What Option Prices tell us about the ECB's Unconventional Monetary Policies

Stan Olijslagers, Annelie Petersen, Nander de Vette and Sweder van Wijnbergen

DeNederlandscheBank

EUROSYSTEEM

What Option Prices tell us about the ECB's Unconventional Monetary Policies

Stan Olijslagers, Annelie Petersen, Nander de Vette and Sweder van Wijnbergen *

What Option Prices tell us about the ECB's Unconventional Monetary Policies[*]

Stan Olijslagers[†]   Annelie Petersen[‡]   Nander de Vette[§]

Sweder van Wijnbergen[¶]

March 29, 2019

Abstract

We use a series of different approaches to extract information about crash risk from option prices for the Euro-Dollar exchange rate, with each step sharpening the focus on extracting more specific measures of crash risk around dates of ECB measures of Unconventional Monetary Policy. Several messages emerge from the analysis. Announcing policies in general terms without precisely describing what exactly they entail does not instantly move asset markets or actually increases crash risk. Also, policies directly focused on changing relative asset supplies do seem to have an impact, while measures aiming at easing financing costs of commercial banks do not.

JEL codes: E44, E52, E58, E65, G12, G13, G14

Key Words: Quantitative Easing, Unconventional Monetary Policies, Exchange Rate Crash Risk, risk reversals, mixed diffusion jump risk models

1 Introduction

After the Lehman bankruptcy transformed a major but manageable problem in American financial markets into a global financial crisis, central banks responded by massively providing liquidity to avoid a market collapse (Brunnermeier, 2009). Although the worldwide intervention managed to avoid a global meltdown, it could not prevent the beginning of what has turned out to become a very prolonged worldwide recession. Subsequent easing of monetary policy quickly ran into what until then had seemed a merely academic possibility, the effective lower bound (ELB) on interest rates. In response major central banks resorted to unconventional monetary policies (UMP), ranging from security market interventions to management by speech and specific measures to support distressed banks. There is a burgeoning literature on assessing the asset price impact of in particular the Fed's intervention (see for example Krishnamurty and Vissing-Jorgenson (2011)), but there is much less known about the impact of the ECB's UMP measures. And there is very little empirical evidence on the extent to which central banks succeeded in what arguably has been among their main objectives, calming the markets in the sense of reducing perceived crash risk.

Although the ECB has no formal mandate to manage or otherwise influence the Euro-Dollar exchange rate, the survival of the Euro has surely been one of its major concerns (*vide* ECB president Draghi's famous "Whatever it takes"-speech (Draghi, 2012) or Coeure (2017)). A crash of its value would have widely been seen as a precursor of the currency's eventual demise. Although there was no official targeting of the Euro-Dollar rate, policymakers surely kept the exchange rate impact in the back of their minds considering the importance of the exchange rate as one of the main transmission channels of monetary policy (Arteta, Kose, Stocker, and Taskin (2018)). We take an explicitly more limited approach than looking at exchange rate impact in general; instead we focus explicitly on the extent to which unconventional ECB policy measures and announcements have reduced crash risk in the Euro-Dollar exchange rate[1].

We can classify the large variety of UMP measures the ECB has taken into two groups. In ECB-speak, some target the ECB's *Monetary Stance (MS)* and others target the *Monetary Transmission Channel (MTC)* given the Monetary Stance[2]. The classification does not entirely fit our purpose since some measures fit in both categories. In our empirical work we employ a classification that matches the ECB terminology closely but where the categories are mutually exclusive. We distinguish measures aiming at the cost of funding of commercial banks and policies aiming at changing relative asset supplies (see Appendix A for a listing). Roughly speaking our null-hypothesis is that bank-directed measures should have no mitigating impact on crash risk and that policies aiming to change relative asset supplies should influence crash risk perceptions, hopefully in the right direction. The expected larger mitigating impact of MS-measures on perceived crash risk in the euro area stems from the broader accommodative impact on financial conditions. Hence the calming effect is expected to be larger than for measures that only aim at relieving stress for banks as linking pin between central banks and the real economy.

We use a series of different approaches to extract information about crash risk from option prices, with each step sharpening the focus on extracting specific measures of crash risk. We start by documenting changes in the skew of the empirical distribution underlying FX options derived from price data by considering so called risk reversals (see section 4.3.3 for the definition). We present both graphic and econometric analysis documenting the impact of ECB UMP measures on skewness, where we attribute a reduction of skew as triggered by a decline in crash-related tail risk. Since these summary measures based on two points from the volatility surface seem promising, we then extract the entire (risk neutral) distribution from FX derivative contracts. The underlying procedure is based on the seminal work of Breeden and Litzenberger (1978) and associated numerical procedures outlined in Malz (2014) and present direct estimates of tail risk based on those procedures. Hattori, Schrimpf, and Sushko (2016) follow a similar procedure in their analysis of the impact of the Fed's UMP measures.

Using the entire volatility smile instead of two (equal delta) implied volatilities yields sharper results by giving us a better measure of tail risk. But a disadvantage of this procedure is that the numerical interpolation procedure used to derive the density function, through its smoothness requirements and endpoint clamping, does not allow us to distinguish crash risks from the regular stochastic process driving the exchange rate in normal times. And yet that is obviously the type of crash risk Draghi had in mind in his famous "Whatever it takes"-speech(Draghi, 2012). To capture that sort of risk we take the analytical approach substantially beyond the procedures outlined in Malz (2014) and base our analysis on an explicit mixed jump-diffusion model driving the process underlying the derivative contracts analyzed and explicitly estimate the jump risk parameter from the option price data. We derive an explicit closed form solution to the resulting FX option pricing problem using the double exponential jump distribution introduced by Kou

---

[1] Even if the ECB does not officially target the exchange rate, the changing attractiveness of the euro versus the dollar is still an important consideration in the transmission of monetary policy.

[2] We thank Christiaan Pattipeilohy (DNB) for introducing the ECB-jargon.

(2002). We calibrate the resulting model by using Non-linear Least Squares estimation to fit it to option price data surrounding the events we want to analyse for changes in jump probabilities.

A number of general results emerge from the analysis. Announcing policies in general terms without precisely describing what exactly they entail does not instantly move asset markets or even moves them in the wrong direction. We find UMP announcements directly focused on changing relative asset supplies do seem to have an impact, while measures more generally aiming at easing financing costs of the commercial banks do not. Moreover, we find *MS* announcements significantly reduced crash risk by an average of 17 percent. Similarly, the perceived likelihood of a jump in the exchange rate significantly declined for most of the UMP announcements we take into consideration. However, one remarkable finding is that all our measures point to an increase in tail risk surrounding the announcement of the Securities Markets Programme (SMP).

The remainder of this paper is organized as follows. In Section 2 we provide an overview of the ECB's UMP measures. Section 3 reviews related literature while Section 4 covers data and gives some useful definitions. Section 5 deals with methodology. There we first describe the event window regressions used in the first part of our analysis; we then present the analytical solution to the mixed diffusion-jump process option pricing model and explain the estimation procedures used to calibrate the model and test for event related changes in its parameters (i.e. the methods used to estimate changes in crash risk probabilities). The results are presented and discussed in section 6. Finally, section 7 concludes.

2 Unconventional Monetary Policy Measures by the ECB

Since the eruption of the global financial crisis in 2007, central banks of hard-hit advanced economies dropped policy rates towards an effective effective lower bound until they could meaningfully ease no further using the policy rate instrument. However, market stress still remained high, whilst the main policy transmission tools had been exhausted. When the crisis progressed and intensified, special instruments and facilities were introduced for refinancing both banks and sovereigns under severe stress (Falagiarda & Reitz, 2015). Early on in the crisis the ECB undertook steps in order to support the interbank money market in the euro area, among which:

i. Unrestricted liquidity provision through Fixed Rate Tenders with Full Allotment (FRFA), which allowed banks to get unlimited access to central bank liquidity at the main refinancing rate, contingent on proper collateral.

ii. Extension of the list of acceptable collateral assets for refinancing operations. (COLL)

iii. Extension of the maturity of Long-Term Refinancing Operations (LTRO) in order to remove uncertainty and enhance liquidity operations for banks.

In May 2009 the ECB extended its operations to the covered bond market. The first Covered Bond Purchase Programme (CBPP1) involved the outright purchase of covered bonds and was complemented in November 2011 by CBPP2. In December 2011, the ECB decided to complement the Eurosystem's regular open market operations by announcing two longer-term refinancing operations, also known as the Main Refinancing Operations (MRO), which mainly served to both steer short-term interest rates and signal the monetary policy stance, along with the management of liquidity (ECB, 2016). Banks hereby obtained full allotment loans against a variety of collateral, with a collateral-specific haircut schedule. Later on in the crisis the Governing Council announced the Securities Market Programme (SMP) which involved the direct purchase of unspecified amounts of euro area sovereign debt of distressed countries. While the SMP announcement stated that purchases might include both private and sovereign debt, only the latter

were purchased. SMP operations have been carried out in two big waves. During the first phase (May 2010–April 2011) the program consisted of purchases of Greek, Irish and Portuguese debt. The second wave covered the period from August 2011 until February 2012 after market perceptions concerning the creditworthiness of Italy and Spain deteriorated. In September 2012, the ECB discontinued the SMP and substituted it by the Outright Monetary Transactions (OMT) program whereby the ECB would intervene for unspecified and unrestrained amounts in secondary sovereign-bond markets if the Governing Council would consider that redenomination risk was impairing Monetary Transmission to an unacceptable degree. The countries affected would have to agree to an economic reform programme (conditionality principle) as a necessary precondition for an OMT intervention. The OMT has never been tested but was introduced with great publicity by ECB president Mario Draghi in his speech with the by now famous line:

> *"Within our mandate, the ECB is ready to do whatever it takes to preserve the euro. And believe me, it will be enough."* (Draghi, 2012)

In a way the OMT was communication without intervention, contrary to the SMP, which mainly entailed intervention with little transparent communication. In July 2013 the ECB embraced forward guidance (FWG) as a new monetary communication strategy order to avoid surprises that might disrupt financial markets. When all this was deemed insufficient, the ECB announced additional measures in the form of a Credit Easing Package (CEP) based on two pillars:

i. A series of targeted longer-term refinancing operations (TLTRO) designed to enhance bank lending to the non-financial private sector of the euro area;

ii. Outright purchases of asset-backed securities (ABSPP) in parallel with a new covered bond purchase programme (CBPP3).

Against the threat of deflation, the ECB adopted in January 2015 the Asset Purchase Programme (APP), which complemented the private sector programmes (CBPP3 and ABSPP) by a purchase programme for public sector securities (PSPP). In particular, under the PSPP the ECB purchased sovereign bonds of euro area countries based on their respective share in the capital key to restore the transmission mechanism of monetary policy and curb soaring risk premia. In June 2016 the Eurosystem started to buy corporate sector bonds under the corporate sector purchase programme (CSPP) which aimed at further strengthening the pass-through of the Eurosystem's asset purchases to financing conditions of the real economy.

Even before the start of the APP, the Governing Council decided to cut the interest rate on the deposit facility with 10 basis points (bps) into negative territory for the first time in history. Every policy rate cut hereafter contained 10 bps as opposed to earlier policy rate decisions which entailed steps of 25 bps. The lowering of the deposit facility rate stopped at the level of -0.4%. A glossary of all program abbreviations is given in Appendix A.

3   Related Literature

Since the ECB embraced these unconventional monetary policy (UMP) actions, there has been a growing body of empirical literature to analyse its transmission mechanisms. The focus has been on four different channels: the exchange rate channel, signaling, portfolio-rebalancing and market functioning (De Pooter, Rebecca, Martin, & Pruitt, 2015; Falagiarda & Reitz, 2015; Hattori et al., 2016):

I. The exchange rate channel is assumed to be one of the main transmission channels within the euro area (Georgiadis & Gräb, 2016). The exchange rate is one of the intermediate policy variables through which monetary policy is transmitted to the larger economy. Lower interest rates as a result of asset purchase programs weaken the domestic currency (i.e. depreciating euro) which in turn makes euro area exports cheaper to foreign buyers, thereby inducing higher competition in domestic markets. The increased demand from foreign buyers leads ceteris-paribus to upward price pressures.

II. Via the signaling channel central bank announcements can signal commitment to monetary stimulus, which will lower the expected path of future short-term rates. Through this channel the central bank enhances the credibility of policy rates staying low for long. This channel is closely related to the forward guidance communication strategies, particularly through the ECB's earlier communicated commitment of "keeping key interest rates to remain at their present levels for an extended period of time, and well past the horizon of our net asset purchases". This channel emphasizes the role of private agents' expectations of future economic conditions and policy actions.

III. In the portfolio-rebalancing channel central banks influence yields by influencing the relative supplies of assets with different maturities. This channel emphasizes the imperfect substitutability among different assets (i.e. assets are not perceived as perfect substitutes by investors) and reflects a degree of market segmentation. Moreover, agents are heterogeneous and hold different portfolios. Consequently, purchases carried out by the central bank will entail a rebalancing of investors' portfolios. Investors with preferences for certain bonds with specific maturities or safety characteristics (i.e. preferred habitat investors) switch to close substitutes of the purchased securities.

IV. Another important channel of UMP is the liquidity premia channel, also referred to as the market functioning channel. In times of financial panic, markets usually are characterized by poor liquidity which means investors demand a higher risk premia. The presence of a central bank acting as a protagonist in financial markets could substantially enhance market liquidity which therefore leads to lower risk premiums. This new role of the central bank might make investors more willing to behave actively in markets, knowing that they can sell the financial products to the monetary authority if necessary.

Clearly transmission channels are not mutually exclusive and can work in parallel (Fratzscher, Duca, & Straub, 2014). More recent academic work has looked at the broader transmission of monetary policy to other assets and markets via their impact on risk perceptions and financial sector risk-taking (Hattori et al., 2016).

The exchange rate channel has been widely recognized as one of the main transmission channel of the APP – reinforced by negative rate policies (Arteta et al., 2018). In this study we focus on that channel and specifically on the impact of unconventional policies on perceptions of downside tail risk in Euro-Dollar options. In a way this study will test the transmission mechanism of Brunnermeier, Sannikov, et al. (2012) who suggest that central bank purchases can serve as insurance against tail events when combined with clear communication and commitment. In their model the central bank can signal its commitment to redistribute tail risk, which can have an immediate effect on market expectations and pricing of downside risks. This choice of focus also follows the views of the ECB's Mario Draghi:

"The main aim of the OMT is to remove tail risk to overcome monetary and financial fragmentation of the euro area that would stem from a redenomination risk. And we would do it in a size that would be adequate to achieve its objective." (Draghi, 2012)

4 Data and Some Definitions

4.1 Data

The data is retrieved from Bloomberg. The conventions for quoting prices in the FX options market are different from other markets. For a given maturity, Bloomberg provides the at-the-money (ATM), risk reversal (RR) and butterfly (BF) quotes for different deltas[3]. In order to apply both the Risk Neutral Probability Density Function (RNPD) and Non-linear Least Squares, we need option prices for different strike prices. These are not directly available in Bloomberg but can be calculated from the data Bloomberg provides.

There are different conventions for how to define deltas, ATM and RR. Reiswich and Wystup (2010) give a detailed summary of the different FX quoting conventions. We will briefly discuss the different conventions that are used and which ones apply to the Euro-Dollar exchange rate.

4.2 FX option pricing under Black Scholes

The pricing formula for FX options was first proposed by Garman and Kohlhagen (1983) but is closely related to the option pricing formula derived by Black and Scholes (1973)[4]. We use the following notation:

S_t = spot exchange rate at time t (€/$)
K = strike price
τ = time to maturity
$r_\$$ = domestic interest rate ($)
$r_€$ = foreign interest rate (€)
μ = drift of the spot rate
σ = volatility of the spot rate
$\Phi(.)$ = Standard normal CDF

Furthermore, the usual assumptions apply: Markets are frictionless (no transaction costs), interest rates are constant and the spot rate follows a Geometric Brownian Motion (GBM):

$$dS_t = \mu S_t dt + \sigma S_t dW_t \tag{1}$$

Then the price of a European FX call-option is given by:

$$C^{\text{BS}}(S, \tau; K, r_\$, r_€, \sigma^2) = e^{-r_€ \tau} C(S, \tau; K, r_\$ - r_€, \sigma^2) \tag{2}$$

Here $C(.)$ is the usual Black-Scholes option pricing formula. Using Put-Call parity , the price of a put option can then be derived from:

$$C^{\text{BS}}(S, \tau; K, r_\$, r_€, \sigma^2) + Ke^{-r_€ \tau} = P^{\text{BS}}(S, \tau; K, r_\$, r_€, \sigma^2) + Se^{-r_\$ \tau} \tag{3}$$

4.3 Some basic definitions

4.3.1 Delta

Let us start with the delta of an option. The delta indicates the sensitivity of the value of the option to the price of the underlying. The delta is commonly defined as the spot delta or the

---

[3]See 4.3.3 and 4.3.4 below for a definition of RR and BF.
[4]The only difference is that the foreign interest rate enters the formula when considering FX options instead of stock options.

forward delta. The spot delta is used for a hedge in the spot market whereas the forward delta is used to hedge in the forward market. Hedging in the forward market also takes interest rate risk into consideration. Therefore, the forward delta is used for longer maturities (> 1 year) or for emerging markets (since there the interest differentials are often large). In this paper we look at maturities shorter than one year and therefore we use spot deltas. Second, the delta can be either regular or premium-adjusted, depending on whether the premium is paid in domestic or foreign currency. For the Euro-Dollar pair, regular deltas are used and therefore we do not discuss the premium-adjusted deltas.

The delta of a call option can then be calculated as follows:

$$
\begin{aligned}
\delta^C &= C_s = \frac{\partial}{\partial S} C^{\text{BS}}(S, \tau; K, r_\$, r_\euro, \sigma^2) = e^{-r_\euro \tau} \Phi(d_1) \\
d_1 &= \frac{\ln(\frac{S}{K}) + (r_\$ - r_\euro + \frac{\sigma^2}{2})\tau}{\sigma\sqrt{\tau}}
\end{aligned}
\tag{4}
$$

By rewriting (4) we can obtain K as function of δ:

$$
K = S \exp((r_\$ - r_\euro + \frac{\sigma^2}{2})\tau - \sigma\sqrt{\tau}\Phi^{-1}(e^{r_\euro \tau}\delta))
\tag{5}
$$

Lastly, we can calculate the delta of a put option, δ^P, using the Put-Call delta parity:

$$
\delta^C + \delta^P = \frac{\partial}{\partial S} C^{\text{BS}}(S, \tau; K, r_\$, r_\euro, \sigma^2) + \frac{\partial}{\partial S} P^{\text{BS}}(S, \tau; K, r_\$, r_\euro, \sigma^2) = e^{-r_\euro \tau}
\tag{6}
$$

4.3.2 At-The-Money Volatility

In the FX markets, there are different ways to define ATM. ATM can be defined as: (i) an option with a strike price equal to the underlying ($S = K$), (ii) an option with strike price equal to the outright forward rate with similar time to maturity ($f = K$ with $f = Se^{(r_\euro - r_\$)\tau}$), (iii) an option with a strike price such that a straddle has zero net delta. A straddle is a combination of a long call and a long put with the same strike price and maturity. Bloomberg uses the last ATM definition. We can then derive the strike price corresponding to this definition.

First, from (4) and (6) we find that the delta of a put option equals:

$$
\delta^P = -e^{-r_\euro \tau} \Phi(-d_1)
\tag{7}
$$

Then solving $\delta^C = \delta^P$ is equivalent to solving $d_1 = 0$. This gives:

$$
K = S \exp\left((r_\$ - r_\euro + \frac{\sigma^2}{2})\tau\right)
\tag{8}
$$

4.3.3 Risk reversal

Our dataset contains the ingredients to construct risk reversals for three different deltas ($\delta = 0.1, 0.25, 0.35$). The risk reversal is defined as the difference between the out-of-the-money (OTM) call and put implied volatility's at the same δ. It measures the skewness of the implied volatility distribution. When the risk reversal is negative, the implied volatility of an OTM put option is larger than for a call option with the same δ. The risk reversal for a given δ equals:

$$
\text{RR}_\delta = \sigma_\delta^C - \sigma_\delta^P
\tag{9}
$$

In the risk reversal regressions described in the methodology in section 4.3.3 below we actually work with a normalized RR variable by normalizing RR_δ by the implicit At-The-Money (ATM) volatility:

$$RR_\delta^n = (\sigma_\delta^C - \sigma_\delta^P)/\sigma_{ATM} \tag{10}$$

4.3.4 Butterfly

Furthermore, the dataset contains butterflies for the same three deltas. The butterfly is defined as the average of the volatility of an OTM call and put option with the same delta minus the ATM volatility. It measures the convexity of the volatility smile. For a given δ, the butterfly equals:

$$\mathrm{BF}_\delta = \frac{\sigma_\delta^C + \sigma_\delta^P}{2} - \sigma_{\mathrm{ATM}} \tag{11}$$

4.3.5 Call option prices

Combining all this information, we can calculate the call option prices for seven different strikes. First, we can obtain seven (σ, K) pairs and then, using the Black Scholes formula we obtain the corresponding call option prices.

The ATM pair is straightforward. We obtain σ_{ATM} from Bloomberg and calculate the corresponding strike price from (8). For each δ, we can calculate the implied volatility for an OTM call and put option using the risk reversal and butterfly. From (9) and (11) we obtain:

$$\sigma_\delta^P = \sigma_{\mathrm{ATM}} + \mathrm{BF}_\delta - \frac{\mathrm{RR}_\delta}{2}, \qquad \sigma_\delta^C = \sigma_\delta^P + \mathrm{RR}_\delta \tag{12}$$

This gives us the implied volatilities of three OTM call options and three OTM put options. We can transform the OTM put options to in-the-money (ITM) call options. Using the Put-Call delta parity (6) we obtain the deltas that correspond to the ITM call options. Lastly, we can use (5) to calculate the strikes that match the deltas.

5 Methodology

We first discuss the procedures we used to extract the Risk Neutral Probability Distribution (RNPD) from option prices and explain the event window regression setup. In the second part of this section we give the analytical solution to the option pricing model when the underlying follows a jump-diffusion process using exponential distributions for the jump risk part; we then present the two different estimation procedures we use to specifically extract and test for (changes in) crash risk.

5.1 Part 1: Risk reversals and RNPD

5.1.1 Derivation procedure of implied distributions and RNPD-based crash risk probabilities

The RNPD is constructed using Euro-Dollar option prices from Bloomberg. The sample consists of daily data between January 2009–2018 and covers option deltas from 10 until 90, hence also covers fairly extreme market states. Breeden and Litzenberger (1978) show that the RNPD of the underlying equals the second derivative of the call price function with respect to the strike

price. For European call options at time zero the RNPD is related to the call price function in the following way: $e^{r_t \tau} \frac{\delta^2}{\delta K^2} C^{BS}(.)$

Instead of approximating the call price function directly, Shinko (1993) recommends fitting the volatility smile through the Implied Volatility (IV) points across a universe of strike prices since this procedure reduces the sensitivity of the eventual RNPD to estimation errors. However the Bloomberg data we use is not quoted in strike-volatility space, but in delta-volatility space. Therefore, in our data, the volatility surface of currency options can be seen as a function $\sigma(t, \delta, \tau)$ (the current date, delta and the time to expiry), instead of as a function of the date, strike price and time to expiry $\sigma(t, K, \tau)$. In order to derive the RNPD we need to transform the data into strike-volatility space. We eventually arrive at the RNPD by taking the following steps: First we interpolate the volatility smile in delta-volatility space. This is done by fitting a clamped cubic spline through the data points. In the next step we need the call price as a function in K-space to derive the RNPD. Therefore, the volatilities in delta space need to be transformed from delta into volatilities in strike space. After this is done we can transform the fitted smile into the call price function, from which the RNPD can be derived following Breeden and Litzenberger (1978). However, Bliss and Panigirtzoglou (2004) point out that it is not possible to map directly between the option delta and the underlying strike price of the option, since the implied volatility varies with both the strike and the delta itself. Instead one can transform any K into a corresponding δ_K using (4) with $\sigma = \sigma_{ATM}$[5]. The fitted implied volatility σ_K can then be evaluated at δ_K using the spline function $g_i(\delta)$ corresponding to the interval (i,i+1) in which δ_K falls. In the last step, the call price $C^{BS}(.)$ can be calculated using (2) and inserting both K and σ_K. The density function then follows from numerically evaluating its second derivative with respect to the strike price K[6].

5.1.2 Event window regression setup

For the first part of the analysis we examine the option implied risk reversal and the RNPD for the main ECB unconventional monetary policy announcements (SMP, OMT, PSPP, refinancing operations and negative interest rate policy (NIRP) where the deposit facility rate enters below-zero territory). We use options on the Euro-Dollar to assess whether or not the perceptions of crash risk in the exchange rate reacted on UMP announcements. The empirical analysis for the risk-reversal is similar to the event-study methodology of Hattori et al. (2016) and is based on the following regression:

$$\Delta 10\delta_t^\tau = \beta \theta_t + Citi_t + \varepsilon_t \qquad (13)$$

where $\Delta 10\delta_t^\tau$ refers to the 10δ risk reversal. Δ is the difference operator. θ_t is a dummy equaling one in the 3 days surrounding the announcement (event window) and zero otherwise[7]. The event window (T=3) is chosen because option markets – although liquid – need some time to digest new information in full. The control variables include contemporaneous macroeconomic data surprises captured by the log difference in the rescaled value of the Citigroup Economic Surprise Index. The Citigroup Index is calculated as the normalized deviation between the actual data release and the market consensus prior to the release and thus captures economic surprises that could interfere with the results.

---

[5]See Bu and Hadri (2007) for several reasons why the ATM volatility should be used instead of the implied volatilities at the different strike price points.

[6]Numerical differentiation requires using a similar procedure to obtain $C(K \pm h)$.

[7]We checked whether monetary policy announcements of the FOMC fell within ECB unconventional monetary policy announcements. Hence FOMC announcements did not pollute the results.

In the next step of the analysis, where we use explicit tail probabilities $F_t(x)$ derived from the RNPD, we use a similar regression, with the tail probability as dependent variable instead of the risk-reversal.

5.2   Part 2: Estimation procedures to extract crash risk probabilities.

5.2.1   Option pricing with jump risk

In order to apply the estimation methods for jump risk, we first need some definitions and option pricing formulas to extract crash risk probabilities if the pricing of the derivative contracts follows a jump-diffusion process.

As is well known, several assumptions of the Black-Scholes model are violated in reality. Bates (1996) proposes to use a model for FX option pricing that incorporates stochastic volatility and jump risk. The model is justified by several empirical observations.[8] First, the distribution of spot rate increments, $\ln(\frac{S_{t+\Delta}}{S_t})$, is not normally distributed, but is leptokurtic. In other words, the distribution has a higher peak and fatter tails compared to the normal distribution. Besides, volatility is not constant over time, but is time-varying. Lastly, the Black-Scholes model cannot explain the volatility smile, i.e. if the Black-Scholes assumptions would hold we would observe constant volatility over the strike prices. The volatility smile refers to the implied volatility pattern for different strike prices. Furthermore ITM and OTM options have a higher implied volatility compared to ATM options. The leptokurtic distribution and the volatility smile can be explained by both stochastic volatility and jump risk models.

In this paper we will only focus on incorporating jump risk. We do not incorporate stochastic volatility, since it turns out to be very hard to distinguish between stochastic volatility and jump risk when calibrating the implied distribution. Conceptually, it is also more interesting to look at jump risk since we are interested in whether the ECB announcements reduce the crash risk of the Euro.

Let us now assume that instead of a GBM, the spot rate follows a jump-diffusion process:

$$dS_t = \left(\mu - \lambda E(V - 1)\right)S_t dt + \sigma S_t dW_t + (V - 1)S_{t-} dN_t \tag{14}$$

Here $S_{t-} = \lim_{h \downarrow 0} S_{t-h}$, N_t is a Poisson process with arrival rate λ and V is a random variable with probability distribution function $f_V(v)$. $V - 1$ can be seen as the percentage change of the spot rate after a jump and should be bounded between $(-1, \infty)$ such that the exchange rate can never be negative.

5.2.2   The Kou model

For the jump part of the process we use the double exponential distribution introduced by Kou (2002), for a number of reasons. First, the model leads to an analytic option pricing formula. Second, the exponential distribution of the model has fat tails and is therefore often used to model tail risk. Lastly, with some additional assumptions, we are able to reduce the number of estimation parameters. This will be explained later in this section, after the pricing formula is introduced.[9]

---

[8] See Bates (1996) for an overview of the empirical literature on exchange rates, this is beyond the scope of this paper.

[9] As a robustness check, we will also perform our analysis using the Merton jump diffusion model in Appendix C.1. The Merton model also has an analytic option pricing formula. However, it has one extra degree of freedom, the jump volatility in the Merton model has to be estimated separately from the expected jump size. This makes the model more flexible and leads to better fits compared to the Kou model, but also increases the chance of overfitting. The possible overfitting of the Merton model is the main reason that we use the Kou model as main model.

Kou (2002) proposes to use a double-exponential distribution to model the jump size distribution. Define $V = e^Y$, where Y has the following probability density function (pdf): $f_Y(y) = p\eta_1 e^{-\eta_1 y}\mathbb{1}_{y \geq 0} + (1-p)\eta_2 e^{\eta_2 y}\mathbb{1}_{y<0}$, $\eta_1 > 1$, $\eta_2 > 0$. Here p is the probability of an upward jump and $1-p$ the probability of a downward jump. η_1 and η_2 are the parameters corresponding to respectively an upward and a downward jump. $E(V) = p\frac{\eta_1}{\eta_1-1} + (1-p)\frac{\eta_2}{\eta_2+1}$. Let λ^*, η_1^*, η_2^* be the risk-neutral parameters. The price of a European option becomes[10]:

$$
\begin{aligned}
& C^{\text{Kou}}(S, \tau; K, r_\$, r_\text{€}, \sigma, \lambda^*, p, \eta_1^*, \eta_2^*) = \\
& Se^{-r_\text{€}\tau}\Upsilon\Big(\ln(\frac{K}{S}), \tau; r_\$ - r_\text{€} + \frac{1}{2}\sigma^2 - \lambda^*\zeta^*, \sigma, \lambda^*(\zeta^*+1), \frac{p}{1+\zeta^*}\frac{\eta_1^*}{\eta_1^*-1}, \eta_1^*-1, \eta_2^*+1\Big) \\
& - Ke^{-r_\$\tau}\Upsilon\Big(\ln(\frac{K}{S}), \tau; r_\$ - r_\text{€} - \frac{1}{2}\sigma^2 - \lambda^*\zeta^*, \sigma, \lambda^*, p, \eta_1^*, \eta_2^*\Big)
\end{aligned}
$$

(15)

where

$$
\zeta^* = p\frac{\eta_1^*}{\eta_1^*-1} + (1-p)\frac{\eta_2^*}{\eta_2^*+1} - 1
$$

The $\Upsilon(.)$ function is defined in Kou (2002).

We make two simplifying assumptions. The first assumption is that we assume that within the Kou model, only downward jumps can take place. After all we want to know whether the ECB's UMP actions (and announcements of its future actions), managed to influence the perception of an impending Euro crisis. An upward jump has no place in such a setting. This means that we set the probability of an upward jump (p) equal to zero. This reduces the set of estimation parameters to three for the Kou model: ($\sigma, \lambda^*, \eta_2^*$).

Second, we assume that only one jump can take place during the duration of an option. It is not plausible that the Euro will crash more than once within a period of six months. This assumption makes it easier to interpret the arrival rate λ, since we can just transform it into a probability of a jump occurring within a certain time period. This translates into the option pricing formula as follows: instead of having an infinite sum within the $\Upsilon(.)$ function (Kou, 2002), we only sum up to and including $n = 1$. The probability of having no jumps remains $\exp\big(-\lambda^*\tau\big)$. The probability of one jump ($n = 1$) changes from $\exp\big(-\lambda^*\tau\big)\lambda^*\tau$ to $1 - \exp\big(-\lambda^*\tau\big)$.

5.3 Estimation

For the estimation of jump risk we want to obtain the distribution implied in the FX option prices. The parameter vector of the Kou model is defined as $\theta = [\sigma\ \lambda^*\ \eta_2^*]$. Assume we want to calibrate our parameters on a set of options with n maturities, m strike prices and T days. Then we obtain the implied parameters by minimizing the error between the theoretical price of an option and the observed market price C^*.

$$
\theta = \arg\min \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T}\omega_{i,j,t}[C^{Kou}(S_t, \tau_i, K_{i,j,t}|\theta) - C^*(S, \tau_i, K_{i,j,t})]^2
$$

(16)

$\omega_{i,j,t}$ are weights that determine the relative importance of the different observations. We want to give more liquid options a higher weight since more liquid prices are more reliable. In order to do so, we could define $\omega_{i,j,t} = \frac{1}{|bid-ask|}$, where the bid-ask spread determines the liquidity of an option. However, bid-ask spreads are not available in our case.
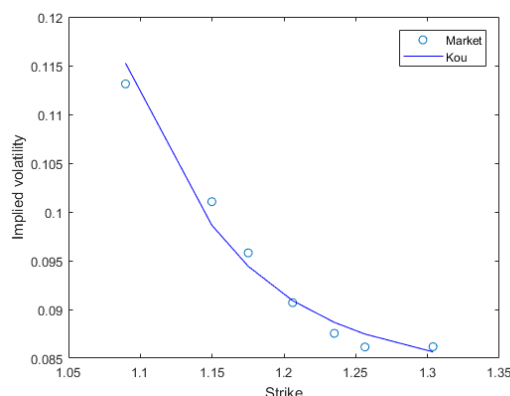
---

[10]The formula is slightly adjusted for the exchange rate option, since we have both a domestic and foreign interest rate in the option formula.

It is possible to calibrate our models using implied volatility's instead of option prices. This gives errors proportional to bid-ask spreads (Cont & Tankov, 2002). However, this requires an inversion of the Black-Scholes formula in every step of the estimation and is therefore costly in terms of computation time. Following Cont and Tankov (2002) we use that minimizing the errors using implied volatilities is approximately equal to minimizing the errors using option prices with weights equal to: $\omega_{i,j,t} = \frac{1}{Vega_{i,j,t}^2}$. Here $Vega$ equals the Black-Scholes Vega (first derivative with respect to the volatility): $Vega_{i,j,t} = S\phi(d_1)\sqrt{\tau}$ where $\phi(.)$ is the standard-normal pdf. The weights are normalized to sum up to one.

5.4 Identification problem

It turns out to be very hard to distinguish between diffusion risk and jump risk. We illustrate this identification problem using an example. The data for this example consists of seven call option prices with 6 month maturity from January 2, 2015. (16) is minimized using a solver (fmincon in Matlab) that locates the local minimum of a function[11]. The estimation yields the following parameter vector: $\theta = [\sigma \ \lambda^* \ \eta_2^*] = [0.080 \ 0.207 \ 9.97]$. Figure 1 below shows that the model can quite accurately produce the volatility smile that is observed in the market.

Figure 1: Volatility smile of the Kou model

Implied volatility smile observed in market (blue dots) and the smile generated by the calibrated Kou model.

Figure 2 is obtained by varying σ and λ after the estimation, leaving the other parameters equal to their calibrated value. It can be seen that the error function is not very convex (almost a flat line). This implies that several parameter combinations can give a good fit. The outcome of the estimation can depend on the starting point of the optimization problem. Especially the contour plot shows that there can be multiple local minima. Increasing the sample of options does not solve this problem.

To tackle the identification problem between diffusion risk and jump risk, we choose to fix the volatility σ before the estimation based on time series information from before the crisis, when perceptions of an impending crisis were small or non-existent. We can use time series data for estimation of the volatility, since the volatility is the same under the risk neutral measure (Girsanov theorem, see Shreve (2004) Ch. 5.2). If we assume that before the crisis there was no jump risk for the Euro-Dollar exchange rate, we can accurately estimate the volatility from

---

[11]Initial parameters (starting point for optimization) equal: $\theta_0 = [0.08 \ 0.5 \ 10]$.

Figure 2: Estimation errors

After the estimation, the volatility σ and jump arrival rate λ are varied to illustrate the identification problem. Left: 3D figure with the estimation errors for different values of σ and λ. Right: Contour plot with estimation errors ($*10^{-6}$).

time series data. Based on daily data from 2-1-2002 until 29-12-2006 (5 years) we estimate that the average annualized volatility equals .0922[12]. During and after the crisis, there can be additional crash risk that is priced in option prices. By fixing the volatility at the pre-crisis level, we implicitly assume that all additional risk will be jump risk. We try to extract this risk from post-crisis option prices and use the results to find out whether the ECB policy announcements have effectively reduced the risk on a crash of the Euro.

However, there is a similar identification problem between the arrival rate and the jump size. A jump distribution with twice the probability on a jump but half the jump size is very hard to distinguish from the initial distribution. Again, several distributions can accurately fit the data. Let us consider a simple example. Assume we perform an estimation before and after an event and we would like to find out whether the event has influenced the implied distribution. The estimation just before the event yields a jump probability of 10% and an expected jump size of -10%. However, there is another local minimum which has an error that is slightly larger with jump probability 5% and jump size -20%. We want to calibrate the distribution implied in option prices just before and just after the event. Now it can happen that with only a slight change in option prices, the other local minimum is selected in the estimation after the event. Then our conclusion might be that the event has a large influence on the implied distributions since the jump probability is halved and the expected jump size has doubled. However, the underlying option prices have hardly changed. To tackle this problem, we use two methods, Regularization and Joint Estimation. We discuss each in turn.

5.5 Regularization

Cont and Tankov (2002) discuss the identification problem and propose a regularization method to tackle it. Instead of solving the estimation problem in (16), they propose to solve:

$$\theta \;=\; \arg\min \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T}\omega_{i,j,t}[C^{Kou}(S_t,\tau_i,K_{i,j,t}|\theta) - C^*(S_t,\tau_i,K_{i,j,t})]^2 + \alpha H(\theta) \quad (17)$$

---

[12]Data is obtained from the ECB (`https://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=120.EXR.D.USD.EUR.SP00.A`). The estimation is based on 255 trading days per year.

where $H(\theta)$ denotes the relative entropy between a pre-specified prior model and the model with parameter θ. Relative entropy measures the distance between two probability measures; we give the formal definition of relative entropy in B. The extra penalty term makes the error function convex. α determines the relative importance between the minimization of the errors and the penalty term. The result is that the optimization outcome is not dependent anymore on the starting point of the optimization. This method gives up accuracy in order to make the estimation stable. Cont and Tankov (2002) propose a non-parametric estimation of the jump risk density, but this might also lead to over-specification and is less tractable. Therefore we apply this method to a parametric estimation. This approach can also be given an ambiguity aversion interpretation where pdf's that differ from a preferred one are incorporated in the objective function with a penalty attached (Anderson, Hansen, & Sargent, 2000).

We apply the regularization method to our problem as follows: Assume we want to find out what the effect of an ECB announcement was on the implied distribution. We first calibrate the model without regularization on data of three trading days before the event using options with one, three and six month maturities. For each maturity we have seven call prices. This gives us 63 observations per estimation (3x3x7). Then we solve (16) to find a vector of parameters.

We cannot just use the solver with any starting point, since there might be multiple local minima. In order to find the global minimum, we first use random search to find a point with the lowest error[13]. Then we use that point as starting point and use the Matlab function fmincon to find the minimum. λ^* and η_2^* should both be positive, furthermore we only look at jump sizes larger or equal to -5%. We want to capture crash risk with the jump distribution and changes of one or two percent are already captured by the diffusion part.

This gives us a vector of parameters before the event. We could do the same for the three days after the event, but then we have the problem that is described before: a small change in option prices might lead to a large change in calibrated parameters. Therefore we perform the estimation after the event using the regularization method. The estimate from before the event is used as prior distribution. Relative entropy is calculated in Appendix B.

The parameter α is chosen as follows: first we perform an unregularized estimation on data after the event and denote the estimation error by err^{unreg}. After that we perform the regularized estimation and we choose α as high as possible, but with the restriction that $err^{reg} \leq 1.25*err^{reg}$. In words, we are willing to give up at most 25% accuracy in order to find a solution closer to the prior. Our prior equals the estimation before the event. This is to make sure that a large change in implied distributions is also really caused by a large change in option prices.

We illustrate how this works by an example. After calibrating the Kou model without regularization on data around 9-12-2015 (Announcement of sixth LTRO), we obtain the following parameters: $\theta^{Kou,B} = (\lambda^*, \eta_2^*) = (0.23, 12.17)$ (Before) and $\theta^{Kou,A} = (\lambda^*, \eta_2^*) = (0.46, 18.97)$ (After). We can translate this to a jump probability and a jump size. The probability of a jump within one year, $P(Jump) = 1 - e^{-\lambda^*}$ and the expected jump size, $E(Jump) = \frac{-1}{\eta_2+1}$. Then $\theta^{Kou,B} = \left(P(Jump), E(Jump) \right) = (20.2\%, -7.6\%)$ and $\theta^{Kou,A} = \left(P(Jump), E(Jump) \right) = (36.9\%, -5.0\%)$. This looks like there has been quite an effect due to the event. However, after regularization of the estimation after the event, we find out without losing more than 25% accuracy that we can select $\theta^{Kou,A} = (\lambda^*, \eta_2^*) = (0.23, 12.17)$, or in terms of jumprisk probability and expected jumpsize: $\theta^{Kou,A} = (21\%, -7.6\%)$ which is almost identical to $\theta^{Kou,B}$. Therefore, we can conclude that the event had no large effect on the implied distributions.

---

[13]We use random search instead of grid search since random search is more efficient (Bergstra & Bengio, 2012). We use 10^5 random combinations of (λ^*, η_2^*) with values between $([0, 1], [1, 19])$.

5.6   Joint estimation

The second method we use to find out whether ECB announcements have reduced crash risk of the Euro, is joint estimation. Instead of performing an estimation on data of three days before and after an event separately, we jointly calibrate our parameters on data before and after the event. However, we allow the jump probability to vary. So we actually restrict the jump size to be the same before and after the event.

This method implies that we assume that the ECB's UMP actions can only reduce the probability of a crash, not the size. With this restriction we give up some flexibility but solve the identification problem between the arrival rate and the jump size.

Moreover, we are able to test whether there has been a significant change in jump probability. Denote by λ^{*B} and λ^{*A} the arrival rate respectively before and after the event. We test the following hypothesis:

$$H_0: \ \lambda^{*B} = \lambda^{*A} \ \ vs. \ \ H_1: \ \lambda^{*B} \neq \lambda^{*A} \tag{18}$$

In order to test the hypothesis, we specify two models. The model described above is called the unrestricted model. In the unrestricted model, the jump size is still restricted to be the same over both periods but the jump probability is unrestricted. Let $t = 1, 2, 3$ be the three trading days before the event and $t = 4, 5, 6$ the three trading days after the event. Then the weighted sum of squared residuals for the unrestricted model equals:

$$SSR^{ur} = \min_{\lambda^{*B}, \lambda^{*A}, \eta_2^*} \sum_{i=1}^{3} \sum_{j=1}^{7} \left\{ \sum_{t=1}^{3} \omega_{i,j,t} \Big[C^{Kou}\Big(S_t, \tau_i, K_{i,j,t} | (\sigma, \lambda^{*B}, \eta_2^*)\Big) \right.$$

$$\left. - C^*\Big(S_t, \tau_i, K_{i,j,t}\Big) \Big]^2 + \sum_{t=4}^{6} \omega_{i,j,t} \Big[C^{Kou}\Big(S_t, \tau_i, K_{i,j,t} | (\sigma, \lambda^{*A}, \eta_2^*)\Big) - C^*\Big(S_t, \tau_i, K_{i,j,t}\Big) \Big]^2 \right\} \tag{19}$$

with $\displaystyle \sum_{i=1}^{3} \sum_{j=1}^{7} \sum_{t=1}^{6} \omega_{i,j,t} = 1$

The restricted model represents the null hypothesis. We perform one joint estimation on the data before and after the event. The weighted sum of squared residuals of this model equals:

$$SSR^{r} = \min_{\lambda^*, \eta_2^*} \sum_{i=1}^{3} \sum_{j=1}^{7} \sum_{t=1}^{6} \omega_{i,j,t} \Big[C^{Kou}\Big(S_t, \tau_i, K_{i,j,t} | (\sigma, \lambda^*, \eta_2^*)\Big) - C^*\Big(S_t, \tau_i, K_{i,j,t}\Big) \Big]^2$$

$$\tag{20}$$

with $\displaystyle \sum_{i=1}^{3} \sum_{j=1}^{7} \sum_{t=1}^{6} \omega_{i,j,t} = 1$

Then we can test whether we can reject the null hypothesis using an F-test with the following F-statistic:

$$F = \frac{(SSR^{ur} - SSR^{r})/1}{SSR^{r}/(126 - 3)} \tag{21}$$

Here 1 is the difference in degrees of freedom between the restricted and unrestricted model, 126 is the number of observations that is used per estimation and 3 is the number of parameters of the unrestricted model. The null hypothesis is rejected if $F > 3.92$ (significance level $= 5\%$) or if $F > 6.85$ (significance level $= 1\%$).

15

6 Results

6.1 Risk reversals

6.1.1 Descriptive analysis

Table 1 lists all the UMP announcements we test in the event regression analysis, along with a short description of the event. The table shows the net change in the 10 delta option volatility over the event-window surrounding the announcement dates of unconventional policies.

Although we observe an increase in the risk reversals in most cases, the effect of the announcements on the risk reversals is far from uniform. Nonetheless there are some takeaways. For the SMP, TLTRO, CBPP, ABSPP, OMT and CSPP the initial announcements caused the risk reversal to decrease (become more negative), which can be interpreted as an increase in perceived tail risk. This can be a signal markets were underwhelmed by the announcement, or simply did not believe the programs would reduce euro break-up risk. The announcement of the PSPP LTRO and NIRP program shows increasing risk reversals, i.e. less break-up risk. Also when the full implications of the OMT were revealed we observe markets priced in lower crash risk.

The most striking observation is made in figure 3 which shows the risk measure for the 1-month horizon surrounding the announcements for the OMT program. It immediately becomes clear that Draghi's 'whatever it takes' did not deliver upon market expectations. Tail risk only slightly decreased in the run-up to the event, but increased substantially afterwards. Seemingly investors were either disappointed by the speech, or found the statement contained too little information to scale down their hedging. The finding is even more remarkable as the price of the euro against the dollar jumped by 1.1 percent after the Draghi's speech. The value of the euro (which reflects the mean price) did increase, but the increase in value did not result in lower crash risk perceptions. This view changed when Draghi announced the ECB would join forces with governments to buy sovereign debt. Figure 3 shows a jump in tail-risk in the days after Draghi's statement (also reflected by the sizeable decrease in tail-risk for these events in Table 1). Definitive relief came in September 2012, when Draghi announced more details and implications of the OMT. In the days following this announcement the risk reversal moved close to zero, signaling a nearly equal probability of the euro moving up or down.

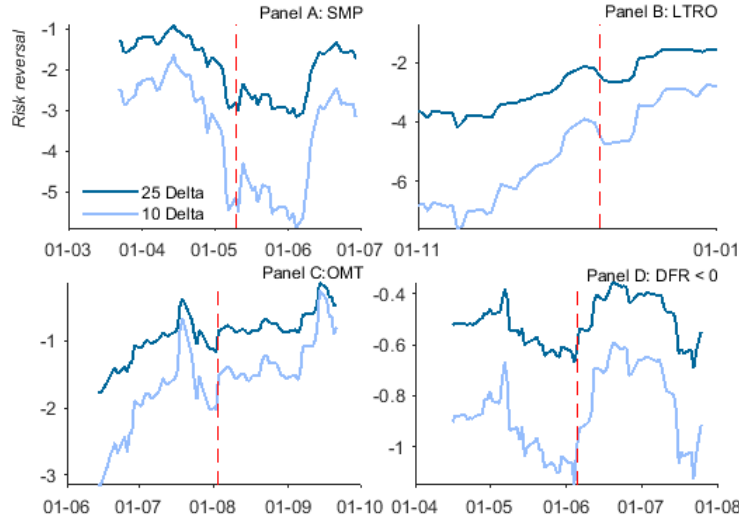Figure 3: Risk reversals surrounding the OMT program announcements
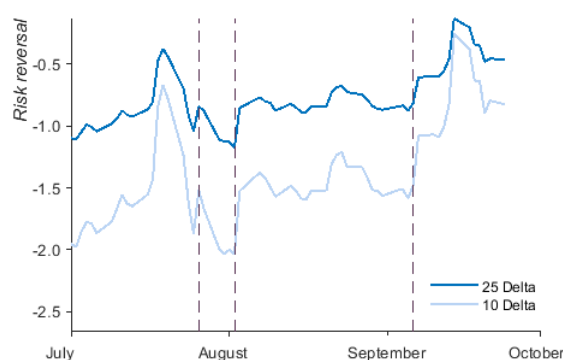
Note: Figure 3 displays the 10 and 25 delta risk reversal derived from 1-month options form July 2012 until October 2011. The dotted lines represent the announcement days (from left to right) of the first, second and third OMT announcement as defined in table 1.

Table 1: Net change in risk reversal during the event window (T=3).

Program	Date		$\Delta 10\delta RR$
SMP	9-5-2010	Launch of the SMP	-1.613
	14-5-2010	ECB publishes the SMP details	0.528
	7-8-2011	Re-launch of the SMP	-1.223
LTRO	8-12-2011	Announcement of two LTROs	-0.858
CBPP	4-6-2009	Start of the first CBPP	-1.845
	10-6-2011	Start of the Second CBPP	0.765
	4-9-2014	Start of the third CBPP	-0.243
ABSPP	10-6-2011	Start of the ABSPP	-0.785
OMT	26-7-2012	Draghi:"whatever it takes"	-0.433
	2-8-2012	Technical features of OMT	0.438
	6-9-2012	Extension of SMP and details of OMT	0.468
NIRP	5-6-2014	DFR below zero (-0.01)	0.135
	4-9-2014	DFR to -0.02	-0.243
	12-3-2015	DFR to -0.03	-0.065
	10-3-2016	DFR to -0.04	-0.098
PSPP	22-1-2015	Announcement of PSPP	0.403
	2-2-2015	Details of the PSPP	0.555
CSPP	10-3-2016	Announcement of the CSPP	-0.098
	21-4-2016	Further details on the CSPP	-0.005
TLTRO	5-6-2014	ECB decides to conduct a series of TLTROs	0.135
	16-9-2014	Announcement of the first LTRO	0.210
	9-12-2014	Announcement of the second LTRO	0.183
	17-3-2015	Announcement of the third LTRO	0.260
	16-6-2015	Announcement of the fourth LTRO	-1.255
	22-9-2015	Announcement of the fifth LTRO	-0.088
	9-12-2015	Announcement of the sixth LTRO	0.195
	22-3-2016	Announcement of the seventh LTRO	-0.628

Note: Table 1 summarizes the net changes in the crash probabilities in the event-window for all UMP announcements. The programmes throughout the paper are grouped into Monetary Transmission Channel *(MTC)* announcements (first six) and Monetary Stance *(MS)* announcements (last three). Δ reflects the net change in the risk reversal over the event-window (T-3).

Figure 4: Risk reversals surrounding key events in the sample

Figure 4 shows the development in the risk reversals over time for some of the other key ECB UMP announcements. The SMP programs caused markets to downplay tail-risk slightly, but the upward move for the SMP announcement was very short-lived. The LTRO announcement actually led to an increase in perceived crash-risk, although that increase was once again short-lived. After this short-lived uptick in perceived crash-risk, the gradual slide downwards (lower risk) continued. We already discussed the OMT, but the lower left panel shows again that announcing the details of the OMT significantly lowered perceived crash-risks, although we saw before that the announcement itself did not have such an impact. The last panel in 4 at the lower-right shows the impact of a bundle of measures announced that day: in the first of a series of announcements on the 4th of June 2014, the ECB both decided to conduct a TLTRO and announced its deposit facility rate would be lowered to -0.1 by the 11th of June. The rate was ultimately lowered to -0.4, whereby markets wondered what the ECB considered as effective lower bound. Panel D in Figure 4 shows a clear direction upwards for the risk reversals, i.e. the risk of a crash decreased substantially after the June 4 announcements.

6.1.2 Event regressions on the RR measure

Table 2 presents the results for UMP announcements on the Euro-Dollar option risk reversals for different maturities. The coefficient θ is the regression coefficient of the UMP announcement dummies on the risk measure (the change in the $10\delta RR$).

As can be expected from the data described in Table 1, we do not find any significant reduction in tail-risk perceptions for the options with a near-term maturity. The data showed a somewhat clearer direction for the initial announcements, but do not show uniform behavior in the other announcement taken into consideration. Table 2 shows there is no effect of macro economic surprises on the tail risk measure. The coefficient for the Citi Surprise index is very

small and insignificant. There is also no significant effect for all UMP announcements combined (column (1)). The coefficient of -0.002 entails that, on average, the risk reversal decreased with 20 bps, i.e. the crash risk on average actually increased, but not significantly so. An objection could be that we combine a wide variety of policy measures, not all of which had the same objective. As discussed earlier, the ECB itself distinguishes measures aimed at influencing the Monetary Stance (MS), broadly speaking measures aimed at changing relative asset supplies, from measures intended specifically to improve the Monetary Transmission Channel (MTC). Appendix A matches specific programs to one or the other objective[14]. When we make a distinction between the MTC programs – which were mainly focused on bank capital requirements and cost of funding, there is, on average, a stronger effect for the MS measures and the latter has the "right" sign, but neither is significant. This changes in a very limited way when we examine the individual announcements. The PSPP has positive and significant impact in the tail-risk perception as measured by the risk reversals. None of the other programs gets a significant coefficient. However it should be noted the risk reversal only captures the relative position of two data points on the volatility curve and therefore a shift in the risk reversal might be hard to interpret. In particular, if the increase in left-skew occurs at the same time that overall volatility declines, it actually cannot be excluded that the crash probability declined in spite of the increased skew. We therefore turn to more direct ways of measuring crash probabilities.

6.2 Tail risk measures based on the full implied distribution

Whereas the first method provides a clear and intuitive way of measuring the perception of tail risk in financial markets via risk reversals, our second – more precise – measure exploits more granular information to construct the entire option-implied densities. This second method relies on risk neutral probability distributions (RNPD) to back out asset price distributions and subsequently estimate the perceived crash likelihood (i.e. the left-tail of the distribution). The area under the RNPD is estimated for all days in the sample resulting in a daily time-series capturing the risk of a crash embedded in the options. This measure then serves as input in event study regressions later on.

6.2.1 Crash probabilities

In Table 3 we list once again all the UMP announcements that will be tested in the regression analysis, with the corresponding change in crash probabilities. The data represents the net change in the crash probability, as the probability of a crash bigger than 10% over a one-month horizon is typically very small, or even zero, we also find small reductions in crash risk. For the OMT we find confirmation on the ineffectiveness of the 'whatever it takes' speech itself or rather the total lack of reaction of the perceived likelihood of a crash at that date, but also of a strong risk reduction effect of the announcements of the technical details later on. For the first SMP announcement we again find the biggest absolute increase in crash risk (+1.942%), the second and third SMP announcement also did not manage to reduce crash-risk. This entails the perceived crash risk increased from almost zero (0.1%) to 1.980%.

To gain some intuition for the data, figure 5 plots the implied distributions around some of the events we study, i.e. the initial announcements for the SMP, LTRO, OMT and NIRP programs. The sometimes rough shape of the RNPD reflects the characteristics of the used cubic spline, on which we do not impose any shape. For most programs we find the distributions shifted downwards after the all UMP announcements except - again - for 'whatever it takes'.

---

[14]We thank Christiaan Pattipeilohy (DNB) for introducing us to the ECB views on program objectives and the associated classification in MS and MTC categories.

Table 2: UMP announcements and changes in risk reversals

	(1)$\Delta 10\delta$	(2)$\Delta 10\delta$	(3)$\Delta 10\delta$
c	-0.007	-0.0001	-0.000
	(0.048)	(0.005)	(0.001)
θ	-0.002		
	(0.215)		
θ_{MTC}		-0.0019	
		(0.0019)	
θ_{MS}		0.0034	
		(0.0028)	
SMP			-0.0057
			(0.0048)
CBPP			0.0040
			(0.0045)
OMT			-0.0018
			(0.0052)
NIRP			-0.0002
			(0.0025)
PSPP			0.0083**
			(0.0033)
CSPP			-0.0020
			(0.0018)
TLTRO			-0.0017
			(0.0028)
Citi	0.004	0.0000	0.0000
	(0.008)	(0.0001)	(0.0001)
N	2498	2498	2498

*$p < 0.05$, **$p < 0.01$; Sample: Daily January 2009 to February 2018. The dependent variable is the first difference in the risk indicator as defined in (13). θ is a 0/1 indicator for the T-days surrounding UMP announcements. The event window equals 3-days (T=3). Citi reflects the change in the European Citi Surprise Index. Hetroskedasticity and autocorrelation (HAC) robust standard errors Newey and West (1987) in the parentheses.

Table 3: Net change in crash probabilities during the event window(T=3).

Program		Date	$\Delta F(x)$ (%)
SMP	launch of the SMP	9-5-2010	1.942
	ECB publishes the SMP details	14-5-2010	0.037
	Re-launch of the SMP	7-8-2011	1.473
LTRO	Announcement of two LTROs	8-12-2011	0.299
CBPP	Start of the first CBPP	4-6-2009	0.203
	Start of the Second CBPP	6-10-2011	-2.036
	Start of the third CBPP	4-9-2014	0.000
ABSPP	Start of the ABPP	6-10-2011	1.578
OMT	Draghi:"whatever it takes"	29-7-2012	0.010
	Technical features of OMT	2-8-2012	-0.061
	Extension of SMP and details of OMT	6-9-2012	-0.114
NIRP	DFR below zero (-0,01)	5-6-2014	0.000
	DFR to -0,02	4-9-2014	0.000
	DFR to -0,03	3-12-2015	-0.383
	DFR to -0,04	10-3-2016	-0.133
PSPP	Announcement of PSPP	22-1-2015	0.104
	Details of the PSPP	2-2-2015	-0.349
CSPP	Announcement of the CSPP	10-3-2016	-0.133
	Further details on the CSPP	21-4-2016	-0.001
TLTRO	Announcement of the first TLTROs	5-6-2014	0.000
	Announcement of the second TLTRO	16-9-2014	0.000
	Announcement of the third TLTRO	9-12-2014	-0.001
	Announcement of the fourth TLTRO	17-3-2015	0.005
	Announcement of the fifth TLTRO	16-9-2014	-0.245
	Announcement of the sixth TLTRO	22-9-2015	-0.267
	Announcement of the seventh TLTRO	9-12-2015	0.026
	Announcement of the eighth TLTRO	22-3-2016	-0.007

Note: Table 3 summarizes the net changes in the RNPD crash probabilities ($\geq 10\%$) in the event-window for all UMP announcements. Δ reflects the net change in the crash-probability.

Figure 5: Option implied distributions from 1-month options
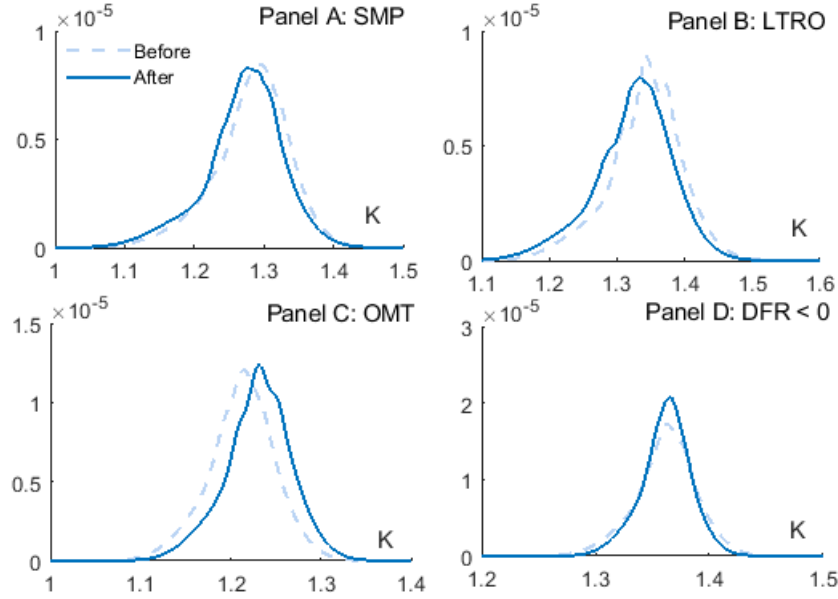
Note: Figure 5 shows risk-neutral probability densities over the event window. Panel A shows the announcement of the SMP program on 9-5-2010, Panel B shows the announcement of the first two LTRO programs on the 8th of december 2011, Panel C shows the RNPD surrounding Draghi's 'Whatever it takes' speech Draghi (2012), Panel D shows the RNPD before and after the ECB decision to lower the deposit rate facility (DFR) below zero. y-axis reflects the density in percentage points, x-axis the strike price K. RNPD derived from options with a maturity of one month.

Figure 6: Time series of a 10% and 20% crash
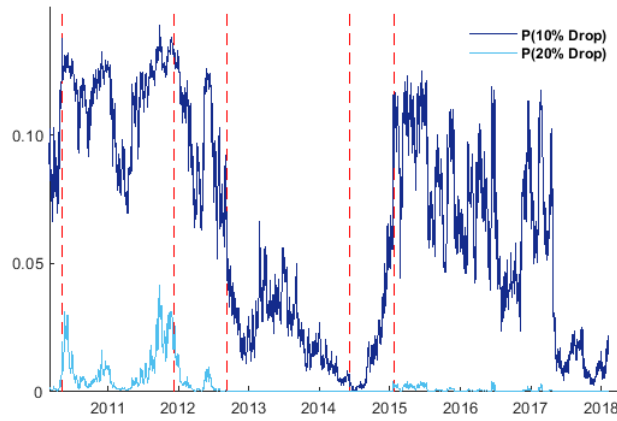
Note: Figure 6 shows the crash probabilities defined as a drop of 10% and 20% derived from the RNPD based on 1-month options. y-axis in percentage points, x-axis in years. Red dotted lines represent (from left to right) the first announcement of the SMP, the first announcement of the TLTRO program, Technical features of the OMT, announcement to lower the DFR below 0 and the announcement of the PSPP.

A shift downwards reflects a lower spot price for the Euro, but does not have to reflect lower crashprobabilities.

From the distributions shown in Figure 5 we can calculate the probability of a drop in the exchange rate in the coming month with 10 percent or more and 20 percent or more. Figure 6 shows this (left) tail probability in a time series. Both the perceived probability of a 10 percent and 20 percent drop spiked just before the announcement of the SMP and stayed high due to an unfolding sovereign debt crisis that threatened the euro. When examining the probabilities surrounding the LTRO in 2011 we find they decreased just after the announcement, with the drop in the probability of a 10% decline being the most notable. The probabilities further declined after the announcement of the OMT late 2012. Against the background of rising deflation risks late 2014 we also find the crash probability increased substantially, where the PSPP only seems to manage a short-lived decrease in tail risk after the announcement. Perceived crash risk also spiked in April 2017, around the French elections. It should be noted though, that the probability of a 20 percent decrease never really went up after 2012. It seems that, at least for the LTRO, OMT and NIRP announcement the risk reduction is sustained.

6.2.2 Event regressions on Tail Risk calculations

Table 4 shows the results for the base-line regression (13), the 10% drop on the dummy setup and the Citi Surprise Index. When we set the dummy to one for every event in the sample we find the coefficient is negative but not significant. It indicates market participants on average revised down the perceived probability of a crash by 19 percent over the event window. Table 4 again differentiates between the announcements made on Quantitative Easing measures aiming directly at relative asset supplies, or, in ECB-speak, on influencing the Monetary Stance (MS) from those aimed directly at the monetary transmission Channel (MTC); see Appendix A for a detailed list matching programs to one or the other objective. The results show MTC announcements were not followed by a significant decline in crash risk and only managed to decrease crash risk by an average of 3 percent. On the contrary we do find bigger and significant crash risk reductions for the remaining programs, with an average reduction of 17% for the MS variable. Hence, the bulk of the reduction in perceived crash risk stems from announcements on the monetary stance of the ECB. When we further differentiate and make separate dummy variables for all UMP programs we find similar results. For the OMT and NIRP announcements we find a significant reduction in crash risk. The NIRP announcements seem to yield the most (-110%) effect on risk perceptions, followed by the OMT(-50%). The result for the NIRP program might seem somewhat extreme, but as the level of the crash risk surrounding these announcements was very small, we find a large reduction terms of percentage change. The combined LTRO and TLTRO dummy proves insignificant. The same holds for both asset purchase programs, the CSPP and PSPP did not cause a uniform, significant reduction in perceived crash risk. For the SMP dummy we also find significant results but with a positive coefficient. This should not come as a surprise given the plots we made earlier (Figure 5 and 6) where we clearly observed an increase in implied crash risk. It should be noted these results are somewhat different than those following from the risk reversals. We only find a coefficient with the same sign for the NIRP. Apparently the more granular data provide us information the risk reversal was unable to pin down.

6.3 Crash risk measures derived from the mixed jump-diffusion option pricing model

The results of the estimation procedures are presented in Table 5 and Table 6 for respectively the regularization method and the joint estimation method. Let us first consider the results

Table 4: UMP Announcements and change in crash probabilities

	(1)$\Delta F_{10d}(x)$	(2)$\Delta F_{10d}(x)$	(3)$\Delta F_{10d}(x)$
c	0.002	0.005	0.003
	(0.013)	(0.013)	(0.013)
θ	-0.189		
	(0.127)		
θ_{MTC}		-0.0271	
		(0.1097)	
θ_{MS}		-0.170**	
		(0.0589)	
SMP			0.204**
			(0.061)
CBPP			0.390
			(0.314)
OMT			-0.470**
			(0.174)
NIRP			-1.111*
			(0.500)
PSPP			-0.063
			(0.057)
CSPP			0.115
			(0.382)
TLTRO			-0.130
			(0.168)
Citi	-0.001	-0.0004	-0.001
	(0.001)	(0.0016)	(0.002)
N	2498	2498	2498

* $p < 0.05$ ** $p < 0.01$; *Sample: Daily January 2009 to February 2018. The dependent variable is the 1-day log change in the risk indicator for options with a maturity of 1 month. θ is a 0/1 indicator for the T-days surrounding UMP announcements. The eventwindow equals 3-days (T=3). Citi reflects the change in the European Citi Surprise Index. Heteroskedasticity and autocorrelation (HAC) Newey and West (1987) robust standard errors in the parentheses.*

obtained using the regularization method. Four events reduced the option-implied jump risk with at least 25%. The largest reduction is after the announcement where the ECB provided the detailed technical features corresponding to the OMT program. The jump risk also decreased significantly after the press conference one month earlier where Draghi answered questions about the specifics of the program. An interesting observation is that the famous 'Whatever it takes'-speech itself had no effect on option implied downside risk. The announcement of the CSPP reduced jump risk in spite of it being a mere announcement without specific details. However, on the same day, the ECB also decided to lower the Deposit Facility Rate (DFR) to -0.4%. Here the further details on the CSPP did not have much effect, but the announcement combined with the lower DFR did. This is contrary to the time pattern of responses to the OMT speech. Apparently the OMT announcement was too vague for investors, where the CSPP announcement did provide enough information about the program for the later announcement of specification details not to have a measurable impact on jump risk. Lastly, the lowering of the DFR to -0.3% on 3-12-2015 had a large impact on jump risk. On this day, Draghi gave a press conference, where the ECB also announced several monetary policy decisions additional to the lower deposit rate. The asset purchasing program was extended, principal payments on purchased securities were announced to be reinvested, the public sector purchasing program was extended to local and regional goverments and the main refinancing operations were extended. Therefore we can say that the total package reduced the risk, but not whether specifically lowering the interest rate had an effect. One unexpected outcome is that the announcement of the seventh LTRO increased jump risk with approximately 30%. However, if we look at the estimated jump probabilities we see that the estimation yields a very small probability of a jump. Therefore, it might be that a small change in option prices can already lead to a change in jump probability from 0.9% to 1.1%. Also the announcement of the fifth LTRO seems to have slightly increased the crash probability.

Table 5: Results of estimation with the Kou model using regularization method (three trading days)

Program	Date	Event	Before Event		After Event (w. reg.)		% change
			P(Jump)	E(Jump)	P(jump)	E(Jump)	P(jump)*E(jump)
SMP	9-5-2010	Announcement of the SMP	59.6%	-9.0%	59.6%	-9.0%	0.0%
	14-5-2010	Details of the SMP	57.6%	-8.4%	57.6%	-8.4%	0.0%
	7-8-2011	Relaunch of SMP	57.4%	-8.4%	57.4%	-8.4%	0.0%
LTRO	8-12-2011	Announcement of two 3y LTROs	60.4%	-9.0%	60.4%	-9.0%	0.0%
CBPP	4-6-2009	Start of the first CBPP	62.1%	-8.3%	62.1%	-8.3%	0.0%
	6-10-2011	Start of the second CBPP	62.4%	-10.5%	62.1%	-10.2%	-2.6%
	4-9-2014[1]	Start of the third CBPP	-		-		-
ABSPP	4-9-2014[1]	Start of the ABSPP	-		-		-
OMT	26-7-2012	Whatever it takes	56.5%	-5.1%	56.5%	-5.1%	0%
	2-8-2012	Key technical features OMT	53.8%	-5.4%	4.2%	-25.5%	-63.7%
	6-9-2012	End SMP, announce OMT in full	13.0%	-13.5%	5.4%	-13.5%	-58.4%
NIRP	5-6-2014	ECB announced DFR will be negative	-		-		-
	4-9-2014	Further lowers DFR to -0.2	-		-		-
	3-12-2015[2]	Further lowers DFR to -0.3	50.9%	-6.2%	29.8%	-6.2%	-41.6%
	10-3-2016[3]	Further lowers DFR to -0.4	53.2%	-5.2%	39.9%	-5.0%	-28.5%
PSPP	22-1-2015	Announcement of the PSPP	44.4%	-6.7%	44.4%	-6.7%	0.0%
	31-1-2015	Further details on the PSPP	48.8%	-6.6%	48.8%	-6.6%	0.0%
CSPP	10-3-2016[3]	Announcement of the CSPP	53.2%	-5.2%	39.9%	-5.0%	-28.5%
	21-4-2016	Further details on the CSPP	1.0%	-80.0%	1.0%	-80.0%	0.0%
TLTRO	5-6-2014	GovC decided to conduct series LTRO	-		-		-
	16-9-2014	Announcement first LTRO	-		-		-
	9-12-2014	Announcement second LTRO	-		-		-
	17-3-2015	Announcement third LTRO	50.0%	-6.9%	50.0%	-6.9%	0.0%
	16-6-2015	Announcement fourth LTRO	51.6%	-7.2%	51.4%	-7.1%	-1.3%
	22-9-2015	Announcement fifth LTRO	41.3%	-5.3%	41.5%	-5.3%	1.4%
	9-12-2015	Announcement sixth LTRO	35.8%	-5.0%	35.8%	-5.0%	0.0%
	22-3-2016	Announcement seventh LTRO	0.9%	-65.7%	1.1%	-67.6%	31.3%

Estimation is performed using three trading days before or after the event on options with one, three and six month maturities. In total 63 option prices are used per estimation (seven per maturity). $P(Jump) = 1 - e^{-\lambda}$, is the probability on a jump occurring within one year. $E(Jump) = \frac{-1}{\eta_2^* + 1}$, is the expected jump size. Parameters before the event are calibrated without regularization, after the event with regularization. The last column shows the change in jump probability multiplied by the expected jump size. '-' implies that the optimal estimation yielded no jump risk ($P(Jump) = 0$). [1] Both the third CBPP and the ABSPP were announced at 4-9-2014. [2] At the same day, in a press conference the ECB announced several other monetary policy decisions. [3] Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.

26

Table 6: Results of estimation with the Kou model using joint estimation (three trading days)

Program	Date	Event	Before P(Jump)	After P(Jump)	E(Jump)	% change P(Jump)	Abs. change P(Jump)	F-stat
SMP	9-5-2010	Announcement of the SMP	60.9%	58.1%	-8.7%	-5%	-3%	0.93
	14-5-2010	Details of the SMP	54.8%	61.0%	-9.0%	11%	6%	4.77*
	7-8-2011	Relaunch of SMP	54.0%	60.3%	-9.0%	12%	6%	7.13**
LTRO	8-12-2011	Announcement of two 3y LTROs	59.4%	61.6%	-9.3%	4%	2%	0.93
CBPP	4-6-2009	Start of the first CBPP	63.2%	60.6%	-8.1%	-4%	-3%	0.32
	6-10-2011	Start of the second CBPP	64.2%	56.8%	-10.0%	-12%	-7%	7.06**
	4-9-2014[1]	Start of the third CBPP	-	-		-	-	
ABSPP	4-9-2014[1]	Start of the ABSPP	-	-			-	
OMT	26-7-2012	Whatever it takes	55.8%	53.9%	-5.2%	-3%	-2%	2.39
	2-8-2012	Key technical features OMT	33.1%	20.2%	-8.6%	-39%	-13%	131.19**
	6-9-2012	End SMP, announce OMT in full	5.5%	1.9%	-25.8%	-66%	-4%	89.67**
NIRP	5-6-2014	ECB announced DFR will be negative	-	-		-	-	
	4-9-2014	Further lowers DFR to -0.2	-	-		-	-	
	3-12-2015[2]	Further lowers DFR to -0.3	50.3%	26.9%	-6.3%	-47%	-23%	46.02**
	10-3-2016[3]	Further lowers DFR to -0.4	53.8%	34.8%	-5.2%	-35%	-19%	49.88**
PSPP	22-1-2015	Announcement of the PSPP	43.8%	50.1%	-6.8%	14%	6%	4.71*
	31-1-2015	Further details on the PSPP	48.0%	44.3%	-6.7%	-8%	-4%	3.62
CSPP	10-3-2016[3]	Announcement of the CSPP	53.8%	34.8%	-5.2%	-35%	-19%	49.88**
	21-4-2016	Further details on the CSPP	0.9%	0.7%	-83.3%	-26%	0%	2.18
TLTRO	5-6-2014	GovC decided to conduct series LTRO	-	-		-	-	
	16-9-2014	Announcement first LTRO	-	-		-	-	
	9-12-2014	Announcement second LTRO	-	-		-	-	
	17-3-2015	Announcement third LTRO	51.3%	50.0%	-6.7%	-3%	-1%	0.21
	16-6-2015	Announcement fourth LTRO	52.6%	45.8%	-7.0%	-13%	-7%	5.18*
	22-9-2015	Announcement fifth LTRO	39.9%	45.2%	-5.5%	13%	5%	10.13**
	9-12-2015	Announcement sixth LTRO	34.4%	36.5%	-5.1%	6%	2%	3.16
	22-3-2016	Announcement seventh LTRO	1.5%	2.4%	-42.9%	60%	1%	24.27**

Estimation is performed jointly using both three trading days before and after the event on options with one, three and six month maturities. In total 126 option prices are used per estimation (seven per maturity). The expected jump size is restricted to be the same both before and after the event. The jump probability is allowed to vary among both periods. '-' implies that the optimal estimation yielded no jump risk ($P(Jump) = 0$). $P(Jump) = 1 - e^{-\lambda}$, is the probability on a jump occurring within one year. The last column gives the F-statistics that compare the estimation with the estimation where $P(Jump)$ is also restricted to be the same before and after the period. Significance levels: $*p < 0.05$, $**p < 0.01$. [1] Both the third CBPP and the ABSPP were announced at 4-9-2014. [2] At the same day, the ECB announced several other monetary policy decisions. [3] Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.

Next let us take a look at the significance of these changes in jump probabilities. To that end we combine the pre- and post-event data and estimate the change in jump risk directly. The same four events that had a large effect for the regularization method are now highly significant using the joint estimation method. Here, we constructed four indicators that capture the total change in jump risk. First of all, we have to take into account the expected jump size. A reduction of jump risk when the expected crash is 20% is more important than when the expected crash would be 5%. Moreover, we calculate both the percentage and absolute change in jump size. Last and maybe even most important, the F-statistic captures the significance of the change in jump probability.

If we consider the F-statistics, the press conference where Draghi answered questions about the key technical features of the OMT has the highest F-statistic. The event is followed by the detailed technical features of the OMT and after that the announcement of the CSPP combined with the lower DFR. The detailed technical OMT features relatively reduced jump risk the most (-66%), where the announcement of the lower DFR at 3-12-2015 combined with several other monetary policy decisions reduced jump risk the most in absolute terms (-23%). We find a similar pattern in OMT announcements. The 'Whatever it takes' speech was too vague and is therefore insignificant, where the more detailed announcements are highly significant. Furthermore, we also find that the start of the second CBPP significantly reduces jump risk.

Lastly, we now find that several events significantly *increased* jump risk. First, the relaunch of the SMP seems to have increased the crash probability. It might be that investors were not convinced of the program. Also two LTRO announcements both significantly increased jump risk at a 1% significance level. For the LTRO announcement at 22-9-2015 it can be the case that the Fed announcement at 17-9-2015 has influenced the results. At that day, investors expected the Fed to increase interest rates, but the Fed decided to keep its benchmark rate at 0-0.25%. This initially led to an increase of the Euro-Dollar rate of more than 2%. However, the days after the spot rate slowly decreased again as investors might have overreacted. This event might cause the significant increase of jump risk around the fifth LTRO announcement. Concerning the other announcement, the jump probability increased from 1.5% to 2.6% which is still very small.

6.4 Summing Up

Table 7 provides an overview of the results coming out of the various approaches. First, although the Risk Reversal numbers seemed suggestive, the event window regressions do not always support the first impressions as significant. Most surprizing is maybe the failure of the OMT to significantly change the risk reversal in that regression. But a more detailed look at the entire distribution nuances that conclusion, a nuance that comes out even stronger in the results obtained with the two variants based on the mixed jump-diffusion model estimation. The initial speech did not have a significant impact on asset markets but when the speech was actually backed up with the specifics of what OMT would entail if employed, there was a strong and favorable market response. The jump risk estimates from the Bates-Kou model do not respond significantly to the speech itself but declined substantially, and significantly at the two later dates on which details of the OMT program were announced. Management by speech does not seem to be enough by itself. The announcement of the Corporate Bond Purchasing Program did have a significant although relatively small risk reduction effect and the later filling in of the details did not, but the CSPP was a clear measure from the beginning while the OMT speech did not give any particular information on what exactly the ECB would do in crisis time, just that whatever it was would be enough. Market participants apparently wanted to see the details before being impressed.

Table 7: Summary results of the various apprpoaches

Program	Date	Event	DELTA_RR plus = LOWER risk	DELTA_F10 plus = HIGHER risk	Kou_Regularization plus = HIGHER risk	Kou_Joint plus = HIGHER risk
SMP	9-5-2010	Announcement of the SMP		[plus**]	-	-
	14-5-2010	Details of the SMP			-	plus*
	7-8-2011	Relaunch of SMP			-	plus**
LTRO	8-12-2011	Announcement of two 3y LTROs			-	-
CBPP	4-6-2009	Start of the first CBPP	[plus**]		-	-
	6-10-2011	Start of the second CBPP			min	min**
	4-9-2014[1]	Start of the third CBPP			-	-
ABSPP	4-9-2014[1]	Start of the ABSPP			-	-
OMT	26-7-2012	Whatever it takes		[min**]	-	-
	2-8-2012	Key technical features OMT			min	min**
	6-9-2012	End SMP, announce OMT in full			min	min**
NIRP	5-6-2014	ECB announced DFR will be negative	[min*]	[min**]	-	-
	4-9-2014	Further lowers DFR to -0.2			min	min**
	3-12-2015[2]	Further lowers DFR to -0.3			min	min**
	10-3-2016[3]	Further lowers DFR to -0.4				
PSPP	22-1-2015	Announcement of the PSPP	[plus**]		-	plus*
	31-1-2015	Further details on the PSPP			-	-
CSPP	10-3-2016[3]	Announcement of the CSPP			min	min**
	21-4-2016	Further details on the CSPP			-	-
TLTRO	5-6-2014	GovC decided to conduct series LTRO			-	-
	16-9-2014	Announcement first LTRO			-	-
	9-12-2014	Announcement second LTRO			-	-
	17-3-2015	Announcement third LTRO			-	-
	16-6-2015	Announcement fourth LTRO			min	min*
	22-9-2015	Announcement fifth LTRO			plus	plus**
	9-12-2015	Announcement sixth LTRO			-	-
	22-3-2016	Announcement seventh LTRO			plus	plus**

*For the underlying details see corresponding earlier tables. Significance levels: *p < 0.05, **p < 0.01. [1] Both the third CBPP and the ABSPP were announced at 4-9-2014. [2] At the same day, in a press conference the ECB announced several other monetary policy decisions. [3] Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.*

29

A similar pattern emerged around the announcement of the ECB's flagship program, the Public Sector Securities Purchase Program, whereby the ECB buys up sovereign debt in line with its capital key distribution.

Another strong result emerging from table 7 is that several programs actually seem to have led to higher downside risk perceptions, possibly signaling panic or ineffectiveness of the measures announced. In particular the SMP program did not really seem to lower risk on the two general measures (RR event window regression and the Kou-Regularization approach) and in the two approaches explicitly focusing on tail risk actually led to significntly higher risk perceptions, the opposite of what the purpose of the announcement was. Reis (2017) possibly provides an explanation for this result: he indicates that mismatches between the composition of asset purchases and the capital key of the ECB governing its distribution of dividends signal ultimately unsustainable redistribution. Since the SMP was completely focused on first Greek and later Italian debt instruments, it was an obviuous example of the mismatch discussed in Reis (2017).

The RR regressions also seem to indicate a perverse increase in risk perceptions for the latest of the ECB's moves into negative interest rate territory, which is somewhat of a surprise because all the three other approaches indicate the opposite, in particular the latest two decreases in the deposit rate lead to significantly lower tail risk perceptions in the other three more focused and information intensive approaches. An explanation for the contradiction may be that at the same time overall volatility declined substantially: although the table suggests the RR decreased (i.e. left skew increased), the overall level of volatility declined significantly at that date: the ATM volatility fell by some 25% that very day.

A general result that comes out is that the measures focused on influencing the Monetary Transmission Channel (MTC), roughly speaking measures aimed at bank support, did not have a significant impact, a result indicated by all four approaches. The Kou_joint estimates allow for most details and indicate significant but small changes in risk perception, but sometimes up and sometimes down, in line with the general ineffectiveness that comes out of the event window regressions.

Finally, the two flagship programs (CSPP and PSPP) seem to give mixed results. According to both methods based on the jump-diffusion process, the initial announcement of the CSPP is effective (and very significantly so) in reducing risk perceptions, but once the details came out the perception of tail risk did not move anymore. Apparently the announcement was already clear enough about the implications of the CSPP. Concerning the PSPP program, the RR regression does suggest that the overall effect of the PSPP program was to lower tail risk perceptions. However, the other methods give different results. The event window regression based on the risk-neutral distribution and the Kou-Regularization approach find no effects. The Kou_Joint method even suggests that after the announcement of the PSPP the risk perceptions actually went up. Overall, we can conclude that the PSPP program does not seem to be very effective, while the CSPP did reduce risk perceptions.

7 Conclusions

In this paper we used a series of methods to analyse market perceptions of the risk impact of specific policy measures, simultaneously increasing in data requirements and model specificity. Risk Reversals provide suggestive results, but, while their sparse and relatively straightforward use of readily available data makes them easy to calculate and use them in regression analysis, those very factors may also explain their relative lack of power. Specifically, it is difficult to assess the net impact of for example a decrease in left skew (i.e. a more negative number) if it coincides with a decline in volatility as indicated by a decline in ATM (At The Money) volatility. Using

the entire volatility smile/smirk to extract the entire (risk neutral) distribution, while still being non-parametric, does allow for more precise measures of risk and allowed for more powerful tests and more precise results focusing on different descriptive measures of the distribution, like fatness of tails versus skewness. Risk reversals only capture the skewness, not the kurtosis and the level of ATM volatility. Especially when the ATM volatility increases while skewness remains the same the two methods (RR versus RNPD extraction) may give different results. But the numerical procedures used in obtaining the empirical density function unavoidably impose restrictions on the shape of the function that did not allow for the sort of mixed process that allows for a precise focus on jump risk probabilities. For this reason we ended up setting up a specific diffusion-jump model, using various methods to estimate its parameters and possible changes in the surrounding policy announcement dates. Using a cascade of methods increasing in complexity proved to be useful since each stage provided information allowing for more precise structuring in the next stage, moving from very general RR all the way to fully analytical derivation and empirical estimation of a mixed diffusion-jump risk model based on exponential densities for the jump risk elements.

A number of general messages emerge from the analysis. First of all, announcing policies in general terms without precisely describing what exactly they entail does not instantly move asset markets or even moves them in the wrong direction. This pattern emerged at the time of the famous OMT speech; risk perceptions only improved once the details were announced one month after the speech; but at the time of the speech itself, risk perceptions actually moved in the wrong direction on several measures, although not significantly so. A similar pattern was revealed by our most powerful approach when analyzing the ECB's flagship program, the PSPP. The initial announcement actually led to higher crash probabilities, a move that was reversed once the details were spelled out ten days later. A second message is that policies aiming at changing relative asset supplies in asset markets do have an impact once they are made clear enough; while measures more generally aiming at easing financing costs of the commercial banks do not. And the third remarkable result is that the SMP program (focusing on providing support for first Greek and later on Italian sovereign debt prices) actually led to higher tail risk perceptions in the Euro-Dollar market, a result possibly related to the fact that it involved a mismatch between the composition of the assets purchased and the ECB's capital key governing its dividend distribution and therefore implied ultimately unsustainable redistribution between member states.

References

Anderson, E., Hansen, L. P., & Sargent, T. (2000). Robustness, detection and the price of risk. *Manuscript, Stanford*, *19*.

Arteta, C., Kose, M. A., Stocker, M., & Taskin, T. (2018). Implications of negative interest rate policies: An early assessment. *Pacific Economic Review*, *23*(1), 8–26.

Bates, D. S. (1988). *Pricing options under jump-diffusion processes*. Citeseer.

Bates, D. S. (1996). Jumps and stochastic volatility: Exchange rate processes implicit in deutsche mark options. *The Review of Financial Studies*, *9*(1), 69–107.

Bergstra, J., & Bengio, Y. (2012). Random search for hyper-parameter optimization. *Journal of Machine Learning Research*, *13*(Feb), 281–305.

Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. *Journal of political economy*, *81*(3), 637–654.

Bliss, R. R., & Panigirtzoglou, N. (2004). Option-implied risk aversion estimates. *The journal of finance*, *59*(1), 407–446.

Breeden, D., & Litzenberger, R. (1978). Prices of state contingent claims implicit in option prices. *Journal of Business*, *51*, 621-652.

Brunnermeier, M. K. (2009, March). Deciphering the liquidity and credit crunch 2007-2008. *Journal of Economic Perspectives*, *23*(1), 77-100. Retrieved from `http://www.aeaweb.org/articles?id=10.1257/jep.23.1.77` doi: 10.1257/jep.23.1.77

Brunnermeier, M. K., Sannikov, Y., et al. (2012). Redistributive monetary policy. In *Jackson hole symposium* (Vol. 1, pp. 331–384).

Bu, R., & Hadri, K. (2007). Estimating option implied risk-neutral densities using spline and hypergeometric functions. *The Econometrics Journal*, *10*(2), 216–244.

Coeure, B. (2017, November). Monetary policy, exchange rates and capital flows. *ONLINE ECB*. (https://www.ecb.europa.eu/press/key/date/2017/html/ecb.sp171103.en.html)

Cont, R., & Tankov, P. (2002). Calibration of jump-diffusion option pricing models: a robust non-parametric approach.

De Pooter, M., Rebecca, D., Martin, R. F., & Pruitt, S. (2015). Cheap talk and thr efficacy of the ecb's securities market programme: Did bond purchases matter?

Draghi, M. (2012). Verbatim of the remarks made by mario draghi. In *Speech at the global investment conference, london* (Vol. 26).

ECB. (2016). *Open market operations.* Retrieved from `https://www.ecb.eu/mopo/implement/omo/html/index.en.html`

Falagiarda, M., & Reitz, S. (2015). Announcements of ecb unconventional programs: Implications for the sovereign spreads of stressed euro area countries. *Journal of International Money and Finance*, *53*, 276–295.

Fratzscher, M., Duca, M. L., & Straub, R. (2014). *Ecb unconventional monetary policy actions: Market impact, international spillovers and transmission channels.* International Monetary Fund.

Garman, M. B., & Kohlhagen, S. W. (1983). Foreign currency option values. *Journal of international Money and Finance*, *2*(3), 231–237.

Georgiadis, G., & Gräb, J. (2016). Global financial market impact of the announcement of the ecb's asset purchase programme. *Journal of Financial Stability*, *26*, 257–265.

Hattori, M., Schrimpf, A., & Sushko, V. (2016). The effects of quantitative easing on interest rates: Channels and implications for policy. *American Economic Journal: Macroeconomics*, *8*(2), 111â136.

Jorion, P. (1988). On jump processes in the foreign exchange and stock markets. *The Review of Financial Studies*, *1*(4), 427–445.

Kou, S. G. (2002). A jump-diffusion model for option pricing. *Management science*, *48*(8), 1086–1101.

Krishnamurty, A., & Vissing-Jorgenson, A. (2011). The effects of quantitative easing on interest rates: Channels and implications for policy. *BPEA*.

Malz, A. (2014). A simple and reliable way to compute optoin-based risk neutral distributions. *Staff reports Federal Reserve Bank of New York*(677).

Merton, R. C. (1976). Option pricing when underlying stock returns are discontinuous. *Journal of financial economics*, *3*(1-2), 125–144.

Reis, R. (2017). Can the central bank alleviate fiscal burdens? *CEPR DP11736*.

Reiswich, D., & Wystup, U. (2010). A guide to fx options quoting conventions. *Journal of Derivatives*, *18*(2), 58.

Shinko, D. (1993). Bounds of probability. *Risk*, *6*(33-37).

Shreve, S. E. (2004). *Stochastic calculus for finance ii: Continuous-time models* (Vol. 11). Springer Science & Business Media.

A List of programs with their abbreviations and an indication of their target[15]

Program		Target
ABSPP	Asset backed security purchasing programma	MTC
APP	Asset purchasing programme	MS
CBPP	Covered bond purchasing programme	MTC
CSPP	Corporate sector purchasing programme	MS/MTC
CEP	Credit easing package	MTC
COLL	Collateral extension	MTC
FRTPFA	Fixed rate tenders with full allotment	MTC
FWG	Forward guidance	MS
LTRO	Long term refinancing operations	MTC
NIRP	Negative interest rate policy	MTC
OMT	Outright monetary transactions	MTC
PSPP	Public sector purchasing programme	MS
SMP	Securities markets programme	MTC
TLTRO	Targeted long-term refinancing operations	MS/MTC

MS refers to Monetary Stance, MTC refers to Monetary transmission

B Derivation of relative entropy

For notational simplicity, we drop the star above the risk-neutral parameters. Then under $\mathcal{Q}$ (risk-neutral measure), S_t has the following distribution.

$$dS_t = -\lambda E[V-1]S_t dt + \sigma S_t dW_t + (V-1)S_{t-}dN_t \tag{22}$$

Here V has distribution $f(v)$. Now assume we want to calculate the relative entropy between $\mathcal{Q}$ and a risk-neutral distribution with different parameters, namely $\tilde{\mathcal{Q}}$ with parameters $\tilde{\lambda}$ and pdf $\tilde{f(v)}$. The we can define the Radon Nykodim derivative of $\mathcal{Q}$ with respect to $\mathcal{Q}$ by $Z_T = \frac{d\tilde{\mathcal{Q}}}{d\mathcal{Q}}$ where

$$dZ_t = -(\tilde{\lambda}-\lambda)Z_t dt - \frac{\tilde{\lambda}\tilde{E}[V-1]-\lambda E[V-1]}{\sigma}dW_t + \left(\frac{\tilde{\lambda}f(\tilde{V})}{\lambda f(V)}-1\right)Z_{t-}dN_t \tag{23}$$

and $Z_0 = 1$. Here $\tilde{E}[.]$ is the expectation under the measure $\tilde{\mathcal{Q}}$. Using that $dW_t = d\tilde{W}_t - \frac{\lambda E(V-1)-\tilde{\lambda}\tilde{E}(V-1)}{\sigma}$, we obtain that under $\tilde{Q}$:

$$dS_t = -\lambda \tilde{E}[V-1]S_t dt + \sigma S_t d\tilde{W}_t + (V-1)S_{t-}dN_t \tag{24}$$

where V has distribution $\tilde{f(v)}$ and N_t has arrival rate $\tilde{\lambda}$ (See Shreve (2004), chapter 11.6.3).

---

[15]We are indebted to Christiaan Pattipeilohy (DNB) for this introduction of ECB language.

Using Ito's lemma for jump processes we get:

$$
\begin{aligned}
d\ln(Z_t) &= -(\tilde{\lambda}-\lambda)dt - \frac{\tilde{\lambda}\tilde{E}V-1]-\lambda E[V-1]}{\sigma}dW_t \\
&\quad - \frac{1}{2\sigma^2}\Big(\tilde{\lambda}\tilde{E}(V-1)-\lambda E(V-1)\Big)^2 dt + \ln\Big(\frac{\tilde{\lambda}f(\tilde{V})}{\lambda f(V)}\Big)dN_t \\
&= -(\tilde{\lambda}-\lambda)dt - \frac{\tilde{\lambda}\tilde{E}[]V-1]-\lambda E[V-1]}{\sigma}d\tilde{W}_t \\
&\quad + \frac{1}{2\sigma^2}\Big(\tilde{\lambda}\tilde{E}[V-1]-\lambda E[V-1]\Big)^2 dt + \ln\Big(\frac{\tilde{\lambda}f(\tilde{V})}{\lambda f(V)}\Big)dN_t
\end{aligned}
\tag{25}
$$

Then the relative entropy from $\tilde{\mathcal{Q}}$ to $\mathcal{Q}$ over the interval $[t,t+\Delta]$ equals:

$$
\begin{aligned}
\mathcal{E}(\tilde{\mathcal{Q}}|\mathcal{Q}) &= \tilde{E}_t\Big[\ln\Big(\frac{Z_{t+\Delta}}{Z_t}\Big)\Big] = \int_t^{t+\Delta} -(\tilde{\lambda}-\lambda)ds \\
&\quad + \int_t^{t+\Delta}\frac{1}{2\sigma^2}\Big(\tilde{\lambda}\tilde{E}[V-1]-\lambda E[V-1]\Big)^2 ds + \int_t^{t+\Delta}\tilde{\lambda}\tilde{E}\Big[\ln\Big(\frac{\tilde{\lambda}f(\tilde{V})}{\lambda f(V)}\Big)\Big]ds \\
&= -(\tilde{\lambda}-\lambda)\Delta + \frac{1}{2\sigma^2}\Big(\tilde{\lambda}\tilde{E}[V-1]-\lambda E[V-1]\Big)^2\Delta + \tilde{\lambda}\tilde{E}\Big[\ln\Big(\frac{\tilde{\lambda}f(\tilde{V})}{\lambda f(V)}\Big)\Big]\Delta
\end{aligned}
\tag{26}
$$

The pdf of the jump distribution for the Kou model equals: $f(v) = \eta v^{\eta-1}$. Therefore the relative entropy between $\tilde{\mathcal{Q}}$ and $\mathcal{Q}$ equals:

$$
\begin{aligned}
\frac{\mathcal{E}(\tilde{\mathcal{Q}}|\mathcal{Q})}{\Delta} &= -(\tilde{\lambda}-\lambda) + \frac{1}{2\sigma^2}\Big(\frac{\lambda}{\eta+1}-\frac{\tilde{\lambda}}{\tilde{\eta}+1}\Big)^2 + \tilde{\lambda}\ln\Big(\frac{\tilde{\lambda}\tilde{\eta}}{\lambda\eta}\Big) + \tilde{\lambda}(\tilde{\eta}-\eta)\tilde{E}\Big[\ln(V)\Big] \\
&= -(\tilde{\lambda}-\lambda) + \frac{1}{2\sigma^2}\Big(\frac{\lambda}{\eta+1}-\frac{\tilde{\lambda}}{\tilde{\eta}+1}\Big)^2 + \tilde{\lambda}\ln\Big(\frac{\tilde{\lambda}\tilde{\eta}}{\lambda\eta}\Big) + \tilde{\lambda}\frac{\eta-\tilde{\eta}}{\tilde{\eta}}
\end{aligned}
\tag{27}
$$

Similarly, for the Merton model we have that $f(v) = \frac{1}{v}\frac{1}{\sqrt{2\pi}\nu}\exp\Big(-\frac{(\ln(v)-\mu)^2}{2\nu^2}\Big)$. and the relative entropy equals:

$$
\begin{aligned}
\frac{\mathcal{E}(\tilde{\mathcal{Q}}|\mathcal{Q})}{\Delta} &= -(\tilde{\lambda}-\lambda) + \frac{1}{2\sigma^2}\Big(\tilde{\lambda}\tilde{\kappa}-\lambda\kappa\Big)^2 + \tilde{\lambda}\ln\Big(\frac{\tilde{\lambda}\nu}{\lambda\tilde{\nu}}\Big) \\
&\quad + \tilde{\lambda}\tilde{E}\Big[\frac{(\ln(v)-\mu)^2}{2\nu^2}-\frac{(\ln(v)-\tilde{\mu})^2}{2\tilde{\nu}^2}\Big] \\
&= -(\tilde{\lambda}-\lambda) + \frac{1}{2\sigma^2}\Big(\tilde{\lambda}\tilde{\kappa}-\lambda\kappa\Big)^2 + \tilde{\lambda}\ln\Big(\frac{\tilde{\lambda}\nu}{\lambda\tilde{\nu}}\Big) + \tilde{\lambda}\Big(\frac{\tilde{\nu}^2+(\tilde{\mu}-\mu)^2}{2\nu^2}-\frac{1}{2}\Big)
\end{aligned}
\tag{28}
$$

C Robustness checks

In this section, we check whether our results are robust under different assumption. Specifically, we will check whether the choice of the model has much influence on the result. Furthermore, we will look whether the number of trading days around an event on which the estimation is performed influences the results.

C.1 Merton model

As a robustness check, we perform the same analysis using the Merton model. Merton (1976) was the first to propose an option-pricing model with jump risk, Jorion (1988) derived the formula for FX options. Recall that the spot rate follows a jump diffusion process with jump size $V - 1$.

$$dS_t = \Big(\mu - \lambda E(V-1)\Big)S_t dt + \sigma S_t dW_t + (V-1)S_{t-}dN_t \tag{29}$$

Now assume that V is i.i.d. distributed and follows a log-normal distribution, instead of a double-exponential distribution: $\ln(V) \sim N\Big(\ln(1+\kappa) - \frac{1}{2}\nu^2, \nu^2\Big)$, $E(V) = 1 + \kappa$. In the Black-Scholes model, the value of an option does not depend on the preference of a representative agent. This is not generally the case for a jump-diffusion model. However, Merton (1976) derived a preference-free option pricing formula for a jump-diffusion model with the assumption that jump risk is firm-specific and perfectly diversifiable. The result is that jump risk has zero price. Denote the risk-neutral arrival rate by λ^* and the risk-neutral expected jump size by κ^*. The assumption of Merton implies that diffusion risk is priced the usual way and that jump risk is not priced, such that $\lambda^* = \lambda$ and $\kappa^* = \kappa$. This assumption might be plausible if we would consider options on specific stocks, but is certainly violated in the case of currency options.

However, Bates (1988) shows that with some additional assumptions, we can also derive a tractable option pricing formula that does price jump risk. Let us assume furthermore that the representative agent has power utility and that wealth of the agent follows a similar jump diffusion process as the underlying. Given these assumptions, we can use the option pricing formula derived by Merton (1976), but with the risk-neutral parameters (λ^*, κ^*) In this case, $(\lambda, \kappa) \neq (\lambda^*, \kappa^*)$. For the exact relation between the risk-neutral and the actual parameters, we refer to Bates (1988). However, it does not play a key role in our analysis, since we only estimate the distribution implied in option prices and do not look at the time-series. The price of a European call-option then equals:

$$C^{\text{Merton}}\Big(S, \tau; K, r_\$, r_\euro, \sigma, \lambda^*, \kappa^*, \nu\Big) = e^{-r_\euro \tau} \sum_{n=0}^{\infty} \frac{e^{\lambda^*(1+\kappa^*)\tau}\Big(\lambda^*(1+\kappa^*)\tau\Big)^n}{n!} *$$
$$C\Big(S, \tau; K, r_\$ - r_\euro - \lambda^*\kappa^* + n\,\frac{\ln(1+\kappa^*)}{\tau}, \sigma^2 + n\frac{\nu^2}{\tau}\Big) \tag{30}$$

Similar to the Kou model, we assume that at most one jump can take place. Therefore we sum only up to and including 1. The probability of having one jump changes from $e^{\lambda^*(1+\kappa^*)\tau}\Big(\lambda^*(1+\kappa^*)\tau\Big)$ to $1 - e^{\lambda^*(1+\kappa^*)\tau}$.

The set of parameters for the estimation becomes $\theta^{Merton} = [\sigma\ \lambda^*\ \kappa^*\ \nu]$. We do exactly the same analysis as we did for the Kou model. To find a starting point for the optimization, we use 10^6 random combinations of $(\lambda^*, \kappa^*, \nu)$ with values between $([0,1], [-0.5, -0.05], [0, 0.2])$.

The results of the regularization method and the joint estimation method are presented in respectively Table 8 and Table 9. Let us first consider the regularization method. We see that for most events, the Merton and Kou model give qualitatively similar results. However, for several events the Kou model finds zero change in jump risk after regularization, where the Merton model does find changes even after regularization. This is the case for in total five events, of which four have a change in jump probability of at most 1.5% in absolute terms. Only the relaunch of the SMP seems to give a slightly different result than in the case of the Kou model

The reason of this difference between the two models is that the Merton model has an additional free parameter, namely the jump volatility. This leads to a lower unregularized error and

increases the problem of multiple local minima. Therefore it is possible that there is no change in jump risk after regularization in the Kou model, but that there is a change in the Merton model.

If we look at the joint estimation method, it can be seen that the outcomes of both models are comparable. However, the F-statistics are higher for the Merton model. For the Merton model we have in total 12 events that are significant at a 1% significance level, against 9 events for the Kou model. The same reason as before causes this difference in significance, namely that the unrestricted sum of squared residuals is lower for the Merton model because of an extra free parameter.

However, we can say that our main conclusions remain valid under the Merton model.

Table 8: Results of estimation with the Merton model, using regularization method (Three trading days)

Program	Date	Event	Before Event			After Event (w. reg.)			% change P(jump)*κ
			P(Jump)	κ	ν	P(Jump)	κ	ν	
SMP	9-5-2010	Announcement of the SMP	62.9%	-5.0%	12.5%	62.9%	-5.0%	12.5%	0.0%
	14-5-2010	Details of the SMP	63.2%	-5.0%	11.0%	64.1%	-5.0%	11.2%	1.3%
	7-8-2011	Relaunch of SMP	57.7%	-11.1%	0.4%	61.4%	-11.1%	0.4%	6.4%
LTRO	8-12-2011	Announcement of two 3y LTROs	68.9%	-5.0%	11.3%	68.9%	-5.0%	11.3%	0.0%
CBPP	4-6-2009	Start of the first CBPP	43.1%	-5.0%	21.1%	43.1%	-5.0%	21.1%	0.0%
	6-10-2011	Start of the second CBPP	75.0%	-5.0%	12.7%	72.6%	-5.0%	12.0%	-3.2%
	4-9-2014[1]	Start of the third CBPP	-			-			-
ABSPP	4-9-2014[1]	Start of the third ABSPP	-			-			-
OMT	26-7-2012	Whatever it takes	58.4%	-5.0%	4.9%	58.2%	-5.0%	4.9%	-0.5%
	2-8-2012	Key technical features OMT	60.2%	-5.1%	4.3%	5.4%	-26.0%	5.0%	-53.8%
	6-9-2012	End SMP, announce OMT in full	8.9%	-17.6%	14.5%	4.1%	-16.1%	12.9%	-58.3%
NIRP	5-6-2014	ECB announced DFR will be negative	-			-			-
	4-9-2014	Further lowers DFR to -0.2	-			-			-
	3-12-2015[2]	Further lowers DFR to -0.3	51.7%	-8.4%	0.2%	13.0%	-10.1%	11.6%	-69.9%
	10-3-2016[3]	Further lowers DFR to -0.4	27.3%	-5.0%	13.4%	7.4%	-9.8%	23.0%	-47.4%
PSPP	22-1-2015	Announcement of the PSPP	44.1%	-8.9%	0.0%	44.2%	-9.0%	0.0%	0.3%
	31-1-2015	Further details on the PSPP	50.9%	-8.4%	0.3%	50.4%	-8.4%	0.3%	-1.0%
CSPP	10-3-2016[3]	Announcement of the CSPP	27.3%	-5.0%	13.4%	7.4%	-9.8%	23.0%	-47.4%
	21-4-2016	Further details on the CSPP	0.9%	-85.9%	50.1%	0.9%	-85.9%	50.1%	0.0%
TLTRO	5-6-2014	GovC decided to conduct series LTRO	-			-			-
	16-9-2014	Announcement first LTRO	-			-			-
	9-12-2014	Announcement second LTRO	-			-			-
	17-3-2015	Announcement third LTRO	51.1%	-9.0%	0.0%	51.1%	-9.0%	0.0%	0.0%
	16-6-2015	Announcement fourth LTRO	53.5%	-9.4%	0.1%	50.8%	-9.4%	0.1%	-5.2%
	22-9-2015	Announcement fifth LTRO	27.5%	-5.0%	9.3%	28.4%	-5.2%	9.5%	6.6%
	9-12-2015	Announcement sixth LTRO	13.9%	-8.8%	10.7%	13.9%	-8.8%	10.7%	0.0%
	22-3-2016	Announcement seventh LTRO	1.2%	-49.8%	1.5%	1.9%	-49.8%	1.6%	62.7%

Estimation is performed using three trading days before or after the event on options with one, three and six month maturities. In total 63 option prices are used per estimation (seven per maturity). $P(Jump) = 1 - e^{-\lambda}$, is the probability on a jump occurring within one year. Parameters before the event are calibrated without regularization, after the event with regularization. The last column shows the change in jump probability multiplied by the expected jump size. '-' implies that the optimal estimation yields no jump risk ($P(Jump) = 0$). [1] Both the third CBPP and the ABSPP were announced at 4-9-2014. [2] At the same day, in a press conference the ECB announced several other monetary policy decisions. [3] Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.

Table 9: Results of estimation with the Merton model, using joint estimation (Three trading days)

Program	Date	Event	Before P(Jump)	After P(Jump)	κ	ν	% change P(Jump)	Abs. change P(Jump)	F-stat
SMP	9-5-2010	Announcement of the SMP	67.2%	63.5%	-5.0%	11.6%	-6%	-4%	5.86*
	14-5-2010	Details of the SMP	55.6%	62.5%	-5.1%	13.4%	12%	7%	14.12**
	7-8-2011	Relaunch of SMP	54.3%	61.5%	-11.8%	0.4%	13%	7%	21.48**
LTRO	8-12-2011	Announcement of two 3y LTROs	68.6%	71.2%	-5.0%	11.4%	4%	3%	4.66*
CBPP	4-6-2009	Start of the first CBPP	44.1%	40.7%	-5.0%	20.6%	-8%	-3%	1.76
	6-10-2011	Start of the second CBPP	76.5%	67.3%	-5.0%	12.2%	-12%	-9%	32.03**
	4-9-2014[1]	Start of the third CBPP (&ABSPP)	-	-	-		-		
ABSPP	4-9-2014[1]	Start of the ABSPP	-	-					
OMT	26-7-2012	Whatever it takes	61.4%	59.4%	-5.1%	3.9%	-3%	-2%	3.43
	2-8-2012	Key technical features OMT	19.1%	10.4%	-11.1%	14.7%	-46%	-9%	129.52**
	6-9-2012	End SMP, announce OMT in full	3.1%	1.1%	-41.7%	3.3%	-66%	-2%	88.54**
NIRP	5-6-2014	ECB announced DFR will be negative	-	-			-		
	4-9-2014	Further lowers DFR to -0.2	-	-			-		
	3-12-2015[2]	Further lowers DFR to -0.3	50.5%	24.0%	-8.6%	0.4%	-53%	-27%	88.29**
	10-3-2016[3]	Further lowers DFR to -0.4	26.0%	13.6%	-5.1%	14.2%	-48%	-12%	93.50**
PSPP	22-1-2015	Announcement of the PSPP	43.5%	50.2%	-9.1%	0.9%	15%	7%	6.79*
	31-1-2015	Further details on the PSPP	51.5%	47.3%	-8.3%	1.0%	-8%	-4%	7.16**
CSPP	10-3-2016[3]	Announcement of the CSPP	26.0%	13.6%	-5.1%	14.2%	-48%	-12%	93.50**
	21-4-2016	Further details on the CSPP	0.8%	0.6%	-98.2%	17.3%	-25%	0%	2.37
TLTRO	5-6-2014	GovC decided to conduct series LTRO	-	-			-		
	16-9-2014	Announcement first LTRO	-	-			-		
	9-12-2014	Announcement second LTRO	-	-			-		
	17-3-2015	Announcement third LTRO	51.0%	49.3%	-9.0%	0.4%	-3%	-2%	0.56
	16-6-2015	Announcement fourth LTRO	54.1%	45.8%	-9.2%	0.4%	-15%	-8%	9.90**
	22-9-2015	Announcement fifth LTRO	29.9%	34.9%	-5.2%	8.5%	16%	5%	14.78**
	9-12-2015	Announcement sixth LTRO	14.0%	15.3%	-7.9%	11.1%	10%	1%	2.74
	22-3-2016	Announcement seventh LTRO	4.1%	7.4%	-13.7%	19.8%	82%	3%	11.19**

Estimation is performed jointly using both three trading days before and after the event on options with one, three and six month maturities. In total 126 option prices are used per estimation (seven per maturity). Parameters κ and ν are restricted to be the same both before and after the event. The jump probability is allowed to vary among both periods. The last column shows the percentage change in jump probability. '-' implies that the optimal estimation yielded no jump risk (P(Jump) = 0). P(Jump) = 1 − e^{−λ}, is the probability on a jump occurring within one year. The last column gives the F-statistics that compare the estimation with the estimation where P(Jump) is also restricted to be the same before and after the period. Significance levels: *p < 0.05, **p < 0.01. [1] Both the third CBPP and the ABSPP were announced at 4-9-2014. [2] At the same day, in a press conference the ECB announced several other monetary policy decisions. [3] Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.

C.2 Number of estimation days

Lastly, we consider the results using two trading days around an event instead of three. When choosing the number of days around an event, one always has to make the trade off between reducing noise by having more observations and having the possibility of other events influencing the results. Choosing four trading days around an event, might result in a too long period since this implies that the estimation period is around two weeks. Furthermore, only one day before and after gives too little observations. Therefore, we will perform a robustness check with two trading days.

First, we consider the regularization method. We see that the results are very similar, except from one event. The 'Whatever it takes' speech has decreased the jump risk with -4.7% if we use two trading days, where it did not do anything for three trading days. However, we still see that the other two OMT announcement have much larger effects.

If we look at the joint calibration method, we see that the % changes and absolute changes in jump probabilities are quite similar. However, the main difference is in the significance of results. The F-statistic is a function of the number of observations, so if we decrease the sample size than we will overall obtain less significant results. We see that five events become insignificant when we use two trading days that were significant using three trading days. Lastly, we see that surprisingly the 'Whatever it takes' speech becomes significant. So similar to the regularization method, we find that if we use two trading days for estimation, the speech seems to have significantly reduced the jump risk. But again, the magnitude and the F-statistic are much smaller for the speech compared to the other two OMT announcement. So again, our main conclusions remain valid.

Table 10: Results of estimation with the Kou model, using regularization method (2 trading days)

Program	Date	Event	Before Event		After Event (w. reg.)		% change
			P(Jump)	E(Jump)	P(jump)	E(Jump)	P(jump)*E(jump)
SMP	9-5-2010	Announcement of the SMP	60.8%	-9.4%	60.8%	-9.4%	0.0%
	14-5-2010	Details of the SMP	56.8%	-8.2%	56.8%	-8.2%	0.0%
	7-8-2011	Relaunch of SMP	57.4%	-8.6%	57.4%	-8.6%	0.0%
LTRO	8-12-2011	Announcement of two 3y LTROs	60.6%	-9.0%	60.6%	-9.0%	0.0%
CBPP	4-6-2009	Start of the first CBPP	62.1%	-8.4%	62.1%	-8.4%	0.0%
	6-10-2011	Start of the second CBPP	62.3%	-10.4%	62.1%	-10.3%	-1.3%
	4-9-2014[1]	Start of the third CBPP (&ABSPP)	-	-	-	-	-
ABSPP	4-9-2014[1]	Start of the third ABSPP	-	-	-	-	-
OMT	26-7-2012	Whatever it takes	55.7%	-5.4%	54.8%	-5.3%	-4.8%
	2-8-2012	Key technical features OMT	53.9%	-5.5%	4.1%	-33.0%	-53.5%
	6-9-2012	End SMP, announce OMT in full	12.0%	-14.1%	5.1%	-14.1%	-57.5%
NIRP	5-6-2014	ECB announced DFR will be negative	-	-	-	-	-
	4-9-2014	Further lowers DFR to -0.2	-	-	-	-	-
	3-12-2015[2]	Further lowers DFR to -0.3	50.8%	-6.2%	30.2%	-6.2%	-40.9%
	10-3-2016[3]	Further lowers DFR to -0.4	52.1%	-5.3%	40.8%	-5.0%	-25.1%
PSPP	22-1-2015	Announcement of the PSPP	44.1%	-6.7%	44.1%	-6.7%	0.0%
	31-1-2015	Further details on the PSPP	48.5%	-6.6%	48.5%	-6.6%	0.0%
CSPP	10-3-2016[3]	Announcement of the CSPP	52.1%	-5.3%	40.8%	-5.0%	-25.1%
	21-4-2016	Further details on the CSPP	0.9%	-81.4%	0.9%	-81.4%	0.0%
TLTRO	5-6-2014	GovC decided to conduct series LTRO	-	-	-	-	-
	16-9-2014	Announcement first LTRO	-	-	-	-	-
	9-12-2014	Announcement second LTRO	-	-	-	-	-
	17-3-2015	Announcement third LTRO	50.5%	-6.9%	50.5%	-6.9%	0.0%
	16-6-2015	Announcement fourth LTRO	51.8%	-7.3%	50.7%	-7.0%	-6.8%
	22-9-2015	Announcement fifth LTRO	39.1%	-5.4%	39.7%	-5.5%	4.6%
	9-12-2015	Announcement sixth LTRO	19.7%	-7.7%	19.7%	-7.7%	0.0%
	22-3-2016	Announcement seventh LTRO	0.8%	-71.3%	0.9%	-72.6%	26.4%

Estimation is performed using two trading days before or after the event on options with one, three and six month maturities. In total 42 option prices are used per estimation (seven per maturity). $P(Jump) = 1 - e^{-\lambda}$, is the probability on a jump occurring within one year. $E(Jump) = \frac{-1}{\eta_2^* + 1}$, is the expected jump size. Parameters before the event are calibrated without regularization, after the event with regularization. The last column shows the change in jump probability multiplied by the expected jump size. '-' implies that the optimal estimation yielded no jump risk ($P(Jump) = 0$). [1] Both the third CBPP and the ABSPP were announced at 4-9-2014. [2] At the same day, in a press conference the ECB announced several other monetary policy decisions. [3] Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.

Table 11: Results of estimation with the Kou model, using joint estimation (2 trading days)

Program	Date	Event	Before P(Jump)	After P(Jump)	E(Jump)	% change P(Jump)	Abs. change P(Jump)	F-stat
SMP	9-5-2010	Announcement of the SMP	61.6%	56.7%	-9.2%	-8%	-5%	2.01
	14-5-2010	Details of the SMP	54.1%	61.0%	-8.7%	13%	7%	4.44*
	7-8-2011	Relaunch of SMP	55.9%	60.8%	-8.9%	9%	5%	2.74
LTRO	8-12-2011	Announcement of two 3y LTROs	60.1%	61.8%	-9.1%	3%	2%	0.38
CBPP	4-6-2009	Start of the first CBPP	62.8%	59.9%	-8.3%	-5%	-3%	0.27
	6-10-2011	Start of the second CBPP	64.1%	57.3%	-10.0%	-11%	-7%	3.96*
	4-9-2014[1]	Start of the third CBPP (&ABSPP)	-	-			-	
ABSPP	4-9-2014[1]	Start of the ABSPP	-	-			-	
OMT	26-7-2012	Whatever it takes	56.3%	51.6%	-5.4%	-8%	-5%	11.99**
	2-8-2012	Key technical features OMT	52.5%	36.7%	-5.6%	-30%	-16%	87.16***
	6-9-2012	End SMP, announce OMT in full	6.0%	2.0%	-23.9%	-66%	-4%	52.79***
NIRP	5-6-2014	ECB announced DFR will be negative	-	-			-	
	4-9-2014	Further lowers DFR to -0.2	-	-			-	
	3-12-2015[2]	Further lowers DFR to -0.3	51.6%	28.6%	-6.1%	-45%	-23%	27.06**
	10-3-2016[3]	Further lowers DFR to -0.4	53.0%	35.0%	-5.1%	-34%	-18%	27.69**
PSPP	22-1-2015	Announcement of the PSPP	43.4%	50.3%	-6.8%	16%	7%	3.36
	31-1-2015	Further details on the PSPP	%	%	%	%	%	
CSPP	10-3-2016[3]	Announcement of the CSPP	53.0%	35.0%	-5.1%	-34%	-18%	27.69**
	21-4-2016	Further details on the CSPP	0.8%	0.7%	-84.5%	-13%	0%	0.24
TLTRO	5-6-2014	GovC decided to conduct series LTRO	-	-			-	
	16-9-2014	Announcement first LTRO	-	-			-	
	9-12-2014	Announcement second LTRO	-	-			-	
	17-3-2015	Announcement third LTRO	51.5%	49.0%	-6.8%	-5%	-3%	0.55
	16-6-2015	Announcement fourth LTRO	52.5%	43.3%	-7.2%	-17%	-9%	6.00*
	22-9-2015	Announcement fifth LTRO	37.2%	43.7%	-5.6%	18%	7%	11.43**
	9-12-2015	Announcement sixth LTRO	27.1%	28.7%	-6.1%	6%	2%	2.56
	22-3-2016	Announcement seventh LTRO	3.1%	5.4%	-21.1%	73%	2%	10.40**

Estimation is performed jointly using both two trading days before and after the event on options with one, three and six month maturities. In total 84 option prices are used per estimation (seven per maturity). The expected jump size is restricted to be the same both before and after the event. The jump probability is allowed to vary among both periods. '-' implies that the optimal estimation yielded no jump risk ($P(Jump) = 0$). $P(Jump) = 1 - e^{-\lambda}$, is the probability on a jump occurring within one year. The last column gives the F-statistics that compare the estimation with the estimation where $P(Jump)$ is also restricted to be the same before and after the period. Significance levels: $*p < 0.05$, $**p < 0.01$. [1]Both the third CBPP and the ABSPP were announced at 4-9-2014. [2]At the same day, in a press conference the ECB announced several other monetary policy decisions. [3]Both lowering the DFR to -0.4% and the start of the CSPP were announced at the same day.

Previous DNB Working Papers in 2019