Did Spillovers From Europe Indeed Contribute to the 2010 U.S. Flash Crash?

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Abstract

Using intraday data, we study spillovers from European stock markets to the U.S. in the hours before the flash crash on 6 May 2010. Many commentators have pointed to negative market sentiment and high volatility during the European trading session before the Flash Crash. However, based on a range of vector autoregressive models, we find no robust evidence that spillovers increased at that time. On the contrary, spillovers on 6 May were mostly smaller than in the preceding days, during which there was great uncertainty surrounding the Greek sovereign debt crisis. The absence of evidence for spillovers underscores the difficulties in understanding the nature of flash events in financial markets.

Keywords: flash crash, spillovers, financial stability, connectedness.
JEL classifications: G15, N22, N24.

1 Introduction

The 2010 U.S. Flash Crash served as a sharp reminder of the potential fragility of the international financial system. On 6 May 2010, around 2:30 in the afternoon, U.S. equity markets started showing extraordinary large declines.[1] Within minutes, the Dow Jones had lost more than 6% of its value. For some individual securities, the declines were even stronger, with some trades being executed at prices as low as a penny. It was only after a brief trading halt at 2:45 p.m. that financial markets recovered (CFTC-SEC, 2010). The Flash Crash also had large international repercussions. In Canada, the equity index declined by more than 3% (IIROC, 2010). On Latin American equity exchanges, prices of individual stocks declined by up to 10% (Jansen, 2018). The importance of understanding why this crash occurred was further underlined by a number of subsequent flash events. For instance, U.S. Treasury yields showed extraordinary volatility after market open on 15 October 2014; the British pound suddenly lost 6% against the U.S. dollar on 7 October 2016; and the euro unexpectedly dropped by 3% against the dollar on Christmas Day 2017.

Although finding a root cause for the 2010 Flash Crash proved difficult, a number of contributing factors have been suggested. A joint staff report by the Commodity Futures Trading Commission and the Securities and Exchange Commission identified the activation of a sell algorithm for E-Mini contracts — index futures contracts based on the S&P 500 — as the immediate trigger for the crash (CFTC-SEC, 2010). From the E-Mini market, the crash then spilled over to the rest of the U.S. financial system (see, e.g., Madhavan (2011), Kirilenko et al. (2017), or Menkveld and Yueshen (2017)). Also, some papers have pointed to adverse developments in order flow dynamics in the days before the crash (Easley, López de Prado, and O'Hara, 2011, 2012).[2] Furthermore, U.S. authorities prosecuted a London-based trader who, in 2016, pleaded guilty to repeated attempts of trying to manipulate the market for E-Mini contracts (Department of Justice, 2016).

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[1]Times in this paper are, unless indicated otherwise, denoted in Eastern Daylight Time (EDT).

[2]Their measure for order flow toxicity has, however, been the subject of some debate. See Andersen and Bondarenko (2014) and Easley et al. (2014).

This paper contributes to the literature on the origins of the flash events by studying the possible role of spillovers from Europe to the U.S. in the hours before the 2010 Flash Crash. As observers already noted at the time, the European trading session on 6 May had been an extremely nervous one.[3] First and foremost, financial markets were closely following social and political developments in Greece, where the lingering sovereign debt crisis was reaching a crucial stage. On 2 May, the International Monetary Fund and the European Union had reached an agreement with the Greek government on a €110 billion financial support package. However, this agreement required Greece to make rigorous adjustments to its government finances.[4] These adjustments, such as reductions in government wages and pensions, had led to severe social unrest. On 6 May, the Greek parliament was scheduled to debate the fiscal adjustment measures, with a crucial vote being expected sometime during the evening in Greece. That same day, there would also be fierce debates in the German parliament, which was divided regarding Germany's sizeable contribution to the financial support package.

A second reason why European markets were nervous was a growing fear of contagion from the Greek sovereign debt crisis to the rest of Europe. Primarily, markets worried about high levels of government debt in Spain, Italy, Portugal, and Ireland. Spreads on credit default swaps for these countries' government debt had been widening considerably. In addition, markets were nervous about the strength of banking sectors in these countries, given the large exposures to their home countries' government debt. More broadly, market participants started thinking about contagion to the banking sectors of other European countries. For instance, various French financial institutions came under scrutiny for their exposures to Greek government debt. A ratings report by Moody's, released during the European morning trading session of 6 May, suggested that sovereign risk contagion could also affect the U.K. banking sector.

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[3]These descriptive paragraphs build on CFTC-SEC (2010) and news reports by CNN (Twin, 2010), the Financial Times, (Nolan, 2010), the Guardian (Roberts, 2010), the New York Times (Bowley, 2010), and the Wall Street Journal (Lauricella and McKay, 2010).

[4]For details, see `https://www.imf.org/en/News/Articles/2015/09/28/04/53/socar050210a`, URL last accessed on 19 October 2018.

A third factor driving market sentiment on 6 May was the upcoming monetary policy decision by the European Central Bank. The ECB's Governing Council was meeting in Lisbon that day, and the ECB would announce its latest monetary policy decision at 13:45 CEST (07:45 EDT). Markets were especially interested in ECB President Trichet's remarks at the subsequent press conference. There was some speculation that the ECB would end up buying government bonds to contain the sovereign debt crisis. However, at the press conference, Trichet immediately indicated that such a step had not even been discussed. Overall, market reactions to the ECB decisions were negative, as investors were disappointed with what was seen as complacency by the ECB.

A final factor adding to the news flow on 6 May was the general election in the United Kingdom. Prime Minister Gordon Brown had called for this election in early-April. Various polls were indicating that it would be a close contest between Brown's Labour Party and the Conservatives led by David Cameron. In the end, neither party was able to win an absolute majority. Throughout the day, however, the market reaction to election news was muted, and dynamics in U.K. equity prices were primarily driven by news on the sovereign debt crisis.

Given the intense news flow and the predominantly negative sentiment in the European trading session, there is good reason to study spillovers from Europe to the U.S. in the hours before the Flash Crash. To do so, this paper uses the approach proposed by Diebold and Yilmaz (2009). Their idea is to start by estimating vector autoregressive models, before subsequently running forecast-error variance decompositions to measure spillovers. Such an approach is especially useful when the key issue is not necessarily to determine whether any spillovers are due to interdependence or contagion (cf. Forbes and Rigobon, 2002). To estimate spillovers, this paper uses minute-by-minute data on stock market indices in Europe and the U.S. In terms of research design, the paper compares intraday spillovers, both for returns and volatility, on 6 May with those during the preceding two weeks of market trading. These intraday spillovers can be estimated by making use of the two-hour time window during which U.S. and European trading hours overlap each business day.

This paper concludes that spillovers from European stock markets to the U.S. did not increase in the hours before the 2010 Flash Crash. During the two-hour time window on 6 May where European and U.S. trading overlapped, spillovers to the U.S. were at levels comparable to, or lower than, those in the preceding two weeks of stock-market trading. This conclusion holds for return as well as volatility spillovers, and it is robust across a range of VAR models that were considered to capture various dynamics in the news flow in Europe on 6 May. Overall, these findings underscore the difficulties in understanding the nature of flash events in financial markets. Though perhaps intuitively appealing, a narrative based on spillovers from the European debt crisis seems to offer little guidance for a deeper understanding of the flash events in financial markets.

2 Research Design

To study spillovers, this paper uses the approach proposed by Diebold and Yilmaz (2009). The literature has since long studied how shocks can spill over via international financial markets. Various approaches are available, for instance the analysis of cross-market correlations (King and Wadhwani, 1990), the use of (G)ARCH frameworks (Lin et al., 1994), and the study of factor models (Bekaert et al., 2014). In many types of analysis, an important question is whether any evidence for spillovers should be attributed to interdependence or contagion. As first stressed by Forbes and Rigobon (2002), contagion only occurs when reactions to shocks are in excess of normal cross-market comovements. For the present paper, however, this distinction between interdependence and contagion is less important. Merely, the aim is to see whether shocks in European markets had a greater effect on U.S. markets in the hours immediately prior to the 2010 Flash Crash. The method by Diebold and Yilmaz offers a straightforward route to answering this question.

Computing Diebold-Yilmaz spillover indices requires taking the following three steps. First, one estimates a vector autoregressive (VAR) model, where the endogenous variables can be either returns or measures for asset price volatility. Second, based on the VAR model, a variance decomposition for forecast errors (FEVD) is

calculated. In the third step, the spillover index is computed based on the FEVD results. The crucial point is using the FEVD to distinguish between *own-variance shares* and *cross-variance shares*. For measuring spillovers, only the cross-variance shares are relevant. These shares measure the contribution to the n-step ahead forecast-error variance in forecasting x_i due to shocks in x_j, where $i \neq j$ (Diebold and Yilmaz, 2009; Diebold and Yilmaz, 2010). The total spillover is the sum of all cross-variance shares. This sum of cross-variance shares is then scaled by the sum of relative contributions to the forecast-error variance. This scaling results in an index that lies between 0 and 100, where 100 would indicate that the forecast-error variance is completely due to cross-variance shares, i.e. spillovers.

At this point, it is important to note that the empirical results of this paper will not center on the standard Diebold-Yilmaz indicator, i.e. the sum of all cross-variance shares divided by the number of variables (Diebold and Yilmaz, 2010). Rather, this paper focuses on a specific sub-set of the cross-variance shares, namely those that measure the contribution of innovations in European returns to the forecast-error variance of U.S. returns. This measure, which also ranges between 0 and 100, is more directly suited for answering the main research question of this paper, namely whether spillovers from Europe were larger in the hours before the Flash Crash. For comparison, however, an extension in Section 5 will discuss results for standard Diebold-Yilmaz indices using all cross-variance shares.

The estimations in this paper use minute-by-minute data for stock market indices in the U.S. and six European countries. The data source is Bloomberg. For European indices, the data set includes observations for Spain (the IBEX 35), Italy (the DJ Titans 30), Portugal (the PSI 20), Greece (the FT/ASE), Germany (the DAX), and the U.K. (the FTSE 100).[5] For the U.S., the paper uses the Dow Jones Industrial Average. The stock index data covers the nine trading days in the period from Monday 26 April to Thursday 6 May 2010. To estimate the VAR models, we transform the levels of the stock market indices to minute-by-minute returns by tak-

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[5]This paper has no intraday stock market data for Ireland available. The assumption is that the dynamics concerning possible contagion are captured by including the four Southern-European economies.

ing percentage differences. To study volatility, we use squared index returns, again on a minute-by-minute basis.[6]

To measure intraday spillovers, this paper makes use of the partial overlap between trading hours in the U.S. and Europe. U.S. markets open at 9:30, which corresponds to 14:30 in the U.K. and 15:30 in most of continental Europe. Therefore, at the end of the each European trading session, there is generally a two-hour window with simultaneous trading at the local stock exchange and in U.S. markets. For any of the nine days in the sample, we can thus estimate a VAR model using 120 minute-by-minute observations. Using these VAR models, we can then calculate the level of spillovers between Europe and the U.S. on any particular trading day. To put dynamics on the day of the Flash Crash in perspective, we can compare the level of spillovers during the last two hours of the European trading session on 6 May to the levels during this time slot on each of the preceding eight business days in the sample.

The analysis is, admittedly, subject to a number of caveats. The most fundamental caveat is that the period with simultaneous trading on 6 May does not include the Flash Crash episode itself. As European equity markets had all closed at 11:30, there is a three-hour gap separating the analysis of this paper from the start of the Flash-Crash episode. Any potential evidence of spillovers should, therefore, not necessarily be seen as evidence for a causal chain of events. However, a larger degree of spillovers on the morning of 6 May would corroborate the notion that negative sentiment from Europe contributed to a market environment in which a flash event could materialise.

Second, it should be remembered that the daily VAR models rely on, at most, a two-hour window. Therefore, 120 minute-by-minute observations are available per trading day, which only leaves sufficient degrees of freedom when the number of lags p and the number of endogenous variables k remain sufficiently small.[7] As a result, the research design cannot readily analyse larger systems with richer types of

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[6]Diebold and Yilmaz (2009) measure volatility using open/high/low/close prices, which are, unfortunately, not available for this paper.

[7]The number of estimated parameters for a VAR model equals $k + pk^2$. For a 5-variable VAR with two lags, this means already the estimation of 55 parameters.

lag specifications. For the baseline results, we consider models with two lags. The robustness analysis in Section 5 will show that the conclusions are robust to using richer lag structures in bivariate VAR systems.

A third complication concerns data availability for Greece and Portugal. The reason for these limitations differs across the two countries. For Greece, the additional time difference of one hour with the U.S. restricts the number of data points per day. Financial markets in Greece close at 17:20, which corresponds to 10:20 in the U.S. This means the number of observations with trading overlap is only 50 per day. For Portugal, some observations are, unfortunately, missing in the data feed. This means the sample with overlap in trading on that day only starts at 10:00 instead of 9:30. We address these two data challenges by never including both Greece and Portugal in the same VAR model.

This paper estimates VAR models for seven distinct combinations of countries. All of the VAR models include, of course, U.S. data. The models differ, however, in their use of European market data. Firstly, by varying the set of countries in the model, we take into account the various dimensions of the news flow in Europe on 6 May. Secondly, using different sets of countries helps in addressing, as much as possible, the data gaps for Greece and Portugal. For all VAR models, rather than showing the Diebold-Yilmaz (2009) spillover index itself, the paper reports the contributions of European cross-variance shares to the forecast errors for the U.S. stock market. This measure gives the most direct answer to the research question.

We start with four models that focus on the separate elements of news flow on 6 May 2010. The first model is a bivariate VAR that uses stock index returns (or volatility) for the U.S. and Greece. In terms of news flow, this model focuses on the key element driving market sentiment on 6 May, namely the debate in the Greek parliament on the EU-IMF financial assistance package. However, in terms of data, this model relies on the smallest number of observations. A second VAR model focuses on the possible contagion to other highly-indebted economies by estimating a system that includes data for the U.S., Spain, Italy, and Portugal. The third model is a bivariate VAR that uses data for the U.S. and Germany. Being the largest euro area economy, using Germany proxies for reactions to the ECB monetary-policy

decision on 6 May. It also directly captures potential reactions to the debates in the German parliament on 6 May. A fourth model is a VAR system for the U.S. and the U.K. This model captures market reactions to the U.K. general election and worries about contagion of the sovereign debt crisis to the U.K. banking sector.

The remaining three models combine the four elements of the news flow on 6 May. First, we estimate a VAR model that includes two Southern-European economies (namely Spain and Italy), the U.K., and Germany. In two subsequent models, we add data for either Portugal or Greece, in light of the data gaps for these two countries. In terms of factorisation for the Cholesky decomposition, the U.S. is always placed first, followed by, respectively, the U.K., Germany, and the Southern-European countries. Section 5 will show that the Cholesky ordering does not fundamentally change the conclusions on spillovers from Europe to the U.S.

3   Descriptives

We start by charting equity-market dynamics in Europe on 6 May. To that end, Figure 1 shows scaled levels of stock market indices. The horizontal axis represents hours according to Eastern Daylight Time. Indices are scaled so that levels at the open of the U.S. market at 9:30 EDT (or 15:30 CEST) equal 100. The solid black lines represent the FT/ASE 20 (Greece), the IBEX 35 (Spain), the Dow Jones Italy Titans 30 (Italy), the PSI 20 (Portugal), the DAX (Germany), and the FTSE 100 (England). The gray dotted line in each panel denotes the scaled level of the Dow Jones Industrial Average between 9:30 and 14:45 EDT.[8]

insert Figure 1 here

During the European trading session on 6 May, there were three distinct patterns in stock-market dynamics. Firstly, in Greece, markets showed particularly large upswings as well as downswings (Figure 1, top-left panel). Greek stock trading

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[8]As noted, for Portugal, observations between 06:30 and 10:00 EDT are missing from the data feed.

opened positively, but showed a sharp downward correction between 5:20 and 5:45 EDT. Sentiment then quickly turned positive again, but only until a second sharp correction shortly before 9:00, presumably as a reaction to the news from the ongoing ECB's monetary-policy press conference in Lisbon. Over the whole trading day, Greek stocks posted small gains, perhaps reflecting the growing belief that the Greek parliament would support the agreement on financial assistance with the IMF and the EU.

Secondly, in the three other Southern-European countries, markets initially posted small gains. This upward trend ended around the time that markets in Greece showed the first sharp downward correction. From that point onwards, stock prices in Spain, Italy, and Portugal continuously declined. Initially, these three markets still moved more or less in line with U.S. markets. However, after 10:00 markets in Southern Europe started posting large declines. For instance, the Italian equity market lost around 3.5% of its value between 10:00 and market close at 11:30.

Thirdly, for most of the trading session, volatility was low in Germany and the U.K. Markets were trending sideways, with indices remaining close to the levels at which equity markets had opened. It was not until the end of the European trading session that German and U.K. markets increasingly started to show losses. This decline came on the back of the ECB's press conference and the sharp fall in Southern-European equities. On the whole, equities in Germany posted a small loss (of 0.2%) during the trading day, while stocks in the U.K. posted a small gain (of 0.2%).

Turning to summary statistics, Table 1 gives an overview of means and standard deviations for index returns and squared returns. The table summarizes data for six European countries and the U.S. These statistics relate to the nine business days in the sample, i.e. the time span between Monday 26 April and Thursday 6 May 2010. The sample includes, for each of these nine days, the time window of roughly two hours where European and U.S. trading hours overlap. These observations form the basis for the estimation of the vector autoregressive models. In terms of mean returns, the Greek equity market is, in fact, the only one that posted gains over this two-week period. Average returns per minute are 0.005% for the FT/ASE index

(Table 1, column 1). The largest losses are for Italy, and Portugal, both of whom lost on average 0.006% per minute during the sample period. In terms of volatility, squared returns were, on average, largest in Southern Europe (Table 1, column 3). In Greece, squared returns averaged 0.015%. In Spain and Italy, the averages for squared returns were, respectively, 0.012% and 0.009%.

insert Table 1 here

4   Baseline results for spillovers

Starting with equity returns, Figures 2 and 3 present baseline spillover results, estimated for each business day between 26 April and 6 May. Each daily sample uses the two-hour window where trading in the U.S. overlaps with European market hours. This means that every data point in Figures 2 and 3 refers to a value for a spillover index, computed on the basis of a vector autoregressive model for that particular business day. The y-axis in the two figures shows the percentage contribution of shocks originating in European stock markets to forecast-error variances for U.S returns. The underlying vector autoregressive models are of order 2 and use minute-by-minute index returns. The ordering for the Cholesky factorisation is shown in the legend of the figures. The forecast errors use a ten-minute horizon. Figure 2 shows results for the four models that capture the individual pieces of news flow on 6 May. Panel A focuses on news dynamics in Southern Europe. Panel B focuses on the interactions between U.S. markets and either Germany or the U.K. Figure 3 summarizes spillovers according to three additional VAR models that combine the news-flow elements. The first model uses stock index returns in the U.S. and five European countries. The second and third model add, respectively, index returns in Portugal or Greece.

insert Figures 2 and 3 here

Most importantly, and to some extent already answering this paper's research ques-

tion, Figures 2 and 3 indicate no clear increase in return spillovers from Europe to the U.S. on the morning of 6 May, the day of the Flash Crash. For the four VAR models summarized in Figure 2, the spillovers from Europe on 6 May are never more than 5%. In fact, for three of the four models, the spillover index on that day is less than 1%. In other words, according to these estimates, around 99% of the forecast error variance for U.S. returns came from the U.S. The spillovers on 6 May were mostly comparable to or, in some cases, smaller than those on the preceding three trading days.

The degree of spillovers in the week of the Flash Crash was, in fact, comparatively limited. This point follows from comparing the left part of the two panels in Figure 2, which report results for the trading week of 26 April, with the right-hand side of each panel. In both weeks, spillovers from Europe to the U.S. were small, as less than 10% of the forecast-error variance came from innovations in European returns. However, in the week preceding the Flash Crash, spillovers were distinctly larger. For instance, spillovers were relatively high on 28 April (around 5% for the model with Greece in Panel A) and 30 April (more than 5% for the model with Germany in Panel B). Overall, these patterns may suggest that the IMF-EU financial support package had something of a calming effect on financial markets in the week of 3 May 2010.

The three VAR models that combine news-flow elements also indicate no increase in spillovers on 6 May. Figure 3 reports the results. The patterns across the two trading weeks generally echo those reported in Figure 2. Firstly, spillovers were higher in the week of 26 April compared to the week after the agreement between the Greek government and the IMF and EU. Second, spillovers were high on 28 April and 30th April, ranging between 30% on the latter and 50% on the former day. Third, there is no clear increase in spillovers in the hours before the crash on 6 May. In fact, based on these three VAR models, the level of spillovers on that day is the lowest of the nine daily estimates in this sample period.

Turning to volatility spillovers, Figures 4 and 5 report results based on models for squared returns. The two panels in Figure 4 focus on the four individual news factors, while Figure 5 reports results for three VAR models with larger sets of en-

dogenous variables.

insert Figures 4 and 5 here

Figure 4 reinforces the point that spillovers were larger in the week of 26 April compared to the week of the Flash Crash. For the bivariate model that includes the U.S. and Greece, volatility spillovers are estimated to have been especially large on 27 and 29 April (Figure 4, panel A). For the other three models in Figure 4, the spillovers are relatively large on Friday 30 April. For instance, on the basis of the model for U.S. and German returns, volatility spillovers are estimated to have been more than 30% on that day. Compared to these levels of spillovers, the week of 3 May was relatively tranquil. For the hours before the crash on 6 May, all four models indicate that volatility spillovers were, at most, 5%.

Finally, the results reported in Figure 5 are in line with the conclusions so far. All three VAR models point to relatively large volatility spillovers on 30 April. These spillovers are, in two cases, around 40%. For the model that includes Greece, the sum of cross-variance shares is close to 50%. For the week of 3 May, spillovers are generally smaller. For the model that includes Greek returns, the spillovers are largest, and these lie around 20%. For the other two VAR models, the spillovers actually decline in the course of the week of the Flash Crash.

5   Robustness and extension

This section starts with discussing two robustness checks concerning the specification of the vector autoregressive models. An extension discusses Diebold-Yilmaz (2009) indices based on all cross-variance shares.

First, we show that the conclusions do not change materially once we consider alternative orderings for the Cholesky decomposition. Here, we focus on the VAR model that combines the four elements of news flow with the highest number of available observations, i.e. the 5-variable VAR denoted by the black lines in Figures 4 and 5. In principle, given the sheer size and importance of U.S. financial markets, it

seems most logical to focus on models that order U.S. returns first. In fact, Diebold and Yilmaz (2009) also use such an ordering in their baseline estimations. However, for a 5-variable VAR, it still possible to study all possible orderings, which is why we report results for 120 different forecast-error variance decompositions. It should be noted that, at some point, alternative strategies are needed, as the dimensions of the VAR system increase with the factorial of the number of variables (Diebold and Yilmaz, 2009; Klößner and Wagner, 2014). Figures 6 and 7 describe the results for these 120 different orderings, where Figure 6 focuses on the 24 models that order the U.S. first, and Figure 7 shows boxplots for the 96 models that do not order the U.S. first. In both figures, the top panel focuses on return spillovers, while the bottom panel reports results for volatility spillovers. In the top panels of Figures 6 and 7, the solid black lines corresponds to the results for the baseline model, i.e. the model that uses the ordering U.S., U.K., Germany, Spain, and Italy.

insert Figures 6 and 7 here

Starting with models that order the U.S. first, we confirm the baseline finding that return spillovers from Europe to the U.S. on 6 May were limited (Figure 6, panel A). The 23 alternative orderings also indicate that return spillovers on the morning of the Flash Crash were lower than on the preceding eight trading days. Compared to the baseline model, spillovers are generally higher when using any of the other 23 permutations. In these alternative specifications, spillovers now reach levels of 20% - 25%.

Turning to volatility, there are again no clear indications that spillovers on 6 May were exceptional, although these spillovers are no longer always estimated to have been lower than during the preceding few trading days (Figure 6, panel B). Spillovers according to the baseline model are among the lowest of the 24 possible models. In particular during the trading week of 26 April, volatility spillovers now often reach levels of 50% - 60%. Most alternative models confirm the relatively high levels of spillovers indicated by the baseline model for 27 and 30 April. For the trading week of 3 May, there is some heterogeneity across models. There are a few

variants suggesting that spillovers increased from around 20% to 50% in that week, but these latter levels are still comparable to those seen for the preceding trading week.

For decompositions that do not order the U.S. first, we generally find that spillovers on 6 May were comparable to those in the preceding days. The two box plots in Figure 7 show distributions for the 96 different orderings, where the boxes indicate the 25th percentile, the median, and the 75th percentile. The diamonds indicate sample means, and the dark circles show outliers. Starting with returns, the average levels of spillovers (Panel A) are generally higher than those reported in Figure 6. Given the different positioning of the U.S. in these decompositions, this finding is not surprising. On average, daily return spillovers range between 70% (for 27 April) and 85% (for 28 April). Average spillovers for 6 May lie towards the top end of this range, but it should also be noted that there are several orderings (as indicated by the outliers) where the spillovers are only between 55% and 65%. For volatility, spillovers for 6 May are around 80% on average, which is a level comparable to that on 5 May and 30 April.

Second, we show that the baseline findings are robust to using richer lag specifications. Given that we can use, at most, 120 observations, the focus is on bivariate models, as otherwise the number of estimated parameters would become too large. We focus on five models that always include the U.S. and then add data from either the U.K., Germany, Spain, Italy, or Greece. For these bivariate models, we consider specifications with lag lengths of up to 5 and 10 minutes. Figure 8 reports the results, once again measured as the contribution of European shocks to the forecast-error variance for the U.S. The two top panels focus on return spillovers, while the bottom panels focus on volatility spillovers.

insert Figure 8 here

The main insight from Figure 8 is, once again, that spillovers on 6 May were not exceptionally large. In most cases, spillovers were again larger in the week preceding the Flash Crash. Having said that, the bivariate models for U.S. and Greece are an

important exception to this latter point. Return spillovers and volatility spillovers now increase during the trading week of 3 May. This finding contrast the baseline findings in Figure 3 and 4. Overall, though, spillovers on 6 May are still estimated to have been lower compared to, say, those on 28 April (Figure 8, top left panel) or 29 April (bottom two panels).

An extension reports Diebold-Yilmaz (2009) spillover indices that use all cross-variance shares. Figure 9 reports these indices for three of the seven baseline models. Panel A focuses on returns, and panel B reports spillovers for volatility.[9] Again, we conclude that spillovers on 6 May were not exceptionally large. For instance, for the model that includes the U.S., the U.K., Germany, Spain, and Italy, return spillovers are constant around a level of 60% during the sample period (Figure 9, panel A). The exception is the bivariate model for the U.S. and Greece, where the spillovers do increase to a level of around 15% in the course of the trading week of 3 May. For volatility spillovers, such an upward trend is not observed.

insert Figure 9 here

6   Conclusions

This paper finds no clear indications that spillovers from Europe contributed to the 2010 Flash Crash in the U.S. financial system. Most importantly, we find no robust evidence that equity-market spillovers were larger during the two-hour time window on 6 May when European and U.S. stock-market trading overlapped. On the contrary, both return spillovers and volatility spillovers were at levels comparable to, or much lower than, those in the preceding few trading days. This finding is based on the Diebold-Yilmaz (2009) approach that uses vector autoregressive models to measure spillovers. The conclusion is robust across a range of VAR models that capture various elements of the news flow in Europe on 6 May.

When contrasted with the tumultuous news flow stemming from Europe on 6 May 2010, this paper's main conclusion may come as a surprise. At the time,

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[9]Results for the additional five models lead to similar conclusions; results available upon request.

it was widely noted that the European trading session was a nervous one, and the intraday stock-market data discussed in this paper indeed corroborates the view that sentiment was negative, especially on Southern-European equity markets. However, this paper helps putting the events of 6 May in perspective. The trading session may have been a nervous one, but to some extent nerves of market participants seemed to have calmed compared to the preceding days. Two elements seem relevant here. First, markets seem to have taken some reassurance from the agreement on financial assistance between the Greek government, the EU, and the IMF. Secondly, on 6 May itself, it became increasingly clear that the Greek parliament would support this agreement, and in the end, Greek stock markets did not post large losses on that day. If spillovers from Europe could have contributed to the materialization of flash events, it is perhaps more surprising that this did not already occur on any of the preceding few trading days, when the levels of spillovers to the U.S. were much higher.

This paper's results further underscore the difficulties in understanding the nature of flash events in financial markets. Very few, if any, commentators have actually argued that negative sentiment surrounding the Greek debt crisis in itself caused the Flash Crash. However, pointing to the high levels of volatility in European markets on 6 May has been an often-used narrative to, at the very least, provide some intuition for the occurrence of this major flash event. This paper suggests that this particular narrative should offer little guidance in future discussions on flash events. As an alternative, it seems more promising to keep studying the role of microstructural factors, such as liquidity (Noss et al., 2017), order flow (Easley et al., 2011), or high-frequency trading (Kirilenko et al., 2017).

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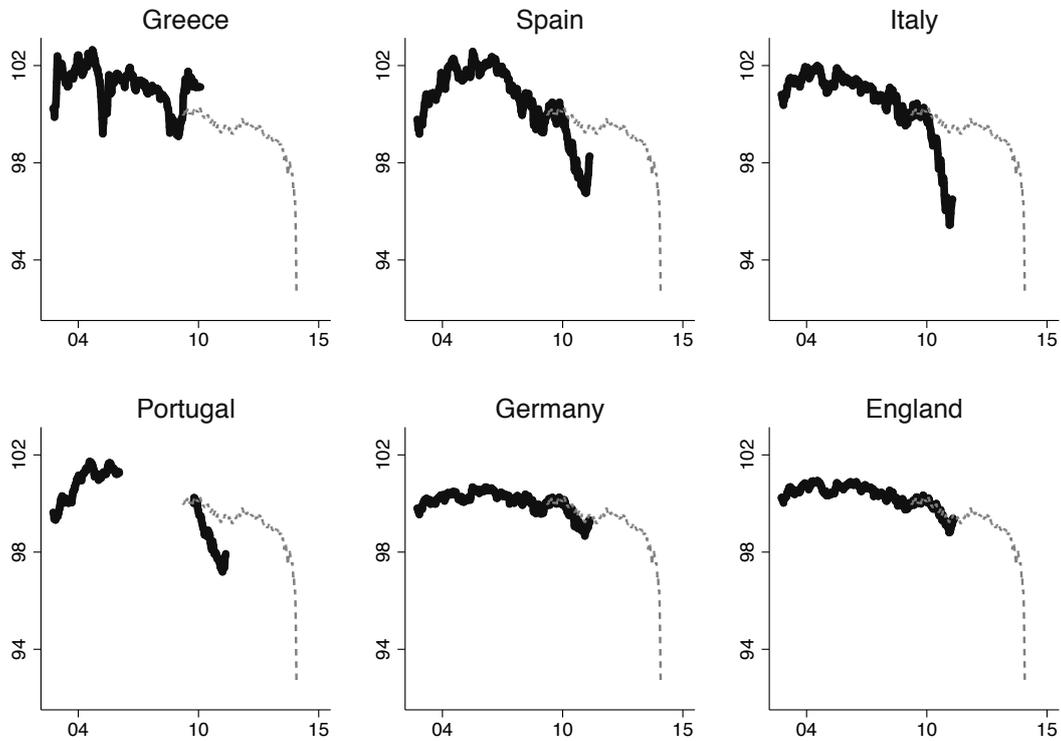`newyork/`, URL last accessed on 19 October 2018.

Figure 1. Equity Markets in Europe and the U.S. on 6 May 2010 The panels show scaled levels of stock market indices in six European countries on 6 May 2010, the day of the flash crash in the U.S. financial system. The horizontal axis represents hours according to Eastern Daylight Time (EDT). Indices are scaled so that levels at the open of the U.S. market at 9:30 EDT equal 100. The solid black lines represent the FT/ASE 20 (Greece), the IBEX 35 (Spain), the Dow Jones Italy Titans 30 (Italy), the PSI 20 (Portugal), the DAX (Germany), and the FTSE 100 (England). The gray dotted line in each panel denotes the scaled level of the Dow Jones Industrial Average between 9:30 and 14:45 EDT. For Portugal, observations between 06:30 and 10:00 EDT are missing from the data feed.
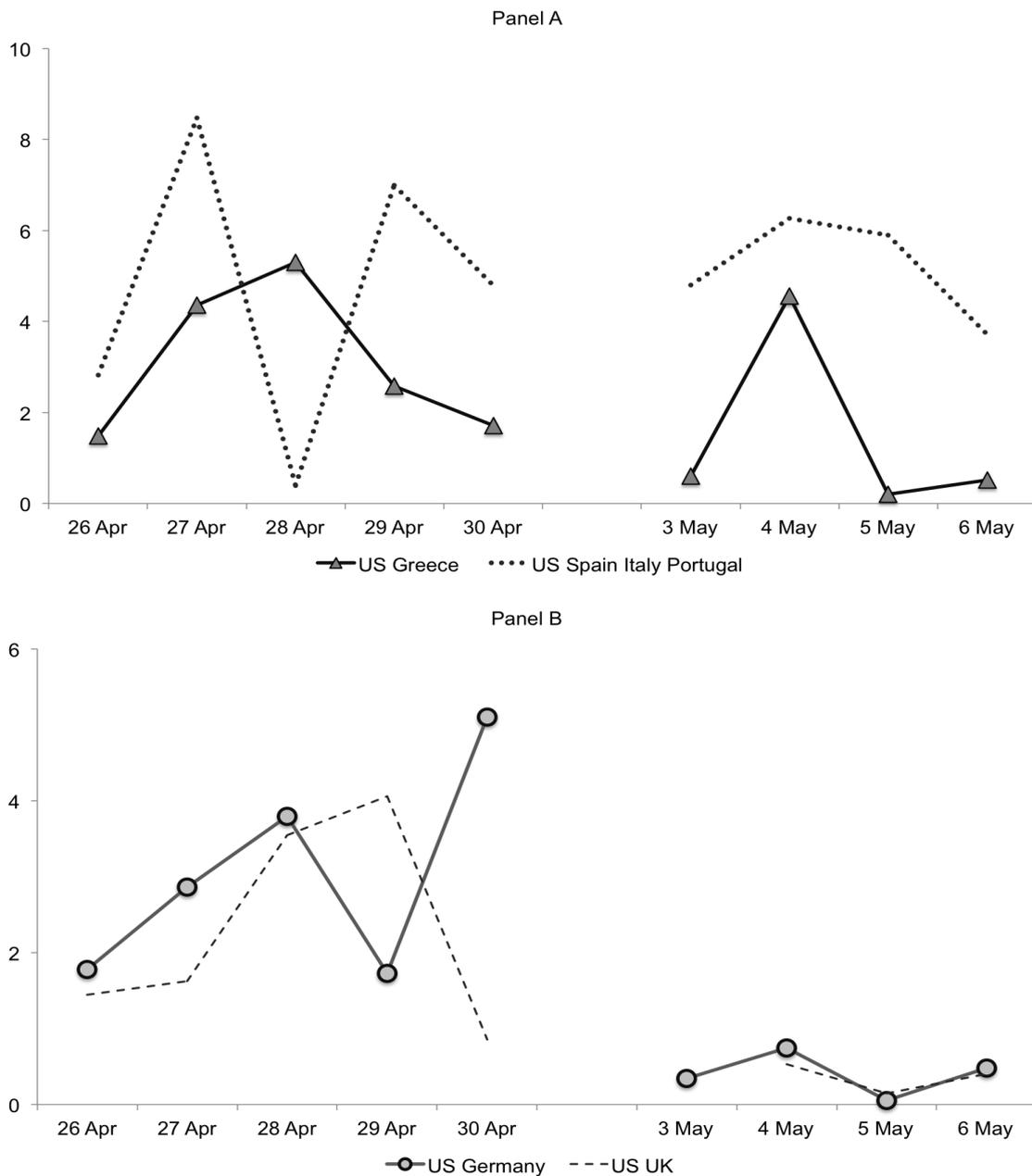
Panel A

Panel B

Figure 2. Return Spillovers From Europe to the U.S. Based on four VAR models, the panels report return spillovers from Europe to the U.S. for nine daily samples between Monday 26 April and Thursday 6 May 2010. Each sample uses the two-hour window where trading in the U.S. overlaps with Europe. The y-axis show the percentage contribution of shocks originating in Europe to the forecast-error variance for U.S index returns, following Diebold-Yilmaz (2009). The panel legends indicate the Cholesky ordering. Forecast errors use a ten-minute horizon. U.K. markets were closed on 3 May.
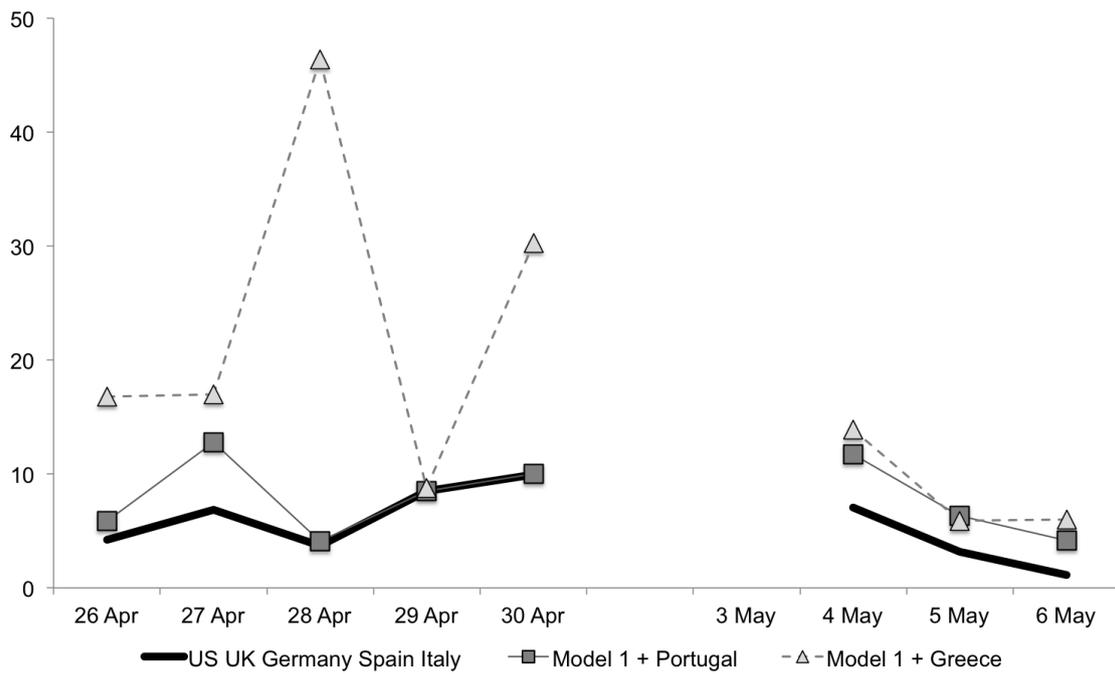
Figure 3. Return Spillovers From Europe to the U.S. The three underlying VAR models combine stock index returns for European markets with index returns on the Dow Jones Industrial Average. U.K. markets were closed on 3 May. For further details, see notes to Figure 2.
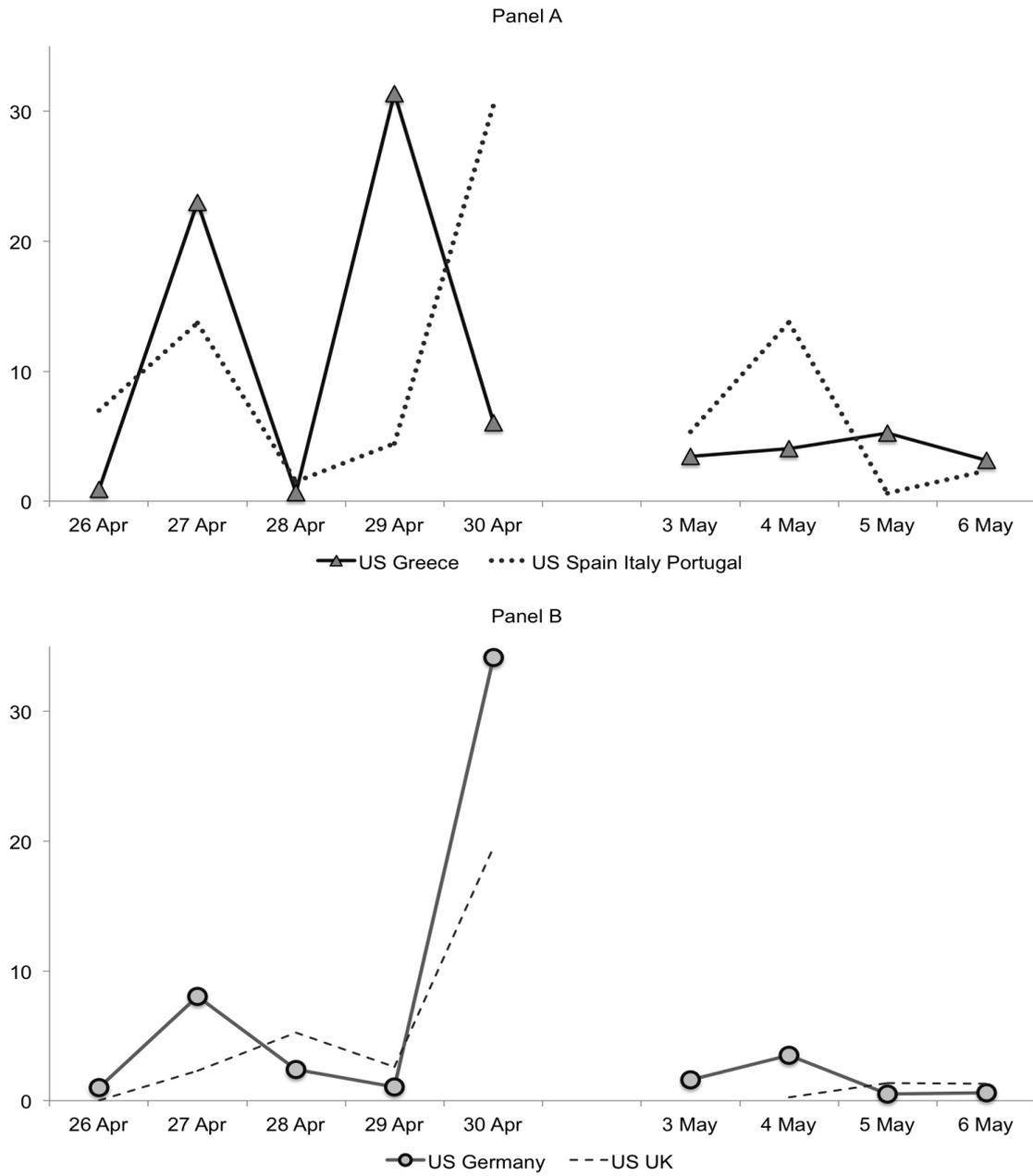
Panel A

Panel B

Figure 4. Volatility Spillovers From Europe to the U.S. See also notes to Figure 2. In this case, the endogenous variables are squared index returns.
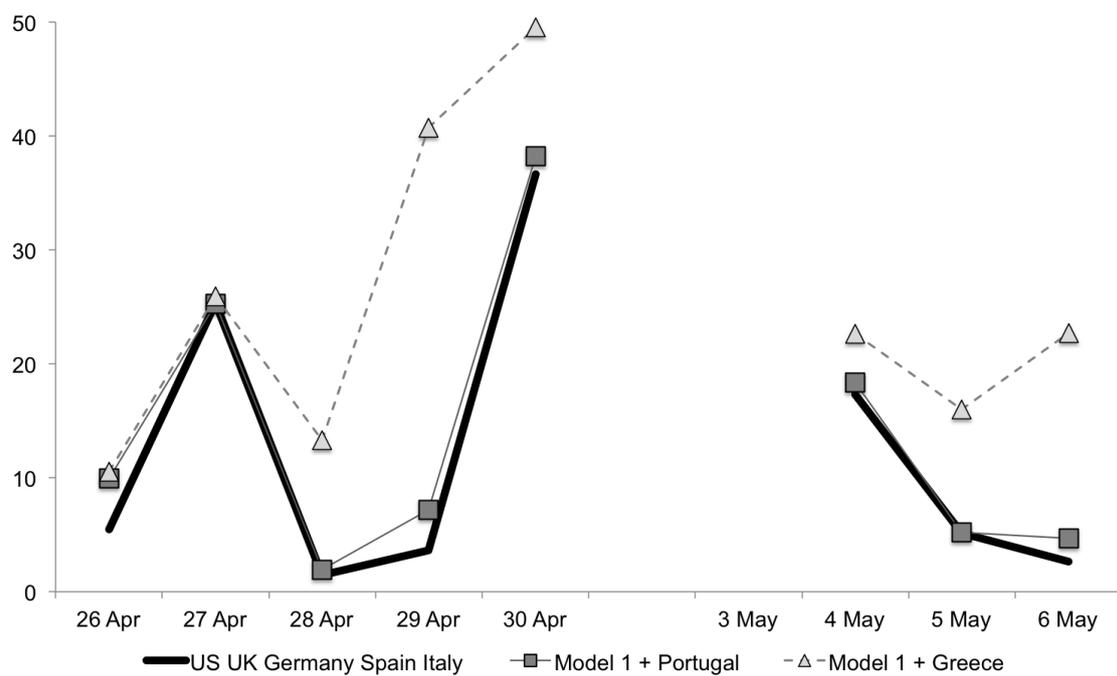
Figure 5. Volatility Spillovers From Europe to the U.S. See also notes to Figure 2. In this case, the endogenous variables are squared index returns.
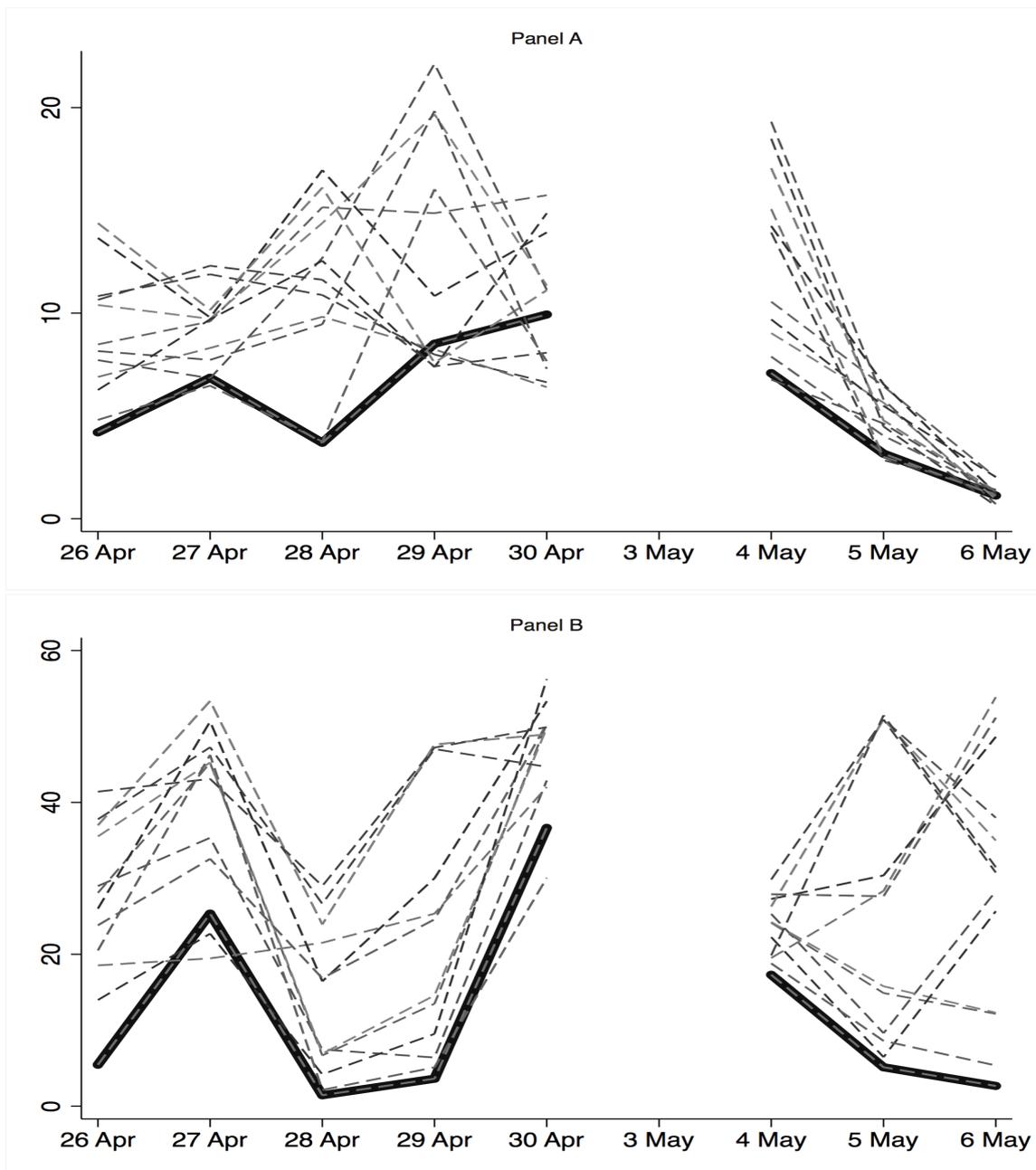
Figure 6. Spillovers for Decompositions Ranking U.S. First. This figure shows spillovers from Europe to the U.S., based on 24 Cholesky decompositions that order the U.S. first. The other countries included are the U.K., Germany, Spain, and Italy. Panel A shows return spillovers, panel B shows volatility spillovers. The black solid line in Panel A corresponds to the black line in Figure 3; the black line in Panel B corresponds to that in Figure 5.
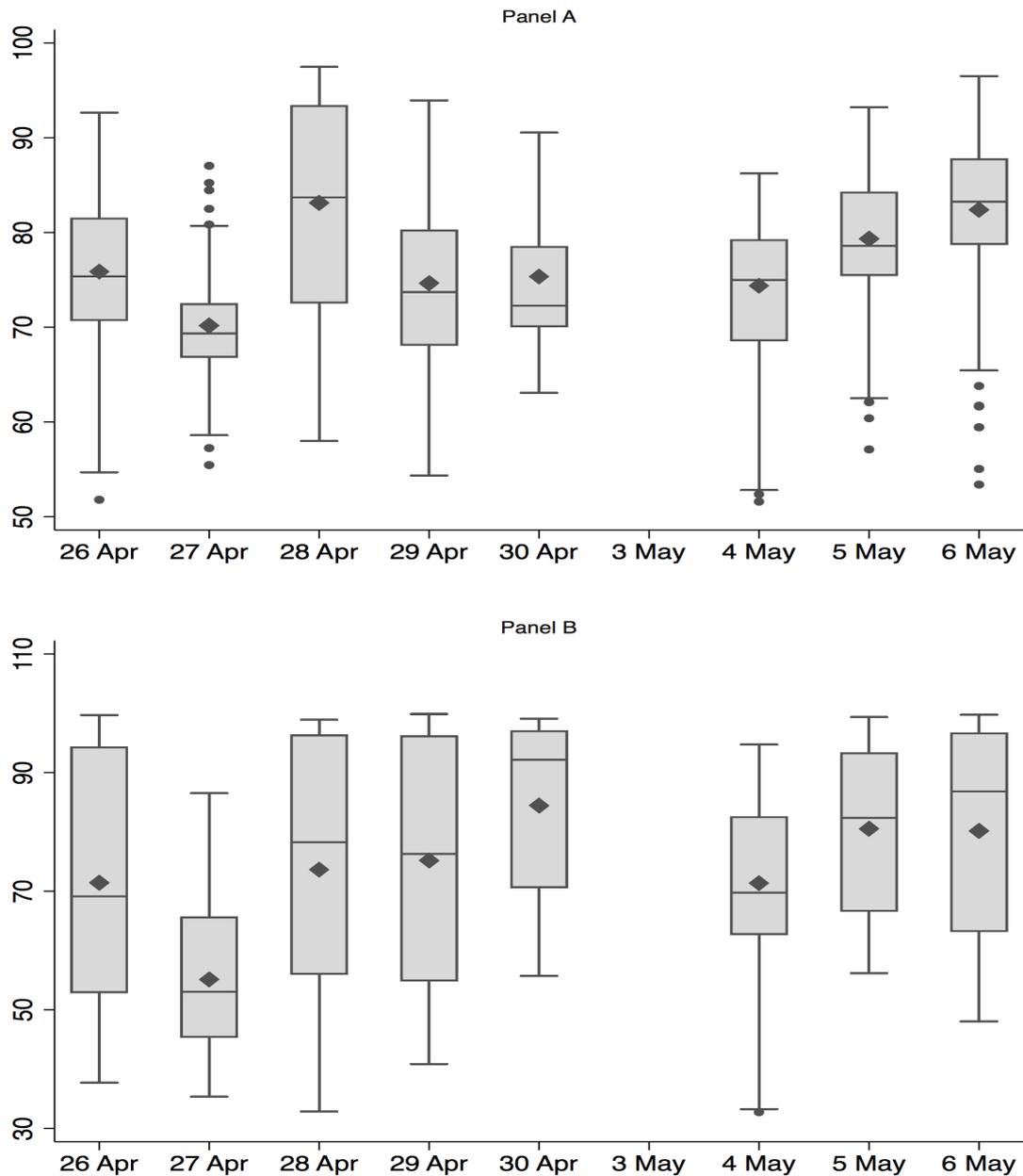
Figure 7. Spillovers for Decompositions Not Ranking U.S. First. The box plots summarize the distribution of spillovers according to 96 Cholesky orderings, all based a five-variable VAR, that do not rank the U.S. first. The other countries in the vector autoregressive model are the U.K., Germany, Spain, and Italy. Panel A shows return spillovers, panel B shows volatility spillovers. The lines in the boxes denote the median, the 25th percentile, and the 75th percentile. The black diamonds denote means, the dark circles outliers.
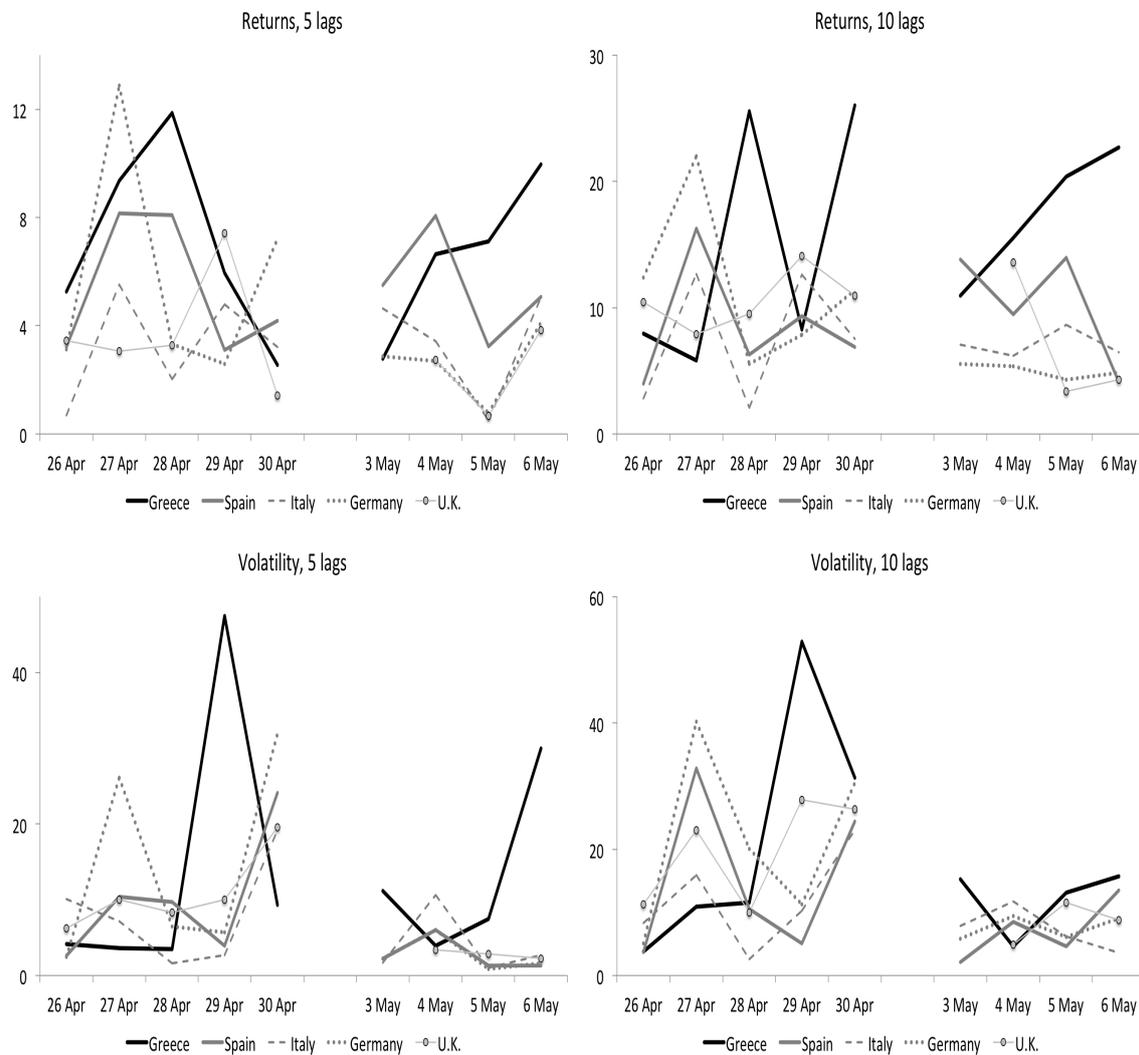
Figure 8. Robustness to Richer Lag Structures. The four panels show spillovers from five European countries to the U.S., based on bivariate vector autoregressive models. The y-axes show the percentage contribution of shocks originating in the respective European country to forecast-error variance for U.S index returns, following Diebold-Yilmaz (2009). The two top panels focus on return spillovers; the bottom panels focus on volatility spillovers. The models include either up to 5 lags (left two panels) or 10 lags (right two panels).
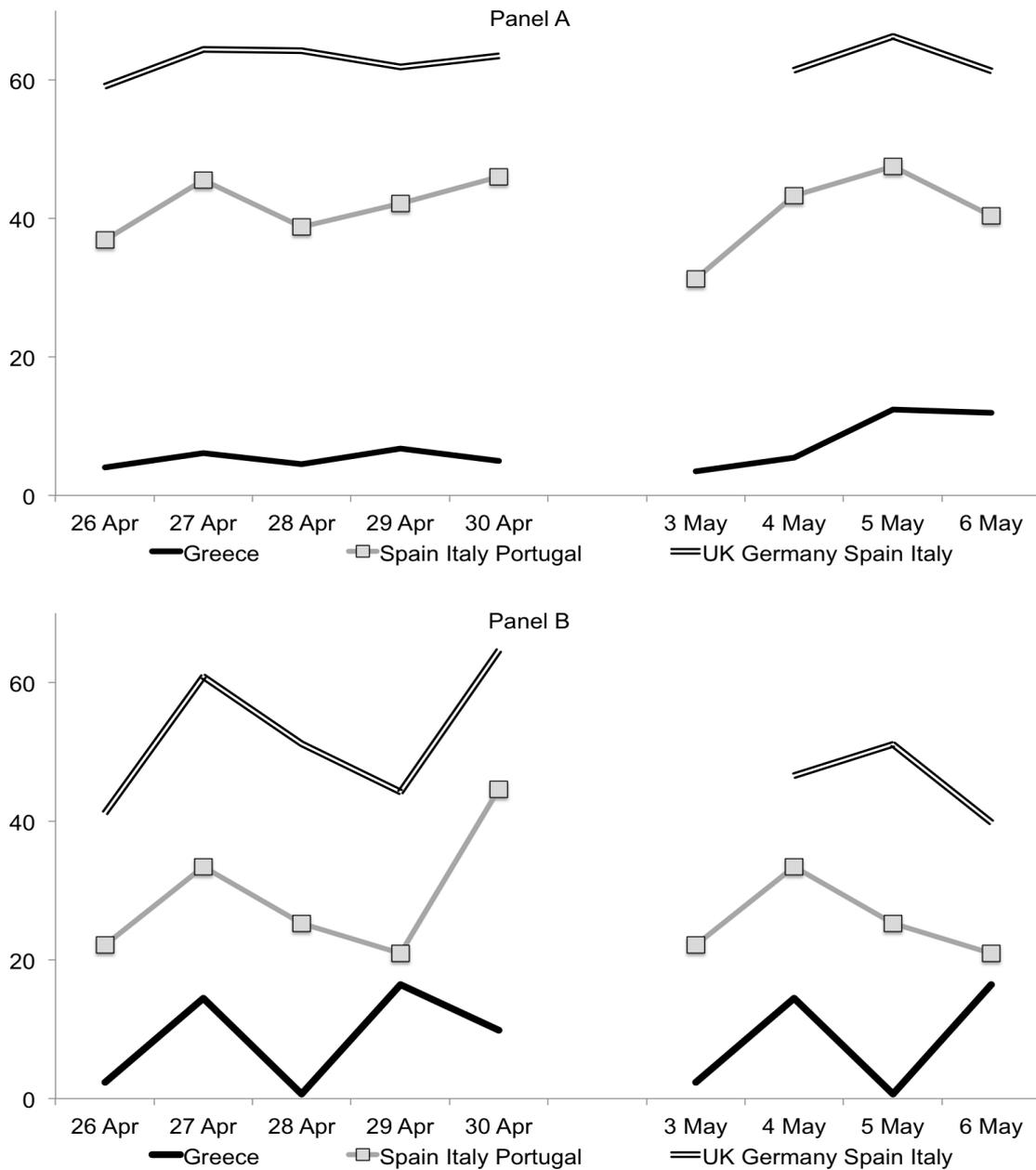
Figure 9. Spillovers Between U.S. and Europe for Selected Models. The two panels report results for the standard Diebold-Yilmaz (2009) spillover index based on all cross-variance shares in a forecast-error variance decomposition. The three selected models also include U.S. data, which is always ordered first in the Cholesky factorisations. Panel A focuses on return spillovers, while panel B focuses on volatility spillovers.

Table 1. Summary Statistics for Returns and Volatility

This table shows descriptive statistics for stock market indicators in six European countries and the U.S. Columns (1) and (2) summarize means and standard deviations for minute-by-minute index returns in percentage terms. Columns (3) and (4) summarize squared returns. The sample period corresponds to the overlap between European and U.S. trading hours, i.e. the time span between 9:30 EDT and 11:30 EDT. The sample includes the nine business days from Monday 26 April to Thursday 6 May 2010.

		(1)	(2)	(3)	(4)
		Returns		**Sq. returns**	
Country	**Index**	*Mean*	*St. dev.*	*Mean*	*St. dev.*
England	FTSE100	-0.003	0.061	0.004	0.011
Germany	DAX	-0.002	0.073	0.005	0.018
Greece	FT/ASE	0.005	0.123	0.015	0.044
Italy	DJ IT30	-0.006	0.095	0.009	0.020
Portugal	PSI 20	-0.006	0.069	0.005	0.011
Spain	IBEX 30	-0.004	0.111	0.012	0.052
United States	DJIA	-0.001	0.051	0.003	0.006

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