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The time-varying degree of inflation expectations anchoring

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The Time-Varying Degree of Inflation Expectations Anchoring

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The Time-Varying Degree of Inflation Expectations Anchoring

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Well-anchored inflation expectations have become a key indicator for the credibility of a central bank's inflation target. Since the outbreak of the recent financial crisis, the existence and the degree of de-anchoring of U.S. inflation expectations have been under debate. This paper introduces an encompassing time-varying parameter model to analyze the changing degree of U.S. inflation expectations anchoring. We confirm that inflation expectations have been partially de-anchored during the financial crisis. Yet, our results suggest that inflation expectations have been successfully re-anchored ever since.

Keywords: Anchoring of Inflation Expectations, Financial Crisis, Break-Even Inflation Rates, Time-Varying Parameter

JEL classification: E31, E52, E58, C22

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1. Introduction

Inflation expectations have become a major source of information about the credibility of a central bank and the appropriateness of its monetary policy stance. Anchoring inflation expectations at a level compatible with the central bank's inflation target is of particular importance. Central banks increasingly justify and explain their policy decisions based on the need to maintain well-anchored inflation expectations. Since the outbreak of the recent financial crisis, the (de-)anchoring of U.S. inflation expectations has been under debate. Empirical results range from perfect anchoring with no crisis-effect, to a severe and persistent crisis-driven de-anchoring. The aim of the current paper is to reconcile the mixed evidence and to shed new light on the time-varying degree of anchorage of U.S. inflation expectations.

The empirical literature on the anchoring of inflation expectations is divided into two groups. The first strand of literature focuses on the level and the dynamics of inflation and inflation expectations. If deviations from the inflation target are small and short-lived, inflation expectations are seen as well-anchored, see e.g. Mehrotra and Yetman (2014) and Strohsal and Winkelmann (2015). Specifically, when inflation expectations are well-anchored, the expectations should not depend on observed rates of inflation but only on the inflation target. According to Bomfim and Rudebusch (2000), a significant impact of inflation on long-term inflation expectations would indicate a lack of credibility and a de-anchoring of expectations. Demertzis et al. (2012) conclude that U.S. long-term inflation expectations have been well-anchored in recent years,

including the financial crisis, because they find that inflation expectations were not significantly affected by lagged rates of inflation.

Transitory economic developments with no implications for the long run may affect *short-term* but should not have any impact on well-anchored *long-term* inflation expectations. Therefore, a second strand of literature investigates how long-term inflation expectations respond to macroeconomic news (Beechey and Wright, 2009, Gürkaynak et al., 2010a, Beechey et al., 2011) and short-term inflation expectations (Jochmann et al., 2010). For the Euro area, Ehrmann et al. (2011) show that the introduction of the Euro led to a substantial increase in the anchoring of long-term inflation expectations in the pre-crisis period, particularly in Italy and Spain. For the U.S., more recent contributions focusing on the effect of macroeconomic news suggest a de-anchoring of expectations since the outbreak of the financial crisis, see Galati et al. (2011) and Autrup and Grothe (2014). According to the results of multiple endogenous break tests provided by Nautz and Strohsal (2015), U.S. inflation expectations have not been re-anchored ever since.

In view of the contradictory results on the anchoring of U.S. inflation expectations, the current paper offers two contributions. First, so far, empirical studies have either accounted for the impact of lagged rates of inflation or for the role of news-driven short-term expectations. To the best of our knowledge, there is no paper considering both criteria jointly to assess the anchoring of inflation expectations. To avoid possibly misleading conclusions caused by ignoring an important source of de-anchoring, we combine the existing approaches to obtain a more complete picture of the determinants of long-term inflation expectations.

Second, there is clear evidence that the degree of anchorage changes over time. Yet, irrespective of the strand of literature, empirical studies tend to assume an intrinsically constant degree of inflation expectations anchoring. Typically, the degree of anchorage is only allowed to have a sudden change in response to a regime shift. Jumps in the degree of anchorage are, however, not always a plausible description of monetary policy and of the dynamics of inflation expectations. In many situations, it seems more realistic to assume that the de- and re-anchoring of inflation expectations is continuously evolving. Note that constant parameter models with regime shifts can both under- and overestimate the empirical relevance of de-anchored inflation expectations. Suppose, for example, there is a brief but probably disconcerting period of de-anchoring. In this case, a constant parameter model with endogenous regime shifts would either ignore the threat of de-anchoring completely if the critical period is too short to be detected, or if the de-anchoring is sufficiently strong the model will produce an extended period of de-anchoring that exaggerates the problem. Therefore, in line with Demertzis et al. (2012), our empirical analysis is based on a time-varying parameter model of inflation expectations.

Our results confirm that U.S. long-term inflation expectations have been almost perfectly anchored since 2004. The only exception is the end of 2008 where the anchoring-parameter drops substantially below the value implied by perfect anchoring. This explains why constant parameter models with endogenous breaks tend to produce evidence in favor of an extended de-anchoring period. Our results also clearly demonstrate that U.S. inflation ex-

pectations only respond to short-term expectations and not to lagged inflation rates. This may explain why studies that exclusively focus on the de-anchoring potential of lagged inflation rates tend to underestimate the credibility problems of monetary policy stirred by the financial crisis.

The rest of the paper is structured as follows. Section 2 discusses the determinants of inflation expectations and introduces the time-varying parameter model of expectations anchoring. The data are presented in Section 3. Section 4 shows the empirical results. Finally, Section 5 offers some concluding remarks.

2. An Empirical Model of Inflation Expectations

2.1. Determinants of Long-Term Inflation Expectations

The Inflation Target A minimum requirement for effective central bank communication is that inflation expectations are – at least to some extent – guided by the central bank’s inflation target π^* . In many countries, the announcement of inflation targets may have contributed to lower inflation rates, see Johnson (2003). However, inflation targets do not have to be officially announced to be effective. Many central banks, including the ECB and the U.S. Federal Reserve, do not publish official inflation targets (as the Bank of England does) but are nevertheless able to communicate the level of their long-term inflation objective to the markets. Over the last decades, it has become increasingly obvious that the Fed’s long-run inflation target is very much in

line with other central banks that focus on price-stability. In the following, we assume that the Fed's inflation target is constant at 2% in our sample period, i.e. from 2004 onwards.¹

The more credible the central bank's inflation target, the larger its role in expectations formation and, thus, the degree of anchorage of inflation expectations. In the limiting case of perfect anchorage, the inflation target should be the only relevant determinant of inflation expectations. In this case, any deviation of inflation from the target is seen as short-lived because markets are convinced that the central bank is able and willing to bring inflation back to target quickly. As a consequence, long-term inflation expectations π_t^e should remain particularly close to the target.

Past Inflation Unfortunately, the anchoring of inflation expectations might not always be perfect. The literature offers a number of explanations why inflation expectations may depend not only on the target for current and future inflation but also on the central bank's past inflation performance. If the credibility of the central bank's inflation target is imperfect, expectations formation incorporates learning from lagged inflation values, see e.g. Orphanides and Williams (2005). Therefore, in accordance with Bomfim and Rudebusch (2000), a significant impact of lagged inflation on long-term inflation expectations can be interpreted as lack of credibility and de-anchoring of inflation expectations.

¹Since 2012, the Fed's implicit inflation target has been clearly communicated via the publication of dot projections. In these projections, the board members report their individual views on the central tendency and range of future output growth, unemployment and inflation. Interestingly, the reported value of the long-run inflation rate is always 2%. In sharp contrast to the projections for output and employment, the long-run projection for inflation neither varies over time nor across board members.

Short-Term Inflation Expectations Movements of *short-term* inflation expectations, π_s^e , do not necessarily imply weak credibility of the central bank's target and de-anchoring of *long-term* inflation expectations. In fact, there is clear evidence that short-term inflation expectations significantly respond to economic surprises stirred by the announcement of macroeconomic variables, see Beechey et al. (2011), Autrup and Grothe (2014), Netšunajev and Winkelmann (2015) and the references therein. Well-anchored *long-term* inflation expectations, however, should not be affected by temporary shocks or transitory economic developments with no implications for the long run. A second criterion for the anchoring of inflation expectations is therefore the extent to which news-driven short-term inflation expectations feed into longer-term expectations, see Jochmann et al. (2010). If expectations are well-anchored, short-term expectations should not play a significant role in the formation of long-term inflation expectations.

2.2. (De-)Anchoring of Inflation Expectations

To obtain a more complete picture of the determinants of inflation expectations, we combine the existing approaches to analyze expectations anchoring. Building on Bomfim and Rudebusch (2000), we start with an equation where long-term inflation expectations $\pi_{l,t}^e$ are a weighted average of the inflation target π^* , lagged inflation π_{t-1} , and news-driven short-term inflation expectations $\pi_{s,t-1}^e$:

$$\pi_{l,t}^e = (1 - \theta_1 - \theta_2)\pi^* + \theta_1\pi_{t-1} + \theta_2\pi_{s,t-1}^e . \quad (1)$$

When $\theta_2 = 0$, short-term expectations play no role and inflation expectations only depend on the inflation target and lagged inflation. When $\theta_1 = 0$, the impact of lagged inflation on the formation of long-term expectations can be ignored. Note that inflation expectations are *perfectly anchored* if $\theta_1 = \theta_2 = 0$ which implies that $\pi_{l,t}^e = \pi^*$. Since we are particularly interested in the dynamics of inflation anchoring, we re-arrange the static level relation by subtracting $\pi_{l,t}^e$ from both sides of equation (1) to obtain a dynamic adjustment equation of long-term inflation expectations:

$$\Delta\pi_{l,t}^e = (1 - \theta_1 - \theta_2)(\pi^* - \pi_{l,t-1}^e) + \theta_1(\pi_{t-1} - \pi_{l,t-1}^e) + \theta_2(\pi_{s,t-1}^e - \pi_{l,t-1}^e) . \quad (2)$$

This equation is easy to interpret and a straightforward generalization of the existing approaches employed in the empirical literature on inflation expectations anchoring. De-anchored long-term inflation expectations may follow actual inflation ($\theta_1 > 0$), or news-driven short-term inflation expectations ($\theta_2 > 0$). Put differently, the overall degree of anchoring and the speed of adjustment of long-term expectations to the target ($1 - \theta_1 - \theta_2$) is greater when the total impact of both sources of de-anchoring ($\theta_1 + \theta_2$) is small. Estimating the adjustment coefficients θ_1 and θ_2 reveals the relative importance of the sources of de-anchoring. Note that $1 - \theta_1 - \theta_2$ can be interpreted as the *degree of anchorage* of inflation expectations.

2.3. Assessing the (De-)Anchoring of Inflation Expectations

Across Time

Central bank credibility can be gained, but it also can be lost. As a consequence, the degree of inflation expectations anchoring might not be constant over time. The history of inflation in the U.S. clearly suggests that the degree of anchorage was lower during the *Great Inflation* of the sixties and seventies, than during the *Great Moderation* that ended with the outbreak of the recent financial crisis. The impact of the financial crisis and related monetary policy on the degree of anchorage is, however, less obvious. So far, the standard approach of the empirical literature to account for time-varying anchoring is simply to split the sample and to estimate a separate constant parameter model for each of the sub-samples, see e.g. Galati et al. (2011) and Autrup and Grothe (2014). Nautz and Strohsal (2015) employ multiple endogenous break point tests to demonstrate that U.S. long-term inflation expectations respond to news and were, therefore, de-anchored by the crisis. Since there is no second break detected, they conclude that expectations have not been re-anchored ever since.

However, estimating the time-varying degree of inflation expectations anchoring using regime-dependent constant parameter models is not without problems. First, constant parameter models with regime-shifts assume that the intrinsically constant degree of anchorage suddenly changes to a new value. However, regaining central bank credibility and re-anchoring inflation expectations might be a long and painful process where the degree of anchorage

rises continuously over time. Particular in turbulent times, monetary policy requires a more flexible measure of expectations anchoring. Second, constant parameter models with endogenous break point tests require a minimum number of observations in each regime. For example, Nautz and Strohsal (2015) have to assume a minimum regime length of 6 months. As a consequence, this model is not designed to reveal shorter de-anchoring periods. Apparently, this inflexibility of constant parameter models may produce misleading results. Suppose, for example, the central bank responds quickly to a drop in the degree of anchorage and is able to re-anchor inflation expectations over the next few months. Although this scenario might be a realistic description of monetary policy in the aftermath of the Lehman crash, it cannot be captured by constant parameter models. In an empirical application, constant parameter models will either ignore the de-anchoring episode completely (because the risky de-anchoring period is less than 6 months) and therefore underestimate the danger of de-anchored inflation expectations, or the models will produce an extended but spurious period of de-anchoring that exaggerates the credibility problem of the central bank.

The natural solution to the above problems is a time-varying parameter (TVP) approach. Therefore, we adopt the standard TVP model representation (see Appendix A) to the constant parameter model for inflation expectations introduced in the previous section. Specifically, our empirical analysis of the time-varying degree of inflation expectations anchoring will be based on the

following model:

$$\Delta\pi_{l,t}^e = (1 - \theta_{1t} - \theta_{2t})(\pi^* - \pi_{l,t-1}^e) + \theta_{1t}(\pi_{t-1} - \pi_{l,t-1}^e) + \theta_{2t}(\pi_{s,t-1}^e - \pi_{l,t-1}^e) . \quad (3)$$

Note that the time-varying de-anchoring parameters θ_{1t} and θ_{2t} provide the information to which extent past inflation or short-term expectations are responsible for the deviation of long-term inflation expectations from the inflation target. Accordingly, the anchoring parameter, $1 - \theta_{1t} - \theta_{2t}$, is also time-varying and, multiplied by 100, may be interpreted as the percentage at which expectations are anchored in period t . Since we additionally account for de-anchoring due to short-term expectations, our measure of the degree of inflation expectations anchoring generalizes the credibility proxy introduced by Demertzis et al. (2012).

3. Data

Inflation-linked securities have become an increasingly important source of information about expected inflation. Yields of index-linked and nominal bonds with equal maturities are used to derive the break-even inflation (BEI) rate, i.e., the rate of inflation at which the payoff of the two types of bonds is equal. In contrast to quarterly or even semi-annual surveys of expected inflation, BEI rates are readily available at high frequency and are therefore particularly suitable to investigate and monitor the time-varying dynamics of inflation expectations. The degree of inflation expectations anchoring is primarily reflected in

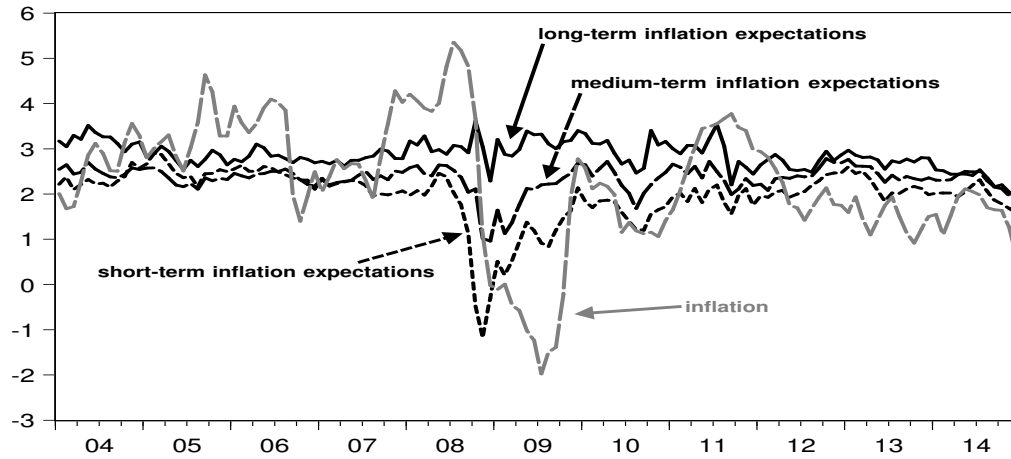
longer-term expectations. In the following, we consider one-year forward rates ending 10 and 5 years ahead, respectively, which have become standard indicators of long- and medium-term inflation expectations, see e.g. Gürkaynak et al. (2010a) and Galati et al. (2011). For short-term inflation expectations, we employ the shortest horizon available which is the one-year forward rate ending 3 years ahead.²

Constant maturity series of BEI rates are available from Federal Reserve Board staff calculations, cf. Gürkaynak et al. (2010b). Our sample covers monthly observations from 2004M1 to 2014M12. We start in 2004 to ensure availability of enough index-linked bonds to estimate real yield curves, see e.g. Gürkaynak et al. (2010b). Inflation is measured by the annual percentage change of the consumer price index. The data of expected and actual inflation are depicted in Figure 1.

The main problem of market based inflation measures is that risk and liquidity conditions may distort the pricing of nominal and inflation-linked bonds. For example, a higher trading volume in inflation-linked bonds may increase the break-even inflation rate only because it reduces the liquidity premium on inflation-linked bonds and, thereby, lowers the real yield. In line with e.g. Gürkaynak et al. (2010a), we account for this problem by including common measures of liquidity and risk as additional controls in the empirical version of equation (3). These measures include the relative trading volume of inflation-indexed bonds with respect to the total trading volume of

²An alternative candidate for short-term expectations is the two-year spot rate. Note, however, that our main results do not depend on that choice.

Figure 1 Forward Break-Even Inflation Rates and Actual Inflation



Notes: The figure shows the yearly inflation rate (dashed gray line), long-term inflation expectations measured as 1-year break-even forward rate ending in 10 years (solid black line), medium-term inflation expectations measured as 1-year break-even forward rate ending in 5 years (dashed black line) and short-term inflation expectations measured as 1-year break-even forward rate ending in 3 years (dotted black line).

nominal and real bonds which is taken from the Federal Reserve Bank of New York. The CBOE stock option price volatility index, VIX, and Moody's AAA corporate bond spread can be obtained from the Federal Reserve Bank of St. Louis. We also included the policy uncertainty index provided by <http://policyuncertainty.com>.

4. What Drives Inflation Expectations?

4.1. Inflation Expectations Anchoring: Results from a Constant Parameter Model

In a first step, we assume that the degree of inflation expectations anchoring is constant during the sample period, i.e. from 2004 until the end of 2014. Table 1 summarizes the estimation results for the constant parameter model (2) governing the formation of long- and medium-term inflation expectations. The estimated coefficient corresponding to lagged inflation (θ_1) is economically small and far from being significant for both expectations horizons. In accordance with Demertzis et al. (2012), this shows that lagged inflation rates have not been a significant source of de-anchoring for U.S. long-term inflation expectations.

However, this is not the whole story. In particular, irrespective of the expectation horizon, the estimated coefficient of short-term expectations (θ_2) is statistically significant and plausibly signed. Accordingly, the constant parameter model provides evidence against perfectly anchored inflation expectations. The model suggests that the degree of anchorage has been 79% for long-term and about 64% for medium-term inflation expectations in each month from 2004 onwards. Thus, as expected, medium-term expectations are less anchored than longer-term expectations. This is also reflected in the test for joint significance of θ_1 and θ_2 , see Table 1.

Table 1 Constant Parameter Model: The (De-)Anchoring of U.S. Inflation Expectations

expectations horizon	past inflation θ_1	short-term inflation expectations θ_2	joint test $\theta_1 = \theta_2 = 0$
10 years	-0.020 (0.489)	0.208 (0.039)	2.390 (0.096)
5 years	-0.003 (0.900)	0.357 (0.000)	19.640 (0.000)

Notes: The table shows the estimation results from the empirical version of equation (2) over the sample 2004M01 - 2014M12. Significance tests are based on Newey-West heteroskedasticity and autocorrelation consistent standard errors with automatic bandwidth selection. Values in parentheses below coefficients are p -values. The joint test has the null hypothesis that the effects of past inflation and short-term inflation expectations are both zero. Regressions include control variables for risk and a constant term.

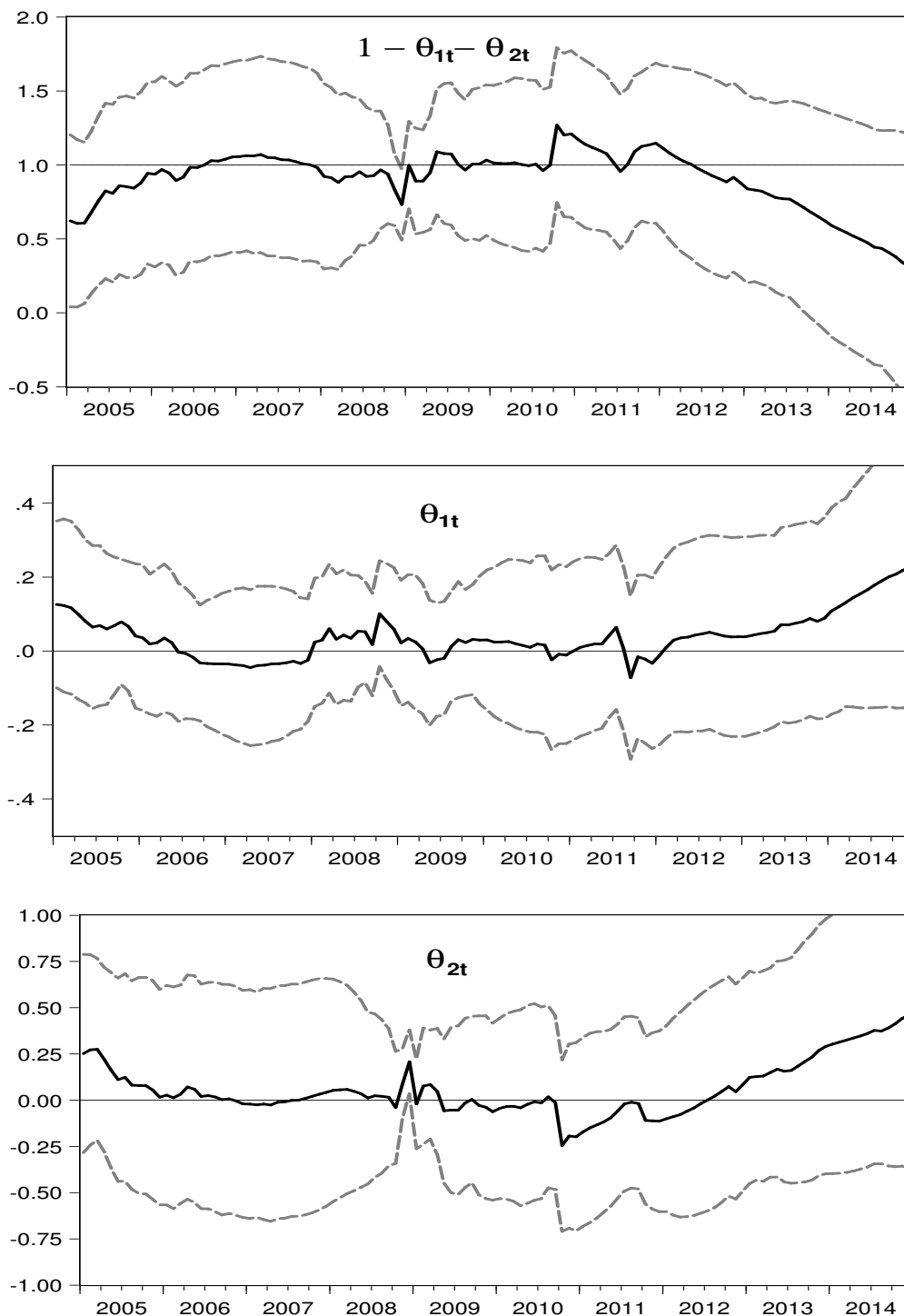
The assumption of a time-invariant degree of inflation expectations anchoring is hard to defend, particularly in view of the increased uncertainty during the financial crisis. In the next section, we therefore estimate the time-varying-parameter version of the inflation expectations adjustment equation.

4.2. Inflation Expectations Anchoring: Results from a Time-Varying Parameter Model

Let us now turn to the time-varying parameter model (3) of inflation expectations anchoring. We estimate the model by maximum likelihood using the Kalman filter. The state space form of the model and the complete set of results are given in Appendix A.

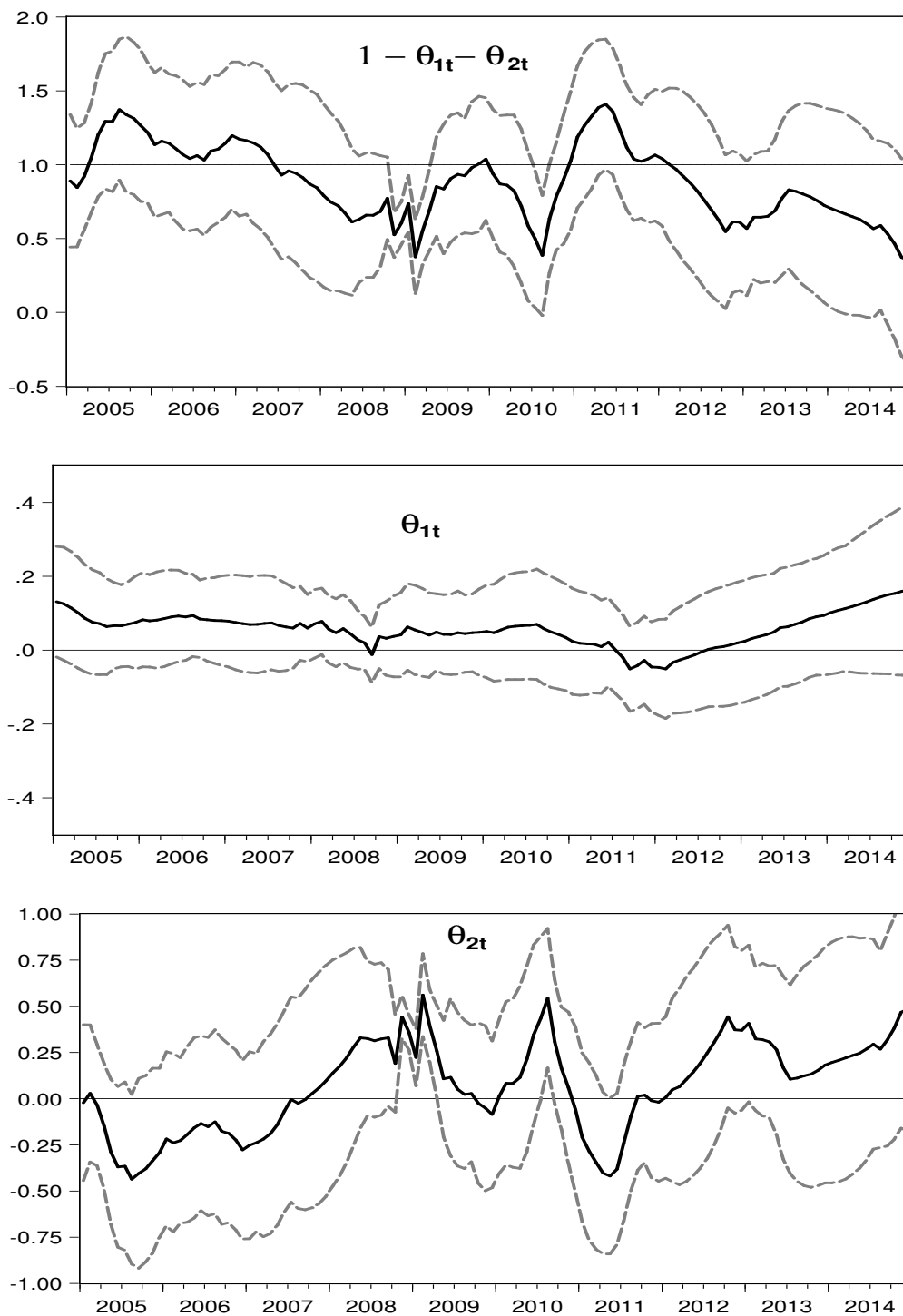
Figure 2 and Figure 3 report the (smoothed) estimates of the time-varying (de-)anchoring parameters θ_{1t} , θ_{2t} , and $1 - \theta_{1t} - \theta_{2t}$ obtained for long- and medium-term inflation expectations, respectively. For long-term expectations, the time-varying estimates of the anchoring-parameter, $1 - \theta_{1t} - \theta_{2t}$, are almost never significantly different from one. As a result, the hypothesis of perfect expectations anchoring cannot be rejected by the data. In fact, the estimated average degree of anchorage is 95% which is very close to perfect anchoring. The only exception is December 2008 where the anchoring-parameter is significantly below one (73%) implying that anchoring was imperfect (but nevertheless well above zero) shortly after the Lehman breakdown. The middle and lower part of Figure 2 reveal the sources of that brief period of de-anchoring. In line with our results obtained for the constant parameter model, the only significant source of de-anchored long-term inflation expectations are movements of short-term inflation expectations. The corresponding estimate θ_{2t} is significantly greater than zero exactly in December 2008. By contrast, the results obtained for θ_{1t} demonstrate that long-term inflation expectations have never responded significantly to lagged inflation. Another noteworthy result is visible at the very end of our sample period. Note that there is a disconcerting (but statistically insignificant) decline in the anchoring-parameter from 2013 onwards.

Figure 2 Anchoring-Percentage and De-Anchoring Sources of 10-Year Inflation Expectations



Notes: The figure refers to 10-year inflation expectations and shows the estimated anchoring parameter $1 - \theta_{1t} - \theta_{2t}$ (top figure), the adjustment to past inflation θ_{1t} (middle figure) and the adjustment to short-term inflation expectations θ_{2t} (bottom figure) as solid black lines and the 95% confidence interval as dashed gray lines; cf. model (3).

Figure 3 Anchoring-Percentage and De-Anchoring Sources of 5-Year Inflation Expectations



Notes: The figure refers to 5-year inflation expectations and shows the estimated anchoring parameter $1 - \theta_{1t} - \theta_{2t}$ (top figure), the adjustment to past inflation θ_{1t} (middle figure) and the adjustment to short-term inflation expectations θ_{2t} (bottom figure) as solid black lines and the 95% confidence interval as dashed gray lines; cf. model (3).

In line with the literature, the time-varying parameter model confirms that medium-term inflation expectations are typically less anchored than long-term expectations. On the one hand, as can be seen from Table 2, the average anchoring-parameter is only 87%. On the other hand, Figure 3 shows that

Table 2 Time-Varying degree of anchorage of U.S. Inflation Expectations

expectations horizon	de-anchoring periods	minimal anchoring percentage	response to		average degree of anchorage
			π_{t-1}	$\pi_{s,t-1}^e$	
10 years	2008M12	73% at 2008M12	no	yes	95%
5 years	2008M10 – 2009M04	38% at 2009M02	no	yes	87%
	2010M07 – 2010M09	39% at 2009M08			

Notes: De-anchoring periods represent periods where the anchoring parameter $1 - \theta_{1t} - \theta_{2t}$ in equation (3) is significantly below 1 at the 5%-level. Minimal anchoring percentage denotes the minimum point estimate of $1 - \theta_{1t} - \theta_{2t}$ and indicates the severity of de-anchoring. A response to past inflation or short-term expectations shows the source of de-anchoring. The last column includes information on the direction of the anchoring parameter towards the end of the sample. The complete set of results is given in Appendix B.

medium-term expectations experienced even two periods of de-anchoring. The first period, from 2008M10 until 2009M04, is related to the Lehman breakdown. During this relatively long period, the estimated degree of anchorage reached a minimum value of only 38%. In the second period of de-anchored medium-term expectations, running from 2010M07 until 2010M09, the degree of anchorage decreases again to 39% but recovers more quickly. Similar to the behavior of long-term expectations, there seems to be a tendency of de-anchoring for medium-term inflation expectations from 2013 onwards. Results for long- and medium-term expectations do agree with respect to the sources of de-anchoring. Both de-anchoring episodes are completely driven by

forward-looking short-term expectations and not by backward-looking lagged inflation.

Our main findings on the (de-)anchoring of U.S. inflation expectations are summarized in Table 2. The results show the benefits of a comprehensive and flexible approach to estimating the degree of expectations anchoring. Using a time-varying parameter model and considering both sources of de-anchoring jointly, our findings may reconcile the mixed evidence regarding inflation expectations anchoring in the U.S. On the one hand, the brief but nevertheless significant period of de-anchored inflation expectations stirred by the outbreak of the financial crisis confirms recent evidence on de-anchoring provided by studies relying on regressions with constant parameters, cf. Nautz and Strohsal (2015). In contrast to constant parameter models with regime-shifts, the more flexible time-varying parameter approach is able to detect that monetary policy re-anchored inflation expectations rather quickly. On the other hand, even if a time-varying model is applied, the danger of de-anchored inflation expectations can be underestimated if one of the two sources of de-anchoring is neglected, see Demertzis et al. (2012).

5. Conclusions

Long-term inflation expectations have become a key indicator for the effectiveness of monetary policy. Specifically, long-term inflation expectations should be well-anchored. That is, they should only depend on the central bank's infla-

tion target and should not be affected by (i) lagged inflation rates or (ii) movements of short-term inflation expectations. The current paper provides new evidence on the anchoring of U.S. long-term inflation expectations in the aftermath of the recent financial crisis. The contribution of this paper is twofold. First, while the literature typically restricts its attention to only one of the above criteria of de-anchoring, we account for both criteria and obtain a more complete picture of the determinants of inflation expectations. Second, building on Demertzis et al. (2012), we estimate the changing degree of anchoring using a time-varying parameter model of inflation expectations. The major advantage of this model is that it avoids the often implausible assumption of sudden regime shifts.

Our results show that U.S. long-term inflation expectations are almost perfectly anchored from 2004 onwards. This does not imply, however, that maintaining anchored inflation expectations has not been an issue. In fact, the time-varying parameter model detects a brief period at the end of 2008, where the estimated anchoring-parameter is significantly below the value implied by perfect anchoring. This remarkable finding is strong evidence that the credibility of the Federal Reserve's inflation target was challenged by the aggressive monetary policy introduced to deal with the financial crisis and the following additional rounds of quantitative easing. According to our estimates, however, the credibility of monetary policy was quickly restored, indicating that the financial crisis had no lasting effect for the anchorage of U.S. inflation expectations.

A. The TVP Model in State Space Form

For estimation purposes, we cast the time-varying parameter model for inflation expectations

$$\Delta\pi_{l,t}^e = (1 - \theta_{1t} - \theta_{2t})(\pi^* - \pi_{l,t-1}^e) + \theta_{1t}(\pi_{t-1} - \pi_{l,t-1}^e) + \theta_{2t}(\pi_{s,t-1}^e - \pi_{l,t-1}^e) + \beta X_t + u_t \quad (4)$$

$$\theta_{1t} = \theta_{1t-1} + \varepsilon_{1t} \quad (5)$$

$$\theta_{2t} = \theta_{2t-1} + \varepsilon_{2t} \quad (6)$$

$$u_t = \alpha_0 + \alpha_1 u_{t-1} + v_t \quad (7)$$

in state space form as follows

$$\Delta\pi_{l,t}^e = c_t + Z_t \Theta_t \quad (8)$$

$$\Theta_t = d + T \Theta_{t-1} + V_t \quad (9)$$

with $Z_t = (\pi_{t-1} - \pi^T \quad \pi_{s,t-1}^e - \pi^T \quad 1)$, $\Theta_t = (\theta_{1t} \quad \theta_{2t} \quad u_t)'$, $c_t = \pi^T - \pi_{l,t}^e + \beta X_t$, $d = (0 \quad 0 \quad \alpha_0)$, $T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \alpha_1 \end{pmatrix}$, $V_t = (\varepsilon_{1t} \quad \varepsilon_{2t} \quad v_t)$ and variance-covariance matrix $\Sigma = \text{Var}(V_t) = \text{diag}(\exp(\sigma_{\varepsilon_1}^2) \quad \exp(\sigma_{\varepsilon_2}^2) \quad \exp(\sigma_v^2))$.

During estimation the variances parameters are expressed in exponential form to ensure that the variances themselves are positive. We use the Kalman filter to compute the one-step ahead estimates of the means and variances of the states. The parameters γ are estimated by maximizing the Gaussian log-

likelihood

$$\ell(\gamma) = -\frac{T}{2} \ln 2\pi - \frac{1}{2} \sum_{t=1}^T \ln |F_t(\gamma)| - \frac{1}{2} \sum_{t=1}^T e_t'(\gamma) F_t(\gamma)^{-1} e_t(\gamma) \quad (10)$$

where $e_t = \Delta\pi_t^e - E(\Delta\pi_t^e | I_{t-1})$ and $F_t = \text{Var}(e_t | I_{t-1})$ are the one-step ahead forecast error and its variance. The information set I_{t-1} contains all information available up to time t .

B. Complete Set of Estimation Results

We used the optimization algorithm of Berndt et al. (1974) to evaluate the likelihood. Convergence and parameter estimates remain almost unchanged when using other algorithms. The results presented in Table 3 imply that there is significant time variation of the parameters θ_{1t} and θ_{2t} . The Q-statistics indicate that almost no autocorrelation is left in the estimated forecast errors implying that the model is flexible enough to capture the dynamics of the underlying time series sufficiently well.

Table 3 Parameter Estimates and Diagnostic Tests for the TVP Model

expectations horizon	estimated parameters				
	$\sigma_{\varepsilon_1}^2$	$\sigma_{\varepsilon_2}^2$	σ_v^2	α_0	α_1
10 years	-5.84***	-4.10***	-3.44***	0.15**	0.78***
	[0.79]	[0.54]	[0.20]	[0.07]	[0.09]
	diagnostics of forecast errors				
		Q(1)	Q(2)	Q(5)	Q(10)
		0.68	0.14	0.16	0.34

	estimated parameters				
	$\sigma_{\varepsilon_1}^2$	$\sigma_{\varepsilon_2}^2$	σ_v^2	α_0	α_1
5 years	-6.82***	-3.64***	-4.43***	0.16*	0.63***
	[0.84]	[0.34]	[0.23]	[0.10]	[0.15]
	diagnostics of forecast errors				
		Q(1)	Q(2)	Q(5)	Q(10)
		0.90	0.94	0.99	0.65

Notes: The table shows the estimated parameters for the model (4) obtained from maximizing (10). Standard errors are given in brackets. *, ** and *** indicate significance at the 10%, 5% and 1%-level, respectively. Variance parameters are in exponential form to ensure positive variances ($\exp(\sigma_{\varepsilon_1}^2)$, $\exp(\sigma_{\varepsilon_2}^2)$, $\exp(\sigma_v^2)$). Q(1), Q(2), Q(5) and Q(10) represent p -values of Q-tests for remaining autocorrelation in the standardized forecast errors.

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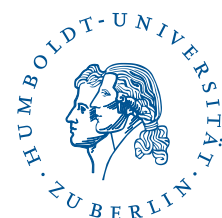
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