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* Views expressed are those of the author and do not necessarily reflect official positions of De Nederlandsche Bank.

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The international spillovers of the 2010 U.S. flash crash*

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Abstract

This paper studies the intraday spillovers of the 2010 U.S. Flash Crash to international equity markets. We document a substantial and almost immediate echo of the crash in Latin America. Using data for 148 firms trading in Argentina, Brazil, Chile, or Mexico, we estimate price declines of up to 10% within minutes after the U.S. crash. Estimates for two different factor models indicate that this echo followed from normal interdependence rather than financial contagion. There is no evidence of contagion for firms with strong links to the U.S. economy.

Keywords: flash crash, stock returns, Latin America, spillovers, contagion.
JEL classifications: G1, N2.

* Comments by Tjeerd Boonman, Michael Ehrmann, Dirk Gerritsen, Job Mangelmans, Albert Menkveld, Matthias Neuenkirch, Robert Vermeulen, Utz Weitzel, Sweder van Wijnbergen, and audiences at various venues are greatly appreciated. Any errors and omissions remain my responsibility. Views expressed in the paper do not necessarily coincide with those of de Nederlandsche Bank or the Eurosystem. Author e-mail: djansenresearch@gmail.com.

1 Introduction

The exceptionally high volatility that U.S. financial markets experienced on the afternoon of 6 May 2010 still resonates today. On that Thursday, shortly after 14:30, prices on U.S. markets unexpectedly took a sharp downward turn.[1] Within minutes, the Dow Jones Industrial Average (DJIA) had lost more than 6% of its value. Market activity increased drastically, with over 20,000 trades taking place, sometimes at prices more than 60% away from pre-crash levels. Fortunately, after a brief trading halt markets quickly recovered, so that by 15:00 most securities were again trading around pre-crash levels (CFTC-SEC, 2010).

The idea that markets could suddenly move that erratically, and for no apparent reason, did not sit well with market participants, financial regulators, and academics. This particular episode of extreme market volatility — in short: the Flash Crash — has, therefore, been the subject of intense scrutiny. The importance of understanding the Flash Crash and its repercussions was further underlined by a number of subsequent flash events, such as the more than 30 basis points drop in U.S. Treasury yields on 15 October 2014, the sudden 6% plunge of the British pound against the dollar on 7 October 2016, and the 3% drop of the euro against the dollar on Christmas Day 2017.[2]

A number of factors have been linked to the occurrence of the 2010 Flash Crash. Firstly, the crash took place against the background of already high levels of volatility and distinctly negative sentiment during the earlier parts of the trading session on 6 May (CFTC-SEC, 2010; Easley, López de Prado, and O'Hara, 2011, 2012). Secondly, the immediate trigger was the activation

[1] All times in this paper are in Eastern Daylight Time (EDT).

[2] Details on the Treasury crash are in a Joint Staff Report (2015). For details on the sterling crash, see Bank for International Settlements (2017) or Noss et al. (2017).

of a sell algorithm for 75,000 E-Mini contracts (index futures on the S&P 500) at 14:32. This algorithm, which originated from a U.S. fundamental trader, quickly led to large sell pressure and a fierce reduction in liquidity of the E-Mini market (CFTC-SEC, 2010). Thirdly, U.S. authorities eventually prosecuted a London-based trader for market manipulation. His attempts to manipulate markets had, however, not been confined to 6 May 2010. Over a number of years, this trader had frequently placed large sell orders for E-Minis at unrealistic prices, before subsequently cancelling them, while profiting in the meantime from small movements in market prices. On 6 May alone, the trader had entered at least 85 such 'spoof' sell orders, thus contributing to large imbalances in the order book of the Chicago Mercantile Exchange (Department of Justice, 2016).

Taking the U.S. events of May 6 as a starting point, this paper studies the intraday spillovers of the Flash Crash to international financial markets. To do so, this paper uses minute-by-minute data for 148 firms trading on four major Latin American stock exchanges, that is on exchanges in Argentina, Brazil, Chile, and Mexico. Latin America is a natural choice for studying international echo effects of the crash, as markets in other continents were closed at the time. Furthermore, this sample of four countries covers a large share of trading in Latin America, in particular as Brazilian markets have by far the largest traded volumes (OECD, 2013). Taken together, the countries used in this paper have a weight of more than 90% in the Dow Jones Latin America Total Stock Market Index. It is also the set of countries that often features in related work on shock transmission, such as Forbes and Rigobon (2002), Edwards, Biscarri, and Pérez de Garcia (2003), or Diebold and Yilmaz (2009).

This paper adds to the literature in two ways. Firstly, this paper contributes to the debate on the Flash Crash by documenting that its immediate ramifications were even larger than commonly discussed. Naturally, most empirical work on the crash centers on the U.S. experience. For instance, Madhavan (2011) shows that the propagation of the crash in the U.S. financial system was related to market fragmentation, as its impact was largest for stocks experiencing fragmentation before 6 May. Kirilenko, Kyle, Samadi, and Tuzun (2017) find that the trading pattern of the most active nondesignated intermediaries did not change as prices fell. Even when faced with large liquidity imbalances, these so-called high-frequency traders did not change inventory dynamics. Menkveld and Yueshen (2017) argue that the crash was not simply the price of demanding immediate liquidity. Rather, a breakdown of cross-market arbitrage between the E-Mini market and the broader U.S. financial system meant that only local buyers could fill the large sell order initiated at 14:32.

Overall then, there is not yet much evidence for the reactions of non-U.S. markets to the crash. Menkveld and Yueshen (2017) note that the crash echoed internationally by pointing to evidence for Canada. For that particular country, a government report found that the decline in equity markets during the crash equalled more than 3% (IIROC, 2010). By analysing developments for a range of Latin American firms, our paper offers a further detailed perspective on the international spillovers of flash crash events.[3]

Secondly, by exploiting the exogenous nature of the crash from the perspective of Latin America, this paper contributes to the literature on financial contagion. In particular, our paper is related to previous work studying the international fall-out of the U.S. crash of October 1987. As Forbes and Rigobon (2002) have argued, it is important in this context to distinguish between normal comovement between financial markets (i.e. interdependence)

[3]For work that studies transmission of a broad range of U.S. shocks to Latin America, see, for instance, Canova (2005).

and an increase in cross-market linkages (i.e. contagion). In earlier work on the 1987 crash, Bennett and Kelleher (1988) had described how equity prices in many countries dropped even more than in the U.S., though they argued that the interactions during the crash were similar to previous volatility spillovers. King and Wadhwani (1990) modelled the contagion after the 1987 market crash as coming from agents inferring information from price changes in other markets. Using hourly data for markets in New York, London, and Tokyo, they found that contagion coefficients increased during the crash. Bertero and Mayer (1990) found similar results, while also concluding that trading halts and capital controls may have moderated the speed of declines in some non-U.S. markets. Forbes and Rigobon (2002) then argued that tests for contagion based on changes in correlation coefficients should have corrected for differences in volatility. When revisiting the evidence on the 1987 crash while correcting for heteroskedasticity, Forbes and Rigobon (2002) no longer found evidence of a significant increase in correlations. They concluded that the market comovement after October 1987 was due to interdependence rather than contagion.

To distinguish between contagion and interdependence during the 2010 flash crash, we follow Bekaert, Ehrmann, Fratzscher, and Mehl (2014) in estimating factor models to interpret international comovements between stock returns. We estimate two such factor models. A first model uses index returns as dependent variables and a U.S. pricing factor. A second model uses returns for individual stocks and adds a global as well as a domestic pricing factor. These factor models allow us to measure normal comovements (i.e. interdependence) of Latin American markets with U.S., global, or domestic pricing factors. To study the extent to which the Flash Crash led to contagion in Latin America, we then focus on the changes in comovements with the U.S. pricing factor during the afternoon of 6 May 2010. We also look into potential heterogeneity in reactions to the crash across country and industry dimensions.

In a final extension, we consider whether particular firm characteristics explain the cross-sectional variation in spillovers. Here, we build on Forbes (2004), who found that firm characteristics were more important than country characteristics in the international transmission of the Asian and Russian crises of the 1990s. We first use four proxies for the extent to which Latin American firms are linked to the U.S. economy. For instance, we consider whether a firm's stock is cross-listed on U.S. exchanges. Secondly, we use a broad range of firm characteristics — such as total assets, market capitalisation or return on equity — taken from company reports.

This paper documents a substantial and almost immediate echo of the May 2010 Flash Crash in Latin American equity markets. We document peak-to-trough price declines of up to 10% within minutes after U.S. markets crashed. We also find that market volatility increased, bid-ask spreads widened, and trading became more intense. At the same time, we find little evidence of financial contagion related to the U.S. Flash Crash. Most crucially, two estimated factor models generally show no evidence of a significant increase in comovements with U.S. markets during or after the crash. Also, there is no evidence of contagion for Latin American firms with particularly strong links to the U.S. economy.

The evidence in this paper points to strong spillovers of the 2010 Flash Crash that were driven by interdependence rather than contagion. These findings are in line with the reinterpretation of the 1987 crash by Forbes and Rigobon (2002). The speed of developments in U.S. markets on 6 May 2010 may well explain the absence of contagion. By the time investors could have gotten excessively worried, U.S. markets had already started to recover. Still, the evidence for strong international echo effects through interdependence underscores the importance of further understanding the causes and consequences of flash events.

2 Research Design

To study the extent to which Latin American markets reacted to the U.S. Flash Crash, this paper uses minute-by-minute stock market data for four Latin American countries: Argentina, Brazil, Chile, and Mexico. This set of countries covers a large share of trading in Latin America, in particular as Brazilian markets have by far the largest traded volumes (OECD, 2013). The data set contains levels of major stock indices, stock prices for the index constituents, bid-ask spreads, the number of trades, and traded volumes. In total, we use data for 148 constituents of these four countries' stock market indices. For Argentina we use 15 constituents of the MERVAL, for Brazil we use 65 constituents of the BOVESPA, for Chile we use 35 constituents of the IPSA, while for Mexico, we use 33 constituents of the IPC. In addition, this paper uses the Dow Jones Industrial Average to proxy the U.S. pricing factor and the MSCI World Index as the global pricing factor. The U.S. three-month T-bill proxies the risk-free rate. The data source is Bloomberg, which ensures a full coverage, as trading data is transmitted directly from the stock exchanges to Bloomberg terminals.

To distinguish whether any spillovers of the U.S. crash should be interpreted as financial contagion or interdependence, this paper follows Bekaert et al. (2014) in estimating factor models. In a first model approach, we regress Latin American index returns on a U.S. pricing factor as follows[4]:

$$R_{i,t} = \alpha_{i,0} + \beta_0 R_t^{US} + \boldsymbol{\gamma}_0' R_t^{US} \boldsymbol{FC}_t + \boldsymbol{\eta}_0' \boldsymbol{FC}_t + \epsilon_{i,t} \quad (1)$$

[4] Papers using a similar set-up include Chan, Hameed, and Lau (2003), Grammatikos and Vermeulen (2012), and Ehrmann and Jansen (2017).

where $R_{i,t}$ denotes the excess return (in percentage terms) for the national stock market index in a given minute t, i indexes either Argentina, Brazil, Chile, or Mexico, while R_t^{US} is the excess return on the DJIA, and α_i is the mean return in country i up to the start of the Flash Crash episode.

The vector FC_t uses three separate dummies that follow the chronology of the Flash Crash in U.S. markets, so that $FC_t' = [FC_t^c, FC_t^r, FC_t^a]$. A first dummy captures the immediate crash period between 14:32 and 14:44. A second dummy captures the recovery between 14:46 and 14:59 after the trading halt in the E-Mini market. A third dummy captures the immediate aftermath of the crash between 15:00 and the close of U.S. markets at 16:00. We compute excess returns as the difference between returns and the U.S. three-month T-bill, where we adjust the latter to match the minute-by-minute frequency.

For a second model approach, we estimate a three-factor pricing model. Here, we use stock returns for all 148 individual constituents in our data set and build on the following specification from Bekaert et al (2014):

$$R_{i,t} = \alpha_{i,0} + \alpha_1 R_{i,t-1} + \boldsymbol{\beta}'\boldsymbol{F}_t + \boldsymbol{\eta}_0'\boldsymbol{FC}_t + \epsilon_{i,t} \tag{2}$$

$$\boldsymbol{\beta} = \boldsymbol{\beta}_0 + \boldsymbol{\gamma}_0'\boldsymbol{FC}_t \tag{3}$$

where $R_{i,t}$ now denotes the excess return (in percentage terms) for stock i in a given minute t, and F_t is a vector with excess returns for U.S., global, and domestic pricing factors, so that $F_t' = [R_t^{US}, R_t^G, R_t^D]$.[5]

We estimate the factor models using a sample that runs from 3 May 2010 up to and including 6 May 2010. In doing so, we use around 3.5 days of minute-by-minute observations to estimate regular levels of comovement.

[5] One difference with Bekaert et al. (2014) is that we directly estimate a panel fixed-effects model, whereas their paper runs a pooled regression and presents averages for individual regression coefficients.

Given the relatively short length of this sample period, the factor models do not include dividend yields as explanatory factors. All returns are in local currency.[6] For the three-factor model, we follow Bekaert et al. (2014) in excluding the return of the individual stock from the domestic pricing factor, in order to avoid picking up a spurious correlation. Also, we follow their approach of orthogonalizing the global factor by regressing MSCI returns on DJIA returns and then using the residuals from this regression as the global factor. We orthogonalize the domestic factor by regressing domestic index returns on the MSCI return and the DJIA return and then using the residual from this regression (see also Bekaert, Hodrick, and Zhang, 2009).

The estimated β coefficients of the factor models can be used to determine the degree of pre-crash equity market comovement. These β coefficients are thus an indication of interdependence between Latin American stock returns and the pricing factors in early-May 2010. An increase in comovement during the Flash Crash episode (measured by the γ coefficients) would be an indication of contagion. In particular, an increase of the comovement with the U.S. factor (γ_0^{US}) would mean that the Flash Crash directly led to contagion to Latin American equity markets.

In the final step of the analysis, we consider whether particular firm-level variables explain the cross-sectional variation in the shock transmission. In particular, we determine whether firms that have stronger linkages to the U.S. economy were differently affected during the Flash Crash. We follow Bekaert et al. (2014) in including each firm characteristic (denoted by Z) individually in the following regression model:

$$R_{i,t} = \alpha_{i,0} + \alpha_1 R_{i,t-1} + \boldsymbol{\beta}'\boldsymbol{F}_t + \boldsymbol{\eta}_0'\boldsymbol{FC}_t + \epsilon_{i,t} \tag{4}$$

$$\boldsymbol{\beta} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1'\boldsymbol{Z}_i + \boldsymbol{\gamma}'\boldsymbol{FC}_t \tag{5}$$

[6] Bekaert et al. (2014) note that their findings were comparable when using U.S. dollar returns or local currency returns.

$$\boldsymbol{\gamma} = \boldsymbol{\gamma}_0 + \boldsymbol{\gamma}_1' \boldsymbol{Z}_i \tag{6}$$

$$\boldsymbol{\eta} = \boldsymbol{\eta}_0 + \boldsymbol{\eta}_1' \boldsymbol{Z}_i \tag{7}$$

For this specific question, the important parameters in equations (4) - (7) are those in β_1 and γ_1. The three parameters in β_1 measure whether an individual Z variable has an effect on the normal comovements with US, global, and domestic pricing factors. The three parameters in γ_1 measure how the Z variables contribute to changes in comovements during the crash episode. Significant and positive estimates for parameters in γ_1 would be evidence for contagion during the Flash Crash related to specific firm characteristics.

Table 1 gives an overview of eleven Z variables that we use. We take information on these eleven Z variables from company reports for the first quarter of 2010, and we convert all data to US dollars. We start with four variables that proxy the strength of linkages with the U.S. economy (Table 1, panel A). A first variable is a dummy that measures whether a firm's stock is traded on any of the US exchanges. Around one third of the Latin American firms in the sample have cross-listed equity, mostly in the form of an American Depositary Receipt (ADR). Next, we use two variables that measure the percentage of assets or liabilities denoted in US dollars. These variables are also dummies, which take the value one if the percentage of assets or liabilities is above 5%.[7] Finally, we use a dummy variable that equals one if the company report presents figures in US dollars rather than local currency. In addition to these four variables, we use a broad set of firm characteristics (Table 1, panel B). As in Forbes (2004), we use common equity, earnings per share (EPS), market capitalisation, net income, net sales, return on equity (ROE), and total assets.

[7] Varying this particular threshold of 5% does not materially impact the conclusions. Further results available upon request.

[insert Table 1 around here]

3 Spillovers of the Crash to Latin America

Figure 1 gives a first indication that the Flash Crash had spillovers to Latin America, albeit to different extents in the four countries in the sample. The figure shows stock market indices for Argentina, Brazil, Chile, and Mexico on the afternoon of 6 May 2010. In each of the four panels, the dark line denotes the level of the index, which is scaled so that the levels at 14:32 equal 100. For comparison, the dashed line in each panel denotes the scaled level of the Dow Jones Industrial Average.

Taking the index decline between 14:32 and 14:45 as a metric, the spillovers of the Flash Crash were largest for the Brazilian equity market. From peak to trough, the decline in the BOVESPA was more than 4%. After 14:45, the Brazilian stock market also tracked the recovery of the Dow Jones quite closely. For Argentina as well as Mexico, the decline of the index was around 2%. However, markets in Argentina took longer to recover, as the MERVAL remained below the pre-crash level for the remainder of the trading session. In contrast, the Mexican IPC index had already returned to pre-crash levels around 15:15. Finally, Figure 1 indicates that the equity market of Chile was only marginally affected, with a decline in the IPSA index of less than 1%.

[insert Figure 1 around here]

Turning to data for index constituents, we find that the cumulative declines in firms' stock prices were sometimes substantial. The top line in Table 2 denotes, for each of the four countries, the largest peak-to-trough decline between 14:32 and 14:59. We observe the largest decline in Brazil, where one stock price declined by a maximum of 9.6%. In Mexico, the largest decline was 6.9%, while in Argentina and Chile the maximum declines were, respectively, 5.5% and 2.6%. These peak-to-trough changes were perhaps not as large as in the United States, where the largest decline in this time frame for a DJIA constituent was 13.9%, but the declines were still sizeable.

[insert Table 2 around here]

The other entries in Table 2 further illustrate how the Flash Crash echoed in Latin America. Table 2 summarizes averages per minute across constituents for stock returns, squared returns (as a proxy for market volatility), bid-ask spreads, the number of trades, and traded volumes. For each of these measures, we present averages for each of the three sub-periods after the crash started. The averages are the coefficients of the three dummies in the vector FC, which we include in fixed-effects panel regressions that also control for time-of-day effects. Column 5 presents, again for comparison, averages across the 25 DJIA constituents.[8]

In general, and in line with the evidence in Figure 1, we conclude that the market in Brazil was most strongly affected. On average, stock returns declined by 0.16% per minute during the immediate crash episode between 14:32 and 14:44, while volatility was up by 0.13%, and bid-ask spreads increased by 0.05%. In addition, there was a significant increase in both the number of trades (by 0.72%) and traded volumes (by 0.96%) for the 55 BOVESPA constituents (Table 2, column 2). After the immediate crash, markets in Brazil recovered quickly alongside U.S. markets, with average gains of 0.16% and 0.03% in, respectively, the recovery and aftermath period. However, between 14:46 and 16:00 markets in Brazil still saw heightened market volatility and

[8]For Chile, bid-ask spreads were not available in the data source.

trading activity.

The other entries in Table 2 illustrate that the effect of the crash was relatively large in Mexico, moderate in Argentina, and marginal in Chile. In Mexico, stock returns declined on average by 0.07% during the crash, before subsequently recovering quickly in the remainder of the trading session. As in Brazil, market volatility in Mexico increased during the crash and its aftermath, while trading activity also significantly increased. In contrast to events in Brazil, bid-ask spreads in Mexico were significantly higher (by 0.34%) only during the recovery period. In Argentina, stock returns turned negative (on average by 0.07%) as soon as U.S. markets crashed. However, there was no immediate recovery in stock prices after 14:45, while trading activity and market volatility were significantly higher during the remainder of the trading session. In Chile, the crash had marginal effects. Stock returns actually increased (by 0.06%) as U.S. markets crashed. Beyond that, there are no indications that volatility or market activity changed. On the contrary, squared returns were significantly lower (by 0.12%) between 15:00 and 16:00.

4 Estimates for Factor Models

Given the evidence for an echo of the Flash Crash in Latin America, we now turn to the interpretation using the factor models. Table 3 reports results for five regressions that use index returns as dependent variables and the U.S. market return as pricing factor. We use these regressions, which are specified as in Equation (1), to see if the comovement with the U.S. market changed during and after the crash. The first line presents the normal comovement with U.S. returns, while the remaining lines give changes in comovements during the crash, recovery, and aftermath periods. Column 1 of Table 3 presents a panel regression that pools the four indices in our data set; Columns 2 - 5 present results for time-series regressions per country.

[insert Table 3 around here]

The key insight given by Table 3 is that, in contrast to a situation of contagion, Latin American index returns decoupled from U.S. markets during and after the crash. The panel model in column 1 indicates that the normal comovement of 0.31 was reduced by 0.12 as U.S. markets crashed. The decoupling was even larger during the time period between 14:46 and 14:59 (-0.23) and still sizeable (-0.19) during the last hour of equity trading. Once again, there are interesting differences across the four countries. Normal comovements for Argentina and Chile, which were already quite low before the crash, were not significantly affected. In contrast, stock returns in Mexico decoupled quickly and, during the recovery period, almost completely from U.S. returns. In Brazil, the regular comovement of 0.74 was more than halved between 14:45 and market close.[9]

Turning to the estimates for index constituents, Table 4 presents estimated coefficients for the three-factor model outlined in equations (2) and (3). Panel A presents the β coefficients that measure interdependence. Panel B presents the γ coefficients that capture changes in comovement. Standard errors (clustered at the firm level) are in column 2.

[insert Table 4 around here]

[9]The indications of interdependence in Table 3 are broadly in line with Lahrech and Sylwester (2011). Based on a dynamic conditional correlations model, they find that Argentina and Chile showed the least comovement, while Mexican equities had the greatest comovement with the U.S. One should note that the sample period in their paper ends in 2004, making a direct comparison not possible.

Firstly, we find the expected evidence of interdependence between U.S. markets and Latin American markets. The estimated β coefficient for the U.S. factor is equal to 0.30 (Table 4, panel A), almost comparable to the point estimate for the analysis based on index returns. During the trading week analysed in this paper, Latin American stocks were relatively more responsive to domestic factors and global factors, as indicated by the β coefficients of 0.92 and 0.62, respectively. These estimates differ somewhat from the parameters reported in Bekaert et al. (2014). In particular, during the longer sample period used in their paper, Latin American stocks were more responsive to U.S. developments, as indicated by their point estimate of 0.54.

Turning to the estimates for the γ parameters, there is again no evidence for contagion of U.S. events to Latin America during the crash. Between 14:32 and 14:44, the comovement with the U.S. and global factor did not change significantly, while the comovement with domestic factors declined by 0.23 (Table 4, panel B). During the subsequent period, when U.S. financial markets recovered, we estimate a significant decrease of comovement with the U.S. and the global factor. The decoupling from U.S. events was relatively strong, as the comovement dropped by one-third to a level of 0.20. Latin American markets also decoupled to a large extent from global price formation. The comovement dropped by 0.41 from a level of 0.56.

In contrast to the analysis of index returns, the analysis of individual stock returns gives some indications of an increase in comovement during the last hour of trading on 6 May. Whereas the estimations using index returns indicate a decoupling from the U.S. market during this phase (Table 3), the analysis of individual stock returns indicates a small increase in comovement (Table 4). One way to explain these differences between the factor models may lie in the fact that index returns presents weighted averages of individual returns. To study this further, we estimated the three-factor model per quartiles of index weights.[10]

Table 5 present the loadings for the U.S. pricing factor per index weight quartile. The increase in comovement during the last hour of trading was located in the bottom quartile, i.e. those 37 firms with the smallest index weights across all 148 stocks in the sample (Table 5, column 1). The analysis based on quartiles also shows that the decoupling during the recovery phase was concentrated in the bottom three quartiles. In addition, Table 5 makes clear that during the crash phase, there was a small increase in comovement with the U.S. for the bottom three quartiles, though the estimated parameter is only significantly different from zero for the third quartile. The γ coefficients for the largest 37 firms point to a general degree of decoupling, though they are no significantly different from zero (column 4).

[insert Table 5 around here]

5 Role of Firm Characteristics

We now consider whether firm characteristics are relevant for the transmission of the Flash Crash to Latin America. Firstly, we analyse whether there was heterogeneity across industries. Table 6 reports normal comovements and changes in comovement during the Flash Crash, where we categorize the 148 individual index constituents using the Industry Classification Benchmark (ICB).[11] There are three interesting findings, though there is no consistent pattern in the sense that one particular industry is always most strongly

[10] We construct these quartiles by pooling all data and categorizing all 148 firms in four groups, as this brings us closest to the analysis in Table 4. We obtain qualitatively similar results when constructing weight quartiles per country.

[11] We exclude the technology industry, as only two Latin American firms in the sample fall into this category.

affected. Firstly, during the crash episode, there is an increase in the consumer goods industry, though the increase is only significant at the 10% level. Still, the normal comovement of 0.22 is almost doubled for this category of firms (Table 6, columns 1 and 2). Second, the decoupling from U.S. markets during the recovery phase was located in three specific industries: oil and gas, consumer services, and telecommunications. This conclusion follows from the significant and negative estimates for γ_0 of, respectively, -0.34, -0.43, and -0.22 (column 3). In particular for the latter two industries, stock returns virtually decoupled from U.S. events. Lastly, the increase in comovement during the aftermath period was located in three industries: industrials, consumer goods and financials. The increase was particularly large for the financial firms, as the normal comovement of 0.20 almost doubled to 0.39 (column 4).

[insert Table 6 around here]

Turning to a further analysis, Tables 7 and 8 report regression results for the extended three-factor model that includes, one Z variable at the time, measures for firm characteristics (equations (4) - (7)). Table 7 reports results for measures of linkages with the U.S. economy, while Table 8 focuses on a broader set of firm characteristics. The two tables report estimates for measures of interdependence (β_1) and contagion (γ_1). The γ parameters are again reported for three sub-periods. The tables show comovements with the U.S. factor, the global factor, and the domestic pricing factor. The key issue is whether there is any evidence of contagion during the crash episode, i.e. positive estimates for γ parameters related to the U.S. pricing factor.

Starting with measures for linkages to the U.S. economy, we again find no evidence for contagion during or after the crash on 6 May. Those γ estimates in Table 7 that are significantly different from zero are negative rather than positive, suggesting once again a degree of decoupling from events in US markets. Interestingly, most of this decoupling took place in the aftermath of the crash, which follows from the negative γ_1^a for firms with more than 5% assets in USD, and firms that report financial results in USD. Regarding interdependence, firms that cross-list have 0.12 higher regular comovement with the U.S. pricing factor. Firms that reports in U.S. dollars also have a 0.18 points higher β_1 coefficient, but this difference is not significant at the 10% level. Whether or not a certain percentage of assets or liabilities is held in U.S. dollars does not seems to be a very relevant factor for normal comovements, which is somewhat surprising. However, it has to be said that these two variables are not very precisely measured, as there is no uniform way of presenting this information in the company reports.

[insert Table 7 around here]

For the broader set of firm characteristics, there is again little evidence for contagion. Most γ estimates related to the U.S. market factor in Table 8 are not significantly different from zero. The only two pieces of evidence suggesting contagion concern return on equity ($\gamma_1^c = 0.01$) and the log of common equity ($\gamma_1^r = 0.06$). This first estimate indicates that a one percentage point increase in ROE meant a stronger comovement with the U.S. factor during the Flash Crash by 0.01 percentage point. The second estimate indicates that a one percentage point increase in common equity meant a stronger comovement with the U.S. factor during the Flash Crash by 0.06 percentage points. In both cases, the economic significance seems small. Moreover, these two γ estimates are only significant from zero at the 10% level. Concerning interdependence, we find that the regular comovement with the U.S.

factor increases with firm size. This conclusion follows from the positive β coefficients for common equity, market capitalisation, net income, and total assets. Overall, the analysis of firm characteristics confirms our earlier finding that contagion was virtually absent during and after the Flash Crash.

[insert Table 8 around here]

6 Conclusions

This paper finds that a flash event in U.S. financial markets can quickly and strongly affect the international financial system. As U.S. financial markets crashed shortly after 14:32 on 6 May 2010, stock returns in three out of the four major Latin American countries studied in this paper also quickly became negative. In addition, market volatility increased, bid-ask spreads widened, and trading activity increased. The effects of the U.S. crash were most visible in Brazil, where the BOVESPA index dropped by more than 4%, while stock prices of individual firms declined by up to 10%.

A natural question is to what extent this echo was a direct reaction coming from normal interlinkages in the international financial system, or, alternatively, a degree of contagion. Estimates from two different factor models give, overall, no indications that comovements between Latin American markets and the U.S. increased during the immediate crash episode. If anything, Latin American equity markets decoupled from U.S. events. It is not until the hour after the crash that there are some indications of increased comovement, but only to a small extent. Overall then, this paper finds that the spillovers of the 2010 Flash Crash occurred through interdependence rather than contagion, a conclusion that is in line with the reinterpretation of the 1987 crash by Forbes and Rigobon (2002).

This paper adds to the narrative evidence concerning the 2010 U.S. Flash Crash. In doing so, it presents evidence for international spillovers of flash events in financial markets, an element that has so far received little attention in the literature. This finding underscores the importance of further understanding the causes of flash crashes. At the same time, the speed of developments during the U.S. crash on 6 May could explain why this particular flash event did not lead to contagion. By the time investors in Latin America might have become excessively worried, U.S. markets had already started to recover. This finding suggests that contagion is less relevant in the context of flash events.

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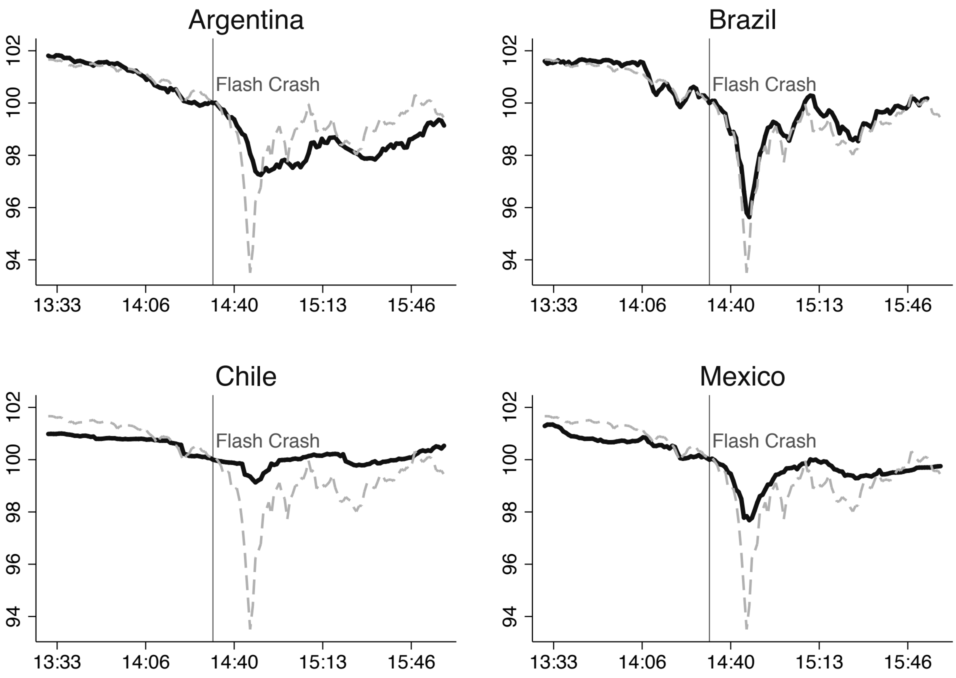

Figure 1. Equity Markets in Latin America and the Flash Crash Indices of four Latin American stock exchanges around the time of the U.S. Flash Crash on 6 May 2010. Horizontal axes in Eastern Daylight Time (EDT). The vertical lines at 14:32 denote the start of the Flash Crash. Indices are scaled so that values at 14:32 equal 100. The indices are the MERVAL (Argentina, top left), BOVESPA (Brazil, top right), IPSA (Chile, bottom left), and IPC (Mexico, bottom right). The dashed gray line in each panel tracks the rescaled level of the Dow Jones Industrial Average.

Table 1. Variable Definitions for Firm Characteristics

Variables that capture cross-sectional variation in factor loadings for the pricing model outlined in equations 4 - 7 of the main text. Firm data is taken from company reports for 2010Q1, apart from market capitalisation, which is taken from Bloomberg. Balance sheet and income statement data are converted to U.S. dollars. [a] denotes variables are in natural logs.

Variable name	*Definition*
A. Linkage with U.S. economy	
Cross-listed in US	Binary dummy, equals 1 if stock traded (mostly via American Depositary Receipt) on U.S. exchanges
Assets in USD	Binary dummy, 1 if % assets in USD > 5
Liabilities in USD	Binary dummy, 1 if % liabilities in USD > 5
Reports in USD	Binary dummy, equals 1 if USD is reporting currency in company report
B. Other firm characteristics	
Common equity[a]	Common shareholder's investment in company
Earnings per share	(Net income - Preferred dividends) / Average common shares
Market capitalisation[a]	Stock price * Shares outstanding
Net income	Income before preferred dividends, in bns. USD
Net sales[a]	Gross sales and other operating revenue minus discounts, returns, and allowances. For financial companies: equal to total operating revenue
Return on equity	100 * (Net income - Preferred dividends) / Common equity previous quarter
Total assets[a]	Sum of current assets and non-current assets

Table 2. The Echo of the Flash Crash in Latin America

Overview of market activity for Latin American and U.S. index constituents during and after the Flash Crash. 'Peak-to-trough' denotes largest cumulative decline (in %) between 14:32 and 14:59. The other entries denote averages across constituents per minute for stock returns (in %), squared returns, bid-ask spreads, number of trades (in logs), and traded volumes (in logs) during the crash (14:32 - 14:44), recovery (14:46-14:59) and aftermath (15:00 - 15:59) period. These averages are coefficients for three dummies in fixed-effects regressions that also control for time-of-day effects. *,**,*** denote significance at the 10%, 5%, 1% levels.

	(1)	(2)	(3)	(4)	(5)
Country	Argentina	Brazil	Chile	Mexico	United States
Stock index	MERVAL	BOVESPA	IPSA	IPC	DJIA
Largest peak-to-trough decline					
	5.5	9.6	2.6	6.9	13.9
Returns					
Crash	-0.07***	-0.16***	0.06	-0.07***	-0.29***
Recovery	0.00	0.16***	0.05*	0.09***	0.37***
Aftermath	0.04*	0.03***	-0.01	0.02***	0.03***
Squared returns					
Crash	0.03	0.13***	0.07	0.08*	0.32***
Recovery	0.42**	0.54***	-0.06	0.28**	0.99***
Aftermath	0.12**	0.15***	-0.12**	0.05**	0.09***
Bid-ask spreads					
Crash	0.27***	0.05***	n.a.	0.08	0.01***
Recovery	0.81***	0.17***	n.a.	0.34***	0.19***
Aftermath	0.20***	0.12***	n.a.	0.08*	0.02***
Number of trades					
Crash	0.22***	0.72***	0.19	0.70***	1.51***
Recovery	0.26**	0.67***	0.13	0.82***	1.57***
Aftermath	0.16***	0.16***	-0.01	-0.09	0.99***
Traded volumes					
Crash	0.59***	0.96***	0.43**	0.51***	1.49***
Recovery	0.34	1.00***	0.19	0.85***	1.49***
Aftermath	0.21	0.34***	-0.05	-0.08	0.72***

Table 3. Estimates Using Index Returns and U.S. Pricing Factor

This table reports results for regression models of the form:

$$R_{i,t} = \alpha_{i,0} + \beta_0 R_t^{US} + \boldsymbol{\gamma}_0' R_t^{US} \boldsymbol{FC}_t + \boldsymbol{\eta}_0' \boldsymbol{FC}_t + \epsilon_{i,t} \tag{8}$$

where $R_{i,t}$ denote index returns per minute on the MERVAL (Argentina), BOVESPA (Brazil), IPSA (Chile), and IPC (Mexico) between 3 and 6 May 2010. As explanatory variables, the model uses a U.S. pricing factor and includes interaction terms between this factor and three dummies that track the chronology of the Flash Crash on 6 May . Column 1 is based on a pooled regression, while the other four columns report time-series regressions per country. Robust standard errors in parentheses. *,**,*** denote significant differences at the 10%, 5%, 1% level, respectively.

	(1)	(2)	(3)	(4)	(5)
	Pooled	Argentina	Brazil	Chile	Mexico
Normal comovement (β_0)	0.31***	0.09*	0.74***	0.03*	0.32***
	(0.01)	(0.04)	(0.05)	(0.02)	(0.06)
Change during					
Crash (14:32 - 14:44)	-0.12***	-0.10	-0.31	0.15	-0.19**
	(0.03)	(0.08)	(0.19)	(0.11)	(0.08)
Recovery (14:46 - 14:59)	-0.23***	-0.11	-0.40***	-0.05	-0.32***
	(0.02)	(0.13)	(0.11)	(0.05)	(0.07)
Aftermath (15:00 - 15:59)	-0.19***	0.03	-0.42***	-0.03	-0.26***
	(0.02)	(0.12)	(0.10)	(0.03)	(0.07)
Number of observations	5541	1163	1536	1286	1556
Adj. R^2	0.13	0.03	0.44	0.02	0.23

Table 4. Estimates for Three-Factor Model

This table reports results for the panel regression:

$$R_{i,t} = \alpha_{i,0} + \alpha_1 R_{i,t-1} + \boldsymbol{\beta}'\boldsymbol{F}_t + \boldsymbol{\eta}_0'\boldsymbol{FC}_t + \epsilon_{i,t} \tag{9}$$

$$\boldsymbol{\beta} = \boldsymbol{\beta}_0 + \boldsymbol{\gamma}_0'\boldsymbol{FC}_t \tag{10}$$

that uses stock returns per minute for 148 firms listed on the exchanges of Argentina, Brazil, Chile, or Mexico between 3 and 6 May 2010. The β_0 coefficients capture interdependence with three pricing factors; γ_0 coefficients measure changes in comovements around the Flash Crash on 6 May. $\alpha_1 =$ -0.16 (st. err. = 0.02). N = 135,600. Standard errors in column 2, clustered by firm. *,**,*** denote significant differences at the 10%, 5%, 1% level.

	(1)	(2)
A. Interdependence	β_0	St. Err.
US factor	0.30***	0.03
Global factor	0.56***	0.05
Domestic factor	0.96***	0.03
B. Contagion	γ_0	St. Err.
Crash (14:32 - 14:44)		
US factor	0.05	0.03
Global factor	-0.09	0.32
Domestic factor	-0.23***	0.08
Recovery (14:46 - 14:59)		
US factor	-0.10**	0.04
Global factor	-0.41***	0.12
Domestic factor	-0.03	0.09
Aftermath (15:00 - 15:59)		
US factor	0.07**	0.04
Global factor	0.31**	0.14
Domestic factor	-0.01	0.06

Table 5. Loading on U.S. Factor per Index Weight Quartile

This table reports loadings on the U.S. factor per quartile of index weights for the three-factor model described in Table 4. Standard errors clustered by firm in parentheses. *,**,*** denote significant differences at the 10%, 5%, 1% level.

	(1) Smallest	(2) Q2	(3) Q3	(4) Largest
Normal comovement (β_0)	0.24***	0.33***	0.30***	0.36***
	(0.05)	(0.06)	(0.06)	(0.07)
Change during				
Crash (14:32 - 14:44)	0.02	0.11	0.12**	-0.11
	(0.06)	(0.07)	(0.06)	(0.08)
Recovery (14:46 - 14:59)	-0.19**	-0.12	-0.07	0.02
	(0.08)	(0.09)	(0.08)	(0.09)
Aftermath (15:00 - 15:59)	0.15**	0.10	0.09	-0.08
	(0.06)	(0.08)	(0.07)	(0.07)
Number of observations	33631	42566	35629	23779
R^2	0.11	0.18	0.14	0.17

Table 6. Comovement with U.S. by Industry

This table reports comovements of individual firms' stock returns with the U.S. pricing factor, based on the three-factor model described in Table 4. We classify the firms using the Industry Classification Benchmark (ICB). We exclude the technology industry, as only two firms fall into this category. Standard errors are clustered by firm. *,**,*** denote significant differences at the 10%, 5%, 1% level, respectively.

	(1)	(2)	(3)	(4)
	Normal	Change during		
		Crash	Recovery	Aftermath
Oil and gas	0.47***	0.09	-0.34**	-0.05
Basic materials	0.49***	-0.13*	-0.05	-0.15
Industrials	0.16**	-0.01	0.07	0.19*
Consumer goods	0.22***	0.18*	0.02	0.14**
Consumer services	0.36***	0.15	-0.43**	0.21
Telecommunications	0.25***	0.13	-0.22**	0.05
Utilities	0.29***	-0.01	-0.10	0.08
Financials	0.20*	-0.01	0.05	0.19***

Table 7. Role of Linkage with U.S. Economy

Contagion (γ_1) and interdependence (β_1) parameters for variables Z that proxy linkage of individual firm with the US economy. Measures are included separately in baseline model as:

$$R_{i,t} = \alpha_{i,0} + \alpha_1 R_{i,t-1} + \boldsymbol{\beta}'\boldsymbol{F}_t + \boldsymbol{\eta}_0'\boldsymbol{FC}_t + \epsilon_{i,t} \tag{11}$$

$$\boldsymbol{\beta} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1'\boldsymbol{Z}_i + \boldsymbol{\gamma}'\boldsymbol{FC}_t \tag{12}$$

$$\boldsymbol{\gamma} = \boldsymbol{\gamma}_0 + \boldsymbol{\gamma}_1'\boldsymbol{Z}_i \tag{13}$$

$$\boldsymbol{\eta} = \boldsymbol{\eta}_0 + \boldsymbol{\eta}_1'\boldsymbol{Z}_i \tag{14}$$

See panel A of Table 1 for description of variables. Standard errors clustered by firm. *,**,*** denote significance at 10%, 5%, 1% level, respectively.

	Normal	Change during		
		Crash	Recovery	Aftermath
	β_1	γ_1^c	γ_1^r	γ_1^a
Cross-listed in US				
US factor	0.12***	-0.04	0.06	-0.09
Global factor	0.15	-0.23	0.28	0.01
Domestic factor	-0.06	-0.17	-0.34**	-0.09
Assets in USD				
US factor	-0.04	0.06	0.05	-0.21***
Global factor	0.07	-1.05	-0.03	0.20
Domestic factor	-0.04	0.02	0.04	-0.24**
Liabilities in USD				
US factor	-0.07	0.07	0.08	-0.05
Global factor	0.15	-1.17*	0.18	0.11
Domestic factor	-0.04	-0.22	-0.25	-0.15
Reports in USD				
US factor	0.18	-0.12	0.16	-0.31***
Global factor	0.15	-1.27	0.39	-0.06
Domestic factor	-0.03	0.42	0.08	-0.23**

Table 8. Results for Broad Set of Firm Characteristics

Contagion (γ_1) and interdependence (β_1) parameters for firm characteristics Z that are included in baseline model as described in notes to Table 7. See panel B of Table 1 for variable descriptions. Standard errors clustered by firm. *,**,*** denote significance at 10%, 5%, 1% level.

	Normal	Change during		
		Crash	Recovery	Aftermath
	β_1	γ_1^c	γ_1^r	γ_1^a
Common equity				
US factor	0.06***	-0.04	0.06*	-0.04
Global factor	0.08***	0.12	0.15	-0.15
Domestic factor	0.00	0.00	-0.06	-0.04
Earning per share				
US factor	-0.01	0.03	0.00	0.00
Global factor	0.02	-0.30	-0.06	-0.02
Domestic factor	-0.03	-0.05	-0.04	0.03
Market capitalisation				
US factor	0.07***	-0.03	0.03	-0.03
Global factor	0.06*	0.17	0.16	-0.14
Domestic factor	0.02	-0.04	0.03	-0.05
Net income				
US factor	0.10***	-0.02	0.02	-0.03
Global factor	0.10***	-0.17	0.11	-0.22**
Domestic factor	-0.03	-0.04	0.15**	0.01
Net sales				
US factor	0.01	-0.02	0.03	-0.01
Global factor	0.08***	0.06	0.06	-0.16*
Domestic factor	-0.02	-0.06	-0.06	-0.06**
Return on equity				
US factor	0.00	0.01*	-0.00	-0.00
Global factor	-0.00	-0.05	0.01	-0.00
Domestic factor	0.00	0.00	0.00	-0.01**
Total assets				
US factor	0.05**	-0.03	0.05	-0.02
Global factor	0.09***	0.07	0.10	-0.20**
Domestic factor	0.00	-0.03	-0.08	-0.04

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