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A Tale of Four Tails: Inflation, the Policy Rate, Longer-Term Rates, and Stock Prices

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Abstract

We analyze empirical links between the perceived tail-risk of inflation, the policy rate, longer-term interest rates, and equity prices in the U.S. Their simultaneous changes enable us to distinguish between a systematic and "exogenous" response to monetary-policy news. And, those tail risks' co-movements are accounted for in quantifying the magnitude and persistence of their responses to key shocks. We find that: (i) in the medium-term, all four tail risks respond significantly and contemporaneously to domestic and foreign monetary-policy announcements, except for the equity tail risk to foreign policy; (ii) all four tail risks rarely change in response to other U.S. macroeconomic news; (iii) the directional pattern of their simultaneous reactions to policy announcements is often consistent with the systematic response to new information about the economic outlook rather than with the response to an exogenous shock; (iv) the few notable instances of the latter response are always in reaction to Fed announcements; and, (v) our impulse responses demonstrate that odds of extreme inflation outcomes and extreme policy-rate outcomes are tightly linked, and that both determine tail outcomes for longer-term interest rates but not for stock prices.

Keywords: Downside Risk, Derivatives, Monetary Policy

JEL Classification: C32, E52, E58, G12, G14

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1 Introduction

The 2007-09 financial crisis, the subsequent prolonged period of the federal funds rate at the effective lower bound (ELB), and the associated weak recovery, characterized by substantial disinflation and even deflation, made economic events, usually viewed as remote possibilities in the U.S., be perceived as more plausible outcomes needing serious consideration. Indeed, market participants have been willing to pay relatively high prices for protection against extreme macroeconomic (e.g., deflation) and financial (e.g., negative interest rates) outcomes, as demonstrated in the last decade by sharp increases in the value of well out-of-the-money options allowing investors to hedge future abnormal realizations in key economic variables.[1]

Thus, quotes on those derivatives have implied significant odds of tail-risk events evaluated through the lens of investors' risk attitude. The level and fluctuations of these odds are carefully monitored by many central banks, and monetary policy makers have repeatedly stressed that both, the underlying amount of economic and financial risk as well as the attitude toward these risks, deserve considerable attention when formulating the appropriate risk management for monetary policy.[2] The basic idea being that, in certain circumstances (e.g., at the ELB), amid elevated downside or upside risks to the economy, policy should be looser or tighter than would be otherwise. More importantly, at times, monetary-policy communication has been used to provide a backstop to destructive scenarios.[3]

The importance of tail risk or rare-disaster risk for asset pricing and business cycles has been widely recognized in the literature.[4] And recently, researchers have started emphasizing the impact of monetary policy on the pricing of risks and risk-taking behavior as an additional channel of the transmission mechanism—the "risk-taking channel." Yet, there is not much evidence on the propagation of monetary policy to key macro and financial risks in the economy, with the exception of Hattori, Schrimpf, and Sushko (2016), who study the impact of the Fed unconventional monetary policy on the stock-market tail risk, and Zhang and Schwaab (2016), who demonstrate the impact of the ECB unconventional policy of the tail risk of government bonds. However, these works consider a specific tail risk in isolation.

In this study, we analyze the empirical link between the perceived tail-risk of inflation, the policy rate, longer-term interest rates, and the stock market in the U.S. over a recent sample period. Like the first moments of these key variables, their higher moments should be strongly related to each other, as most likely driven by

[1] See, e.g., Kitsul and Wright (2013) and Gao, Lu, and Song (2017).

[2] See, e.g., Evans, Fisher, Gourio and Krane (2015); and Feldman, Heinecke, Kocherlakota, Schulhofer-Wohl, and Tallarini (2016).

[3] See for example ECB President Draghi's statements about OMTs and the "whatever it takes" remark in July 2012.

[4] See for example, Barro (2006), Gourio (2008 and 2011), Watcher (2013), Tsai and Watcher (2015).

common macroeconomic factors: above all, the stance of monetary policy. Therefore, measures of macro and financial tail risks *should not be considered in isolation*, especially when evaluating the impact of policy actions and communications meant to alleviate downside risks in the broader economy. This requires to uncover reactions to common shocks and estimate high-frequency dynamic models to account for those tail risks' co-movements in quantifying the magnitude and persistency of their responses to key shocks.

Specifically, we investigate the impact of domestic and foreign monetary policy on the tail risks of U.S. inflation, the policy rate, longer-term interest rates, and equities. Our main objective is to verify whether policy announcements alleviate downside risks to financial markets and the macro-economy at expectation horizons relevant for fundamental consumption and investment decisions. This is done by investigating first, how these tail risks are connected to each other beyond the short term, and second, by estimating their joint dynamic responses to key macro and financial shocks. In particular, we demonstrate that the probability of extreme inflation outcomes is tightly linked to the probability of extreme policy-rate outcomes and that both determine tail outcomes for longer-term interest rates and stock prices. These findings could be very relevant, for example, to policy makers evaluating the possibility of negative interest rates in the U.S. and/or the prospects of returning to the ELB more frequently and for extended periods of time in case of economic downturns.

To this purpose, we use daily measures of tail risks derived from inflation and interest-rate derivatives such as inflation caps and floors as well as options on Eurodollar futures and on interest-rate swaps. And for stock prices, we rely on S&P500 Index options. Then, we use the event-study methodology to analyze the response of those measures to monetary policy announcements, including those of the Federal Reserve and other major foreign central banks (CBs), to macroeconomic releases, and to risk events like the British referendum to leave the European Union (Brexit). The simultaneous analysis of multiple measures of tail risks helps us to distinguish between the systematic and exogenous response of those variables to monetary policy, in the spirit of D'Amico and King (2015) and D'Amico, King and Wei (2016).

Finally, exploiting the richness of our high-frequency data, we estimate impulse responses to key shocks using Jordà local projection method (Jordà, 2005), which allows to account for non-linearities in the relation between tails risks. Our sample is dominated by the ELB, thus it is harder to assume that historical relationships between key economic variables hold unchanged over this period and are well approximated by a linear VAR. Consequently, we do favor the idea of estimating impulse responses without having to specify an underlying linear multivariate dynamic system.

Our study offers three main empirical contributions. First, in our sample, at medium-term horizons, all four measures of domestic tail risks respond significantly and contemporaneously to the Fed and foreign CBs announcements, with the exception of the equity tail risk in the case of foreign monetary-policy announcements. Further, all four tail risks rarely change in response to other U.S. macroeconomic news, except for the inflation tail risk that is affected by CPI data releases. Second, when considered together, the directional pattern across the four tail reactions to monetary-policy announcements is often consistent with the systematic response to new information about the economic outlook rather than with the response to an exogenous monetary-policy shock. The few notable instances of the latter response are always in reaction to Fed communication and not to foreign CBs' announcements.

Third, our impulse responses indicate that an increase in the risk of deflation induces an immediate increase in the probability of the policy rate falling below the ELB and in the risk of a large decline in longer-term rates, but not in the risk of large reductions in equity prices, with most of those responses dying out after about two months. This is in line with the systematic response that would be predicted by a policy rule accounting for higher-order moments. In addition, an increase in the odds of negative policy rates pushes the risk of disinflation/deflation down for about four months, and significantly reduces the probability of large declines in longer-term rates but again not in equity prices, although these responses are short lived. In contrast, a surge in the probability of very low long-term rates, similarly to what is observed in flight-to-quality episodes, does not elicit any significant change in the odds of disinflation/deflation and of very low policy rates. Similarly, a higher probability of a large decline in stock prices does not affect the dynamics of the other tail risks, which is a bit puzzling if we think that the risk of extreme downward movements in a broad stock-market index can signal poor growth prospects (Adrian, Boyarchenko, and Giannone, 2017). On the other hand, this last finding might indicate that extreme negative events in financial markets do not affect monetary policy above and beyond their impact on macroeconomic risk, like deflation, which we control for.

Our paper is related to a few studies in the literature, although none of them consider the co-movements of tail risks an their joint dynamic responses to key shocks. As already mentioned, Hattori, Schrimpf, and Sushko (2016) study the impact of unconventional monetary policy on the U.S. equity-market tail risk, which is one of the risks included in this study. However, at the longer horizon analyzed here, it does not seem to comove with or be very relevant for other fairly extreme risks in the economy. For the measurement of the disinflation/deflation risk we rely on the Kitsul and Wright's (2013) methodology, and similarly to Longstaff, Fleckenstein, and Lustig (2014) we also focus on deflation risk extracted from inflation derivatives. Regarding our results, some aspects are consistent with Evans, Fisher, Gourio, and Krane (2015), who show that, near the ELB, measures of risks (such as the uncertainty and skewness of individual SPF forecasts) matter for the monetary-policy reaction function. In the same spirit, Gnabo and Moccero (2015) show that the risk to the inflation outlook and in financial markets are powerful drivers of monetary-policy regime changes. More broadly, our study is also related to Feldman, Heinecke, Kocherlakota, Schulhofer-Wohl, and Tallarini (2016) that emphasize the importance of extracting information from financial tools such as those used in this paper.

The rest of the paper is organized as follows. Section 2 describes the data and the four tail-risk measures. Section 3 provides an overview of the recent evolution of tail risks in the U.S. Section 4 summarizes the results of the event-study methodology. Section 5 presents the estimates of the impulse responses to key shocks. Section 6 offers concluding remarks.

2 Data and measures of tail risk

Our 2013-16 sample covers an out of the ordinary period in the U.S. economy, during which most financial and economic risks are perceived as mostly tilted to the downside. For this reason, we focus on measuring the probabilities of extremely low outcomes across four key domestic variables: the policy rate, inflation rate, longer-term nominal interest rates, and a broad stock-market index.

To measure the tail risk associated to the possibility of extreme low realizations of the policy rate, we use the probability mass in the left tail of the risk-neutral probability density function (pdf) implied by options on Eurodollar futures that pay off when at a given horizon the 3-month Libor rate falls below a certain value. Clearly, the probabilities implied by these pdfs reflect not only the perceived odds of a low policy rate, but also premiums that investors are willing to pay to insure against such outcome. Although it is quite difficult to quantify risk premia for very short-term rates, alternative specifications of dynamic term structure models of U.S. nominal interest rates estimated over recent periods often obtain negative term premia across the maturity spectrum, and even more so at shorter maturities.[5] This would suggest that risk-neutral probabilities likely overestimate the "true" probabilities as the risk-neutral pdfs are shifted to the left relative to the objective pdfs.

These pdfs are derived using a mixture-of-normals model to fit the non-parametric risk-neutral pdfs computed each single day at specific maturities from options with different strike prices.[6] Using the mixture of normals is particularly appealing at the ELB because it allows to better capture the asymmetry of the policy-rate distribution around zero and thus its left tail defined over negative values. Figure 1 plots the number of outstanding contracts (open interest) for three options delivering positive payoffs when Libor falls below zero by the end of 2016, 2017, and 2018, respectively. As can be seen, over the summer of 2015, speculations about negative interest rates

[5] See, for example, Kim and Wright (2005), Priebsch (2013), Longstaff, Fleckenstein, and Lustig (2014), D'Amico, Kim, and Wei (2016).

[6] These probabilities are kindly provided by the staff of the Board of Governors of the Federal Reserve System, and are based on Eurodollar futures options because, at the two-year horizon and beyond, are more liquid than the federal funds futures options.

in the U.S. do materialize in traders' positions. At the beginning of 2016, following the decision by the Bank of Japan and the Riksbank to cut their key policy rates into negative territory, those open interests start surging and stabilize at unusually elevated level by mid-2016.[7] To grasp the relative importance of these positions, it can be helpful to know that at the two-year horizon, those contracts accounted for about 16 percent of all outstanding positions at that horizon.

In the rest of the paper, we focus on options that pay off when the Libor falls below zero and below 50 basis points. The average wedge between Libor and FFR in our sample is of about 18 basis points and their correlation is 0.96; therefore, we treat the derived pdfs as proxies of the policy-rate distribution. Specifically, by choosing the threshold of 50 basis points, we are effectively tracking the probability of returning to the ELB. Further, we focus on options with maturity of about 4 years, as changes in believes at the medium-term horizon are more relevant for monetary policy, as by persisting beyond the short term are more likely to affect economic fundamentals. In addition, this horizon allows us to obtain the longest time series of these probabilities by rolling into contracts whose expiration date at each point in time is about 4 years out.

The pdfs for consumer price index (CPI) inflation are derived from inflation caps and floors using the methodology described in Kitsul and Wright (2013) and are updated regularly by the staff of the Board of Governors of the Federal Reserve System. To match as closely as possible the horizon of the policy-rate pdfs, we focus on probabilities of average inflation being less or equal zero, 1 percent, and 2 percent, respectively, over the next 5 years. The first threshold is relevant for measuring the perceived risk of deflation, the second to capture the risk of very low inflation (even disinflation), and the third one to summarize the risk of inflation falling below the objective of the Federal Reserve.

To measure the tail risk for longer-term rates, that is, the five- and ten-year nominal interest rates, we rely on swaptions. These are options that give their holders the right at the expiration date to enter into an interest rate swap at a predetermined fixed rate, which should measure the interest rate expected to prevail over the pertinent horizon. In particular, we compute the skewness of the risk-neutral pdfs taking the difference between the implied volatility (IV) of a call with a strike price equal to the at-the-money strike price plus 25 basis points (ATM+25) and the IV of a put with a strike price equal to the at-the-money strike price minus 25 basis points (ATM−25). A negative value of this proxy indicates that market participants are more fearful of a large decline in interest rates than of a large increase, as they are willing to pay more for protection against sharp fall in interest

[7] Federal Reserve Chair Janet Yellen, when asked about the prospect of negative interest rates in the US, during the February 11, 2016 Congressional hearing, stated: "We're taking a look at them ... I wouldn't take those off the table." Similarly, in the subsequent Congressional hearing on May 12, 2016, Yellen said "I would not completely rule out the use of negative interest rates in some future very adverse scenario."

rates. Also for this measure of tail risk we try to match as closely as possible the horizon of the tails computed for the policy rate and inflation. Given that at times we are constrained by the available quotes, we are able to obtain a consistent times series for the skewness of the 5- and 10-year yields at the 2- and 5-year horizons.

Finally, to derive the tail risk for the U.S. equity market, which can be also viewed as a proxy of the tail risk for growth, we use the IVs for the S&P500 Index options at two different strike prices; in particular, we focus on moneyness (strike/spot price) of the quoted option prices at 120 percent and 80 percent of the current spot price, which cover the two fairly extreme states of a 20-percent increase and a 20-percent decline in the S&P 500 Index, respectively. And, more importantly, the difference between these two IVs can inform us on the asymmetry of the perceived risk to equities and perhaps growth, as a negative value of this skewness would indicate that investors are more concerned about a 20-percent decline than an increase of the same magnitude. We refer to this measure as the skewness of the S&P500 Index. Given the liquidity of the available quotes, we are able to focus at most on the 2-year horizon, which is close enough to the horizons of the other three tail risks described above.

3 Recent evolution of tail risks

Figure 2 depicts the evolution over time of three measures of tail risk from December 2013 to September 2016. In particular, the top panel plots the probabilities of inflation falling below 0, 1, and 2 percent, respectively, over the next five years. They indicate that, over this sample period, market participants become increasingly confident that, over the next five years, the Fed will not be able to hit the 2-percent inflation target, inflation below 1 percent can become a pretty frequent event, and the risk of deflation is not negligible. The middle-panel plots the probability that the 3-month Libor falls below 0 and 50 basis points, respectively, in four years' time; indicating that, during 2013-16, the odds of the U.S. policy rate turning negative in the medium term varies from 5 to 23 percent and of staying/returning to the ELB fluctuate between 10 and 35 percent. The bottom panel plots the skewness of the S&P500 Index at the two-year horizon, which in this period is always below zero, suggesting that investors believe that odds of a 20-percent decline in stock prices are much larger than those of a 20-percent increase. Figure 2 is complemented by Figure 3, which in the top two panels shows the same variables plotted in Figure 2, but in the bottom panel plots the skewness of the 5- and 10-year nominal interest rates distributions at the two- and five-year horizons. Also this measure is always negative in our sample.

These two graphs should help visualize the co-movements across the four tail risks, which we are going to describe shortly; even though, implications for longer-term yields are discussed separately in Section 4.1, as those are a bit harder to interpret due to the different moving parts within yields, mainly the expectation and term-premium components. Further, to illustrate the triggers of the changes common to all four measures, in each panel, the black vertical lines mark the days of the most relevant Fed communications, the blue vertical lines mark major foreign CBs' announcements, which include those of the European Central Bank (ECB), the Bank of England (BoE), the Bank of Japan (BoJ), and the Riksbank, and the red vertical lines mark four risk events unrelated to monetary policy, that is, the flash crash of October 2014, the Greek bailout referendum in July 2015, the International Monetary Fund (IMF) release of the global economic forecast, and Brexit in June 2016.[8] To avoid crowded plots, we had to include only selected events, as we have more than 200 foreign policy announcements in this sample period.

Importantly, in what follows, we classify the reactions to those events in two broad categories: 1) a *systematic response* to new information emerging about the economic outlook, characterized by the probabilities of a very low policy rate and very low inflation moving in the same direction, as well as the S&P500 skewness changing in the direction opposite to these two probabilities; and 2) an *exogenous response* to a monetary-policy shock, characterized instead by the odds of a very low policy rate and very low inflation moving in opposite directions, as well as the S&P500 skewness varying in the same direction as the policy-rate tail risk. These are the only patterns consistent with a reaction to an exogenous policy shock (for more details see D'Amico and King, 2015; and D'Amico, King, and Wei, 2016). In other words, if market participants perceive the FOMC decision as more accommodative than expected, the probability of a very low policy rate should increase and the probability of very low inflation should decrease, while also the prospects for equities should improve, making the stock-market skewness less negative (and therefore increasing toward zero in our graph), as the economy is expected to improve because of the policy easing.

It is evident from the description of these two types of responses that it would be impossible to distinguish them by focusing on a single measure of tail risk as done in previous studies.

Before going in more details, we briefly summarize the most relevant events as, interestingly, we find that only a handful of reactions to policy announcements in our sample can be safely classified as exogenous responses. That is, December 17, 2014, when the FOMC stated that it would be "patient in beginning to normalize the stance of monetary policy;" January 28, 2015, when the FOMC retained the "patient" language but was perceived as more upbeat about the economic outlook; and March 18, 2015, when the FOMC removed the "patient" language but indicated that it will take a slow and steady approach to rate hikes. Most of the domestic tail risk reactions to foreign CBs' announcements are in line with a systematic response.

[8] As a reminder, on the day of the Greek bailout referendum, the conditions imposed for the bailout were rejected and this in turn led to the resignation of the Prime Minister.

However, also Fed policy actions, like those announced at the September 2015 FOMC that delayed the first liftoff expected in about seven years, seem to be interpreted in a pessimistic way, eliciting reactions consistent with a systematic response.

3.1 What makes those tails wag

From the beginning of the sample until about August 2014 all three measures are mostly stable. Following the September 17, 2014 FOMC meeting, when the Fed slashed its 2015 forecast range for GDP growth down to just 2.6% to 3%, from 3.0% to 3.2% in June, the risk of very low inflation jumps higher while the other two measures stay almost unchanged, indicating a pessimistic interpretation of the Fed communication.

Subsequently, both, the risk of negative rates and the risk of very low inflation rise around the flash crash of October 15, 2014, while the S&P500 skewness becomes notably more negative; although, these moves are quickly reverted. On October 31, 2014, the BoJ surprised markets with a significant expansion of its QE program, and odds of a very low policy rate and very low inflation decrease simultaneously, in line with a positive revision to the global economic outlook. But, on November 6, 2014, the ECB tried reassuring the markets while still postponing the beginning of QE. Amid declining oil prices, increased concerns about global economic growth and deflationary pressure in Europe, the probability of very low inflation starts souring. However, odds of negative rates stay flat and the S&P500 skewness does not change much.

Following the December 17, 2014 FOMC announcement, in which the Fed stated that it would be "patient in beginning to normalize the stance of monetary policy," the probability of very low policy rate starts raising, the probability of very low inflation declines, and the S&P500 skewness becomes significantly less negative, in line with a reaction to an accommodative policy shock.

On January 22, 2015, as expected, the ECB announced the beginning of a large QE program, and both probabilities of a low policy rate and low inflation decline a bit, while the equity risk stays flat, suggesting perhaps an endogenous response to better foreign economic conditions in the future. But, after a few days, on January 28, 2015, as the Fed retained the “patient” language and was perceived as more upbeat about the economic outlook, the probability of low rates increases a touch, the probability of very low inflation declines, and the S&P500 skewness spikes toward zero, hinting again at an accommodative policy shock.

On February 5, 2015, also the BoE held its policy rate unchanged, postponing further the time of its first rate hike in six years, and both probabilities of a very low policy rate and very low inflation move down together, while the S&P500 skewness is about unchanged, in line with an endogenous response to good economic news from abroad. Similarly, also the skewness of longer rates became less negative. Starting on March 5, 2015, when the ECB decreased the interest rate on the deposit facility from -0.20% to -0.30%, both probabilities of negative rates and very low inflation begin rising again, implying a pricing in of a deteriorating global outlook.

In contrast, at the March 18, 2015 FOMC meeting, when the Fed removed the "patient" language and indicated that it will take a slow and steady approach to rate hikes, the probability of low rates increases and the probability of low inflation decreases, consistently with an easier-than-expected monetary policy stance. In line with this interpretation, the skewness of longer rates became a bit more negative and the S&P500 skewness increases a touch, becoming less negative.

Starting with the Greek referendum on July 5, 2015, all measures in the top two panels start co-moving more closely: odds of a very low policy rate increase slowly but steadily and so does the probability of deflation rising from 10 to 20 percent, while the probability of inflation falling below 1% climbs much faster reaching 60 percent. Further, after the September 17, 2015 FOMC, as the Fed postponed the first liftoff, both probabilities of a very low/negative rate and of very low inflation get a further boost and re-start increasing after a brief pause, implying a pessimistic interpretation of the policy move. However, equity investors seem positively surprised as the S&P500 skewness jumps higher.

Subsequently to the October 28, 2015 FOMC, as market participants became increasingly confident that the first rate hike would occur at the next FOMC meeting, the probability of low/negative rates declines a bit, the probability of very low inflation is about unchanged, and the S&P500 skewness becomes more negative, suggesting an ambiguous response, whose imprint is extremely short lived. At the end of December 2015, as crude oil data came in worse than expected[9] and the head of the IMF, Christine Lagarde, forecasted that global economic growth will be "disappointing and patchy" in 2016, the probability of a low/negative policy rate and the probability of very low inflation start drifting higher. In addition, bad news about China's stock market during the first two weeks of January 2016 seem to only accelerate this upward trend in tail risks.

On January 14, 2016, BoE gave a more gloomy verdict on economic prospects while voting to keep interest rates on hold. On January 28, 2016 BoJ cuts its policy rate into negative territory for the first time, and on February 10, 2016 the Riksbank lowered its already negative rate further. Following these sequence of events the probability of a negative policy rate in the U.S. soars from 7% to 23%, and the odds of the policy rate to return to the ELB reach 35%. Similarly, the probability of deflation in the U.S. gets to 20% and the probability of inflation lower than 1% becomes as high as 65%. These probabilities moving in lock steps, and in response to foreign events, is a clear example of a systematic response to worsening global economic conditions. Similarly, longer-term rates skewness declined from -3% to

[9] On December 30 2015, government data revealed that inventories of U.S. commercial crude oil surprisingly increased by 2.6 million barrels for the week ended Dec 25. This was in contrast to projections from analysts surveyed by The Wall Street Journal that U.S. crude inventories will decline by 1 million barrels.

−6%; while, in contrast, the S&P500 skewness becomes a bit less negative amid elevated volatility.

In contrast, on March 10, 2016, when the ECB decreased the interest rate on the deposit facility from −0.30% to −0.40%, both probabilities of a negative policy rate and very low inflation decline slightly, but the equity tail is very little changed, implying a mixed reaction of U.S. investors to the ECB action. However, around the time of this event, the odds of a very low policy rate continue to seesaw around the newly-reached high levels, but the probability of very low inflation has already returned to levels observed before the Greek referendum.

On June 23, 2016, due to Brexit, probabilities of a negative/low policy rate and very low inflation rise again, even if for a short time period. At the same time, the S&P500 skewness plunges to its most negative level of about −10%, followed shortly after by a very large decline in the longer yields' skewness. All four movements strongly suggest an endogenous response to a negative revision of the foreign economic outlook. On July 14, 2016, as the BoE surprised the markets by leaving interest rates unchanged, the odds of a very low policy rate decline, those of very low inflation are about unchanged, and the S&P500 skewness turns significantly less negative, indicating one more time a systematic response to an upward revision in the foreign outlook.

The main lessons we learned by analyzing the contemporaneous changes in these tail risks are the following. First, measures of tails risks in the U.S. are very sensitive to foreign developments. Second, the responses to foreign CBs' announcements do not follow the directional pattern expected in the case of exogenous monetary policy shocks, but rather the pattern prescribed by a systematic response to changes in the economic outlook. Finally, reactions across all measures that would be consistent with the response to an exogenous policy shocks are few in our sample and occur only in response to the FOMC announcements, that is, to domestic monetary policy shocks.

4 Event studies

To asses the existence of shocks common to all four measures, we analyze the high-frequency reaction of the described tail risks to monetary policy announcements in the U.S. and abroad, as well as to macroeconomic news.

Specifically, the monetary policy shocks are approximated by changes in the OIS rates of different maturities on the days of the policy announcements. Those maturities span an horizon from one month to four years ahead. We focus on OIS rates changes at different horizons because similarly to Gurkainak, Sack, and Swanson (2005) we are interested in capturing the shift in the entire policy-rate path, which is more relevant for consumption and investment decisions. In contrast, rate jumps at the shortest horizons tend to capture the time-surprise component, which is less persistent and should not matter for economic fundamentals. The macroeconomic surprises are obtained as the difference between the actual released value and the median survey expectations from Bloomberg.

In the event-study, we relate daily changes in our measures of tail risks (TR) to the monetary policy surprises (mps) and the domestic macroeconomic news (mn) running simple OLS regressions of the form:

$$\Delta TR_{t,h} = \sum_{i=1}^{n} mps_{i,t,h} + \sum_{j=1}^{k} mn_{j,t} + \varepsilon_{t,h} \tag{1a}$$

where h is the horizon of the market participants' expectations, n is the number of central banks under consideration, and k is the number of macro data releases included in the event study. In the tables summarizing the regression results, we report the coefficients for the macro news only when statistically significant. The data releases included in our analysis are: CPI, GDP (advance), housing starts, new home sales, existing home sales, retail sales, jobless claims, business investments, factory orders, construction spending, and nonfarm payrolls.

The events common to all four tail risks include 23 FOMC announcements, 6 semiannual testimonies of the Chair of the Federal Reserve to Congress, and 74 announcements of major foreign CBs, that is, the ECB, the BoE, the BoJ, and the Riksbank. However, for the tail risks that are available to us on longer sample periods, we are able to include a larger number of monetary-policy announcements, up to 72 for the FOMC and 202 for foreign CBs. This is because in the case of the CPI and stock-market tail risks we can extend the sample back to January 2010;[10] while, when we include in the analysis the policy-rate risk we are limited to the period 2013-2016.

As shown in Table 1 through 8, all four measures of tail risks respond significantly to Fed communication (FOMC announcements and Chair testimonies) and to major foreign CBs announcements, with the exception of the stock-market tail risk in the case of foreign monetary policy. Overall, a larger-than-expected increase in the U.S. short-rate expectations today reduces the odds of an extremely low policy rate in the future, increases the odds of very low inflation in the future, lowers the odds of large decline in longer-term rates (i.e., leads to less negative skewness), and increases the probability of large losses in the stock market (i.e., leads to a more negative skewness). In contrast, if the positive change in the OIS rates is driven by foreign CBs' announcements, it reduces the odds of very low U.S. inflation in the future. In other words, it seems to be interpreted as positive news about the foreign economic outlook that can therefore have positive implications for the domestic inflation outlook.

In the case of probabilities of an extremely low/negative policy rate (Table 1 and

[10] In this case, the 72 Fed events include 52 FOMC, 14 semiannual testimonies of the Chair of the Federal Reserve to Congress, and 6 Jackson Hole Speeches.

2), the explanatory power of the Fed policy surprises is almost twice as big as that of foreign CBs, and it increases with the horizon of the short-rate expectations (i.e., the R^2 is the largest for changes in the 4-year OIS rates). Intuitively, a monetary-policy shock that affects expectations four years into the future has a higher likelihood to affect investment and consumption decisions today, affecting current and future growth relatively more than short-term shocks. This, in turn, implies that it should be more relevant for the variations in the probability of the ELB or negative rates to occur. Further, the magnitude of the estimated coefficients decreases as the maturity of the OIS rate increases, implying that, at the 4-year horizon, a 25-basis-point increase in the OIS rate reduces the probability of a very low/negative policy rate by about 2.5 percent. The results are practically unchanged if we focus only on the FOMC announcements by excluding the six testimonies.

For the U.S. inflation tail risk (Table 3 and 4), we also find that the explanatory power of the Fed announcements is much larger than those of foreign CBs and it is the highest for changes in the one- and two-year OIS rates. In particular, a 25-basis-point increase in the one-year OIS rate raises the odds of very low/negative inflation by 9 and 2 percent, respectively. In addition, at certain horizons, the CPI data releases are also statistically significant when they occur on the same days of the policy events: a higher-than-expected increase in CPI lowers the odds of very low inflation in the future. And, in Table 9, we show that in our sample, similarly to Kitsul and Wright (2013), among all of the macroeconomic news considered (at daily and not just at FOMC frequency), only the CPI surprise has a significant impact on the 5-year probabilities of very low/negative inflation. As those authors suggest, part of this significant response could be mechanical as inflation caps and floors are based on the CPI, but it should be less so at longer horizons like the five year. Finally, as already mentioned, in the case of foreign CBs announcements the sign of the response is negative and it is more relevant for the 4-year OIS changes, implying that these policy changes are viewed as an endogenous response to a better outlook rather than as a tightening policy shock.

Turning to the risk for longer-term interest rates (Table 5 and 6), we find that only the skewness of the 5-year interest rate responds positively and significantly to the Fed communications, while both the skewness of 5- and 10-year interest rates display a positive and significant response to the foreign CBs announcements. Further, the explanatory power of the Fed and foreign CBs changes is quite similar, perhaps suggesting the relevance of flight-to-quality and search-for-yield episodes in this period. In particular, a looser-than-expected policy abroad would push investors toward U.S. Treasury securities pressuring their prices higher and their yields lower, therefore leading to a more negative skewness. This could be particularly likely since many long-term government bonds of European countries like Switzerland, Germany, and Denmark have been trading at negative nominal yields in our sample.

Finally, in the case of the equity tail risks (Table 7 and 8), we find that only the responses to Fed policy changes are negative and significant, but not across all four maturities of the OIS rates. In particular, those policy changes are relevant only if they affect the front end of the policy-rate path and the R^2 are very low. Our results are not directly comparable to those of Hattori et al. (2016) because of various factors. First, we do not focus on the probability of a 20-percent drop in the stock market but we focus on the difference between the probability of a 20-percent increase (+20%) and the probability of a 20-percent decline (−20%), as both tails might change in the same direction, but the net variation might better reveal whether the policy announcement has been interpreted as a positive or negative event for equities. Interestingly, when we run the regressions with each of these probabilities separately, we do find that in reaction to a larger-than-expected policy tightening, both the probability of +20% and the probability of −20% raise, but the latter increases relatively more leading to the negative coefficient observed in Table 7. Second, our sample period is slightly different as it covers the period 2010-2016, while theirs goes from 2008 to 2012, as those authors are mainly interested in unconventional monetary policy. Finally, we analyze the equity tail risk at a longer horizon (2 years), as we are not particularly interested in near-term risk variations. However, as a term of comparison, we also show the results for the two-month horizon in the bottom panels of Table 7 and 8. In this case, the coefficient is positive and significant across all OIS maturities, which seems to suggest that, in the short-run and in this particular sample dominated by the ELB, a larger-than-expected tightening is interpreted as a good news, as it might reveal that the Fed is more upbeat about the economic outlook than previously thought.

4.1 Implications for longer-term Treasury yields

The evidence presented so far can have important implications for longer-term yields. First, the prospect of the policy rate turning negative in the future would lower the average expected component of longer-term yields, even if the modal path of the policy rate remains unchanged. If this was the case, what could be changing is the skewness of the distribution of interest rates approximated by the difference between the mean and mode of the policy-rate pdf. This, in turn, could push down the risk premiums component of the yields as investors move toward longer duration bonds to obtain positive yields, or to hedge against potential losses on more risky financial assets if the higher probability of negative rates is viewed as a response to a deteriorating economic outlook.

Table 10 summarizes the impact of the inflation and policy-rate tail risks on the 10-year nominal Treasury yield and on its term premium estimated with the model of Kim and Wright (2005). The coefficients for the probability of a negative policy rate and the probability of returning at the ELB (i.e., probability of Libor ≤ 50) are negative and significant, indicating that an increase of 10% in the probability of very low/negative short rates can reduce the 10-year nominal yield by about $40-50$ basis points and the term premium by about $27-35$ basis points. This suggests that a nonnegligible probability of shot-term rates turning negative or reverting to the ELB have been likely putting downward pressure on longer-term Treasury yields in recent years, and that this downward pressure has been working in large part through the term premium component.

In contrast, the probability of deflation or very low inflation are not significant as probably subsumed by the probability of very low short rates.

5 Joint dynamics of tail risks

In this section, we estimate impulse response functions (IRFs) using Jordà local projection approach (Jordà, 2005) with daily observations, as it does not require specific assumptions about the data generating process (DGP), which we find particularly appealing at the ELB and in dealing with higher-order moments of pdfs. The methodology consists in estimating for each horizon s locally-linear approximation of the DGP by simple linear regression methods and to use heteroskedasticity and autocorrelation (HAC) robust coefficients' standard errors, which in turn are used to build a 95% confidence interval for each element of the IRF at time s.

Specifically, we estimate the following empirical model:

$$y_{t+s} = \alpha^s + \Psi^s(L)z_{t-1} + \Psi^s(L)y_{t-1} + \beta^s TR_t + u_{t+s} \qquad s = 0, 1, ..H \tag{2a}$$

where y is the tail risk of interest, z_{t-1} is a vector of control variables and in our specification just includes the other tail risks, $\Psi^s(L)$ is a polynomial lag operator, and TR_t is the specific risk that is shocked and to which the variable of interest is allowed to respond contemporaneously, and H is the longest horizon considered in the IRF. The results are not sensitive to the choice of lags for the control variables but in all the figures that follow 10 lags are used, and H is set equal to 90 days, although we have been experimenting with much longer horizon without observing any relevant difference in the estimates.

In the baseline equations, the identification is based on a simple Cholesky decomposition that resembles the rationale behind monetary-policy VARs commonly used to model the first moments. Our equation specifications are equivalent to the following variable ordering: inflation tail risk, policy-rate tail risk, tail risk of longer-term rates, and equity tail risk. This implies that the policy-rate tail risk can respond contemporaneously to inflation tail risk, and that the skewness of longer-term rates and the S&P 500 Index can respond contemporaneously to both inflation and policy-rate tail risks. It is important to note that in the case of daily data, the zero restrictions are less stringent as the variables are allowed to respond with one-day delay and not after one month or one quarter. Nevertheless, we will show some robustness to this assumption by using an alternative identification scheme.

In what follows we focus first on three different specifications including only three tail risks, as based on the event-study results the equity tail risk does not respond as strongly and consistently as the other tail risks to the selected key shocks, and thus might not be very relevant for the tail risk co-movements. However, we then proceed to add the equity tail risk and estimate a model with all four measures.

Model 1 includes the probability of average CPI over the next 5 years $\leq 0\%$, the probability of the policy rate over the next 4 years $\leq$ 0bp, and either the skewness of the 5-year yield 2 years ahead or the skewness of 10-year yield 2 years ahead. Model 2 includes the probability of average CPI over the next 5 years $\leq 0\%$, the probability of the policy rate over the next 4 years$\leq$ 50bp, and either the skewness of the 5-year yield 2 years ahead or the skewness of 10-year yield 2 years ahead. Model 3 includes the probability of average CPI over the next 5 years $\leq 1\%$, the probability of the policy rate over the next 4 years$\leq$ 50bp, and either the skewness of the 5-year yield 2 years ahead or the skewness of 10-year yield 2 years ahead.

The IRFs resulting from Model 1 are plotted in Figure 4. The first column shows that a one-standard-deviation shock to the risk of deflation implies an increase in the probability of deflation of 0.4%, which in turn elicits an increase of about 0.2% in the probability of a negative policy rate, and raises the probability of a large decline in the 5-year nominal interest rate by making the skewness more negative. These effects materialize at impact and tend to wear off in about 30 business days. The second column shows the responses to a one-standard-deviation shock to the risk of a negative policy rate. This is equivalent to an increase of 0.4% in that probability and lowers the probability of deflation by half as much in about a month, with this drop persisting for about 4 months. The third column summarizes the IRFs to a one-standard-deviation shock to the skewness of the 5-year yield 2 years ahead. It is easy to note that none of the other tail risks respond significantly. If the skewness of the 5-year yield is replaced by that of the 10-year yield, the entire picture is unchanged, hence it is not shown for brevity.

Figure 5 plots the IRFs resulting from Model 2, in which the probability of a negative policy rate over the next 4 years has been replaced by the probability of the policy rate returning to the ELB over the same horizon (i.e., the policy rate over the next 4 years $\leq$ 50bp). It can be seen that the responses are very similar to those obtained for Model 1, the only noticeable difference is that now the reaction of the policy-rate risk to an increase in the deflation risk is a bit larger and persists for about 50 business days (middle panel in the first column). As shown in Figure 6, if within Model 2 the skewness of the 5-year yield is replaced by that one of the 10-year yield, the results are very similar, except that the size of the responses of the 10-year yield skewness is about half as much as those of the 5-year yield skewness. This is not surprising as the tail risk at the longer end of the yield curve should be less sensitive to medium-term shocks than the belly of the curve.

Figure 7 displays the responses obtained from Model 3, in which the probability of deflation has been replaced by the probability of very low inflation (i.e., average CPI over the next 5 years $\leq 1\%$). In this case, it is worth noting that even if the responses are very similar in magnitude and persistence to those shown for Model 1 and 2, in the case of the risk of very low inflation, a one-standard-deviation shock is three times larger than the shock to the deflation risk, and nevertheless its impact on the other tail risks is very little changed, suggesting overall a lower sensitivity to this less extreme event. Again, the results for the 10-year yield skewness are not shown because extremely similar to those obtained using the 5-year yield skewness.

Finally, Figure 8 shows the results from the model including also the equity tail risk (i.e. the skewness of the S&P 500 Index two years ahead). Across the first three columns, it can be seen that the responses in the first three rows are very similar to those obtained in the previous models. In other words, controlling for the equity tail risk has not affected our results. Further, as shown in the last row, the equity tail risk does not respond significantly to any of the three shocks considered so far. And, as shown in the last column, none of the other tail risks is impacted by shocks to the equity tail risk. This would suggest, for example, that the probability of a negative policy rate is not affected by extreme realizations of the stock market above and beyond their impact on the probability of deflation and very low inflation, when this key macro risk is controlled for.

5.1 Robustness

Based on the event-study results, we do know that both the risk of deflation/very-low inflation and the risk of a negative/very-low policy rate react immediately to monetary-policy shocks approximated by changes in the OIS rates. Hence, the assumption that the inflation tail risk responds with one-day delay to the policy-rate tail risk might not be well grounded, as both those tail risks are affected at the same time by changes in the policy rate path (i.e., the first moments of the policy rate distribution at different horizons) and those changes are omitted from equation (2) for parsimony.

For this reason, we use an alternative identification approach, very similar to that developed in D'Amico and Farka (2011), to verify the robustness of our results. In particular, using the coefficients estimated in Table 3, we build measures of the deflation/low-inflation risk purified from the impact of the Fed policy announcements, and use these new measures as an instrument for the original inflation tail risk in the local projection equations. This allows us to analyze in a cleaner way the responses of the other tail risks to shocks to the deflation/low-inflation risk and vice versa, as this new measure of inflation tail risk, including only the component not explained by jumps in the OIS rates, by construction cannot respond simultaneously to policy changes.

The results based on this alternative identification are shown in Figure 9. It is evident that they are extremely similar to those shown in Figure 8, although the one-standard-deviation shock to the instrumentalized probability of deflation is slightly larger. This is true for any of the specifications included in Model 1, 2 and 3, not shown for brevity. In interpreting these results, it is important to keep in mind that, even if the tail risk of inflation has been purified by the impact of changes in the first moments of the policy-rate distribution, it does not necessarily mean that cannot respond to changes in the higher moments of the same distribution.

Figure 10 illustrates our second and last robustness exercise, in which, to provide a term of comparison, we show the results based on a traditional VAR using the same Cholesky decomposition described above (the green responses) with the baseline IRFs obtained with the local projection method. It is worth noting that, relative to the VAR, our results do not tend to overestimate the magnitude or persistence of responses, and, at times, the VAR-estimates are outside the confidence bands implied by the local projection method, suggesting that most likely allowing for a non-linear DGP in this sample did make a difference.

6 Conclusions

Our findings indicate that key macro and financial tail risks in the economy are indeed related. First, higher perceived odds of extremely low policy rates in the medium term can effectively reduce the probability of deflation or very low inflation, and this response materializes fast and is quite persistent. This suggests that certain types of monetary-policy announcements/strategies can likely provide a backstop to destructive scenarios.

Second, the probability of a very low/negative policy rate seems to increase in response to shocks that raise perceived deflation risk. This perhaps is not surprising considering that, in recent years, Fed policymakers have often related their decisions to a desire to reduce the risk of deflation (e.g., Fed Chairman Bernanke's statement in his July-2012 Testimony).

Third, longer-term U.S. nominal Treasury yields seem to be strongly affected by changes in the odds of these extreme macro and policy events. In particular, we find that a ten-percent increase in the probability of a very low/negative policy rate can reduce the 10-year nominal yield by about $40 - 50$ basis points and about two thirds of this impact materializes through a lower term premium.

Clearly, there is still some work to do, as, for example, the sample period is too short to determine how actual macro data respond to changes in those tail risks, and we leave this to feature research.

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Table 1: Impact of Fed policy on the U.S. policy-rate tail risk

	4y-Pr(Libor≤0)	4y-Pr(Libor≤0)	4y-Pr(Libor≤0)	4y-Pr(Libor≤0)
ΔOIS_{3m}	-45.2^{*}			
ΔOIS_{1y}		-18.9^{***}		
ΔOIS_{2y}			-12.2^{***}	
ΔOIS_{4y}				-8.0^{***}
N	29	29	29	29
R^2	0.30	0.53	0.65	0.71

	4y-Pr(Libor≤50)	4y-Pr(Libor≤50)	4y-Pr(Libor≤50)	4y-Pr(Libor≤50)
ΔOIS_{3m}	-73.8^{**}			
ΔOIS_{1y}		-30.6^{***}		
ΔOIS_{2y}			-19.8^{***}	
ΔOIS_{4y}				-12.9^{***}
N	29	29	29	29
R^2	0.32	0.56	0.70	0.76

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.model.

Table 2: Impact of foreign CBs' policy on the U.S. policy-rate tail risk

	4y-Pr(Libor≤0)	4y-Pr(Libor≤0)	4y-Pr(Libor≤0)	4y-Pr(Libor≤0)
ΔOIS_{3m}	-32.8^{***}			
ΔOIS_{1y}		-25.1^{***}		
ΔOIS_{2y}			-16.7^{***}	
ΔOIS_{4y}				-9.8^{***}
N	74	74	74	74
R^2	0.07	0.26	0.33	0.32

	4y-Pr(Libor≤50)	4y-Pr(Libor≤50)	4y-Pr(Libor≤50)	4y-Pr(Libor≤50)
ΔOIS_{3m}	-52.7^{***}			
ΔOIS_{1y}		-38.9^{***}		
ΔOIS_{2y}			-26.2^{***}	
ΔOIS_{4y}				-15.7^{***}
N	74	74	74	74
R^2	0.09	0.28	0.36	0.37

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 3: Impact of Fed policy on the U.S. inflation tail risk

	5y-Pr(CPI≤0%)	5y-Pr(CPI≤0%)	5y-Pr(CPI≤0%)	5y-Pr(CPI≤0%)
CPI	−0.14	−0.17	−0.27	−0.37*
ΔOIS_{3m}	15.9*			
ΔOIS_{1y}		8.8***		
ΔOIS_{2y}			4.9***	
ΔOIS_{4y}				2.2**
N	72	72	72	72
R^2	0.25	0.33	0.33	0.28

	5y-Pr(CPI≤1%)	5y-Pr(CPI≤1%)	5y-Pr(CPI≤1%)	5y-Pr(CPI≤1%)
CPI	−0.26	−0.47	−0.91	−1.28*
ΔOIS_{3m}	72.4***			
ΔOIS_{1y}		37.2***		
ΔOIS_{2y}			19.4***	
ΔOIS_{4y}				8.07***
N	72	72	72	72
R^2	0.29	0.41	0.37	0.27

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 4: Impact of foreign CBs' policy on the U.S. inflation tail risk

	5y-Pr(CPI≤0%)	5y-Pr(CPI≤0%)	5y-Pr(CPI≤0%)	5y-Pr(CPI≤0%)
CPI	−0.34*	−0.33*	−0.32*	−0.31
ΔOIS_{3m}	−4.3			
ΔOIS_{1y}		−4.9		
ΔOIS_{2y}			−4.85**	
ΔOIS_{4y}				−3.2***
N	175	175	175	175
R^2	0.01	0.02	0.06	0.10

	5y-Pr(CPI≤1%)	5y-Pr(CPI≤1%)	5y-Pr(CPI≤1%)	5y-Pr(CPI≤1%)
CPI	−0.88	−0.87	−0.84	−0.81
ΔOIS_{3m}	−4.05			
ΔOIS_{1y}		−12		
ΔOIS_{2y}			−14.8***	
ΔOIS_{4y}				−10.4***
N	175	175	175	175
R^2	0.02	0.03	0.09	0.15

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 5: Impact of Fed policy on U.S. longer-term interest rates tail risk

	2y-Skew(5yR)	2y-Skew(5yR)	2y-Skew(5yR)	2y-Skew(5yR)
ΔOIS_{3m}	7.4			
ΔOIS_{1y}		3.9^{*}		
ΔOIS_{2y}			2.6^{**}	
ΔOIS_{4y}				1.5^{**}
N	42	42	42	42
R^2	0.09	0.16	0.21	0.22

	2y-Skew(10yR)	2y-Skew(10yR)	2y-Skew(10yR)	2y-Skew(10yR)
ΔOIS_{3m}	1.95			
ΔOIS_{1y}		1.34		
ΔOIS_{2y}			1.0	
ΔOIS_{4y}				0.64^{*}
N	42	42	42	42
R^2	0.06	0.10	0.14	0.17

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 6: Impact of foreign CBs' policy on U.S. longer-term interest rates tail risk

	2y-Skew(5yR)	2y-Skew(5yR)	2y-Skew(5yR)	2y-Skew(5yR)
ΔOIS_{3m}	16.3^{***}			
ΔOIS_{1y}		10^{***}		
ΔOIS_{2y}			5.7^{***}	
ΔOIS_{4y}				2.7^{***}
N	110	110	110	110
R^2	0.21	0.25	0.23	0.18

	2y-Skew(10yR)	2y-Skew(10yR)	2y-Skew(10yR)	2y-Skew(10yR)
ΔOIS_{3m}	8.16^{***}			
ΔOIS_{1y}		5.06^{***}		
ΔOIS_{2y}			2.97^{***}	
ΔOIS_{4y}				1.48^{***}
N	110	110	110	110
R^2	0.17	0.20	0.20	0.17

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 7: Impact of Fed policy on the U.S. S&P500 tail risk

	2y-SkewSP500	2y-SkewSP500	2y-SkewSP500	2y-SkewSP500
ΔOIS_{3m}	-5.39^{*}			
ΔOIS_{1y}		-1.71^{*}		
ΔOIS_{2y}			-0.67	
ΔOIS_{4y}				-0.18
N	72	72	72	72
R^2	0.22	0.19	0.17	0.15

	2m-SkewSP500	2m-SkewSP500	2m-SkewSP500	2m-SkewSP500
CPI	1.76^{*}	1.74^{**}	1.51^{*}	1.28^{*}
ΔOIS_{3m}	33.8			
ΔOIS_{1y}		21.02^{**}		
ΔOIS_{2y}			11.85^{**}	
ΔOIS_{4y}				5.41^{*}
N	72	72	72	72
R^2	0.12	0.18	0.18	0.15

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 8: Impact of foreign CBs' policy on the U.S. S&P500 tail risk

	2y-SkewSP500	2y-SkewSP500	2y-SkewSP500	2y-SkewSP500
ΔOIS_{3m}	0.19			
ΔOIS_{1y}		0.10		
ΔOIS_{2y}			0.06	
ΔOIS_{4y}				0.04
N	202	202	202	202
R^2	0.03	0.02	0.02	0.02

	2m-SkewSP500	2m-SkewSP500	2m-SkewSP500	2m-SkewSP500
ΔOIS_{3m}	1.16			
ΔOIS_{1y}		1.30		
ΔOIS_{2y}			1.37	
ΔOIS_{4y}				1.19
N	202	202	202	202
R^2	0.025	0.027	0.03	0.033

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 9: Impact of macro data releases on inflation tail risk

	5y-Pr(CPI≤2%)	5y-Pr(CPI≤1%)
CPI	−0.396***	−0.976***
Housing starts	0.0138	0.0707
New home sales	−0.0767	−0.0984
Existing home sales	0.341	0.781*
Retails sales	0.233	0.407
Jobless claims	0.0265	0.0217
GDP (advance)	0.06	0.04
Business Invest	0.145	0.479
Factory orders	0.0623	0.125
Construction spending	−0.188	−0.112
Nonfarm Payrolls	−0.246	−0.513
constant	−0.0563	−0.124
N	543	543
R^2	0.033	0.055

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

Table 10: Impact of inflation and policy-rate tail risks on
U.S. 10-year nominal Treasury yield and term premium

	Δ10Y-yield	Δ10Y-yield	Δ10Y-NTP	Δ10Y-NTP
5y-Pr(CPI≤0%)	0.0012		0.0007	
4y-Pr(Libor≤ 0)	−0.0554***		−0.0357***	
5y-Pr(CPI≤1%)		0.0012		0.0008
4y-Pr(Libor≤ 50)		−0.0417***		−0.0269***
constant	−0.002	−0.0013	−0.0005	−0.0002
N	537	537	537	537
R^2	0.62	0.70	0.61	0.69

Note: HAC robust standard errors. *p<0.05, **p<0.01, ***p<0.001.

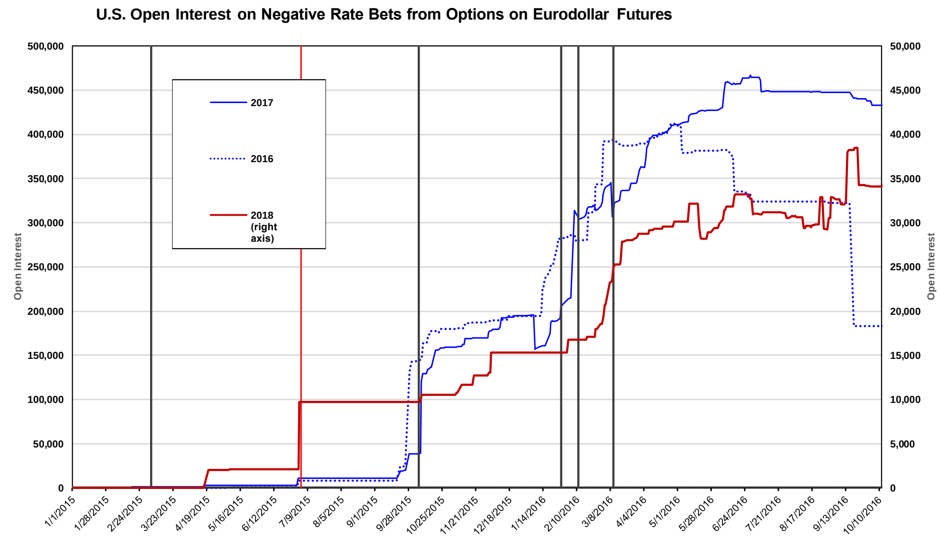

Figure 1: Open interest on Eurodollar options that pay off when Libor falls below zero by the end of 2015, 2016, and 2017, respectively. The vertical red line indicated the Greek bailout referendum in July 2015. The black vertical lines indicate the following events: 3/5/2015 the ECB cuts interest rate from -0.20% to -0.30%; 10/6/2015 IMF downgrades global economic outlook again; 1/28/2016 BoJ cuts interest rate into negative territory; 2/10/2016 Riksbank lowers its already negative rate; 3/10/2016 the ECB cuts interest rate from -0.30% to -0.40%.

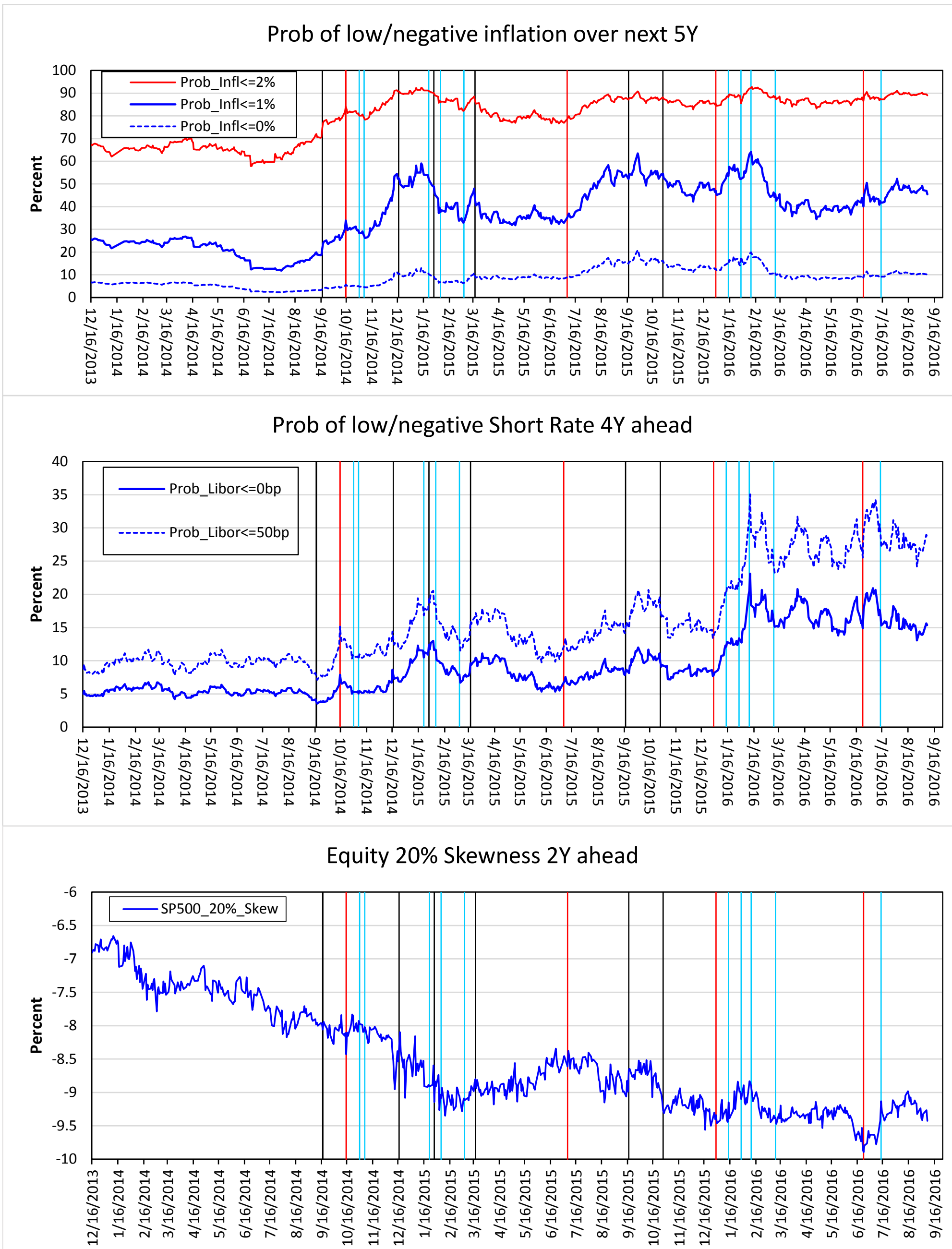

Figure 2: Time series of tail risks. The top panel plots the probabilities that over the next 5 years CPI inflation is less or equal zero, 1 percent, and 2 percent, respectively. The middle panel plots the probabilities that Libor falls below zero and below 50 basis points over the next 4 years. The bottom panel plots the 2-year skewness of the SP500 Index pdf.

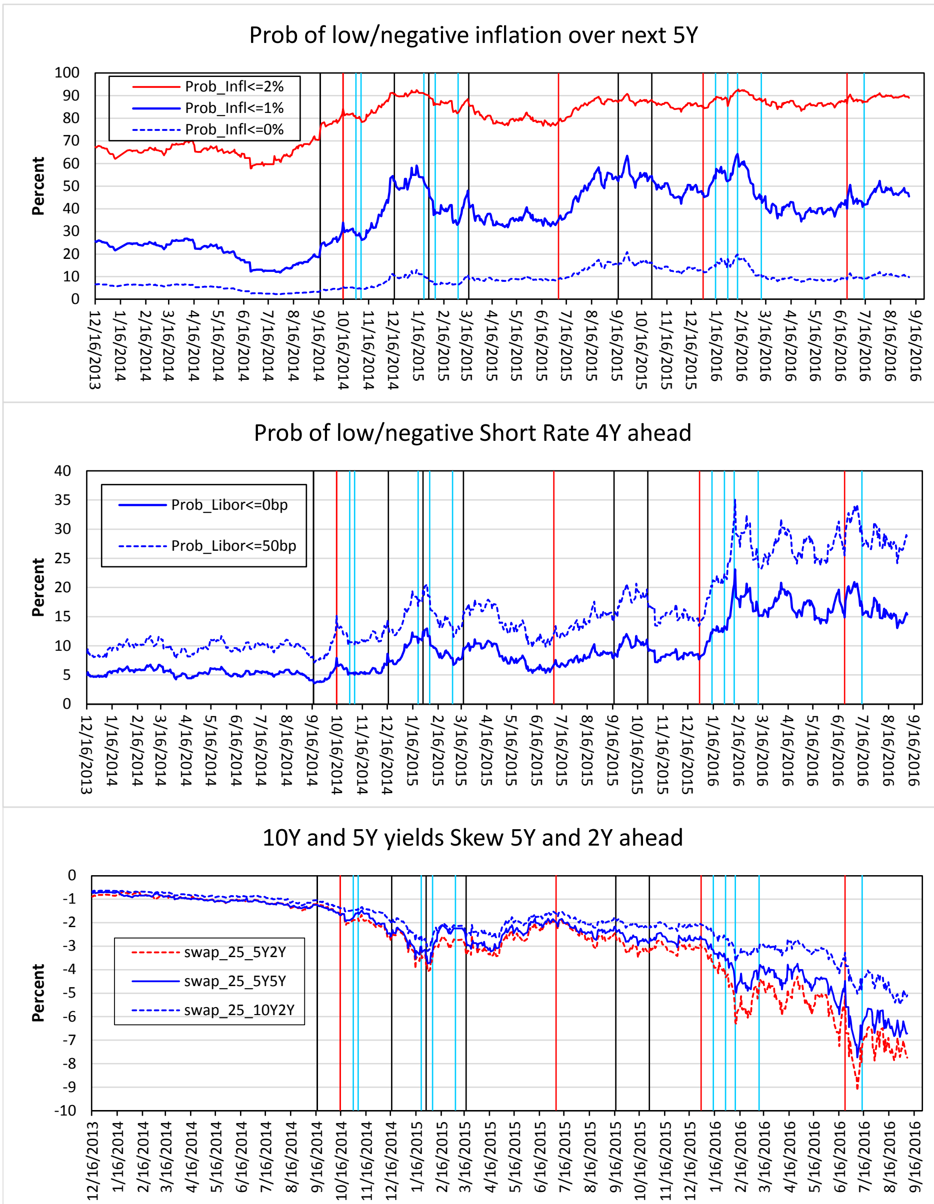

Figure 3: Time series of tail risks. The top two panels plot the same probabilities shown in Figure 2. The bottom panel plots the 2- and 5-year skewness of the pdfs for the 5- and 10-year nominal interest rates.

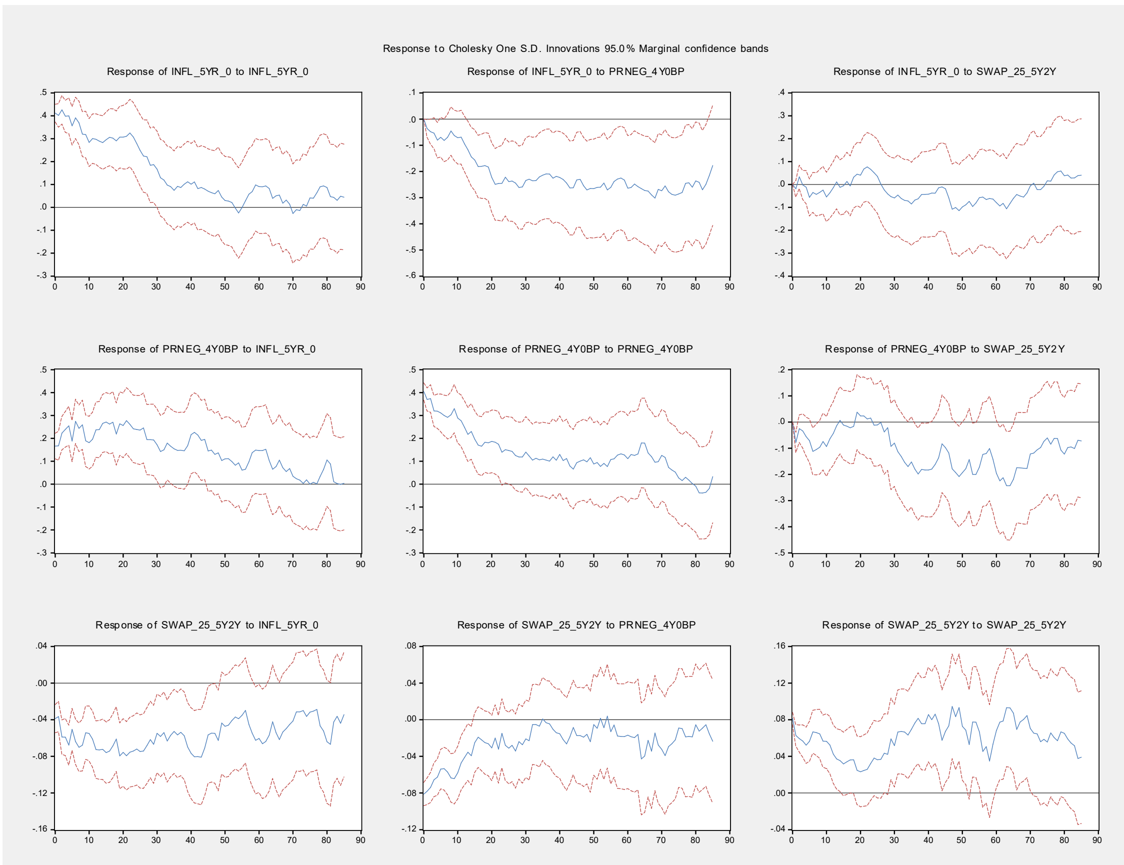

Figure 4: IRFs from equations including the probability that over the next five years CPI inflation is less or equal zero, the probability that Libor falls below zero basis points over the next 4 years, and the 2-year skewness of the pdf for the 5-year interest rate.

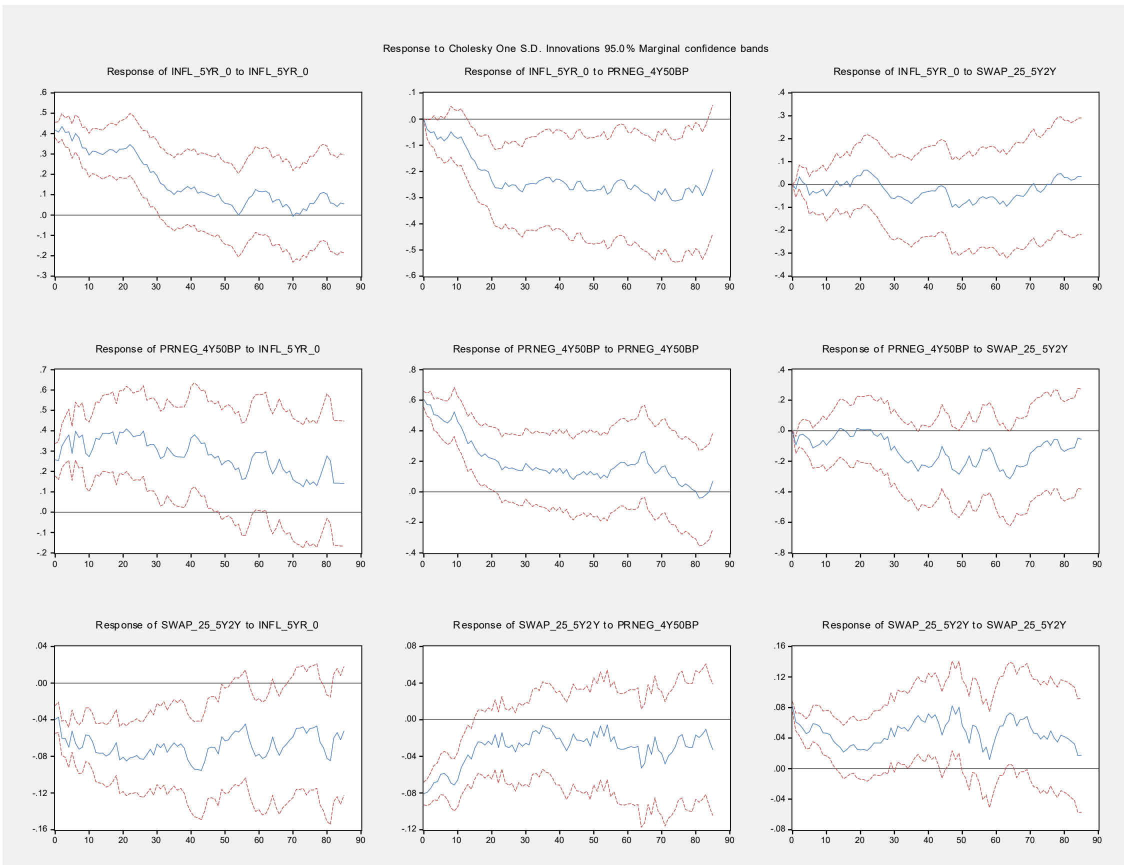

Figure 5: IRFs from equations including the probability that over the next five years CPI inflation is less or equal zero, the probability that Libor falls below 50 basis points over the next 4 years, and the 2-year skewness of the pdf for the 5-year interest rate.

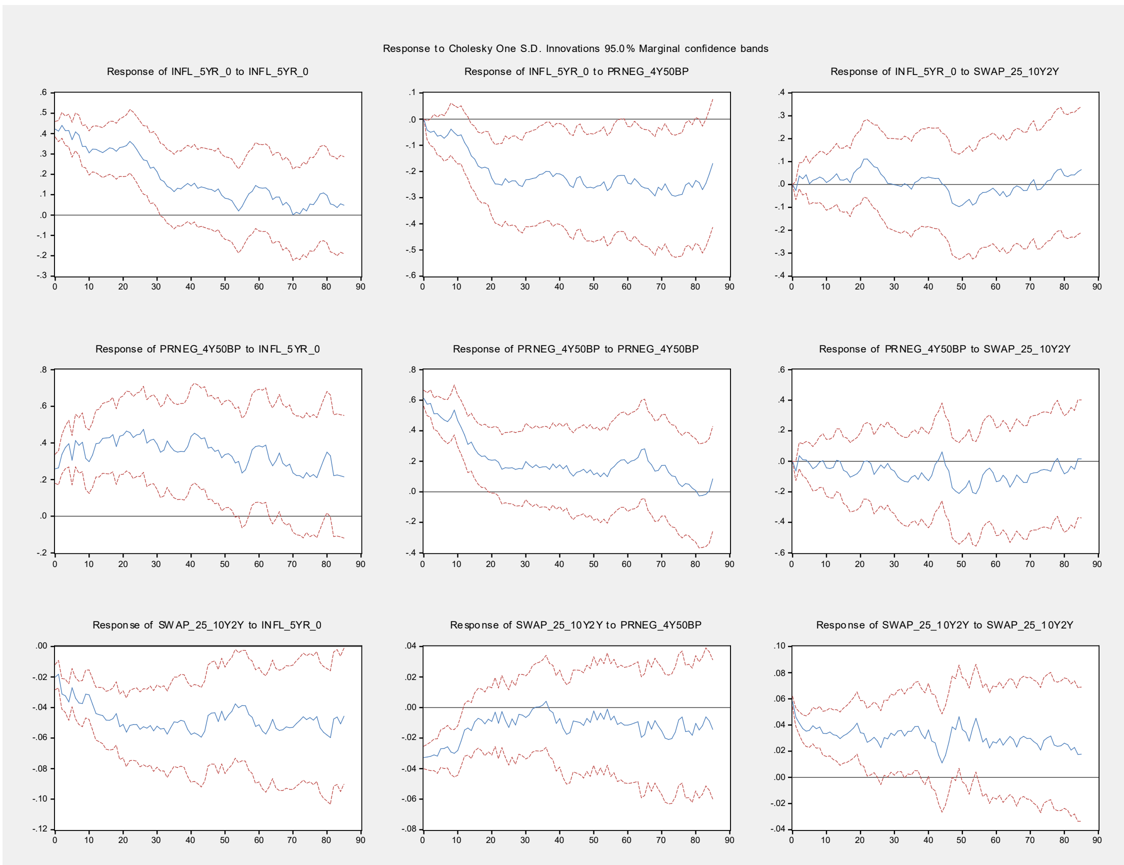

Figure 6: IRFs from equations including the probability that over the next five years CPI inflation is less or equal zero, the probability that Libor falls below 50 basis points over the next 4 years, and the 2-year skewness of the pdf for the 10-year interest rate.

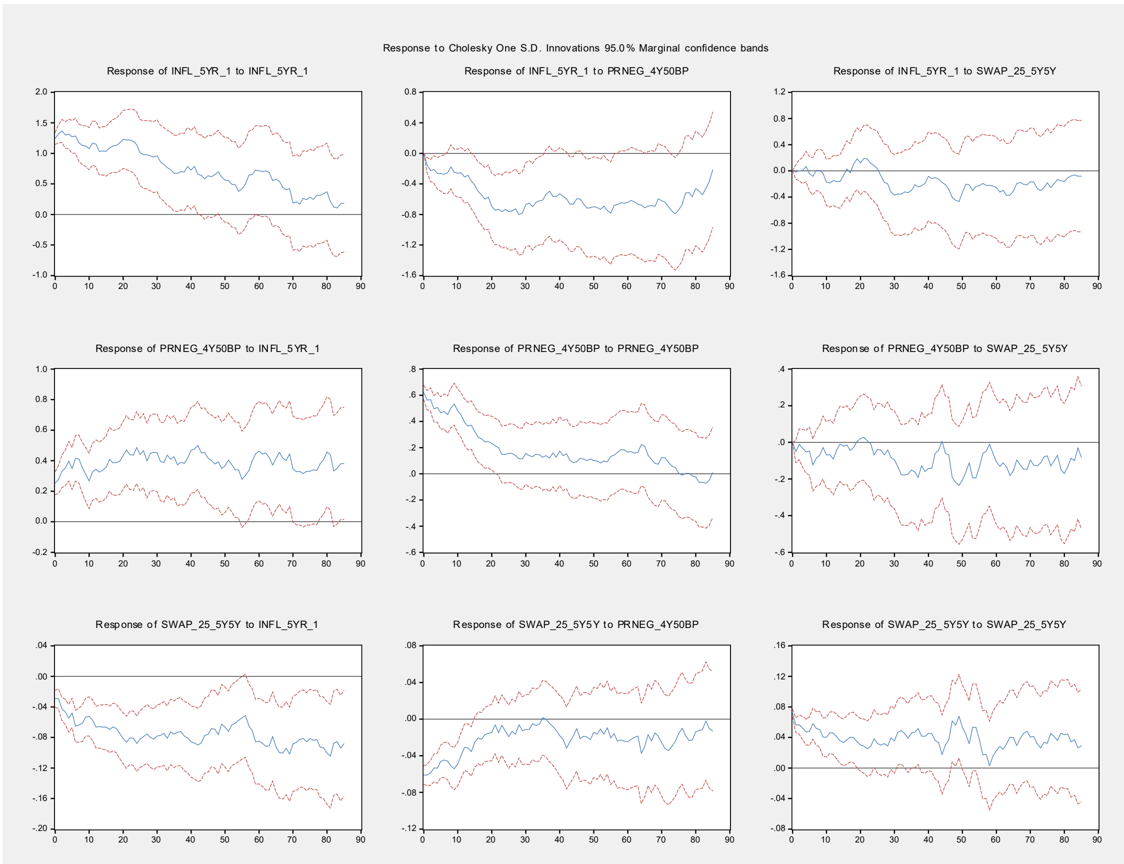

Figure 7: IRFs from equations including the probability that over the next five years CPI inflation is less or equal 1 percent, the probability that Libor falls below 50 basis points over the next 4 years, and the 2-year skewness of the pdf for the 5-year interest rate.

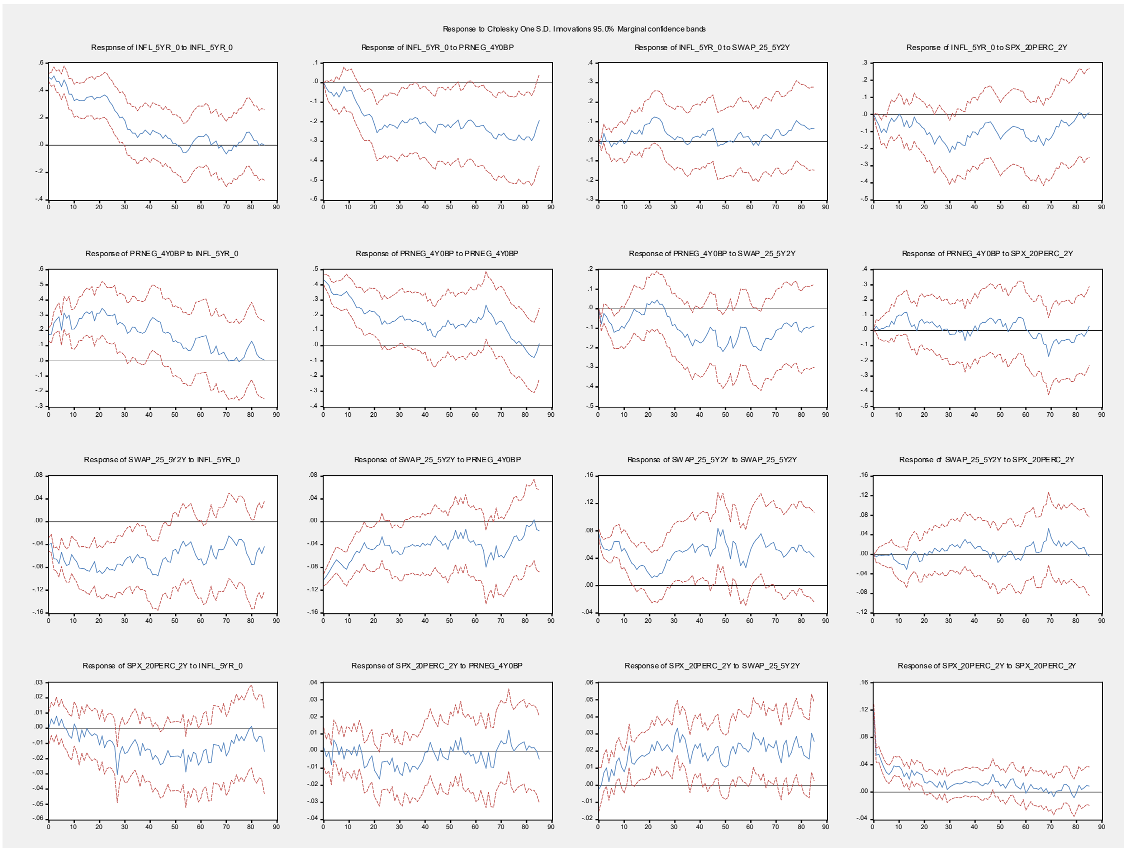

Figure 8: IRFs from local projections including 4 variables: the probability that over the next five years CPI inflation is less or equal zero, the probability that Libor falls below zero basis points over the next 4 years, the 2-year skewness of the pdf for the 5-year interest rate, and the 2-year skewness of the SP500 Index.

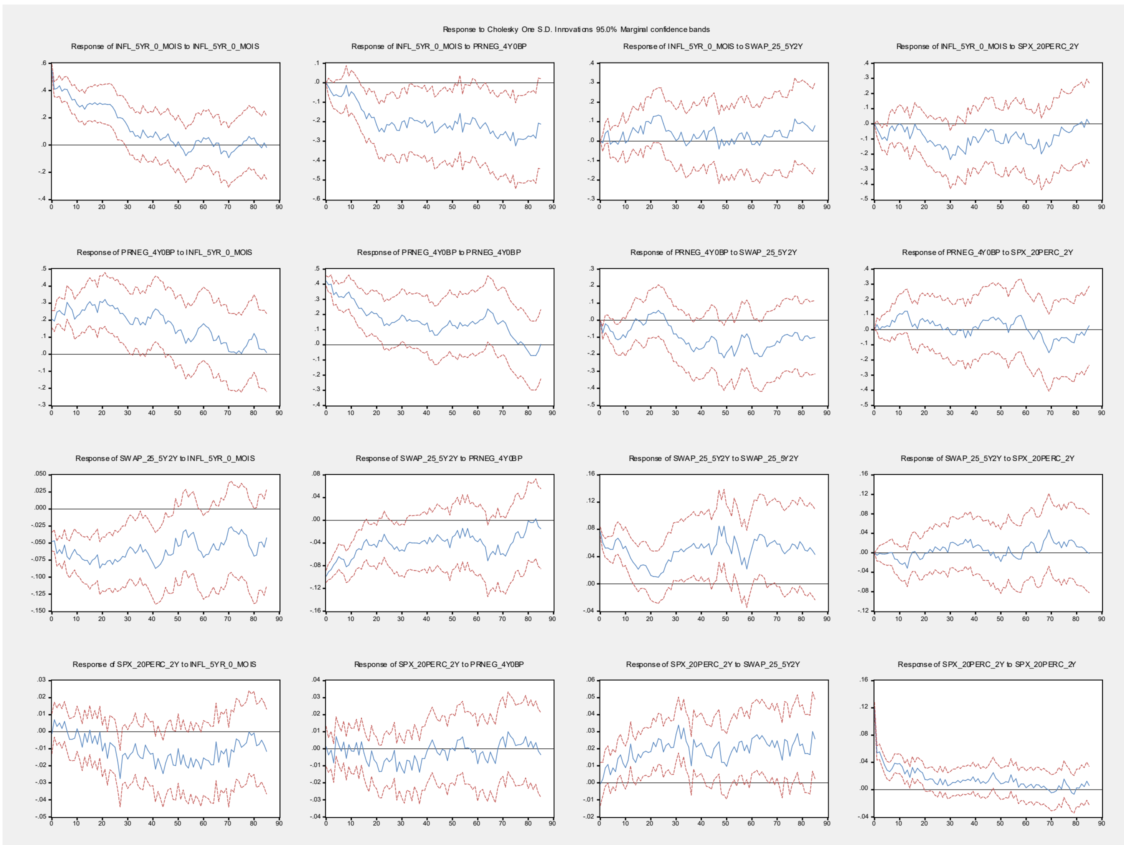

Figure 9: IRFs from local projections including 4 variables, where for robustness we have used the methodology of D'Amico and Farka (2011) and built the probability that over the next five years CPI inflation is less or equal zero purified from the impact of monetary-policy announcements; while, the probability that Libor falls below zero basis points over the next 4 years, the 2-year skewness of the pdf for the 5-year interest rate, and the 2-year skewness of the SP500 Index are as in the baseline.

Figure 10: IRFs from Jorda local projections as in the baseline and in green, shown for comparison, the IRFs from VAR including the probability that over the next five years CPI inflation is less or equal zero, the probability that Libor falls below zero basis points over the next 4 years, and the 2-year skewness of the pdf for the 5-year interest rate.

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