_t^{\$}$ is then given by:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}. \tag{1}$$

Equation (1) implies that one dollar today has to be equal to the certain dollar amount $R_t^{\$}$ in period $t+1$, appropriately discounted by the expected marginal value of wealth across the two periods. Similarly, denoting $R_t^{€}$ the one-period risk-free euro nominal rate, $F_{t,t+1}$ the forward dollar price of one euro and S_t the spot price (expressed in amount of dollars per euro), the investor would price the nominally safe investment of one dollar today into $1/S_t$ euro yielding the safe dollar payoff $F_{t,t+1}R_t^{€}$ in period $t+1$ as:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}\right) \frac{F_{t,t+1}R_t^{€}}{S_t}. \tag{2}$$

[3]Under general conditions, the stochastic discount factor is equal to the ratio of Lagrange multipliers on the agent's future and current budget constraint, i.e., her marginal value of wealth (see Lucas, 1978). The nominal discount factor is not necessarily a function of consumption growth only. For instance, with Epstein-Zin-Weil preferences, it is a nontrivial function of wealth growth itself.

More generally, if the investor is potentially borrowing constrained.[4,5] In this case the two Euler equations above read as follows:

$$1 \geq 1 - \lambda_t^{\$} = E_t \left(\mathcal{D}_{t+1}^{\$} \right) R_t^{\$}, \tag{3}$$

and

$$1 \geq 1 - \lambda_t^{€} = E_t \left(\mathcal{D}_{t+1}^{\$} \right) \frac{F_{t,t+1} R_t^{€}}{S_t}. \tag{4}$$

When $\lambda_t^{\$} = 0$, Equation (3) holds with equality and the investor is not facing a binding borrowing constraint at the desired level of investment in the dollar risk-free rate. Even in the presence of borrowing constraints, this is the case when the desired investment is positive, i.e. the investor is saving. When $\lambda_t^{\$} > 0$, one dollar in period t is worth more than (the appropriately discounted value of) $R_t^{\$}$ in $t+1$. In the absence of borrowing constraints, the investor would borrow against future income until the values of one dollar in periods t and $t+1$ are equalised. Thus, $\lambda_t^{\$} \geq 0$ can be interpreted as the shadow value of borrowing one additional dollar. The rationale for $\lambda_t^{€}$ is analogous, but refers to borrowing and saving in the synthetic risk-free dollar rate $\frac{F_{t,t+1} R_t^{€}}{S_t}$.

Combining Equations (3) and (4) implies the CIP condition:

$$R_t^{\$} = \frac{F_{t,t+1} R_t^{€}}{S_t} \cdot (1 - \lambda_t), \tag{5}$$

where $\lambda_t \equiv 1 - \frac{1-\lambda_t^{\$}}{1-\lambda_t^{€}}$ represents CIP deviations.[6] In particular, in case $\lambda_t > 0$, meaning that $\lambda_t^{\$} > \lambda_t^{€} \geq 0$, we have that the return on the forward dollar-euro is larger than the safe dollar return if borrowing is more expensive at the synthetic dollar rate $\frac{F_{t,t+1} R_t^{€}}{S_t}$ than at the cash dollar rate $R_t^{\$}$ (or at the cash euro rate $R_t^{€}$ than at the synthetic euro rate $\frac{S_t R_t^{\$}}{F_{t,t+1}}$); this implies that cash dollar borrowing constraints are tighter. Taking logs of Equation (5) yields:

$$r_t^{\$} \simeq r_t^{€} + f_{t,t+1} - s_t - \lambda_t, \tag{6}$$

where we have assumed that CIP deviations λ_t are small.[7]

[4] We can also interpret $\lambda_t^{\$}$ and $\lambda_t^{€}$ as transaction costs. In this case, allocating one US dollar to either strategy only translates into an effective investment of $1 - \lambda_t^i$ US dollars. A key difference is that $\lambda_t^i > 0$ even when the investor is long in either position.

[5] In the Online Appendix C we show that CIP deviations cannot arise because of counterparty risk in the forward market.

[6] The CIP condition could also be derived from the perspective of a euro area investor whose relevant nominal discount factor is $\mathcal{D}_t^{€}$ based on:

$$1 \geq 1 - \lambda_t^{€} = E_t \left(\mathcal{D}_{t+1}^{€} \right) R_t^{€},$$
$$1 \geq 1 - \lambda_t^{\$} = E_t \left(\mathcal{D}_{t+1}^{€} \right) \frac{S_t R_t^{\$}}{F_{t,t+1}}.$$

[7] Deviations from CIP can also arise when the dollar or euro interest rates are actually not safe, say because

As regards the pricing of the forward rate, arbitrage forces [ARBITRAGE BETWEEN WHO?] ensure that the one-period risk-adjusted expected return of investing in the dollar-euro forward market or in the dollar-euro spot market are the same, namely:

$$\frac{E_t\left(\mathcal{D}^{\$}_{t+1}\right)F_{t,t+1}}{S_t}R^{€}_t = \frac{E_t\left(\mathcal{D}^{\$}_{t+1}S_{t+1}\right)}{S_t}R^{€}_t. \tag{8}$$

Hence, we have the following relation between the forward and the expected spot exchange rate:

$$F_{t,t+1} = E_t\left(S_{t+1}\right) + \frac{Cov_t\left(\mathcal{D}^{\$}_{t+1}, S_{t+1}\right)}{E_t\left(\mathcal{D}^{\$}_{t+1}\right)}. \tag{9}$$

Assuming log-normality and taking logs yields:

$$\begin{aligned} f_{t,t+1} &= E_t s_{t+1} + Cov_t\left(d^{\$}_{t+1}, s_{t+1}\right) + \frac{1}{2}Var_t\left(s_{t+1}\right) \\ &= E_t s_{t+1} + \pi_t. \end{aligned} \tag{10}$$

Taking into account Jensen's inequality (the term $\frac{1}{2}Var_t\left(s_{t+1}\right)$), the forward exceeds (falls short of) the expected spot rate when the investor is willing to pay a positive (negative) premium. The latter is the case when the spot rate is expected to covary positively (negatively) with the investor's discount factor.[8]

Substituting the forward rate in Equation (10) in the CIP condition in Equation (6), we obtain the UIP condition:

$$s_t = E_t s_{t+1} + dr_t - \lambda_t + \pi_t, \tag{11}$$

where $dr_t \equiv r^{€}_t - r^{\$}_t$. Iterating forward Equation (11) for T periods yields:

$$s_t = E_t s_{t+T} + \sum_{j=0}^{T-1} E_t dr_{t+j} - \sum_{j=0}^{T-1} E_t \lambda_{t+j} + \sum_{j=0}^{T-1} E_t \pi_{t+j}, \tag{12}$$

which shows that the spot exchange rate in period t is determined by current and expected future

of default risk, and that this risk differs between them. Clearly, in this case the conditions under which CIP was derived above fail, leading to the following expression:

$$1 = E_t\left(\mathcal{D}^{\$}_{t+1}R^{€}_t\right)\frac{F_{t,t+1}}{S_t} = E_t\left(\mathcal{D}^{\$}_{t+1}R^{\$}_t\right). \tag{7}$$

In this case, arbitrage does not ensure anymore that the forward-spot discount is equal to the interest rate differential. However, several contributions have shown that interest rate default risk has not been a key source of CIP deviations recently (see, for example, Du et al., 2017).

[8] Specifically, the premium π_t is positive if dollar depreciation against the euro (a higher S_{t+1}) is expected to go hand in hand with a higher marginal value of wealth (higher $\mathcal{D}^{\$}_{t+1}$). This means that the dollar currency risk of a nominally safe euro investment provides a hedge to the investor, who then requires compensation to hold the forward. Conversely, the premium π_t is negative when dollar depreciation is expected to be associated with a lower discount factor of the investor.

fundamentals—i.e. interest rate differentials, risk premia, CIP deviations, and the expected value of the exchange rate at horizon T. Equation (12) implies that QE measures can impact the current value of the exchange rate only to the extent that they affect current and expected future fundamentals.

2.2 Deriving a local projection equation for the exchange rate

Consider the UIP condition in Equation (12) and subtract from both sides the corresponding equation lagged by one period:

$$\begin{aligned} s_t - s_{t-1} = &- dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\ &+ E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ &- \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{13}$$

The terms in the second and third row involve differences between the same variables, but in terms of expectations formed in period t and $t-1$, respectively. Hence, these terms are functions of the structural shocks in period t, i.e. the vector of mutually uncorrelated white noise variables $\boldsymbol{\varepsilon}_t$ with $E_{t-1}(\boldsymbol{\varepsilon}_t) = 0$. Assuming linearity, we can replace the changes in expectations by the impact of structural shocks and write Equation (13) as:

$$s_t - s_{t-1} = \omega_{t-1,0} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t, \tag{14}$$

where

$$\omega_{t-1,0} \equiv - dr_{t-1} + \lambda_{t-1} - \pi_{t-1}, \tag{15}$$

$$\begin{aligned} \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t \equiv & E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ &- \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{16}$$

Analogously, for the difference between the exchange rate in periods $t+h$ and $t-1$ we have:

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_{t+h} + \boldsymbol{\alpha}_1' \boldsymbol{\varepsilon}_{t+h-1} + \ldots + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t, \tag{17}$$

where

$$\omega_{t-1,h} \equiv -dr_{t-1} + \lambda_{t-1} - \pi_{t-1}$$
$$- \sum_{j=1}^{h-1} E_{t-1} dr_{t+j-1} + \sum_{j=1}^{h-1} E_{t-1}\lambda_{t+j-1} - \sum_{j=0}^{h-1} E_{t-1}\pi_{t+j-1}. \quad (18)$$

Taking expectations of Equation (17) as of period t yields:

$$E_t s_{t+h} - s_{t-1} = \omega_{h,t-1} + \boldsymbol{\alpha}'_h \boldsymbol{\varepsilon}_t, \quad (19)$$

which shows that the coefficients $\boldsymbol{\alpha}_h$ represent the impulse response of the exchange rate at horizon h to the structural shocks $\boldsymbol{\varepsilon}_t$ in period t. We can estimate the coefficients $\boldsymbol{\alpha}_h$ from the regression

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}'_h \boldsymbol{\varepsilon}_t + \nu_{t,h}, \quad (20)$$

where

$$\nu_{t,h} \equiv \sum_{j=0}^{h-1} \boldsymbol{\alpha}'_h \boldsymbol{\varepsilon}_{t+h-j}, \quad (21)$$

as the structural shocks are serially uncorrelated and unforecastable, i.e. $Cov(\nu_{t,h}, \boldsymbol{\varepsilon}_t) = Cov(\nu_{t,h}, \omega_{t-1,h}) = 0$.

2.3 Introducing QE shocks

In order to see how the local projection equation in Equation (20) can be used to estimate the effects of QE shocks specifically, partition the structural shocks into $\boldsymbol{\varepsilon}_t = (\varepsilon_t^{qe}, \boldsymbol{e}'_t)'$; ε_t^{qe} is a QE shock and $\boldsymbol{e}_t$ includes all other structural shocks, such as conventional monetary policy shocks or money demand shocks. Notice that because the dollar-euro exchange rate is a relative price, the term ε_t^{qe} should be interpreted as a *relative* QE shock, i.e. QE measures implemented by the ECB or the Federal Reserve and which affect the size of their relative balance sheet. Moreover, borrowing from the news shock literature (see, for example, Schmitt-Grohe and Uribe, 2008), we assume that ε_t^{qe} can be written as

$$\varepsilon_t^{qe} = \sum_{m=1}^{M} \eta_{t+m|t}, \quad (22)$$

where $\eta_{t+m|t}$ reflects unexpected QE shock that materialise in period t but which affect the relative balance sheet only in period $t+m$.[9] The intuition underlying the specification in Equation (23) is that because the exchange rate is a forward-looking asset price it will also respond to QE measures that are announced in period t but that will only be—and are anticipated by agents to be—implemented in period $t+m$ in the future. Partitioning the vector of impulse response coefficients accordingly as $\boldsymbol{\alpha}_h = (\alpha_h^{qe}, \boldsymbol{a}_h')'$, we can then write the local projection equation for the exchange rate in Equation (20) as:

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=1}^{M} \eta_{t+m|t} \right) + \omega_{t-1,h} + \boldsymbol{a}_0' \boldsymbol{e}_t + \nu_{t,h}. \tag{24}$$

2.4 Proxying QE shocks by future central bank balance sheet changes

Estimating the effects of QE measures in the euro area and the US on the dollar-euro exchange rate in Equation (24) is of course complicated by the fact that the QE shocks $\eta_{t+m|t}$ are unobserved by the econometrician. However, we can proxy these relative QE shocks by changes in the relative balance sheet. Specifically, assume that the relative balance sheet evolves according to:

$$\Delta BS_t = \delta_0 + \boldsymbol{\rho}' \boldsymbol{w}_{t-1} + \sum_{m=1}^{M} \eta_{t|t-m} + \boldsymbol{\delta}' \boldsymbol{e}_t, \tag{25}$$

where $\boldsymbol{w}_{t-1}$ includes macroeconomic and financial variables to which the central banks' balance sheets respond systematically as well as the lagged relative balance sheet.[10] We can substitute the anticipated QE shock $\eta_{t+m|t}$ in the local projection of the exchange rate in Equation (24) using Equation (25), namely

$$\eta_{t+m|t} = \Delta BS_{t+m} - \left(\delta_0 + \boldsymbol{\rho}' \boldsymbol{w}_{t+m-1} + \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \boldsymbol{e}_{t+m} \right),$$

to obtain:

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=1}^{M} \Delta BS_{t+m} \right) + \omega_{t-1,h} - \alpha_h^{qe} \rho \sum_{m=1}^{M} \boldsymbol{w}_{t-1+m} + \widetilde{\delta}_0 + \zeta_{t,h}, \tag{26}$$

[9] In general one would write

$$\varepsilon_t^{qe} = \sum_{m=1}^{M} \phi_m \eta_{t+m|t}. \tag{23}$$

We assume $\phi_m = 1$, $m = 0, 1, \ldots, M$ for simplicity.

[10] Notice that there is no need to include any contemporaneous variables $\boldsymbol{w}_t$ in Equation (25) on the right-hand side because of the presence of the contemporaneous values of the structural QE and non-QE shocks $\boldsymbol{e}_t$.

where

$$\zeta_{t,h} \equiv -\alpha_h^{qe}\boldsymbol{\delta}' \sum_{m=1}^{M} \boldsymbol{e}_{t+m} - \alpha_h^{qe} \sum_{m=1}^{M} \sum_{\substack{k=1\\k\neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{a}_0'\boldsymbol{e}_t + \nu_{t,h}. \tag{27}$$

2.5 Two-stage least squares regression framework

Of course, the variable of interest in Equation (26), $\sum_{m=1}^{M} \Delta BS_{t+m}$, is endogenous due to its correlation with $\zeta_{t,h}$.[11] Intuitively, and as reflected in Equation (25), central banks' balance sheets change not only in response to QE shocks, but also because of non-QE shocks $\boldsymbol{e}_t$, such as money demand and conventional monetary policy shocks.[12] In order to address this endogeneity we adopt a two-stage least squares approach using QE announcements as instruments for $\sum_{m=1}^{M} \Delta BS_{t+m}$ in Equation (26). In particular, we assume that ECB and Federal Reserve QE announcements a_t^{ECB} and a_t^{Fed} are related to anticipated relative QE shocks according to:

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} a_t^{\text{ECB}} + \mu_m^{\text{Fed}} a_t^{Fed} + u_{t,m}, \quad m = 1, \ldots, M. \tag{28}$$

The intuition for Equation (28) is that a QE announcement in period t is followed by changes in the relative balance sheet m periods in the future. Summing Equation (28) over horizons m yields:

$$\begin{aligned} \sum_{m=1}^{M} \eta_{t+m|t} &= \left(\sum_{m=1}^{M} \sigma_m\right) + \left(\sum_{m=1}^{M} \mu_m\right) a_t^{\text{ECB}} + \left(\sum_{m=1}^{M} \mu_m\right) a_t^{\text{Fed}} + \left(\sum_{m=1}^{M} u_{t,m}\right) \\ &= \overline{\sigma} + \overline{\mu}^{\text{ECB}} a_t^{\text{ECB}} + \overline{\mu}^{\text{Fed}} a_t^{\text{Fed}} + \overline{u}_t. \end{aligned} \tag{29}$$

In turn, summing the relative balance sheet equation in Equation (25) over horizons $m = 1, 2, \ldots, M$ yields:

$$\begin{aligned} \sum_{m=1}^{M} \Delta BS_{t+m} &= M\delta_0 + \rho \sum_{m=1}^{M} \boldsymbol{w}_{t-1+m} + \sum_{m=1}^{M} \sum_{k=1}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=1}^{M} \boldsymbol{e}_{t+m} \\ &= M\delta_0 + \rho \sum_{m=1}^{M} \boldsymbol{w}_{t-1+m} + \sum_{m=1}^{M} \eta_{t+m|t} + \sum_{m=1}^{M} \sum_{\substack{k=1\\k\neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=1}^{M} \boldsymbol{e}_{t+m}, \end{aligned} \tag{30}$$

[11] As we do not have information on the sign of $\boldsymbol{\delta}$ in Equation (25) we cannot predict whether the endogeneity bias affecting the estimate of α_h^{qe} is positive or negative.

[12] Notice that there is also a possibility of endogeneity of some of the determinants of the relative balance sheet $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ in the second-stage regression in Equation (26); for example, $\boldsymbol{w}_{t-1}$ includes the lagged relative balance sheet, see Equation (25). We address this possibility by estimating Equation (26) without controlling for $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ in the baseline regression. We discuss in more detail the specification of the dependent and the explanatory variables in Section 3.

which shows that our variable of interest that is affected by endogeneity in Equation (26), $\sum_{m=1}^{M} \Delta BS_{t+m}$, should be correlated with the sum of future anticipated QE shocks $\sum_{m=1}^{M} \eta_{t+m|t}$ that can be forecast by QE announcements in Equation (29). Against the background of Equations (26), (29) and (30), we thus consider a two-stage least squares regression approach in which the second-stage regression is given by Equation (26) and the first-stage regression by

$$\sum_{m=1}^{M} \Delta BS_{t+m} = \varpi + \theta^{\text{ECB}} a_t^{\text{ECB}} + \theta^{\text{Fed}} a_t^{\text{Fed}} + \omega_{t-1,h} + \sum_{m=1}^{M} \boldsymbol{\gamma}_m' \boldsymbol{w}_{t-1+m} + \xi_t. \tag{31}$$

Our identifying assumptions are that the instruments for the relative balance sheet variable $\sum_{m=1}^{M} \Delta BS_{t+m}$ in Equation (26) given by the QE announcements a_t^{ECB} and a_t^{Fed} in period t:

(i) are uncorrelated with the error term in the second-stage regression $\zeta_{t,h}$ defined in Equation (27), i.e. with contemporaneous non-QE structural shocks, $\boldsymbol{e}_t$, as well as future QE and non-QE structural shocks $\nu_{t,h}$ and $\boldsymbol{e}_{t+m}$ (instrument validity)

(ii) predict changes in the relative balance sheet between periods t and $t+m$ in the future, i.e. $\theta^{\text{ECB}} \neq 0$ and/or $\theta^{\text{Fed}} \neq 0$ in Equation (31) (instrument meaningfulness)

Notice that (ii) is satisfied already when $\mu_m^{\text{ECB}} \neq 0$ and/or $\mu_m^{\text{Fed}} \neq 0$ from Equation (28) for *some* m, as this is enough to imply $\overline{\mu}^{\text{ECB}} \neq 0$ and/or $\overline{\mu}^{\text{Fed}} \neq 0$ in Equation (29). We test these assumptions by means of the Hansen J-test of over-identification and the Kleibergen-Paap test of under-identification. We also consider tests for weak instruments (Pflueger and Wang, 2015).

3 Empirical specification

3.1 Sample period

Since we are interested in the effects of QE measures introduced in the wake of the global financial crisis and its aftermath, our sample period spans January 2009 to October 2017. Our analysis is carried out using data sampled at the monthly frequency; we consider weekly data in robustness checks in Section 5. We transform the data for financial variables available at higher frequencies to monthly observations by calculating averages over daily or weekly data. The data on the dollar-euro exchange rate as well as the size of the ECB's and the Federal Reserve's balance sheets are obtained from Haver Analytics.

3.2 Dependent variable and controls

We specify the relative balance sheet BS_t as the logarithm of the ratio of the ECB's and the Federal Reserve's nominal balance sheet in their respective currencies. The variable $\sum_{m=1}^{M} \Delta BS_{t+m}$ then boils down to the percentage point change of the relative balance sheet between periods $t+m$ and t, i.e. $BS_{t+m} - BS_t$. Notice that $BS_{t+m} - BS_t$ also represents the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets between periods $t+m$ and t.

We proxy the variables in the vector $\omega_{t-1,h}$ that includes lagged values and lagged expectations of future values of the fundamental determinants of the exchange rate by lagged values of the three-month money-market and policy rate rate differentials, CIP deviations, the VIX, as well as ECB and Federal Reserve QE announcements. For interest rates, we consider three-month money market rates obtained from Haver Analytics. For the respective policy rates we use the Federal Funds target rate as well as the deposit facility rate (DFR), i.e. the ECB's interest rate "corridor" floor. We derive CIP deviations at the three-month maturity using data on the three-month dollar-euro forward exchange rate from Bloomberg. As the term $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ on the right-hand side of the second-stage regression in Equation (26) might be endogenous due to its correlation with non-QE shocks $\sum_{m=1}^{M} \boldsymbol{e}_{t+m}$, in our baseline we do not include it as control. We report results for regressions which include these controls in Section 5.

In order to more cleanly identify a QE shock and to distinguish it from a conventional monetary policy shock, we include the contemporaneous policy rate differential as control in the second and first-stage regressions. This element of our identification strategy corresponds to the assumption of a Choleski ordering in a VAR in which the relative balance sheet would be ordered after those variables whose contemporaneous values appear in our first stage regression. Intuitively, our identification assumption here is that QE shocks do not contemporaneously affect the policy rate differential; notice that this is true by definition as the policy rate and the balance sheet are distinct policy instruments that are both under the control of the central bank.

Finally, in order to decompose the response of the exchange rate to QE shocks as laid out in Equation (12), we also estimate the dynamic responses of the euro area short-term money market rate differential as well as the CIP deviation by replacing the left-hand side variable in the second-stage regression in Equation (26) accordingly.

3.3 QE announcements

We specify the announcements a_t^{ECB} and a_t^{FED} as indicator variables which equal unity if the Federal Reserve or the ECB reveal some information about future asset purchases or credit easing programmes. The dates of the announcements of QE measures by the ECB and the Federal Reserve are reported in Tables 1 and 2, respectively.[13] The dates in question are assigned to their respective calendar month t.[14] We only consider announcements that can be assumed to have a tangible impact on the size of the central bank balance sheet. For example, we do not include the announcements of the ECB's intention to do "whatever it takes to preserve the euro" in July 2012 and of the Outright Monetary Transactions programme in September 2012, because these announcements did not result in asset purchases by the time of writing. Furthermore, we do not include the ECB announcement of the Securities Market Programme in May 2010, because the associated asset purchases were sterilised and hence did not increase the ECB's balance sheet. Following the same logic, we do not consider the Federal Reserves' announcements of "Operation twist", i.e. its maturity extension programme, which resulted in an increase of the weighted average maturity of the central banks' asset holdings, but did not lead to a change in the nominal balance sheet. In these cases, th epower of the announcements as instruments in the first-stage regression is nil by construction. Tables 1 and 2 also report information on the response of the Eurostoxx and S&P500 stock markets on the day of the ECB and Federal Reserve announcements, respectively. In most cases, the stock market movements on the announcement days have been notable, i.e. greater than 0.5%, corroborating the notion that these announcements can be treated as surprise monetary policy actions.

An alternative to the use of simple QE announcement dummies would be to consider surprises constructed based on surveys or polls, which could also take into account differences in the size and scope of the QE measures. For a subset of the QE announcements survey data and polls on the size of the QE measures expected by professional forecasters are indeed available. However, these data are not available for all QE measures, not least because the size of the measures in question was not known ex ante in some cases; for example, in the case of various exceptional liquidity operations conducted by the ECB, the overall size ultimately depended on take-up by banks. In addition, such survey data capture expectations of selected professional forecasters, and hence may not necessarily overlap with expectations of the market as a whole. In Section 5 we use the changes in equity prices on the day of the announcement to weight unconventional monetary policy measures.

[13]The announcement dates of the QE measures of the Federal Reserve are taken from Rogers et al. (2014). Those for the ECB are taken from the ECB's website.

[14]The dummies also equal unity when there is more than one announcement in a given month, but this occurs only once in our dataset in the case of Federal Reserve announcements in October 2010.

4 Estimation results

4.1 First-stage regression: Predictive content of QE announcements

Table 3 reports the estimation results for the first-stage regression in Equation (31).[15] Columns (1) to (3) report the results for $M = 1, 2, \ldots, 5$ in Equation (23). The estimates indicate that ECB and Federal Reserve QE announcements in period t predict future changes in the relative balance sheet. Specifically, following an ECB QE announcement, the ECB's balance sheet expands statistically significantly relative to that of the Federal Reserve by 2.2 percentage after one month, 3.8 percentage after two months and up to 8.6 percentage after five months. To put these numbers in perspective, notice that a one percentage point expansion of the ECB's balance sheet relative to that of the Federal Reserve in September 2015 when the ECB's APP was announced for the first time amounted to an expansion by roughly 45 bil. euro.[16] [CHECK?] Notice that this is slightly below the amount of monthly asset purchases of 60 bil. euro under the ECB's Expanded Asset Purchase Programme launched in 2015. In turn, following a Federal Reserve QE announcement, the Federal Reserve's balance sheet expands statistically significantly only after two months by 3.4% relative to that of the ECB, and by up to 9.3% after five months. Finally, the results reported in Table 3 document that the estimated models pass the Hansen-J over-identification and the Kleibergen-Paap under-identification tests. Moreover, at least the specifications with $M > 2$ are associated with an effective F-statistic above ten, suggesting that the instruments in these cases are unlikely to be weak. We choose the specification with $M = 5$ as our baseline in the following.

4.2 Second-stage regression: Dynamic effects of QE shocks

We now turn to the dynamic responses of the nominal bilateral US dollar-euro exchange rate, the relative balance sheet, and the fundamental determinants of the exchange rate in Equation (12). All impulse response estimates are reported with asymptotic confidence bands at the 95% significance level that account for heteroskedasticity and serial correlation.

4.2.1 Relative balance sheet response

The top left-hand side panel in Figure 2 shows the dynamic response of the relative balance sheet to the relative QE shock ε_t^{qe} in Equation (23). Specifically, the impulse response is obtained

[15] Standard errors are robust to heteroskedasticity and serial correlation.

[16] In September 2015 the ECB's balance sheet stood at about 2 tn. euro, and that of the Federal Reserve at around 4.5 tn. USD. The relative balance sheet was thus $(2\,tn.euro)/(4.5\,tn.USD) = 0.4444$. The implied balance sheet of the ECB in case of an expansion of the relative balance sheet by one percentage point is given by $x\,tn.euro = (4.5\,tn.USD) \times 0.4544$.

from a two-stage least squares estimation analgous to that for the exchange rate in Equation (26), but in which the dependent variable in the second stage is the relative balance sheet. Our estimates suggest that in response to the relative QE shock, the ECB's balance sheet expands statistically significantly relative to that of the Federal Reserve for around ten months. The peak expansion of around 1.8% occurs after seven months. On the one hand, the gradual build-up of the relative balance sheet in response to the relative QE shock shown in Figure 2 is consistent with the fact that ECB and Federal Reserve QE measures were typically not one-off instances of asset purchases or liquidity injections, but were carried out repeatedly over time. On the other hand, the mean reversion in the response of the relative balance sheet might seem at odds with the very persistent nature of the QE measures of the ECB and the Federal Reserve. Yet, recall that the left-hand side panel of Figure 1 shows that the *relative* balance sheet has been mean reverting over the sample period we consider.

4.2.2 Policy-rate differential

The top right-hand side panel in Figure 2 shows dynamic response of the policy rate differential to the relative QE shock.[17] While the impact response is by assumption restricted to be zero, also the point estimates for one and two months after the QE shock are essentially zero.[18], After three months the point estimates indicate a drop in the policy rate differential, which, however, becomes statistically significant only after nine months. The policy rate differential falls by up to five basis points after 18 months. The lack of a statistically significant drop in the policy rate differential in the very short term suggests that we are not confounding the effects of a QE shock with those of a conventional monetary policy shock. Instead, the delayed drop in the policy rate differential suggests that QE measures were successful in signalling further monetary policy accommodation in the short to medium term. The finding of no contemporaneous drop in the policy rate differential in response to a relative QE shock is all the more noteworthy as, in contrast to the case of the Federal Reserve, the changed its ECB policy rate several times during the sample period we consider; for example, the MRO was lowered from 2.5% to -0.05% between January 2009 and March 2016, including four instances when ECB QE measures were announced alongside conventional measures.

[17]The results are almost identical when we consider the ECB's main refinancing operations (MRO) rate rather than the DFR.

[18]Recall that we assume that the policy rate differential does not react to QE shocks on impact, see Section 3. Technically, this results because the right-hand side variables in the local projection regression in Equation (26) include the contemporaneous policy rate differential as control. As a consequence, for $h = 0$ the fit of the local projection regression is perfect, with a coefficient estimate of unity on the contemporaneous policy rate differential, and a coefficient estimate of zero on the instrumented relative balance sheet change.

4.2.3 Dollar-euro exchange rate response

The bottom panel in Figure 2 shows that the euro depreciates persistently and statistically significantly in response to the relative QE shock. The depreciation bottoms at around 1% after nine months. Read in connection with the response of the relative balance sheet, the estimates suggest that a QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve by up to about 1.8% depreciates the euro by up to 1%. These results imply that the ECB's APP program, which expanded the ECB's balance sheet by 35% relative to that of the Federal Reserve between September 2014 when the APP was announced for the first time and the end of 2016, led to a depreciation of the euro vis-à-vis the US dollar by about 20% (= 35%/1.8% × 1%). This is a substantial effect when compared to the overall depreciation of the euro vis-à-vis the US dollar by roughly 20% over the same time period. Of course, one has to bear in mind that in the data the exchange rate is also affected by other shocks, and that we do not carry out a historical decomposition. For example, the euro started to appreciate notably vis-à-vis the US dollar from mid-2017 on the back of a strengthening euro area economy despite the continuation of the ECB's asset purchases under the APP program.

4.2.4 Decomposition of the exchange rate response

We now consider the channels through which QE shocks are transmitted to the exchange rate by investigating the responses of its fundamental determinants according to Equation (12), i.e. the interest rate differential, the CIP deviation and currency risk premia.

Interest rate differential The left-hand side panel in Figure 3 shows the response of the three-month euro-dollar money market rate differential. The results suggests that euro area money market rates decline statistically significantly and persistently relative to those in the US in response to a relative QE shock. The three-month money market rate differential falls statistically significantly after three months, and bottoms at around five basis points after eleven months. Overall, the response of the short-term money market rate differential is consistent with that of the policy rate differential, in the sense that the former at every point in time reflects expectations of the policy rate differential over the subsequent three months.

CIP deviation Recall the definition of the CIP deviation in Equation (6)

$$\lambda_t = r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t \right). \tag{32}$$

We thus define the CIP deviation such that a positive value amounts to a euro money market rate larger than the synthetic euro rate (or a larger synthetic dollar rate than its cash counterpart); notice that the market convention is to denote the CIP deviation with the opposite sign. On the one hand, a relative QE shock lowers the CIP deviation through a fall in interest rate differentials. On the other hand, lower funding costs in the euro area may attract foreign borrowers, who then desire to hedge their euro exposure, increasing the demand for swap contracts. Against the background of a limited supply of such contracts, this widens the cross-currency basis swap, i.e. the CIP deviation. It is an empirical question which of these effects dominates. The right-hand side panel in Figure 3 presents the response of the CIP deviation at the three-month maturity to the relative QE shock. The results suggest that the three-month CIP deviation falls statistically significantly by up to around four basis points in response to a relative QE shock. Given that over our sample period CIP deviations have been positive with cash euro rates larger than their synthetic counterparts—recall again that market convention is to denote the CIP deviation with the opposite sign—our results imply that a relative QE shock resulted in a narrowing of the CIP deviation. In the framework of Section 2.1 our results imply that the CIP deviation becomes negative due to a reduction in borrowing costs—and thereby a tightening in the borrowing constraint at the euro cash rate relative to that at the synthetic euro rate. [CAN WE RELATE THESE FINDINGS TO THE LITERATURE Avdjiev et al. (2016); Borio et al. (2016); Sushko et al. (2016); Du et al. (2017)?]

Contributions of individual fundamentals to overall exchange rate response Figure 4 presents the decomposition of the exchange rate response to the relative QE shock into the contributions accounted for by the estimated responses of the short-term money market interest rate differential, the CIP deviation, and the expected future exchange rate.[19] The contribution of currency risk premia is obtained as a residual, given the estimates of the responses of the exchange rate, the interest rate differential and the CIP deviation. The results suggest that falling current and expected future interest rate differentials and the expected depreciation after 18 months depreciate the euro relative to the US dollar on impact in response to the relative QE shock; however, the increase in CIP deviations and currency risk premia almost completely offset this. Because the depreciating influence of the decline in the interest rate differential and the countervailing effect of a narrowing CIP deviation fade monotonically over time, the hump shape of the euro depreciation can only be accounted for by the response of the dollar-euro currency risk premia. All four channels—interest rate differentials, CIP deviations, currency risk premia and the future expected exchange rate—contribute to a similar extent to the overall exchange rate response. That risk premia play an important role in the dynamics of exchange rates echoes the findings of the classic study of Engel and West (2010), who find that a large

[19]The decomposition is based on the point estimates and does not take into account estimation uncertainty.

share of the variation in the dollar exchange rate are attributable to a residual risk premium component.

Other financial market variables Even though they are not directly related to the exchange rate response, it is still insightful to explore the effects of QE shocks on other financial variables. We focus here on the responses of euro area variables, and correspondingly consider only the ECB balance sheet as well as ECB QE announcements. The relevant first-stage regression results are reported in Table 4. Figure 5 presents the responses of sovereign bond yield differentials at the two and ten-year maturities, the expectations and the term-premium component in the ten-year rate[20], as well as euro area equity prices. The two-year sovereign bond yield drops marginally statistically significantly by two basis points after three months in response to the ECB QE shock. The estimates of the response of the ten-year sovereign bond yield are larger and more precisely estimated. The drop in the ten-year yield is economically significant; for instance, applying the same logic as for the exchange rate above, these results imply that the ECB's APP program, which expanded the ECB's balance sheet by 35% relative to that of the Federal Reserve between September 2014 when the APP was announced for the first time and the end of 2016 led to a drop of the ten-year yield by about one percentage point ($= 35\%/1.8\% \times 0.05\%$). This is a substantial effect when compared to the overall decline of ten-year yield of ?? over the same time period. Interestingly, the decline in the ten-year sovereign bond yield can be traced back to a commensurate drop in the term-premium component. Finally, somewhat surprisingly, equity prices only rise with a substantial delay after nine months by up to 1.2%. The rise is economically significant, as the results imply that the ECB's APP program raised equity prices cumulatively by almost 25% between September 2015 and the end of 2016 ($= 35\%/1.8\% \times 1.2\%$). [CHECK THIS ENTIRE PARAGRAPH].

5 Robustness

Consistent with the presentation of the results for the baseline specification, for all robustness checks we report the first-stage regression results for the cases of $M = 1, 2, \ldots, 5$, and impulse response estimates for the case $M = 5$.

[20] We consider two and ten-year sovereign bond yields obtained from Haver Analytics; we use German Bund yields as measures of euro area sovereign yields. The expectations and the term premium component are taken from ??.

5.1 Regression with control variables $\sum_{m=1}^{M} \boldsymbol{w}_{t+m-1}$

In our baseline we exclude the determinants of the relative balance sheet $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ from the control variables of the first and second-stage regressions, as it might be endogenous due to its correlation with non-QE shocks $\sum_{m=1}^{M} \boldsymbol{e}_{t+m}$ in the second-stage regression in Equation (26). Including these controls may be preferable in case of absence of endogeneity as the fit would be improved and standard errors would be smaller. Table 5 and Figure 6 present the results for the specification in which we include $\boldsymbol{w}_{t-1+m}$ for $m = 1, 2, \ldots, M$ in the first and second-stage regressions as controls; in $\boldsymbol{w}_t$ we include the relative balance sheet only. The results are very similar to those from our baseline, even though the coefficient estimates are less precise and the effective F-statistic is somewhat lower compared to the baseline.

5.2 Allowing for contemporaneous effects of QE shocks

One could argue that QE shocks which materialise in period t not only elicit central bank asset purchases in the future, but also contemporaneously. Formally, instead of Equation (23) one would then have to specify

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \eta_{t+m|t}, \tag{33}$$

which now includes $\eta_{t|t}$ on the right-hand side. If Equation (33) is true rather than Equation (23), then our instruments in the baseline might be invalid. Specifically, notice that in this case, substituting only $\eta_{t+m|t}$ for $m > 0$ in Equation (24) as we do in Section 2.4 implies that $\eta_{t|t}$ appears in the error term $\zeta_{t,h}$ of the second-stage regression in Equation (26). If QE announcements in period t also contain information about contemporaneous central bank asset purchases, i.e. $Cov(a_t^i, \eta_{t|t}) \neq 0$, our instruments would be correlated with the error term $\zeta_{t,h}$ of the second-stage regression.

We address this possibility by a change in the specification of the variable of interest. In particular, in case Equation (33) is true rather than Equation (23) we can substitute $\eta_{t|t}$ in Equation (24) using

$$\eta_{t|t} = \Delta BS_t - \left(\delta_0 + \boldsymbol{\rho}' \boldsymbol{w}_{t-1} + \sum_{k=1}^{M} \eta_{t|t-k} + \boldsymbol{\delta}' \boldsymbol{e}_t \right),$$

based on a generalisation of Equation (25). The local projection equation for the exchange rate is then given by

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \Delta BS_{t+m} \right) + \omega_{t-1,h} - \alpha_h^{qe} \rho \sum_{m=0}^{M} \boldsymbol{w}_{t-1+m} + \widetilde{\delta}_0 + \zeta_{t,h}, \tag{34}$$

where

$$\zeta_{t,h} \equiv -\alpha_h^{qe}\boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m} - \alpha_h^{qe} \sum_{m=0}^{M} \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{a}_0'\boldsymbol{e}_t + \nu_{t,h}, \tag{35}$$

which boils down to considering $BS_{t+m} - BS_{t-1}$ rather than $BS_{t+m} - BS_t$ as variable of interest. The results reported in Table 6 and Figure 7 are very similar to those from our baseline. If anything, the coefficients in the first-stage regression are estimated more precisely, and the effective F-statistic is substantially higher compared to the baseline.

5.3 Heterogeneity of QE measures and separating monetary policy from information shocks

One concern with our approach is that the economic significance of the QE shocks underlying the announcements might not have been identical across measures. For example, some measures are bigger in magnitude than others, and some measures target specific asset classes. Moreover, even if the measures underlying the QE announcements have the same size and scope, they might still not elicit the same market responses because they were expected to different degrees. And finally, it could also be that rather than being perceived as an expansionary monetary policy shock, some QE announcements might have been perceived by market participants as a revelation of private information of the central bank regarding negative demand or financial shocks (see Nakamura and Steinsson, 2013; Campbell et al., 2017).

In order to address this concern, we borrow from the literature on the identification of QE shocks at high-frequency (see, for example, Rogers et al., 2014; Jarocinski and Karadi, 2017). Specifically, rather than Equation (28) we assume the following relation between unobserved QE shocks and announcements:

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} a_t^{\text{ECB}} \cdot \Delta e_t^{€} \cdot I(\Delta e_t^{€} > 0) + \mu_m^{\text{Fed}} a_t^{\text{Fed}} \cdot \Delta e_t^{\$} \cdot I(\Delta e_t^{\$} > 0) + u_{t,m}, \quad m = 1, 2, \ldots, M, \tag{36}$$

where $\Delta e_t^{€}$ and $\Delta e_t^{\$}$ represent the change in euro area and US equity prices on the day of the QE announcements, respectively, and $I(\Delta e_t^{€} > 0)$ and $I(\Delta e_t^{\$} > 0)$ are indicator variables which equal unity when the equity price changes are positive and zero otherwise. Equation (36) implies that we weight QE announcements a_t^j by the domestic equity price response on the day of the announcement, and that we additionally only consider those QE announcements which were followed by a positive equity price response. By focusing on these announcements, we also consider only those QE announcements for which the QE shock component dominated any possible informational shock reflecting the revelation of a more negative outlook of the central bank.

The results for the first-stage regression of this specification are reported in Table 7, and the impulse responses in Figure 8. The results are overall very similar to those from our baseline.

5.4 Identifying QE shocks narratively

The power of the QE announcement dummies as instruments is reduced by the fact that not all announcements we consider were actually followed by changes in the central banks' balance sheets. For example, some of the QE announcements we consider were pre-announcements, such as ??. We could thus improve the power of our instruments if we could somehow consider only those QE announcements which were actually followed by increases in central banks' balance sheets. To do so, notice that the coefficient estimates of the QE announcement dummies in the first-stage regression are given by the average of the residuals of the first-stage regression in the months in which the ECB and the Federal Reserve made QE announcements estimated *without* the announcements. The residuals of the first-stage regression estimated without the QE announcements are positive (negative) in the months in which ECB (Federal Reserve) QE announcements were made which were followed by changes in the balance sheet. Inspecting the first-stage residuals from a regression without the QE announcement dummies shows that for the ECB the corresponding coefficient estimates are indeed all positive except for one case [STILL TRUE?]; in contrast to what one would expect, the relevant coefficient estimates are also all positive for the Federal Reserve, except for two cases [STILL TRUE?]. The implication is that the QE shocks we identify were mostly followed by an increase of the balance sheet in the case of the ECB, but not in the case of the Federal Reserve.

In order to improve the power of our instruments by identifying QE shocks which actually did increase the central banks' balance sheets, we pursue a "narrative approach". In particular, we only consider those ECB (Federal Reserve) QE announcements which are associated with positive (negative) residuals in the first-stage regression estimated without the announcements. The results for the first-stage regression are reported in Table 8 and the impulse responses in Figure 9. Not surprisingly, both the coefficient estimate of the ECB and Federal Reserve QE announcement dummies have the expected signs and are statistically significant, and the effective F-statistic is also higher than in the baseline. The impulse response estimates are very similar compared to those from the baseline.

5.5 Weekly data

In our baseline we do not use weekly data even if this would allow us to more accurately assign QE announcements to the respective periods. The reason for considering monthly rather than weekly data is that because of fluctuations in banks' short-term liquidity needs, the weekly central bank balance sheet data are significantly more noisy than the monthly data. Tables 9 and 10 reports the first-stage regression results for the specification based on weekly data. In particular, Table 9 reports the results for our baseline regression specification, and Table 10 for the robustness checks discussed above; Figures 10 and 11 show the corresponding impulse response estimates. The results are very similar to those from our baseline.

6 Concluding remarks

In this paper we have studied the dynamic effects of exogenous policy changes in central bank balance sheets, focusing on the foreign exchange market as a case study. We have used announcements about quantitative easing policies as instruments to identify surprise policy changes in central bank balance sheets. We have then explicitly related the response of the exchange rate and its fundamental determinants to actual changes in central bank balance sheets over time, in order to disentangle the workings of different transmission channels. We have found that announcements of quantitative easing by the ECB and the Federal Reserve bring about persistent but mean-reverting changes in their balance sheets. An increase in the ECB balance sheet relative to that of the Fed results in a persistent but temporary euro depreciation vis-à-vis the dollar. Since the euro-dollar exchange rate is expected to revert to its baseline after less than a year, central bank signalling about fundamentals over longer horizons (the "signalling" channel) cannot contribute much to the effects of quantitative easing on the exchange rate. We find instead that these policies mainly work by impinging on money market conditions throughout the period of their implementation, and also on frictions in foreign exchange markets, such as failures of covered interest rate parity. Surprisingly, currency risk premia play the most important role in driving the exchange rate response. A persistent fall in the three-month euro-dollar differential accounts for a sizable share of the estimated euro depreciation. Finally, balance sheet policies affect limits to arbitrage in foreign currency markets, by persistently reducing the differential between euro money market rates and their synthetic counterpart in euro-dollar currency swaps. In turn, this channel contributes to dampening the overall euro depreciation. To the extent that deviations from covered interest parity can be ultimately traced back to borrowing constraints in dollar and euro money markets, our results suggest that financing frictions play a key role in the transmission of the balance sheet shocks to the exchange rate. And they suggest that the deviations in question have emerged from the global financial crisis as a key variable that needs to be understood further still in future research and that policy-makers need to monitor closely.

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A Tables

Table 1: ECB announcements of unconventional monetary policy measures

Date	**Event**	**Stock market response**
07/05/2009	12-month SLTROs and other measures	-0.99%
04/08/2011	SLTROs and other measures	0.39%
06/10/2011	12/13-month SLTROs	2.74%
08/12/2011	36-month VLTROs and other measures	-2.09%
05/06/2014	Targeted longer term refinancing operations (TLTROs)	0.62%
04/09/2014	Announcement of ABSPP and CBPP3	0.73%
22/01/2015	Expanded Asset purchase programme (APP)	1.44%
05/03/2015	Implementation details of APP	0.65%
03/09/2015	Increase of PSPP's issue share limit	1.40%
10/03/2016	CSPP announcement	-0.98%
21/04/2016	CSPP starting date announcement and details	-0.30%
02/06/2016	CSPP Implementation details	0.07%
08/12/2016	Extension of APP	0.78%
26/10/2017	Extension of APP	0.75%

Note: The stock market response is the one-day change of the Eurostoxx 300 on the day of the announcements.

Table 2: Fed announcements of unconventional monetary policy measures

Date	**Event**	**Stock market response**
28/01/2009	Fed stands ready to expand QE and buy Treasuries	1.62%
18/03/2009	LSAPs expanded	0.08%
27/08/2010	Bernanke suggest role for additional QE	1.04%
12/10/2010	FOMC members 'sense' 'additional accommodation appropriate'	-1.07%
15/10/2010	Bernanke reiterates Fed stands ready to further ease policy	-0.54%
03/11/2010	QE2 announced: Fed will purchase $600 bn in Treasuries	0.00%
22/08/2012	FOMC members 'judge additional accommodation likely warranted'	-0.60%
13/09/2012	QE3 announced: Fed will purchase $40 bn of MBS per month	0.67%
12/12/2012	QE3 expanded	0.42%

Note: The stock market response is the one-day change of the S&P 500 on the day of the announcements.

Table 3: First-stage regression results: Baseline

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	0.022***	0.038***	0.070***	0.078***	0.086***
	(3.15)	(3.56)	(5.08)	(4.65)	(4.45)
Fed QE announcement	-0.005	-0.034*	-0.045*	-0.052*	-0.093***
	(-0.48)	(-1.69)	(-1.67)	(-1.73)	(-3.50)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.17	0.64	0.34	0.33	0.60
Kleibergen-Paap-Test (p-value)	0.02	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	5.15	9.31	19.83	15.98	20.75
Effective F Stat	4.70	6.81	11.17	10.68	17.65
R-squared	0.41	0.51	0.54	0.55	0.59

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4: First-stage regression results: Using only ECB announcements as instruments

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	0.024***	0.044***	0.080***	0.094***	0.108***
	(3.60)	(4.03)	(5.67)	(5.75)	(5.47)
Observations	107	106	105	104	103
Hansen-J (p-value)	.	.	.	.	.
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	12.96	16.28	32.18	33.07	29.93
Effective F Stat	12.96	16.28	32.18	33.07	29.93
R-squared	0.38	0.48	0.50	0.49	0.50

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: First-stage regression results: Baseline—All controls (incl. BS_t)

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	0.017**	0.036***	0.068***	0.078***	0.086***
	(2.46)	(3.01)	(4.82)	(4.55)	(4.35)
Fed QE announcement	0.000	-0.031+	-0.043+	-0.052*	-0.094***
	(0.03)	(-1.55)	(-1.58)	(-1.71)	(-3.46)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.13	0.65	0.34	0.33	0.60
Kleibergen-Paap-Test (p-value)	0.06	0.01	0.00	0.00	0.00
F-Stat (1st-stage)	3.03	6.18	17.43	14.95	18.86
Effective F Stat	2.77	5.22	9.95	10.21	16.69
R-squared	0.43	0.51	0.54	0.55	0.59

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6: First-stage regression results: $(BS_{t+M} - BS_{t-1})$

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_{t-1}$	$BS_{t+2} - BS_{t-1}$	$BS_{t+3} - BS_{t-1}$	$BS_{t+4} - BS_{t-1}$	$BS_{t+5} - BS_{t-1}$
ECB QE announcement	0.043***	0.059***	0.092***	0.100***	0.107***
	(4.59)	(4.81)	(5.46)	(5.27)	(4.79)
Fed QE announcement	-0.021	-0.049**	-0.060**	-0.067**	-0.109***
	(-1.10)	(-2.04)	(-2.16)	(-2.24)	(-3.75)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.19	0.50	0.27	0.26	0.49
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	11.05	14.82	21.82	21.19	22.36
Effective F Stat	7.86	11.11	15.99	15.96	20.57
R-squared	0.51	0.59	0.60	0.60	0.62

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7: First-stage regression results: QE announcements weighted by stock market surprise

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	0.587	1.202*	2.882***	3.654**	5.701***
	(1.18)	(1.89)	(2.72)	(2.16)	(3.87)
Fed QE announcement	-0.440	-2.348*	-2.705*	-1.872	-3.402+
	(-0.45)	(-1.83)	(-1.79)	(-1.20)	(-1.64)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.90	0.49	0.84	0.37	0.33
Kleibergen-Paap-Test (p-value)	0.34	0.09	0.03	0.02	0.04
F-Stat (1st-stage)	0.87	4.47	7.31	3.75	10.76
Effective F Stat	0.61	3.71	5.66	3.85	9.00
R-squared	0.34	0.44	0.45	0.47	0.48

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8: First-stage regression results: Narrative approach

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	0.023***	0.045***	0.069***	0.083***	0.095***
	(3.40)	(3.90)	(4.92)	(5.08)	(5.45)
Fed QE announcement	-0.017+	-0.058***	-0.072**	-0.080***	-0.093***
	(-1.59)	(-2.67)	(-2.50)	(-2.68)	(-3.57)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.25	0.86	0.46	0.46	0.64
Kleibergen-Paap-Test (p-value)	0.01	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	7.98	16.13	23.27	21.48	27.85
Effective F Stat	7.89	12.41	14.85	16.50	21.95
R-squared	0.42	0.53	0.54	0.55	0.61

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 9: First-stage regression results: Weekly data

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.013**	0.029***	0.054***	0.065***	0.069***
	(2.00)	(2.78)	(4.94)	(4.59)	(4.17)
Fed QE announcement	-0.007	-0.027*	-0.038*	-0.047*	-0.083***
	(-0.94)	(-1.66)	(-1.77)	(-1.78)	(-3.25)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.11	0.36	0.16	0.19	0.39
Kleibergen-Paap-Test (p-value)	0.11	0.02	0.00	0.00	0.00
F-Stat (1st-stage)	2.57	5.41	14.35	12.62	14.67
Effective F Stat	2.80	4.96	9.92	9.25	13.63
R-squared	0.28	0.36	0.41	0.42	0.43

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 10: First-stage regression results: Weekly data robustness

	(1)	(2)	(3)	(4)	(5)
	control	$BS_{t+20} - BS_{t-1}$	Weighted	Narrative	ECB
ECB QE announcement	0.064***	0.070***	2.892**	0.080***	0.072***
	(3.72)	(4.07)	(2.02)	(6.03)	(4.42)
Fed QE announcement	-0.077***	-0.082***	-6.115***	-0.115***	
	(-3.00)	(-3.08)	(-2.81)	(-5.85)	
Observations	448	448	448	448	448
Hansen-J (p-value)	0.39	0.35	0.91	0.95	.
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.02	0.00	0.00
F-Stat (1st-stage)	11.47	13.68	6.20	38.24	19.51
Effective F Stat	11.13	12.72	6.17	35.74	19.51
R-squared	0.43	0.45	0.41	0.44	0.41

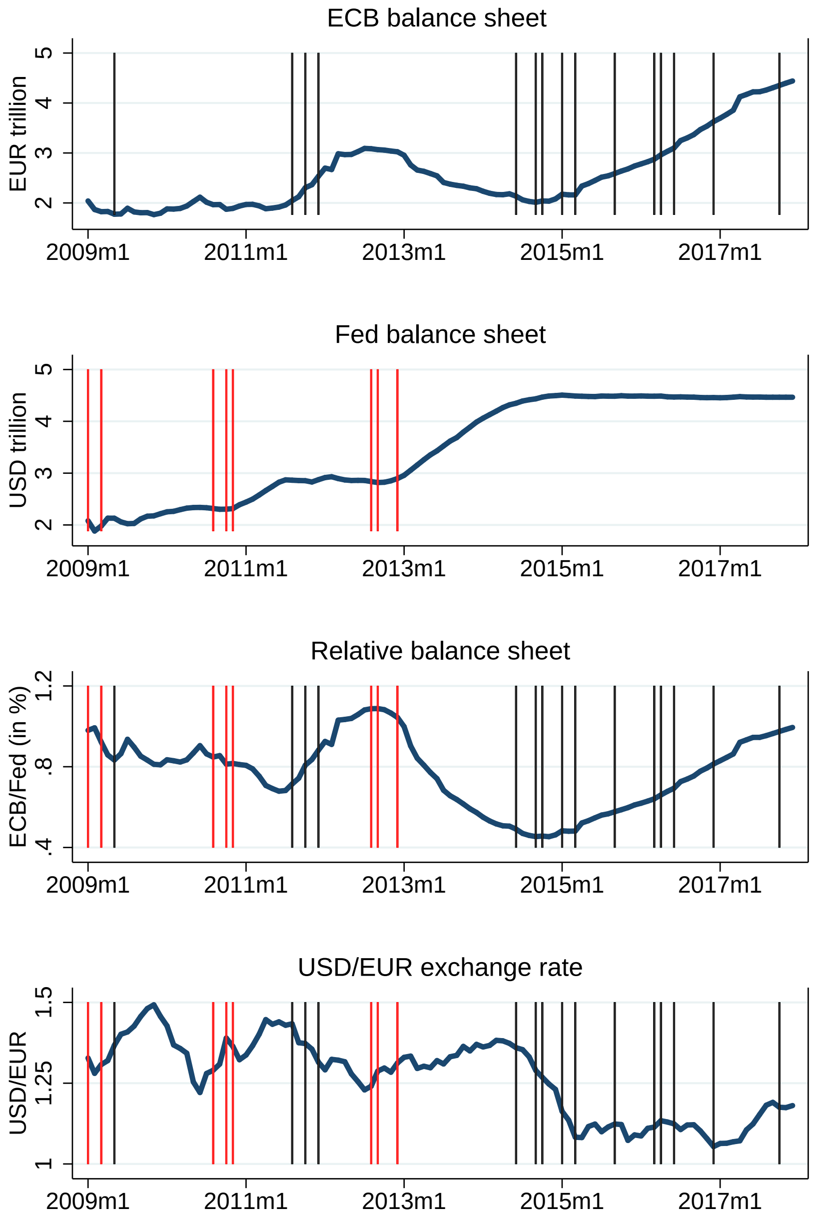
t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

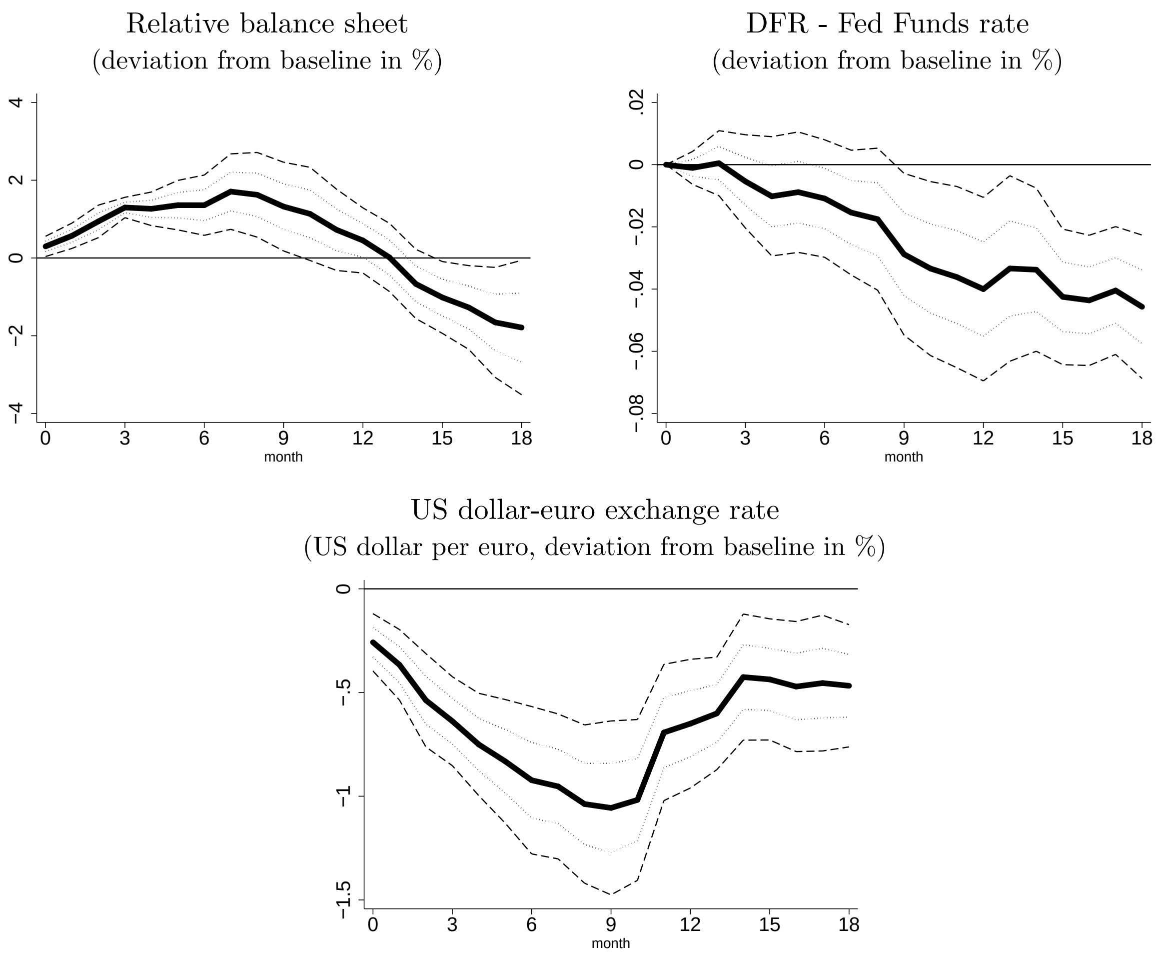
B Figures

Figure 1: Balance sheet movements and QE announcements



Notes: The upper two panels of the figure show the evolution of the ECB's (top panel) and the Federal Reserve's (second from top panel) balance sheets. The second from the bottom panel shows the relative balance sheet (ECB/Fed). The bottom panel plots the USD/EUR exchange rate. Across all charts, the black (red) vertical lines indicate the dates of QE announcements by the ECB (Federal Reserve).

Figure 2: Relative balance sheet, policy rate and exchange rate responses

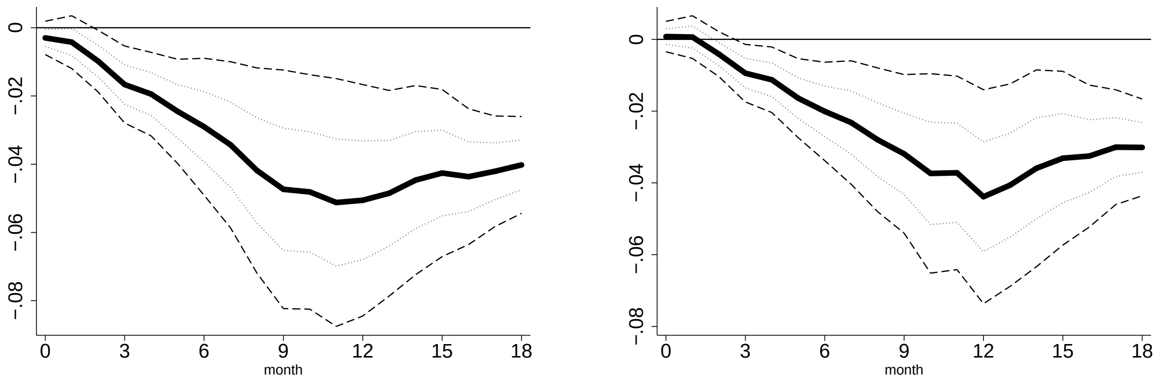


Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 3: Three-month money market rate differential and CIP deviation

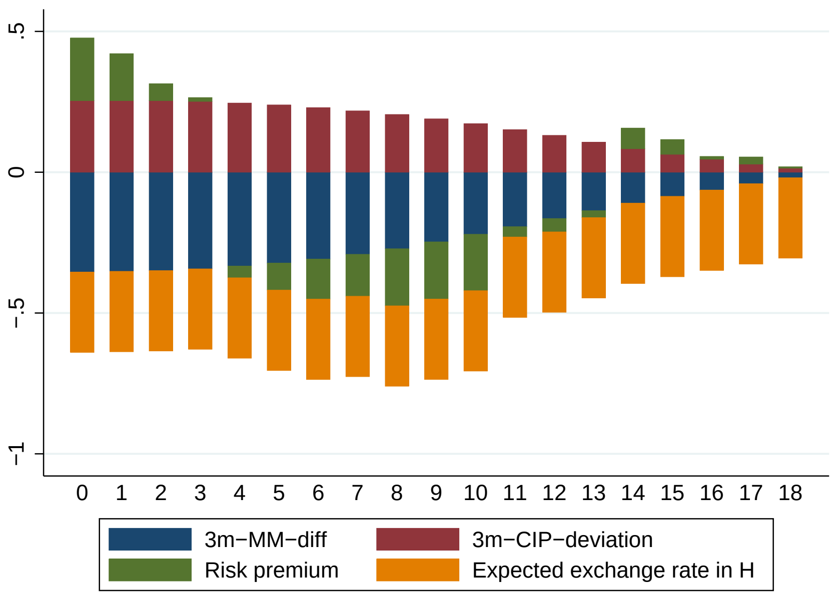
Three-month money market rate differential
$(r^{€,3m} - r^{\$,3m})$
(deviation from baseline in %-age points)

CIP deviation
$(\lambda_t = f^{3m}_{t,t+1} - s_t + r^{€,3m}_t - r^{\$,3m}_t)$
(deviation from baseline in %-age points)



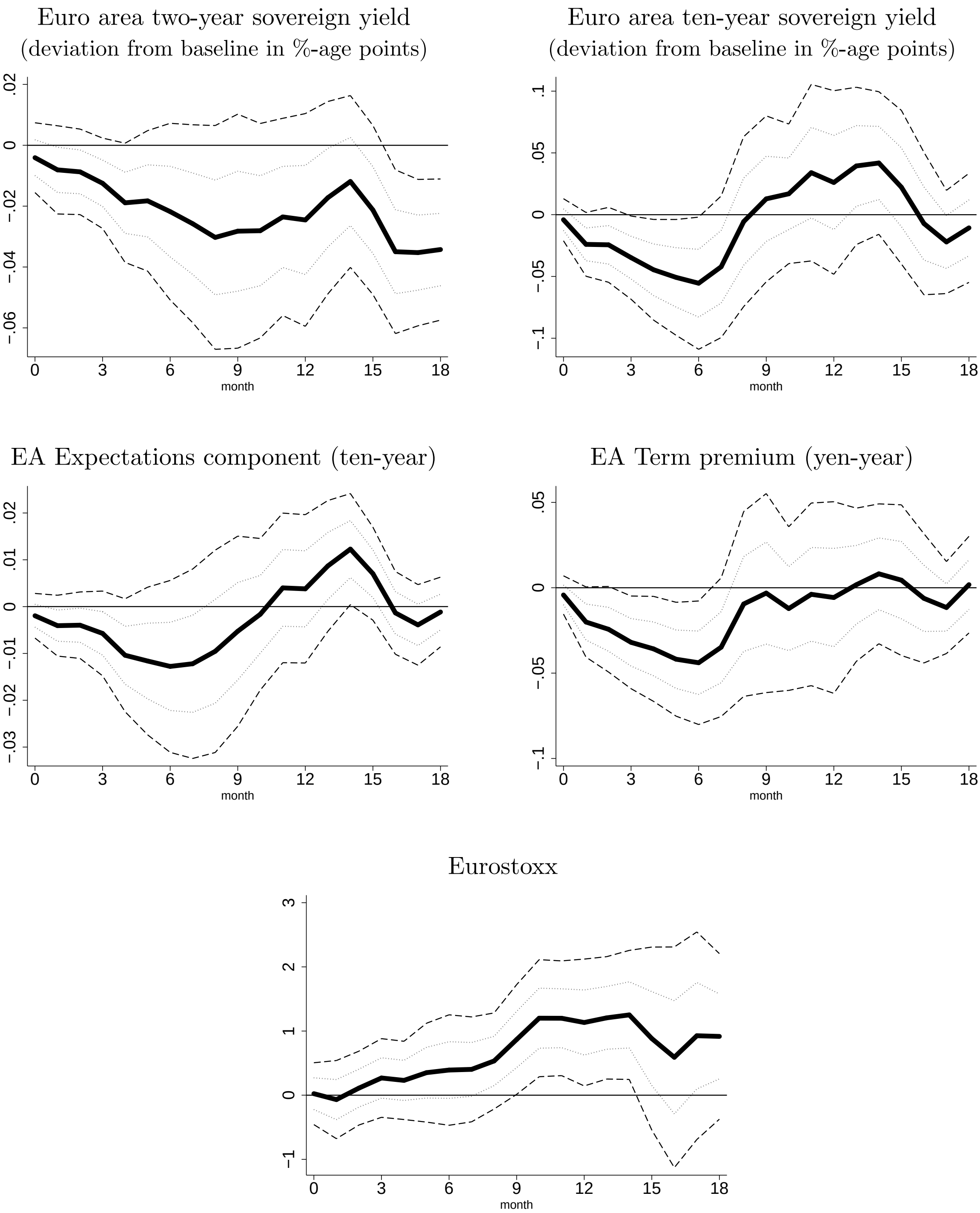
Notes: The panels show the responses to a relative QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 4: Decomposition of exchange rate response to QE shocks



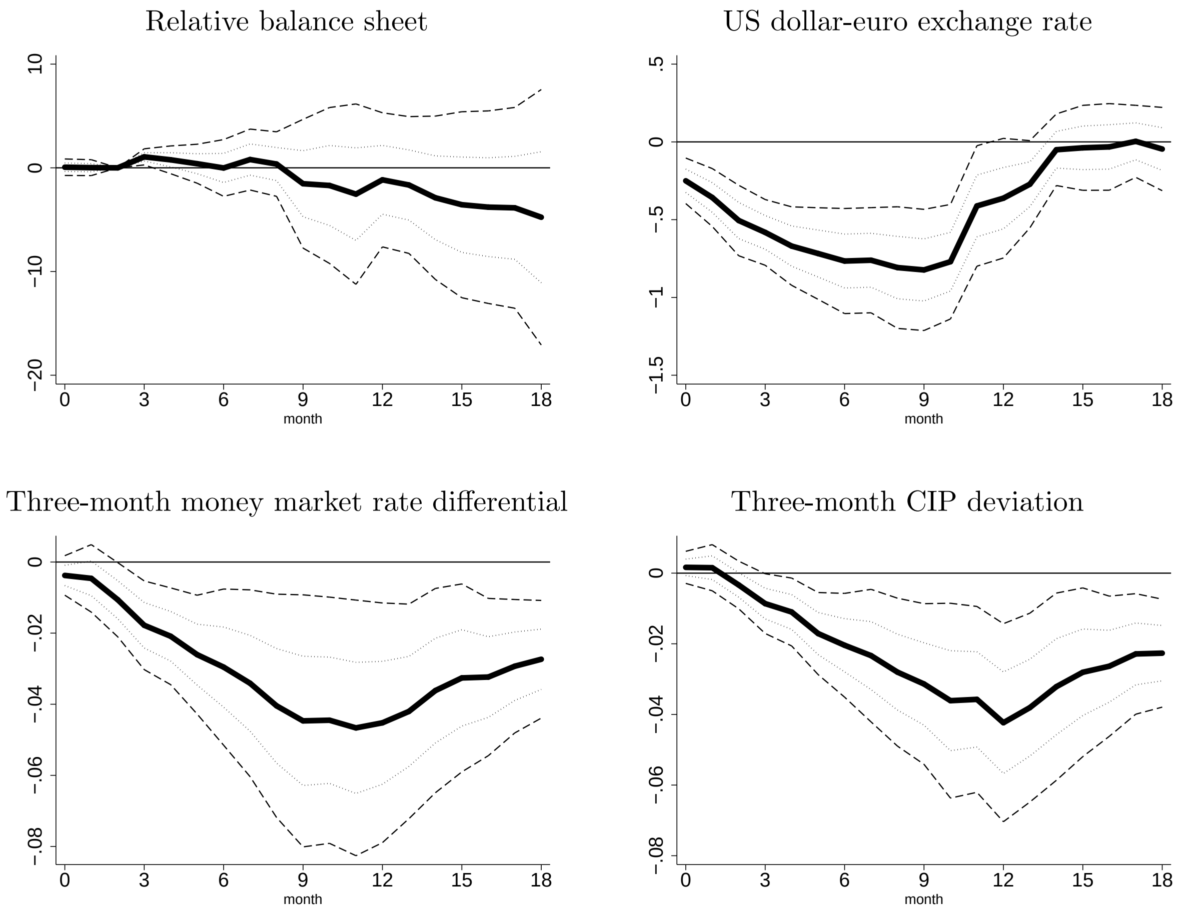
Notes: The figure shows the decomposition of the exchange rate effect of a relative QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point into the transmission channels according to Equation (12).

Figure 5: Other financial and macroeconomics variables



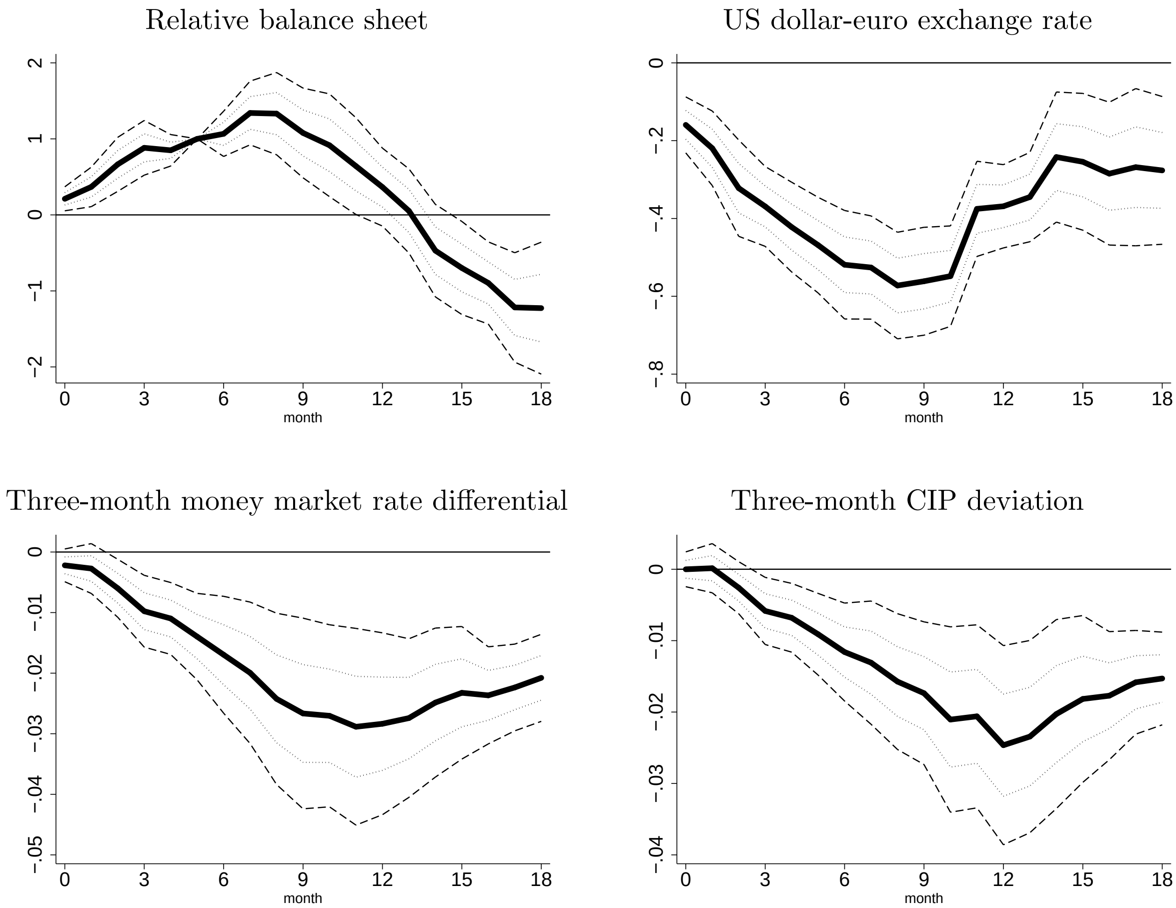
Notes: The panels show the responses to a QE shock that increases the ECB's balance sheet by one percentage point.

Figure 6: With controls $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$



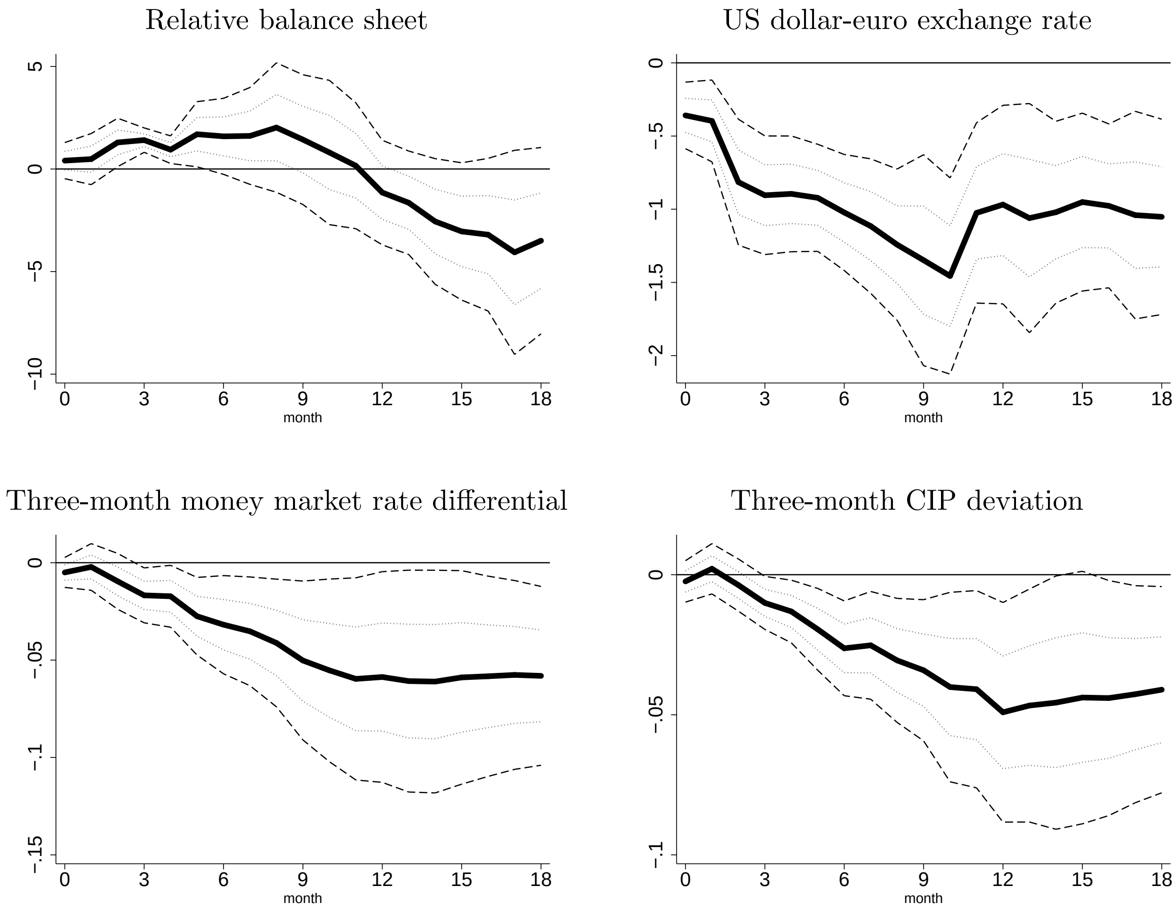
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 7: $(BS_{t+5} - BS_{t-1})$



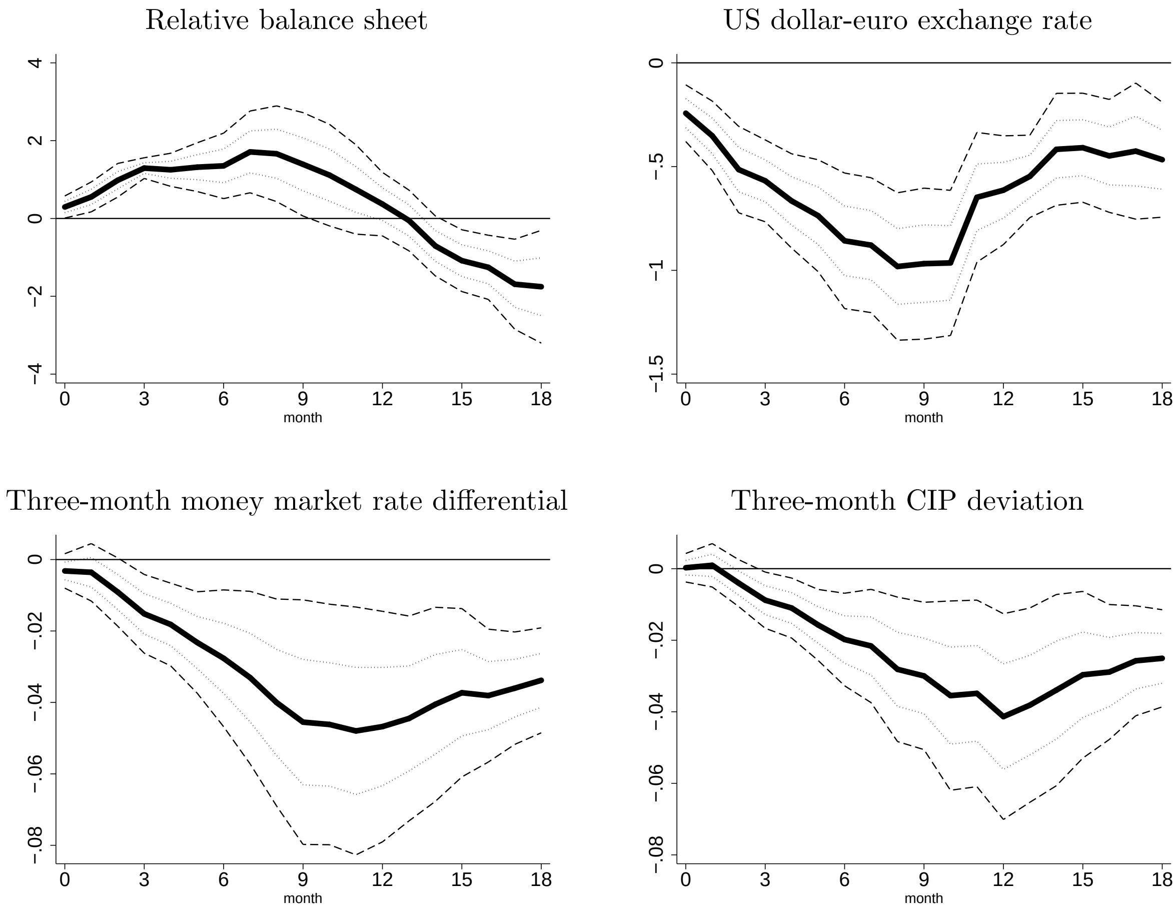
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 8: QE announcements weighted by stock market surprise on day of announcement



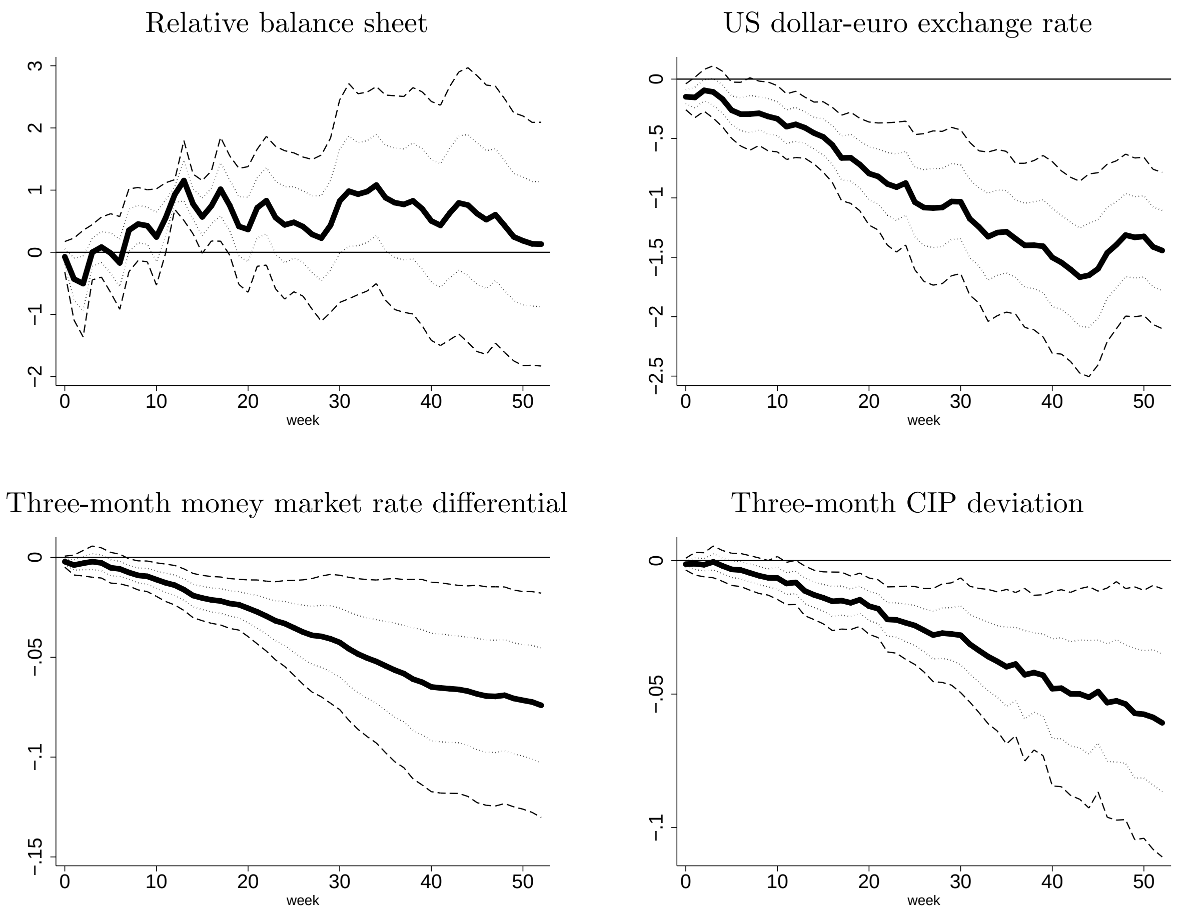
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 9: Narrative identification



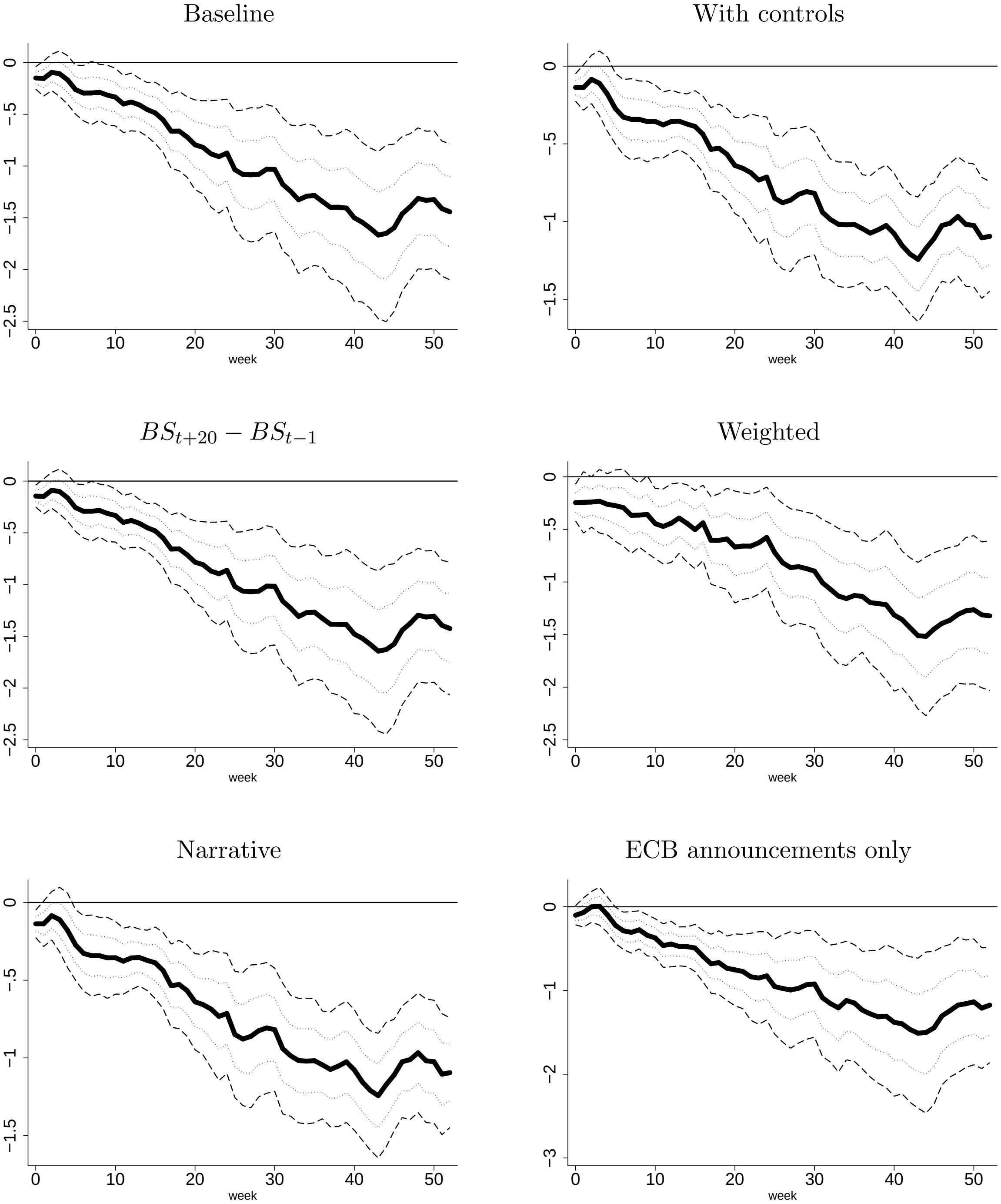
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 10: Weekly data, $(BS_{t+12} - BS_t)$



Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 11: Weekly data: Exchange rate—Robustness



Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

C Can CIP deviations arise due to counterparty risk?

Under the maintained assumption that R_t^E is risk free, a simple way of thinking of counterparty risk in the forward exchange rate market is the following. Rather than at the contracted, known exchange rate $F_{t,t+1}$, the conversion into dollars of the one-period euro payoff R_t^E may be risky if there is a probability that it has to take place on the spot market at the uncertain (risky) exchange rate S_{t+1} because the counterparty cannot deliver dollars anymore. Assuming the (conditional) probability of the latter event is π_t, we have that no-arbitrage under no borrowing constraints implies the following:[21]

$$\frac{(1-\pi_t)\, E_t\left(\mathcal{D}_{t+1}^{\$}\right) F_{t,t+1} + \pi_t E_t\left(S_{t+1}\mathcal{D}_{t+1}^{\$}\right)}{S_t} R_t€ = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$} = 1$$

$$\frac{F_{t,t+1}R_t€}{S_t} > R_t^{\$} <=> \left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right) R_t^{\$} > 0.$$

Thus a sufficient condition for positive CIP deviations ($\frac{F_{t,t+1}R_t€}{S_t} > R_t^{\$}$) is that the expression $\left[\left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right) R_t^{\$}\right]$ is different from zero. However, it is possible to show that this expression is always zero, as it corresponds to the expected forward premium (see e.g. Engel 1999). For our investor, it should be the case that the one period risk-adjusted expected return of investing in the dollar euro forward market or in the dollar euro spot market should be the same, namely

$$\frac{\pi_t E_t\left(S_{t+1}\mathcal{D}_{t+1}^{\$}\right) + (1-\pi_t)\, E_t\left(\mathcal{D}_{t+1}^{\$}\right) F_{t,t+1}}{S_t} R_t€ = \frac{E_t\left(\mathcal{D}_{t+1}^{\$} S_{t+1}\right)}{S_t} R_t€$$

$$(1-\pi_t)\, \frac{E_t\left(\mathcal{D}_{t+1}^{\$}\right) F_{t,t+1}}{S_t} R_t€ = (1-\pi_t)\, \frac{E_t\left(\mathcal{D}_{t+1}^{\$} S_{t+1}\right)}{S_t} R_t€.$$

$$F_{t,t+1} = E_t\left(S_{t+1}\right) - \frac{Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right)}{E_t\left(\mathcal{D}_{t+1}^{\$}\right)} \tag{C.1}$$

Notably, these returns are equalized also if they are subject to the same borrowing constraints and transaction costs. But then it is immediate that deviations from CIP cannot arise from counterparty forward market risks that are perfectly correlated with future spot market risks.The

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$$\frac{E_t\left(\mathcal{D}_{t+1}^{\$}\right) F_{t,t+1} + \pi_t \left[E_t\left(\mathcal{D}_{t+1}^{\$}\right)\left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right)\right]}{S_t} R_t€ = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}$$

$$\frac{F_{t,t+1}R_t€}{S_t}\left[1 + \pi_t \frac{\left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - R_t^{\$} Cov_t\left(\mathcal{D}_{t+1}^{\$}, F_{t,t+1}\right)}{F_{t,t+1}}\right] = R_t^{\$}$$

same relation for the “European” investor would read

$$F_{t,t+1} = \left[E_t \left(1/S_{t+1} \right) - \frac{Cov_t \left(\mathcal{D}_{t+1}€, 1/S_{t+1} \right)}{E_t \left(\mathcal{D}_{t+1}€ \right)} \right]^{-1}.$$

D Additional tables not for publication

Table 11: First-stage regression results: QE announcements weighted by stock market surprise—Controls

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	-0.099	0.465	1.941*	2.972*	5.203***
	(-0.21)	(0.76)	(1.80)	(1.69)	(3.13)
Fed QE announcement	-0.293	-2.219*	-2.753*	-1.948^{+}	-3.422*
	(-0.32)	(-1.68)	(-1.73)	(-1.33)	(-1.80)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.24	0.26	0.99	0.49	0.42
Kleibergen-Paap-Test (p-value)	0.93	0.26	0.05	0.03	0.02
F-Stat (1st-stage)	0.07	1.93	4.09	2.83	7.94
Effective F Stat	0.08	2.34	3.46	2.76	7.42
R-squared	0.40	0.46	0.47	0.48	0.48

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 12: First-stage regression results: Narrative approach—Controls

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+1} - BS_t$	$BS_{t+2} - BS_t$	$BS_{t+3} - BS_t$	$BS_{t+4} - BS_t$	$BS_{t+5} - BS_t$
ECB QE announcement	0.028***	0.041***	0.068***	0.083***	0.095***
	(4.01)	(3.14)	(4.76)	(4.82)	(5.14)
Fed QE announcement	-0.021^{+}	-0.072***	-0.082***	-0.080***	-0.099***
	(-1.53)	(-3.36)	(-2.73)	(-2.64)	(-3.67)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.25	0.74	0.68	0.46	0.89
Kleibergen-Paap-Test (p-value)	0.01	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	9.97	13.59	24.28	18.56	26.20
Effective F Stat	8.95	12.48	15.46	15.10	21.31
R-squared	0.46	0.55	0.56	0.55	0.60

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 13: First-stage regression results: Using only ECB announcements as instruments—Controls

	(1) $BS_{t+1} - BS_t$	(2) $BS_{t+2} - BS_t$	(3) $BS_{t+3} - BS_t$	(4) $BS_{t+4} - BS_t$	(5) $BS_{t+5} - BS_t$
ECB QE announcement	0.018**	0.038***	0.074***	0.091***	0.106***
	(2.56)	(3.01)	(5.07)	(5.31)	(5.26)
Observations	107	106	105	104	103
Hansen-J (p-value)	.	.	.	.	.
Kleibergen-Paap-Test (p-value)	0.02	0.01	0.00	0.00	0.00
F-Stat (1st-stage)	6.54	9.08	25.70	28.17	27.68
Effective F Stat	6.54	9.08	25.70	28.17	27.68
R-squared	0.42	0.49	0.51	0.49	0.50

t statistics in parentheses
Standard errors robust to heteroskedasticity and serial correlation
$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 14: First-stage regression results: Robustness—Controls

	(1) $BS_{t+1} - BS_{t-1}$	(2) $BS_{t+2} - BS_{t-1}$	(3) $BS_{t+3} - BS_{t-1}$
ECB QE announcement	0.036***	0.023**	0.031**
	(3.65)	(2.07)	(2.23)
Fed QE announcement	-0.013	-0.039***	-0.010
	(-0.68)	(-2.80)	(-0.72)
Observations	107	106	105
Hansen-J (p-value)	0.18	0.95	0.10
Kleibergen-Paap-Test (p-value)	0.01	0.02	0.10
F-Stat (1st-stage)	6.68	6.03	2.72
Effective F Stat	4.64	6.10	3.47
R-squared	0.53	0.83	0.88

t statistics in parentheses
Standard errors robust to heteroskedasticity and serial correlation
$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 15: Weekly First-stage regression results: Baseline—Controls

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.008	0.023**	0.049***	0.059***	0.064***
	(1.26)	(1.99)	(4.14)	(4.03)	(3.72)
Fed QE announcement	-0.000	-0.019	-0.031^{+}	-0.039^{+}	-0.077***
	(-0.04)	(-1.20)	(-1.41)	(-1.43)	(-3.00)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.07	0.36	0.16	0.18	0.39
Kleibergen-Paap-Test (p-value)	0.47	0.11	0.01	0.01	0.00
F-Stat (1st-stage)	0.80	2.65	9.67	9.23	11.47
Effective F Stat	0.95	2.66	7.09	6.89	11.13
R-squared	0.30	0.37	0.42	0.42	0.43

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 16: Weekly First-stage regression results: QE announcements weighted by stock market surprise—Controls

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.104	0.291	2.147***	2.300**	2.329^{+}
	(0.26)	(0.60)	(3.29)	(2.36)	(1.60)
Fed QE announcement	-0.732	-2.649*	-3.944*	-4.299*	-5.519**
	(-0.89)	(-1.96)	(-1.84)	(-1.68)	(-2.44)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.51	0.13	0.91	0.93	0.84
Kleibergen-Paap-Test (p-value)	0.60	0.16	0.05	0.04	0.04
F-Stat (1st-stage)	0.43	2.14	7.57	4.34	4.37
Effective F Stat	0.54	3.06	4.50	3.41	4.40
R-squared	0.30	0.37	0.40	0.41	0.42

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 17: Weekly First-stage regression results: QE announcements weighted by stock market surprise—No control

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.459	0.775^{+}	2.654^{***}	2.894^{***}	2.892^{**}
	(1.15)	(1.63)	(4.07)	(2.89)	(2.02)
Fed QE announcement	-1.190^{+}	-3.243^{***}	-4.533^{**}	-5.068^{**}	-6.115^{***}
	(-1.57)	(-2.64)	(-2.28)	(-2.12)	(-2.81)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.70	0.24	0.87	0.88	0.91
Kleibergen-Paap-Test (p-value)	0.12	0.04	0.02	0.02	0.02
F-Stat (1st-stage)	1.98	5.08	11.83	6.68	6.20
Effective F Stat	2.04	5.94	7.26	5.51	6.17
R-squared	0.28	0.35	0.40	0.40	0.41

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 18: Weekly First-stage regression results: Narrative approach—Controls

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.024^{***}	0.044^{***}	0.060^{***}	0.072^{***}	0.089^{***}
	(3.77)	(3.78)	(5.86)	(5.54)	(7.30)
Fed QE announcement	-0.017^{+}	-0.064^{***}	-0.069^{***}	-0.088^{***}	-0.110^{***}
	(-1.55)	(-4.76)	(-2.82)	(-3.20)	(-5.25)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.12	0.62	0.48	0.69	0.95
Kleibergen-Paap-Test (p-value)	0.02	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	8.41	18.81	22.16	20.74	40.94
Effective F Stat	7.33	17.24	15.88	16.78	36.90
R-squared	0.31	0.39	0.43	0.43	0.44

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 19: Weekly First-stage regression results: Narrative approach—No control

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.022***	0.045***	0.065***	0.078***	0.080***
	(3.71)	(4.43)	(6.80)	(6.26)	(6.03)
Fed QE announcement	-0.020***	-0.058***	-0.077***	-0.083***	-0.115***
	(-2.61)	(-3.96)	(-3.30)	(-3.41)	(-5.85)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.32	0.38	0.48	0.79	0.95
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	11.14	18.85	31.11	26.83	38.24
Effective F Stat	10.91	17.98	21.41	20.76	35.74
R-squared	0.29	0.38	0.42	0.43	0.44

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 20: Weekly First-stage regression results: Using only ECB announcements as instruments—Controls

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.008	0.023*	0.049***	0.059***	0.065***
	(1.27)	(1.95)	(4.05)	(4.03)	(3.80)
Observations	464	460	456	452	448
Hansen-J (p-value)	.	.	.	.	.
Kleibergen-Paap-Test (p-value)	0.22	0.08	0.00	0.00	0.01
F-Stat (1st-stage)	1.61	3.79	16.44	16.24	14.45
Effective F Stat	1.61	3.79	16.44	16.24	14.45
R-squared	0.29	0.36	0.41	0.41	0.42

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 21: Weekly First-stage regression results: Using only ECB announcements as instruments—No control

	(1)	(2)	(3)	(4)	(5)
	$BS_{t+4} - BS_t$	$BS_{t+8} - BS_t$	$BS_{t+12} - BS_t$	$BS_{t+16} - BS_t$	$BS_{t+20} - BS_t$
ECB QE announcement	0.013**	0.030***	0.056***	0.067***	0.072***
	(2.08)	(2.86)	(5.03)	(4.73)	(4.42)
Observations	464	460	456	452	448
Hansen-J (p-value)	.	.	.	.	.
Kleibergen-Paap-Test (p-value)	0.06	0.02	0.00	0.00	0.00
F-Stat (1st-stage)	4.35	8.17	25.26	22.37	19.51
Effective F Stat	4.35	8.17	25.26	22.37	19.51
R-squared	0.27	0.34	0.40	0.40	0.41

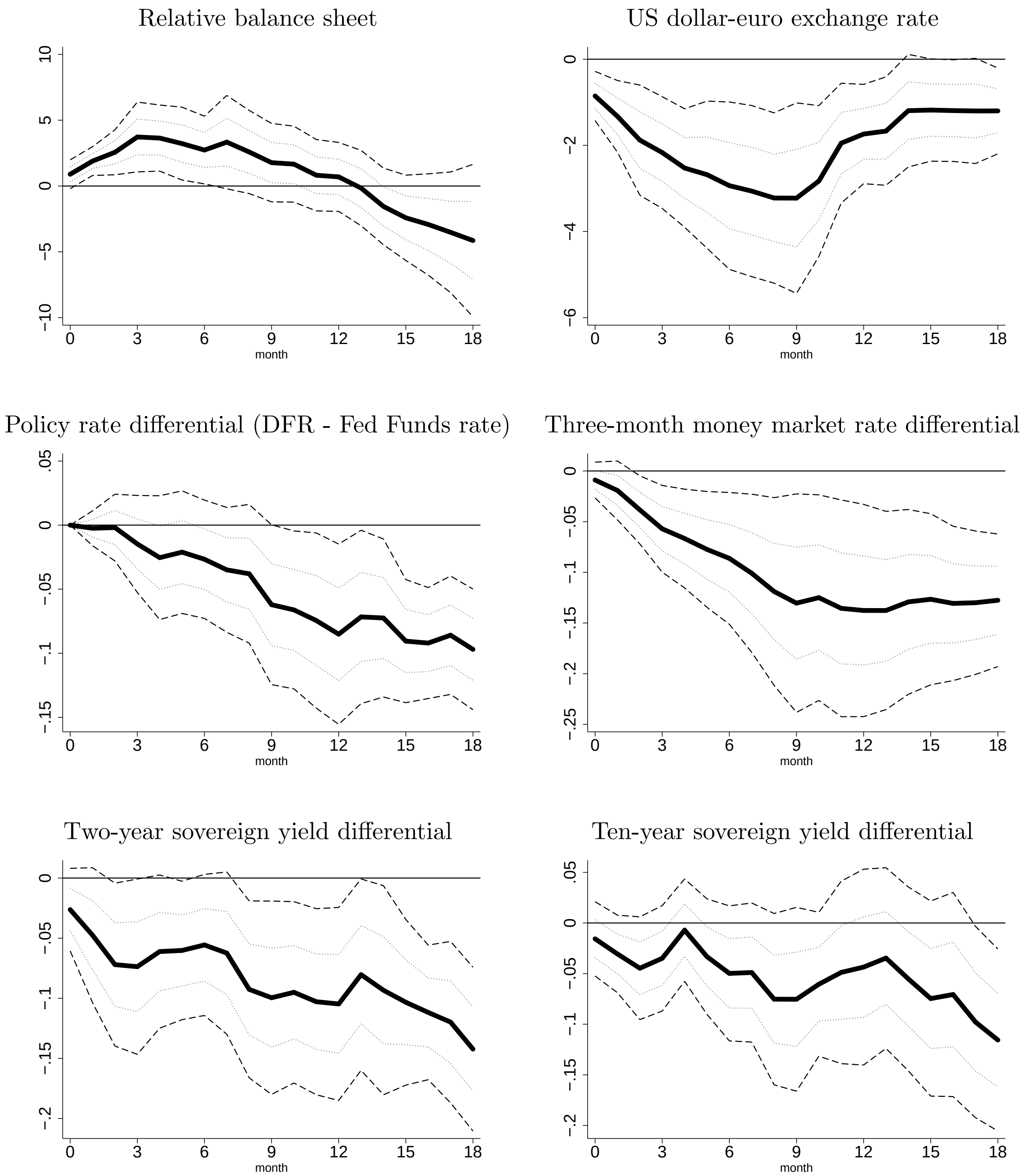
t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

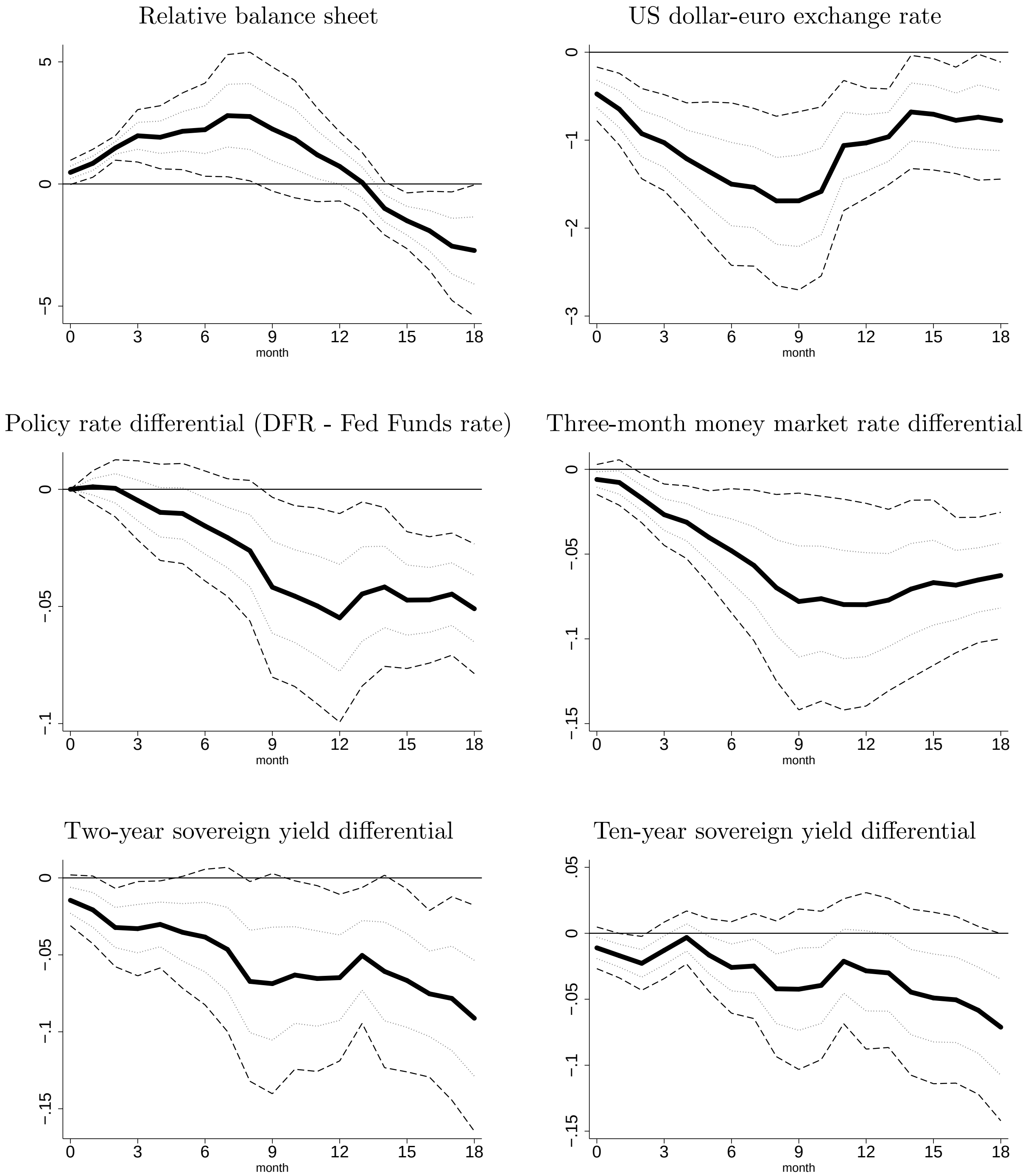
E Additional figures not for publication

Figure 12: $(BS_{t+1} - BS_t)$



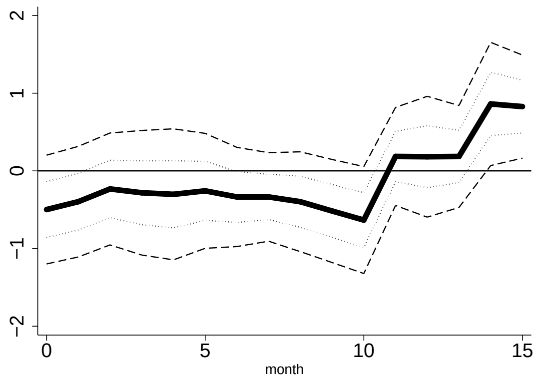
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 13: $(BS_{t+2} - BS_t)$



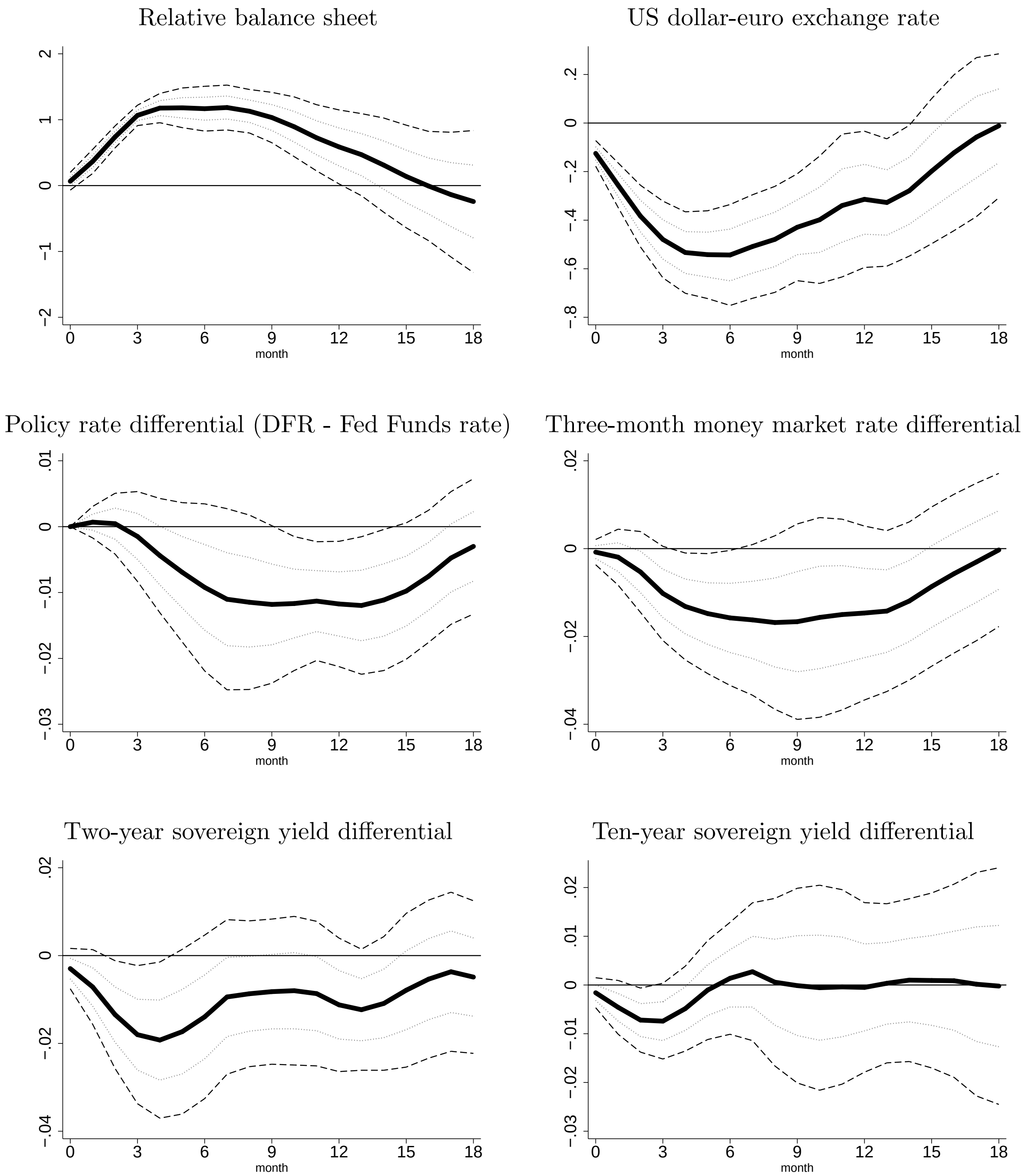
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 14: US dollar-euro real exchange rate in levels r_t (US dollar per euro deflated with CPI, %-deviations from baseline)



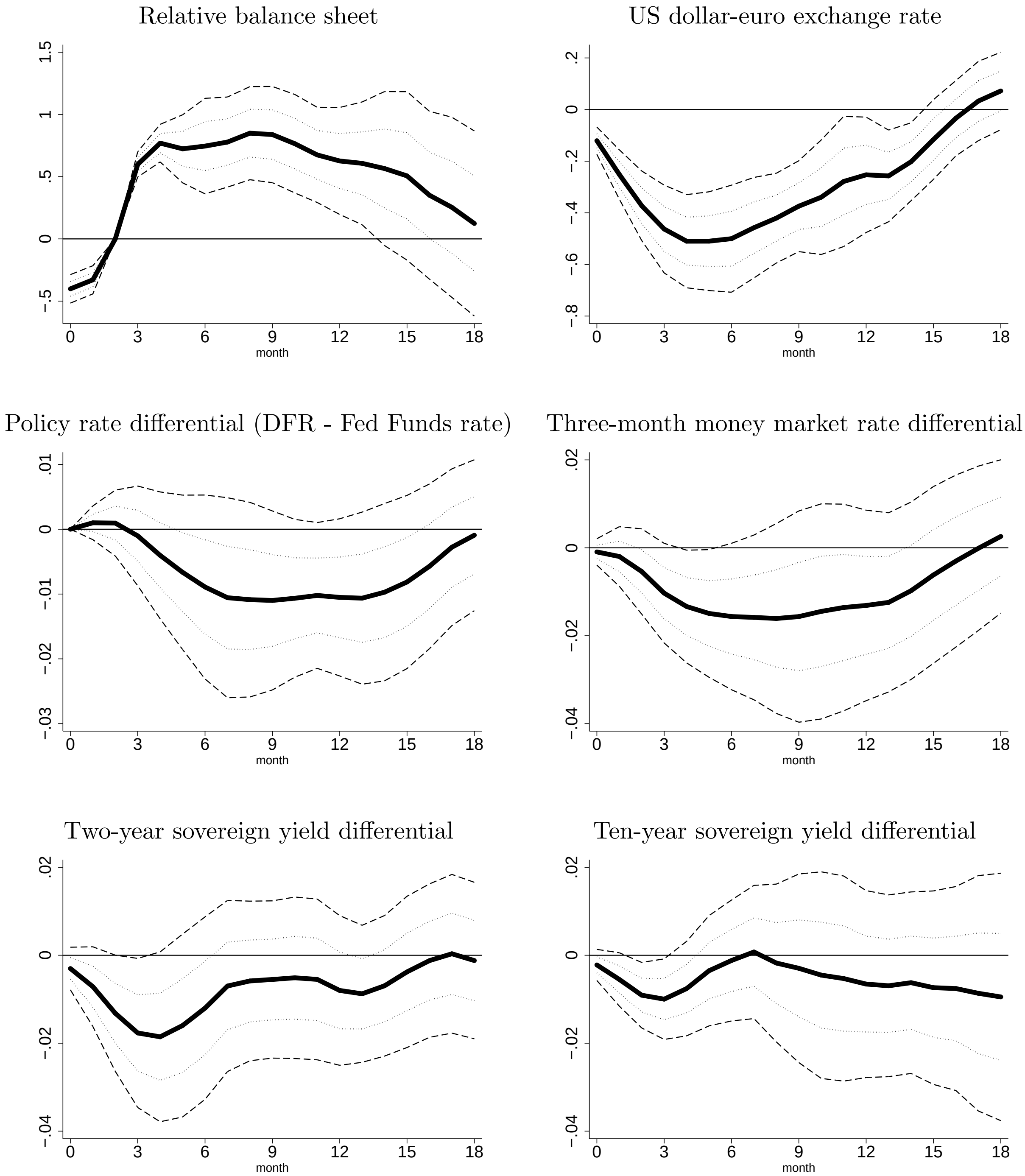
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 15: OLS results



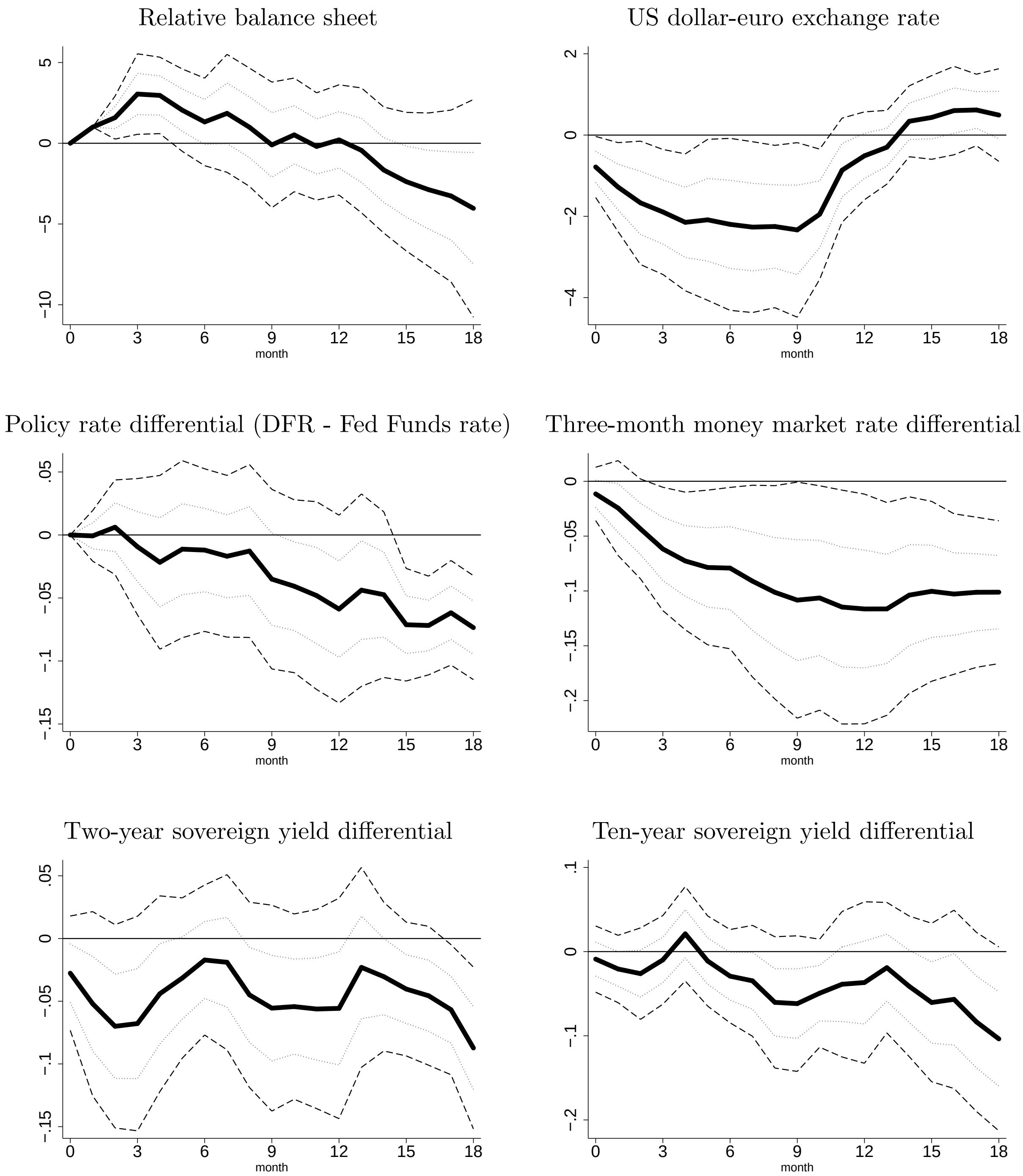
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 16: OLS results—All controls



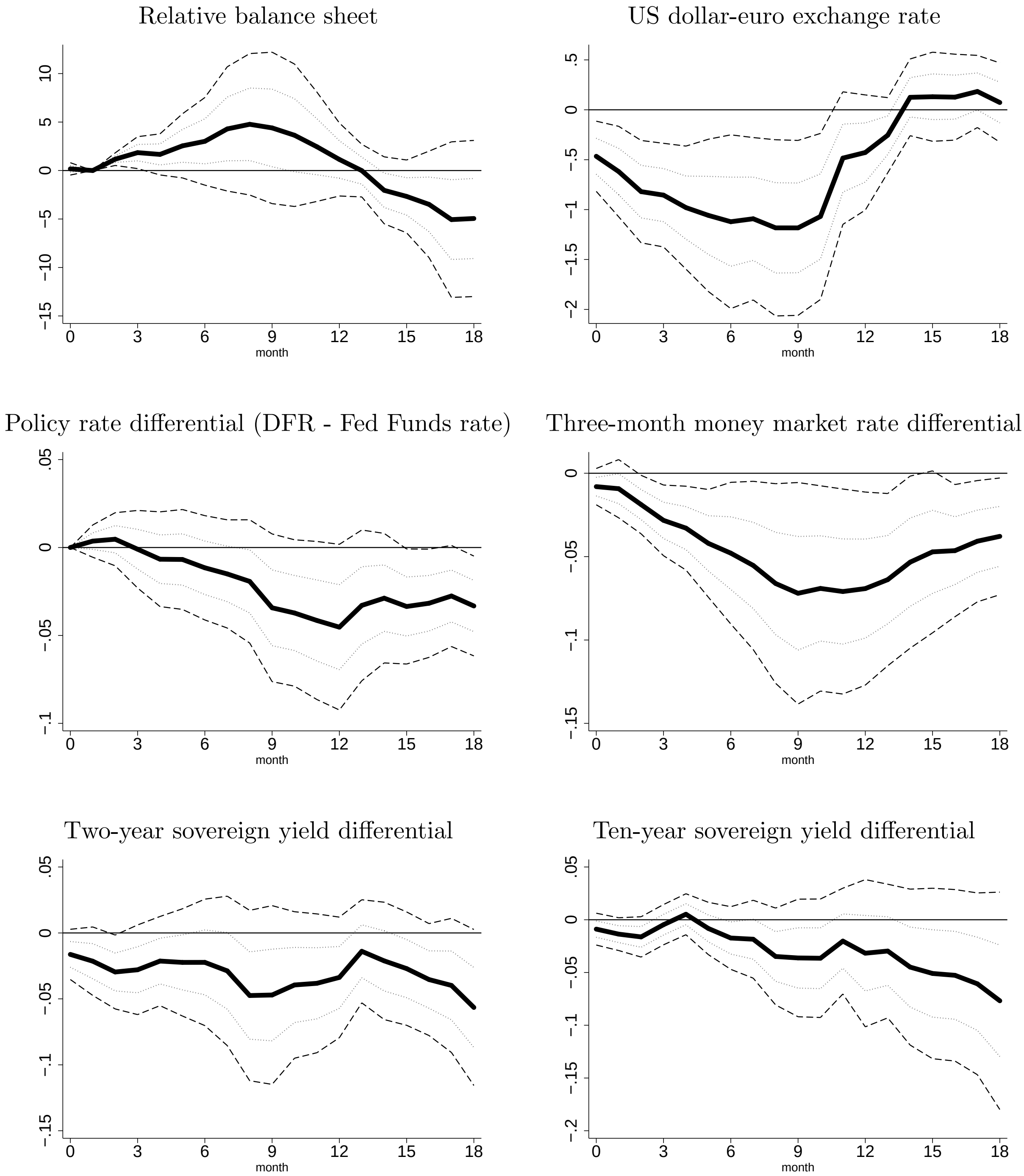
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 17: $(BS_{t+1} - BS_t)$—All controls



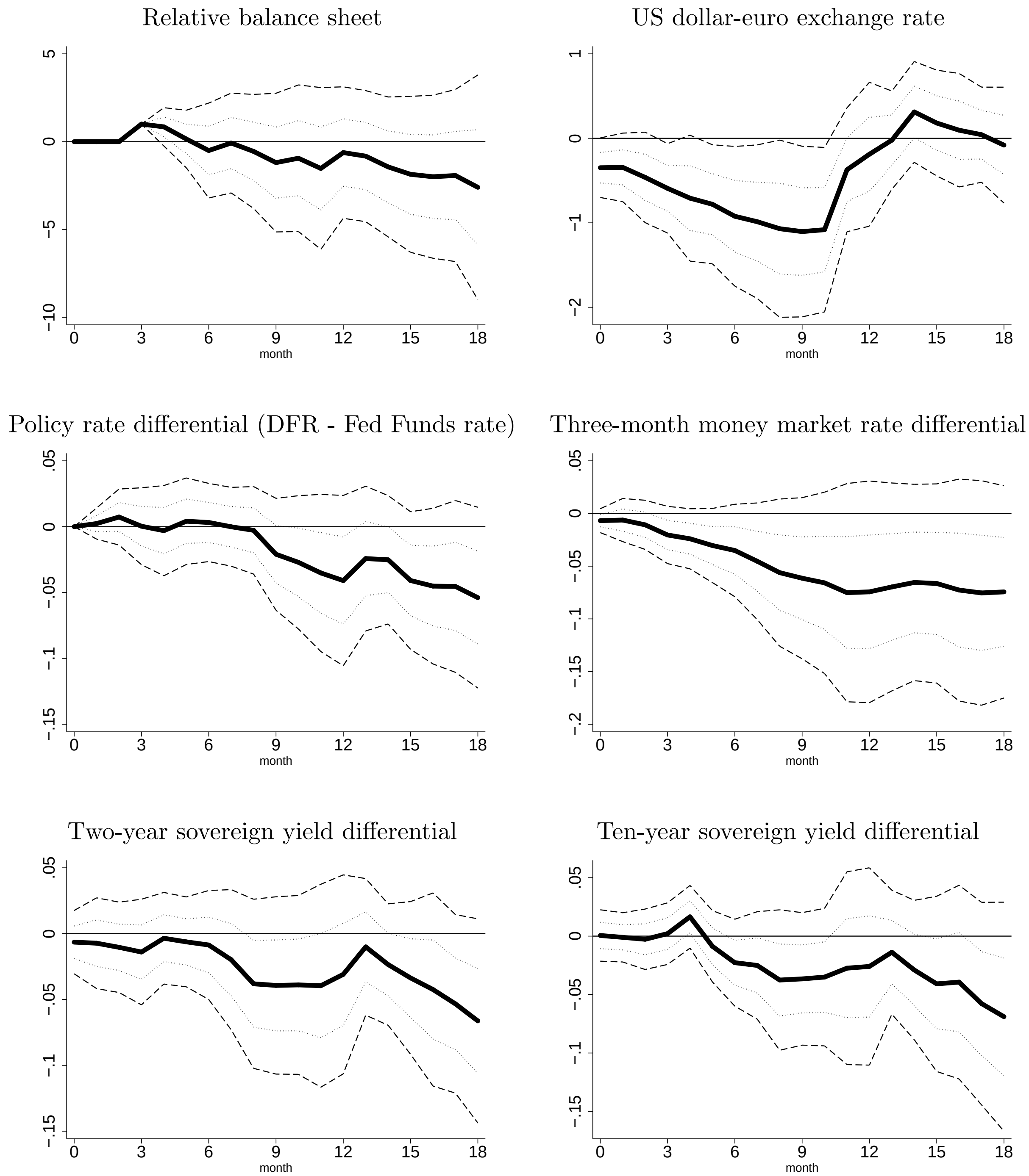
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 18: $(BS_{t+2} - BS_t)$—All controls



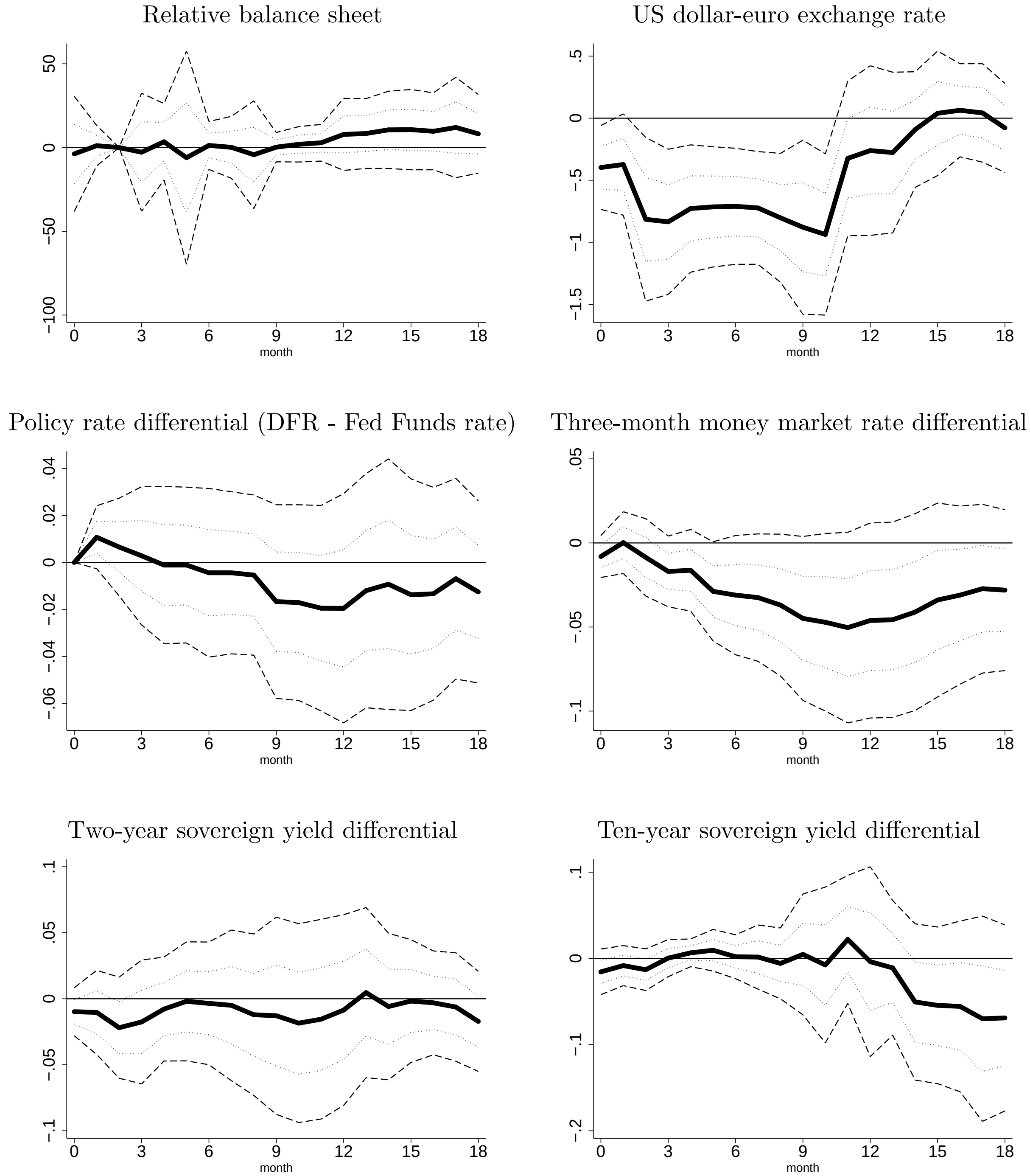
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 19: $(BS_{t+3} - BS_{t-1})$—All controls



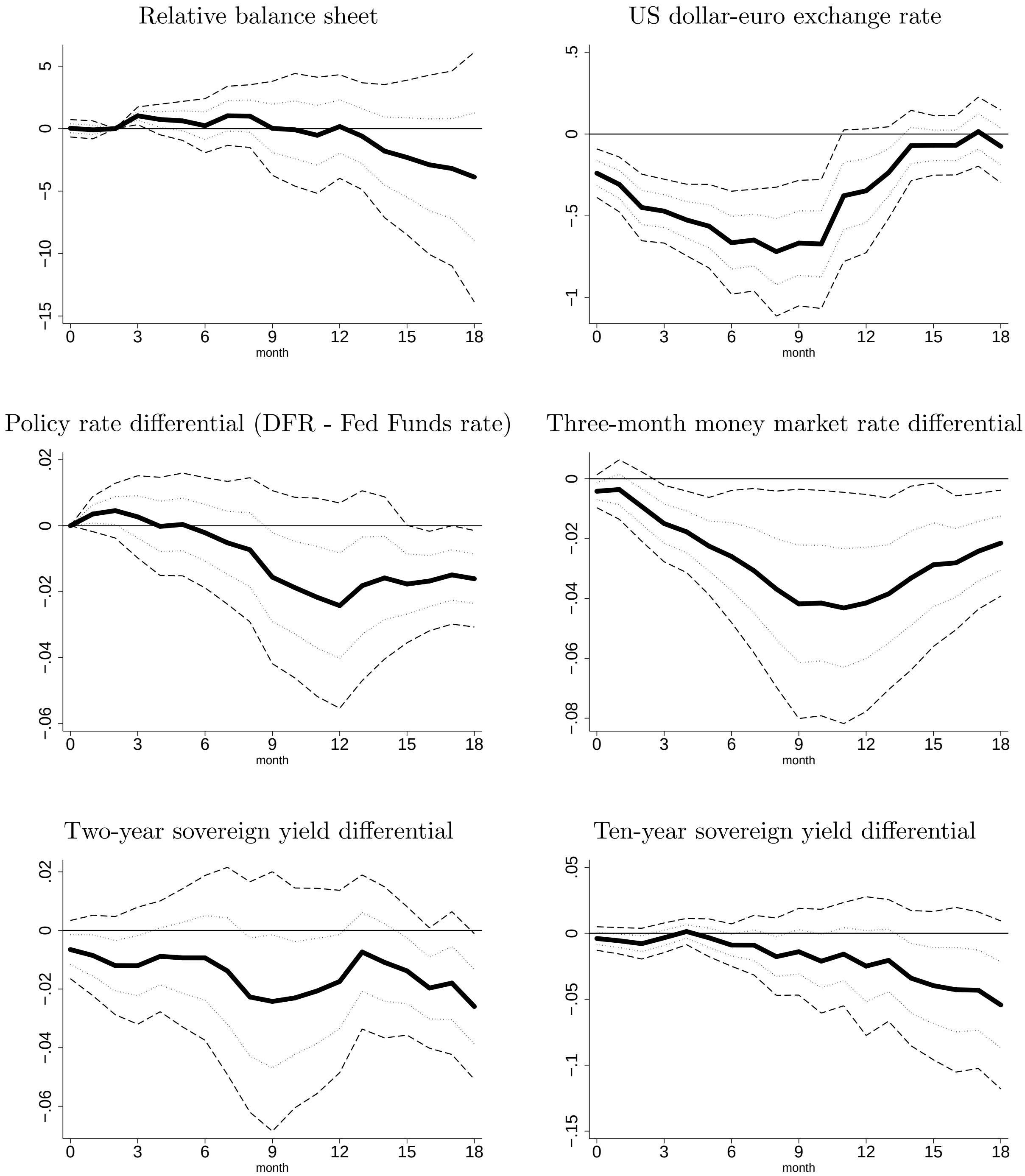
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 20: QE announcements weighted by stock market surprise on day of announcement—All controls



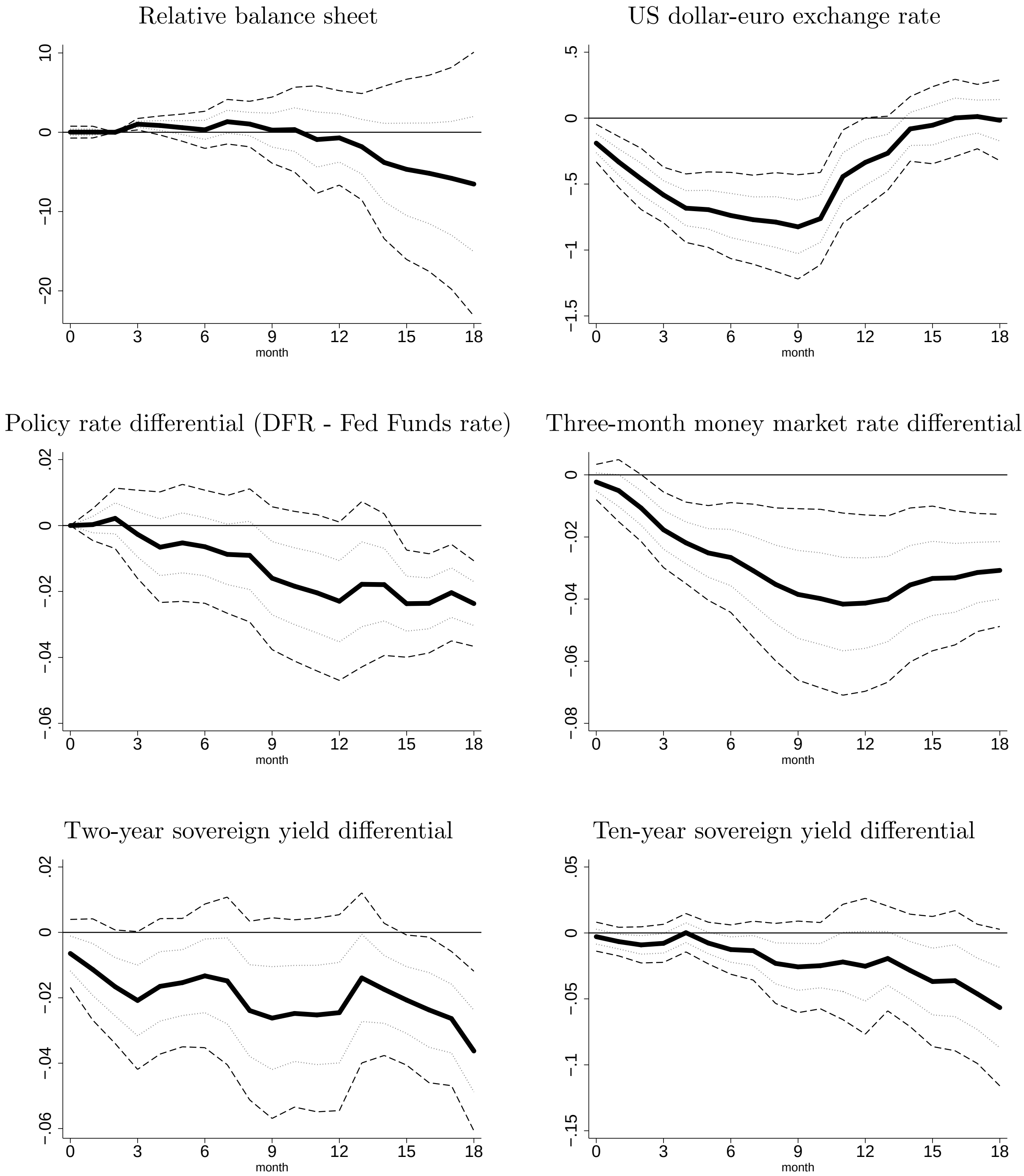
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 21: QE announcements—Narrative approach—All controls



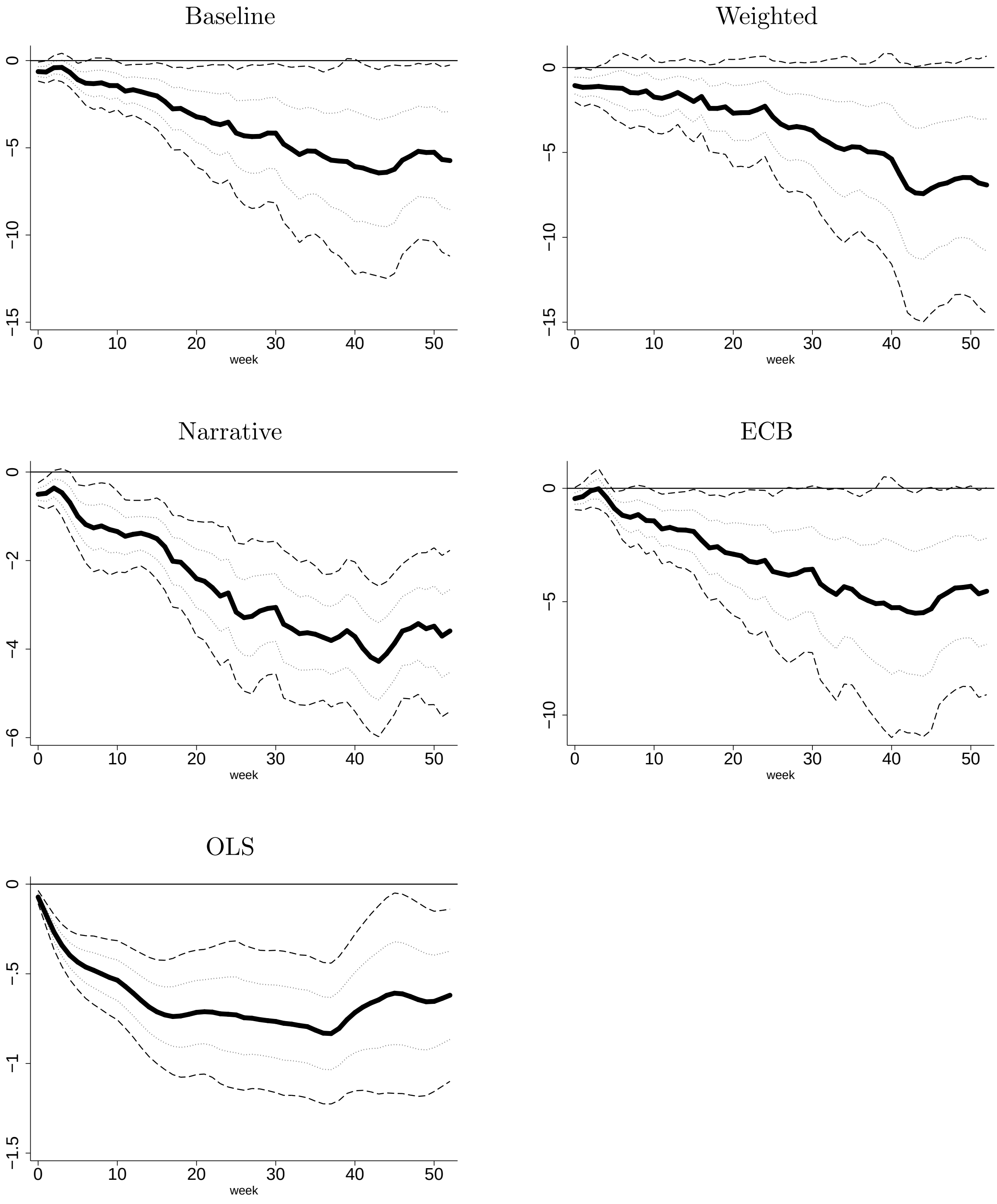
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 22: Using only ECB announcements as instruments—All controls



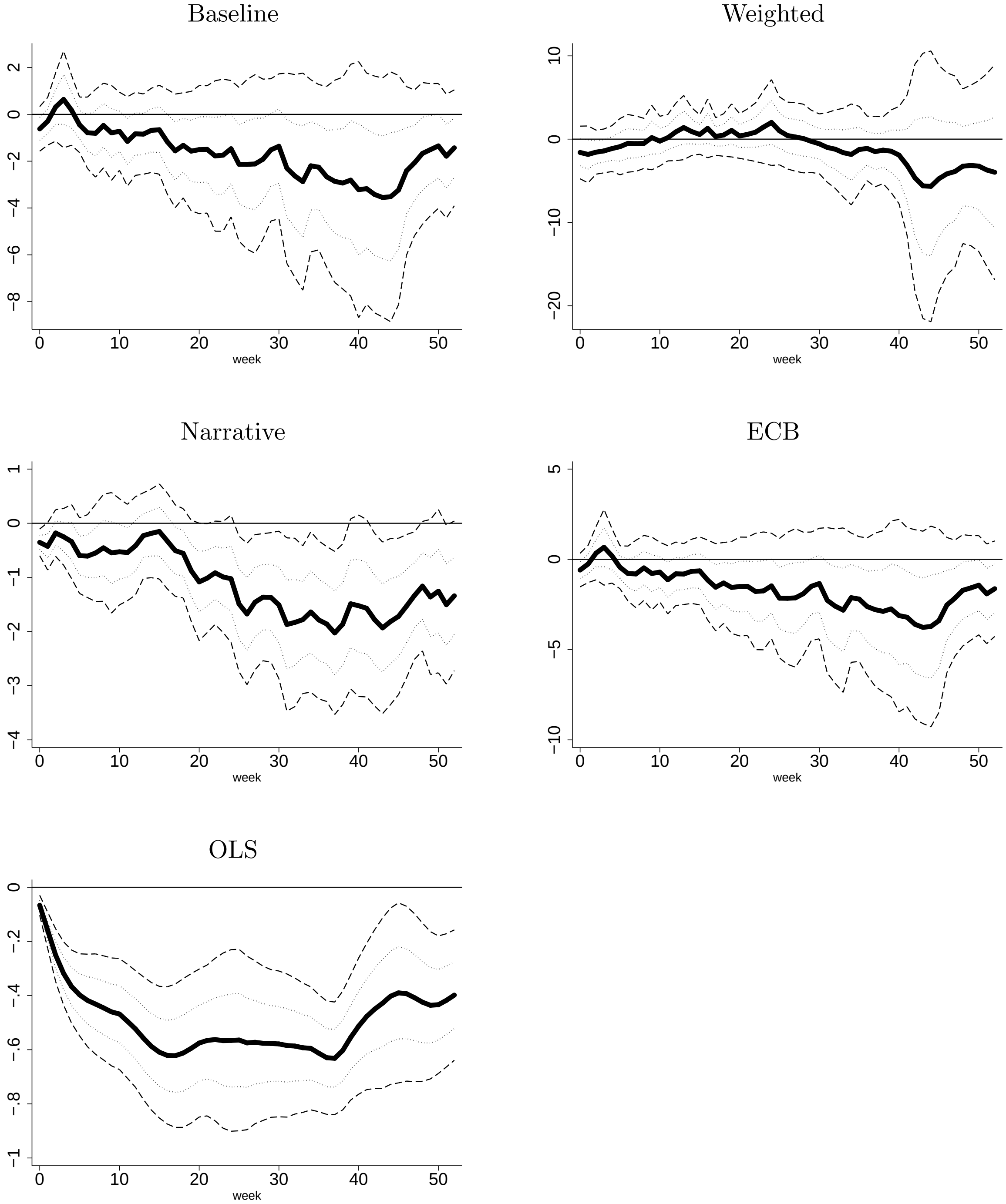
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 23: Weekly—$(BS_{t+4} - BS_t)$



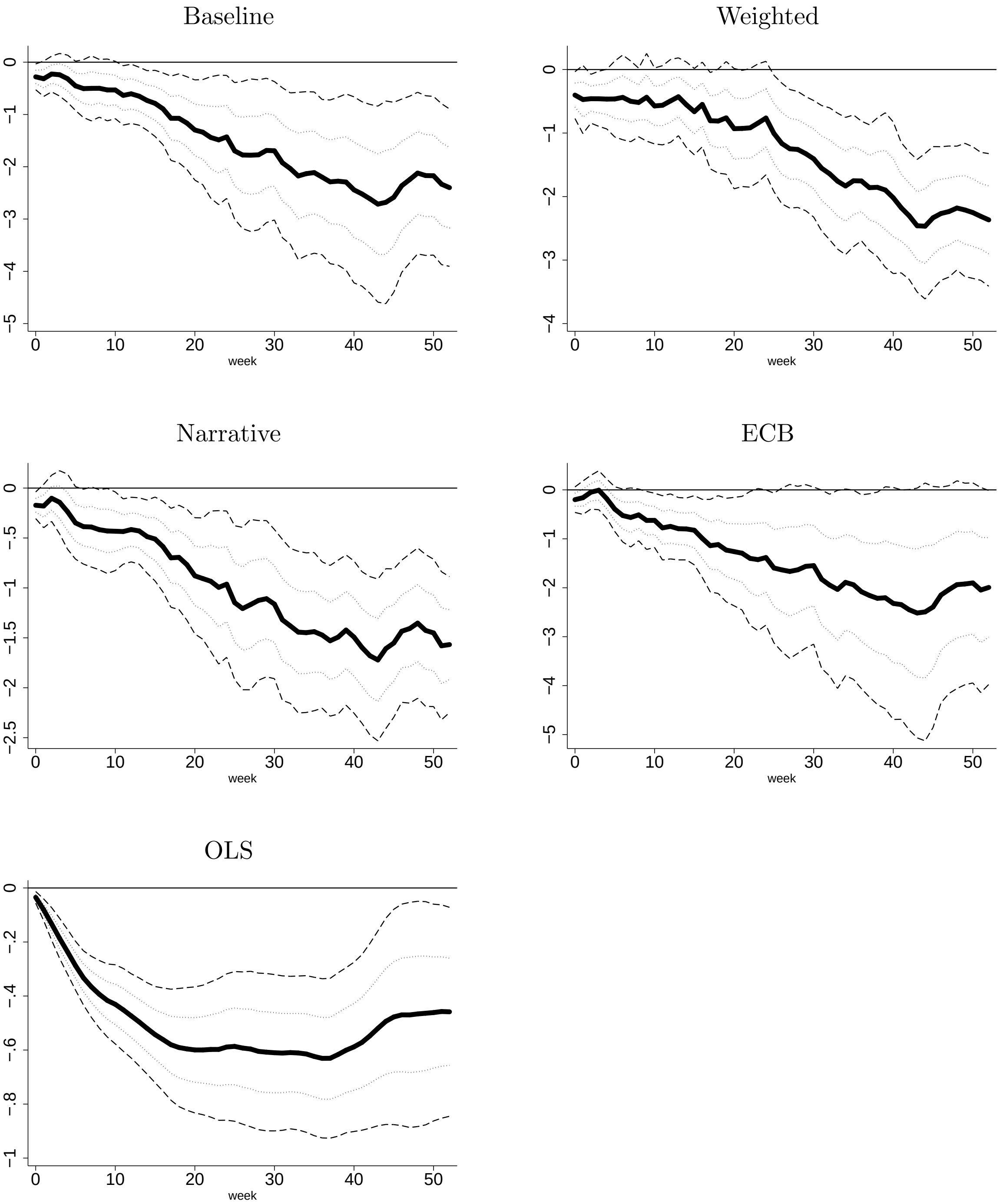
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 24: Weekly—$(BS_{t+4} - BS_t)$—All controls



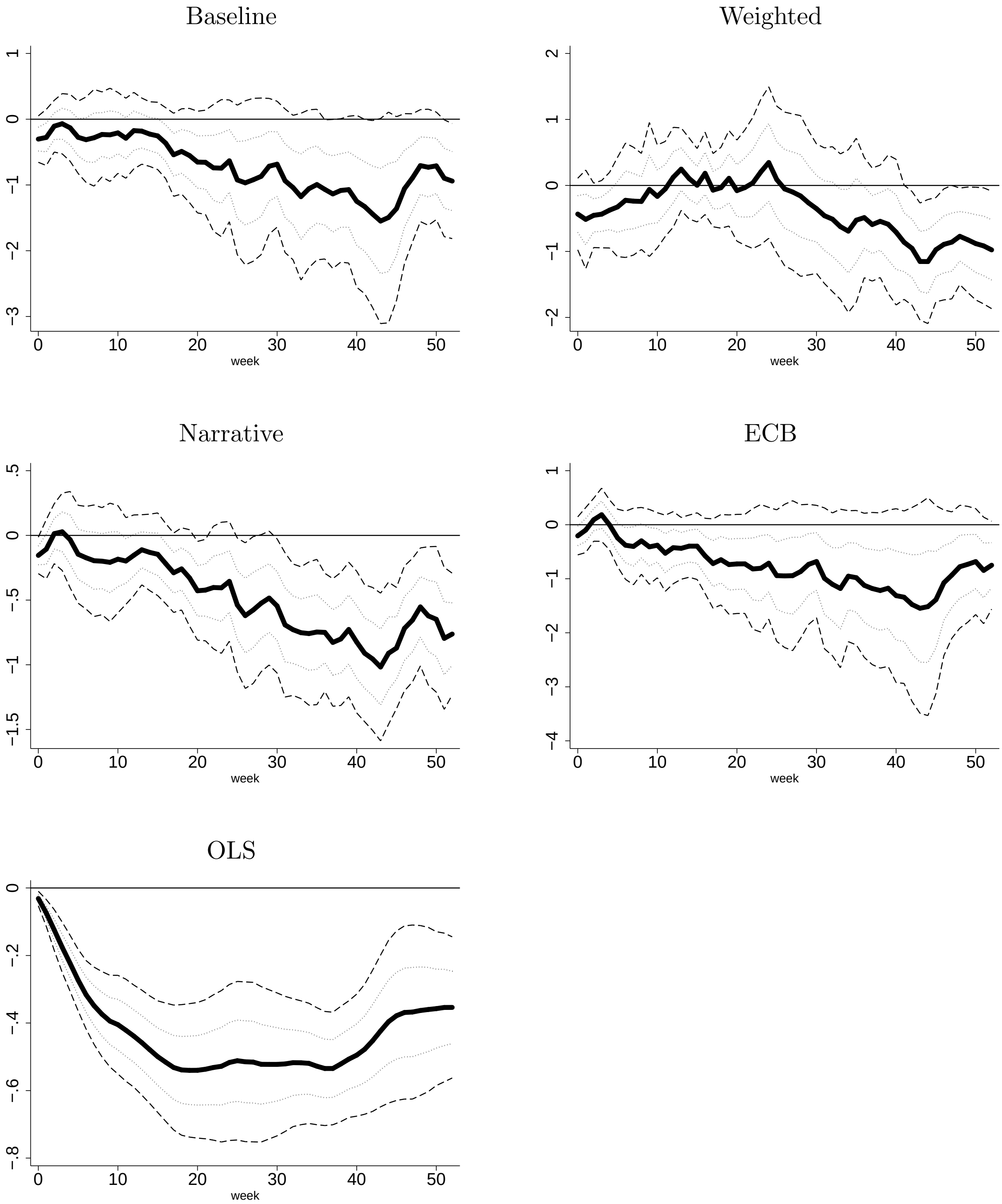
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 25: Weekly—$(BS_{t+8} - BS_t)$



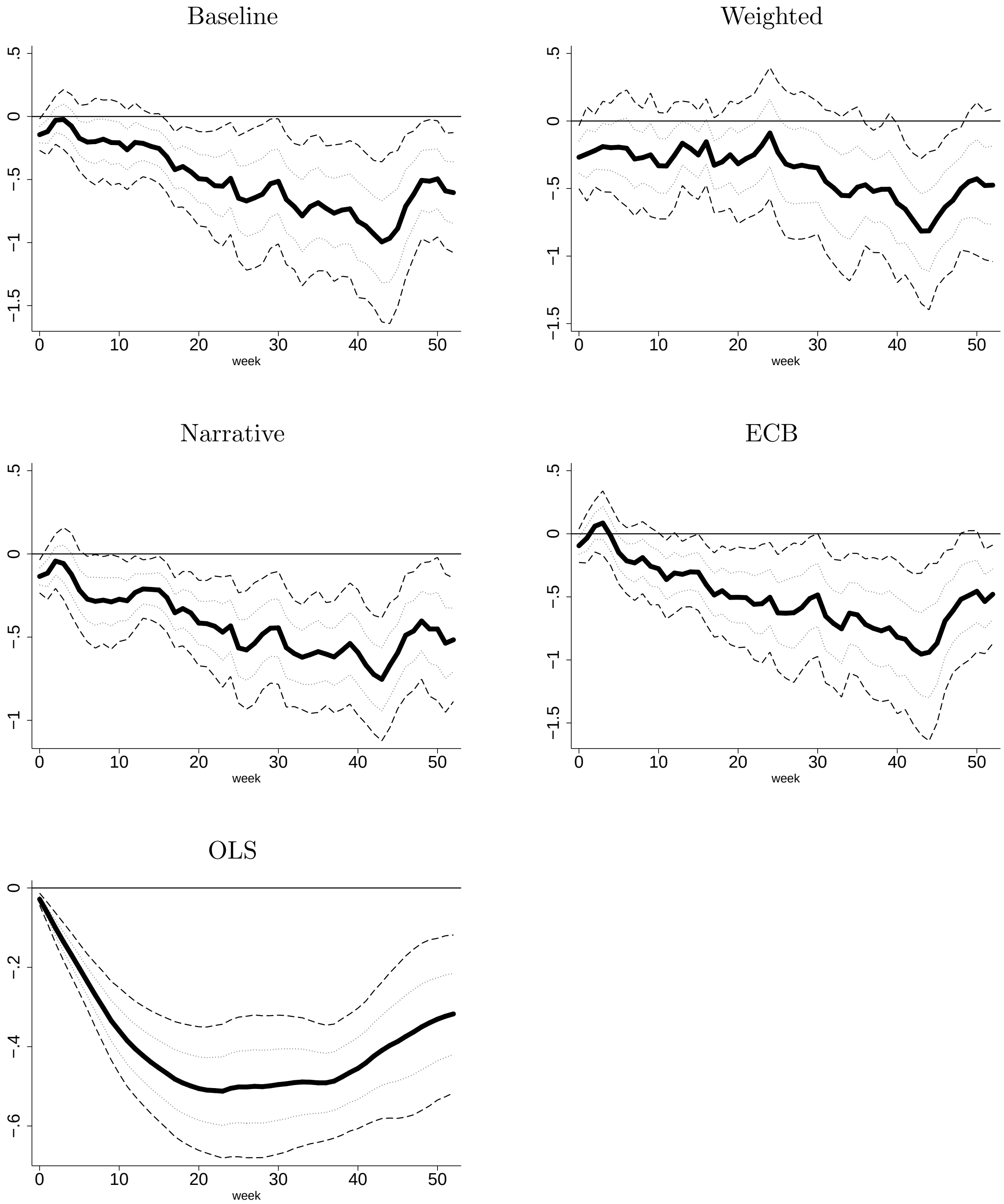
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 26: Weekly—$(BS_{t+8} - BS_t)$—All controls



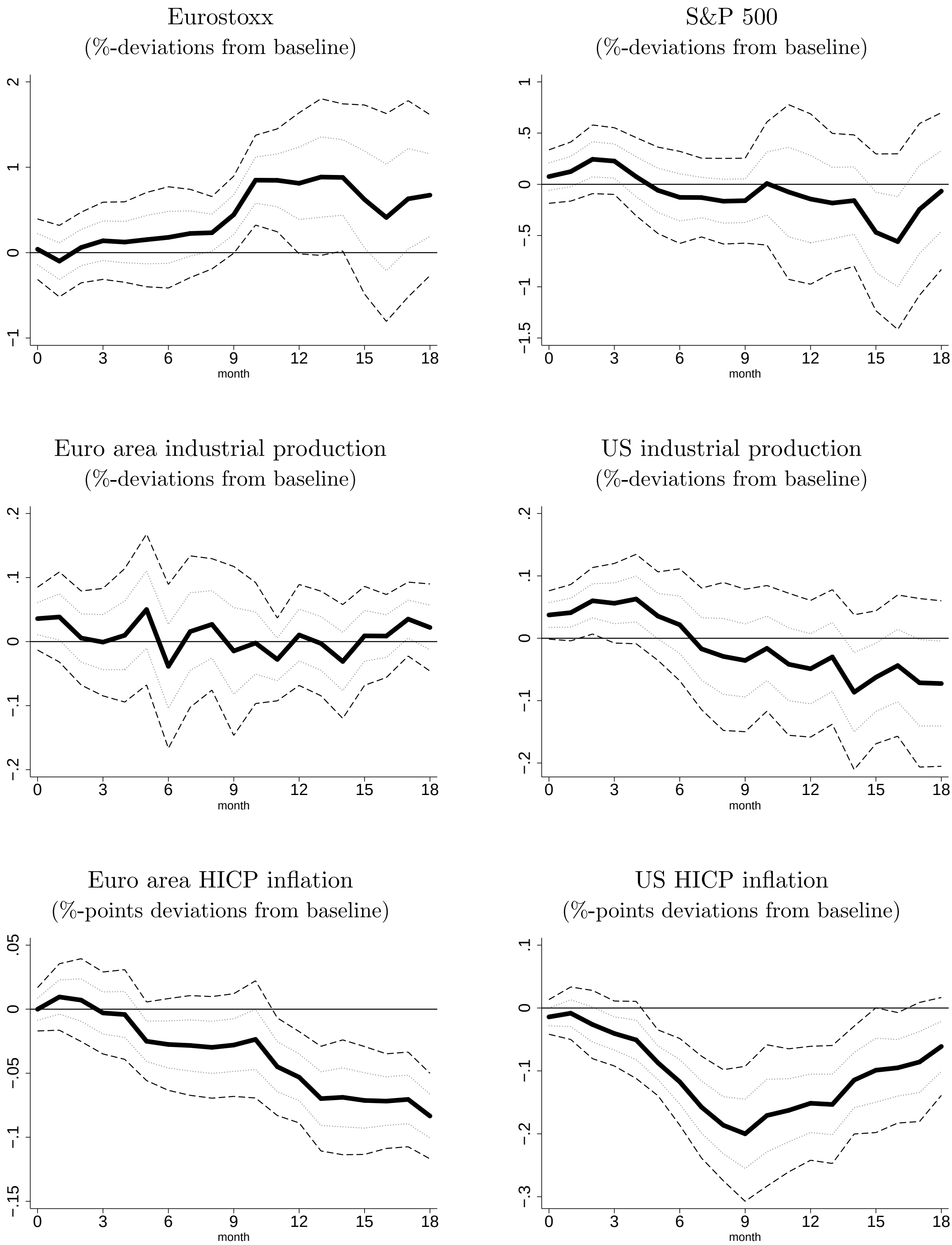
Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 27: Weekly—$(BS_{t+12} - BS_t)$—All controls



Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.

Figure 28: Other financial and macroeconomics variables



Notes: The panels show the responses to a QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point.