Financial Crises, Price Discovery, and Information Transmission: A High-Frequency Perspective

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Abstract

This paper examines the price discovery processes before and during the 2007-09 subprime and financial crisis, as well as the subsequent European sovereign crisis, for American and German stock and bond markets, as well as for U.S. Dollar/Euro FX. Based on five-second intervals, we analyze how asset prices interact conditional on macroeconomic announcements from the U.S. and Germany. Our results show significant co-movement and spillover effects in returns and volatility, reflecting systematic information transmission mechanisms among asset markets. We document strong state-dependence with a substantial increase in inter-asset spillovers and feedback effects during times of crisis.

Keywords: *Financial crises, macroeconomic announcements, price discovery process, information transmission process, high-frequency data.*

JEL Codes: $G01$, $G12$, $G14$, $G15$

1 Introduction

Nowadays, trades can be executed within a few milliseconds. The development of efficient trading systems and electronic news processing based on machine-readable news, as well as the market entry of sophisticated players, such as quant funds and algorithmic traders, have created (most of the time) highly liquid markets (Chaboud et al. (2010), Hendershott et al. (2011)). We posit that this influences the price discovery process. Markets become more efficient and prices (almost) instantaneously reflect new information.[1] We examine the following questions: How quickly do bond, stock, and currency markets incorporate new information, i.e. macroeconomic news, into prices? Are there systematic information transmission mechanisms among these asset markets? How did the 2007–09 subprime and financial crisis as well as the subsequent European sovereign crisis affect these information transmission processes? The use of high frequency data allows us to identify the intra-day structure of financial markets around macroeconomic announcements and compare processes of price discovers. It further mitigates dual-causality problems.

We provide answers to the above questions by focusing on price adjustment processes around macroeconomic announcements. We contribute to the literature several fold. We analyze news effects on asset returns and volatility with respect to direction, size, and response time, as well as the patterns in trading volume of different assets around macroeconomic announcements. Empirically, we capture co-movement and spillover effects among returns and volatility of the three main asset classes—bonds and stocks of the U.S. and Germany, and the USD/EUR exchange rate—in order to detect systematic transmission channels that are conditional on news from these countries.

Further, we provide a detailed analysis of reactions to macroeconomic announcements conditional on different states of the economy. Most previous studies have used

[1] Ederington and Lee (1993) document that most of the price adjustments to major announcements occur within the first minute. See also Christensen et al. (2011) for a literature overview on sampling intervals over the last four decades.

macroeconomic announcements from one country (mainly the U.S.) only. We consider real-time announcement data from the U.S. and Germany, as well as expectations of the announcements, to analyze effects on both U.S. and German assets. All these effects are interpreted in relation to the type and origin of the news as well as the state of the economy. As our sample covers the pre-crisis period from 2006 to 2007, the 2007-09 subprime and financial crisis period, as well as the subsequent European sovereign crisis period, we can distinguish between "normal" and "crisis" times in the economy. Moreover, our sample enables us to disentangle the effects that macroeconomic news has during a global financial crisis compared to those being provoked by a regional crisis, i.e., when only one market is affected directly. In addition, moving from pre-crisis to crisis periods provides insights into changes in the price reactions to announcements, and thus, the short-term pricing of risk factors.

We show that the response pattern of asset returns to macroeconomic news is gradual, lasting from one to eight minutes, with the largest movement occurring within the first minute after the announcement release. In general, the magnitude of price responses increases from pre-crisis period to subprime and financial crisis period, and bounces back for most of the assets during the European sovereign crisis. Nevertheless, it still remains at a higher level compared to the pre-crisis period. In particular, asset prices react more sensitively to news released in the market where the crisis originated. Based on five-second sampling intervals we identify transmission patterns, i.e. co-movements and spillovers in return and volatility processes. The transmissions exhibit distinctive inter-asset characteristics (i.e., among different asset classes within and between countries) and intra-asset features (i.e., within the same asset class across countries) in an international cross-border context depending on the origin of the fundamental news and the state of the economy. We identify different effects for the price discovery process and risk-return transmission mechanisms conditional on news during the pre-crisis and crisis periods.

The remainder of this paper is organized as follows. In Section 2, we provide a literature review on market responses to fundamentals and information transmissions among asset markets. Section 3 describes the data. In Section 4, we specify the estimation models, and Section 5 presents our empirical results. Section 6 concludes.

2 Related Literature

Academic research has a strong interest in investigating the impact of macroeconomic news releases on asset prices and exchange rates. Many studies focus on the news releases of the Federal Open Market Committee (FOMC) as they seem to have the greatest impact on asset returns (e.g., Bernanke and Kuttner (2005); Lucca and Moench (2015)). Other studies use intraday data around announcements (e.g., D'Amico and Farka (2011); Fernandez-Perez et al. (2017)). Lucca and Moench (2015) document a pre-announcement drift with positive excess returns ahead of FOMC announcements. In general, markets react within minutes to macroeconomic surprises, whereas volatility remains elevated for longer. The volatility conditional on macroeconomic news has been investigated in a number of studies (e.g., Lobo (2002); Bomfim (2003) and using intraday data Andersen et al. (2003a,b, 2007); Farka (2009)). Andersson (2010) investigates the effect on monetary decisions in the U.S. and the Euro Zone.

In our paper, we explicitly account for different states of the economy. Macroeconomic news reveal information about future interest rates, the equity risk premium, and corporate earnings that affect asset prices and exchange rates, which in turn influence markets conditional of the state of the economy. For example, Boyd et al. (2005) find that the discount rate and cash flow effect are related to the business cycle. A higher unemployment rate is positively correlated with stock prices during economic expansions, but negatively correlated during economic recessions. Andersen et al. (2007) argue fur-

ther that the discount rate effect dominates in expansion phases due to lower interest rates, while lower future cash flows during contraction periods lead to decreasing stock returns.

Bernanke and Kuttner (2005) explain stock market reactions by unexpected changes in the federal funds target rate, which directly affects the equity risk premium. Hence, an unexpected positive inflationary shock or unexpected positive real innovation to the economy can lead to a monetary policy surprise, where an unexpected increase in the target rate leads to an increase of the equity risk and falling stock prices. During "normal" market periods, the interest rate effect plays a dominant role. A positive shock thus leads to increasing discount rates, which lowers stock prices, while higher expected cash flows drive stock prices in the opposite direction. During "crisis" periods, however, a positive announcement surprise will reduce the equity risk premium, which leads to increasing stock prices.

Also Chen (2007) and Basistha and Kurov (2008) finds an asymmetric effect of stock price reactions to monetary policy during 'good' and 'bad times'. Neely (2015) analyzes the effect of unconventional monetary policy announcements of the Federal Reserve in 2008-2009. He finds a substantial impact on bond yield and the US dollar spot rate as markets react stronger during times of high monetary uncertainty. Investigating yield curves and exchange rates, Goldberg and Grisse (2013) document time-variation in return and volatility responses to macroeconomic announcements that can be explained by the state of the economy and changes in risk perceptions.

Early studies based on lower frequencies document interdependencies of the first and second moment across capital markets (e.g., Eun and Shim (1989); King and Wadhwani (1990)). For instance, in the long run, stock and bond markets exhibit negative correlations (see, e.g., Campbell and Ammer (1993) for monthly data). Recent studies based on intraday data including Wu et al. (2005) and Hou and Li (2016) document

spillovers between international markets and intraday periodicity. In addition, Ranaldo and Söderlind (2010) find that bond, equity, and FX markets are significantly interrelated also at sampling intervals of several hours or days. Brenner et al. (2009), who study responses of U.S. stock, Treasury, and bond markets to U.S. macroeconomic surprises, also find fundamentals-driven interrelations on a daily basis. This finding is in line with Bongaerts et al. (2014) and Füss et al. (2017), who document that jumps and co-jumps in prices are often found in relation to U.S. macroeconomic announcements.

Such systematic transmission patterns among stock, bond, and FX markets can be traced back to common informational shocks and cross-market hedging effects (Fleming et al. (1998)). The announcement surprises can lead to covariance shifts (see, e.g., Karolyi and Stulz (1996) and Connolly and Wang (2003)), and to increases in portfolio rebalancing activities across asset markets (see, e.g., Fleming et al. (1998) and Kodres and Pritsker (2002)). Before we analyze the intraday dependency structure and price discovery process of financial markets around macroeconomic announcements in Section 5, we first introduce our data in the next section and then specify the econometric models in Section 4.

3 Data

3.1 Asset Markets

We choose E-mini S&P500, 10-year Treasury note, DAX, Bund futures, and the USD/EUR spot rate as major internationally traded and integrated assets. We restrict our choice on the U.S. and German market and do not extend the sample further, because these are the most liquid markets with largely overlapping trading hours. For futures data, we use the contract closest to maturity and roll over when the next maturity contract becomes more actively traded. The data for the DAX and Bund futures come from Deutsche Börse

(tick-by-tick transaction data). Both futures markets are highly liquid, and are already open by 8:00 Central European Time (CET), when important German macroeconomic news such as GDP, PPI, and retail sales numbers are released. The E-mini S&P500 and 10-year Treasury note futures tick-by-tick transaction data are from Tickdatamarket.com. The USD/EUR spot exchange rates (second-by-second transaction data) are from the Electronic Broking System (EBS) of ICAP, London, a twenty-four-hour liquid electronic FX trading platform for USD/EUR, which is used by virtually all FX dealers worldwide who trade in major currency pairs.[2] The USD/EUR futures market at the CME only trades from 8:20 to 15:00 Eastern Standard Time (EST), and thus the marketplace is closed when many European announcements are released. Chen and Gau (2010) find that the FX market on ICAP is leading the FX futures market. Also, spot market's liquidity is higher than that of the EUR/USD futures markets.

Our full sample spans 1,528 trading days from January 2006 through December 2011. We only use the overlapping trading hours of all five markets from 8:00 to 22:00 CET. To avoid contamination from overnight news or from hedging activities at the end of the trading day, we remove opening prices. We split our sample to cover the pre-crisis period (January 2006 through July 2007), the subprime and financial crisis period (August 2007 through August 2009), and the period thereafter (September 2009 through December 2011), which includes the European sovereign crisis.

[2]We refrained from using quotes mainly for two reasons. First, in our sample we usually see only low liquidity at the top levels of the bid and ask side. This concern was further exacerbated by the upcoming discussion on order spoofing and other manipulation attempts. We therefore decided to use transaction data. Secondly, we find substantial differences in the market interactions for our three different subsamples, but all three subsamples should be affected similarly by bounces in transaction prices between trades at the bid and ask quote (negative autocorrelation).

3.2 Basic Facts of One-Minute Series

We first examine price reactions conditional on macroeconomic surprises based on one-minute time series. We then refine our sampling interval to five seconds to analyze how macroeconomic surprises trigger spillover effects among markets.[3] This also reduces a potential omitted variable bias.

Figure 1 plots the average one-minute absolute returns over the entire trading day. For all five assets, we find a first spike at 9:00 CET, when the German and London stock markets open.[4] The DAX futures show the largest jump as the underlying starts to trade. At 14:30 CET (8:30 U.S. EST), major U.S. macroeconomic announcements are released, such as CPI, GDP, and PPI. The volatilities of the five markets sharply increase. At 15:30 CET (9:30 EST), when the U.S. stock market begins to trade, we see strong effects in the E-mini S&P500. At 16:00 CET (10:00 EST), many U.S. macroeconomic announcements, such as the manufacturing ISM (Institute of Supply Management) index and the composite index of leading indicators, arrive at the market. Again, we find that the volatilities of all markets jump instantly. The German stock market closes at 17:30 CET (11:30 EST) when the volatilities slightly increase.[5]

« Insert Figure 1 about here »

Figure 2 plots the average (calculated over all macroeconomic announcements) one-minute trading volume of each asset market, beginning thirty minutes prior to and ending one hour after the announcements. Note that the proportion of one-minute intervals

[3]To convert the irregularly spaced tick-by-tick prices into time series with fixed time intervals, we take the last transaction price within the interval [t,t+1] as the price, P_t.

[4]We remove the opening and closing prices resulting from the respective auctions at 8:00 and 22:00 when the German futures markets open and close. When the underlying markets open at 9:00, we find a spike in the futures markets, showing that there is a daily volatility pattern associated with stock market opening and closing.

[5]We also find significant negative first-order autocorrelations in asset returns with higher-order autocorrelations around or within the 95% confidence band. The volatilities of all five markets follow a long-memory process.

with no trading ranges between 0.03% (for DAX futures during crisis period) and 1.04% (for Bund futures during pre-crisis period). Trading volume immediately jumps after news releases for all five markets and decreases gradually afterward, which confirms the reliability of our announcement stamps. Compared with DAX futures, Bund futures, and USD/EUR, the surge in trading volume of the two U.S. assets, E-mini S&P500 futures and 10-year Treasury note futures, is much larger after U.S. news than after German news. This indicates that domestic information triggers stronger reactions in the U.S. than in foreign asset markets.

« Insert Figure 2 about here »

3.3 Basic Facts of Five-Second Series

Table 1 shows exemplarily the descriptive statistics for returns and trading volume of the three assets (DAX futures, Bund futures, and USD/EUR exchange rate) on the five-second interval for the entire sample as well as the sub-sample periods. Average returns for all three assets are negative during the crisis period, whereas arithmetic returns are the lowest during the post-crisis period, being negative for the DAX futures market. Interestingly, the volatility in terms of standard deviation does vary significantly among the sub-sample periods. However, all times series exhibit a significant leptokurtosis, which is common for high-frequency data.

« Insert Table 1 about here »

The trading volume of the DAX futures and the Bund futures is denoted in the number of contracts, whereas trading volume of U.S. dollar-Euro exchange rate is denoted in millions of Euros. We only see few zero returns in any market within the time window half an hour before and one hour after macroeconomic announcements. The percentage

of five-second intervals without trading activity lies in the range between 0.29% (for DAX futures in the crisis period) and 3.09% (for USD/EUR FX in the pre-crisis period). The average trading decreases significantly when going from the pre-crisis into the crisis period, and reaches higher levels in the post-crisis period compared to pre-crisis period (with the exception of the Bund futures market).

Figure 3 presents the average five-second trading volume over all significant macroeconomic announcements within one minute after the release of the respective announcement. We see exemplarily for the German markets and the USD/EUR exchange rate a high level of trading activity after the macroeconomic news release during the first five-second interval (except for the USD/EUR exchange rate which peaks during the second five-second interval) with an immediate decline after 10 seconds and a subsequent gradual decrease thereafter.

« Insert Figure 3 about here »

3.4 Macroeconomic Announcement Data

We use macroeconomic announcement data for the U.S. and Germany from the Market News International (MNI) database.[6] Table 2 summarizes the announcements.[7]

« Insert Table 2 about here »

We further control for overlapping subprime and financial crisis and European sovereign crisis events by adding dummy variables for respective news from mid-2007

[6]We also analyzed announcement data from the European Monetary Union (EMU). However, we find that aggregate EMU news is generally insignificant, with the exception of a minor impact on the USD/EUR exchange rate. One explanation for the insignificant effect of macroeconomic data from the EMU lies in the non-revision of forecasts. Only some survey participants revise their reported forecasts for the EMU after announcements from single countries, but most do not, which leads to a biased measurement of surprises.

[7]In total we use 18 different macroeconomic indicators from the US and Germany. For all US announcements we have 72 observations except for initial unemployment rate with 313 observations. For Germany the number varies between 61 and 71. For German GDP we only have 23 observations.

through the end of 2011. We identified 39 relevant news releases within the sample. They were collected from Bloomberg, the Federal Reserve Bank of St. Louis and the European Central Bank, and are summarized in Table A1 in the Internet Appendix.[8] Following Balduzzi et al. (2001) and Andersen et al. (2003b, 2007), we construct standardized news to control for market expectations and different measurement units. The surprise, defined as actual value minus forecasted value, is divided by the sample standard deviation of the surprise, as follows:

$$S_{kt} = \frac{R_{kt} - F_{kt}}{\hat{\sigma}_k}, \tag{1}$$

where R_{kt} and F_{kt} are the actual value and the market expectation of announcement k measured by the median MNI forecast, respectively, and $\hat{\sigma}_k$ is the sample standard deviation of the surprise, $R_{kt} - F_{kt}$.[9]

4 Model Specifications

4.1 Modeling Average Intraday Volatility

We follow Zhou (1996) and Hansen and Lunde (2003, 2005, 2006), who develop a kernel-based volatility estimator that remains consistent and unbiased even at very high frequencies (Chaboud et al. (2010)). We define the realized kernel (RK) as:

$$RK(X) = \gamma_0(X) + \sum_{h=1}^{H} k\left(\frac{h-1}{H}\right)\{\gamma_{-h}(X) + \gamma_h(X)\}, \tag{2}$$

with the price process, $X = P + U$, consisting of the efficient price P plus the market friction U, the realized autocovariances $\gamma_h(X) \equiv \sum_{i=1}^{n} R_i R_{i-h}$ between actual and

[8] It is important to note that only those events that coincide with announcements are listed. For example, the Lehman Brothers collapse took place when no macroeconomic news was released.

[9] We do not apply a minimum threshold as a deviation from the expectation (as, e.g., in Hanousek and Kocenda (2011)), as this would only eliminate very few observations.

lagged return for $i = 1, ..., n$ and $h = 0, 1, ..., H$, and a kernel function (weight) of $k(\frac{h-1}{H})$. We use the modified Tukey-Hanning kernel, $sin^2\left\{\frac{\pi^2}{2}(1-x)^2\right\}$, which has been tested by Barndorff-Nielsen et al. (2008), and offers a balance between computational efficiency and accuracy with respect to power.

In the literature, it is usually assumed that the noise process is independent of the efficient price and the noise is time-independent. Hansen and Lunde (2006) show that these assumptions only hold for lower sampling frequencies of intraday returns. For ultra-high frequencies, such as in our empirical analysis, volatility signature plots indicate a negative dependency structure between noise and efficient transaction price. However, the authors also show that kernel-based estimators are able to capture the time dependence in the noise component, provide better asymptotic properties, and thus, reduce the realized variance's bias problem. Bandi and Russel (2006) and Chaboud et al. (2010) show that, in highly liquid markets, sampling intervals of less than one minute do not lead to biases for the realized variance. And for simple realized kernel estimators, this window can be as short as two to five seconds without causing a noticeable bias.[10]

For our time-varying volatility estimation approach, where average daily volatility is treated merely as a control variable, we follow Andersen et al. (1999) and use signature plots to detect the optimal frequency for calculating intraday volatility.[11] Based on the signature plots in Figure B1 of the Internet Appendix, we find that a one-minute interval

[10] Chaboud et al. (2010) use a USD/EUR dataset from ICAP and demonstrate that fifteen- to twenty-second intervals can be used without contaminating the realized variance with market microstructure noise. For a simple realized kernel estimator, they find no noticeable bias, even for two- to five-second intervals. They show that sampling intervals may be even shorter for days when U.S. macroeconomic data are released.

[11] We compare the realized variance with the realized kernel for DAX and Bund futures and for the USD/EUR exchange rate for different sampling frequencies. The realized kernels converge to a stable level at a frequency of roughly one minute, while realized volatility approaches true volatility at a twenty-minute frequency. The volatilities of E-mini S&P500 and 10-year Treasury note futures tend to be underestimated using realized kernels at lower frequencies. Realized kernels based on five-second to one-minute intervals are closer to the true volatilities. We also use Bandi and Russel's (2005) MSE approach to calculate the optimal time interval for realized volatility, which confirms the results from the signature plot (i.e., an optimal interval of about twenty minutes).

is a good balance between noise and sampling errors. We therefore construct one-minute return and trading volume time series.

4.2 Modeling News Effects

We construct time series for a window of ten minutes before and one hour after macroeconomic announcements.[12] To detect the macroeconomic news effects on the markets, we follow Andersen et al. (2003b, 2007), and use a two-step regression model. In the first step, we apply the following dynamic regression model for each return series:

$$R_t = \beta_0 + \sum_{i=1}^{I} \beta_i R_{t-i} + \sum_{k=1}^{K} \sum_{j=0}^{J} \beta_{kj} S_{k,t-j} + \sum_{l=0}^{L} \beta_l C_{t-l} + \varepsilon_t \qquad \text{for } t = 1, \dots T, \tag{3}$$

where R_t are logarithmic returns based on one-minute sampling frequency, $K = 19$ is the total number of macroeconomic announcements, S_{kt} denotes news surprises, and C_t is the crisis dummy. We choose $I = 15$, $J = 8$, and $L = 6$, according to the Akaike information criterion.

The autoregressive terms play a role similar to that in Stoll and Whaley (1990), who propose an ARMA(p,q) filter with infinite order to mitigate the bid-ask bounce and discreteness effects. We estimate the conditional mean of Equation (3) by using ordinary least squares regressions, and then extract the heteroskedastic residuals to model the time-varying volatility $|\varepsilon_t|$ as follows:

$$\begin{aligned} |\varepsilon_t| = c + \Psi \frac{\hat{\sigma}_{d(t)}}{\sqrt{840}} + \sum_{k=1}^{K} \sum_{j'=-10}^{J'} \delta_{kj'} |SD_{k,t-j'}| + \sum_{m=1}^{M} \sum_{j''=0}^{J''} \varphi_{mj} D_{m,t-j''} \\ + \sum_{l'=0}^{L'} \beta_{l'} C_{t-l'} + \sum_{n=1}^{N} \theta_n W_n + u_t. \end{aligned} \tag{4}$$

The first part of Equation (4), $\hat{\sigma}_{d(t)}$, is the daily volatility measured by realized

[12] We also extend the time window to one and a half hours after the announcements. However, the results do not change materially. Furthermore, a one-hour time window is sufficient to capture the volatility response.

kernels, standardized with the square root of the number of one-minute intervals from 08.00 CET (02:00 EST) to 22.00 CET (16:00 EST).[13] In line with Andersen et al. (2007), we use macroeconomic dummies instead of absolute values, which make it also easier to compare the effects. D_m are calendar event dummies, including the opening and closing of German and U.S. bond and stock markets, while W is the trading day dummy with $N = 4$ to capture a day-of-the-week effect on volatility. SD_k are the macroeconomic news dummies, which have much longer effects on volatilities, where $J' = 60$. The residuals of the conditional mean in Equation (3) exhibit clear heteroskedasticity. In order to obtain robust coefficients, we apply a weighted least squares (WLS) procedure to the conditional mean equation. Thus, we use the fitted time-varying volatility from Equation (4) to estimate a WLS regression of Equation (3).

To get an overview of the volatility response pattern while maintaining flexibility, we next impose two third-order polynomial response functions to capture the pre- and post-news effects, as follows:

$$p(j') = a_1(1 - (j'/60^3)) + a_2(1 - (j'/60)^2)j' + a_3(1 - (j'/60))j'^2, \tag{5a}$$

$$p(j'') = b_1(1 - (j''/10^3)) + b_2(1 - (j''/10)^2)j' + b_3(1 - (j''/10))j''^2, \tag{5b}$$

where $j' = 0, ..., 60$ and $j'' = 0, ..., 10$ denotes the one-minute intervals 60 minutes after and 10 minutes before the macroeconomic announcement, respectively. Hence, Equations (5a) and (5b) model the well-known long-lasting effect of a news announcement on asset volatility after an instantaneous jump at the time of its release and a smooth decay of the average news impact pattern thereafter until volatility reaches its mean level. The impact after one hour, $p(60)$, and before ten minutes prior to the announcement,

[13] Note that $\hat{\sigma}_{d(t)}$ is the daily unconditional volatility based on a realized kernel, whereas $|\varepsilon_t|$ is the conditional (mean) volatility on a one-minute sampling frequency. Related to the unbiased estimate based on realized kernels, the conditional volatility $|\varepsilon_t|$ converges towards the one-minute adjusted unconditional volatility $\hat{\sigma}_{d(t)}$ in the long term. Under this assumption, the one-minute adjusted expected value of $\hat{\sigma}_{d(t)}$ equals the expected value of $|\varepsilon_t|$.

$p(10)$, is assumed to be zero, i.e. the third-order polynomial is restricted to reach zero at the beginning and at the end of the response horizon. The coefficients of macroeconomic news dummies in Equation (4) are replaced by the polynomial response functions. This considerably reduces the number of coefficients to be estimated.

The use of estimation windows around macroeconomic news allows us to separate information-driven movements in the efficient price from movements in the noise component of prices independent from information on fundamentals. To be more precise, the immediate reaction to macroeconomic announcements can be interpreted that the market reacts efficiently. However, if volatility is longer lasting it is very likely that noise traders are present and information from price changes in other markets are transmitted, i.e. contagion effects exist. King and Wadhwani (1990) show that, in particular during crisis periods rational agents infer information from price changes in other markets rather than based on macroeconomic news. In addition, this affect might be stronger among the same asset markets, i.e. between the German and U.S. stock market, as well as between the bond markets of the two countries, but to a less extend between different asset markets.

4.3 Conditional Information Transmission

We test for return and volatility co-movements and spillover effects by using correlation structure and Granger causality, as well as VAR processes and HAC-robust OLS estimates for macroeconomic announcements, which are identified as significant for at least two asset markets in the single asset estimations of Sub-section 5.1. We define information transmissions as return and volatility co-movements and spillovers across assets conditional on fundamental news. Thus, in line with Franses et al. (1997), we interpret interactions in the first and second moments as alternative measures of information transmission. In other words, we analyze how macroeconomic news surprises influence the joint behavior of returns (i.e., the information transmission channels and the contemporaneous

and lagged price discovery processes) among the three asset categories.

We use a realized kernel-corrected correlation coefficient to measure return co-movements. We calculate the correlation coefficient based on the realized kernel as $\rho_{12}^{RK} \frac{\sum_{n=1}^{N} R_{1,n} R_{2,n}}{\sqrt{RK_1}\sqrt{RK_2}}$, where the means of returns R_1 and R_2 are approximately zero. In the denominator, the variances of R_1 and R_2 are replaced by the realized kernels RK_1 and RK_2, calculated throughout the aggregated one-minute time windows.

To examine the conditional spillover effects among asset returns, we specify the following vector autoregressive (VAR) model:

$$\begin{bmatrix} R_t^{\text{E-mini S\&P}} \\ R_t^{\text{10YR T-Note}} \\ R_t^{\text{USD/EUR}} \\ R_t^{\text{DAX}} \\ R_t^{\text{Bund}} \end{bmatrix} = \begin{bmatrix} c^{\text{E-mini S\&P}} \\ c^{\text{10YR T-Note}} \\ c^{\text{USD/EUR}} \\ c^{\text{DAX}} \\ c^{\text{Bund}} \end{bmatrix} + \begin{bmatrix} a_{t-1}^{11} & a_{t-1}^{12} & a_{t-1}^{13} & a_{t-1}^{14} & a_{t-1}^{15} \\ a_{t-1}^{21} & a_{t-1}^{22} & a_{t-1}^{23} & a_{t-1}^{24} & a_{t-1}^{25} \\ a_{t-1}^{31} & a_{t-1}^{32} & a_{t-1}^{33} & a_{t-1}^{34} & a_{t-1}^{35} \\ a_{t-1}^{41} & a_{t-1}^{42} & a_{t-1}^{43} & a_{t-1}^{44} & a_{t-1}^{45} \\ a_{t-1}^{51} & a_{t-1}^{52} & a_{t-1}^{53} & a_{t-1}^{54} & a_{t-1}^{55} \end{bmatrix} \cdot \begin{bmatrix} R_{t-1}^{\text{E-mini S\&P}} \\ R_{t-1}^{\text{10YR T-Note}} \\ R_{t-1}^{\text{USD/EUR}} \\ R_{t-1}^{\text{DAX}} \\ R_{t-1}^{\text{Bund}} \end{bmatrix} + \dots$$

$$\dots + \begin{bmatrix} a_{t-p}^{11} & a_{t-p}^{12} & a_{t-p}^{13} & a_{t-p}^{14} & a_{t-p}^{15} \\ a_{t-p}^{21} & a_{t-p}^{22} & a_{t-p}^{23} & a_{t-p}^{24} & a_{t-p}^{25} \\ a_{t-p}^{31} & a_{t-p}^{32} & a_{t-p}^{33} & a_{t-p}^{34} & a_{t-p}^{35} \\ a_{t-p}^{41} & a_{t-p}^{42} & a_{t-p}^{43} & a_{t-p}^{44} & a_{t-p}^{45} \\ a_{t-p}^{51} & a_{t-p}^{52} & a_{t-p}^{53} & a_{t-p}^{54} & a_{t-p}^{55} \end{bmatrix} \cdot \begin{bmatrix} R_{t-p}^{\text{E-mini S\&P}} \\ R_{t-p}^{\text{10YR T-Note}} \\ R_{t-p}^{\text{USD/EUR}} \\ R_{t-p}^{\text{DAX}} \\ R_{t-p}^{\text{Bund}} \end{bmatrix} + \begin{bmatrix} \epsilon_t^{\text{E-mini S\&P}} \\ \epsilon_t^{\text{10YR T-Note}} \\ \epsilon_t^{\text{USD/EUR}} \\ \epsilon_t^{\text{DAX}} \\ \epsilon_t^{\text{Bund}} \end{bmatrix} \tag{6}$$

We select lag length p according to the Hannan-Quinn and Schwarz information criteria. We construct time series of five-second volatility processes, approximated by five-second absolute returns $|R_t|$, in order to detect conditional volatility co-movements and spillovers. We again select news that significantly impacts at least two markets during the first hour after the release of the announcement. As the volatility series exhibit long-

memory process properties, we filter the volatility series of all three markets by using an ARFIMA(1,d,1) model, $(1-\rho L)(1-L)^d|R_t| = (1-\theta L)\xi_t$.[14]

We model the filtered volatility series separately using OLS regressions for the following equation for each asset market:

$$\xi_t^i = c^i + \sum_{q=1}^{Q} \rho_q^i \xi_{t-q}^i + \sum_{j=1}^{4} \sum_{q=0}^{Q} \varphi_q^j \xi_{t-q}^j + \varepsilon_t^i, \tag{8}$$

where i represents the response market, and j is the impact market. We choose lag length Q according to the Hannan-Quinn and Schwarz information criterion.[15] The independent variables are comprised of lagged volatilities from their markets to account for persistence in the filtered volatility process, and the contemporaneous and lagged volatilities from the other four markets to capture volatility co-movements and spillovers among assets.

The ARFIMA filter cannot completely eliminate the long-memory autoregressive structure of the volatility on our very high-frequency basis, but it does substantially reduce its magnitude and persistence.[16] We use HAC-robust standard errors when we study the short-term co-movements and spillovers in the filtered volatility processes among the five markets.

[14] Because of its periodic patterns (see Figure 1), we further filter the USD/EUR exchange rate volatility by using a flexible Fourier form (FFF), $\sum_{q=1}^{Q} (\varphi_q \, cos(\frac{q2\pi t}{720}) + \eta_q \, sin(\frac{q2\pi t}{720}))$ as in Andersen et al. (2003b). We also tested other ARFIMA(p,d,q) model specifications. However, we found that the selected filter is most suitable for whitening the volatility process.

[15] In order to keep the number of lags consistent for all five OLS regressions, we choose the lag length based on a VAR model. We also test specific lag lengths for each single OLS regression model. However, the lag lengths vary only slightly and the results are qualitatively the same.

[16] Note that we use ξ_t from the ARFIMA process as the filtered volatility, and not the absolute values, because the absolute returns, $|R_t|$, already represent the volatility process. Thus, taking the absolute values of the residuals derived from the ARFIMA process would reflect the filtered volatility of the return volatility process. From the filtering process, we necessarily obtain positive and negative values; however, the negative deviations are not significantly different from zero.

5 Empirical Results

5.1 News Effects on Single Assets

Before we refer to our main research questions on (i) information transmission and (ii) its pattern during normal and crisis periods, we first take a look at the impact that news has on returns and volatility of individual assets. Figure 4 presents return responses to selected macroeconomic U.S. and German news for the whole sample period, together with 95% confidence intervals and average trading volumes from three minutes before until eight minutes after the news releases.[17]

« Insert Figure 4 about here »

We observe return jumps lasting from one to eight minutes for most economic announcements.[18] For almost all of the indicators, the largest impact on all five assets occurs within the first minute after the announcement (denoted as contemporaneous response), which is in line with the results reported by Ederington and Lee (1993). The findings complement the results of earlier studies that use a five-minute interval. For example, Almeida et al. (1998) and Andersen et al. (2007) record a contemporaneous price jump of five minutes for the Deutsche Mark/USD exchange rate. In contrast, Lucca and Moench (2015) report significant excess returns in pre-announcement periods to monetary policy decisions for U.S. equities. However, we do not find such pre-announcement drifts. All contemporaneous responses are significant at least at the 95% level. The impact generally decreases during the following minutes. Trading volumes also surge as macroeconomic

[17] We also tried to include first and second leads in the model, but we found no pre-announcement impact on returns. The choice of minutes around the news releases shown in Figure 4 was done on the basis of significant price changes in the data, with effects mainly observed in the -3 to +8 minute window around announcements.

[18] Table C1 in the Internet Appendix shows the results for the whole sample and for all macroeconomic news.

news is released, and decrease gradually thereafter.[19] Before the news release, trading volumes appear to be unaffected with no distinctive pattern.

Table C2 in the Internet Appendix reports the contemporaneous and cumulative return responses to macroeconomic news for the three time periods and the five asset classes based on the different types of macroeconomic indicators from the U.S. and Germany. The significant response length ranges mainly from one to three minutes, with the cumulative response being larger than the contemporaneous response.[20] Most announcements show only a contemporaneous impact on the USD/EUR exchange rate, whereas the price discovery for the stock and bond markets takes longer, with one to two minutes for the U.S. assets and one to three minutes for the German assets. The effects are also economically significant. For instance, one standard deviation unexpected increase in non-farm payroll leads to a 0.6% increase of the DAX futures price during the post-crisis period. The impact of German news is generally lower than that of U.S. macroeconomic news. Overall, the results are in line with theoretical considerations of news effects discussed in Section 2 and the related literature discussed above. Thus the initial return analysis provides a reliable ground for further investigations on our main research questions. Especially the finding of price adjustment processes is interesting in light of our first main research question on the gradual adjustment of prices not only on basis of the public announcements, but also on basis of market interrelations thereafter.

The volatility is affected by most of the macroeconomic news in all five markets.[21] Figure 5 shows the average polynomial response of volatilities to selected U.S. and German

[19] We also added a variable for standardized trading volume in our return equation in order to capture liquidity effects on the volatility. However, the coefficients are economically small.

[20] We define the cumulative impact on return as the sum of continuous significant coefficients (as long as they do not involve a sign change). The accumulation of return responses begins from the first significant coefficient, and ceases when an insignificant coefficient or changing sign is observed. We impose this relatively conservative measure to avoid overestimation or amplification of the cumulative responses.

[21] We also examine the volatility response for ten minutes before the news release. We find slight increases in volatility for some important economic indicators. However, the magnitude is very small, and there is no distinctive pattern.

macroeconomic news, respectively, for one hour after the release.[22] We note an immediate surge in volatility, followed by a sharp decrease within the first twenty minutes and finally a complete phase-out. Thus, the volatility response patterns are much longer than those of returns. Our estimated response coefficients are in line with Andersen and Bollerslev (1998) and Andersen et al. (2003b), who report similar results for a longer-lasting volatility impact. Accordingly, like for the return dimension, the volatility results allow us to next investigate whether there are effects beyond the single asset responses, i.e., whether there are significant interrelations among the assets.

« Insert Figure 5 about here »

Below we turn the focus on our two main research questions by investigating the adjustment processes and thus whether information transmission is present as expected. Furthermore, in order to address the question of whether differences in the information transmission process arise from various states in recent business cycles, we split the sample into pre-crisis (from January 2006 through July 2007), subprime and financial crisis (from August 2007 through August 2009), and European sovereign crisis period (from September 2009 to December 2011). In the sections below, we show a noticeable shift in the impact of different macroeconomic news over the different states of the economy.

5.2 Conditional Information Transmission Among Asset Markets

With the single asset estimations revealing significant and economically relevant announcement effects, we are interested in the price discovery mechanism within the first

[22] The polynomial response functions of Equations (5a) and (5b) replace the coefficients of news dummies in Equation (4). The average intraday volatility accounts for most of the variation. Other factors (news dummies and average intraday volatility, as well as calendar, event, crisis, and day-of-the-week dummies) that influence volatilities are also incorporated into the volatility equation as discussed in the previous section. Thus, the polynomial responses capture only the macroeconomic news effects.

minute after the announcement. By examining the responses of returns and volatility based on five-second sampling intervals, we gain insight into the transmission of information across the asset markets.

The largest price movements occur within the first minute after announcements, and most of the announcements influence asset markets only in this very minute. Hence, we consider it straightforward to capture conditional return and volatility co-movements and spillovers by using five-second sampling intervals in the first minute after the announcement. The results on the information transmission among asset returns and volatility are discussed in the following sub-sections.

5.2.1 Information Transmission in Returns

Return Co-movements. To measure return co-movements we first refer to the realized kernel-corrected correlation coefficient. The signs of conditional correlation coefficients, i.e., conditional on macroeconomic announcements, are as expected and reported in Table 3.[23] The bond and USD/EUR exchange markets move in opposite direction to the stock markets in response to unexpected U.S. news. We find that the correlations between each pair of stock and bond markets increase substantially from pre-crisis to the subprime and financial crisis period. The co-movements are further strengthened in the third period, when the European sovereign crisis emerged. The opposite holds true for the correlation between the USD/EUR exchange rate and the bond markets, which can be traced back to lower responses of the USD/EUR exchange rate to unexpected U.S. news in the latter two sub-samples. The co-movements between the two bond markets remain at a high level all the time, while the positive correlation between the two stock markets increases from the subprime and financial crisis onward. This indicates that German and U.S.

[23] By definition, positive U.S. news has a negative impact on the USD/EUR exchange rate, while positive German news affects FX positively. Therefore, we observe opposite signs of conditional correlation coefficients between USD/EUR exchange rate and any other market in response to U.S. and German news, e.g. $\rho^{US;\ Pre-crisis}_{USD/EUR,Bund\ Futures} = 0.479$ and $\rho^{German;\ Pre-crisis}_{USD/EUR,Bund\ Futures} = -0.303$.

bond and stock markets became very sensitive to U.S. macroeconomic news.[24]

« Insert Table 3 about here »

Correlation coefficients conditional on German news as compared to U.S. news are generally smaller in magnitude, and this is largely because of a lower response of U.S. asset markets to German news. Stock and bond markets are negatively correlated, and the strength of negative correlation is amplified in crisis times. While Longin and Solnik (2001) and Forbes and Rigobon (2001) among others report increased correlations during market turmoil, most related studies use lower frequencies such as daily, weekly or monthly data. We however focus on the five-second frequency, and the standard negative correlation is preserved. This result could be explained by a high proportion of market participants trading these assets against each other (at a very high frequency), a noticeable finding with regard to the classical stock and bond relationship.

The changes in the magnitudes of correlations conditional on German news are quite similar to those on U.S. news. The only exception is the correlation structure among the FX and the other markets, which tend to decline during the global financial crisis and increase afterward. The increase in the size of coefficients during the global financial crisis persists during the European sovereign debt crisis. The time-varying co-movements, if any, are mainly reflected in increasing magnitude rather than in a change of the direction of the coefficients. This result points to a higher sensitivity to news during crises. Following Franses et al. (1997), we consider these findings not only as evidence of increased attention to news, but also of increased information transmission during market turmoil.

There are also commonalities across all periods, with short-term co-movements being lowest among stock and FX as well as bond and FX markets. Furthermore, intra-

[24] We also calculated the Bravais-Pearson correlation coefficient and a realized volatility-based coefficient. Both qualitatively confirm our realized kernel-based results.

asset co-movements are stronger than inter-asset ones, even in an international context, and the co-movement in the stock market is higher since the subprime and financial crisis. Our results for the dependence structure between FX and the other markets confirm those of Ranaldo and Söderlind (2010) for futures contracts of S&P500 and ten-year Treasury notes on an hourly sampling interval (up to twelve hours).

We interpret the results as evidence for assets being interconnected more strongly, which we interpret as an increase in information transmission, we further study the price dynamics, i.e., spillover effects, among national and international asset markets.

Return Spillovers. To examine conditional spillover effects, we use a vector autoregressive model as specified in Sub-section 4.3. Table 4 shows the significant coefficients for return spillovers at the 5% significance level.[25]

« Insert Table 4 about here »

The sign of return spillover coefficients are in line with our expectations based on economic considerations and the results derived from the correlation analysis. We see negative coefficients between bond and stock markets as well as between FX and stock markets. Intra-asset (i.e., DAX—E-mini S&P500 futures and Bund—T-Treasury note futures) return spillovers have positive coefficients. In contrast, the coefficients between FX and bond markets conditional on U.S. news show inconsistent signs from the beginning of the subprime and financial crisis onwards. The negative coefficients between FX and the Bund futures can be explained by the interest rate channel; if Bund futures prices increase, the interest rate declines, and thus the Euro depreciates in the short run, which leads the USD/EUR exchange rate to decrease.

[25]To conserve space we do not report the full tables with the estimated coefficients here; however, they are shown in Table E1 in the Internet Appendix.

For U.S. news we observe intra-asset lagged return spillover and feedback effects between markets of the same asset class before the crisis, i.e., between DAX and E-mini S&P500 futures, as well as Bund and 10-year Treasury note futures, but no inter-asset return spillovers. We further find return spillovers uni-directionally from the German and U.S. bond markets to the USD/EUR exchange market. During the subprime and financial crisis, the return spillover effects become intensified. Feedback effects do not exist only within the same asset markets across countries, but also across different asset markets, which implies that all markets become more sensitive to new information revealed in other markets.

During the European sovereign crisis, inter-asset spillovers and feedback effects are mitigated. Information flows from the USD/EUR to the two stock markets. Returns of all other markets spill over to E-mini S&P500. Generally the USD/EUR impacts the other markets only in the second crisis period. This is straightforward on economic grounds, as during the financial crisis the currency market was only affected indirectly on the basis of the general economic outlook and the approaching recession, whereas the European sovereign crisis posed a threat to the European Monetary Union and, ultimately, to the Euro.

During the pre-crisis period we mainly see spillovers and feedbacks between German assets and some interactions with the USD/EUR market. In the subprime and financial crisis, we find additional feedback effects between DAX and E-mini S&P500 futures, and from the Bund to the Treasury note futures. However, during the European sovereign crisis and in line with the related economic reasoning, the increased significance of German news spurs information spillovers from DAX futures to E-mini S&P500 futures, and feedback effects between Bund and 10-year Treasury note futures. Overall, German asset markets lead other markets when German economic news is revealed.

From the results above, we can observe that market participants do act not only

on the news itself, but also on the effect this news has in the closely related assets. This result can only be uncovered by slicing the one-minute interval into shorter (i.e., five-second) observation periods after the release of announcements. This reveals that trading is sensitive to both new information and the immediate impact of it. We interpret the resulting structure as a dynamic network of transmissions from news-related and (observed) trading-related information, and strong evidence for our first main research question on whether and how the price processes of assets are interconnected conditional on macroeconomic news.

Also, the results above confirm our hypothesis that asset prices react more sensitively to news released in the market where a crisis originated, which is an important result regarding our second main research question on the state-dependence of information transmission. Therefore, in a further step we test whether and how information is transmitted among asset prices. We apply bivariate Granger-causality tests for each pair of markets and estimate a heteroskedasticity-consistent covariance matrix of coefficients.

Figure 6 illustrates the results of the Granger causality tests. The interaction among the assets in response to U.S. news increases during the global financial crisis. Afterward, it returns to a level similar to the pre-crisis period, i.e., the information sensitivity is temporary. This could be explained by a temporarily increased attention to the U.S. economy, where the crisis originated. For German macroeconomic news, where the interaction also intensifies during the first crisis, we cannot see a decline afterward. Specifically, we see no increase in the number of causal relationships regarding German assets, but of pairs including the USD/EUR exchange rate. This further strengthens our notion of the influence of the European crisis and the Euro currency risk associated with Bund and DAX Futures, as well as FX spot markets.

« Insert Figure 6 about here »

Like the implications derived from the correlation structure and the VAR model uncovered by the five-second interval, this change in the pricing of several assets has strong consequences for trading. Market participants can expect that the reactions of assets to macroeconomic news are strongly dependent on the state of the market where the news is released.[26] In the following sub-section, we analyze the transmissions in the second statistical moment in order to see whether also return fluctuations are interrelated.

5.2.2 Information Transmission in Volatility

We report the significant parameters in Table 5.

« Insert Table 5 about here »

We observe volatility co-movements and spillovers conditional on U.S. macroeconomic news across all five assets. Their (significant) occurrence and magnitude increases in the global financial crisis and remains above the pre-crisis level during the European sovereign crisis period. International volatility spillovers conditional on German news are rather rare in the pre-crisis period, but both inter- and intra-asset co-movements and spillovers intensify during the first crisis and further increase thereafter. This is in line with economic reasoning and our findings from above. We again see strong increases in the spillovers related to the USD/EUR exchange rate, triggered by the Euro currency crisis.[27]

In addition to the state-dependent reactions of returns to news, we find that the price dispersion is also affected by macroeconomic announcements, in particular by those

[26] We also run a placebo test by choosing days without announcements. Unsurprisingly, the robustness checks for selected days reported in Table D1 in the Internet Appendix show substantially lower estimates. This finding supports the assumption that information transmissions predominantly occur at the time of a news release.

[27] We used the same days without announcements that were used for the placebo test for the return spillovers (see Footnote 26). The indicative robustness checks reported in Table D2 show again much smaller interaction coefficients.

where the crises originated. This can be attributed to the increased uncertainty in the markets and the increased sensitivity to surprises in phases of turmoil. Based on our five-second sampling interval, different origins of the crisis become apparent as drivers for the ways how assets affect each other. This is a crucial insight in addition to what we can learn from single-asset analyses. Thus, studying the data in five-second intervals again enables insight into the mechanisms across asset markets in the presence of crises and conditional on macroeconomic news.

To sum up, our empirical results demonstrate that investors react differently to news announcements in different states of the market. More importantly, there is a systematic difference in the incorporation of information from other asset markets. In general, investors react stronger to price movements in other markets during financial crises. We argue that these systematic differences cannot be traced back to changes in the market microstructure, because investors could have traded on a five-second basis 10-15 years ago as well. Furthermore, we do not see a steady increase in the speed of incorporation of information over our sample period. Instead, we see variation in the interconnectedness and the level of speed among pre-crisis, crisis, and post-crisis periods, with a significant increase during financial crises and a return to the pre-crisis in the aftermath. This observation provides evidence that systematic differences in the speed of information incorporation can be attributed to a change in investors' behavior rather than a change in the evolution of the markets.

6 Conclusion

In this paper, we analyze asset price processes around macroeconomic announcements from the U.S. and Germany. We study the interactions among markets conditional on the release of macroeconomic announcements based on high-frequency sampling intervals

for “normal” and “crisis” times. Such intervals can mitigate the omitted variable bias and dual-causality problems. We first analyze the impact that news effects have on returns and volatility of individual assets on a one-minute sampling interval. We find return jumps lasting from one to eight minutes for most macroeconomic announcements with largest changes in returns occurring within the first five minutes after the news release. In contrast, volatility patterns are much longer with an immediate surge when macroeconomic news is released and a sharp decline within the next twenty minutes.

To further analyze the gradual price discovery processes, we increase our sampling frequency to five-second intervals. Addressing our first main research question this allows us to analyze the data in detail for interconnectedness and (information) transmissions across assets and markets. Our second main research question on the state-dependence of transmissions is answered by findings for the macroeconomic news impact on stock, bond, and foreign exchange markets that varies over time depending on the state of the economy. In general, we find negative inter-asset return spillover coefficients, whereas intra-asset spillover coefficients are positive. The correlation structure based on realized kernel estimates show increasing co-movements between asset markets when going from pre- to crisis periods. Market participants pay more attention to news during crisis and react stronger. A prevailing negative correlation between bonds and stocks in crisis times on very high frequency are in line with theory but contradicts findings in the empirical literature based on lower sampling frequencies.

We document pronounced state-dependence in the way assets react to news from the respective locations: U.S. asset markets mainly pay attention to their domestic indicators, but during the European sovereign crisis they respond strongly to German news as well. In addition, the impacts of U.S. news are also larger in this period as economic uncertainty continues. This change in the estimates of macroeconomic announcement effects could be explained as a lasting change in risk perception as a result of continuing economic

uncertainty. During the subprime and financial crisis feedback effects do not only appear within the same assets across countries but also across different asset markets. This implies that asset prices become more sensitive to new information revealed in other markets. Volatility co-movements and spillovers are rather rare in the pre-crisis period but increase in significance and magnitude during the global financial crisis and remains on a high level during the European sovereign debt crisis. We also see large spillover coefficients for the USD/EUR exchange rate triggered by the Euro currency crisis. This finding can be directly attributed to the economic condition of the region during the European sovereign crisis, and shows up in the way information is transmitted between the assets in a dynamic way. In summary, we interpret our results, i.e. the interaction in first and second moments conditional on fundamental news, as a dynamic network of news-based and trading-based information transmissions. However, if volatility is longer lasting it is very likely that noise traders are active in the market and information from price changes in other markets are transmitted. We leave the disentangling of news-based information transmissions from contagion effects for future research.

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References

Almeida, A., Goodhart, C., and Payne, R. (1998). The effects of macroeconomic news on high frequency exchange rate behavior. *Journal of Financial and Quantitative Analysis*, 33:383–408.

Andersen, T. G. and Bollerslev, T. (1998). Deutsche mark-dollar volatility: Intraday activity patterns, macroeconomic announcements, and longer run dependencies. *Journal of Finance*, 53:219–265.

Andersen, T. G., Bollerslev, T., Diebold, F. X., and Labys, P. (1999). Understanding, optimizing, using and forecasting realized volatility and correlation. Working Paper.

Andersen, T. G., Bollerslev, T., Diebold, F. X., and Labys, P. (2003a). Modeling and forecasting realized volatility. *Econometrica*, 71:579–626.

Andersen, T. G., Bollerslev, T., Diebold, F. X., and Vega, C. (2003b). Micro effects of macro announcements: Real-time price discovery in foreign exchange. *American Economic Review*, 93:38–62.

Andersen, T. G., Bollerslev, T., Diebold, F. X., and Vega, C. (2007). Real-time price discovery in global stock, bond and foreign exchange markets. *Journal of International Economics*, 73:251–277.

Andersson, M. (2010). Using intraday data to gauge financial market responses to ferderal reserve and ECB monetary policy decisions. *International Journal of Central Banking*, 6:117–146.

Balduzzi, P., Elton, E. J., and Green, T. C. (2001). Economic news and bond prices: Evidence from the U.S. treasury market. *Journal of Financial and Quantitative Analysis*, 36:523–543.

Bandi, F. M. and Russel, J. R. (2005). Microstructure noise, realized variance, and optimal sampling. *Review of Economic Studies*, 75:339–369.

Bandi, F. M. and Russel, J. R. (2006). Separating microstructure noise from volatility. *Journal of Financial Economics*, 79:655–692.

Barndorff-Nielsen, O. E., Hansen, P. R., Lunde, A., and Shephard, N. (2008). Designing realised kernels to measure the ex-post variation of equity prices in the presence of noise. *Econometrica*, 76:1481–1536.

Basistha, K. and Kurov, A. (2008). Macroeconomic cycles and the stock market's reaction to monetary policy. *Journal of Banking and Finance*, 32:2606–2616.

Bernanke, B. S. and Kuttner, K. N. (2005). What explains the stock market's reaction to federal reserve policy. *Journal of Finance*, 60:1221–1257.

Bomfim, A. N. (2003). Pre-announcement effects, news effects, and volatility: Monetary policy and the stock market. *Journal of Banking and Finance*, 27:133–151.

Bongaerts, D., Roll, R., Rösch, D., Van Dijk, M. A., and Yuferova, D. (2014). On the propagation of shocks across international equity markets: A microstructure perspective. Working Paper.

Boyd, J. H., Hu, J., and Jagannathan, R. (2005). The stock market's reaction to unemployment news: Why bad news is usually good for stocks. *Journal of Finance*, 60:649–672.

Brenner, M., Pasquariello, P., and Subrahmanyam, M. (2009). On the volatility and comovement of U.S. financial markets around macroeconomic news announcements. *Journal of Financial and Quantitative Analysis*, 44:1265–1289.

Campbell, J. Y. and Ammer, J. (1993). What moves the stock and bond markets? A variance decomposition for long-term asset returns. *Journal of Finance*, 48:3–37.

Chaboud, A., Chiquoine, B., Hjalmarsson, E., and Loretan, M. (2010). Frequency of observation and the estimation of integrated volatility in deep and liquid financial markets. *Journal of Empirical Finance*, 17:212–240.

Chen, S.-S. (2007). Does monetary policy have asymmetric effects on stock returns? *Journal of Money, Credit and Banking*, 39:667–688.

Chen, Y.-L. and Gau, Y.-F. (2010). News announcements and price discovery of FX spot and futures markets. *Journal of Banking and Finance*, 34:1628–1636.

Christensen, K., Oomen, R., and Podolskij, M. (2011). Fact or fiction: Jumps at ultra high frequency. *Review of Financial Economics*, 114:576–599.

Connolly, R. and Wang, A. F. (2003). International equity market comovements: Economic fundamentals and contagion. *Pacific-Basin Finance Journal*, 11:23–43.

D'Amico, S. and Farka, M. (2011). The Fed and the stock market: An identification based on intraday futures data. *Journal of Business and Economic Statistics*, 29:126–137.

Ederington, L. H. and Lee, J. H. (1993). How markets process information: News releases and volatility. *The Journal of Finance*, 48:1161–1191.

Eun, C. S. and Shim, S. (1989). International transmission of stock market movements. *Journal of Financial and Quantitative Analysis*, 24:241–256.

Farka, M. (2009). The effect of monetary policy shocks on stock prices accounting for endogeneity and omitted variable biases. *Review of Financial Economics*, 18:47–55.

Fernandez-Perez, A., Frijns, B., and Tourani-Rad, A. (2017). When no news is good news – the decrease in investor fear after the fomc announcement. *Journal of Empirical Finance*, 41:187–199.

Fleming, J., Kirb, C., and Ostdiek, B. (1998). Information and volatility linkages in the stock, bond and money market. *Journal of Financial Economics*, 49:111–137.

Forbes, K. and Rigobon, R. (2001). No contagion, only interdependence: measuring stock market co-movements. *Journal of Financial Economics*, 57:2223–2261.

Franses, P. H., van Ieperen, R. A., Kofman, P., Martens, M., and Menkveld, A. J. (1997). Volatility patterns and spillovers in bund futures. *Journal of Financial Research*, 10:459–482.

Füss, R., Grabellus, M., Mager, F., and Stein, M. (2017). Something in the air: Information density, news surprises, and price jumps. *Journal of International Financial Markets, Institutions and Money*, 53:50–75.

Goldberg, L. S. and Grisse, C. (2013). Time variation in asset price responses to macro announcements. NBER Working Paper Series.

Hanousek, J. and Kocenda, E. (2011). Foreign news and spillovers in emerging markets. *Review of International Economics*, 19:170–188.

Hansen, P. R. and Lunde, A. (2003). An optimal and unbiased measure of realized variance based on intermittent high-frequency data. *Unpublished paper, Department of Economics, Stanford University.*

Hansen, P. R. and Lunde, A. (2005). A realized variance for the whole day based on intermittent high-frequency data. *Journal of Financial Econometrics*, 3:525–554.

Hansen, P. R. and Lunde, A. (2006). Realized variance and market microstructure noise. *Journal of Business and Economic Statistics*, 24:127–218.

Hendershott, T., Jones, C. M., and Menkveld, A. J. (2011). Does algorithmic trading improve liquidity? *Journal of Finance*, 66:1–33.

Hou, Y. and Li, S. (2016). Information transmission between U.S. and China index futures markets: An asymmetric DCC GARCH approach. *Economic Modelling*, 52:884–897.

Karolyi, G. and Stulz, R. (1996). Why do markets move together? An investigation of U.S.-Japan stock return comovements. *Journal of Finance*, 51:961–986.

King, M. A. and Wadhwani, S. (1990). Transmission of volatility between stock markets. *Review of Financial Studies*, 3:5–33.

Kodres, L. and Pritsker, M. (2002). A rational expectations model of financial contagion. *Journal of Finance*, 57:769–799.

Lobo, B. J. (2002). Interest rate surprises and stock prices. *Financial Review*, 37:73–91.

Longin, F. and Solnik, B. (2001). Extreme correlation and international equity markets. *Journal of Finance*, 56:649–676.

Lucca, D. O. and Moench, E. (2015). The pre-FOMC announcement drift. *Journal of Finance*, 70:329–371.

Neely, C. (2015). Unconventional monetary policy had large international effects. *Journal of Banking and Finance*, 52:101–111.

Ranaldo, A. and Söderlind, P. (2010). Safe haven currencies. *Review of Finance*, 14:385–407.

Stoll, H. R. and Whaley, R. E. (1990). The dynamics of stock index and stock index futures returns. *Journal of Financial and Quantitative Analysis*, 25:441–468.

Wu, C., Li, J., and Zhang, W. (2005). Intradaily periodicity and volatility spillovers between international stock index futures markets. *Journal of Futures Markets*, 25:553–585.

Zhou, B. (1996). High-frequency data and volatility in foreign exchange rates. *Journal of Business and Economic Statistics*, 14:45–52.

Table 1: Summary Statistics of Five-Second Asset Returns and Trading Volumes around Macroeconomic Announcements

	Mean	Std. Dev.	Minimum	Maximum	Skewness	Kurtosis
Total Period						
FDAX Return	-1.87E-07	3.34E-03	-2.39E-02	2.33E-02	0.08	22.99
FGBL Return	-7.53E-06	7.12E-04	-7.14E-03	7.09E-03	-0.17	45.32
USD/EUR Return	-1.08E-07	2.98E-04	-2.96E-03	3.18E-03	0.52	19.78
FDAX Volume	125.64	150.65	0	2516	4.42	35.98
FGBL Volume	1185.58	1499.20	0	32242	4.92	52.14
USD/EUR Volume	32.55	28.74	0	557	2.54	21.15
Pre-Crisis Period						
FDAX Return	1.31E-05	3.16E-03	-2.22E-02	2.32E-02	0.11	21.87
FGBL Return	-7.42E-06	7.61E-04	-7.14E-03	7.09E-03	-0.25	53.14
USD/EUR Return	2.51E-06	3.17E-04	-2.37E-03	2.92E-03	0.82	15.34
FDAX Volume	132.82	166.51	0	2516	4.39	34.04
FGBL Volume	1579.87	1751.52	0	32242	4.55	44.32
USD/EUR Volume	38.99	30.83	0	557	2.59	25.04
Crisis Period						
FDAX Return	-1.56E-05	3.53E-03	-2.39E-02	2.33E-02	0.06	23.27
FGBL Return	-7.66E-06	6.51E-04	-5.21E-03	4.50E-03	0.00	24.93
USD/EUR Return	-3.08E-06	2.75E-04	-2.96E-03	3.18E-03	-0.03	27.29
FDAX Volume	117.33	129.43	0	2045	4.10	32.50
FGBL Volume	728.88	953.67	0	15006	5.22	50.65
USD/EUR Volume	25.23	24.16	0	273	2.45	10.86
Post-Crisis Period						
FDAX Return	-8.19E-07	2.82E-03	-4.04E-02	3.81E-02	-1.02E-02	35.82
FGBL Return	3.54E-07	6.31E-04	-1.48E-02	1.45E-02	-1.20E-02	35.69
USD/EUR Return	4.16E-08	2.39E-04	-5.84E-03	6.07E-03	6.24E-03	19.66
FDAX Volume	221.16	371.33	0	96008	45.77	8424.60
FGBL Volume	1277.26	1953.07	0	140360	9.99	333.96
USD/EUR Volume	65.07	70.70	0	2157	3.39	23.22

This table shows exemplarily for the German markets DAX and Bund futures as well as the USD/EUR exchange rate the descriptive statistics on asset returns and trading volume for the five second interval. The entire observation period ranges from January 2006 to December 2011, the pre-crisis period from January 2006 to July 2007, the crisis period from August 2007 to August 2009, and the post-crisis period from September 2009 to December 2011. The trading volume of the DAX futures and the Bund futures is denoted in the number of contracts, and trading volume of U.S. dollar-Euro exchange rate is denoted in million of Euros. FDAX, FGBL, and USD/EUR stand for the DAX and Bund future, as well as U.S. Dollar-Euro exchange rate.

Table 2: Macroeconomic Announcements

Announcement	**# of Observations**	**Announcement Time**	**Frequency**
U.S. Announcements			
Durable Goods Orders	72	14:30	Monthly
GDP	72	14:30	Monthly
Non-Farm Payroll	72	14:30	Monthly
Trade Balance	72	14:30	Monthly
Consumer Price Index	72	14:30	Monthly
Producer Price Index	72	14:30	Monthly
Initial Unemployment Claim	313	14:30	Weekly
Housing Starts	72	14:30	Monthly
New Home Sales	72	16:00	Monthly
Consumer Confidence Index	72	16:00	Monthly
Manufacturing ISM	72	16:00	Monthly
Non-Manufacturing ISM	72	16:00	Monthly
German Announcements			
GDP	23	08:00	Quarterly
Industrial Production	61	12:00	Monthly
Consumer Price Index	65	Varies	Monthly
Producer Price Index	63	08:00	Monthly
IFO Business Climate	72	10:00	Monthly
ZEW Survey	71	11:00	Monthly

All timestamps are Central European Time (CET); U.S. GDP includes advanced, preliminary, and final GDP announcements, each is announced quarterly at different months.

Table 3: Realized-Kernels Corrected Conditional Correlation Coefficients

	Pre-Crisis					Subprime and Financial Crisis					European Sovereign Crisis				
	E-mini S&P500 F.	10Y T-Note F.	USD/EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/EUR	DAX F.	Bund F.
U.S. Announcements															
E-mini S&P500 F.	1					1					1				
10Y T-Note Futures	-0.064	1				-0.463	1				-0.537	1			
USD/EUR	0.017	0.491	1			-0.087	0.198	1			0.068	0.149	1		
DAX Futures	0.560	-0.107	-0.035	1		0.862	-0.453	-0.113	1		0.830	-0.593	0.066	1	
Bund Futures	-0.020	0.699	0.479	-0.073	1	-0.497	0.605	0.221	-0.542	1	-0.576	0.671	0.097	-0.645	1
German Announcements															
E-mini S&P500 F.	1					1					1				
10Y T-Note Futures	-0.132	1				-0.328	1				-0.258	1			
USD/EUR	0.148	-0.250	1			0.197	-0.187	1			0.416	-0.231	1		
DAX Futures	0.164	-0.206	0.391	1		0.792	-0.239	0.232	1		0.611	-0.242	0.348	1	
Bund Futures	0.006	0.163	-0.303	-0.226	1	-0.220	0.348	-0.149	-0.290	1	-0.350	0.335	-0.363	-0.370	1

This table shows the realized-kernel corrected correlation coefficients conditional on macroeconomic announcements in the three subsamples: pre-crisis (January 2006 through July 2007), subprime and financial crisis (August 2007 through August 2009), and European sovereign crisis period (September 2009 through December 2011). The correlation coefficients are calculated using five-second returns within one minute after the release of U.S. and German announcements, respectively.

Table 4: VAR Model Results of Conditional Return Spillovers

			U.S. News			German News		
			Pre-Crisis	Subpr. and Fin. Crisis	Europ. Crisis	Pre-Crisis	Subpr. and Fin. Crisis	Europ. Sov. Crisis
E-mini S&P500 F.	→	10Y T-Note F.					-0.025	
10Y T-Note F.	→	E-mini S&P500 F.			-0.321	-0.119		
E-mini S&P500 F.	→	DAX Futures	0.159	0.236			0.230	
DAX Futures	→	E-mini S&P500 F.	0.194	0.122	0.204	0.089	0.168	0.124
E-mini S&P500 F.	→	Bund Futures						
Bund Futures	→	E-mini S&P500 F.		-0.263	-0.191	-0.060	-0.284	-0.150
E-mini S&P500 F.	→	USD/EUR		0.016	0.017	-0.121		
USD/EUR	→	E-mini S&P500 F.	0.059		0.211			0.160
10Y T-Note F.	→	DAX Futures			-0.316			
DAX Futures	→	10Y T-Note F.		-0.023				
10Y T-Note F.	→	Bund Futures				0.261		0.085
Bund Futures	→	10Y T-Note F.	0.079	0.053	0.065	0.122	0.176	0.092
10Y T-Note F.	→	USD/EUR	0.087		0.046			
USD/EUR	→	10Y T-Note F.		0.096	-0.052		-0.034	
DAX Futures	→	Bund Futures		-0.018				-0.039
Bund Futures	→	DAX Futures		-0.253		-0.695	-0.452	
DAX Futures	→	USD/EUR					0.058	0.058
USD/EUR	→	DAX Futures			0.107			
Bund Futures	→	USD/EUR	0.326	0.119	-0.142	-0.737	-0.529	-0.397
USD/EUR	→	Bund Futures					-0.069	-0.039

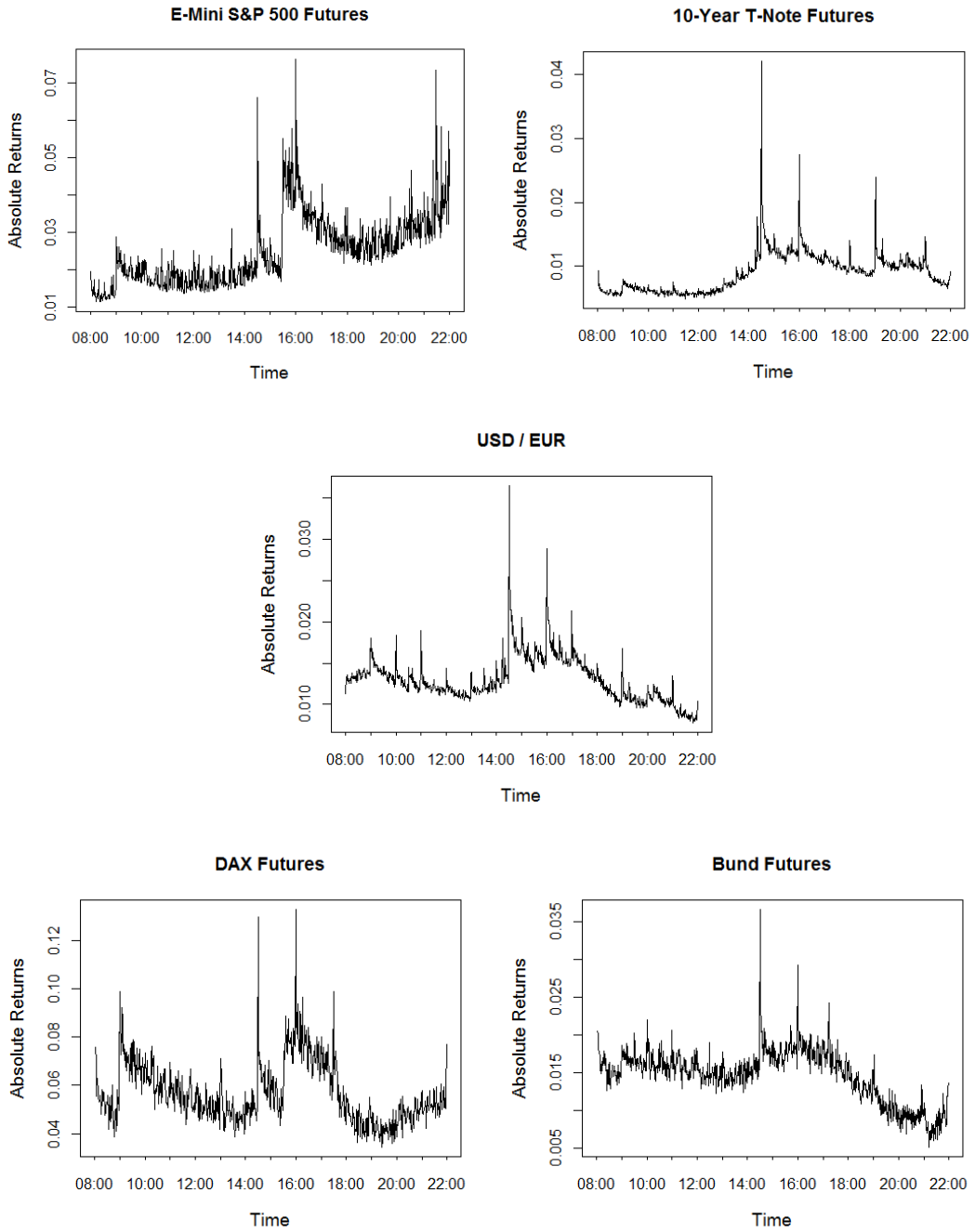
This table shows the VAR model estimation results for five-second returns of E-mini S&P500 futures, 10-year Treasury note futures, USD/EUR exchange rate, DAX futures, and Bund futures, falling into the one-minute window after all U.S. news with a significant impact on at least two of the three markets, in the three subsamples: pre-crisis (January 2006 through July 2007), subprime and financial crisis period (August 2007 through August 2009), and European sovereign crisis period (September 2009 through December 2011). The lag length, selected according to the Hannan-Quinn and Schwarz criteria, is two. The coefficient from one market is the sum of coefficients significant at 95% confidence level.

Table 5: Conditional Five-Second Volatility Co-movements and Spillovers

	Pre-Crisis					Subprime and Financial Crisis					European Sovereign Crisis				
	E-mini S&P500 F.	10Y T-Note F.	USD/EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/EUR	DAX F.	Bund F.
U.S. Announcements															
E-mini S&P500 F. (0)		0.036	0.041	0.006	0.001		0.042	0.031	0.138	0.004		0.035	0.032	0.399	0.022
10Y T-Note F. (0)	0.090		0.130		0.002	0.229		0.054	0.058	0.041	0.143		0.057	0.238	0.139
USD/EUR (0)	0.130	0.165				0.204	0.066		0.061	0.014	0.136	0.058		0.203	0.056
DAX Futures (0)	0.135				0.019	0.404	0.031	0.027		0.045	0.428	0.062	0.052		0.065
Bund Futures (0)	0.373	0.243		0.319		0.129	0.250	0.077	0.511		0.160	0.244	0.096	0.437	
E-mini S&P500 F. (L)		0.009	0.007	0.011	0.002		0.024	0.019	0.006	-0.002		0.008	0.018	0.095	-0.006
10Y T-Note F. (L)	0.070		0.046			0.085		0.019	-0.016	0.007			0.043	-0.090	0.022
USD/EUR (L)	0.046	0.045		-0.011	-0.003	0.043	0.057				0.010	0.025		0.032	0.046
DAX Futures (L)	0.169		-0.033		0.056	0.022		0.011		0.040	0.163		0.013		0.040
Bund Futures (L)	0.527		-0.203	0.863		-0.126	0.184	0.095	0.238		-0.028	0.091	0.107	0.169	
German Announcements															
E-mini S&P500 F. (0)		0.010					0.014	0.010	0.116	0.004		0.013	0.031	0.238	0.018
10Y T-Note F. (0)	0.032		0.027			0.087			0.019	0.023	0.072		0.040	0.086	0.088
USD/EUR (0)		0.021		0.005		0.048			0.035	0.006	0.101	0.023		0.195	0.047
DAX Futures (0)			0.026		0.003	0.261	0.007	0.016		0.014	0.221	0.014	0.055		0.038
Bund Futures (0)				0.024		0.056	0.060		0.100		0.029	0.024	0.023	0.065	
E-mini S&P500 F. (L)		0.020			0.001		0.006	0.007	0.007				0.011	0.018	
10Y T-Note F. (L)	0.026		0.014			0.030		0.016		0.010			0.014	0.028	0.018
USD/EUR (L)		0.008			-0.001	0.030	0.015		0.015	0.007	0.020			0.028	0.024
DAX Futures (L)	0.075				0.017	0.040	0.006	0.015		0.015	0.016	0.007	0.024		0.007
Bund Futures (L)			0.062	0.122			0.032		0.102			0.005	0.009	0.008	

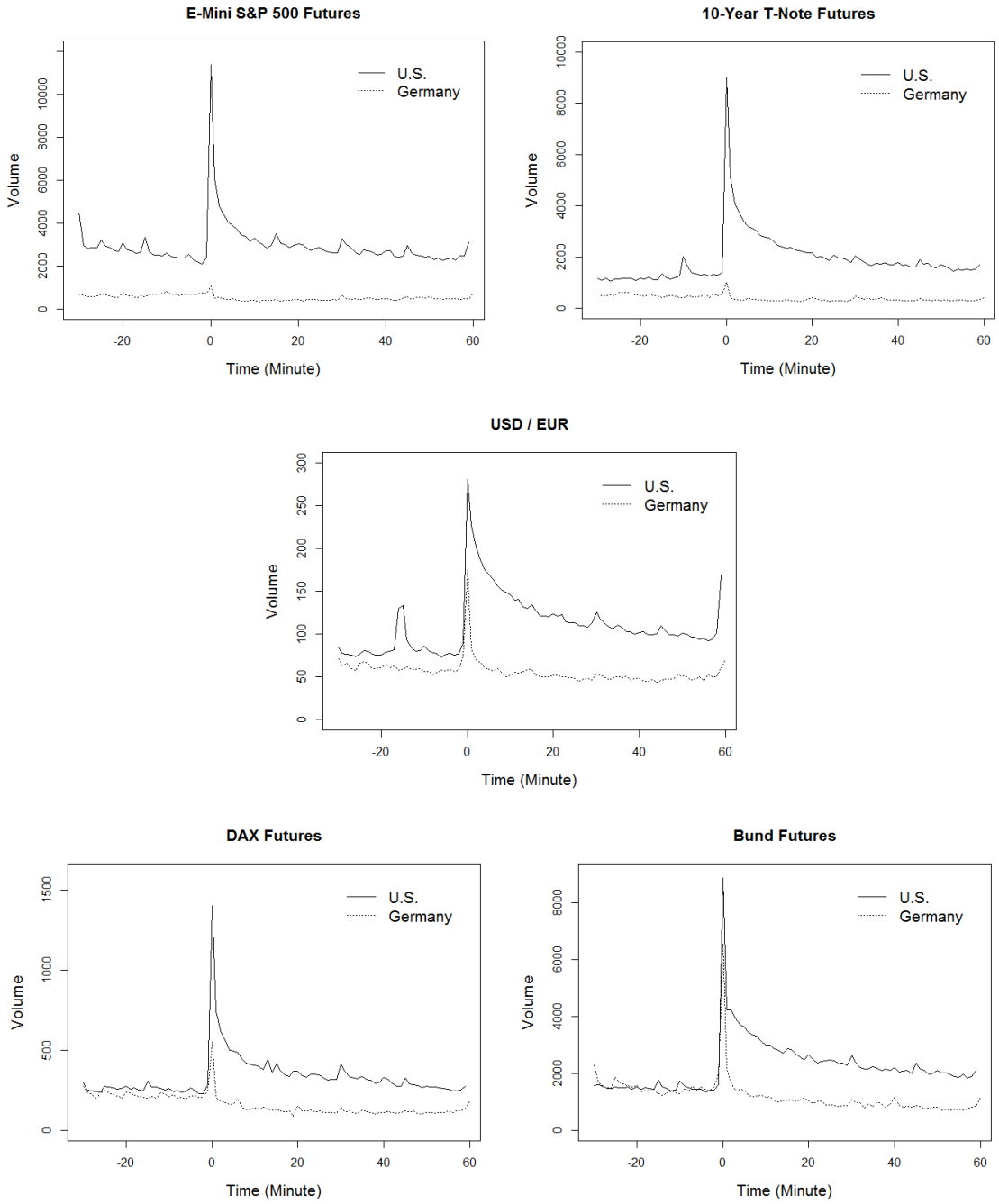
This table shows the volatility co-movements and spillovers among the E-mini S&P500 futures, 10-year Treasury note futures, USD/EUR exchange rate, DAX futures, and Bund futures markets within one hour after macroeconomic announcement releases for five-second sampling intervals. The volatility processes are first filtered using an ARFIMA(1,d,1) model, $(1-\rho L)(1-L)^d|R_t| = (1-\theta L)\xi_t$, while the USD/EUR volatility is additionally filtered by means of a flexible Fourier form to capture the periodic patterns. We then derive the co-movement and spillover estimates from OLS estimates with HAC-robust standard errors. We estimate the following model specifications for five-second filtered volatility processes within one hour after the announcements: $\xi_t^i = c^i + \sum_{q=1}^{Q} \varphi_q^i \xi_{t-q}^i + \sum_{j=1}^{4} \sum_{q=0}^{Q} \varphi_q^j \xi_{t-q}^j + \varepsilon_t^i$. The independent variables are comprised of lagged volatilities (L) from their own markets, and the contemporaneous (0) and lagged volatilities (L) from the other four markets. Given space constraints, the coefficient of lagged variables from one market is the sum of coefficients significant at the 95% confidence level. The coefficients of contemporaneous effects are also significant at the 95% confidence level.

Figure 1: Average Intraday One-Minute Absolute Asset Returns



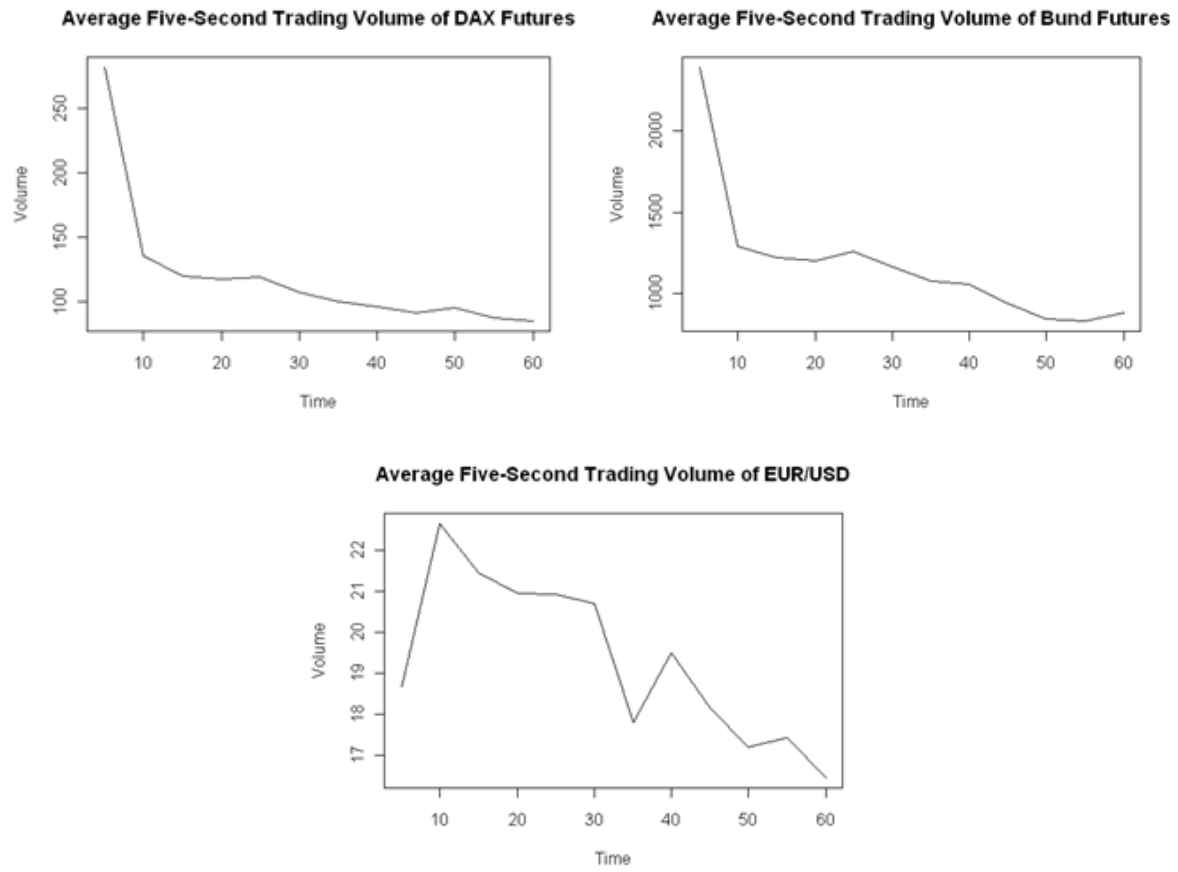
This figure plots the average intraday one-minute absolute returns from 8:00 CET (2:00 EST) to 22:00 CET (16:00 EST). The spikes on the figures represent the following important daily events: 9:00am CET (1:00 EST): German and London stock markets open; 14:30 CET (8:30 EST): U.S. macroeconomic announcements are released; 15:30 CET (9:30 EST): U.S. stock market opens; 16:00 CET (10:00 EST), U.S. macroeconomic announcements are released; and 17:30 CET (11:30 EST): German stock market closes.

Figure 2: Asset Average One-Minute Trading Volumes around Announcements



The figures show one-minute trading volume (in contracts for E-mini S&P500, 10-Year T-Note, DAX and Bund futures, in millions of Euro for the USD/EUR exchange rate) half an hour before and one hour after macroeconomic announcements (averaged through announcements from the U.S. and Germany, respectively).

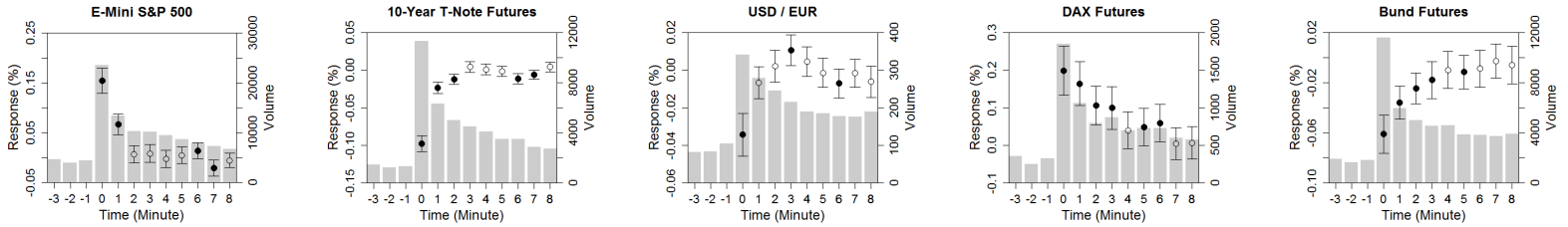
Figure 3: Average Five-Second Trading Volume within One Minute after Announcements



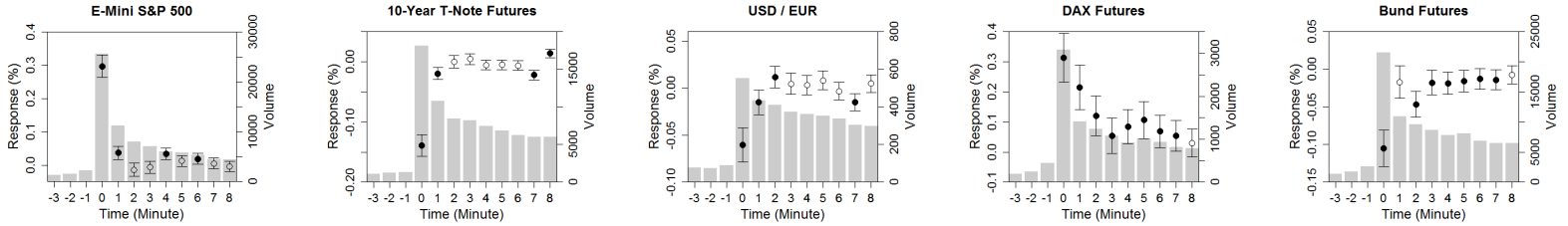
This table shows exemplarily (for the German asset markets DAX and Bund futures, as well as the USD/EUR exchange rate) the average five-second trading volume over all significant announcements within one minute after the release of the macroeconomic announcement according to Table 2.

Figure 4: Asset Return and Trading Volume Responses to Macroeconomic News (Full Sample)

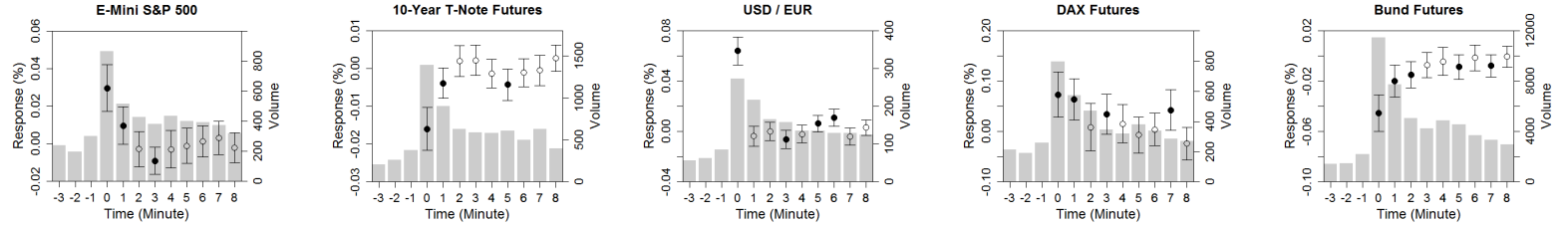
U.S. Manufacturing ISM



U.S. Non-Farm Payroll



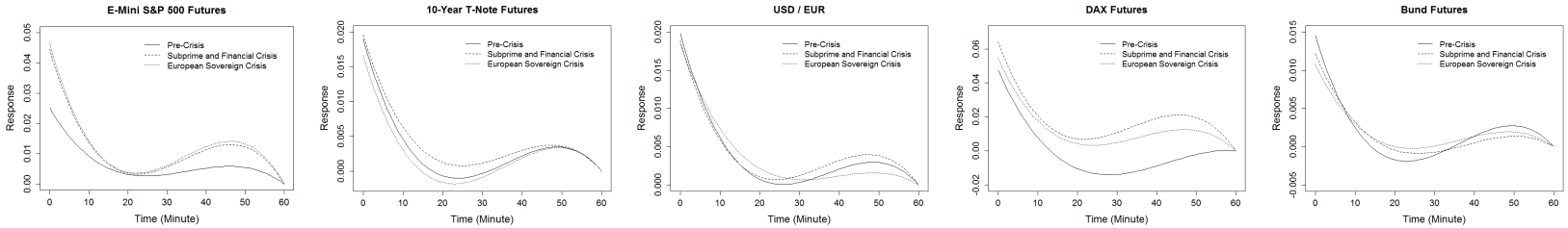
German IFO Business Climate



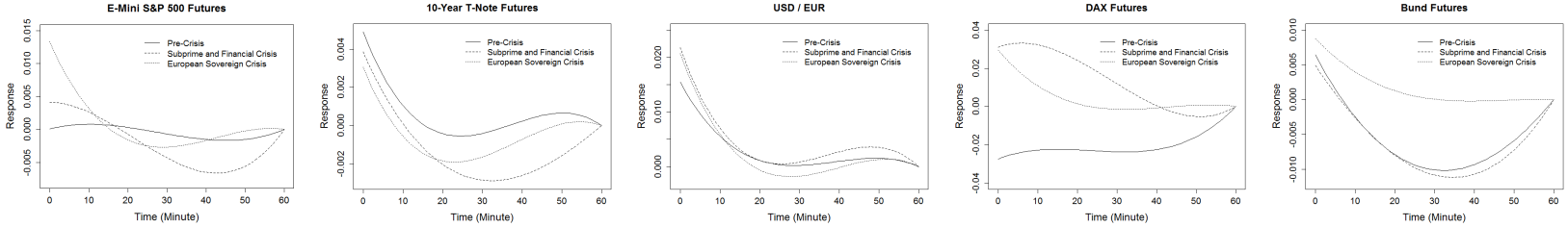
The figures plot the return response with a 95% confidence interval to selected U.S. and German macroeconomic news within eight minutes after release, and the average trading volumes within three minutes before and eight minutes after release. The solid circles represent significant responses at the 95% confidence level.

Figure 5: One-Hour Average Polynomial Response of Volatility

Panel A: U.S. Macroeconomic Announcements

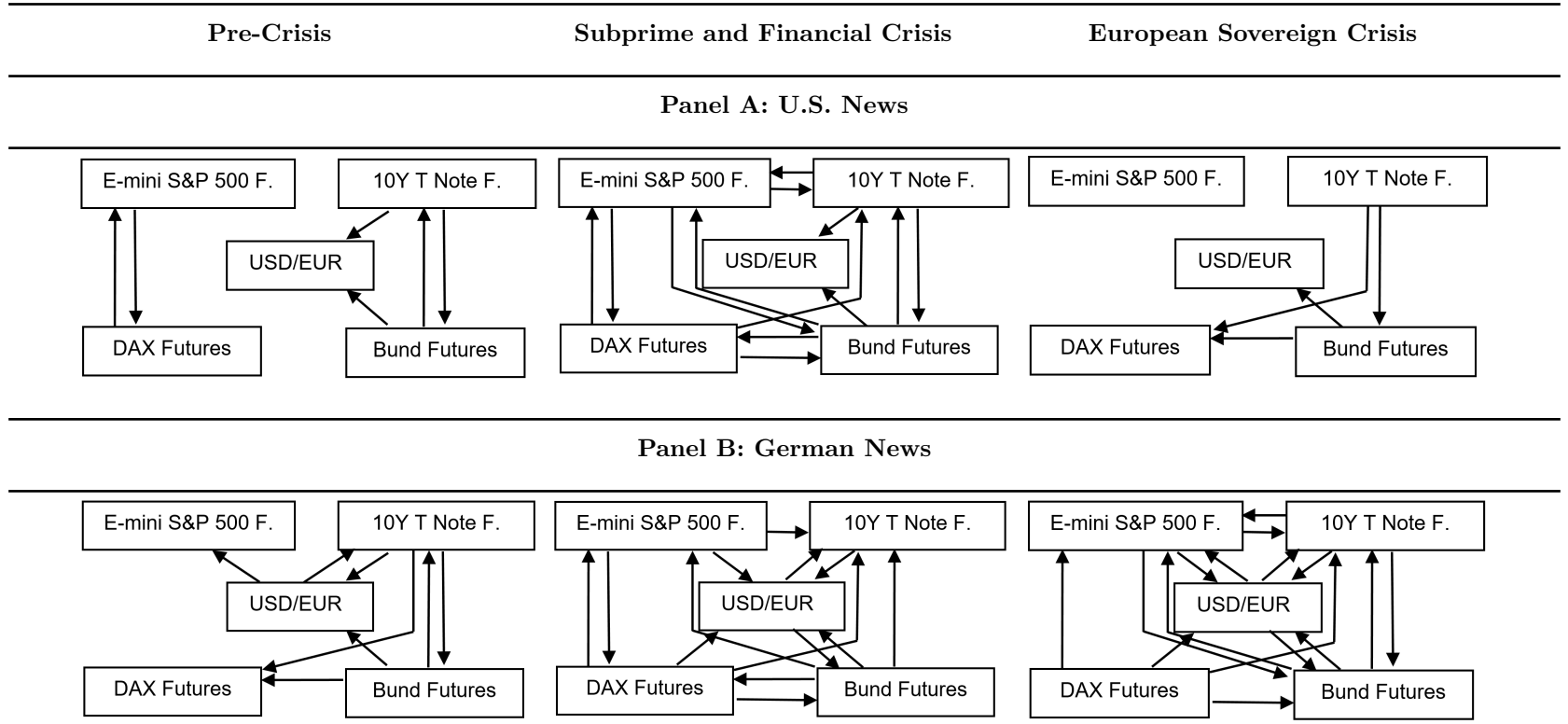


Panel B: German Macroeconomic Announcements



Panels A and B show the polynomial response of volatilities averaged through important macroeconomic announcements in the three subsamples: pre-crisis (January 2006 through July 2007), subprime and financial crisis period (August 2007 through August 2009), and European sovereign crisis period (September 2009 through December 2011).

Figure 6: Heteroskedasticity-Consistent Granger Causality between Each Pair of Asset Markets



These figures show the heteroskedasticity-consistent (HC) bivariate Granger causality of five-second returns falling into one-minute windows after all news that significantly impacts at least two of the five markets. Panels A and B show the results for the U.S. and German macroeconomic news in the three subsamples: pre-crisis (January 2006 through July 2007), subprime and financial crisis period (August 2007 through August 2009), and European sovereign crisis period (September 2009 through December 2011), respectively. Based on the F-statistic, the arrow means the Granger causality exists at the 95% confidence level.

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Internet Appendix for: Financial Crises, Price Discovery, and Information Transmission: A High-Frequency Perspective

Roland Füss* Ferdinand Mager† Michael Stein‡ Lu Zhao§

Abstract

This paper examines the price discovery processes before and during the 2007-09 subprime and financial crisis, as well as the subsequent European sovereign crisis, for American and German stock and bond markets, as well as for U.S. Dollar/Euro FX. Based on five-second intervals, we analyze how asset prices interact conditional on macroeconomic announcements from the U.S. and Germany. Our results show significant co-movement and spillover effects in returns and volatility, reflecting systematic information transmission mechanisms among asset markets. We document strong state-dependence with a substantial increase in inter-asset spillovers and feedback effects during times of crisis.

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Financial Crises, Price Discovery, and Information Transmission: A High-Frequency Perspective

Abstract

This paper examines the price discovery processes before and during the 2007-09 subprime and financial crisis, as well as the subsequent European sovereign crisis, for American and German stock and bond markets, as well as for U.S. Dollar/Euro FX. Based on five-second intervals, we analyze how asset prices interact conditional on macroeconomic announcements from the U.S. and Germany. Our results show significant co-movement and spillover effects in returns and volatility, reflecting systematic information transmission mechanisms among asset markets. We document strong state-dependence with a substantial increase in inter-asset spillovers and feedback effects during times of crisis.

Keywords: *Financial crises, macroeconomic announcements, price discovery process, information transmission process, high-frequency data.*

JEL Codes: *G*01, *G*12, *G*14, *G*15

Content

Appendix A:
Crisis Events

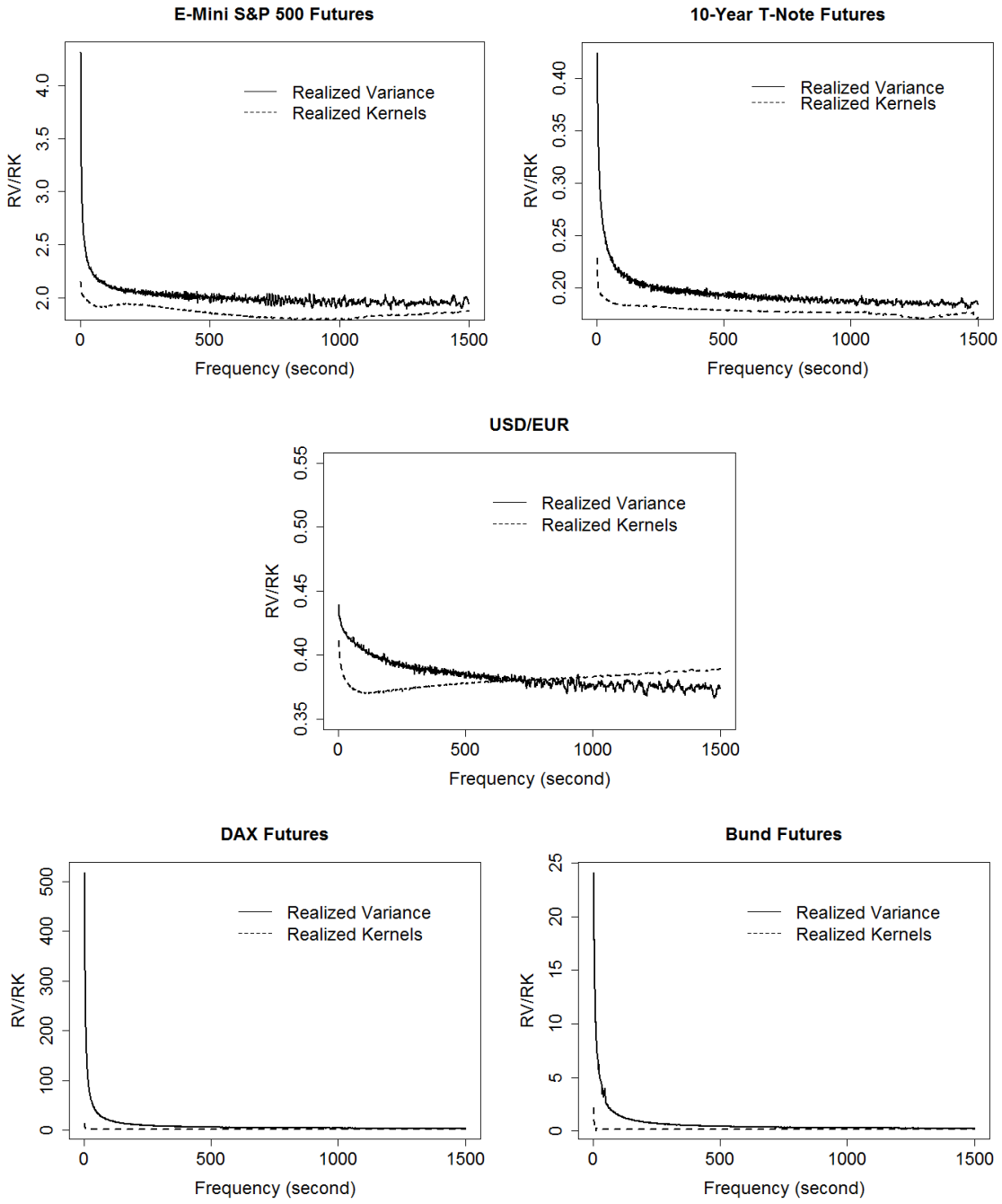
Table A1: Crisis Events from August 2007 through December 2011

Time		**Crisis Events**
August 13, 2007	16:36	Goldman and investors to put $3 billion into fund after 30% loss in one week.
August 15, 2007	15:46	Countrywide Financial "risks bankruptcy".
November 08, 2007	08:20	Morgan Stanley takes $3.7 billion hit.
December 12, 2007	15:00	The Fed announces the creation of a Term Auction Facility (TAF).
December 14, 2007	11:17	Citigroup rescues SIVs with $58 billion debt bailout.
December 27, 2007	15:00	Subprime bank losses reach $97 billion, led by Citigroup.
February 26, 2008	16:30	Banks cut more than 28,000 jobs as subprime losses mount .
May 14, 2008	10:56	Fitch: Subprime losses by global banks total U.S. $400 billion.
June 12, 2008	14:41	KeyCorp to raise $1.5 billion, cut dividend by 50%.
June 25, 2008	15:14	Countrywide Financial faces Illinois suit over mortgage loans.
October 03, 2008	16:06	Dutch part of Fortis is nationalized.
October 15, 2008	11:43	Iceland cuts key interest rate to 0.12 from 15.5%.
October 15, 2008	15:04	European central banks pump $250 billion in liquidity.
October 20, 2008	16:40	Sweden launches financial rescue package.
November 13, 2008	15:29	Ranieri's Franklin Bank files for Chapter 7 bankruptcy.
December 16, 2008	15:08	AIG sells $39.3 billion in assets to NY Fed's fund.
January 14, 2009	14:46	European debt crisis evident in Greek mire.
January 16, 2009	14:30	Treasury Dep., FED and FDIC finalize their guarantee agreement with Citigroup.
February 5, 2009	13:00	The Bank of England reduced interest rates to a record low of 1% from 1.5%.
March 25, 2009	10:28	The IMF and other lenders agreed in principle to provide Romania €20bn in aid.
May 7, 2009	13:00	The Bank of England announced that it will inject £50bn into the UK economy.
May 8, 2009	15:19	Wells Fargo plans to raise $7.5bn from selling new shares.
August 6, 2009	13:00	The Bank of England decided to pump another £50bn into the economy.
July 13, 2010	11:17	Greece returns to bond markets for the first time since bailout.
July 28, 2010	15:06	ECB announces stricter rules on bank collateral.
November 24, 2010	15:02	Ireland's government outlines €15bn in spending cuts and tax hikes.
January 12, 2011	11:48	Portugal will sell 4- and 10-year bonds for up to €1.25bn.
February 22, 2011	15:00	EC, ECB, and IMF made statement on Greece.
March 3, 2011	14:31	ECB announces details of refinancing operations.
June 9, 2011	14:33	ECB announces details of refinancing operations.
August 4, 2011	14:30	ECB announces details of refinancing operations.
August 12, 2011	10:52	EC, ECB, and IMF made statements on Portugal.
September 15, 2011	15:00	ECB announces additional US dollar liquidity-providing operations.
September 29, 2011	15:09	The Bundestag approved expanded EU bailout fund.
October 6, 2011	14:37	ECB announces details of refinancing operations.
October 6, 2011	14:46	ECB announces second covered bond purchase program.
November 3, 2011	13:46	ECB lowers interest rates by 25 basis points.
December 8, 2011	14:33	ECB announces measures to support bank lending and money market activity.

This table shows overlapping crisis events within the time windows we constructed. All events are from the Federal Reserve Bank of St. Louis, Bloomberg, and the European Central Bank. The timestamps of the events are matched from the MNI database. It is important to note that only those crisis events that coincide with macroeconomic announcements are listed. For example, the Lehman Brothers collapse took place when no macroeconomic news is released.

Appendix B:
Signature Plots of Realized Variance and Realized Kernels

Figure B1: Signature Plots of Realized Variance and Realized Kernels



The signature plots show daily average realized kernels and realized variances of E-mini S&P500 futures, 10-year Treasury note futures, USD/EUR exchange rates, DAX futures, and Bund futures, calculated at various frequencies from one second to 1,500 seconds. The solid lines are realized variances, and the dashed lines are realized kernels.

Appendix C:
Response of Asset Returns to Macroeconomic News

Table C1: Full Sample Response of Asset Returns

	E-mini S&P500 F.		10-Year T-Note F.		USD/EUR		DAX Futures		Bund Futures	
	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response
Panel 1: Response of Asset Returns to U.S. News										
Durable Goods Orders	0.0736***		-0.0350***	-0.0438**	-0.0194***		0.1088***	0.2329*	-0.0259***	-0.0482*
	(0.0104)		(0.0050)	[0-1]	(0.0051)		(0.0264)	(0-3)	(0.0057)	[0-2]
GDP	0.1080***		-0.0373***	-0.0499***	-0.0348***	-0.0470***	0.1485***	0.3454*	-0.0368***	-0.0762***
	(0.0108)		(0.0045)	[0-1]	(0.0060)	[0-1]	(0.0294)	[0-3]	(0.0072)	[0-2]
Non-Farm Payroll	0.2970***	0.3337***	-0.1388***	-0.1581***	-0.0604***	-0.0756*	0.3130***	1.0162*	-0.1047***	
	(0.0172)	[0-1]	(0.0092)	[0-1]	(0.0093)	[0-1]	(0.0414)	[0-7]	(0.0123)	
Trade Balance	0.0294***		-0.0125***	-0.0225***	-0.0129***		0.0344		-0.0065	
	(0.0077)		(0.0034)	[0-1]	(0.0049)		(0.0215)		(0.0045)	
Consumer Price Index	-0.1069***		-0.0432***	-0.0533***	-0.0264***		-0.1242***		-0.0294***	-0.0578***
	(0.0114)		(0.0059)	[0-1]	(0.0053)		(0.0359)		(0.0073)	[0-1]
Producer Price Index	-0.0434***		-0.0223		-0.0230***		-0.0337		-0.0196***	-0.0383*
	(0.0117)		(0.0050)		(0.0052)		(0.0301)		(0.0071)	[0-2]
Initial Unemployment Claims	-0.0800***	-0.0875**	0.0305***	0.0424***	0.0068***		-0.0981***	-0.2434*	0.0234***	0.0555**
	(0.0049)	(0-1)	(0.0020)	(0-2)	(0.0021)		(0.0136)	(0-4)	(0.0028)	(0-3)
Housing Starts	0.0448***	0.0554*	-0.0340***		-0.0155***		0.0862***	0.1858*	-0.0292***	-0.0399*
	(0.0103)	[0-1]	(0.0043)		(0.0051)		(0.0305)	[0-2]	(0.0055)	[0-1]
New Home Sales	0.0878***		-0.0409***	-0.0478**	-0.0215***	-0.0296**	0.1026***	0.2491***	-0.0290***	-0.0440***
	(0.0099)		(0.0038)	[0-1]	(0.0047)	[0-1]	(0.0263)	[0-2]	(0.0054)	[0-1]
Consumer Confidence Index	0.1548***	0.1873*	-0.0409***	-0.0528***	0.0113**	0.0185*	0.2082***	0.5163**	-0.0400***	-0.0724*
	(0.0109)	[0-2]	(0.0039)	[0-1]	(0.0054)	[0-1]	(0.0310)	[0-3]	(0.0062)	[0-2]
Manufacturing ISM	0.1545***	0.2211***	-0.0974***	-0.1323***	-0.0342***		0.1994***	0.5715***	-0.0608***	-0.1385**
	(0.0127)	[0-1]	(0.0054)	[0-2]	(0.0058)		(0.0333)	[0-3]	(0.0077)	[0-3]
Non-Manufacturing ISM	0.0975***		-0.0557***		-0.0248***		0.1571***	0.2061*	-0.0403***	-0.0863**
	(0.0097)		(0.0041)		(0.0049)		(0.0284)	[0-1]	(0.0082)	[0-2]
Panel 2: Response of Asset Returns to German News										
GDP	NA	-0.0098**	NA		NA	0.0120***	NA		NA	
		[0-1]				[0-1]				
Industrial Production	0.0009		-0.0034*		0.0168***		0.0349***	0.0642**	-0.0084	-0.0102**
	(0.0031)		(0.0018)		(0.0032)		(0.0144)	[0-1]	(0.0055)	[0-2]
Consumer Price Index	-0.0029***		0.0007		-0.0017		0.0189	0.0274**	-0.0031	
	(0.0044)		(0.0026)		(0.0031)		(0.0199)	[0-1]	(0.0043)	
Producer Price Index	NA	0.0085*	NA		NA		NA		NA	0.0140**
		[0-1]								[0-2]
IFO Business Climate	0.0297***	0.0395*	-0.0160***	-0.0198*	0.0642***		0.0733***	0.1376***	-0.0453***	-0.0799***
	(0.0064)	[0-1]	(0.0029)	[0-1]	(0.0057)		(0.0229)	[0-1]	(0.0074)	[0-2]
ZEW Survey	0.0389		-0.0103*		0.0685***		0.0937***	0.1498***	-0.0389***	-0.0780***
	(0.0068)		(0.0028)		(0.0054)		(0.0214)	[0-1]	(0.0056)	[0-2]

This table shows the return responses of the E-mini S&P500 and 10-Year T-Note futures, the USD/EUR exchange rate, as well as the DAX and Bund futures to the selected macroeconomic news in the full sample. The returns are in percentages. ***, **, and * denote significance at the 99%, 95%, and 90% confidence levels, respectively. Standard errors are in parentheses below the corresponding *contemporaneous* response coefficients. The numbers in brackets below the *cumulative* response coefficients are the lag lengths used to calculate the *cumulative* response. NA denotes missing values for returns at the time of news releases according to Table 2, so that we only report *cumulative* coefficients.

Table C2: Response of Asset Returns to Macroeconomic News

	Pre-Crisis Period		Subprime and Financial Crisis Period		European Sovereign Crisis Period	
	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response
Panel 1: Response of E-mini S&P500 Futures Returns						
U.S. News						
Durable Goods Orders	0.0206**		0.1192***		0.1495***	
	(0.0103)		(0.0204)		(0.0235)	
GDP	0.0531***		0.1154***	0.1405*	0.1561***	
	(0.0112)		(0.0191)	[0-1]	(0.0184)	
Non-Farm Payroll	-0.0575***	-0.0878*	0.2817***		0.4744***	0.5726***
	(0.0204)	[0-1]	(0.0266)		(0.0283)	[0-1]
Trade Balance	0.1410*		0.0241***		0.1524***	
	(0.0736)		(0.0076)		(0.0403)	
Consumer Price Index	-0.1242***	-0.1436*	-0.1079***		-0.0982***	
	(0.0187)	[0-1]	(0.0184)		(0.0204)	
Producer Price Index	-0.0364***		-0.0447**		-0.0137	
	(0.0096)		(0.0206)		(0.0218)	
Initial Unemployment Claims	-0.0041		-0.0698***	-0.1052*	-0.1381***	
	(0.0059)		(0.0088)	[0-2]	(0.0075)	
Housing Starts	0.0038		0.1094***	0.1453**	0.1140***	
	(0.0076)		(0.0252)	[0-1]	(0.0275)	
New Home Sales	0.0449***		0.2083***		0.1226***	
	(0.0085)		(0.0343)		(0.0137)	
Consumer Confidence Index	0.0867***		0.1240***		0.2203***	0.2513**
	(0.0143)		(0.0177)		(0.0190)	[0-1]
Manufacturing ISM	0.1271***	0.1844***	0.1482***	0.2016**	0.1802***	0.2509***
	(0.0183)	[0-1]	(0.0229)	[0-1]	(0.0195)	[0-1]
Non-Manufacturing ISM	0.0416***		0.1380***		0.1221***	0.1609**
	(0.0092)		(0.0153)		(0.0230)	[0-1]
German News						
GDP	NA		NA		NA	
Industrial Production	0.0080		0.0200		0.0215***	0.0386***
	(0.0060)		(0.0071)		(0.0064)	[0-1]
Consumer Price Index	-0.0051		-0.0031		0.0035	
	(0.0034)		(0.0107)		(0.0070)	
Producer Price Index	NA		NA		NA	0.0122*
						[1]
IFO Business Climate	0.0066		0.0342***		0.0446***	0.0572*
	(0.0057)		(0.0130)		(0.0102)	[0-1]
ZEW Survey	0.0123**		0.0318***		0.0939***	
	(0.0048)		(0.0110)		(0.0151)	

Table C2 continues on the next page.

Table C2: Response of Asset Returns to Macroeconomic News

Table C2 continued.

Panel 2: Response of 10-Y T-Note Futures Returns

	Pre-Crisis Period		Subprime and Financial Crisis Period		European Sovereign Crisis Period	
	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response
U.S. News						
Durable Goods Orders	-0.0291***	-0.0443*	-0.0362***		-0.0603***	
	(0.0074)	[0-2]	(0.0096)		(0.0085)	
GDP	-0.0471***	-0.0639***	-0.0151**		-0.0567***	
	(0.0061)	[0-1]	(0.0076)		(0.0072)	
Non-Farm Payroll	-0.0827***		-0.0681***		-0.2608***	-0.2808***
	(0.0172)		(0.0139)		(0.0130)	[0-1]
Trade Balance	-0.0974***	-0.1745***	-0.0116***	-0.0189**	-0.0713***	
	(0.0368)	[0-1]	(0.0038)	[0-1]	(0.0168)	
Consumer Price Index	-0.0666***		-0.0327***		-0.0537***	
	(0.0136)		(0.0081)		(0.0102)	
Producer Price Index	-0.0067		-0.0258***		-0.0487***	
	(0.0065)		(0.0081)		(0.0095)	
Initial Unemployment Claims	0.0224***	0.0375*	0.0260***		0.0442***	0.0570*
	(0.0039)	[0-2]	(0.0032)		(0.0029)	[0-2]
Housing Starts	-0.0292***	-0.0341*	-0.0279***		-0.0531***	
	(0.0055)	[0-1]	(0.0071)		(0.0115)	
New Home Sales	-0.0403***	-0.0468*	-0.0637***		-0.0259***	
	(0.0038)	[0-1]	(0.0103)		(0.0063)	
Consumer Confidence Index	-0.0770***	-0.1029***	-0.0286***		-0.0496***	-0.0602**
	(0.0101)	[0-1]	(0.0055)		(0.0058)	[0-1]
Manufacturing ISM	-0.1053***		-0.0903***	-0.1142***	-0.1026***	
	(0.0096)		(0.0107)	[0-1]	(0.0071)	
Non-Manufacturing ISM	-0.0603***		-0.0583***		-0.0441***	
	(0.0058)		(0.0073)		(0.0069)	
German News						
GDP	NA		NA		NA	
Industrial Production	-0.0031		-0.0022		-0.0088***	
	(0.0027)		(0.0024)		(0.0030)	
Consumer Price Index	0.0006		-0.0055		0.0092	
	(0.0032)		(0.0047)		(0.0039)	
Producer Price Index	NA		NA		NA	
IFO Business Climate	-0.0184***		-0.0121**		-0.0175***	
	(0.0050)		(0.0056)		(0.0036)	
ZEW Survey	-0.0131***		-0.0041	-0.0048*	-0.0158***	
	(0.0033)		(0.0045)	[1]	(0.0061)	

Table C2 continues on the next page.

Table C2: Response of Asset Returns to Macroeconomic News

Table C2 continued.

Panel 3: Response of USD/EUR Returns

	Pre-Crisis Period		Subprime and Financial Crisis Period		European Sovereign Crisis Period	
	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response
U.S. News						
Durable Goods Orders	-0.0403***		-0.0082		0.0176*	
	(0.0076)		(0.0094)		(0.0106)	
GDP	-0.0948***		-0.0128	-0.0133*	0.0028	
	(0.0087)		(0.0087)	[1]	(0.0102)	
Non-Farm Payroll	-0.2062***		-0.0219	-0.0489***	-0.0502***	
	(0.0178)		(0.0137)	[1]	(0.0150)	
Trade Balance	-0.4591***		-0.0091**		-0.0186	
	(0.0604)		(0.0043)		(0.0260)	
Consumer Price Index	-0.0725***		-0.0108		-0.0457***	
	(0.0126)		(0.0067)		(0.0113)	
Producer Price Index	-0.0189***		-0.0185**		-0.0096	
	(0.0066)		(0.0075)		(0.0106)	
Initial Unemployment Claims	0.0273***		0.0067**		-0.0093**	
	(0.0042)		(0.0027)		(0.0039)	
Housing Starts	-0.0224***		-0.0066		-0.0065	
	(0.0069)		(0.0102)		(0.0124)	
New Home Sales	-0.0297***	-0.0404***	-0.0120		-0.0071	
	(0.0048)	[0-1]	(0.0143)		(0.0082)	
Consumer Confidence Index	-0.0829***		0.0214***	0.0398***	0.0298***	
	(0.0121)		(0.0075)	[0-1]	(0.0082)	
Manufacturing ISM	-0.0905***	-0.1062**	-0.0248**		-0.0052	
	(0.0076)	[0-1]	(0.0110)		(0.0083)	
Non-Manufacturing ISM	-0.0635***		-0.0049	-0.0141**	-0.0034	
	(0.0075)		(0.0081)	[3]	(0.0093)	
German News						
GDP	NA	0.0184*	NA	0.0099**	NA	
		[1]		[1]		
Industrial Production	0.0082***		0.0151***		0.0280***	
	(0.0027)		(0.0045)		(0.0064)	
Consumer Price Index	-0.0028		-0.0008		-0.0041	
	(0.0038)		(0.0047)		(0.0063)	
Producer Price Index	NA		NA		NA	
IFO Business Climate	0.0412***		0.0838***		0.0611***	
	(0.0086)		(0.0109)		(0.0085)	
ZEW Survey	0.0534***		0.0621***		0.1090***	
	(0.0068)		(0.0078)		(0.0124)	

Table C2 continues on the next page.

Table C2: Response of Asset Returns to Macroeconomic News

Table C2 continued.

Panel 4: Response of DAX Futures Returns						
	Pre-Crisis Period		Subprime and Financial Crisis Period		European Sovereign Crisis Period	
	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response
U.S. News						
Durable Goods Orders	0.0439		0.1749***	0.3510**	0.1964***	
	(0.0472)		(0.0441)	[0-2]	(0.0264)	
GDP	0.0816*		0.1682***	0.2643**	0.2107***	
	(0.0484)		(0.0498)	[0-1]	(0.0223)	
Non-Farm Payroll	-0.1179		0.3093***	0.4535**	0.5344***	0.6034***
	(0.0852)		(0.0562)	[0-1]	(0.0329)	[0-1]
Trade Balance	0.2896		0.0277		0.1267***	
	(0.2776)		(0.0217)		(0.0284)	
Consumer Price Index	-0.1723*		-0.1226**		-0.0864***	
	(0.0921)		(0.0513)		(0.0222)	
Producer Price Index	-0.0657		-0.0018		-0.0372	
	(0.0656)		(0.0421)		(0.0245)	
Initial Unemployment Claims	-0.0594*		-0.0876***	-0.2002***	-0.1315***	
	(0.0331)		(0.0218)	[0-2]	(0.0086)	
Housing Starts	0.0359		0.2233***	0.3694***	0.1494***	
	(0.0355)		(0.0744)	[0-1]	(0.0302)	
New Home Sales	0.0413	0.0912**	0.1756**	0.4702*	0.1513***	
	(0.0309)	[2]	(0.0862)	[0-2]	(0.0193)	
Consumer Confidence Index	0.1044		0.1864***	0.4564*	0.2763***	
	(0.0765)		(0.0453)	[0-3]	(0.0232)	
Manufacturing ISM	0.1167***	0.2206**	0.1805***	0.4832**	0.2100***	0.2534***
	(0.0324)	[0-1]	(0.0523)	[0-3]	(0.0239)	[0-1]
Non-Manufacturing ISM	0.0918		0.1725***	0.2588**	0.1807***	
	(0.0585)		(0.0392)	[0-1]	(0.0239)	
German News						
GDP	NA		NA		NA	0.0306**
						[1]
Industrial Production	0.0369*		0.0410*		0.0532***	0.0794**
	(0.0216)		(0.0246)		(0.0132)	[0-1]
Consumer Price Index	0.1026*		-0.0141		0.0068	
	(0.0525)		(0.0254)		(0.0091)	
Producer Price Index	NA	-0.3331**	NA		NA	
		[1]				
IFO Business Climate	0.0514	0.1789*	0.0835**	0.1534*	0.0819***	
	(0.0400)	[1-2]	(0.0411)	[0-1]	(0.0162)	
ZEW Survey	0.0851**	0.1681**	0.0493*		0.1749***	
	(0.0345)	[0-1]	(0.0285)		(0.0232)	

Table C2 continues on the next page.

Table C2: Response of Asset Returns to Macroeconomic News

Table C2 continued.

	Pre-Crisis Period		Subprime and Financial Crisis Period		European Sovereign Crisis Period	
	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response	Contemp. Response	Cumulative Response
Panel 5: Response of Bund Futures Returns						
U.S. News						
Durable Goods Orders	-0.0115		-0.0424***		-0.0495***	
	(0.0115)		(0.0102)		(0.0082)	
GDP	-0.0294	-0.0656*	-0.0319***		-0.0539***	
	(0.0202)	[1-2]	(0.0115)		(0.0061)	
Non-Farm Payroll	-0.0664	-0.0843**	-0.0678***		-0.1740***	-0.1989*
	(0.0473)	[1]	(0.0145)		(0.0110)	[0-2]
Trade Balance	0.0180	-0.1224**	-0.0047		-0.0365**	
	(0.0485)	[1]	(0.0037)		(0.0164)	
Consumer Price Index	-0.0539*	-0.0988*	-0.0259***	-0.0577***	-0.0115	
	(0.0282)	[0-1]	(0.0081)	[0-1]	(0.0085)	
Producer Price Index	-0.0330		-0.0116		-0.0359***	
	(0.0204)		(0.0093)		(0.0075)	
Initial Unemployment Claims	0.0334***	0.0817*	0.0140***		0.0336***	0.0457**
	(0.0073)	[0-3]	(0.0039)		(0.0025)	[0-2]
Housing Starts	-0.0189*		-0.0509***		-0.0620***	
	(0.0103)		(0.0104)		(0.0095)	
New Home Sales	-0.0251***	-0.0740***	-0.0299**		-0.0240***	
	(0.0036)	[0-2]	(0.0141)		(0.0062)	
Consumer Confidence Index	-0.0627**	-0.1659*	-0.0271***	-0.0392**	-0.0551***	-0.0759*
	(0.0272)	[0-2]	(0.0078)	[0-1]	(0.0050)	[0-2]
Manufacturing ISM	-0.0501**	-0.1058**	-0.0665***	-0.1508**	-0.0655***	
	(0.0237)	[0-1]	(0.0133)	[0-3]	(0.0058)	
Non-Manufacturing ISM	-0.0302	-0.1001*	-0.0434***	-0.0797***	-0.0399***	
	(0.0247)	[1-3]	(0.0120)	[0-1]	(0.0068)	
German News						
GDP	NA		NA		NA	
Industrial Production	-0.0033		-0.0056		-0.0194***	
	(0.0241)		(0.0057)		(0.0039)	
Consumer Price Index	-0.0090		-0.0018		0.0077*	0.0221*
	(0.0123)		(0.0052)		(0.0042)	[0-2]
Producer Price Index	NA	0.2660	NA		NA	
		[2-4]				
IFO Business Climate	-0.0771***	-0.2058**	-0.0327***		-0.0319***	
	(0.0221)	[0-3]	(0.0115)		(0.0049)	
ZEW Survey	-0.0517***	-0.1550**	-0.0282***	-0.0482***	-0.0459***	
	(0.0145)	[0-3]	(0.0067)	[0-1]	(0.0071)	

This table shows the return responses of the E-mini S&P500 futures, 10-year Treasury note futures, USD/EUR exchange rates, DAX futures, and Bund futures to the selected macroeconomic news in the full sample. The returns are in percentages. ***, **, and * denote significance at the 99%, 95%, and 90% confidence levels, respectively. Standard errors are in parentheses below the corresponding *contemporaneous* response coefficients. The numbers in brackets below the *cumulative* response coefficients are the lag lengths used to calculate the *cumulative* response. NA denotes missing values for returns at the time of news releases according to Table 2, so that we only report *cumulative* coefficients.

Appendix D:
Placebo Tests

Table D1: Placebo Test for VAR Model Results of Return Spillovers

			2008-10-06 to to 2008-10-08	2011-08-08 to to 2011-08-09
E-mini S&P500 F.	→	10-Y T-Note Futures	-0.0283	-0.0343
10-Y T-Note Futures	→	E-mini S&P500 F.	-0.2224	
E-mini S&P500 F.	→	DAX Futures	1.5357	0.3430
DAX Futures	→	E-mini S&P500 F.	0.0717	0.1661
E-mini S&P500 F.	→	Bund Futures	-0.0490	-0.0122
Bund Futures	→	E-mini S&P500 F.		
E-mini S&P500 F.	→	USD/EUR	0.0525	0.0477
USD/EUR	→	E-mini S&P500 F.		0.0770
10-Y T-Note Futures	→	DAX Futures	-0.1612	
DAX Futures	→	10-Y T-Note Futures		
10-Y T-Note Futures	→	Bund Futures	0.4802	0.1425
Bund Futures	→	10-Y T-Note Futures		0.1274
10-Y T-Note Futures	→	USD/EUR	-0.0221	-0.0244
USD/EUR	→	10-Y T-Note Futures	-0.0226	
DAX Futures	→	Bund Futures	-0.0100	-0.0140
Bund Futures	→	DAX Futures		
DAX Futures	→	USD/EUR		0.0019
USD/EUR	→	DAX Futures		
Bund Futures	→	USD/EUR		-0.0659
USD/EUR	→	Bund Futures	-0.0554	-0.0189

This table shows the results for five-second returns of E-mini S&P500 futures, 10-year treasury note futures, USD/EUR exchange rates, DAX futures, and Bund futures in two sample periods (October 6 to 8, 2008, and August 8 to 9 August, 2011), when none of our selected macroeconomic announcements is released. The lag lengths, selected according to the Hannan-Quinn and Schwarz criteria, are six and three for the two samples, respectively. The coefficient from one market is the sum of coefficients significant at 95% confidence level.

Table D2: Placebo Test for Volatility Co-Movements and Spillovers

	2008-10-06 to 2008-10-08					**2011-08-08 to 2011-08-09**				
	E-mini S&P500 F.	10-Y T-Note F.	USD/ EUR	DAX F.	Bund F.	E-mini S&P500 F.	10-Y T-Note F.	USD/ EUR	DAX F.	Bund F.
E-mini S&P500 Futures (0)		0.042		0.464	0.015		0.019	0.024	0.622	0.016
10-Year T-Note Futures (0)	0.808		0.017		0.052	0.178		0.028	0.268	0.114
USD/EUR (0)		0.016				0.220	0.027		0.237	0.063
DAX Futures (0)	0.062				0.004	0.513	0.024	0.021		0.018
Bund Futures (0)	0.041	0.008		0.091		0.214	0.164	0.092	0.286	
E-mini S&P500 Futures (L)		0.008	0.009	-0.195						
10-Year T-Note Futures (L)	0.075									
USD/EUR (L)										
DAX Futures (L)								0.010		
Bund Futures (L)								0.041		

This table shows the volatility co-movements and spillovers among the E-mini S&P500 futures, 10-year Treasury note futures, USD/EUR exchange rate, DAX futures, and Bund futures markets in two sample periods (October 6 to 8, 2008 and August 8 to 9, 2011), when none of our selected macroeconomic announcements is released. The volatility processes are first filtered using an ARFIMA(1,d,1) model, $(1-\rho L)(1-L)^d|R_t| = (1-\theta L)\xi_t$, and additionally filtered by means of a flexible Fourier form to capture the periodic patterns. We then derive the co-movement and spillover estimates from OLS estimates with HAC-robust standard errors. We estimate the following model specifications for five-second filtered volatility processes within one hour after the announcements: $\xi_t^i = c^i + \sum_{q=1}^{Q} \varphi_q^i \xi_{t-q}^i + \sum_{j=1}^{4} \sum_{q=0}^{Q} \varphi_q^j \xi_{t-q}^j + \varepsilon_t^i$. The independent variables are comprised of lagged volatilities (L) from their own markets, and the contemporaneous (0) and lagged volatilities (L) from the other four markets. The coefficient of lagged variables from one market is the sum of coefficients significant at 95% confidence level. The coefficients of contemporaneous effects are also significant at 95% confidence level.

Appendix E:
VAR Model Results of Asset Returns

Table E1: VAR Model Results of Asset Returns

Panel 1: Responses to U.S. News

	Pre-Crisis					Subprime and Financial Crisis Period					European Sovereign Crisis Period				
	E-mini S&P500 F.	10Y T-Note F.	USD/ EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/ EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/ EUR	DAX F.	Bund F.
E-mini S&P500 F. (-1)	-0.128***	-0.017	0.025	0.104***	-0.006	-0.177***	-0.015*	0.019**	0.146***	0.001	-0.308***	0.002	0.017**	0.040	-0.009
	(0.018)	(0.016)	(0.017)	(0.024)	(0.011)	(0.022)	(0.009)	(0.007)	(0.024)	(0.006)	(0.023)	(0.011)	(0.008)	(0.027)	(0.007)
E-mini S&P500 F. (-2)	-0.073***	-0.028*	0.001	0.055**	-0.008	-0.071***	-0.003	0.002	0.090***	-0.004	-0.081***	-0.004	0.008	0.027	-0.009
	(0.018)	(0.016)	(0.017)	(0.024)	(0.011)	(0.022)	(0.009)	(0.007)	(0.024)	(0.006)	(0.023)	(0.011)	(0.008)	(0.026)	(0.007)
10-Y T-Note F. (-1)	0.039*	-0.134***	0.087***	0.049	0.053***	-0.008	-0.093***	0.0243*	0.030	0.053***	-0.191***	-0.038**	0.046***	-0.185***	0.065***
	(0.023)	(0.020)	(0.022)	(0.031)	(0.014)	(0.041)	(0.017)	(0.014)	(0.046)	(0.011)	(0.042)	(0.019)	(0.014)	(0.048)	(0.012)
10-Y T-Note F. (-2)	-0.001	-0.021	0.011	-0.024	0.027**	-0.025	-0.067***	-0.009	0.027	0.017	-0.131***	0.006	0.035**	-0.131***	0.044
	(0.023)	(0.020)	(0.022)	(0.031)	(0.014)	(0.041)	(0.017)	(0.014)	(0.045)	(0.011)	(0.042)	(0.019)	(0.014)	(0.048)	(0.012)
USD/EUR (-1)	0.059***	0.011	-0.093***	0.023	0.017	0.039	0.096***	0.038***	0.043	-0.013	0.132***	-0.052***	0.010	0.107**	-0.019
	(0.019)	(0.017)	(0.018)	(0.025)	(0.011)	(0.043)	(0.017)	(0.014)	(0.047)	(0.012)	(0.039)	(0.018)	(0.013)	(0.045)	(0.012)
USD/EUR (-2)	-0.020	0.015	-0.130***	-0.007	0.013	-0.058	0.021	-0.092***	-0.041	0.012	0.079**	0.013	-0.026**	0.073	0.001
	(0.019)	(0.017)	(0.018)	(0.025)	(0.011)	(0.043)	(0.017)	(0.014)	(0.047)	(0.012)	(0.039)	(0.018)	(0.013)	(0.045)	(0.012)
DAX Futures (-1)	0.136***	0.002	-0.022*	-0.079***	0.007	0.122***	-0.023***	-0.005	-0.206***	-0.018***	0.204***	0.004	0.001	-0.094***	-0.004
	(0.014)	(0.012)	(0.013)	(0.018)	(0.008)	(0.020)	(0.008)	(0.007)	(0.022)	(0.005)	(0.021)	(0.010)	(0.007)	(0.024)	(0.006)
DAX Futures (-2)	0.059***	0.019	-0.003	0.021	-0.003	0.036*	-0.010	0.007	-0.115***	-0.001	0.020	0.014	-0.007	-0.101***	0.006
	(0.014)	(0.012)	(0.013)	(0.019)	(0.008)	(0.020)	(0.008)	(0.007)	(0.022)	(0.005)	(0.021)	(0.010)	(0.007)	(0.024)	(0.006)
Bund Futures (-1)	-0.067*	0.183***	0.196***	-0.033	-0.134***	-0.263***	0.126***	0.067***	-0.253***	-0.142***	-0.191***	0.120***	-0.068***	-0.117	-0.080***
	(0.035)	(0.031)	(0.032)	(0.046)	(0.021)	(0.063)	(0.026)	(0.021)	(0.070)	(0.017)	(0.071)	(0.033)	(0.023)	(0.082)	(0.021)
Bund Futures (-2)	0.014	0.106***	0.130***	-0.042	-0.017	-0.074	0.133***	0.052**	-0.121*	-0.054***	-0.022	0.019	-0.074***	0.031	-0.066***
	(0.035)	(0.031)	(0.033)	(0.046)	(0.021)	(0.063)	(0.026)	(0.021)	(0.070)	(0.017)	(0.071)	(0.033)	(0.023)	(0.082)	(0.021)

Table E1 continues on the next page.

Table E1: VAR Model Results of Asset Returns

Table E1 continued.

Panel 1: Responses to German News

	Pre-Crisis					Subprime and Financial Crisis Period					European Sovereign Crisis Period				
	E-mini S&P500 F.	10Y T-Note F.	USD/ EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/ EUR	DAX F.	Bund F.	E-mini S&P500 F.	10Y T-Note F.	USD/ EUR	DAX F.	Bund F.
E-mini F. (-1)	-0.136***	-0.023	-0.002	0.187*	-0.014	-0.174***	-0.012	0.046*	0.230***	-0.009	-0.318***	0.003	0.062*	0.118*	-0.027
	(0.032)	(0.019)	(0.049)	(0.098)	(0.049)	(0.033)	(0.011)	(0.025)	(0.053)	(0.019)	(0.034)	(0.011)	(0.035)	(0.061)	(0.017)
E-mini F. (-2)	-0.042	-0.008	-0.121**	0.143	0.022	-0.132***	-0.025**	-0.013	-0.022	0.019	-0.107***	-0.009	0.028	0.029	-0.017
	(0.031)	(0.019)	(0.048)	(0.096)	(0.048)	(0.032)	(0.011)	(0.025)	(0.053)	(0.019)	(0.034)	(0.011)	(0.035)	(0.061)	(0.017)
10-Y T-Note F. (-1)	-0.119**	-0.168***	-0.146*	-0.275*	0.261***	0.102	-0.214***	-0.018	0.003	0.055	-0.134	-0.139***	-0.056	-0.267*	0.085**
	(0.053)	(0.032)	(0.082)	(0.162)	(0.081)	(0.086)	(0.030)	(0.067)	(0.140)	(0.049)	(0.083)	(0.026)	(0.086)	(0.150)	(0.042)
10-Y T-Note F. (-2)	-0.088*	-0.057*	-0.007	-0.033	-0.093	0.140	-0.082***	0.052	-0.006	0.086*	0.136*	-0.083***	0.025	-0.011	-0.003
	(0.052)	(0.032)	(0.081)	(0.160)	(0.080)	(0.086)	(0.029)	(0.067)	(0.139)	(0.049)	(0.082)	(0.026)	(0.085)	(0.149)	(0.042)
USD/EUR (-1)	-0.011	-0.002	-0.117***	0.003	-0.003	0.015	-0.034***	0.088***	0.016	-0.069***	0.098***	-0.014	-0.108***	0.057	-0.039***
	(0.022)	(0.013)	(0.033)	(0.066)	(0.033)	(0.037)	(0.013)	(0.029)	(0.060)	(0.021)	(0.027)	(0.009)	(0.028)	(0.049)	(0.014)
USD/EUR (-2)	-0.026	-0.023*	-0.103***	-0.055	-0.012	-0.025	0.015	-0.078***	-0.029	-0.008	0.062**	-0.013	-0.090***	0.089*	-0.010
	(0.020)	(0.012)	(0.030)	(0.060)	(0.030)	(0.035)	(0.012)	(0.027)	(0.056)	(0.020)	(0.027)	(0.009)	(0.028)	(0.048)	(0.014)
DAX Futures (-1)	0.050***	0.003	0.007	-0.454***	0.004	0.098***	-0.004	0.058***	-0.230***	-0.015	0.124***	-0.006	0.058***	-0.076**	-0.020**
	(0.010)	(0.006)	(0.016)	(0.032)	(0.016)	(0.021)	(0.007)	(0.016)	(0.034)	(0.012)	(0.019)	(0.006)	(0.019)	(0.034)	(0.010)
DAX Futures (-2)	0.039***	-0.003	0.004	-0.199***	-0.005	0.070***	-0.008	0.007	-0.063***	-0.005	0.014	-0.005	-0.014	-0.107***	-0.019**
	(0.010)	(0.006)	(0.016)	(0.032)	(0.016)	(0.021)	(0.007)	(0.016)	(0.034)	(0.012)	(0.019)	(0.006)	(0.020)	(0.034)	(0.010)
Bund Futures (-1)	-0.060***	0.122***	-0.553***	-0.480***	0.069**	-0.284***	0.134***	-0.393***	-0.452***	-0.059**	-0.150***	0.092***	-0.397***	-0.107	-0.099***
	(0.022)	(0.013)	(0.034)	(0.068)	(0.034)	(0.053)	(0.018)	(0.041)	(0.086)	(0.030)	(0.057)	(0.018)	(0.059)	(0.103)	(0.029)
Bund Futures (-2)	-0.032	0.029*	-0.183***	-0.215***	-0.002	-0.086	0.042**	-0.146***	-0.060	-0.004	-0.063	0.019	-0.099*	0.069	-0.062**
	(0.025)	(0.015)	(0.039)	(0.077)	(0.038)	(0.055)	(0.019)	(0.043)	(0.090)	(0.032)	(0.058)	(0.018)	(0.060)	(0.105)	(0.029)

This table shows the VAR model estimation results for five-second returns of E-mini S&P500 futures, 10-year treasury note futures, USD/EUR exchange rate, DAX futures and Bund futures falling into the one-minute window after all U.S. and German news with a significant impact on at least two of the three markets. The lag lengths are selected according to the Hannan-Quinn and Schwarz criteria. The bold numbers denote significant coefficients. ***, **, and * denote significance at the 99%, 95%, and 90% confidence levels, respectively.